REVIEW OF PARTICLE PROPERTIES†

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Abstract

In this Review, we list, evaluate, and average measured properties of gauge bosons, leptons, quarks, mesons, and baryons. We also summarize searches for hypothetical particles such as Higgs bosons, the top quark, heavy neutrinos, monopoles, and supersymmetric particles. All the particle properties and search limits are listed in Summary Tables. We also give numerous tables, figures, formulae, and reviews of topics such as the Standard Model, particle detectors, probability, and statistics. A booklet is available containing the Summary Tables and abbreviated versions of some other sections of this full Review.

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1.4

INTRODUCTION

ACCESSING AND USING PARTICLE PHYSICS DATABASES

INTRODUCTION

I. OVERVIEW

This review is an updating through December 1991 of the *Review of Particle Properties*, a compilation of experimental results on the properties of the particles studied in elementary particle physics. These properties include masses, widths or lifetimes, branching ratios, and so on. We nearly always suggest a "best" value of each property, based on what we judge to be the best available data.

We also give an extensive summary of searches for hypothetical particles. Results of searches usually take the form of limits on masses under specified assumptions. Since such limits are often complex functions of model parameters and may be model-dependent, our summary cannot provide the detailed information given in the original papers.

Our compilation is presented in two sections, the "Summary Tables of Particle Properties" and the "Full Listings." The Summary Tables give our best values of the properties of the particles we consider to be well established; we try to be conservative in judging whether or not a particle is well established. The Summary Tables also give a condensed version of search limits for hypothetical particles, and a summary of experimental tests of conservation laws.

All data used to get the values in the Summary Tables are given in the Full Listings, with references and occasional comments. Other measurements considered recent enough or important enough to mention, but which for some reason are not used to get the best values, appear separately just beneath the data we do use for the Summary Tables. The Full Listings also give information on unconfirmed particles and on particle searches, as well as short "minireviews" on subjects of particular interest.

The Full Listings were once an archive of all published data on particle properties. This is no longer possible because there is too much data. We refer interested readers to earlier editions for data now considered to be obsolete.

We organize the particles into five categories:

Gauge and Higgs Bosons
Leptons and Quarks
Mesons
Baryons
Searches for Free Quarks, Monopoles,
Supersymmetry, Compositeness, etc.

The last category is for searches for particles, such as supersymmetric particles, that do not belong to the previous groups; searches for heavy leptons, massive neutrinos, etc., for example, are in the lepton section.

In addition to the compilations of measurements and best values, we give a long section of "Miscellaneous Tables, Figures, and Formulae," a quick reference for the practicing particle physicist.

In Sec. II of this Introduction, we list the main areas of responsibility of the authors, and also list our large number of consultants on special topics. In Sec. III, we mention the naming scheme for hadrons. In Sec. IV, we discuss our procedures for selecting measurements of particle properties and for obtaining best values of the properties from the measurements.

The accuracy and usefulness of this compilation depend in large part on interaction between the users and the authors and consultants. We appreciate comments, criticisms, and suggestions for improvements of any kind. Please send them to the appropriate author, according to the list of responsibilities in Sec. II below, or to

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Or send them via computer mail to

LBL::PDG on HEPNET,
PDG@LBL on BITNET, or
PDG@LBL.GOV on INTERNET

A pocket-sized Particle Properties Data Booklet is available. This contains the complete Summary Tables of Particle Properties and the most frequently used parts of the Miscellaneous Section, but not the Full Listings. For North and South America, Australia, and the Far East, write to

Technical Information Department
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Consultants

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M. Della Negra (CERN), Chair
J. Donoghue (University of Massachusetts)
E. Eichten (Fermilab)
B. Taylor (National Inst. of Standards & Technology)
W. Toki (SLAC)

III. THE NAMING SCHEME FOR HADRONS

We introduced in the 1986 edition [Particle Data Group (1986)] a new naming scheme for the hadrons. Changes from older terminology affected mainly the heavier mesons made of u, d, and s quarks. Otherwise, the only important change to known hadrons was that the $F^{\pm}$ became the $D_s^{\pm}$. None of the lightest pseudoscalar or vector mesons changed names, nor did the $c\bar{c}$ or $b\bar{b}$ mesons (we do, however, now use χ_c for the $c\bar{c}$ χ states), nor did any of the established baryons. The Summary Tables give both the new and old names whenever a change has occurred.

The scheme is described in "Naming Scheme for Hadrons" in Section III of this *Review*.

We give here our conventions on type-setting style. Particle symbols are italic (or slanted) characters: e^-, p, Λ, π^0, K_L, D_s^+, b. Charge is indicated by a superscript: B^-, Δ^{++}. Charge is not normally indicated for p, n, and quarks, and is optional for neutral isosinglets: η or η^0. Antiparticles and particles are distinguished by charge for charged leptons and mesons: τ^+, K^-. Otherwise, distinct antiparticles are indicated by a bar (overline): $\overline{\nu}_\mu$, $\bar{t}$, $\overline{p}$, $\overline{K}^0$, and $\overline{\Sigma}^+$ (the antiparticle of the Σ^-).

IV. PROCEDURES

A. Selection and treatment of data

The Full Listings contain a complete record of all *relevant* data we know of; with few exceptions, however, we do not include results from preprints or conference reports. Nor do we any longer maintain an archival record of data of historical importance only, although we try to retain the references of discoveries, even when the data are no longer useful.

In the Full Listings, we clearly separate measurements that are used to calculate or estimate values given in the Summary Tables from measurements that are not used. We give explanatory comments in many such cases. Among the reasons a measurement might be excluded are the following:

- It is superseded by or included in later results.
- No error is given.
- It involves some assumptions we question.
- It has a poor signal-to-noise ratio, low statistical significance, or is otherwise of poorer quality than other data available.
- It is clearly inconsistent with other results that appear to be more reliable.
- It is not independent of other results.
- It is not the best limit (see below).

In some cases, *none* of the measurements is entirely reliable and no average is calculated. For example, the masses of many of the baryon resonances, obtained from partial-wave analyses, are quoted as estimated ranges thought to probably include the true values, rather than as averages with errors. This is discussed in the Baryon Full Listings.

For upper limits, we normally quote in the Summary Tables the strongest limit. We do not average or combine upper limits except in a very few cases where they may be re-expressed as measured numbers with Gaussian errors.

As is customary, we assume that particle and antiparticle share the same spin, mass, and mean life. The Tests of Conservation Laws table, following the Summary Tables, lists tests of CPT as well as other conservation laws.

We use the following indicators in the Full Listings to tell how we get values from the tabulated measurements:

- OUR AVERAGE—From a weighted average of selected data.
- OUR FIT—From a constrained or overdetermined multi-parameter fit of selected data.
- OUR EVALUATION—Not from a direct measurement, but evaluated from measurements of other quantities.
- OUR ESTIMATE—Based on the observed range of the data. Not from a formal statistical procedure.
- OUR LIMIT—For special cases where the limit is evaluated by us from measured ratios or other data. Not from a direct measurement.

An experimentalist who sees indications of a particle will of course want to know what has been seen in that region in the past. Hence we include in the Full Listings all reported states that, in our opinion, have sufficient statistical merit and that have not been disproved by more reliable data.

We promote to the Summary Tables only those states that we feel are well established. This judgment is, of course, somewhat subjective and no precise criteria can be given. For more detailed discussions, see the minireviews in the Full Listings.

B. Averages and fits

We divide this discussion on obtaining averages and errors into three sections: (1) treatment of errors; (2) unconstrained averaging; (3) constrained fits.

1. Treatment of errors

In what follows, the "error" δx means that the range $x \pm \delta x$ is intended to be a 68.3% confidence interval about the central value x. We treat this error as if it were Gaussian. Thus when the error *is* Gaussian, δx is the usual one standard deviation (1σ). Many experimenters now give statistical and systematic errors separately, in which case we usually quote both errors, with the statistical error first. For averages and fits, we then add the the two errors in quadrature and use this combined error for δx.

When experimenters quote asymmetric errors $(\delta x)^+$ and $(\delta x)^-$ for a measurement x, the error that we use for that measurement in making an average or a fit with other measurements is a continuous function of these three quantities. When the resultant average or fit $\overline{x}$ is less than $x-(\delta x)^-$, we use $(\delta x)^-$; when it is greater than $x+(\delta x)^+$, we use $(\delta x)^+$. In between, the error we use is a linear function of x. Since the errors we use are functions of the result, we iterate to get the final result. Asymmetric output errors are determined from the input errors assuming a linear relation between the input and output quantities.

In fitting or averaging, we usually do not include correlations between different measurements, but we try to select data in such a way as to reduce correlations. Correlated errors are, however, treated explicitly when there are a number of results of the form $A_i \pm \sigma_i \pm \Delta$ that have identical systematic errors Δ. In this case, one can first average the $A_i \pm \sigma_i$ and then combine the resulting statistical error with Δ. One obtains, however, the same result by averaging $A_i \pm (\sigma_i^2 + \Delta_i^2)^{1/2}$, where $\Delta_i = \sigma_i \Delta[\sum(1/\sigma_j^2)]^{1/2}$. This procedure has the advantage that, with the modified systematic errors Δ_i, each measurement may be treated as independent and averaged in the usual way with other data. Therefore, when appropriate, we adopt this procedure. We tabulate Δ and invoke an automated procedure that computes Δ_i before averaging and we include a note saying that there are common systematic errors.

Another common case of correlated errors occurs when experimenters measure two quantities and then quote the two and their difference, *e.g.*, m_1, m_2, and $\Delta = m_2 - m_1$. We cannot enter m_1, m_2 and Δ into a constrained fit because they are not independent. In some cases, it is a good approximation to ignore the quantity with the largest error and put the other two into the fit. However, in some cases correlations are such that the errors on m_1, m_2 and Δ are comparable and none of the three values can be ignored. In this case, we put all three values into the fit and invoke an automated procedure to increase the errors prior to fitting such that the three quantities can be treated as independent measurements in the constrained fit. We include a note saying that this has been done.

2. Unconstrained averaging

To average data, we use a standard weighted least-squares procedure and in some cases, discussed below, increase the errors with a "scale factor." We begin by assuming that measurements of a given quantity are uncorrelated, and calculate a weighted average and error as

$$\overline{x} \pm \delta\overline{x} = \left(\Sigma_i w_i\, x_i\right) \Big/ \Sigma_i\, w_i \,\pm\, \left(\Sigma_i w_i\right)^{-1/2} \ , \tag{1}$$

where

$$w_i = 1/(\delta x_i)^2 \ .$$

Here x_i and δx_i are the value and error reported by the ith experiment, and the sums run over N experiments. We then calculate $\chi^2 = \sum w_i(\overline{x} - x_i)^2$ and compare it with $N-1$, which is the expectation value of χ^2 if the measurements are from a Gaussian distribution.

If $\chi^2/(N-1)$ is less than or equal to 1, and there are no known problems with the data, we accept the results.

If $\chi^2/(N-1)$ is very large, we may choose not to use the average at all. Alternatively, we may quote the calculated average, but then make an educated guess of the error, a conservative estimate designed to take into account known problems with the data.

Finally, if $\chi^2/(N-1)$ is greater than 1, but not greatly so, we still average the data, but then also do the following:

(a) We increase our quoted error, $\delta\overline{x}$ in Eq. (1), by a scale factor S defined as

$$S = \left[\chi^2/(N-1)\right]^{1/2} \ . \tag{2}$$

Our reasoning is as follows. The large value of the χ^2 is likely to be due to underestimation of errors in at least one of the experiments. Not knowing which of the errors are underestimated, we assume they are all underestimated by the same factor S. If we scale up all the input errors by this factor, the χ^2 becomes $N-1$, and of course the output error $\delta\overline{x}$ scales up by the same factor. See Rosenfeld (1975).

When combining data with widely varying errors, we modify this procedure slightly. We evaluate S using only the experiments with smaller errors. Our cutoff or ceiling on δx_i is arbitrarily chosen to be

$$\delta_0 = 3N^{1/2}\,\delta\overline{x} \ ,$$

where $\delta\overline{x}$ is the unscaled error of the mean of all the experiments. Our reasoning is that although the low-precision experiments have little influence on the values $\overline{x}$ and $\delta\overline{x}$, they can make significant contributions to the χ^2, and the contribution of the high-precision experiments thus tends to be obscured. Note that if each experiment has the same error δx_i, then $\delta\overline{x}$ is $\delta x_i/N^{1/2}$, so each δx_i is well below the cutoff. (More often, however, we simply exclude measurements with relatively large errors from averages and fits: new, precise data chase out old, imprecise data.)

Our scaling procedure has the property that if there are two values with comparable errors separated by much more than their stated errors (with or without a number of other values of lower accuracy), the scaled-up error $\delta\overline{x}$ is approximately half the interval between the two discrepant values.

We emphasize that our scaling procedure for *errors* in no way affects central values. In addition, to recover the unscaled error $\delta\overline{x}$, simply divide the quoted error by S.

(b) If, after removing experiments with errors larger than δ_0, the number M remaining is at least three, and if $\chi^2/(M-1)$ is greater than 1.25, we show in the Full Listings an ideogram of the data. Fig. 1 is an example. We extract no numbers from these ideograms; they are simply visual aids. Sometimes one or two data points lie apart from the main body; other times the data split into two or more groups. The reader can use this information in deciding upon an alternative average.

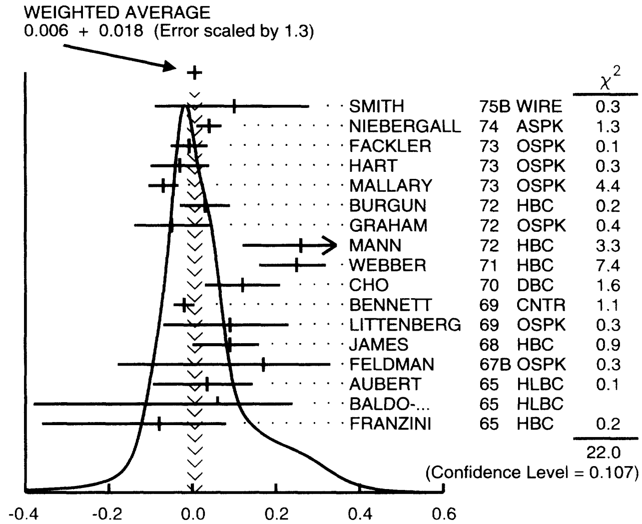

Fig. 1. A typical ideogram. The "data point" at the top shows the position of the weighted average, while the width of the error bar (and the shaded pattern beneath it) shows the error in the average after scaling by the factor S. The column on the right gives the χ^2 contribution of each of the experiments. Note that the experiment second from the bottom, denoted by the incomplete error flag ($\perp$), is not used in the calculation of S (see the text).

Each measurement in an ideogram is represented by a Gaussian with a central value x_i, error δx_i, and area proportional to $1/\delta x_i$. The choice of $1/\delta x_i$ for the area is somewhat arbitrary. With this choice, the center of gravity of the ideogram corresponds to an average that uses weights $1/\delta x_i$ rather than the $(1/\delta x_i)^2$ used in the averages. This may be appropriate for the case in which some of the experiments have seriously underestimated systematic errors. However, since for this choice of area the height of the Gaussian for each measurement is proportional to $(1/\delta\, x_i)^2$, the peak position of the ideogram will often favor the high-precision measurements at least as much as does the least-squares average. See our 1986 edition [Particle Data Group (1986)] for a detailed discussion of the use of ideograms.

3. Constrained fits

Except for trivial cases, all branching ratios and rate measurements are analyzed by making a simultaneous least-squares fit to all the data and extracting the partial decay fractions P_i, the partial widths Γ_i, the full width Γ (or mean life), and the associated error matrix.

Assume, for example, that a state has m partial decay fractions P_i, where $\sum P_i = 1$. These have been measured in N_r different ratios R_r, where, e.g., $R_1 = P_1/P_2$, $R_2 = P_1/P_3$, etc. [We can handle any ratio R of the form

$\sum \alpha_i P_i / \sum \beta_i P_i$, where α_i and β_i are constants, usually 1 or 0. The forms $R = P_i P_j$ and $R = (P_i P_j)^{1/2}$ are also allowed.] Further assume that *each* ratio R has been measured by N_k experiments (we designate each experiment with a subscript k, e.g., R_{1k}). We then find the best values of the fractions P_i by minimizing the χ^2 as a function of the $m-1$ independent parameters:

$$\chi^2 = \sum_{r=1}^{N_r} \left[\sum_{k=1}^{N_k} \left(\frac{R_{rk} - R_r}{\delta R_{rk}} \right)^2 \right] , \tag{3}$$

where the R_{rk} are the measured values and R_r are the fitted values of the branching ratios.

In addition to the fitted values $\overline{P}_i$, we calculate an error matrix $\langle \delta \overline{P}_i \; \delta \overline{P}_j \rangle$. We tabulate the diagonal elements of $\delta \overline{P}_i = \langle \delta \overline{P}_i \; \delta \overline{P}_i \rangle^{1/2}$ (except that some errors are scaled as discussed below). In the Full Listings, we give the complete correlation matrix; we also calculate the fitted value of each ratio, for comparison with the input data, and list it above the relevant input, along with a simple unconstrained average of the same input.

Three comments on the example above:

(1) There was no connection assumed between measurements of the full width and the branching ratios. But often we also have information on partial widths Γ_i as well as the total width Γ. In this case we must introduce Γ as a parameter in the fit, along with the P_i, and we give correlation matrices for the widths in the Full Listings.

(2) We do *not* allow for correlations between input data. We *do* try to pick those ratios and widths that are as independent and as close to the original data as possible. When one experiment measures all the branching fractions and constrains their sum to be one, we leave one of them (usually the least well-determined one) out of the fit to make the set of input data more nearly independent.

(3) We calculate scale factors for both the R_r and P_i when the measurements for any R give a larger-than-expected contribution to the χ^2. According to Eq. (3), the double sum for χ^2 is first summed over experiments $k = 1$ to N_k, leaving a single sum over ratios $\chi^2 = \sum \chi_r^2$. One is tempted to define a scale factor for the ratio r as $S_r^2 = \chi_r^2 / \langle \chi_r^2 \rangle$. However, since $\langle \chi_r^2 \rangle$ is not a fixed quantity (it is somewhere between N_k and N_{k-1}), we do not know how to evaluate this expression. Instead we define

$$S_r^2 = \frac{1}{N_k} \sum_{k=1}^{N_k} \left[\frac{\left(R_{rk} - \overline{R}_r \right)^2}{(\delta R_{rk})^2 - (\delta \overline{R}_r)^2} \right] , \tag{4}$$

where $\delta \overline{R}_r$ is the fitted error for ratio r. With this definition the expected value of S_r^2 is one.

The fit is redone using errors for the branching ratios that are scaled by the larger of S_r and unity, from which new and often larger errors $\delta \overline{P}_i'$ are obtained. The scale factors we finally list in such cases are defined by $S_i = \delta \overline{P}_i' / \delta \overline{P}_i$. However, in line with our policy of not letting S affect the central values, we give the values of $\overline{P}_i$ obtained from the original (unscaled) fit.

There is one special case in which the errors that are obtained by the preceding procedure may be changed. When a fitted branching ratio (or rate) $\overline{P}_i$ turns out to be less than three standard deviations $(\delta \overline{P}_i')$ from zero, a new smaller error $(\delta \overline{P}_i'')^-$ is calculated on the low side by requiring the area under the Gaussian between $\overline{P}_i - (\delta \overline{P}_i'')^-$ and $\overline{P}_i$ to be 68.3% of the area between zero and $\overline{P}_i$. A similar correction is made for branching fractions that are within three standard deviations of one. This keeps the quoted errors from overlapping the boundary of the physical region.

C. Discussion

The problem of averaging data containing discrepant values is nicely discussed by Taylor (1982). He considers a number of algorithms that attempt to incorporate inconsistent data into a meaningful average. However, it is difficult to develop a procedure that handles simultaneously in a reasonable way two basic types of situations: (a) data that lie apart from the main body of the data are incorrect (contain unreported errors); and (b) the opposite—it is the main body of data that is incorrect. Unfortunately, as Taylor shows, case (b) is not infrequent. He concludes that the choice of procedure is less significant than the initial choice of data to include or exclude.

We place much emphasis on this choice of data. Often we solicit the help of outside experts (consultants). Sometimes, however, it is simply impossible to determine which of a set of discrepant measurements are correct. Our scale-factor technique is an attempt to address this ignorance by increasing the error. In effect, we are saying that present experiments do not allow a precise determination of this constant because of unresolvable discrepancies, and one must await further measurements. The reader is warned of this situation by the size of the scale factor, and if he or she desires can go back to the literature (via the Full Listings) and redo the average with a different choice of data.

Our situation is less severe than most of the cases Taylor considers, such as estimates of the fundamental constants like $\hbar$, etc. Most of the errors in his case are dominated by systematic effects. For our data, statistical errors are often at least as large as systematic errors, and statistical errors are usually easier to estimate. A notable exception occurs in partial-wave analyses, where different techniques applied to the same data yield different results. In this case, as stated earlier, we often do not make an average but just quote a range of values.

A brief history of early Particle Data Group averages is given in Rosenfeld (1975). Updated versions of some of Rosenfeld's figures are shown in Fig. 2.

Some cases of wild fluctuation are shown. This usually reflects the introduction of significant new data or the discarding of older data. Older data are discarded in favor of newer data when it is felt that the newer data have smaller systematic errors, or have more checks on systematic errors, or have made corrections unknown at the time of the older experiments, or simply have much smaller errors. Sometimes, the scale factor becomes large near the time at which a large jump takes place, reflecting the uncertainty introduced by the new and inconsistent data. By and large, however, a full scan of our history plots shows a dull progression toward greater precision at central values quite consistent with the first data points shown.

We conclude that the reliability of the combination of experimental data and Particle Data Group averaging procedures is usually good, but it is important to be aware that fluctuations outside of the quoted errors can and do occur.

ACKNOWLEDGMENTS

The publication of the *Review of Particle Properties* is supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract No. DE–AC03–76SF00098, by the U.S. National Science Foundation under Agreement No. PHY86–15529, and by the Italian Istituto Nazionale de Fisica Nucleare (INFN). Partial funding to cover the cost of this *Review* is also provided by the European Laboratory for Particle Physics (CERN) and by an implementing arrangement between the governments of Japan (Monbusho) and the United States (DOE) on cooperative research and development.

We thank all those who have assisted in the many phases of preparing this *Review*. We particularly thank the many who have responded to our requests for verification of data entered in the Listings, and those who have made suggestions or pointed out errors. The Berkeley members of the Particle Data Group acknowledge the organizational, secretarial, and baking skills of Gail Harper.

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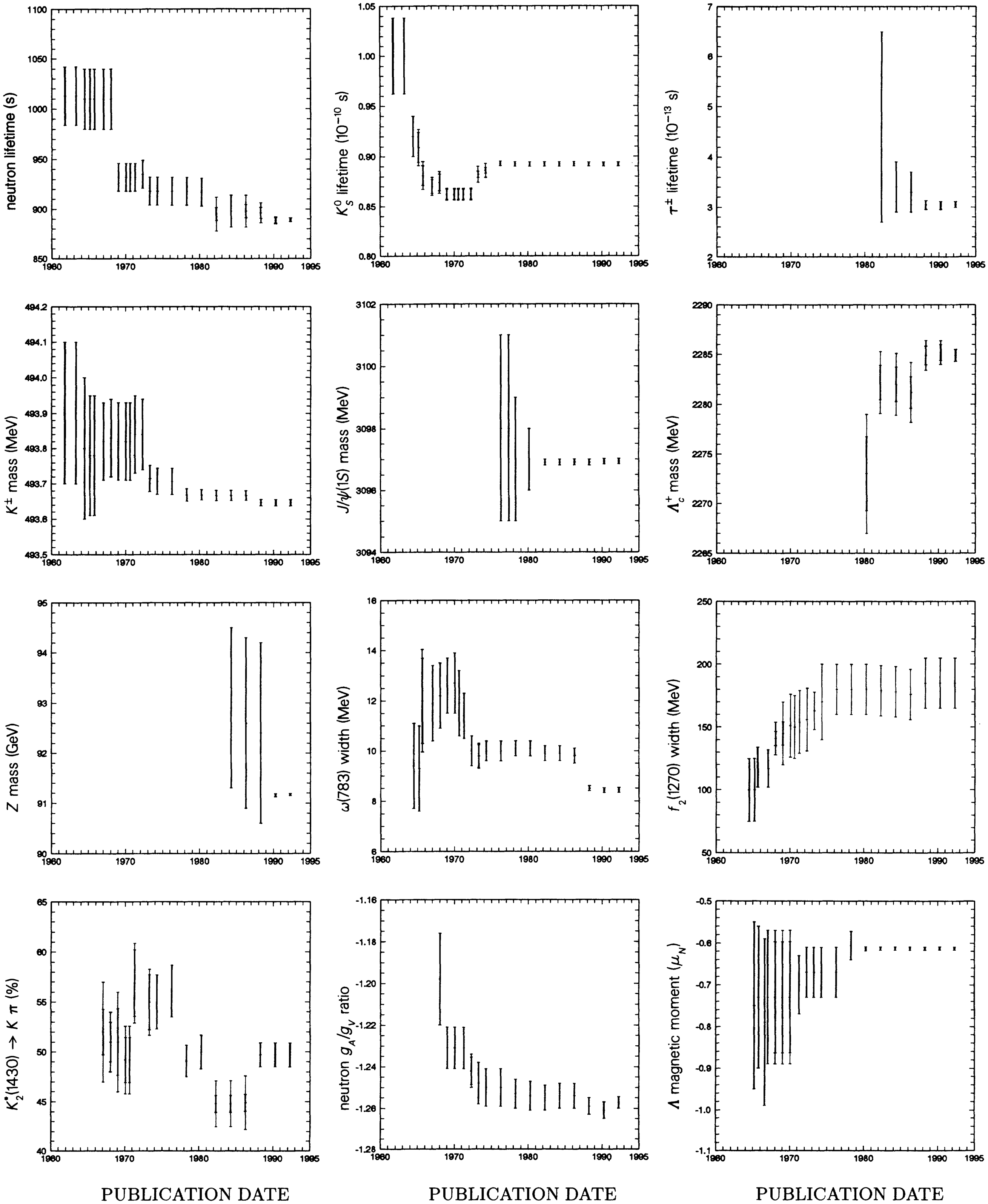

Fig. 2. An historical perspective of values of a few particle properties tabulated in this *Review* as a function of date of publication of the *Review*. A full error bar indicates the quoted error; a thick-lined portion indicates the same but without the "scale factor."

ACCESSING AND USING PARTICLE PHYSICS DATABASES

The Full Listings in this *Review of Particle Properties*, as well as other particle physics databases, are accessible by computer. Some of the databases help find papers of interest, while others contain actual numerical data. Here we tell what databases there are and how to start using them, for databases maintained at SLAC, CERN, Durham, and Serpukhov.

A. The SLAC Particle Physics Databases

(1) PARTICLES contains the Full Listings from this *Review of Particle Properties*, indexed by particle and particle property.

(2) HEP is a guide to particle physics preprints, journal articles, reports, theses, conference papers, etc., indexed by standard bibliographic entities as well as by citations and topics. HEP is a joint project of the SLAC and DESY libraries and, as of January 1992, contained more than 239,000 records dating from late 1974. It is updated daily with nearly 20,000 new records added each year.

(3) CONF lists past and future conferences of interest to particle physicists.

(4) HEPNAMES lists e-mail addresses of many people working in high-energy physics. As of January 1992, more than 19,000 e-mail addresses were available. Additions and corrections may be sent to: HEPNAMES@SLACVM.BITNET.

(5) INST lists nearly 3,000 addresses (often with phone and fax numbers) of high-energy physics related institutions.

(6) DATAGUIDE, an adjunct to HEP, indexes papers containing experimental data by accelerator, detector, beam momentum, reactions, and particles studied. (Not current; see DOCUMENT under the Serpukhov databases below.)

(7) REACTIONS gives numerical data (*e.g.*, cross sections, polarizations, etc.) on reactions.

(8) EXPERIMENTS is a guide to current and past particle physics experiments, indexed similarly to HEP and DATAGUIDE.

Anyone with a SLAC computing account can access these databases online. If you do not have an account and cannot find anyone who does (at major laboratories, ask at the library), contact SLAC directly or see below for alternative access via QSPIRES. More information on the databases may be found in "A User's Guide to Particle Physics Computer-Searchable Databases on the SLAC-SPIRES System," LBL-19173, available from the Particle Data Group, MS 50-308, Lawrence Berkeley Laboratory, Berkeley, CA 94720, USA. Search guides to HEP, CONF, and other SLAC library SPIRES databases are available from the Library, SLAC, P.O. Box 4349, Stanford, CA 94309, USA. Or contact Louise Addis (ADDIS@SLACVM.BITNET), tel. 1-(415)-926-2411 or Harvey Galic (GALIC@SLACVM.BITNET) tel. 1-(415)-926-4406 at SLAC.

A.1. QSPIRES Access to SLAC/SPIRES

People without a SLACVM computing account can use QSPIRES to access the databases at SLAC either interactively via BITNET with the '**send**' command ('**tell**', '**bsend**', or other system-specific command) or by using e-mail.

Working interactively: In the following interactive search example, a query to HEP is refined as QSPIRES sends responses to your screen:

send QSPIRES@SLACVM FIND TITLE Z0

(SPIRES responds)

send QSPIRES@SLACVM AND HIGGS

(SPIRES responds)

send QSPIRES@SLACVM AND DATE JAN 1992

(SPIRES responds)

To receive the search result on your screen ($\leq$ 10 records)

send QSPIRES@SLACVM OUTPUT (TYPE BRIEF

Otherwise, to receive the search result as a file (via e-mail) :

send QSPIRES@SLACVM OUTPUT (FILE BRIEF

You can combine search criteria in a single command:

FIND TITLE TOP AND DATE 1991 (OUT FILE BRIEF

A QSPIRES search defaults to the HEP database. To search another database, like CONF:

send QSPIRES@SLACVM FIND PLACE DALLAS AND DATE 1992 (IN CONF

send QSPIRES@SLACVM OUTPUT (TYPE BRIEF

To access the electronic version of the *Review of Particle Properties* (results always being returned as e-mail):

send QSPIRES@SLACVM EXPLAIN PARTICLES (IN PARTICLES

send QSPIRES@SLACVM FIND PP ETA MODES (IN PARTICLES

For the HEPNAMES and INST databases, there are special short-cut searches:

send QSPIRES@SLACVM WHOIS ARMSTRONG,B

send QSPIRES@SLACVM WHEREIS FERMILAB

Using e-mail: If your system does not support interactive communication or is not on the BITNET network, send e-mail to:

QSPIRES AT SLACVM	(for BITNET)
LBL::"QSPIRES@SLACVM.BITNET"	(for DECNET)
QSPIRES@VM.SLAC.STANFORD.EDU	(for INTERNET)

You **must** remove the '**send** QSPIRES@SLACVM' from all examples and type just the search commands, e.g.,

FIND EXP BNL-802 (IN EXPERIMENTS

Each e-mail message must contain **only one line**, and the e-mail 'subject' must be blank. QSPIRES will send its responses as e-mail.

ACCESSING AND USING PARTICLE PHYSICS DATABASES (Cont'd)

• Use of QSPIRES is free. Anyone may use the special WHOIS and WHEREIS searches for the HEPNAMES and INST databases. Other use of QSPIRES requires that your computer node be registered with SLAC. For questions about node registration or for material on QSPIRES commands, send e-mail to QSPI@SLACVM.BITNET. You can get a 'HELP' file by mailing the command 'HELP' to QSPIRES@SLACVM.BITNET.

SPIRES HEP Databases at Other Institutions

SLAC/DESY HEP and several of the other databases mentioned above are available on SPIRES at DESY, KEK, and the Yukawa Institute, Kyoto. These clones of HEP are updated nightly. Contacts at these institutions are:

DESY—H. Preissner (L00HTP@DHHDESY3.BITNET);

KEK—Y. Miura (MIURA@JPNKEKVM.BITNET);

Yukawa Inst., Kyoto—K. Aoki (AOKI@JPNRIFP.BITNET).

The Yukawa Institute also operates QSPIRES for the Far East.

B. The CERN Library Databases on ALICE

Several databases run under the ALICE system at CERN. Those of particular interest are LIB, PREP, CONF, and DIR.

(1) LIB contains the Library catalogue of books, preprints, reports, and some other information.

(2) PREP is a subset of LIB containing entries for preprints, reports, conference papers, and CERN publications. At the beginning of 1992, it contained 107,000 entries, nearly all preprints and reports received in the CERN Library since 1980. It also has publication details for all papers published with CERN as an affiliation and for most conference papers published in Proceedings since about 1987.

(3) CONF is a subset of LIB listing forthcoming conferences of interest for high-energy physics and accelerator research, as well as past conferences back to 1986.

(4) DIR is a separate database giving the Directory of Research Institutes in High Energy Physics, with addresses, telephone, fax, and telex numbers, and e-mail nodes, as well as brief information on research programmes and on-site accelerators.

ALICE can be accessed via DECnet or INTERNET. It runs on the CERN Library's VAX computer called VXLIB, alias ALICE.CERN.CH (IP number 128.141.201.44). After connection, enter Username ALICE (no password required) and select the terminal type according to the menu. ALICE is a full-screen system using the DEC international character set which can be displayed on suitable terminals. Simple searching can be done by using a menu system or by using the full power of the ISO Common Command Language; HELP displays are provided to guide searching. With the MAIL command, the results of searches can be sent to any e-mail address for printing.

A User's Guide can be requested online or by e-mail to SISSECR@CERNVM.CERN.CH or by writing to Anita Olofsson, Scientific Information Service, CERN, CH-1211 Geneva 23, Switzerland. For specific assistance, contact MALICE@VXLIB.CERN.CH.

B.1. QALICE Access to CERN/ALICE

Remote users with no login access to the CERN Ethernet can use QALICE, which is very similar to QSPIRES except that there is no direct connection to the VM system.

Typical messages from VAX/VMS:

msg VXLIB QALICE base prep;f black hole?;

msg VXLIB QALICE base and 1991–>1992/yr;show

msg VXLIB QALICE base dir;f org=cern;show full

More generally, send e-mail to: QALICE@VXLIB.CERN.CH (not ALICE); put the query in the 'subject' field and leave the 'message' area blank. For further information, send the 'subject' HELP to QALICE or contact the CERN Scientific Information Service (see above) for printed documentation.

SDI (Selective Dissemination of Information) Service on QALICE Access

Regular weekly or monthly searches of the CERN databases can be arranged according to a personal search 'profile', with the results sent automatically by e-mail. Contact David Dallman, Scientific Information Service (SIS), CERN, CH-1211 Geneva 23, Switzerland (DALLMAN@CERNVM.CERN.CH) for details.

Other Services

The DIR database can be made available in a Filemaker PRO format for Macintosh computers. Contact the SIS Secretariat at CERN or Wolfgang Simon (ISI@CERNVM.CERN.CH).

LBL will implement an interactive, user-friendly interface to a *Review of Particle Properties* database on VXCERN in 1992. It will be announced through the VXCERN NEWS utility. For further information contact Gary Wagman (WAGMAN@LBL.GOV).

ACCESSING AND USING PARTICLE PHYSICS DATABASES (Cont'd)

C. The Durham-RAL Particle Physics Databases

The following databases are available on the RAL VM, CERN VM, and DURPDG VMS computers:

(1) PARTICLE PROPERTIES gives the Full Listings from this *Review of Particle Properties*, indexed by particle and property.

(2) REACTION DATA is a compilation of numerical values of experimental particle physics reaction data. These values include data from 2-body (and quasi-2-body) scattering, e^+e^- annihilation, and inclusive hadron, photon, and lepton physics such as total and differential cross sections, fragmentation functions, structure functions, and polarization measurements. They are compiled by the Durham-RAL HEP database group and the COMPAS group (Serpukhov).

(3) EXPERIMENTS is a guide to current and past particle physics experiments.

(4) SLACPPF and CITATIONS are subsets of the SLAC/DESY HEP literature-searching guide. They contain references to papers and preprints since 1980, being comprised of the SLAC PPF (preprint) records with PPA (published references to PPF) updates compiled by the SLAC library. Also included are many journal publications compiled by the DESY library.

(5) E-MAIL IDS is the same as the HEPNAMES database in SLAC/SPIRES. It contains the e-mail addresses of many people working in high-energy physics.

All the databases run under the Berkeley Database Management System and are menu driven with on-line help information. They are available on both the RAL and CERN IBM/VM systems and also on the Durham VAX/VMS system to which there is DECnet and TCP/IP access. On the VM systems, the program HEPDATA resides on the user disk. To use it, enter GIME UDISK followed by HEPDATA. The RAL system has two guest accounts, PDG and PDG2, both with password HEPDATA. HEPDATA is entered directly from these accounts. To use the Durham VMS system, either SET HOST DURPDG or SET HOST 19788 for DECnet access, or TELNET 129.234.8.100 for TCP/IP access. Again, a guest account PDG, password HEPDATA, is available on this machine.

In all cases, the data are retrieved using simple keyword-based searches, and resulting data records can be listed on the terminal, sent to a printer, or transferred to the user's own host machine.

For more information or a user guide, contact Mike Whalley at Durham University, South Rd., Durham City, DH1 3LE, England (MRW@UKACRL.BITNET or MRW@CERNVM.BITNET) or Dick Roberts at the Rutherford Appleton Laboratory, Chilton, Didcot, Oxon. OX11 0QX, England (RGR@UKACRL.BITNET). At CERN, user guides may be obtained from Alec Hester of the CERN library (HES@CERNVM.BITNET).

D. The Serpukhov Particle Physics Databases

Large user-friendly high-energy physics databases are available at IHEP, Serpukhov under VMS. Copies of the databases are also installed at CERN and JINR (Dubna) and are accessible from VMS systems via DECnet. They are maintained by the Serpukhov COMPAS group with assistance from the world-wide Particle Data Group collaboration. They are managed by BDMS/4, a menu-driven database management system with on-line help information. This system consists of the archival databases EXPERIMENTS, DOCUMENTS, and REACTIONS; the evaluated data compilations PP (Particle Properties) and CS (integrated reaction cross sections); and the supplementary database VOCABULARY (controlled vocabulary used by the other databases).

(1) PP contains information from the *Review of Particle Properties* Summary Tables.

(2) DOCUMENT contains information extracted from experimental papers (but no actual data). It covers 1984 to the present, with many earlier papers as far back as 1936.

(3) EXPERIMENTS contains information extracted from laboratory proposals. It covers 1961 to the present.

(4) REACTIONS contains actual physics data extracted from experimental papers. It covers 1952 to the present.

(5) CS contains data from the CERN-HERA, UCLRL, and LBL cross-section compilations. It is regularly updated from the REACTIONS database. It covers 1950 to the present.

These databases (except for CS) overlap in large part with those maintained under SPIRES at SLAC, where they are called PARTICLES, DATAGUIDE, EXPERIMENTS, and REACTIONS, respectively. They are not, however, even when titled the same, identical to the SLAC databases. For example, the PP database contains only Summary Table information from the *Review of Particle Properties* rather than the Full Listings available in the SLAC database PARTICLES. As another example, the DATAGUIDE database at SLAC is out-of-date and will eventually be replaced with data taken from DOCUMENTS.

Contact Sergey Alekhin (ALEKHIN@M9.IHEP.SU) or Vladimir Ezhela (EZHELA@M9.IHEP.SU) at the Inst. for High Energy Physics, Serpukhov, Protvino, Moscow Region, Russia for more information.

Revised April 1992.

SUMMARY TABLES OF PARTICLE PROPERTIES

* There are also search limits in the Summary Tables for the Gauge and Higgs Bosons, the Leptons and Quarks, and the Mesons.

SUMMARY TABLES OF PARTICLE PROPERTIES

June 1992

Particle Data Group

M. Aguilar-Benitez, R.M. Barnett, C. Caso, G. Conforto, R.L. Crawford, R.E. Cutkosky, R.A. Eichler, S. Eidelman, D.E. Groom , K. Hagiwara, K.G. Hayes, J.J. Hernández, K. Hikasa, G. Höhler, S. Kawabata, D.M. Manley, L. Montanet, R.J. Morrison, K.A. Olive, F.C. Porter, M. Roos, R.H. Schindler, R.E. Shrock, J. Stone, N.A. Törnqvist, T.G. Trippe, C.G. Wohl, and G.P. Yost
Technical Associates: B. Armstrong, K. Gieselmann, G.S. Wagman

(Approximate closing date for data: January 1, 1992)

GAUGE AND HIGGS BOSONS

γ

$I(J^{PC}) = 0{,}1(1^{--})$

Mass $m < 3 \times 10^{-33}$ MeV
Charge $q < 2 \times 10^{-32}$ e
Mean life τ = Stable

W

$J = 1$

Mass $m = 80.22 \pm 0.26$ GeV
$m_{W^+} - m_{W^-} = -0.2 \pm 0.6$ GeV
Full width $\Gamma = 2.12 \pm 0.11$ GeV

W^- modes are charge conjugates of the modes below.

W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$e^+\nu$		(10.5±0.9) %		40300
$e^+\nu\gamma$	[a]	< 1.1 %	90%	40300
$\mu^+\nu$		(10.5±1.9) %		40300
$\tau^+\nu$		(10.6±1.6) %		40300
$\pi^\pm\gamma$		< 5 $\times 10^{-4}$	95%	–

Z

$J = 1$

Mass $m = 91.173 \pm 0.020$ GeV [b]
$m_Z - m_W = 10.96 \pm 0.26$ GeV
Full width $\Gamma = 2.487 \pm 0.010$ GeV

Z DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
e^+e^-		(3.345±0.025) %		45600
$\mu^+\mu^-$		(3.34 ±0.04) %	S=1.3	45600
$\tau^+\tau^-$		(3.32 ±0.04) %		45600
$\ell^+\ell^-$		(3.337±0.022) %	S=1.1	–
$\nu\overline{\nu}$ (or other invisible modes)		(20.2 ±0.4) %		45600
hadrons		(69.80 ±0.33) %		–
$(u\overline{u} + c\overline{c})/2$		(13.3 ±3.5) %		–
$(d\overline{d} + s\overline{s} + b\overline{b})/3$		(14.4 ±2.4) %		–
$c\overline{c}$		(12.6 ±2.1) %		–
$b\overline{b}$		(15.2 ±1.0) %		–
$\pi^0\gamma$		< 1.4 $\times 10^{-4}$	CL=95%	45600
$\eta\gamma$		< 5.1 $\times 10^{-5}$	CL=95%	45600
$\eta'(958)\gamma$		< 4.2 $\times 10^{-5}$	CL=95%	45600
$\gamma\gamma$		< 1.4 $\times 10^{-4}$	CL=95%	45600
$\gamma\gamma\gamma$		< 6.6 $\times 10^{-5}$	CL=95%	45600
$\pi^\pm W^\mp$		< 7 $\times 10^{-5}$	CL=95%	–
$\rho^\pm W^\mp$		< 8.3 $\times 10^{-5}$	CL=95%	–
$J/\psi(1S)$ X		(4.5 ±1.1) $\times 10^{-3}$		–
$D^*(2010)^\pm$ X		(18.1 ±3.5) %		–
anomalous γ + hadrons	[a]	< 3.2 $\times 10^{-3}$	CL=95%	–
$e^+e^-\gamma$	[a]	< 5.2 $\times 10^{-4}$	CL=95%	–
$\mu^+\mu^-\gamma$	[a]	< 5.6 $\times 10^{-4}$	CL=95%	–
$\tau^+\tau^-\gamma$	[a]	< 7.3 $\times 10^{-4}$	CL=95%	–
$e^\pm\mu^\mp$	LF	< 2.4 $\times 10^{-5}$	CL=95%	45600
$e^\pm\tau^\mp$	LF	< 3.4 $\times 10^{-5}$	CL=95%	–
$\mu^\pm\tau^\mp$	LF	< 4.8 $\times 10^{-5}$	CL=95%	–

g or gluon

$I(J^P) = 0(1^-)$

Mass $m = 0$ [c]
SU(3) color octet

Searches for Higgs Bosons — H^0 and $H^\pm$

H^0 Mass $m > 48$ GeV, CL = 95%
$H^\pm$ Mass $m > 41.7$ GeV, CL = 95%

See the Full Listings for a Note giving details of Higgs Bosons.

Searches for Heavy Bosons Other Than Higgs Bosons

Additional W Bosons

W_R — right-handed W
Mass $m > 406$ GeV, CL = 90%
(assuming light right-handed neutrino)
W' with standard couplings decaying to $e\nu$, $\mu\nu$
Mass $m > 520$ GeV, CL = 95%

Additional Z Bosons

Z_1 with standard couplings
Mass $m > 412$ GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m > 426$ GeV, CL = 90% (electroweak fit)
Z_{LR} of $SU(2)_L \times SU(2)_R \times U(1)$
(with $g_L = g_R$)
Mass $m > 310$ GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m > 325$ GeV, CL = 90% (neutral current fit)
Z_χ of $SO(10) \to SU(5) \times U(1)_\chi$
(coupling constant derived from G.U.T.)
Mass $m > 340$ GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m > 320$ GeV, CL = 95% (neutral current fit)
Z_ψ of $E_6 \to SO(10) \times U(1)_\psi$
(coupling constant derived from G.U.T.)
Mass $m > 320$ GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m > 154$ GeV, CL = 90% (neutral current fit)
Z_η of $E_6 \to SU(3) \times SU(2) \times U(1) \times U(1)_\eta$
(coupling constant derived from G.U.T.;
charges are $Q_\eta = \sqrt{3/8}Q_\chi - \sqrt{5/8}Q_\psi$)
Mass $m > 340$ GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m > 125$ GeV, CL = 90% (electroweak fit)

Leptoquarks

(for charge $-1/3$, isospin 0, scalar)
Mass $m > 44.2$ GeV, CL = 95% (1st or 2nd generation)
Mass $m > 45$ GeV, CL = 95% (3rd generation)

Gauge & Higgs Boson Summary Table

Searches for Axions (A^0) and Other Very Light Bosons

The standard Peccei-Quinn axion is ruled out. Variants with reduced couplings or much smaller masses are constrained by various data. The Listings in the full-sized edition of the Review of Particle Properties contain a Note discussing axion searches.

The best limit for the half-life of neutrinoless double beta decay with Majoron emission is $> 1.4 \times 10^{21}$ years (CL = 90%).

NOTES

In this Summary Table:

When a quantity has "(S = ...)" to its right, the error on the quantity has been enlarged by the "scale factor" S, defined as $S = \sqrt{\chi^2/(N-1)}$, where N is the number of measurements used in calculating the quantity. We do this when $S > 1$, which often indicates that the measurements are inconsistent. When $S > 1.25$, we also show in the Full Listings an ideogram of the measurements. For more about S, see the Introduction.

A decay momentum p is given for each decay mode. For a 2-body decay, p is the momentum of each decay product in the rest frame of the decaying particle. For a 3-or-more-body decay, p is the largest momentum any of the products can have in this frame.

[*a*] See the Full Listings for the γ energy range used in this measurement.

[*b*] The Z-boson mass listed here corresponds to a Breit-Wigner resonance parameter. It lies 25.5 MeV above the real part of the position of the pole (in the energy plane) in the Z-boson propagator.

[*c*] Theoretical value. A mass as large as a few MeV may not be precluded.

LEPTONS

Neutrinos

See the Full Listings for a Note giving details of neutrinos, masses, mixing, and the status of experimental searches.

ν_e

$J = \frac{1}{2}$

Mass m: The formal upper limit for the mass, as obtained from the value of the mass squared (see the Full Listings), is 7.3 eV at the 90% CL. Caution is urged in interpreting this result, however, because the m^2 average is dominated by the ROBERTSON 91 [Physical Review Letters **67** 957 (1991)] result, which is nearly 2σ negative.

Mean life/mass, $\tau/m_{\nu_e} > 300$ s/eV, CL = 90%

Magnetic moment $\mu < 1.08 \times 10^{-9}\ \mu_B$, CL = 90%

ν_μ

$J = \frac{1}{2}$

Mass $m <$ 0.27 MeV, CL = 90%

Mean life/mass, $\tau/m_{\nu_\mu} > 15.4$ s/eV, CL = 90%

Magnetic moment $\mu < 7.4 \times 10^{-10}\ \mu_B$, CL = 90%

ν_τ

$J = \frac{1}{2}$

Mass $m <$ 35 MeV, CL = 95%

Mean life/mass, τ/m_{ν_τ}

Magnetic moment $\mu < 4 \times 10^{-6}\ \mu_B$, CL = 90%

e

$J = \frac{1}{2}$

Mass $m = 0.51099906 \pm 0.00000015$ MeV [a]

$= (5.48579903 \pm 0.00000013) \times 10^{-4}$ u

Mean life $\tau > 1.9 \times 10^{23}$ yr, CL = 68% [b]

Magnetic moment $\mu = 1.001159652193 \pm 0.000000000010\ \mu_B$

Electric dipole moment $d = (-0.3 \pm 0.8) \times 10^{-26}$ e-cm

μ

$J = \frac{1}{2}$

Mass $m = 105.658389 \pm 0.000034$ MeV [a]

$= 0.113428913 \pm 0.000000017$ u

Mean life $\tau = (2.19703 \pm 0.00004) \times 10^{-6}$ s

$c\tau = 658.653$ m

Magnetic moment $\mu = 1.001165923 \pm 0.000000008\ e\hbar/2m_\mu$

Electric dipole moment $d = (3.7 \pm 3.4) \times 10^{-19}$ e-cm

Decay parameters [c]

$\rho = 0.7518 \pm 0.0026$

$\eta = -0.007 \pm 0.013$

$\delta = 0.749 \pm 0.004$

$\xi P_\mu = 1.003 \pm 0.008$ [d]

$\xi P_\mu \delta/\rho > 0.99677$, CL = 90% [d]

$\xi' = 1.00 \pm 0.04$

$\xi'' = 0.6 \pm 0.4$

$\alpha/A = (0 \pm 4) \times 10^{-3}$

$\alpha'/A = (0 \pm 4) \times 10^{-3}$

$\beta/A = (4 \pm 6) \times 10^{-3}$

$\beta'/A = (2 \pm 6) \times 10^{-3}$

$\bar{\eta} = 0.02 \pm 0.08$

μ^+ modes are charge conjugates of the modes below.

μ^- DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$e^-\bar{\nu}_e\nu_\mu$		~ 100 %		53
$e^-\bar{\nu}_e\nu_\mu\gamma$	[e]	(1.4 ± 0.4) %		53
$e^-\bar{\nu}_e\nu_\mu e^+e^-$	[f]	$(3.4 \pm 0.4) \times 10^{-5}$		53

Lepton Family number (*LF*) violating modes

$e^-\nu_e\bar{\nu}_\mu$	*LF*	< 1.8 %	90%	53
$e^-\gamma$	*LF*	$< 4.9 \times 10^{-11}$	90%	53
$e^-e^+e^-$	*LF*	$< 1.0 \times 10^{-12}$	90%	53
$e^-2\gamma$	*LF*	$< 7.2 \times 10^{-11}$	90%	53

τ

$J = \frac{1}{2}$

Mass $m = 1784.1^{+2.7}_{-3.6}$ MeV

Mean life $\tau = (0.305 \pm 0.006) \times 10^{-12}$ s

$c\tau = 91.4\ \mu$m

Michel parameter $\rho = 0.727 \pm 0.033$

$2g_A g_V/(g_A^2+g_V^2) = 1.1^{+0.5}_{-0.4}$

$g_V/g_A = 0.01 \pm 0.04$

See the Full Listings for a Note giving details of the τ lepton.

τ^+ modes are charge conjugates of the modes below. "$h^\pm$" stands for $\pi^\pm$ or $K^\pm$. "ℓ" stands for e or μ. "Neutral" means neutral hadron whose decay products include γ's and/or π^0's.

τ^- DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
particle$^-$ ≥ 0 neutrals ν_τ ("1-prong")	(85.82 ± 0.25) %	S=1.3	–
$\mu^-\bar{\nu}_\mu\nu_\tau$	(17.58 ± 0.27) %	S=1.1	889
$\mu^-\bar{\nu}_\mu\nu_\tau\gamma$ ($E_\gamma > 37$ MeV)	$(2.3 \pm 1.1) \times 10^{-3}$		–
$e^-\bar{\nu}_e\nu_\tau$	(17.93 ± 0.26) %	S=1.1	892
h^- ≥ 0 neutrals ν_τ	(50.3 ± 0.4) %	S=1.2	–
$h^-\nu_\tau$	(12.7 ± 0.4) %	S=1.1	–
$\pi^-\nu_\tau$	(11.6 ± 0.4) %	S=1.2	887
K^- ≥ 0 neutrals ν_τ	(1.68 ± 0.24) %		–
$K^-\nu_\tau$	$(6.7 \pm 2.3) \times 10^{-3}$	S=1.3	824
K^- ≥ 1 neutrals ν_τ	$(1.2\ ^{+0.5}_{-0.6})$ %		–
h^- ≥ 1 neutrals ν_τ	(37.6 ± 0.5) %	S=1.2	–
$h^-\pi^0\nu_\tau$	(24.4 ± 0.6) %	S=1.1	–
$\pi^-\pi^0\nu_\tau$	(24.0 ± 0.6) %	S=1.1	881
h^- $\geq 2\pi^0\nu_\tau$	(13.2 ± 0.7) %	S=1.3	–
$h^-2\pi^0\nu_\tau$	(10.3 ± 0.9) %	S=1.7	866
h^- $\geq 3\pi^0\nu_\tau$	(2.7 ± 0.9) %	S=1.9	–
$2h^-h^+$ ≥ 0 neutrals ν_τ ("3-prong")	(14.06 ± 0.25) %	S=1.3	–
$h^-h^-h^+\nu_\tau$	(8.4 ± 0.4) %	S=1.4	–
$\pi^-\pi^-\pi^+\nu_\tau$	(5.6 ± 0.7) %		864
$\pi^-\rho^0\nu_\tau$	(5.4 ± 1.7) %		719
$\pi^-\pi^-\pi^+$ non-$\rho(770)^0\nu_\tau$	< 1.4 %	CL=95%	864
$h^-h^-h^+$ ≥ 1 neutrals ν_τ	(5.3 ± 0.4) %	S=1.3	–
$\omega\pi^-$ ≥ 0 neutrals ν_τ	(1.6 ± 0.4) %		–
$\omega\pi^-\nu_\tau$	(1.6 ± 0.5) %		713
$K^-h^+h^-$ ≥ 0 neutrals ν_τ	$< 6 \times 10^{-3}$	CL=90%	–
$K^-\pi^+\pi^-$ ≥ 0 neutrals ν_τ	$(2.2\ ^{+1.6}_{-1.3}) \times 10^{-3}$		–
$K^-K^+\pi^-\nu_\tau$	$(2.2\ ^{+1.7}_{-1.1}) \times 10^{-3}$		689
$3h^-2h^+$ ≥ 0 neutrals ν_τ ("5-prong")	$(1.11 \pm 0.24) \times 10^{-3}$		–
$3h^-2h^+\nu_\tau$	$(5.6 \pm 1.6) \times 10^{-4}$		–
$3h^-2h^+\pi^0\nu_\tau$	$(5.1 \pm 2.2) \times 10^{-4}$		–
$4h^-3h^+$ ≥ 0 neutrals ν_τ ("7-prong")	$< 1.9 \times 10^{-4}$	CL=90%	–
K^0h^- ≥ 0 neutrals ν_τ	(1.30 ± 0.30) %		–
$K^*(892)^-$ ≥ 0 neutrals ν_τ	(1.43 ± 0.17) %		–
K^-K^0 ≥ 0 neutrals ν_τ	$< 8 \times 10^{-3}$	CL=90%	–
$K^*(892)^0K^-$ ≥ 0 neutrals ν_τ	$(3.2 \pm 1.4) \times 10^{-3}$		–
$\overline{K}^*(892)^0\pi^-$ ≥ 0 neutrals ν_τ	$(3.8 \pm 1.7) \times 10^{-3}$		–
$K^*(892)^-\nu_\tau$	(1.42 ± 0.18) %		669
$K_2^*(1430)^-\nu_\tau$	$< 3 \times 10^{-3}$	CL=95%	323
$K^0K^-\nu_\tau$	$< 2.6 \times 10^{-3}$	CL=95%	742
K^0K^- ≥ 1 neutrals ν_τ	$< 2.6 \times 10^{-3}$	CL=95%	–
$K^0h^+h^-h^-$ ≥ 0 neutrals ν_τ	$< 1.7 \times 10^{-3}$	CL=95%	–
$\eta\pi^-$ ≥ 0 neutrals ν_τ	< 1.3 %	CL=95%	–
$\eta\pi^-\nu_\tau$	$< 9 \times 10^{-3}$	CL=95%	801
$\eta\pi^-\pi^0\nu_\tau$	< 1.1 %	CL=95%	782
$\eta\pi^-\pi^0\pi^0\nu_\tau$	< 1.2 %	CL=95%	750

Lepton & Quark Summary Table

The following are sometimes subreactions of 3-prong inclusive η searches

Mode		Fraction		CL	p
$\eta\pi^+\pi^-\pi^- \geq 0$ neutrals ν_τ		< 3	$\times 10^{-3}$	CL=90%	–
$\eta\eta\pi^- \geq 0$ neutrals ν_τ		< 5	$\times 10^{-3}$	CL=90%	–
$\eta\eta\pi^-\nu_\tau$		< 8.3	$\times 10^{-3}$	CL=95%	641
$\eta\eta\pi^-\pi^0\nu_\tau$		< 9	$\times 10^{-3}$	CL=95%	563

Lepton number (L) or Lepton Family number (LF) violating modes
(In the modes below, ℓ means a sum over e and μ modes)

Mode		Fraction		CL	p
e^- charged particles + μ^-charged particles	LF	< 4	%	CL=90%	–
$\mu^-\gamma$	LF	< 5.5	$\times 10^{-4}$	CL=90%	889
$e^-\gamma$	LF	< 2.0	$\times 10^{-4}$	CL=90%	892
$\mu^-\pi^0$	LF	< 8.2	$\times 10^{-4}$	CL=90%	884
$e^-\pi^0$	LF	< 1.4	$\times 10^{-4}$	CL=90%	887
μ^-K^0	LF	< 1.0	$\times 10^{-3}$	CL=90%	819
e^-K^0	LF	< 1.3	$\times 10^{-3}$	CL=90%	823
$\mu^-\rho^0$	LF	< 3.8	$\times 10^{-5}$	CL=90%	722
$e^-\rho^0$	LF	< 3.9	$\times 10^{-5}$	CL=90%	727
$e^-K^*(892)^0$	LF	< 5.4	$\times 10^{-5}$	CL=90%	667
$\mu^-K^*(892)^0$	LF	< 5.9	$\times 10^{-5}$	CL=90%	662
$e^-\eta$	LF	< 2.4	$\times 10^{-4}$	CL=90%	808
$\ell^-\ell^-\ell^+$	LF	< 3.4	$\times 10^{-5}$	CL=90%	–
$e^-e^+e^-$	LF	< 2.7	$\times 10^{-5}$	CL=90%	892
$(e\mu\mu)^-$	LF	< 2.7	$\times 10^{-5}$	CL=90%	886
$e^-\mu^+\mu^-$	LF	< 2.7	$\times 10^{-5}$	CL=90%	886
$e^+\mu^-\mu^-$	LF	< 1.6	$\times 10^{-5}$	CL=90%	886
$(\mu ee)^-$	LF	< 2.7	$\times 10^{-5}$	CL=90%	889
$\mu^-e^+e^-$	LF	< 2.7	$\times 10^{-5}$	CL=90%	889
$\mu^+e^-e^-$	LF	< 1.6	$\times 10^{-5}$	CL=90%	889
$\mu^-\mu^+\mu^-$	LF	< 1.7	$\times 10^{-5}$	CL=90%	876
$\ell^\pm\pi^\mp\pi^-$	L,LF	< 6.3	$\times 10^{-5}$	CL=90%	–
$e^\mp\pi^\pm\pi^-$	L,LF	< 6.0	$\times 10^{-5}$	CL=90%	881
$e^-\pi^+\pi^-$	LF	< 4.2	$\times 10^{-5}$	CL=90%	881
$e^+\pi^-\pi^-$	L,LF	< 1.7	$\times 10^{-5}$	CL=90%	881
$\mu^\mp\pi^\pm\pi^-$	L,LF	< 3.9	$\times 10^{-5}$	CL=90%	870
$\mu^-\pi^+\pi^-$	LF	< 3.9	$\times 10^{-5}$	CL=90%	870
$\mu^+\pi^-\pi^-$	L,LF	< 3.9	$\times 10^{-5}$	CL=90%	870
$\ell^\pm\pi^\mp K^-$	L,LF	< 1.2	$\times 10^{-4}$	CL=90%	–
$(e\pi K)^-$, all charged	L,LF	< 7.7	$\times 10^{-5}$	CL=90%	817
$e^-\pi^\pm K^\mp$	LF	< 5.8	$\times 10^{-5}$	CL=90%	817
$e^-\pi^+K^-$	LF	< 4.2	$\times 10^{-5}$	CL=90%	817
$e^-\pi^-K^+$	LF	< 5.8	$\times 10^{-5}$	CL=90%	817
$e^+\pi^-K^-$	L,LF	< 4.9	$\times 10^{-5}$	CL=90%	817
$(\mu\pi K)^-$, all charged	L,LF	< 7.7	$\times 10^{-5}$	CL=90%	804
$\mu^-\pi^\pm K^\mp$	LF	< 7.7	$\times 10^{-5}$	CL=90%	804
$\mu^-\pi^+K^-$	LF	< 7.7	$\times 10^{-5}$	CL=90%	804
$\mu^-\pi^-K^+$	LF	< 7.7	$\times 10^{-5}$	CL=90%	804
$\mu^+\pi^-K^-$	L,LF	< 4.0	$\times 10^{-5}$	CL=90%	804
e^- light spinless boson	LF	< 3.2	$\times 10^{-3}$	CL=95%	–
μ^- light spinless boson	LF	< 6	$\times 10^{-3}$	CL=95%	–

Number of Light Neutrino Types

(including ν_e, ν_μ, and ν_τ)

Number $N = 2.99 \pm 0.04$ (in the Standard Model)

Heavy Lepton Searches

$L^\pm$ – charged lepton

Mass $m >$ 44.3 GeV, CL = 95% $m(\nu) \approx 0$

$L^\pm$ – stable charged heavy lepton

Mass $m >$ 42.8 GeV, CL = 95%

L^0 – stable neutral heavy lepton

Mass $m >$ 45.0 GeV, CL = 95%

E^0 – neutral para- or ortho-lepton

Mass $m >$ 19.6 GeV, CL = 95% (all $|U_{\ell j}|^2$)
Mass $m >$ 41 GeV, CL = 95% ($|U_{\ell j}|^2 > 10^{-10}$
Mass $m >$ 45.7 GeV or $m < 25$, CL = 95% ($|U_{\ell j}|^2 > 10^{-13}$

Searches for Massive Neutrinos and Lepton Mixing

For excited leptons, see Compositeness Limits below.

See the Full Listings for a Note giving details of neutrinos, masses, mixing, and the status of experimental searches.

No direct, uncontested evidence for massive neutrinos or lepton mixing has been obtained. Sample limits are:

ν oscillation: $\overline{\nu}_e \not\to \overline{\nu}_e$

$\Delta(m^2) < 0.0083$ eV^2, CL = 90% (if $\sin^2 2\theta = 1$)
$\sin^2 2\theta < 0.14$, CL = 68% (if $\Delta(m^2)$ is large)

ν oscillation: $\nu_\mu \to \nu_e$ (θ = mixing angle)

$\Delta(m^2) < 0.09$ eV^2, CL = 90% (if $\sin^2 2\theta = 1$)
$\sin^2 2\theta < 3.4 \times 10^{-3}$, CL = 90% (if $\Delta(m^2)$ is large)

QUARKS

This year we are introducing a Quark Table. The quark masses shown are not based on a set of papers in the Full Listings. Since the subject of their masses is controversial, the purpose of this table is to provoke discussion. We ask that our readers send us comments and references (particularly on quark mass definitions and values). The masses that enter a QCD Lagrangian are "running" masses and depend on scale and renormalization scheme. These can be different from the heavy quark masses obtained in potential models. For this edition we have attempted to give a conservative range of masses. In the next edition we will provide a more extensive treatment.

d

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 5 to 15 MeV [g] m_d/m_s = 0.04 to 0.06
Charge = $-\frac{1}{3}$ e
$I_z = -\frac{1}{2}$

u

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 2 to 8 MeV [g] m_u/m_d = 0.25 to 0.70
Charge = $\frac{2}{3}$ e
$I_z = +\frac{1}{2}$

s

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 100 to 300 MeV [g]
Charge = $-\frac{1}{3}$ e
Strangeness = -1

c

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 1.3 to 1.7 GeV [h]
Charge = $\frac{2}{3}$ e
Charm = $+1$

b

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 4.7 to 5.3 GeV [h]
Charge = $-\frac{1}{3}$ e
Bottom = -1

t

$I(J^P) = 0(\frac{1}{2}^+)$

(not discovered)

Mass $m >$ 91 GeV [i]
Charge = $\frac{2}{3}$ e
Top = $+1$

NOTES

In this Summary Table:

When a quantity has "(S = ...)" to its right, the error on the quantity has been enlarged by the "scale factor" S, defined as $S = \sqrt{\chi^2/(N-1)}$, where N is the number of measurements used in calculating the quantity. We do this when S > 1, which often indicates that the measurements are inconsistent. When S > 1.25, we also show in the Full Listings an ideogram of the measurements. For more about S, see the Introduction.

A decay momentum p is given for each decay mode. For a 2-body decay, p is the momentum of each decay product in the rest frame of the decaying particle. For a 3-or-more-body decay, p is the largest momentum any of the products can have in this frame.

[a] The masses of the e and μ are most precisely known in u (unified atomic mass units). The conversion factor to MeV, 1 u = 931.49432(28) MeV, is less well known than are the masses in u.

[b] This is the best "electron disappearance" limit. The best limit for the mode $e^- \rightarrow \nu\gamma$ is $> 1.5 \times 10^{25}$ yr (CL=68%).

[c] See the Note on Muon Decay Parameters in the Full Listings for definitions and details.

[d] P_μ is the longitudinal polarization of the muon from pion decay. In standard $V{-}A$ theory, $P_\mu = 1$ and $\rho = \delta = 3/4$.

[e] This only includes events with the γ energy > 10 MeV. Since the $e^- \overline{\nu}_e \nu_\mu$ and $e^- \overline{\nu}_e \nu_\mu \gamma$ modes cannot be clearly separated, we regard the latter mode as a subset of the former.

[f] See the Full Listings for the energy limits used in this measurement.

[g] The d-, u-, and s-quark masses are estimates of so-called "current-quark masses," with ratios m_u/m_d and m_d/m_s extracted from pion and kaon masses using chiral symmetry. The estimates of d and u masses are not without controversy and remain under active investigation. Within the literature there are even suggestions that the u quark could be essentially massless. The s-quark mass is estimated from SU(3) splitting in hadron masses.

[h] The c- and b-quark masses are estimated from charmonium, bottomonium, D, and B masses. They correspond to potential model masses and not to "running" masses.

[i] The t-quark mass shown assumes that the t quark would decay with 100% branching ratio as $t \rightarrow bW^+$ rather than to other modes such as $t \rightarrow bH^+$. Without this assumption the mass limit is $m > 55$ GeV. Standard Model analyses of precision experiments on the electroweak interactions suggest a mass between 110 and 190 GeV with $m < 200$ GeV at 95% CL (see the section on Top Hadrons).

LIGHT UNFLAVORED MESONS
($S = C = B = 0$)

$\pi^\pm$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.5679 \pm 0.0007$ MeV (S = 2.2)
Mean life $\tau = (2.6030 \pm 0.0024) \times 10^{-8}$ s
$c\tau = 7.804$ m

$\pi^\pm \to \ell^\pm \nu \gamma$ form factors [a]

$F_V = 0.017 \pm 0.008$
$F_A = 0.0116 \pm 0.0016$ (S = 1.3)
$R = 0.059^{+0.009}_{-0.008}$

π^- modes are charge conjugates of the modes below.

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$		(99.98782 ± 0.00014) %		30
$\mu^+\nu_\mu\gamma$	[b]	$(1.24 \pm 0.25) \times 10^{-4}$		30
$e^+\nu_e$		$(1.218 \pm 0.014) \times 10^{-4}$		70
$e^+\nu_e\gamma$	[b]	$(1.61 \pm 0.23) \times 10^{-7}$		70
$e^+\nu_e\pi^0$		$(1.025 \pm 0.034) \times 10^{-8}$		4
$e^+\nu_e e^+ e^-$		$(3.2 \pm 0.5) \times 10^{-9}$		70
$e^+\nu_e\nu\bar{\nu}$		$< 5 \times 10^{-6}$	90%	70
Lepton number (L) or Lepton Family number (LF) violating modes				
$\mu^+\bar{\nu}_e$	L	$< 1.5 \times 10^{-3}$	90%	30
$\mu^+\nu_e$	LF	$< 8.0 \times 10^{-3}$	90%	30
$\mu^- e^+ e^+ \nu$	LF	$< 7.7 \times 10^{-6}$	90%	30

π^0

$I^G(J^{PC}) = 1^-(0^{-+})$

Mass $m = 134.9743 \pm 0.0008$ MeV (S = 1.5)
$m_{\pi^\pm} - m_{\pi^0} = 4.5936 \pm 0.0005$ MeV
Mean life $\tau = (8.4 \pm 0.6) \times 10^{-17}$ s (S = 3.0)
$c\tau = 25.2$ nm

π^0 DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ		(98.798 ± 0.032) %	S=1.1	67
$e^+e^-\gamma$		(1.198 ± 0.032) %	S=1.1	67
γ positronium		$(1.82 \pm 0.29) \times 10^{-9}$		67
$e^+e^+e^-e^-$		$(3.14 \pm 0.30) \times 10^{-5}$		67
e^+e^-		$< 1.3 \times 10^{-7}$	CL=90%	67
4γ		$< 2 \times 10^{-8}$	CL=90%	67
$\nu\bar{\nu}$	[c]	$< 8.3 \times 10^{-7}$	CL=90%	67
$\nu_e\bar{\nu}_e$		$< 1.7 \times 10^{-6}$	CL=90%	67
$\nu_\mu\bar{\nu}_\mu$		$< 3.1 \times 10^{-6}$	CL=90%	67
$\nu_\tau\bar{\nu}_\tau$		$< 2.1 \times 10^{-6}$	CL=90%	67
Charge conjugation (C) or Lepton Family number (LF) violating modes				
3γ	C	$< 3.1 \times 10^{-8}$	CL=90%	67
μ^+e^-	LF	$< 1.6 \times 10^{-8}$	CL=90%	26

η

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 547.45 \pm 0.19$ MeV (S = 1.6)
Full width $\Gamma = 1.19 \pm 0.11$ keV [d] (S = 1.8)

C-nonconserving decay parameters [e]

$\pi^+\pi^-\pi^0$ Left-right asymmetry $= (0.09 \pm 0.17) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ Sextant asymmetry $= (0.18 \pm 0.16) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ Quadrant asymmetry $= (-0.17 \pm 0.17) \times 10^{-2}$
$\pi^+\pi^-\gamma$ Left-right asymmetry $= (0.9 \pm 0.4) \times 10^{-2}$
$\pi^+\pi^-\gamma$ $\beta = 0.05 \pm 0.06$ (S = 1.5)

η DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
neutral modes		(70.8 ± 0.8) %	S=1.2	–
2γ		(38.9 ± 0.5) %	S=1.2	274
$3\pi^0$		(31.9 ± 0.4) %	S=1.2	180
$\pi^0 2\gamma$		$(7.1 \pm 1.4) \times 10^{-4}$		258
charged modes		(29.2 ± 0.8) %	S=1.2	–
$\pi^+\pi^-\pi^0$		(23.6 ± 0.6) %	S=1.2	175
$\pi^+\pi^-\gamma$		(4.88 ± 0.15) %	S=1.2	236
$e^+e^-\gamma$		$(5.0 \pm 1.2) \times 10^{-3}$		274
$\mu^+\mu^-\gamma$		$(3.1 \pm 0.4) \times 10^{-4}$		253
e^+e^-		$< 3 \times 10^{-4}$	CL=90%	274
$\mu^+\mu^-$		$(6.5 \pm 2.1) \times 10^{-6}$		253
$\pi^+\pi^-e^+e^-$		$(1.3 {}^{+1.3}_{-0.8}) \times 10^{-3}$		236
$\pi^+\pi^-2\gamma$		$< 2.1 \times 10^{-3}$		236
$\pi^+\pi^-\pi^0\gamma$		$< 6 \times 10^{-4}$	CL=90%	175
$\pi^0\mu^+\mu^-\gamma$		$< 3 \times 10^{-6}$	CL=90%	211
Charge conjugation (C), Parity (P), or Charge conjugation × Parity (CP) violating modes				
3γ	C	$< 5 \times 10^{-4}$		274
$\pi^+\pi^-$	P,CP	$< 1.5 \times 10^{-3}$		236
$\pi^0e^+e^-$	C	$< 4 \times 10^{-5}$	CL=90%	258
$\pi^0\mu^+\mu^-$	C	$< 5 \times 10^{-6}$	CL=90%	211

$\rho(770)$

$I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 768.1 \pm 0.5$ MeV (S = 1.1)
Full width $\Gamma = 151.5 \pm 1.2$ MeV
$\Gamma_{ee} = 6.77 \pm 0.32$ keV

$\rho(770)$ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi\pi$		~ 100 %		358
$\rho(770)^\pm$ decays				
$\pi^\pm\gamma$		$(4.5 \pm 0.5) \times 10^{-4}$	S=2.2	371
$\pi^\pm\eta$		$< 8 \times 10^{-3}$	CL=84%	144
$\pi^\pm\pi^+\pi^-\pi^0$		$< 2.0 \times 10^{-3}$	CL=84%	249
$\rho(770)^0$ decays				
$\pi^+\pi^-\gamma$		$(9.9 \pm 1.6) \times 10^{-3}$		358
$\pi^0\gamma$		$(7.9 \pm 2.0) \times 10^{-4}$		372
$\eta\gamma$		$(3.8 \pm 0.7) \times 10^{-4}$		188
$\mu^+\mu^-$	[f]	$(4.60 \pm 0.28) \times 10^{-5}$		369
e^+e^-	[f]	$(4.44 \pm 0.21) \times 10^{-5}$		384
$\pi^+\pi^-\pi^0$		$< 1.2 \times 10^{-4}$	CL=90%	318
$\pi^+\pi^-\pi^+\pi^-$		$< 2 \times 10^{-4}$	CL=90%	246
$\pi^+\pi^-\pi^0\pi^0$		$< 4 \times 10^{-5}$	CL=90%	251

$\omega(783)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 781.95 \pm 0.14$ MeV (S = 1.6)
Full width $\Gamma = 8.43 \pm 0.10$ MeV
$\Gamma_{ee} = 0.60 \pm 0.02$ keV (S = 1.1)

$\omega(783)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi^+\pi^-\pi^0$	(88.8 ± 0.6) %		327
$\pi^0\gamma$	(8.5 ± 0.5) %		379
$\pi^+\pi^-$	(2.21 ± 0.30) %		365
neutrals (excluding $\pi^0\gamma$)	$(4.4 {}^{+7.9}_{-2.9}) \times 10^{-3}$		–
$\pi^0e^+e^-$	$(5.9 \pm 1.9) \times 10^{-4}$		379
$\eta\gamma$	$(4.7 {}^{+2.2}_{-1.8}) \times 10^{-4}$	S=1.1	198
$\pi^0\mu^+\mu^-$	$(9.6 \pm 2.3) \times 10^{-5}$		349
e^+e^-	$(7.15 \pm 0.19) \times 10^{-5}$		391
$\pi^+\pi^-\pi^0\pi^0$	< 2 %	CL=90%	261
$\pi^+\pi^-\gamma$	$< 3.6 \times 10^{-3}$	CL=95%	365
$\pi^+\pi^-\pi^+\pi^-$	$< 1 \times 10^{-3}$	CL=90%	256
$\pi^0\pi^0\gamma$	$< 4 \times 10^{-4}$	CL=90%	367
$\mu^+\mu^-$	$< 1.8 \times 10^{-4}$	CL=90%	376

$\eta'(958)$

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 957.75 \pm 0.14$ MeV
Full width $\Gamma = 0.198 \pm 0.019$ MeV (S = 1.4)

$\eta'(958)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi^+\pi^-\eta$	(44.1 ± 1.7) %	S=1.2	231
$\rho^0\gamma$	(30.0 ± 1.4) %	S=1.1	171
$\pi^0\pi^0\eta$	(20.6 ± 1.2) %	S=1.2	238
$\omega\gamma$	(3.00 ± 0.30) %		160
$\gamma\gamma$	(2.17 ± 0.17) %	S=1.5	479
$3\pi^0$	$(1.53 \pm 0.26) \times 10^{-3}$	S=1.1	430

$\mu^+\mu^-\gamma$	$(1.06\pm0.27)\times10^{-4}$		467
$\pi^+\pi^-\pi^0$	< 5 %	CL=90%	427
$\pi^0\rho^0$	< 4 %	CL=90%	120
$\pi^+\pi^-$	< 2 %	CL=90%	458
$\pi^0 e^+e^-$	< 1.3 %	CL=90%	469
ηe^+e^-	< 1.1 %	CL=90%	322
$\pi^+\pi^+\pi^-\pi^-$	< 1 %	CL=90%	372
$\pi^+\pi^+\pi^-\pi^-$ neutrals	< 1 %	CL=95%	–
$\pi^+\pi^+\pi^-\pi^-\pi^0$	< 1 %	CL=90%	298
6π	< 1 %	CL=90%	189
$\pi^+\pi^-e^+e^-$	$< 6\times10^{-3}$	CL=90%	458
$\pi^0\pi^0$	$< 9\times10^{-4}$	CL=90%	459
$\pi^0\gamma\gamma$	$< 8\times10^{-4}$	CL=90%	469
$4\pi^0$	$< 5\times10^{-4}$	CL=90%	379
3γ	$< 9\times10^{-5}$	CL=90%	479
$\mu^+\mu^-\pi^0$	$< 6.0\times10^{-5}$	CL=90%	445
$\mu^+\mu^-\eta$	$< 1.5\times10^{-5}$	CL=90%	273
e^+e^-	$< 2.1\times10^{-7}$	CL=90%	479

$f_0(975)$ was $S(975)$

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 974.1 \pm 2.5$ MeV (S = 1.4)
Full width $\Gamma = 47 \pm 9$ MeV (S = 2.0)

$f_0(975)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\pi\pi$	(78.1 ± 2.4) %		467
$K\overline{K}$	(21.9 ± 2.4) %		–
$\gamma\gamma$	$(1.19\pm0.33)\times10^{-5}$		487
e^+e^-	$< 3\times10^{-7}$	90%	487

$a_0(980)$ was $\delta(980)$

$I^G(J^{PC}) = 1^-(0^{++})$

Mass $m = 982.7 \pm 2.0$ (S = 1.1)
Full width $\Gamma = 57 \pm 11$ MeV

$a_0(980)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\eta\pi$	seen	319
$K\overline{K}$	seen	–
$\gamma\gamma$	seen	491

$\phi(1020)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 1019.413 \pm 0.008$ MeV
Full width $\Gamma = 4.43 \pm 0.06$ MeV
$\Gamma_{ee} = 1.37 \pm 0.05$ keV

$\phi(1020)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
K^+K^-	(49.1 ± 0.8) %	S=1.2	127
$K^0_L K^0_S$	(34.4 ± 0.7) %	S=1.2	110
$\rho\pi$	(12.9 ± 0.7) %		183
$\pi^+\pi^-\pi^0$	(2.4 ± 0.9) %	S=1.1	462
$\eta\gamma$	(1.28 ± 0.06) %	S=1.2	362
$\pi^0\gamma$	$(1.31\pm0.13)\times10^{-3}$		501
e^+e^-	$(3.09\pm0.07)\times10^{-4}$		510
$\mu^+\mu^-$	$(2.48\pm0.34)\times10^{-4}$		499
ηe^+e^-	$(1.3\ ^{+0.8}_{-0.6})\times10^{-4}$		362
$\pi^+\pi^-$	$(8\ ^{+5}_{-4})\times10^{-5}$	S=1.5	490
$\omega\gamma$	< 5 %	CL=84%	210
$\rho\gamma$	< 2 %	CL=84%	220
$\pi^+\pi^-\gamma$	$< 7\times10^{-3}$	CL=90%	490
$f_0(975)\gamma$	$< 2\times10^{-3}$	CL=90%	44
$\pi^0\pi^0\gamma$	$< 1\times10^{-3}$	CL=90%	492
$\pi^+\pi^-\pi^+\pi^-$	$< 8.7\times10^{-4}$	CL=90%	410
$\eta'(958)\gamma$	$< 4.1\times10^{-4}$	CL=90%	60
$\pi^+\pi^+\pi^-\pi^-\pi^0$	$< 1.5\times10^{-4}$	CL=95%	341
$\pi^0 e^+e^-$	$< 1.2\times10^{-4}$	CL=90%	501
$\pi^0\eta\gamma$	$< 2.5\times10^{-3}$	CL=90%	345
$a_0(980)\gamma$	$< 5\times10^{-3}$	CL=90%	36

$h_1(1170)$ was $H(1190)$

$I^G(J^{PC}) = 0^-(1^{+-})$

Mass $m = 1170 \pm 20$ MeV
Full width $\Gamma = 360 \pm 40$ MeV

$h_1(1170)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	seen	311

$b_1(1235)$ was $B(1235)$

$I^G(J^{PC}) = 1^+(1^{+-})$

Mass $m = 1232 \pm 10$ MeV [g]
Full width $\Gamma = 155 \pm 8$ MeV

$b_1(1235)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\omega\pi$	dominant		349
[D/S amplitude ratio = 0.26 ± 0.04]			
$\pi^\pm\gamma$	$(1.5\pm0.4)\times10^{-3}$		608
$\eta\rho$	seen		–
$\pi^+\pi^+\pi^-\pi^0$	< 50 %	84%	536
$\eta\pi$	< 25 %	90%	482
$\pi\pi$	< 15 %	90%	600
$(K\overline{K})^\pm\pi^0$	< 8 %	90%	248
$K^0_S K^0_L\pi^\pm$	< 6 %	90%	238
$K\overline{K}$	< 2 %	84%	368
$K^0_S K^0_S\pi^\pm$	< 2 %	90%	238
$\pi\phi$	< 1.5 %	84%	146

$a_1(1260)$ was $A_1(1270)$

$I^G(J^{PC}) = 1^-(1^{++})$

Mass $m = 1260 \pm 30$ MeV [g]
Full width $\Gamma \sim 400$ MeV

$a_1(1260)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\rho\pi$	dominant		379
$\pi\gamma$	seen		622
$\pi(\pi\pi)_{S\text{-wave}}$	[g] <0.7 %	90%	591

$f_2(1270)$

$I^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 1275 \pm 5$ MeV [g]
Full width $\Gamma = 185 \pm 20$ MeV [g]

$f_2(1270)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi\pi$	$(84.9\ ^{+2.5}_{-1.3})$ %	S=1.3	622
$\pi^+\pi^-2\pi^0$	$(6.9\ ^{+1.5}_{-2.7})$ %	S=1.4	562
$K\overline{K}$	(4.6 ± 0.5) %	S=2.9	403
$2\pi^+2\pi^-$	(2.8 ± 0.4) %	S=1.2	559
$\eta\eta$	$(4.5\pm1.0)\times10^{-3}$	S=2.4	324
$4\pi^0$	$(3.0\pm1.0)\times10^{-3}$		564
$\gamma\gamma$	$(1.39\pm0.20)\times10^{-5}$	S=1.1	637
$\eta\pi\pi$	$< 8\times10^{-3}$	CL=95%	474
$K^0K^-\pi^+$ + c.c.	$< 3.4\times10^{-3}$	CL=95%	293
e^+e^-	$< 9\times10^{-9}$	CL=90%	637

$f_1(1285)$ was $D(1285)$

$I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 1282 \pm 5$ MeV [g]
Full width $\Gamma = 24 \pm 3$ MeV [g]

$f_1(1285)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
4π	(38 ± 4) %	S=1.1	563
$\rho\pi\pi$	dominates 4π		342
$\eta\pi\pi$	(50 ± 5) %	S=1.1	478
$a_0(980)\pi$	(37 ± 7) %		233
$K\overline{K}\pi$	(11.9 ± 1.4) %	S=1.1	308

$\phi\gamma$	$(10 \pm 4) \times 10^{-4}$		236
$\gamma\gamma^*$	$(11 \pm 3) \times 10^{-5}$		–
$4\pi^0$	$< 7 \times 10^{-4}$	CL=90%	568
$\gamma\rho^0$	$> 4 \times 10^{-3}$	CL=90%	411
$K\overline{K}^*(892)$	not seen		–

$\eta(1295)$ was $\eta(1275)$

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 1295 \pm 4$ MeV
Full width $\Gamma = 53 \pm 6$ MeV

$\eta(1295)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\eta\pi^+\pi^-$	seen	487
$a_0(980)\pi$	seen	245

$\pi(1300)$

$I^G(J^{PC}) = 1^-(0^{-+})$

Mass $m = 1300 \pm 100$ MeV [g]
Full width $\Gamma = 200$ to 600 MeV

$\pi(1300)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	seen	407
$\pi(\pi\pi)_{S\text{-wave}}$	seen	612

$a_2(1320)$ was $A_2(1320)$

$I^G(J^{PC}) = 1^-(2^{++})$

Mass $m = 1318.2 \pm 0.7$ MeV (S = 1.1) (3π and $K^\pm K^0_S$ modes)
Full width $\Gamma = 110 \pm 5$ MeV [g] ($K^\pm K^0_S$ and $\eta\pi$ modes)

$a_2(1320)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\rho\pi$	(70.1 ± 2.7) %	S=1.2	420
$\eta\pi$	(14.5 ± 1.2) %		534
$\omega\pi\pi$	(10.6 ± 3.2) %	S=1.3	362
$K\overline{K}$	(4.9 ± 0.8) %		437
$\pi^\pm\gamma$	$(2.7 \pm 0.5) \times 10^{-3}$		652
$\gamma\gamma$	$(9.5 \pm 0.9) \times 10^{-6}$		659
$\pi^+\pi^-\pi^-$	< 8 %	CL=90%	621
$\eta'(958)\pi$	< 1.0 %	CL=95%	287
e^+e^-	$< 2.3 \times 10^{-7}$	CL=90%	659

$\omega(1390)$ [h]

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 1394 \pm 17$ MeV
Full width $\Gamma = 229 \pm 40$ MeV

$\omega(1390)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	dominant	472

$f_0(1400)$ was $\epsilon(1300)$

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m \sim 1400$ MeV
Full width $\Gamma = 150$ to 400 MeV
$\Gamma_{\gamma\gamma} = 5.4 \pm 2.3$ KeV
$\Gamma_{ee} < 20$ eV, CL = 90%

$f_0(1400)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	$(93.6^{+1.9}_{-1.5})$ %	686
$K\overline{K}$	(7.5 ± 0.9) %	496
$\eta\eta$	seen	435
$\gamma\gamma$	seen	700
e^+e^-	not seen	700

$f_1(1420)$ [h] was $E(1420)$

$I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 1426.1 \pm 1.6$ MeV (S = 1.3)
Full width $\Gamma = 56.0 \pm 3.0$ MeV

$f_1(1420)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}\pi$	dominant	438
$\eta\pi\pi$	possibly seen	570
$a_0(980)\pi$	possibly seen	355

$\eta(1440)$ [h] was $\iota(1440)$

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 1420 \pm 20$ MeV [g]
Full width $\Gamma = 60 \pm 30$ MeV [g]

$\eta(1440)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}\pi$	seen	433
$\eta\pi\pi$	seen	566
$a_0(980)\pi$	seen	350
4π	seen	640

$\rho(1450)$ [h]

$I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 1465 \pm 25$ MeV [g]
Full width $\Gamma = 310 \pm 60$ MeV [g]

$\rho(1450)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	seen	719
4π	seen	665
e^+e^-	seen	732
$\eta\rho$	<4 %	317
$\phi\pi$	<1 %	358

$f_1(1510)$ was $D(1530)$

$I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 1512 \pm 4$ MeV
Full width $\Gamma = 35 \pm 15$ MeV

$f_1(1510)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}^*(892)$ + c.c.	seen	292

$f'_2(1525)$ was $f'(1525)$

$I^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 1525 \pm 5$ MeV [g]
Full width $\Gamma = 76 \pm 10$ MeV [g]

$f'_2(1525)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}$	$(71.2 \ ^{+2.0}_{-2.5})$ %	581
$\eta\eta$	$(27.9 \ ^{+2.5}_{-2.0})$ %	529
$\pi\pi$	$(8.2 \pm 1.6) \times 10^{-3}$	750
$\gamma\gamma$	$(1.23 \pm 0.22) \times 10^{-6}$	763

$f_0(1590)$

$I^G(J^{PC}) = 0^+(0^{++})$

Seen by one group only.
Mass $m = 1587 \pm 11$ MeV
Full width $\Gamma = 175 \pm 19$ MeV (S = 1.3)

$f_0(1590)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\eta\eta'(958)$	dominant	241
$\eta\eta$	large	573
$4\pi^0$	large	735

$\omega(1600)$ [h]

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 1594 \pm 12$ MeV
Full width $\Gamma = 100 \pm 30$ MeV

$\omega(1600)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	seen	602
$\omega\pi\pi$	seen	564
e^+e^-	seen	797

$\omega_3(1670)$

$I^G(J^{PC}) = 0^-(3^{--})$

Mass $m = 1668 \pm 5$ MeV
Full width $\Gamma = 166 \pm 15$ MeV [g]

$\omega_3(1670)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	seen	648
$\omega\pi\pi$	seen	614
$b_1(1235)\pi$	possibly seen	359

$\pi_2(1670)$
was $A_3(1680)$

$I^G(J^{PC}) = 1^-(2^{-+})$

Mass $m = 1670 \pm 20$ MeV [g]
Full width $\Gamma = 250 \pm 20$ MeV [g]
$\Gamma_{ee} = 1.35 \pm 0.26$ KeV

$\pi_2(1670)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$f_2(1270)\pi$	(56.2 ± 3.2) %		325
$\rho\pi$	(31 ± 4) %		649
$f_0(1400)\pi$	(8.7 ± 3.4) %		212
$K\overline{K}^*(892)$ + c.c.	(4.2 ± 1.4) %		453
$\eta\pi$	<5 %	90%	738
$\pi^\pm 2\pi^+ 2\pi^-$	<5 %	90%	734
$\gamma\gamma$	$(5.4\pm1.1)\times10^{-3}$		835

$\phi(1680)$

$I^G(J^{PC}) = 0^-(1^{--})$

Not a well-established resonance.
Mass $m = 1680 \pm 50$ MeV [g]
Full width $\Gamma = 150 \pm 50$ MeV [g]

$\phi(1680)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}^*(892)$ + c.c.	dominant	462
$K\overline{K}$	seen	680
e^+e^-	seen	840
$\omega\pi\pi$	possibly seen	621
$K_S^0 K\pi$	seen	619

$\rho_3(1690)$
was $g(1690)$

$I^G(J^{PC}) = 1^+(3^{--})$

J^P from the 2π and $K\overline{K}$ modes.
Mass $m = 1691 \pm 5$ MeV [g] (2π, $K\overline{K}$, and $K\overline{K}\pi$ modes)
Full width $\Gamma = 215 \pm 20$ MeV [g] (2π, $K\overline{K}$, and $K\overline{K}\pi$ modes)

$\rho_3(1690)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
4π	(71.1 ± 1.9) %		787
$\pi\pi$	(23.6 ± 1.3) %		834
$K\overline{K}\pi$	(3.8 ± 1.2) %		628
$K\overline{K}$	(1.58 ± 0.26) %	1.2	686
$\eta\pi^+\pi^-$	seen		728

$\rho(1700)$ [h]

$I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 1700 \pm 20$ MeV [g] ($\eta\rho^0$ and mixed modes)
Full width $\Gamma = 235 \pm 50$ MeV [g] ($\eta\rho^0$, $\pi^+\pi^-$, and mixed modes)

$\rho(1700)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi\pi$	dominant	641
$\rho^0\pi^+\pi^-$	large	641
$\rho^\pm\pi^\mp\pi^0$	large	642
$2(\pi^+\pi^-)$	large	792
$\pi^+\pi^-$	seen	838
$K\overline{K}^*(892)$ + c.c.	seen	479
$\eta\rho$	seen	533
$K\overline{K}$	seen	692
e^+e^-	seen	850

$f_0(1710)$
was $\theta(1690)$

$I^G(J^{PC}) = 0^+(0^{++})$
J needs confirmation.

Mass $m = 1709 \pm 5$ MeV
Full width $\Gamma = 146 \pm 12$ MeV ($S = 1.1$)

$f_0(1710)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}$	seen	697
$\pi\pi$	seen	843
$\rho\rho$	possibly seen	374

$\phi_3(1850)$
was $X(1850)$
was $\phi_J(1850)$

$I^G(J^{PC}) = 0^-(3^{--})$

Mass $m = 1854 \pm 7$ MeV
Full width $\Gamma = 87^{+28}_{-23}$ MeV ($S = 1.2$)

$\phi_3(1850)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}$	seen	785
$K\overline{K}^*(892)$ + c.c.	seen	602

$f_2(2010)$
was $g_T(2010)$

$I^G(J^{PC}) = 0^+(2^{++})$

Seen by one group only.
Mass $m = 2011^{+60}_{-80}$ MeV
Full width $\Gamma = 202 \pm 60$ MeV

$f_2(2010)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\phi\phi$	seen	–

$f_4(2050)$
was $h(2030)$

$I^G(J^{PC}) = 0^+(4^{++})$

Mass $m = 2049 \pm 10$ MeV ($S = 1.2$)
Full width $\Gamma = 203 \pm 12$ MeV

$f_4(2050)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\omega\omega$	(25 ± 6) %	662
$\pi\pi$	(17.0 ± 1.5) %	1015
$K\overline{K}$	$(6.8^{+3.4}_{-1.8})\times10^{-3}$	898
$\eta\eta$	$(2.1\pm0.8)\times10^{-3}$	865
$4\pi^0$	<1.2 %	980

$f_2(2300)$
was $g'_T(2300)$

$I^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 2297 \pm 28$ MeV
Full width $\Gamma = 149 \pm 40$ MeV

$f_2(2300)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\phi\phi$	seen	529

$f_2(2340)$
was $g''_T(2340)$

$I^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 2339 \pm 60$ MeV
Full width $\Gamma = 319^{+80}_{-70}$ MeV

$f_2(2340)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\phi\phi$	seen	573

STRANGE MESONS
$(S = \pm1, C = B = 0)$

$K^\pm$

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 493.646 \pm 0.009$ MeV
Mean life $\tau = (1.2371 \pm 0.0029) \times 10^{-8}$ s (S = 2.2)
$c\tau = 3.709$ m

Slope parameter g [l]

(See Full Listings for quadratic coefficients)

$K^+ \to \pi^+\pi^+\pi^- = -0.2154 \pm 0.0035$ (S = 1.4)
$K^- \to \pi^-\pi^-\pi^+ = -0.217 \pm 0.007$ (S = 2.5)
$K^\pm \to \pi^\pm\pi^0\pi^0 = 0.594 \pm 0.019$ (S = 1.3)

$K^\pm$ decay form factors [j,k]

K^+_{e3} $\lambda_+ = 0.0286 \pm 0.0022$
$K^+_{\mu3}$ $\lambda_+ = 0.033 \pm 0.008$ (S = 1.6)
$K^+_{\mu3}$ $\lambda_0 = 0.004 \pm 0.007$ (S = 1.6)
K^+_{e3} $|f_S/f_+| = 0.084 \pm 0.023$ (S = 1.2)
K^+_{e3} $|f_T/f_+| = 0.38 \pm 0.11$ (S = 1.1)
$K^+_{\mu3}$ $|f_T/f_+| = 0.02 \pm 0.12$
$K^+ \to e^+\nu_e\gamma$ $|F_A + F_V| = 0.148 \pm 0.010$
$K^+ \to \mu^+\nu_\mu\gamma$ $|F_A + F_V| < 0.23$, CL = 90%
$K^+ \to e^+\nu_e\gamma$ $|F_A - F_V| < 0.49$
$K^+ \to \mu^+\nu_\mu\gamma$ $|F_A - F_V| = -2.2$ to 0.3

K^- modes are charge conjugates of the modes below.

K^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\mu^+\nu_\mu$		(63.51 ± 0.19) %	S=1.2	236
$e^+\nu_e$		$(1.55\pm0.07) \times 10^{-5}$		247
$\pi^+\pi^0$		(21.17 ± 0.16) %	S=1.1	205
$\pi^+\pi^+\pi^-$		(5.59 ± 0.05) %	S=2.0	125
$\pi^+\pi^0\pi^0$		(1.73 ± 0.04) %	S=1.2	133
$\pi^0\mu^+\nu_\mu$ Called $K_{\mu3}$.		(3.18 ± 0.08) %	S=1.6	215
$\pi^0 e^+\nu_e$ Called K_{e3}.		(4.82 ± 0.06) %	S=1.3	228
$\pi^0\pi^0 e^+\nu_e$		$(2.1\pm0.4) \times 10^{-5}$		206
$\pi^+\pi^- e^+\nu_e$		$(3.91\pm0.17) \times 10^{-5}$		203
$\pi^+\pi^-\mu^+\nu_\mu$		$(1.4\pm0.9) \times 10^{-5}$		151
$\pi^0\pi^0\pi^0 e^+\nu_e$		$< 3.5 \times 10^{-6}$	CL=90%	135
$\pi^+\gamma\gamma$	[l]	$< 1 \times 10^{-6}$	CL=90%	227
$\pi^+ 3\gamma$	[l]	$< 1.0 \times 10^{-4}$	CL=90%	227
$e^+\nu_e\nu\bar{\nu}$		$< 6 \times 10^{-5}$	CL=90%	247
$\mu^+\nu_\mu\nu\bar{\nu}$		$< 6.0 \times 10^{-6}$	CL=90%	236
$\mu^+\nu_\mu e^+e^-$		$(1.06\pm0.32) \times 10^{-6}$		236
$e^+\nu_e e^+e^-$		$(2.1^{+2.1}_{-1.1}) \times 10^{-7}$		247
$\mu^+\nu_\mu\mu^+\mu^-$		$< 4.1 \times 10^{-7}$	CL=90%	185
$\mu^+\nu_\mu\gamma$	[l,m]	$(5.50\pm0.28) \times 10^{-3}$		236
$\pi^+\pi^0\gamma$	[l,m]	$(2.75\pm0.15) \times 10^{-4}$		205
$\pi^+\pi^0\gamma$ (DE)	[l,n]	$(1.8\pm0.4) \times 10^{-5}$		205
$\pi^+\pi^+\pi^-\gamma$	[l,m]	$(1.04\pm0.31) \times 10^{-4}$		125
$\pi^+\pi^0\pi^0\gamma$	[l,m]	$(7.4^{+5.5}_{-2.9}) \times 10^{-6}$		133
$\pi^0\mu^+\nu_\mu\gamma$	[l,m]	$< 6.1 \times 10^{-5}$	CL=90%	215
$\pi^0 e^+\nu_e\gamma$	[l,m]	$(2.62\pm0.20) \times 10^{-4}$		228
$\pi^0 e^+\nu_e\gamma$ (SD)	[o]	$< 5.3 \times 10^{-5}$	CL=90%	228
$\Delta S = \Delta Q$ (SQ), Lepton number (L), Lepton Family number (LF) violating modes or Flavor-Changing neutral current (FC) modes				
$\pi^+\pi^+e^-\bar{\nu}_e$	SQ	$< 1.2 \times 10^{-8}$	CL=90%	203
$\pi^+\pi^+\mu^-\bar{\nu}_\mu$	SQ	$< 3.0 \times 10^{-6}$	CL=95%	151
$\pi^+e^+e^-$	FC	$(2.7\pm0.5) \times 10^{-7}$		227
$\pi^+\mu^+\mu^-$	FC	$< 2.3 \times 10^{-7}$	CL=90%	172
$\pi^+\nu\bar{\nu}$	FC	$< 3.4 \times 10^{-8}$	CL=90%	227
$\mu^-\nu e^+e^+$	LF	$< 2.0 \times 10^{-8}$	CL=90%	236
$\mu^+\nu_e$	LF	$< 4 \times 10^{-3}$	CL=90%	236
$\pi^+\mu^+e^-$	LF	$< 2.1 \times 10^{-10}$	CL=90%	214
$\pi^+\mu^-e^+$	LF	$< 7 \times 10^{-9}$	CL=90%	214
$\pi^-\mu^+e^+$	L	$< 7 \times 10^{-9}$	CL=90%	214
$\pi^-e^+e^+$	L	$< 1.0 \times 10^{-8}$	CL=90%	227
$\pi^-\mu^+\mu^+$	L	$< 1.5 \times 10^{-4}$	CL=90%	172
$\mu^+\bar{\nu}_e$	L	$< 3.3 \times 10^{-3}$	CL=90%	236
$\pi^0 e^+\bar{\nu}_e$	L	$< 3 \times 10^{-3}$	CL=90%	228

K^0

$I(J^P) = \frac{1}{2}(0^-)$

50% K_S, 50% K_L
Mass $m = 497.671 \pm 0.031$ MeV
$m_{K^0} - m_{K^\pm} = 4.024 \pm 0.032$ MeV

K^0_S

$I(J^P) = \frac{1}{2}(0^-)$

Mean life $\tau = (0.8922 \pm 0.0020) \times 10^{-10}$ s
$c\tau = 2.675$ cm

CP-violation parameters [p]

$|\eta_{+-0}|^2 < 0.12$, CL = 90%
$|\eta_{000}|^2 < 0.1$, CL = 90%

K^0_S DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi^+\pi^-$		(68.61 ± 0.28) %	S=1.2	206
$\pi^0\pi^0$		(31.39 ± 0.28) %	S=1.2	209
$\pi^+\pi^-\gamma$	[l,m]	$(1.85\pm0.10) \times 10^{-3}$		206
$\gamma\gamma$		$(2.4\pm1.2) \times 10^{-6}$		249
$\pi^+\pi^-\pi^0$		$< 4.9 \times 10^{-5}$	CL=90%	133
$3\pi^0$		$< 3.7 \times 10^{-5}$	CL=90%	139
Flavor-Changing neutral current (FC) modes				
$\mu^+\mu^-$	FC	$< 3.2 \times 10^{-7}$	CL=90%	225
e^+e^-	FC	$< 1.0 \times 10^{-5}$	CL=90%	249
$\pi^0 e^+e^-$	FC	$< 4.5 \times 10^{-5}$	CL=90%	231

K^0_L

$I(J^P) = \frac{1}{2}(0^-)$

$m_{K_L} - m_{K_S} = (0.5351 \pm 0.0024) \times 10^{10}\ \hbar\ s^{-1}$
$= (3.522 \pm 0.016) \times 10^{-12}$ MeV
Mean life $\tau = (5.17 \pm 0.04) \times 10^{-8}$ s
$c\tau = 15.50$ m

Slope parameter g [l]

(See Full Listings for quadratic coefficients)

$K^0_L \to \pi^+\pi^-\pi^0 = 0.670 \pm 0.014$ (S = 1.6)

K_L decay form factors [j]

K^0_{e3} $\lambda_+ = 0.0300 \pm 0.0016$ (S = 1.2)
$K^0_{\mu3}$ $\lambda_+ = 0.034 \pm 0.005$ (S = 2.3)
$K^0_{\mu3}$ $\lambda_0 = 0.025 \pm 0.006$ (S = 2.3)
K^0_{e3} $|f_S/f_+| < 0.04$, CL = 68%
K^0_{e3} $|f_T/f_+| < 0.23$, CL = 68%
$K^0_{\mu3}$ $|f_T/f_+| = 0.12 \pm 0.12$
$K_L \to e^+e^-\gamma$: $\alpha_{K^*} = -0.28 \pm 0.08$

CP-violation parameters [p]

$\delta = (0.327 \pm 0.012)\%$
$|\eta_{00}| = (2.253 \pm 0.024) \times 10^{-3}$ (S = 1.1)
$|\eta_{+-}| = (2.268 \pm 0.023) \times 10^{-3}$ (S = 1.1)
$|\eta_{00}/\eta_{+-}| = 0.9935 \pm 0.0032$ [q] (S = 1.3)
$\epsilon'/\epsilon = (2.2 \pm 1.1) \times 10^{-3}$ [q] (S = 1.3)
$\phi_{+-} = (46.6 \pm 1.2)°$
$\phi_{00} = (46.6 \pm 2.0)°$

$\Delta S = -\Delta Q$ in $K^0_{\ell3}$ decay

Re $x = 0.006 \pm 0.018$ (S = 1.3)
Im $x = -0.003 \pm 0.026$ (S = 1.2)

K^0_L DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$3\pi^0$		(21.6 ±0.8) %	S=1.5	139
$\pi^+\pi^-\pi^0$		(12.38±0.21) %	S=1.5	133
$\pi^\pm\mu^\mp\nu$ Called $K_{\mu3}$.	[r]	(27.0 ±0.4) %	S=1.3	216
$\pi^\pm e^\mp\nu$ Called K_{e3}.	[r]	(38.7 ±0.5) %	S=1.4	229
2γ		(5.70±0.27) $\times 10^{-4}$	S=1.9	249
$\pi^0 2\gamma$	[l]	(2.0 ±0.5) $\times 10^{-6}$		231
$\pi^0\pi^\pm e^\mp\nu$	[r]	(6.2 ±2.0) $\times 10^{-5}$		207
($\pi\mu$ atom) ν		(1.05±0.11) $\times 10^{-7}$		216
$\pi^\pm e^\mp\nu_e\gamma$	[l,m]	(1.3 ±0.8) %		229
$\pi^+\pi^-\gamma$	[l,m]	(4.41±0.32) $\times 10^{-5}$		206

Charge conjugation × Parity (CP) or Lepton Family number (LF) violating modes, or Flavor-Changing neutral current (FC) modes

$\pi^+\pi^-$	CP		(2.03±0.04) $\times 10^{-3}$	S=1.2	206
$\pi^0\pi^0$	CP		(9.09±0.35) $\times 10^{-4}$	S=1.8	209
$\pi^0\nu\overline{\nu}$	CP,FC		< 7.6 $\times 10^{-3}$	CL=90%	231
$e^\pm\mu^\mp$	LF	[r]	< 9.4 $\times 10^{-11}$	CL=90%	238
$\mu^+\mu^-$	FC		(7.3 ±0.4) $\times 10^{-9}$		225
$\mu^+\mu^-\gamma$	FC		(2.8 ±2.8) $\times 10^{-7}$		225
$\pi^0\mu^+\mu^-$	CP,FC		< 1.2 $\times 10^{-6}$	CL=90%	177
e^+e^-	FC		< 1.6 $\times 10^{-10}$	CL=90%	249
$e^+e^-\gamma$	FC		(9.1 ±0.5) $\times 10^{-6}$		249
$e^+e^-\gamma\gamma$	FC	[l]	(6.6 ±3.2) $\times 10^{-7}$		249
$\pi^0 e^+e^-$	CP,FC		< 5.5 $\times 10^{-9}$	CL=90%	231
$\pi^+\pi^-e^+e^-$	FC		< 2.5 $\times 10^{-6}$	CL=90%	206
$\mu^+\mu^-e^+e^-$	FC		< 4.9 $\times 10^{-6}$	CL=90%	225
$e^+e^-e^+e^-$	FC		(4.0 ±3.0) $\times 10^{-8}$		249

$K^*(892)$

$I(J^P) = \frac{1}{2}(1^-)$

$K^*(892)^\pm$ mass $m = 891.59 \pm 0.24$ MeV (S = 1.1)
$K^*(892)^0$ mass $m = 896.10 \pm 0.28$ MeV (S = 1.4)
$K^*(892)^\pm$ full width $\Gamma = 49.8 \pm 0.8$ MeV
$K^*(892)^0$ full width $\Gamma = 50.5 \pm 0.6$ MeV (S = 1.1)

$K^*(892)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$K\pi$	~ 100 %		291
$K^0\gamma$	(2.30±0.20) $\times 10^{-3}$		310
$K^\pm\gamma$	(1.01±0.09) $\times 10^{-3}$		309
$K\pi\pi$	< 7 $\times 10^{-4}$	95%	224

$K_1(1270)$
was $Q(1280)$

$I(J^P) = \frac{1}{2}(1^+)$

Mass $m = 1270 \pm 10$ MeV [g]
Full width $\Gamma = 90 \pm 20$ MeV [g]

$K_1(1270)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\rho$	(42 ±6) %	71
$K^*_0(1430)\pi$	(28 ±4) %	–
$K^*(892)\pi$	(16 ±5) %	299
$K\omega$	(11.0±2.0) %	–
$K f_0(1400)$	(3.0±2.0) %	–

$K_1(1400)$
was $Q(1400)$

$I(J^P) = \frac{1}{2}(1^+)$

Mass $m = 1402 \pm 7$ MeV
Full width $\Gamma = 174 \pm 13$ MeV (S = 1.6)

$K_1(1400)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K^*(892)\pi$	(94 ±6) %	401
$K\rho$	(3.0±3.0) %	300
$K f_0(1400)$	(2.0±2.0) %	–
$K\omega$	(1.0±1.0) %	285

$K^*(1410)$

$I(J^P) = \frac{1}{2}(1^-)$

Mass $m = 1412 \pm 12$ MeV (S = 1.1)
Full width $\Gamma = 227 \pm 22$ MeV (S = 1.1)

$K^*(1410)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$K^*(892)\pi$	> 40 %	95%	408
$K\pi$	(6.6±1.3) %		611
$K\rho$	< 7 %	95%	311

$K^*_0(1430)$
was $K^*_0(1350)$
was $\kappa(1350)$

$I(J^P) = \frac{1}{2}(0^+)$

Mass $m = 1429 \pm 6$ MeV
Full width $\Gamma = 287 \pm 23$ MeV

$K^*_0(1430)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\pi$	(93±10) %	621

$K^*_2(1430)$
was $K^*(1430)$

$I(J^P) = \frac{1}{2}(2^+)$

$K^*_2(1430)^\pm$ mass $m = 1425.4 \pm 1.3$ MeV (S = 1.1)
$K^*_2(1430)^0$ mass $m = 1432.4 \pm 1.3$ MeV
$K^*_2(1430)^\pm$ full width $\Gamma = 98.4 \pm 2.3$ MeV
$K^*_2(1430)^0$ full width $\Gamma = 109 \pm 5$ MeV (S = 1.9)

$K^*_2(1430)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$K\pi$	(49.7±1.2) %		622
$K^*(892)\pi$	(25.2±1.7) %		423
$K^*(892)\pi\pi$	(13.0±2.3) %		375
$K\rho$	(8.8±0.8) %	S=1.2	333
$K\omega$	(2.9±0.8) %		319
$K^+\gamma$	(2.4±0.5) $\times 10^{-3}$		627
$K\eta$	($1.4^{+2.8}_{-0.9}$) $\times 10^{-3}$	S=1.1	489
$K\omega\pi$	< 7.2 $\times 10^{-4}$	CL=95%	110
$K^0\gamma$	< 9 $\times 10^{-4}$	CL=90%	631

$K^*(1680)$ was $K^*(1790)$

$I(J^P) = \frac{1}{2}(1^-)$

Mass $m = 1714 \pm 20$ MeV (S = 1.1)
Full width $\Gamma = 323 \pm 110$ MeV (S = 4.2)

$K^*(1680)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\pi$	(38.7 ± 2.5) %	779
$K\rho$	$(31.4^{+4.7}_{-2.1})$ %	573
$K^*(892)\pi$	$(29.9^{+2.2}_{-4.7})$ %	615

$K_2(1770)$ [h] was $L(1770)$

$I(J^P) = \frac{1}{2}(2^-)$

Mass $m = 1768 \pm 14$ MeV (S = 1.6)
Full width $\Gamma = 136 \pm 18$ MeV (S = 1.2)

$K_2(1770)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K_2^*(1430)\pi$	dominant	282
$K^*(892)\pi$	seen	650
$K f_2(1270)$	seen	–
$K\phi$	seen	437
$K\omega$	seen	604

$K_3^*(1780)$ was $K^*(1780)$

$I(J^P) = \frac{1}{2}(3^-)$

Mass $m = 1770 \pm 10$ MeV (S = 1.7)
Full width $\Gamma = 164 \pm 17$ MeV (S = 1.1)

$K_3^*(1780)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$K\rho$	(45 ± 4) %	S=1.4	613
$K^*(892)\pi$	(27.3 ± 3.2) %	S=1.5	651
$K\pi$	(19.3 ± 1.0) %		810
$K\eta$	(8.0 ± 1.5) %	S=1.4	715
$K_2^*(1430)\pi$	< 21 %	CL=95%	284

$K_4^*(2045)$ was $K^*(2060)$

$I(J^P) = \frac{1}{2}(4^+)$

Mass $m = 2045 \pm 9$ MeV (S = 1.1)
Full width $\Gamma = 198 \pm 30$ MeV

$K_4^*(2045)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\pi$	(9.9 ± 1.2) %	958
$K^*(892)\pi\pi$	(9 ± 5) %	800
$K^*(892)\pi\pi\pi$	(7 ± 5) %	764
$\rho K\pi$	(5.7 ± 3.2) %	743
$\omega K\pi$	(4.9 ± 3.0) %	736
$\phi K\pi$	(2.8 ± 1.4) %	591
$\phi K^*(892)$	(1.4 ± 0.7) %	363

CHARMED MESONS ($C = \pm 1$)

$D^\pm$

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1869.3 \pm 0.5$ MeV
Mean life $\tau = (10.66 \pm 0.23) \times 10^{-13}$ s
$c\tau = 320$ μm

D^- modes are charge conjugates of the modes below.

D^+ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Inclusive modes			
e^+ anything	(17.2 ± 1.9) %		–
K^- anything	(20.8 ± 2.8) %	S=1.3	–
K^+ anything	(5.8 ± 1.4) %		–
K^0 anything + $\overline{K}^0$ anything	(59 ± 7) %		–
η anything	[s] < 13 %	CL=90%	–
Semileptonic modes			
$\mu^+\nu_\mu$	$< 7.2 \times 10^{-4}$	CL=90%	932
$\overline{K}^0 e^+\nu_e$	$(5.5^{+1.2}_{-1.1})$ %		868
$\overline{K}^0 \mu^+\nu_\mu$	$(7.0^{+3.0}_{-2.0})$ %		865
$K^-\pi^+ e^+\nu_e$	$(3.8^{+0.9}_{-0.7})$ %		863
$\overline{K}^*(892)^0 e^+\nu_e$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	(2.7 ± 0.4) %		720
$K^-\pi^+ e^+\nu_e$ nonresonant	$< 7 \times 10^{-3}$	CL=90%	863
$(\overline{K}^*(892)\pi)^0 e^+\nu_e$	< 1.2 %	CL=90%	713
$(\overline{K}\pi\pi)^0 e^+\nu_e$ non-$\overline{K}^*(892)$	$< 9 \times 10^{-3}$	CL=90%	845
$\pi^+\pi^- e^+\nu_e$	< 5.7 %	CL=90%	924
$\rho^0 e^+\nu_e$	$< 3.7 \times 10^{-3}$	CL=90%	777
Fractions of some of the following modes have already appeared above.			
$\overline{K}^*(892)^0 e^+\nu_e$	(4.1 ± 0.6) %	S=1.1	720
$\rho^0 e^+\nu_e$	$< 3.7 \times 10^{-3}$	CL=90%	777
$\phi e^+\nu_e$	< 2.09 %	CL=90%	657
$\phi\mu^+\nu_\mu$	< 3.72 %	CL=90%	651
Hadronic modes with one or three K's			
$\overline{K}^0\pi^+$	(2.6 ± 0.4) %	S=1.2	862
$K^-\pi^+\pi^+$	$(8.0^{+0.8}_{-0.7})$ %	S=1.2	845
$\overline{K}^*(892)^0\pi^+$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	(1.3 ± 0.5) %		712
$K^-\pi^+\pi^+$ nonresonant	(6.7 ± 0.8) %	S=1.1	845
$\overline{K}^0\pi^+\pi^0$	(8.4 ± 1.8) %		845
$\overline{K}^*(892)^0\pi^+$ $\times$ B($\overline{K}^{*0} \to \overline{K}^0\pi^0$)	(0.6 ± 0.2) %		712
$\overline{K}^0\rho^+$	(6.6 ± 1.7) %		680
$\overline{K}^0\pi^+\pi^0$ nonresonant	$(1.2^{+1.0}_{-0.7})$ %		845
$K^-\pi^+\pi^+\pi^0$	[t] $(4.9^{+1.4}_{-0.8})$ %	S=1.1	816
$\overline{K}^*(892)^0\rho^+$ S-wave $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	$(2.7^{+1.0}_{-0.8})$ %		424
$\overline{K}_1(1400)^0\pi^+$ $\times$ B($\overline{K}_1(1400)^0 \to K^-\pi^+\pi^0$)	(2.0 ± 0.5) %		390
$K^-\rho^+\pi^+$ 3-body	$(8 \pm 5) \times 10^{-3}$		617
$K^-\pi^+\pi^+\pi^0$ nonresonant	$(9 \pm 5) \times 10^{-3}$		816
$\overline{K}^0\pi^+\pi^+\pi^-$	(6.9 ± 1.1) %		814
$\overline{K}^0 a_1(1260)^+$ $\times$ B($a_1(1260)^+ \to \pi^+\pi^+\pi^-$)	(3.8 ± 0.9) %		290
$\overline{K}_1(1400)^0\pi^+$ $\times$ B($\overline{K}_1(1400)^0 \to \overline{K}^0\pi^+\pi^-$)	(2.0 ± 0.5) %		390
$\overline{K}^0\pi^+\pi^+\pi^-$ nonresonant	(1.2 ± 0.8) %		814
$K^-\pi^+\pi^+\pi^+\pi^-$	$(6.1 \pm 1.5) \times 10^{-3}$	S=1.6	772
$\overline{K}^*(892)^0\pi^+\pi^+\pi^-$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	$(5.1 \pm 1.7) \times 10^{-3}$		642
$\overline{K}^*(892)^0\rho^0\pi^+$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	$(3.8 \pm 1.8) \times 10^{-3}$		245

$K^-\pi^+\pi^+\pi^0\pi^0$	$(2.2\ ^{+5.0}_{-0.9})$ %		775
$\overline{K}^0\pi^+\pi^+\pi^-\pi^0$	$(8.7\ ^{+3.5}_{-1.6})$ %	S=1.2	772
$\overline{K}^0\pi^+\pi^+\pi^+\pi^-\pi^-$	$(1.0\ \pm1.0) \times 10^{-3}$		714
$K^-\pi^+\pi^+\pi^+\pi^-\pi^0$	$(1.9\ ^{+2.6}_{-1.3}) \times 10^{-3}$		718
$\overline{K}^0\overline{K}^0K^+$	$(2.7\ \pm0.6)$ %		545

Fractions of some of the following modes (those with values rather than limits) have already appeared above.

$\overline{K}^0\rho^+$	$(6.6\ \pm1.7)$ %		680
$\overline{K}^*(892)^0\pi^+$	$(1.9\ \pm0.7)$ %	S=1.1	712
$\overline{K}^*(892)^0\rho^+$ *S*-wave	$(4.1\ ^{+1.5}_{-1.2})$ %		424
$\overline{K}^*(892)^0\rho^+$ *P*-wave	$< 5 \times 10^{-3}$	CL=90%	424
$\overline{K}^*(892)^0\rho^+$ *D*-wave longitudinal	$< 7 \times 10^{-3}$	CL=90%	424
$\overline{K}^0a_1(1260)^+$	$(7.5\ \pm1.7)$ %		290
$\overline{K}^0a_2(1320)^+$	$< 8 \times 10^{-3}$	CL=90%	199
$\overline{K}_1(1270)^0\pi^+$	< 1.1 %	CL=90%	489
$\overline{K}_1(1400)^0\pi^+$	$(4.4\ \pm1.2)$ %		390
$\overline{K}^*(1410)^0\pi^+$	$< 7 \times 10^{-3}$	CL=90%	383
$K^*(892)^-\pi^+\pi^+$ 3-body	< 1.3 %	CL=90%	688
$\overline{K}^*(892)^0\pi^+\pi^0$ 3-body	$< 8 \times 10^{-3}$	CL=90%	687
$K^-\rho^+\pi^+$ 3-body	$(8\ \pm5) \times 10^{-3}$		617
$\overline{K}^0\rho^0\pi^+$ 3-body	$< 4 \times 10^{-3}$	CL=90%	615
$\overline{K}^*(892)^0\pi^+\pi^+\pi^-$	$(7.6\ \pm2.5) \times 10^{-3}$		642
$\overline{K}^*(892)^0\rho^0\pi^+$	$(5.7\ \pm2.7) \times 10^{-3}$		245

Pionic modes

$\pi^+\pi^0$	$< 5.3 \times 10^{-3}$	CL=90%	925
$\pi^+\pi^+\pi^-$	$(2.8\ \pm0.6) \times 10^{-3}$		908
$\rho^0\pi^+$	$< 1.2 \times 10^{-3}$	CL=90%	769
$\pi^+\pi^+\pi^-$ nonresonant	$(2.2\ \pm0.6) \times 10^{-3}$		908
$\pi^+\pi^+\pi^-\pi^0$	$(2.3\ ^{+2.0}_{-1.3})$ %		883
$\eta\pi^+ \times B(\eta \to \pi^+\pi^-\pi^0)$	$(1.6\ \pm0.5) \times 10^{-3}$		848
$\omega\pi^+ \times B(\omega \to \pi^+\pi^-\pi^0)$	$< 5 \times 10^{-3}$	CL=90%	764
$\pi^+\pi^+\pi^+\pi^-\pi^-$	$(1.5\ \pm1.1) \times 10^{-3}$		845
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$	$(2.8\ ^{+3.8}_{-2.0}) \times 10^{-3}$		799
$\eta'(958)\pi^+ \times B(\eta' \to \eta\pi^+\pi^-) \times B(\eta \to \pi^+\pi^-\pi^0)$	$< 8 \times 10^{-4}$	CL=90%	680

Fractions of most of the following modes have already appeared above.

$\rho^0\pi^+$	$< 1.2 \times 10^{-3}$	CL=90%	769
$\eta\pi^+$	$(6.6\ \pm2.2) \times 10^{-3}$		848
$\omega\pi^+$	$< 6 \times 10^{-3}$	CL=90%	764
$\eta\rho^+$	< 1.0 %	CL=90%	659
$\eta'(958)\pi^+$	$< 8 \times 10^{-3}$	CL=90%	680
$\eta'(958)\rho^+$	< 1.4 %	CL=90%	357

Hadronic modes with two *K*'s

$\overline{K}^0K^+$	$(7.3\ \pm1.8) \times 10^{-3}$		792
$K^+K^-\pi^+$	(1.01 ± 0.13) %	S=1.1	744
$\phi\pi^+ \times B(\phi \to K^+K^-)$	$(3.0\ \pm0.4) \times 10^{-3}$		647
$\overline{K}^*(892)^0K^+ \times B(\overline{K}^{*0} \to K^-\pi^+)$	$(3.1\ \pm0.6) \times 10^{-3}$		610
$K^+K^-\pi^+$ nonresonant	$(4.0\ \pm0.8) \times 10^{-3}$		744
$K^+K^-\pi^+\pi^0$			682
$\phi\pi^+\pi^0 \times B(\phi \to K^+K^-)$	$(1.2\ ^{+0.6}_{-0.5})$ %		619
$\phi\rho^+ \times B(\phi \to K^+K^-)$	$< 7 \times 10^{-3}$	CL=90%	271
$K^+K^-\pi^+\pi^0$ non-ϕ	$(1.5\ ^{+0.7}_{-0.5})$ %		682
$K^+\overline{K}^0\pi^+\pi^-$	< 2 %	CL=90%	681
$K^0K^-\pi^+\pi^+$	$(10\ \pm5) \times 10^{-3}$		681
$K^*(892)^+\overline{K}^*(892)^0 \times B^2(K^* \to K\pi^+)$	$(1.2\ \pm0.5)$ %		273
$K^0K^-\pi^+\pi^+$ non-$K^{*+}\overline{K}^{*0}$	$< 7.9 \times 10^{-3}$	CL=90%	681
$K^+K^-\pi^+\pi^+\pi^-$			600
$\phi\pi^+\pi^+\pi^- \times B(\phi \to K^+K^-)$	$< 1 \times 10^{-3}$	CL=90%	565
$K^+K^-\pi^+\pi^+\pi^-$ nonresonant	< 3 %	CL=90%	600

Fractions of the following modes have already appeared above.

$\phi\pi^+$	$(6.0\ \pm0.8) \times 10^{-3}$	S=1.1	647
$\overline{K}^*(892)^0K^+$	$(4.7\ \pm0.9) \times 10^{-3}$		610
$\phi\pi^+\pi^0$	$(2.4\ ^{+1.1}_{-0.9})$ %		619
$\phi\rho^+$	< 1.3 %	CL=90%	271
$K^*(892)^+\overline{K}^*(892)^0$	$(2.6\ \pm1.1)$ %		273
$\phi\pi^+\pi^+\pi^-$	$< 2 \times 10^{-3}$	CL=90%	565

Flavor-Changing neutral current (*FC*), Lepton number (*L*) violating, Lepton Family number (*LF*) violating, or Doubly Cabibbo suppressed (*DC*) modes

$\pi^+e^+e^-$	*FC*	$< 2.5 \times 10^{-3}$	CL=90%	929
$\pi^+\mu^+\mu^-$	*FC*	$< 2.9 \times 10^{-3}$	CL=90%	917
$\pi^+e^\pm\mu^\mp$	*LF*	$< 3.8 \times 10^{-3}$	CL=90%	926
$\pi^+e^+\mu^-$	*LF*	$< 3.3 \times 10^{-3}$	CL=90%	926
$\pi^+e^-\mu^+$	*LF*	$< 3.3 \times 10^{-3}$	CL=90%	926
$K^+e^+e^-$		$< 4.8 \times 10^{-3}$	CL=90%	869
$K^+\mu^+\mu^-$		$< 9.2 \times 10^{-3}$	CL=90%	856
$K^+e^+\mu^-$	*LF*	$< 3.4 \times 10^{-3}$	CL=90%	866
$K^+e^-\mu^+$	*LF*	$< 3.4 \times 10^{-3}$	CL=90%	866
$\pi^-e^+e^+$	*L*	$< 4.8 \times 10^{-3}$	CL=90%	929
$\pi^-\mu^+\mu^+$	*L*	$< 6.8 \times 10^{-3}$	CL=90%	917
$\pi^-e^+\mu^+$	*L*	$< 3.7 \times 10^{-3}$	CL=90%	926
$K^-e^+e^+$	*L*	$< 9.1 \times 10^{-3}$	CL=90%	869
$K^-\mu^+\mu^+$	*L*	$< 4.3 \times 10^{-3}$	CL=90%	856
$K^-e^+\mu^+$	*L*	$< 4.0 \times 10^{-3}$	CL=90%	866
$K^+\pi^+\pi^-$	*DC*	$< 4 \times 10^{-3}$	CL=90%	845

D^0

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1864.5 \pm 0.5$ MeV

$|m_{D^0_1} - m_{D^0_2}| < 1.3 \times 10^{-4}$ eV, CL = 90% [u]

$m_{D^\pm} - m_{D^0} = 4.77 \pm 0.27$ MeV

Mean life $\tau = (4.20 \pm 0.08) \times 10^{-13}$ s

$c\tau = 125.9\ \mu$m

$|\tau_{D^0_1} - \tau_{D^0_2}|/\tau_{D^0} < 0.17$, CL = 90% [u]

$\Gamma(\mu^-\ X\ (\text{via}\ \overline{D}^0))/\Gamma(\mu^+\ X) < 0.0056$, CL = 90%

$\Gamma(K^+\pi^-\ (\text{via}\ \overline{D}^0))/\Gamma(K^-\pi^+) < 0.0037$, CL = 90%

$[\Gamma(D^0 \to K^+K^-) - \Gamma(\overline{D}^0 \to K^+K^-)]/\text{sum} < 0.45$, CL = 90%

$\overline{D}^0$ modes are charge conjugates of the modes below.

D^0 DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Inclusive modes			
e^+ anything	$(7.7\ \pm\ 1.2)$ %	S=1.1	–
μ^+ anything	$(8.8\ \pm\ 2.5)$ %		–
K^- anything	$(46\ \pm\ 4)$ %	S=1.5	–
K^+ anything	$(3.4\ ^{+0.6}_{-0.5})$ %		–
K^0 anything + $\overline{K}^0$ anything	$(42\ \pm\ 5)$ %		–
η anything	[s] < 13 %	CL=90%	–
Semileptonic modes			
$K^-e^+\nu_e$	$(3.31\pm\ 0.29)$ %		867
$K^-\mu^+\nu_\mu$	$(2.9\ \pm\ 0.5)$ %		863
$K^-\pi^0e^+\nu_e$	[v] $(1.6\ ^{+1.3}_{-0.5})$ %		861
$\overline{K}^0\pi^-e^+\nu_e$	[v] $(2.8\ ^{+1.7}_{-0.9})$ %		860
$\overline{K}^*(892)^-e^+\nu_e \times B(\overline{K}^{*0} \to K^-\pi^+)$	$(1.1\ \pm\ 0.4)$ %		719
$\overline{K}^*(892)^0\pi^-e^+\nu_e$	< 1.1 %	CL=90%	708
$\pi^-e^+\nu_e$	$(3.9\ ^{+2.3}_{-1.2}) \times 10^{-3}$		927

A fraction of the following mode has already appeared above.

$K^*(892)^-e^+\nu_e$	$(1.7\ \pm\ 0.6)$ %		719

Meson Summary Table

Hadronic modes with one or three K's

$\overline{K}^0\pi^0$	$(2.1 \pm 0.5)\ \%$		860
$K^-\pi^+$	$(3.65 \pm 0.21)\ \%$	S=1.1	861
$\overline{K}^0\pi^+\pi^-$	$(5.4 \pm 0.5)\ \%$	S=1.1	842
$\overline{K}^0\rho^0$	$(6.1 \pm 3.0) \times 10^{-3}$		677
$K^*(892)^-\pi^+$ $\times$ B($K^{*-} \to \overline{K}^0\pi^-$)	$(3.0 \pm 0.4)\ \%$		711
$\overline{K}^0\pi^+\pi^-$ nonresonant	$(1.8 \pm 0.5)\ \%$		842
$K^-\pi^+\pi^0$	$(11.3 \pm 1.1)\ \%$	S=1.2	844
$K^-\rho^+$	$(7.3 \pm 1.1)\ \%$	S=1.3	679
$K^*(892)^-\pi^+$ $\times$ B($\overline{K}^{*-} \to K^-\pi^0$)	$(1.5 \pm 0.2)\ \%$		711
$\overline{K}^*(892)^0\pi^0$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	$(1.4 \pm 0.7)\ \%$		709
$K^-\pi^+\pi^0$ nonresonant	$(1.1 {+0.8 \atop -0.6})\ \%$	S=1.6	844
$K^-\pi^+\pi^+\pi^-$ [t]	$(7.5 \pm 0.5)\ \%$	S=1.1	812
$K^-\pi^+\rho^0$	$(6.4 \pm 0.5)\ \%$		613
$K^-\pi^+\rho^0$ 3-body	$(6.3 \pm 3.4) \times 10^{-3}$		613
$\overline{K}^*(892)^0\rho^0$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	$(1.0 \pm 0.4)\ \%$		419
$K^-a_1(1260)^+$ $\times$ B($a_1(1260)^+ \to \pi^+\pi^+\pi^-$)	$(3.7 \pm 0.7)\ \%$		289
$K_1(1270)^-\pi^+$ $\times$ B($K_1(1270)^- \to K^-\pi^+\pi^-$)	$(3.7 \pm 1.1) \times 10^{-3}$		485
$\overline{K}^*(892)^0\pi^+\pi^-$ 3-body $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	$(1.1 \pm 0.3)\ \%$		683
$K^-\pi^+\pi^+\pi^-$ nonresonant	$(1.8 \pm 0.5)\ \%$		812
$\overline{K}^0\pi^+\pi^-\pi^0$	$(10.3 \pm 1.7)\ \%$		812
$\overline{K}^0\omega$ $\times$ B($\omega \to \pi^+\pi^-\pi^0$)	$(2.2 \pm 0.4)\ \%$		670
$K^*(892)^-\rho^+$ $\times$ B($K^{*-} \to \overline{K}^0\pi^-$)	$(4.1 \pm 1.7)\ \%$		423
$\overline{K}^*(892)^0\rho^0$ $\times$ B($\overline{K}^{*0} \to \overline{K}^0\pi^0$)	$(5.0 \pm 2.0) \times 10^{-3}$		419
$K_1(1270)^-\pi^+$ $\times$ B($K_1(1270)^- \to \overline{K}^0\pi^-\pi^0$)	$(5.2 \pm 1.6) \times 10^{-3}$		485
$\overline{K}^*(892)^0\pi^+\pi^-$ 3-body $\times$ B($\overline{K}^{*0} \to \overline{K}^0\pi^0$)	$(5.3 \pm 1.7) \times 10^{-3}$		683
$\overline{K}^0\pi^+\pi^-\pi^0$ nonresonant	$(2.2 \pm 2.2)\ \%$		812
$K^-\pi^+\pi^0\pi^0$	$(15 \pm 5)\ \%$		815
$K^-\pi^+\pi^+\pi^-\pi^0$	$(3.5 \pm 0.6)\ \%$	S=1.6	771
$\overline{K}^*(892)^0\pi^+\pi^-\pi^0$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	$(1.1 \pm 0.5)\ \%$		641
$\overline{K}^*(892)^0\eta$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$) $\times$ B($\eta \to \pi^+\pi^-\pi^0$)	$(3.3 \pm 1.9) \times 10^{-3}$		579
$\overline{K}^0\pi^+\pi^+\pi^-\pi^-$	$(8.5 \pm 1.4) \times 10^{-3}$		768
$\overline{K}^0\pi^+\pi^-\pi^0\pi^0(\pi^0)$	$(12.7 {+3.5 \atop -2.4})\ \%$		771
$\overline{K}^0\phi$ $\times$ B($\phi \to K^+K^-$)	$(4.4 \pm 0.6) \times 10^{-3}$		520
$\overline{K}^0K^+K^-$ non-ϕ	$(5.2 \pm 0.9) \times 10^{-3}$	S=1.1	544
$K^0_SK^0_SK^0_S$	$(8.9 \pm 2.5) \times 10^{-4}$		538
$K^+K^-\overline{K}^0\pi^0$	$(9 {+6 \atop -4}) \times 10^{-3}$		435

Fractions of many of the following modes have already appeared above. (Modes for which there are only upper limits and $\overline{K}^*(892)\rho$ submodes only appear below.)

$\overline{K}^0\eta$	$< 2.3\ \%$	CL=90%	771
$\overline{K}^0\rho^0$	$(6.1 \pm 3.0) \times 10^{-3}$		677
$K^-\rho^+$	$(7.3 \pm 1.1)\ \%$	S=1.2	679
$\overline{K}^0\omega$	$(2.5 \pm 0.5)\ \%$		670
$\overline{K}^0\phi$	$(8.8 \pm 1.2) \times 10^{-3}$	S=1.1	520
$K^*(892)^-\pi^+$	$(4.5 \pm 0.6)\ \%$		711
$\overline{K}^*(892)^0\pi^0$	$(2.1 \pm 1.0)\ \%$	S=1.5	709
$\overline{K}^*(892)^0\pi^+\pi^-$ 3-body	$(1.6 \pm 0.5)\ \%$		683
$\overline{K}^*(892)^0\rho^0$	$(1.5 \pm 0.6)\ \%$		419
$\overline{K}^*(892)^0\rho^0$ transverse	$(1.5 \pm 0.5)\ \%$		419
$\overline{K}^*(892)^0\rho^0$ S-wave longitudinal	$< 3 \times 10^{-3}$	CL=90%	419
$\overline{K}^*(892)^0\rho^0$ P-wave	$< 3 \times 10^{-3}$	CL=90%	419
$\overline{K}^*(892)^-\rho^+$	$(6.2 \pm 2.5)\ \%$		423
$\overline{K}^*(892)^-\rho^+$ longitudinal	$(3.0 \pm 1.2)\ \%$		423
$\overline{K}^*(892)^-\rho^+$ transverse	$(3.3 \pm 1.9)\ \%$		423
$\overline{K}^*(892)^-\rho^+$ P-wave	$< 1.5\ \%$	CL=90%	423
$K^-a_1(1260)^+$	$(7.4 \pm 1.3)\ \%$		289
$\overline{K}^0a_1(1260)^0$	$< 1.9\ \%$	CL=90%	284
$K^-a_2(1320)^+$	$< 6 \times 10^{-3}$	CL=90%	197
$K_1(1270)^-\pi^+$	$(1.09 \pm 0.33)\ \%$		485
$K_1(1400)^-\pi^+$	$< 1.2\ \%$	CL=90%	386
$\overline{K}_1(1400)^0\pi^0$	$< 3.7\ \%$	CL=90%	387
$K^*(1410)^-\pi^+$	$< 1.2\ \%$	CL=90%	413
$\overline{K}^*(892)^0\pi^+\pi^-\pi^0$	$(1.6 \pm 0.8)\ \%$		641
$\overline{K}^*(892)^0\eta$ [w]	$(2.1 \pm 1.2)\ \%$		579
$\overline{K}^*(892)^0\omega$	$< 1.5\ \%$	CL=90%	406

Pionic modes

$\pi^+\pi^-$	$(1.63 \pm 0.19) \times 10^{-3}$		922
$\pi^0\pi^0$	$< 4.6 \times 10^{-3}$	CL=90%	922
$\pi^+\pi^-\pi^0$	$(1.5 \pm 1.0)\ \%$	S=2.5	907
$\pi^+\pi^+\pi^-\pi^-$	$(7.5 \pm 0.9) \times 10^{-3}$		879
$\pi^+\pi^+\pi^-\pi^-\pi^0$	$(1.7 \pm 0.5)\ \%$		844
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$	$(4.0 \pm 3.0) \times 10^{-4}$		795

Hadronic modes with two K's

K^+K^-	$(4.1 \pm 0.4) \times 10^{-3}$	S=1.1	791
$K^0\overline{K}^0$	$(1.1 \pm 0.4) \times 10^{-3}$		788
$K^0K^-\pi^+$	$(6.4 \pm 1.1) \times 10^{-3}$	S=1.1	739
$\overline{K}^*(892)^0K^0$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	$< 1.1 \times 10^{-3}$	CL=90%	605
$K^*(892)^+K^-$ $\times$ B($K^{*+} \to K^0\pi^+$)	$(2.3 \pm 0.5) \times 10^{-3}$		609
$K^0K^-\pi^+$ nonresonant	$(2.2 \pm 2.2) \times 10^{-3}$		739
$\overline{K}^0K^+\pi^-$	$(4.9 \pm 1.0) \times 10^{-3}$		739
$K^*(892)^0\overline{K}^0$ $\times$ B($K^{*0} \to K^+\pi^-$)	$< 5 \times 10^{-4}$	CL=90%	605
$K^*(892)^-K^+$ $\times$ B($K^{*-} \to \overline{K}^0\pi^-$)	$(1.3 \pm 0.7) \times 10^{-3}$		609
$\overline{K}^0K^+\pi^-$ nonresonant	$(3.7 {+2.2 \atop -1.8}) \times 10^{-3}$		739
$K^+K^-\pi^+\pi^-$	$(2.4 \pm 0.4) \times 10^{-3}$		676
$\phi\pi^+\pi^-$ $\times$ B($\phi \to K^+K^-$)	$(1.2 \pm 0.4) \times 10^{-3}$		614
$\phi\rho^0$ $\times$ B($\phi \to K^+K^-$)	$(9.0 \pm 2.5) \times 10^{-4}$		262
$K^*(892)^0K^-\pi^+$ + cc $\times$ B($K^{*0} \to K^-\pi^+$)	$(5 {+8 \atop -5}) \times 10^{-4}$		528
$K^*(892)^0\overline{K}^*(892)^0$ $\times$ B^2($K^{*0} \to K^-\pi^+$)	$(1.2 {+0.7 \atop -0.5}) \times 10^{-3}$		257
$K^+K^-\pi^+\pi^-$ nonresonant	$(7 {+80 \atop -8}) \times 10^{-5}$		676
$K^+K^-\pi^0\pi^0$	seen		681
$K^0K^-\pi^+\pi^0$	seen		677
$K^+K^-\pi^+\pi^-\pi^0$	$(2.8 {+2.5 \atop -1.5}) \times 10^{-3}$		600

Fractions of the following modes have already appeared above.

$\overline{K}^*(892)^0K^0$	$< 1.6 \times 10^{-3}$	CL=90%	605
$K^*(892)^+K^-$	$(3.5 \pm 0.8) \times 10^{-3}$		609
$K^*(892)^0\overline{K}^0$	$< 8 \times 10^{-4}$	CL=90%	605
$K^*(892)^-K^+$	$(2.0 \pm 1.0) \times 10^{-3}$		609
$\phi\pi^+\pi^-$	$(2.4 \pm 0.8) \times 10^{-3}$		614
$\phi\rho^0$	$(1.8 \pm 0.5) \times 10^{-3}$		262
$K^*(892)^0K^-\pi^+$ +c.c.	$(7 {+12 \atop -8}) \times 10^{-4}$		528
$K^*(892)^0\overline{K}^*(892)^0$	$(2.7 {+1.5 \atop -1.2}) \times 10^{-3}$		257

Lepton Family number (LF) violating, Flavor-Changing neutral current (FC), decay via Mixing (MX), or Doubly Cabibbo suppressed (DC) modes

e^+e^-	FC	$< 1.3 \times 10^{-4}$	CL=90%	932
$\mu^+\mu^-$	FC	$< 1.1 \times 10^{-5}$	CL=90%	926
$\mu^{\pm}e^{\mp}$	LF	[r] $< 1.0 \times 10^{-4}$	CL=90%	929
$\overline{K}^0e^+e^-$	FC	$< 1.7 \times 10^{-3}$	CL=90%	866
$\rho^0e^+e^-$	FC	$< 4.5 \times 10^{-4}$	CL=90%	774
$\rho^0\mu^+\mu^-$	FC	$< 8.1 \times 10^{-4}$	CL=90%	757
μ^- anything (via $\overline{D}^0$)	MX	$< 5 \times 10^{-4}$	CL=90%	–
$K^+\pi^-$	DC	$< 4 \times 10^{-4}$	CL=90%	861
$K^+\pi^-$ (via $\overline{D}^0$)	MX	$< 1.4 \times 10^{-4}$	CL=90%	861
$K^+\pi^+\pi^-\pi^-$	DC	$< 1.3 \times 10^{-3}$	CL=90%	812

$D^*(2010)^{\pm}$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

Mass $m = 2010.1 \pm 0.6$ MeV
$m_{D^{*+}} - m_{D^0} = 145.44 \pm 0.06$ MeV
Full width $\Gamma < 1.1$ MeV, CL = 90%

$D^*(2010)^-$ modes are charge conjugates of the modes below.

$D^*(2010)^+$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^0\pi^+$	(55 ±4) %	40
$D^+\pi^0$	(27.2±2.5) %	39
$D^+\gamma$	(18 ±4) %	136

$D^*(2010)^0$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

Mass $m = 2007.1 \pm 1.4$ MeV
$m_{D^{*0}} - m_{D^0} = 142.5 \pm 1.3$ MeV
Full width $\Gamma < 2.1$ MeV, CL = 90%

$\overline{D}^*(2010)^0$ modes are charge conjugates of modes below.

$D^*(2010)^0$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^0\pi^0$	(55±6) %	44
$D^0\gamma$	(45±6) %	138

$D_1(2420)^0$

$I(J^P) = \frac{1}{2}(1^+)$
I, J, P need confirmation.

Mass $m = 2424 \pm 6$ MeV (S = 2.2)
Full width $\Gamma = 20^{+9}_{-5}$ MeV

$\overline{D}_1(2420)^0$ modes are charge conjugates of modes below.

$D_1(2420)^0$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^*(2010)^+\pi^-$	seen	356

$D_2^*(2460)^0$

$I(J^P) = \frac{1}{2}(2^+)$
I, J, P need confirmation.

Mass $m = 2459.4 \pm 2.2$ MeV
Full width $\Gamma = 19 \pm 7$ MeV

$\overline{D}_2^*(2460)^0$ modes are charge conjugates of modes below.

$D_2^*(2460)^0$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^+\pi^-$	seen	504
$D^*(2010)^+\pi^-$	seen	388

CHARMED STRANGE MESONS ($C = S = \pm 1$)

$D_s^{\pm}$ was $F^{\pm}$

$I(J^P) = 0(0^-)$

Mass $m = 1968.8 \pm 0.7$ MeV (S = 1.1)
$m_{D_s^{\pm}} - m_{D^{\pm}} = 99.5 \pm 0.6$ MeV (S = 1.1)
Mean life $\tau = (4.50^{+0.30}_{-0.26}) \times 10^{-13}$ s
$c\tau = 135$ μm

D_s^- modes are charge conjugates of the modes below.

Nearly all the other modes are measured relative to the $\phi\pi^+$ mode. However, none of the determinations of the $\phi\pi^+$ branching fraction are direct measurements: all rely on calculated relations between D^+ and D_s^+ decay widths or on estimates of D_s^+ cross sections. Thus a better determination of the $\phi\pi^+$ branching fraction could cause the other branching fractions to slide up or down, all together.

D_s^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
Inclusive modes				
K^- anything		$(13\ ^{+14}_{-12})$ %		–
K^+ anything		$(20\ ^{+18}_{-14})$ %		–
K^0 anything + $\overline{K}^0$ anything		(39 ±28) %		–
non-$K\overline{K}$ anything		(64 ±17) %		–
e^+ anything		< 20 %	90%	–
Modes with two K's (including from ϕ's)				
$K^+\overline{K}^0$		(2.8± 0.7) %		851
$K^+K^-\pi^+$	[x]	(3.9± 0.4) %		805
$\phi\pi^+$	[y]	(2.8± 0.5) %		712
$K^+\overline{K}^*(892)^0$	[y]	(2.6± 0.5) %		683
$K^+K^-\pi^+$ nonresonant		(8.1± 3.0) × 10^{-3}		805
$K^0\overline{K}^0\pi^+$				802
$K^*(892)^+\overline{K}^0$	[y]	(3.3± 0.9) %		683
$K^+K^-\pi^+\pi^0$				748
$\phi\pi^+\pi^0$	[y]	(6.7± 3.3) %		687
$\phi\rho^+$	[y]	$(5.2^{+1.4}_{-1.6})$ %		409
$\phi\pi^+\pi^0$ 3-body	[y]	< 2.0 %	90%	687
$K^+K^-\pi^+\pi^0$ non-ϕ		< 7 %	90%	748
$K^+\overline{K}^0\pi^+\pi^-$		< 2.1 %	90%	745
$K^0K^-\pi^+\pi^+$		(3.3± 1.0) %		745
$K^*(892)^+\overline{K}^*(892)^0$	[y]	(5.0± 1.7) %		412
$K^0K^-\pi^+\pi^+$ non-$K^{*+}\overline{K}^{*0}$		< 2.2 %	90%	745
$K^+K^-\pi^+\pi^+\pi^-$				673
$\phi\pi^+\pi^+\pi^-$	[y]	(1.2± 0.4) %		640
$K^+K^-\pi^+\pi^+\pi^-$ non-ϕ		(1.9± 1.4) × 10^{-3}		673
Other hadronic modes				
$\pi^+\pi^+\pi^-$		(1.2± 0.4) %		960
$\rho^0\pi^+$		< 2.2 × 10^{-3}	90%	828
$f_0(975)\pi^+$	[y]	(7.8± 3.2) × 10^{-3}		735
$\pi^+\pi^+\pi^-$ nonresonant		(8.0± 3.0) × 10^{-3}		960
$\pi^+\pi^+\pi^-\pi^0$		< 9 %	90%	935
$\eta\pi^+$	[y]	(1.5± 0.4) %		902
$\omega\pi^+$	[y]	< 1.4 %	90%	822
$\pi^+\pi^+\pi^+\pi^-\pi^-$		(1.9± 2.0) × 10^{-3}		899
$\pi^+\pi^+\pi^-\pi^0\pi^0$				902
$\eta\rho^+$	[y]	(7.9± 2.1) %		727
$\eta\pi^+\pi^0$ 3-body	[y]	< 2.3 %	90%	787
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$				856
$\eta\pi^+\pi^+\pi^-$				855
$\eta'(958)\pi^+$	[y]	(3.7± 1.2) %		744
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$				803
$\eta'(958)\rho^+$	[y]	(9.5± 2.7) %		472
$\eta'(958)\pi^+\pi^0$ 3-body	[y]	< 2.4 %	90%	720
$K^0\pi^+$		< 6 × 10^{-3}	90%	916
$K^+\pi^+\pi^-$		(1.4± 2.0) × 10^{-3}		900

	Leptonic and semileptonic modes		
$\mu^+ \nu$		< 3 %	982
$\phi e^+ \nu$	[y]	(1.6± 0.7) %	721
$\phi \ell^+ \nu$	[y,z]	(1.4± 0.5) %	–

$D_s^{*\pm}$ was $F^{*\pm}$

$I(J^P) = ?(?^?)$

Mass $m = 2110.3 \pm 2.0$ MeV (S = 1.3)
$m_{D_s^{*\pm}} - m_{D_s^{\pm}} = 141.5 \pm 1.9$ MeV (S = 1.3)
Full width $\Gamma < 4.5$ MeV, CL = 90%

D_s^{*-} modes are charge conjugates of the modes below.

D_s^{*+} DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D_s^+ \gamma$	dominant	137

$D_{s1}(2536)^{\pm}$

$I(J^P) = 0(1^+)$
I, J, P need confirmation.

Mass $m = 2536.5 \pm 0.8$ MeV
Full width $\Gamma < 4.6$ MeV, CL = 90%

$D_{s1}(2536)^-$ modes are charge conjugates of the modes below.

$D_{s1}(2536)^+$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^*(2010)^+ K^0$	seen	153
$D_s^{*+} \gamma$	possibly seen	390

BOTTOM MESONS ($B = \pm 1$)

$B^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

I, J, P need confirmation. Quantum numbers shown are quark-model predictions. Measurements which do not identify the charge state of B also appear here.

Mass $m_{B^{\pm}} = 5278.6 \pm 2.0$ MeV
Mean life τ (average over B hadrons) $= (12.9 \pm 0.5) \times 10^{-13}$ s
$c\tau = 387$ μm

B^- modes are charge conjugates of the modes below.

Only data from $\Upsilon(4S)$ decays are used for branching fractions, with rare exceptions. Each paper makes an estimate of the $\Upsilon(4S) \to B^+ B^-$ and $B^0 \overline{B}^0$ branching fractions, usually 50:50 in recent papers.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

B^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Semileptonic modes				
$B^+ \to \overline{D}^0 \ell^+ \nu$	[aa]	(1.6 ± 0.7) %		–
$B^+ \to \overline{D}^*(2010)^0 \ell^+ \nu$	[aa]	(4.6 ± 1.0) %		–
$B^+ \to \pi^0 e^+ \nu_e$		< 2.2 × 10^{-3}	CL=90%	2638
$B^+ \to \omega \mu^+ \nu_\mu$		seen		2580
D, D^*, or D_s modes				
$B^+ \to \overline{D}^0 \pi^+$		(3.8 ± 1.1) × 10^{-3}	S=1.7	2308
$B^+ \to \overline{D}^0 \rho^+$		(1.3 ± 0.6) %		2238
$B^+ \to \overline{D}^0 \pi^+ \pi^+ \pi^-$		(1.1 ± 0.4) %		2289
$B^+ \to \overline{D}^0 \pi^+ \pi^+ \pi^-$ nonresonant		(5 ± 4) × 10^{-3}		2289
$B^+ \to \overline{D}^0 \pi^+ \rho^0$		(4.2 ± 3.0) × 10^{-3}		2209
$B^+ \to \overline{D}^0 a_1(1260)^+$		(5 ± 4) × 10^{-3}		2113
$B^+ \to D^*(2010)^- \pi^+ \pi^+$		(2.5 ± 1.2) × 10^{-3}		2247
$B^+ \to D^- \pi^+ \pi^+$		(2.5 $^{+4.8}_{-2.4}$) × 10^{-3}		2299
$B^+ \to \overline{D}^*(2010)^0 \pi^+$		(5.2 ± 1.5) × 10^{-3}	S=1.1	2254
$B^+ \to \overline{D}^*(2010)^0 \rho^+$		(1.0 ± 0.7) %		2181
$B^+ \to D^*(2010)^- \pi^+ \pi^+ \pi^0$		(1.8 ± 0.9) %		2235
$B^+ \to D^*(2010)^- \pi^+ \pi^+ \pi^+ \pi^-$		< 1 %	CL=90%	2217
$B^+ \to \overline{D}^0 D_s^+$		(1.9 ± 1.1) %		1814
$J/\psi(1S)$ or $\psi(2S)$ modes				
$B^+ \to J/\psi(1S) K^+$		(7.7 ± 2.0) × 10^{-4}		1683
$B^+ \to J/\psi(1S) K^+ \pi^+ \pi^-$		(1.1 ± 0.5) × 10^{-3}		1612
$B^+ \to J/\psi(1S) K^*(892)^+$		(1.4 ± 0.7) × 10^{-3}		1571
$B^+ \to \psi(2S) K^+$		< 2 × 10^{-3}	CL=90%	1283
$B^+ \to \psi(2S) K^*(892)^+$		< 3.5 × 10^{-3}	CL=90%	1115
$B^+ \to \psi(2S) K^*(892)^+ \pi^+ \pi^-$		(1.9 ± 1.2) × 10^{-3}		909
K or K^* modes				
$B^+ \to K^0 \pi^+$		< 9 × 10^{-5}	CL=90%	2614
$B^+ \to K^*(892)^0 \pi^+$		< 1.3 × 10^{-4}	CL=90%	2561
$B^+ \to K^+ \pi^- \pi^+$ (no charm)		< 1.7 × 10^{-4}	CL=90%	2609
$B^+ \to K_1(1400)^0 \pi^+$		< 2.6 × 10^{-3}	CL=90%	2451
$B^+ \to K_2^*(1430)^0 \pi^+$		< 6.8 × 10^{-4}	CL=90%	2444
$B^+ \to K^+ \rho^0$		< 7 × 10^{-5}	CL=90%	2559
$B^+ \to K^*(892)^+ \pi^+ \pi^-$		< 1.1 × 10^{-3}	CL=90%	2556
$B^+ \to K^*(892)^+ \rho^0$		< 9.0 × 10^{-4}	CL=90%	2505
$B^+ \to K_1(1400)^+ \rho^0$		< 7.8 × 10^{-4}	CL=90%	2388
$B^+ \to K_2^*(1430)^+ \rho^0$		< 1.5 × 10^{-3}	CL=90%	2381
$B^+ \to K^+ K^- K^+$		< 3.5 × 10^{-4}	CL=90%	2522
$B^+ \to K^+ \phi$		< 8 × 10^{-5}	CL=90%	2516
$B^+ \to K^*(892)^+ K^+ K^-$		< 1.6 × 10^{-3}	CL=90%	2466
$B^+ \to K^*(892)^+ \phi$		< 1.3 × 10^{-3}	CL=90%	2460
$B^+ \to K_1(1400)^+ \phi$		< 1.1 × 10^{-3}	CL=90%	2339
$B^+ \to K_2^*(1430)^+ \phi$		< 3.4 × 10^{-3}	CL=90%	2331
$B^+ \to K^+ f_0(975)$		< 7 × 10^{-5}	CL=90%	2524
$B^+ \to K^*(892)^+ \gamma$		< 5.5 × 10^{-4}	CL=90%	2564
$B^+ \to K_1(1270)^+ \gamma$		< 6.6 × 10^{-3}	CL=90%	2487
$B^+ \to K_1(1400)^+ \gamma$		< 2.0 × 10^{-3}	CL=90%	2453
$B^+ \to K_2^*(1430)^+ \gamma$		< 1.3 × 10^{-3}	CL=90%	2446
$B^+ \to K^*(1680)^+ \gamma$		< 1.7 × 10^{-3}	CL=90%	2373
$B^+ \to K_3^*(1780)^+ \gamma$		< 5 × 10^{-3}	CL=90%	2341
$B^+ \to K_4^*(2045)^+ \gamma$		< 9.0 × 10^{-3}	CL=90%	2243
Light unflavored meson modes				
$B^+ \to \pi^+ \pi^0$		< 2.4 × 10^{-4}	CL=90%	2636
$B^+ \to \pi^+ \pi^+ \pi^-$		< 1.7 × 10^{-4}	CL=90%	2630
$B^+ \to \rho^0 \pi^+$		< 1.5 × 10^{-4}	CL=90%	2581
$B^+ \to \pi^+ f_0(975)$		< 1.2 × 10^{-4}	CL=90%	2547
$B^+ \to \pi^+ f_2(1270)$		< 2.1 × 10^{-4}	CL=90%	2483
$B^+ \to \pi^+ \pi^0 \pi^0$		< 8.9 × 10^{-4}	CL=90%	2631
$B^+ \to \rho^+ \pi^0$		< 5.5 × 10^{-4}	CL=90%	2582
$B^+ \to \pi^+ \pi^- \pi^+ \pi^0$		< 4.0 × 10^{-3}	CL=90%	2621
$B^+ \to \rho^+ \rho^0$		< 1.0 × 10^{-3}	CL=90%	2525
$B^+ \to a_1(1260)^+ \pi^0$		< 1.7 × 10^{-3}	CL=90%	2487
$B^+ \to a_1(1260)^0 \pi^+$		< 9.0 × 10^{-4}	CL=90%	2487
$B^+ \to \omega \pi^+$		< 4.0 × 10^{-4}	CL=90%	2579
$B^+ \to \eta \pi^+$		< 7.0 × 10^{-4}	CL=90%	2609
$B^+ \to \pi^+ \pi^+ \pi^+ \pi^- \pi^-$		< 8.6 × 10^{-4}	CL=90%	2608
$B^+ \to \rho^0 a_1(1260)^+$		< 5.4 × 10^{-4}	CL=90%	2426
$B^+ \to \rho^0 a_2(1320)^+$		< 6.3 × 10^{-4}	CL=90%	2411
$B^+ \to \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^0$		< 6.3 × 10^{-3}	CL=90%	2592
$B^+ \to a_1(1260)^+ a_1(1260)^0$		< 1.3 %	CL=90%	2319
Baryon modes				
$B^+ \to p \overline{p} \pi^+$		< 1.4 × 10^{-4}	CL=90%	2438
$B^+ \to p \overline{p} \pi^+ \pi^+ \pi^-$		< 4.7 × 10^{-4}	CL=90%	2369
$B^+ \to p \overline{\Lambda}$		< 5 × 10^{-5}	CL=90%	2430
$B^+ \to p \overline{\Lambda} \pi^+ \pi^-$		< 1.8 × 10^{-4}	CL=90%	2367
$B^+ \to \overline{\Delta}^0 p$		< 3.3 × 10^{-4}	CL=90%	2402
$B^+ \to \Delta^{++} \overline{p}$		< 1.3 × 10^{-4}	CL=90%	2402
Lepton number (L) or Lepton Family number (LF) violating modes, or Flavor-Changing neutral current (FC) modes				
$B^+ \to K^*(892)^+ e^+ e^-$	FC	< 6.3 × 10^{-4}	CL=90%	2564
$B^+ \to K^*(892)^+ \mu^+ \mu^-$	FC	< 1.1 × 10^{-3}	CL=90%	2559
$B^+ \to \pi^+ e^+ e^-$	FC	< 3.9 × 10^{-3}	CL=90%	2637
$B^+ \to \pi^+ \mu^+ \mu^-$	FC	< 9.1 × 10^{-3}	CL=90%	2633
$B^+ \to K^+ e^+ e^-$	FC	< 5 × 10^{-5}	CL=90%	2616
$B^+ \to K^+ \mu^+ \mu^-$	FC	< 1.5 × 10^{-4}	CL=90%	2612
$B^+ \to \pi^+ e^+ \mu^-$	LF	< 6.4 × 10^{-3}	CL=90%	2636
$B^+ \to \pi^+ e^- \mu^+$	LF	< 6.4 × 10^{-3}	CL=90%	2636
$B^+ \to K^+ e^+ \mu^-$	LF	< 6.4 × 10^{-3}	CL=90%	2615
$B^+ \to K^+ e^- \mu^+$	LF	< 6.4 × 10^{-3}	CL=90%	2615
$B^+ \to \pi^- e^+ e^+$	L	< 3.9 × 10^{-3}	CL=90%	2637
$B^+ \to \pi^- \mu^+ \mu^+$	L	< 9.1 × 10^{-3}	CL=90%	2633
$B^+ \to \pi^- e^+ \mu^+$	L	< 6.4 × 10^{-3}	CL=90%	2636
$B^+ \to K^- e^+ e^+$	L	< 3.9 × 10^{-3}	CL=90%	2616
$B^+ \to K^- e^+ \mu^+$	L	< 6.4 × 10^{-3}	CL=90%	2615
$B^+ \to K^- \mu^+ \mu^+$	L	< 9.1 × 10^{-3}	CL=90%	2612

B DECAY MODES

For the following modes, the charge of B was not determined.

Mode		Fraction	Scale factor/ Confidence level	p (MeV/c)
Semileptonic and leptonic modes				
$B \to e^{\pm}\nu_e$ hadrons		(10.7 ± 0.5) %	S=1.4	–
$B \to D^*(2010) e \nu_e$		(7.0 ± 2.3) %		–
$B \to \overline{p} e^+ \nu_e$ anything		< 1.6 × 10^{-3}	CL=90%	–
$B \to \mu^{\pm}\nu_\mu$ hadrons		(10.3 ± 0.5) %		–
D, D^*, or D_s modes				
$B \to D^{\pm}$ anything		(22.7 ± 3.3) %		–
$B \to D^0/\overline{D}^0$ anything		(46 ± 5) %	S=1.2	–
$B \to D^*(2010)^{\pm}$ anything		(26.9 ± 3.5) %		–
$B \to D_s^{\pm}$ anything		(11.5 ± 2.8) %		–
$B \to D_s D$, $D_s^* D$, $D_s D^*$, or $D_s^* D^*$	[r]	(6.5 ± 1.9) %		–
$J/\psi(1S)$ or $\psi(2S)$ modes				
$B \to J/\psi(1S)$ anything		(1.12± 0.16) %		–
$B \to \psi(2S)$ anything		(4.6 ± 2.0) × 10^{-3}		–
K or K^* modes				
$B \to K^{\pm}$ anything		(85 ±11) %		–
$B \to K^0/\overline{K}^0$ anything		(63 ± 8) %		–
$B \to K^*(892)\gamma$		< 2.4 × 10^{-4}	CL=90%	–
$B \to K_1(1400)\gamma$		< 4.1 × 10^{-4}	CL=90%	–
$B \to K_2^*(1430)\gamma$		< 8.3 × 10^{-4}	CL=90%	–
$B \to K_3^*(1780)\gamma$		< 3.0 × 10^{-3}	CL=90%	–
Light unflavored meson modes				
$B \to \phi$ anything		(2.3 ± 0.8) %		–
Baryon modes				
$B \to$ charmed-baryon anything		< 11.2 %	CL=90%	–
$B \to p$ anything		(8.2 $^{+1.4}_{-1.1}$) %		–
$B \to p$ (direct) anything		(5.5 ± 1.6) %		–
$B \to \Lambda$ anything		(4.2 ± 0.8) %		–
$B \to \Xi^-$ anything		(2.8 ± 1.4) × 10^{-3}		–
$B \to$ baryons anything		(7.6 ± 1.4) %		–
$B \to p\overline{p}$ anything		(2.50± 0.28) %		–
$B \to \Lambda\overline{p}$ anything		(2.3 ± 0.5) %		–
$B \to \Lambda\overline{\Lambda}$ anything		< 8.8 × 10^{-3}	CL=90%	–
Flavor-Changing neutral current (FC) modes				
$B \to e^+e^-$ anything FC		< 2.4 × 10^{-3}	CL=90%	–
$B \to \mu^+\mu^-$ anything FC	[bb]	< 5.0 × 10^{-5}	CL=90%	–

B^0

$I(J^P) = \frac{1}{2}(0^-)$

I, J, P need confirmation. Quantum numbers shown are quark-model predictions.

Mass $m_{B^0} = 5278.7 \pm 2.1$ MeV

$|m_{B^0_1} - m_{B^0_2}| = (3.6 \pm 0.7) \times 10^{-10}$ MeV [u]

$m_{B^0} - m_{B^{\pm}} = 0.1 \pm 0.8$ MeV (S = 1.3)

Mean life τ (average over B hadrons) $= (12.9 \pm 0.5) \times 10^{-13}$ s

$c\tau = 387$ μm

$\tau_{B^+}/\tau_{B^0} = 0.93 \pm 0.16$

$\Gamma(\mu^-$ anything (via $\overline{B}^0$))$/\Gamma(\mu^{\pm}$ anything$) = 0.16 \pm 0.04$

$\overline{B}^0$ modes are charge conjugates of the modes below. Decays in which the charge of the B is not determined are in the $B^{\pm}$ section.

Only data from $\Upsilon(4S)$ decays are used for branching fractions, with rare exceptions. Each paper makes an estimate of the $\Upsilon(4S) \to B^+B^-$ and $B^0\overline{B}^0$ branching fractions, usually 50:50 in recent papers.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

B^0 DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
Semileptonic and leptonic modes				
$D^-\ell^+\nu$	[aa]	(1.8 ±0.5) %		–
$D^*(2010)^-\ell^+\nu$	[aa]	(4.9 ±0.8) %		–
$\pi^-\mu^+\nu_\mu$		seen		2636
D, D^*, or D_s modes				
$D^-\pi^+$		(3.2 ±0.7) × 10^{-3}		2306
$D^-\rho^+$		(9 ±6) × 10^{-3}		2236
$\overline{D}^0\pi^+\pi^-$		< 7 × 10^{-3}	90%	2301
$\overline{D}^0\rho^0$		< 6 × 10^{-4}	90%	2238
$D^*(2010)^-\pi^+$		(3.2 ±0.7) × 10^{-3}		2254
$D^-\pi^+\pi^+\pi^-$		(8.0 ±2.5) × 10^{-3}		2287
$(D^-\pi^+\pi^+\pi^-)$ nonresonant		(3.9 ±1.9) × 10^{-3}		2287
$D^-\pi^+\rho^0$		(1.1 ±1.0) × 10^{-3}		2207
$D^-a_1(1260)^+$		(6.0 ±3.3) × 10^{-3}		2111
$D^*(2010)^-\pi^+\pi^0$		(1.8 ±0.6) %		2247
$D^*(2010)^-\rho^+$		(8 ±4) × 10^{-3}		2181
$D^*(2010)^-\pi^+\pi^+\pi^-$		(1.41±0.34) %		2234
$(D^*(2010)^-\pi^+\pi^+\pi^-)$ nonresonant		(0.0 ±2.5) × 10^{-3}		2234
$D^*(2010)^-\pi^+\rho^0$		(7 ±4) × 10^{-3}		2151
$D^*(2010)^-a_1(1260)^+$		(1.8 ±0.8) %		2051
$D^*(2010)^-\pi^+\pi^+\pi^-\pi^0$		(4.1 ±2.2) %		2218
$D^-D_s^+$		(8 ±5) × 10^{-3}		1812
$D^*(2010)^-D_s^+$		(1.6 ±1.1) %		1734
$\pi^-D_s^+$		< 1.3 × 10^{-3}	90%	2270
$K^+D_s^-$		< 1.3 × 10^{-3}	90%	2242
$J/\psi(1S)$ or $\psi(2S)$ modes				
$J/\psi(1S)K^0$		(6.5 ±3.1) × 10^{-4}		1682
$J/\psi(1S)K^+\pi^-$		(1.0 ±0.5) × 10^{-3}		1652
$J/\psi(1S)K^*(892)^0$		(1.3 ±0.4) × 10^{-3}		1569
$\psi(2S)K^0$		< 1.5 × 10^{-3}	90%	1283
$\psi(2S)K^+\pi^-$		< 1 × 10^{-3}	90%	1238
$\psi(2S)K^*(892)^0$		(1.4 ±0.9) × 10^{-3}		1112
K or K^* modes				
$K^+\pi^-$		< 9 × 10^{-5}	90%	2614
$K^0\pi^+\pi^-$		< 4.4 × 10^{-4}	90%	2608
$K^0\rho^0$		< 3.2 × 10^{-4}	90%	2559
$K^0f_0(975)$		< 4.2 × 10^{-4}	90%	2524
$K^*(892)^+\pi^-$		< 4.4 × 10^{-4}	90%	2562
$K_2^*(1430)^+\pi^-$		< 2.6 × 10^{-3}	90%	2444
$K^0K^+K^-$		< 1.3 × 10^{-3}	90%	2522
$K^0\phi$		< 4.9 × 10^{-4}	90%	2516
$K^*(892)^0\pi^+\pi^-$		< 1.4 × 10^{-3}	90%	2555
$K^*(892)^0\rho^0$		< 4.6 × 10^{-4}	90%	2504
$K^*(892)^0f_0(975)$		< 2.0 × 10^{-4}	90%	2468
$K_1(1400)^+\pi^-$		< 1.1 × 10^{-3}	90%	2451
$K^*(892)^0K^+K^-$		< 6.1 × 10^{-4}	90%	2465
$K^*(892)^0\phi$		< 3.2 × 10^{-4}	90%	2459
$K_1(1400)^0\rho^0$		< 3.0 × 10^{-3}	90%	2389
$K_1(1400)^0\phi$		< 5.0 × 10^{-3}	90%	2339
$K_2^*(1430)^0\rho^0$		< 1.1 × 10^{-3}	90%	2381
$K_2^*(1430)^0\phi$		< 1.4 × 10^{-3}	90%	2331
$K^*(892)^0\gamma$		< 2.8 × 10^{-4}	90%	2563
$K_1(1270)^0\gamma$		< 7.8 × 10^{-3}	90%	2487
$K_1(1400)^0\gamma$		< 4.8 × 10^{-3}	90%	2453
$K_2^*(1430)^0\gamma$		< 4.4 × 10^{-4}	90%	2446
$K^*(1680)^0\gamma$		< 2.2 × 10^{-3}	90%	2373
$K_3^*(1780)^0\gamma$		< 1.1 %	90%	2341
$K_4^*(2045)^0\gamma$		< 4.8 × 10^{-3}	90%	2243
Light unflavored meson modes				
$\pi^+\pi^-$		< 9 × 10^{-5}	90%	2636
$\pi^+\pi^-\pi^0$		< 7.2 × 10^{-4}	90%	2630
$\rho^0\pi^0$		< 4.0 × 10^{-4}	90%	2582
$\rho^{\mp}\pi^{\pm}$	[r]	< 5.2 × 10^{-4}	90%	2582
$\pi^+\pi^-\pi^+\pi^-$		< 6.7 × 10^{-4}	90%	2621
$\rho^0\rho^0$		< 2.8 × 10^{-4}	90%	2525
$a_1(1260)^{\mp}\pi^{\pm}$	[r]	< 5.7 × 10^{-4}	90%	2487
$a_2(1320)^{\mp}\pi^{\pm}$	[r]	< 3.5 × 10^{-4}	90%	2473
$\pi^+\pi^-\pi^0\pi^0$		< 3.1 × 10^{-3}	90%	2622
$\rho^+\rho^-$		< 2.2 × 10^{-3}	90%	2525
$a_1(1260)^0\pi^0$		< 1.1 × 10^{-3}	90%	2487
$\omega\pi^0$		< 4.6 × 10^{-4}	90%	2580
$\eta\pi^0$		< 1.8 × 10^{-3}	90%	2609
$\pi^+\pi^+\pi^-\pi^-\pi^0$		< 9.0 × 10^{-3}	90%	2608
$a_1(1260)^+\rho^-$		< 3.4 × 10^{-3}	90%	2426
$a_1(1260)^0\rho^0$		< 2.4 × 10^{-3}	90%	2426
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$		< 3.0 × 10^{-3}	90%	2591
$a_1(1260)^+a_1(1260)^-$		< 3.2 × 10^{-3}	90%	2319
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0$		< 1.1 %	90%	2572

Baryon modes				
$p\overline{p}$		< 4 $\times 10^{-5}$	90%	2467
$p\overline{p}\pi^+\pi^-$		$(6.0 \pm 3.0) \times 10^{-4}$		2406
$p\overline{\Lambda}\pi^-$		< 2.0 $\times 10^{-4}$	90%	2401
$\Delta^0\overline{\Delta}^0$		< 1.8 $\times 10^{-3}$	90%	2334
$\Delta^{++}\Delta^{--}$		< 1.3 $\times 10^{-4}$	90%	2334
Lepton Family number (*LF*) violating, Flavor-Changing neutral current (*FC*), or decay via Mixing (*MX*) modes				
e^+e^-	*FC*	< 3 $\times 10^{-5}$	90%	2639
$\mu^+\mu^-$	*FC*	< 1.2 $\times 10^{-5}$	90%	2638
$K^0 e^+ e^-$	*FC*	< 3.0 $\times 10^{-4}$	90%	2616
$K^0 \mu^+ \mu^-$	*FC*	< 4.5 $\times 10^{-4}$	90%	2612
$K^*(892)^0 e^+ e^-$	*FC*	< 2.9 $\times 10^{-4}$	90%	2563
$K^*(892)^0 \mu^+ \mu^-$	*FC*	< 2.3 $\times 10^{-5}$	90%	2559
$e^\pm \mu^\mp$	*LF*	[r] < 4 $\times 10^{-5}$	90%	2638

B^*

$I(J^P) = \frac{1}{2}(1^-)$

I, *J*, *P* need confirmation. Quantum numbers shown are quark-model predictions.

Mass $m = 5324.6 \pm 2.1$ MeV

HEAVY QUARK SEARCHES

Searches for Top and Fourth Generation Hadrons

See the Full Listings for a Note giving details of indirect limits for top hadrons.

T — hadron with t quark

Mass $m >$ 91 GeV, CL = 95% (Standard Model decays)
Mass $m >$ 55 GeV, CL = 95% (all decays)
Mass $m <$ 200 GeV, CL = 95% [cc] (indirect limit)

B' — hadron with b' quark (4th generation)

Mass $m >$ 72 GeV, CL = 95% ($p\overline{p}$, charged current decays)
Mass $m >$ 46.0 GeV, CL = 95% (e^+e^-, all decays)

$c\overline{c}$ MESONS

$\eta_c(1S)$ or $\eta_c(2980)$

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 2978.8 \pm 1.9$ MeV (S = 1.8)
Full width $\Gamma = 10.3^{+3.8}_{-3.4}$ MeV

$\eta_c(1S)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
Decays involving hadronic resonances			
$\eta'(958)\pi\pi$	(4.1 ± 1.7) %		1319
$\rho\rho$	(2.6 ± 0.9) %		1276
$K^*(892)^0 K^- \pi^+$ + c.c.	(2.0 ± 0.7) %		1273
$K^*(892)\overline{K}^*(892)$	$(8.5 \pm 3.1) \times 10^{-3}$		1193
$\phi\phi$	$(7.1 \pm 2.8) \times 10^{-3}$		1086
$a_0(980)\pi$	< 2 %	90%	1323
$a_2(1320)\pi$	< 2 %	90%	1193
$K^*(892)\overline{K}$ + c.c.	< 1.28 %	90%	1307
$f_2(1270)\eta$	< 1.1 %	90%	1142
$\omega\omega$	< 3.1 $\times 10^{-3}$	90%	1268
Decays into stable hadrons			
$K\overline{K}\pi$	(6.6 ± 1.8) %		1378
$\eta\pi\pi$	(4.9 ± 1.8) %		1425
$\pi^+\pi^- K^+ K^-$	$(2.0\ ^{+0.7}_{-0.6})$ %		1342
$2(\pi^+\pi^-)$	(1.2 ± 0.4) %		1457
$p\overline{p}$	$(1.2 \pm 0.4) \times 10^{-3}$		1157
$K\overline{K}\eta$	< 3.1 %	90%	1262
$\pi^+\pi^- p\overline{p}$	< 1.2 %	90%	1023
$\Lambda\overline{\Lambda}$	< 2 $\times 10^{-3}$	90%	987
Radiative decays			
$\gamma\gamma$	$(6\ ^{+6}_{-5}) \times 10^{-4}$		1489

$J/\psi(1S)$ or $J/\psi(3097)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 3096.93 \pm 0.09$ MeV
Full width $\Gamma = 86 \pm 6$ keV
$\Gamma_{ee} = 5.36 \pm 0.29$ keV (Assuming $\Gamma_{ee} = \Gamma_{\mu\mu}$)

$J/\psi(1S)$ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
hadrons		(86.0 ± 2.0) %		–
virtual $\gamma \to$ hadrons		(17.0 ± 2.0) %		–
e^+e^-		(6.27 ± 0.20) %		1548
$\mu^+\mu^-$		(5.97 ± 0.25) %	S=1.1	1545
Decays involving hadronic resonances				
$\rho\pi$		(1.28 ± 0.10) %		1450
$\rho^0\pi^0$		$(4.2 \pm 0.5) \times 10^{-3}$		1450
$a_2(1320)\rho$		(1.09 ± 0.22) %		1126
$\omega\pi^+\pi^+\pi^-\pi^-$		$(8.5 \pm 3.4) \times 10^{-3}$		1392
$\omega\pi^+\pi^-$		$(7.2 \pm 1.0) \times 10^{-3}$		1435
$K^*(892)^0\overline{K}^*_2(1430)^0$ + c.c.		$(6.7 \pm 2.6) \times 10^{-3}$		1005
$\omega K^*(892)\overline{K}$ + c.c.		$(5.3 \pm 2.0) \times 10^{-3}$		1098
$\omega f_2(1270)$		$(4.3 \pm 0.6) \times 10^{-3}$		1143
$K^+\overline{K}^*(892)^-$ + c.c.		$(5.0 \pm 0.4) \times 10^{-3}$		1373
$K^0\overline{K}^*(892)^0$ + c.c.		$(4.2 \pm 0.4) \times 10^{-3}$		1371
$\omega\pi^0\pi^0$		$(3.4 \pm 0.8) \times 10^{-3}$		1436
$b_1(1235)^\pm\pi^\mp$	[dd]	$(3.0 \pm 0.5) \times 10^{-3}$		1299
$\omega K^\pm K^0_S \pi^\mp$	[dd]	$(2.9 \pm 0.7) \times 10^{-3}$		1210
$b_1(1235)^0\pi^0$		$(2.3 \pm 0.6) \times 10^{-3}$		1299
$\phi K^*(892)\overline{K}$ + c.c.		$(2.04 \pm 0.28) \times 10^{-3}$		969
$\omega K\overline{K}$		$(1.9 \pm 0.4) \times 10^{-3}$		1268
$\omega f_0(1710) \to \omega K\overline{K}$		$(4.8 \pm 1.1) \times 10^{-4}$		878
$\phi 2(\pi^+\pi^-)$		$(1.60 \pm 0.32) \times 10^{-3}$		1318
$\Delta(1232)^{++}\overline{p}\pi^-$		$(1.6 \pm 0.5) \times 10^{-3}$		1030
$\omega\eta$		$(1.58 \pm 0.16) \times 10^{-3}$		1394
$\phi K\overline{K}$		$(1.48 \pm 0.22) \times 10^{-3}$		1179
$\phi f_0(1710) \to \phi K\overline{K}$		$(3.6 \pm 0.6) \times 10^{-4}$		714
$p\overline{p}\omega$		$(1.30 \pm 0.25) \times 10^{-3}$	S=1.3	769
$\Delta(1232)^{++}\overline{\Delta}(1232)^{--}$		$(1.10 \pm 0.29) \times 10^{-3}$		938
$\Sigma(1385)^-\overline{\Sigma}(1385)^+$ (or c.c.)	[dd]	$(1.03 \pm 0.13) \times 10^{-3}$		692
$p\overline{p}\eta'(958)$		$(9 \pm 4) \times 10^{-4}$	S=1.7	596
$\phi f'_2(1525)$		$(8 \pm 4) \times 10^{-4}$	S=2.7	871
$\phi\pi^+\pi^-$		$(8.0 \pm 1.2) \times 10^{-4}$		1365
$\phi K^\pm K^0_S \pi^\mp$	[dd]	$(7.2 \pm 0.9) \times 10^{-4}$		1114
$\omega f_1(1420)$		$(6.8 \pm 2.4) \times 10^{-4}$		1062
$\phi\eta$		$(6.5 \pm 0.7) \times 10^{-4}$		1320
$\Xi(1530)^-\overline{\Xi}^+$		$(5.9 \pm 1.5) \times 10^{-4}$		597
$pK^-\overline{\Sigma}(1385)^0$		$(5.1 \pm 3.2) \times 10^{-4}$		645
$\omega\pi^0$		$(4.2 \pm 0.6) \times 10^{-4}$	S=1.4	1447
$\phi\eta'(958)$		$(3.3 \pm 0.4) \times 10^{-4}$		1192
$\phi f_0(975)$		$(3.2 \pm 0.9) \times 10^{-4}$	S=1.9	1185
$\Xi(1530)^0\overline{\Xi}^0$		$(3.2 \pm 1.4) \times 10^{-4}$		608
$\Sigma(1385)^-\overline{\Sigma}^+$ (or c.c.)	[dd]	$(3.1 \pm 0.5) \times 10^{-4}$		857
$\phi f_1(1285)$		$(2.6 \pm 0.5) \times 10^{-4}$	S=1.1	1032
$\rho\eta$		$(1.93 \pm 0.23) \times 10^{-4}$		1398
$\omega\eta'(958)$		$(1.67 \pm 0.25) \times 10^{-4}$		1279
$\omega f_0(975)$		$(1.4 \pm 0.5) \times 10^{-4}$		1273
$\rho\eta'(958)$		$(1.05 \pm 0.18) \times 10^{-4}$		1283
$p\overline{p}\phi$		$(4.5 \pm 1.5) \times 10^{-5}$		527
$a_2(1320)^\pm\pi^\mp$	[dd]	< 4.3 $\times 10^{-3}$	CL=90%	1263
$K\overline{K}^*_2(1430)$ + c.c.		< 4.0 $\times 10^{-3}$	CL=90%	1159
$K^*_2(1430)^0\overline{K}^*_2(1430)^0$		< 2.9 $\times 10^{-3}$	CL=90%	588
$K^*(892)^0\overline{K}^*(892)^0$		< 5 $\times 10^{-4}$	CL=90%	1263
$\phi f_2(1270)$		< 3.7 $\times 10^{-4}$	CL=90%	1036
$p\overline{p}\rho$		< 3.1 $\times 10^{-4}$	CL=90%	780
$\phi\eta(1440) \to \phi\eta\pi\pi$		< 2.5 $\times 10^{-4}$	CL=90%	946
$\omega f'_2(1525)$		< 2.2 $\times 10^{-4}$	CL=90%	1003
$\Sigma(1385)^0\overline{\Lambda}$		< 2 $\times 10^{-4}$	CL=90%	911
$\Delta(1232)^+\overline{p}$		< 1 $\times 10^{-4}$	CL=90%	1100
$\Sigma^0\overline{\Lambda}$		< 9 $\times 10^{-5}$	CL=90%	1032
$\phi\pi^0$		< 6.8 $\times 10^{-6}$	CL=90%	1377

Decays into stable hadrons				
$2(\pi^+\pi^-)\pi^0$		(3.37±0.26) %		1496
$3(\pi^+\pi^-)\pi^0$		(2.9 ±0.6) %		1433
$\pi^+\pi^-\pi^0$		(1.50±0.15) %		1533
$\pi^+\pi^-\pi^0 K^+K^-$		(1.20±0.30) %		1368
$4(\pi^+\pi^-)\pi^0$		(9.0 ±3.0) $\times 10^{-3}$		1345
$\pi^+\pi^- K^+K^-$		(7.2 ±2.3) $\times 10^{-3}$		1407
$K\overline{K}\pi$		(6.1 ±1.0) $\times 10^{-3}$		1440
$p\overline{p}\pi^+\pi^-$		(6.0 ±0.5) $\times 10^{-3}$	S=1.3	1107
$2(\pi^+\pi^-)$		(4.0 ±1.0) $\times 10^{-3}$		1517
$3(\pi^+\pi^-)$		(4.0 ±2.0) $\times 10^{-3}$		1466
$n\overline{n}\pi^+\pi^-$		(4 ±4) $\times 10^{-3}$		1106
$\Sigma\overline{\Sigma}$		(3.8 ±0.5) $\times 10^{-3}$		992
$2(\pi^+\pi^-)K^+K^-$		(3.1 ±1.3) $\times 10^{-3}$		1320
$p\overline{p}\pi^+\pi^-\pi^0$	[ee]	(2.3 ±0.9) $\times 10^{-3}$	S=1.9	1033
$p\overline{p}$		(2.16±0.11) $\times 10^{-3}$		1232
$p\overline{p}\eta$		(2.09±0.18) $\times 10^{-3}$		948
$p\overline{n}\pi^-$		(2.00±0.10) $\times 10^{-3}$		1174
$\Xi\overline{\Xi}$		(1.8 ±0.4) $\times 10^{-3}$	S=1.8	818
$n\overline{n}$		(1.8 ±0.9) $\times 10^{-3}$		1231
$\Lambda\overline{\Lambda}$		(1.35±0.14) $\times 10^{-3}$	S=1.2	1074
$p\overline{p}\pi^0$		(1.09±0.09) $\times 10^{-3}$		1176
$\Lambda\overline{\Sigma}^-\pi^+$ (or c.c.)	[dd]	(1.06±0.12) $\times 10^{-3}$		945
$pK^-\overline{\Lambda}$		(8.9 ±1.6) $\times 10^{-4}$		876
$2(K^+K^-)$		(7.0 ±3.0) $\times 10^{-4}$		1131
$pK^-\overline{\Sigma}^0$		(2.9 ±0.8) $\times 10^{-4}$		820
K^+K^-		(2.37±0.31) $\times 10^{-4}$		1468
$\Lambda\overline{\Lambda}\pi^0$		(2.2 ±0.7) $\times 10^{-4}$		998
$\pi^+\pi^-$		(1.47±0.23) $\times 10^{-4}$		1542
$K^0_S K^0_L$		(1.08±0.14) $\times 10^{-4}$		1466
$\Lambda\overline{\Sigma}$ + c.c.		< 1.5 $\times 10^{-4}$	CL=90%	1032
$K^0_S K^0_S$		< 5.2 $\times 10^{-6}$	CL=90%	1466
Radiative decays				
$\gamma\eta_c(1S)$		(1.3 ±0.4) %		116
$\gamma\pi^+\pi^- 2\pi^0$		(8.3 ±3.1) $\times 10^{-3}$		1518
$\gamma\eta\pi\pi$		(6.1 ±1.0) $\times 10^{-3}$		1486
$\gamma\eta(1440) \to \gamma K\overline{K}\pi$	[ff]	(9.1 ±1.8) $\times 10^{-4}$		1223
$\gamma\eta(1440) \to \gamma\gamma\rho^0$		(6.4 ±1.4) $\times 10^{-5}$		–
$\gamma\rho\rho$		(4.5 ±0.8) $\times 10^{-3}$		1343
$\gamma\eta'(958)$		(4.34±0.34) $\times 10^{-3}$		1400
$\gamma 2\pi^+ 2\pi^-$		(2.8 ±0.5) $\times 10^{-3}$	S=1.9	1517
$\gamma f_4(2050)$		(2.7 ±0.7) $\times 10^{-3}$		871
$\gamma\omega\omega$		(1.59±0.33) $\times 10^{-3}$		1337
$\gamma\eta(1440) \to \gamma\rho^0\rho^0$		(1.4 ±0.4) $\times 10^{-3}$		1223
$\gamma f_2(1270)$		(1.38±0.14) $\times 10^{-3}$		1286
$\gamma f_0(1710) \to \gamma K\overline{K}$		(9.7 ±1.2) $\times 10^{-4}$		1077
$\gamma\eta$		(8.6 ±0.8) $\times 10^{-4}$		1500
$\gamma f_1(1420) \to \gamma K\overline{K}\pi$		(8.3 ±1.5) $\times 10^{-4}$		1220
$\gamma f_1(1285)$		(7.0 ±1.8) $\times 10^{-4}$		1283
$\gamma f'_2(1525)$		(6.3 ±1.0) $\times 10^{-4}$		1173
$\gamma\phi\phi$		(4.0 ±1.2) $\times 10^{-4}$	S=2.1	1166
$\gamma p\overline{p}$		(3.8 ±1.0) $\times 10^{-4}$		1232
$\gamma\eta(2100)$		(2.9 ±0.6) $\times 10^{-4}$		834
$\gamma\eta(1760) \to \gamma\rho^0\rho^0$		(1.3 ±0.9) $\times 10^{-4}$		1048
$\gamma\pi^0$		(3.9 ±1.3) $\times 10^{-5}$		1546
$\gamma p\overline{p}\pi^+\pi^-$		< 7.9 $\times 10^{-4}$	CL=90%	1107
$\gamma\gamma$		< 5 $\times 10^{-4}$	CL=90%	1548
$\gamma\Lambda\overline{\Lambda}$		< 1.3 $\times 10^{-4}$	CL=90%	1074
3γ		< 5.5 $\times 10^{-5}$	CL=90%	1548

$\chi_{c0}(1P)$
or $\chi_{c0}(3415)$ [was $\chi(3415)$]

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 3415.1 \pm 1.0$ MeV
Full width $\Gamma = 14 \pm 5$ MeV

$\chi_{c0}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
Hadronic decays			
$2(\pi^+\pi^-)$	(3.7±0.7) %		1679
$\pi^+\pi^- K^+K^-$	(3.0±0.7) %		1580
$\rho^0\pi^+\pi^-$	(1.6±0.5) %		1609
$3(\pi^+\pi^-)$	(1.5±0.5) %		1633
$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	(1.2±0.4) %		1522
$\pi^+\pi^-$	(7.5±2.1) $\times 10^{-3}$		1702
K^+K^-	(7.1±2.4) $\times 10^{-3}$		1635
$\pi^+\pi^- p\overline{p}$	(5.0±2.0) $\times 10^{-3}$		1320
$\pi^0\pi^0$	(3.1±0.6) $\times 10^{-3}$		1702
$\eta\eta$	(2.5±1.1) $\times 10^{-3}$		1617
$p\overline{p}$	< 9.0 $\times 10^{-4}$	90%	1427
Radiative decays			
$\gamma J/\psi(1S)$	(6.6±1.8) $\times 10^{-3}$		303
$\gamma\gamma$	(4.0±2.3) $\times 10^{-4}$		1708

$\chi_{c1}(1P)$
or $\chi_{c1}(3510)$ [was $\chi(3510)$]

$I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 3510.53 \pm 0.12$ MeV
Full width $\Gamma = 0.88 \pm 0.14$ MeV

$\chi_{c1}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
Hadronic decays			
$3(\pi^+\pi^-)$	(2.2±0.8) %		1683
$2(\pi^+\pi^-)$	(1.6±0.5) %		1727
$\pi^+\pi^- K^+K^-$	(9 ±4) $\times 10^{-3}$		1632
$\rho^0\pi^+\pi^-$	(3.9±3.5) $\times 10^{-3}$		1659
$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	(3.2±2.1) $\times 10^{-3}$		1576
$\pi^+\pi^- p\overline{p}$	(1.4±0.9) $\times 10^{-3}$		1381
$p\overline{p}$	(8.6±1.2) $\times 10^{-5}$		1483
$\pi^+\pi^-$ + K^+K^-	< 2.1 $\times 10^{-3}$		–
Radiative decays			
$\gamma J/\psi(1S)$	(27.3±1.6) %		389
$\gamma\gamma$	< 1.5 $\times 10^{-3}$	90%	1755

$\chi_{c2}(1P)$
or $\chi_{c2}(3555)$ [was $\chi(3555)$]

$I^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 3556.17 \pm 0.13$ MeV
Full width $\Gamma = 2.00 \pm 0.18$ MeV

$\chi_{c2}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
Hadronic decays			
$2(\pi^+\pi^-)$	(2.2 ±0.5) %		1751
$\pi^+\pi^- K^+K^-$	(1.9 ±0.5) %		1656
$3(\pi^+\pi^-)$	(1.2 ±0.8) %		1707
$\rho^0\pi^+\pi^-$	(7 ±4) $\times 10^{-3}$		1683
$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	(4.8 ±2.8) $\times 10^{-3}$		1601
$\pi^+\pi^- p\overline{p}$	(3.3 ±1.3) $\times 10^{-3}$		1410
$\pi^+\pi^-$	(1.9 ±1.0) $\times 10^{-3}$		1773
K^+K^-	(1.5 ±1.1) $\times 10^{-3}$		1708
$p\overline{p}$	(10.0 ±1.0) $\times 10^{-5}$		1510
$\pi^0\pi^0$	(1.10±0.28) $\times 10^{-3}$		1773
$\eta\eta$	(8 ±5) $\times 10^{-4}$		1691
$J/\psi(1S)\pi^+\pi^-\pi^0$	< 1.5 %	90%	185
Radiative decays			
$\gamma J/\psi(1S)$	(13.5 ±1.1) %		430
$\gamma\gamma$	< 50 %	95%	1778

$\psi(2S)$
or $\psi(3685)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 3686.00 \pm 0.10$ MeV
Full width $\Gamma = 278 \pm 32$ keV (S = 1.1)
$\Gamma_{ee} = 2.14 \pm 0.21$ keV (Assuming $\Gamma_{ee} = \Gamma_{\mu\mu}$)

$\psi(2S)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
hadrons	(98.10±0.30) %		–
virtual $\gamma \to$ hadrons	(2.9 ±0.4) %		–
e^+e^-	(8.8 ±1.3) $\times 10^{-3}$		1843
$\mu^+\mu^-$	(7.7 ±1.7) $\times 10^{-3}$		1840

Decays into $J/\psi(1S)$ and anything			
$J/\psi(1S)$ anything	(57 ±4) %		–
$J/\psi(1S)$ neutrals	(23.2 ±2.6) %		–
$J/\psi(1S)\pi^+\pi^-$	(32.4 ±2.6) %		477
$J/\psi(1S)\pi^0\pi^0$	(18.4 ±2.7) %		481
$J/\psi(1S)\eta$	(2.7 ±0.4) %	S=1.7	196
$J/\psi(1S)\pi^0$	(9.7 ±2.1) × 10^{-4}		527
Hadronic decays			
$3(\pi^+\pi^-)\pi^0$	(3.5 ±1.6) × 10^{-3}		1746
$2(\pi^+\pi^-)\pi^0$	(3.1 ±0.7) × 10^{-3}		1799
$\pi^+\pi^- K^+K^-$	(1.6 ±0.4) × 10^{-3}		1726
$\pi^+\pi^- p\overline{p}$	(8.0 ±2.0) × 10^{-4}		1491
$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	(6.7 ±2.5) × 10^{-4}		1673
$2(\pi^+\pi^-)$	(4.5 ±1.0) × 10^{-4}		1817
$\rho^0\pi^+\pi^-$	(4.2 ±1.5) × 10^{-4}		1751
$\overline{p}p$	(1.9 ±0.5) × 10^{-4}		1586
$3(\pi^+\pi^-)$	(1.5 ±1.0) × 10^{-4}		1774
$\overline{p}p\pi^0$	(1.4 ±0.5) × 10^{-4}		1543
K^+K^-	(1.0 ±0.7) × 10^{-4}		1776
$\pi^+\pi^-$	(8 ±5) × 10^{-5}		1838
$\pi^+\pi^-\pi^0$	(8 ±5) × 10^{-5}		1830
$\Lambda\overline{\Lambda}$	< 4 × 10^{-4}	CL=90%	1467
$\Xi^-\overline{\Xi}^+$	< 2 × 10^{-4}	CL=90%	1285
$\rho\pi$	< 8.3 × 10^{-5}	CL=90%	1760
$K^+K^-\pi^0$	< 2.96 × 10^{-5}	CL=90%	1754
$K^+\overline{K}^*(892)^-$ + c.c.	< 1.79 × 10^{-5}	CL=90%	1698
Radiative decays			
$\gamma\chi_{c0}(1P)$	(9.3 ±0.8) %		261
$\gamma\chi_{c1}(1P)$	(8.7 ±0.8) %		171
$\gamma\chi_{c2}(1P)$	(7.8 ±0.8) %		127
$\gamma\eta_c(1S)$	(2.8 ±0.6) × 10^{-3}		639
$\gamma\pi^0$	< 5.4 × 10^{-3}	CL=95%	1841
$\gamma\eta'(958)$	< 1.1 × 10^{-3}	CL=90%	1719
$\gamma\eta$	< 2 × 10^{-4}	CL=90%	1802
$\gamma\gamma$	< 1.5 × 10^{-4}	CL=90%	1843
$\gamma\eta(1440) \to \gamma K\overline{K}\pi$	[ff] < 1.2 × 10^{-4}	CL=90%	1569

$\psi(3770)$

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 3769.9 \pm 2.5$ MeV (S = 1.8)
Full width $\Gamma = 23.6 \pm 2.7$ MeV (S = 1.1)
$\Gamma_{ee} = 0.26 \pm 0.04$ keV (S = 1.2)

$\psi(3770)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
$D\overline{D}$	dominant		242
e^+e^-	(1.12±0.17) × 10^{-5}	1.2	1885

$\psi(4040)$ [gg]

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 4040 \pm 10$ MeV
Full width $\Gamma = 52 \pm 10$ MeV
$\Gamma_{ee} = 0.75 \pm 0.15$ keV

$\psi(4040)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
e^+e^-	(1.4±0.4) × 10^{-5}	2020
$D^0\overline{D}^0$	seen	777
$D^*(2010)^0\overline{D}^0$ + c.c.	seen	577
$D^*(2010)^0\overline{D}^*(2010)^0$	seen	228

$\psi(4160)$ [gg]

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 4159 \pm 20$ MeV
Full width $\Gamma = 78 \pm 20$ MeV
$\Gamma_{ee} = 0.77 \pm 0.23$ keV

$\psi(4160)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
e^+e^-	(10±4) × 10^{-6}	2079

$\psi(4415)$ [gg]

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 4415 \pm 6$ MeV
Full width $\Gamma = 43 \pm 15$ MeV (S = 1.8)
$\Gamma_{ee} = 0.47 \pm 0.10$ keV

$\psi(4415)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
hadrons	dominant	–
e^+e^-	(1.1±0.4) × 10^{-5}	2207

$b\overline{b}$ MESONS

$\Upsilon(1S)$ or $\Upsilon(9460)$

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 9460.32 \pm 0.22$ MeV (S = 2.5)
Full width $\Gamma = 52.1 \pm 2.1$ keV
$\Gamma_{ee} = 1.34 \pm 0.04$ keV

$\Upsilon(1S)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\tau^+\tau^-$	(2.97±0.35) %		4381
$\mu^+\mu^-$	(2.48±0.06) %		4729
e^+e^-	(2.52±0.17) %		4730
Hadronic decays			
$J/\psi(1S)$ anything	(1.1 ±0.4) × 10^{-3}		–
$\rho\pi$	< 2 × 10^{-4}	90%	4698
$\pi^+\pi^-$	< 5 × 10^{-4}	90%	4728
K^+K^-	< 5 × 10^{-4}	90%	4704
$p\overline{p}$	< 9 × 10^{-4}	90%	4636
Radiative decays			
$\gamma 2\pi^+2\pi^-$	(2.5 ±0.9) × 10^{-4}		4720
$\gamma\pi^+\pi^-K^+K^-$	(2.9 ±0.9) × 10^{-4}		4686
$\gamma\pi^+\pi^-p\overline{p}$	(1.5 ±0.6) × 10^{-4}		4604
$\gamma 2K^+2K^-$	(2.0 ±2.0) × 10^{-5}		4601
$\gamma 3\pi^+3\pi^-$	(2.5 ±1.2) × 10^{-4}		4703
$\gamma 2\pi^+2\pi^-K^+K^-$	(2.4 ±1.2) × 10^{-4}		4658
$\gamma 2\pi^+2\pi^-p\overline{p}$	(4 ±6) × 10^{-5}		4563
$\gamma 2h^+2h^-$	(7.0 ±1.5) × 10^{-4}		–
$\gamma 3h^+3h^-$	(5.4 ±2.0) × 10^{-4}		–
$\gamma 4h^+4h^-$	(7.4 ±3.5) × 10^{-4}		–
$\gamma\eta'(958)$	< 1.3 × 10^{-3}	90%	4682
$\gamma\eta$	< 3.5 × 10^{-4}	90%	4714
$\gamma f_2'(1525)$	< 1.4 × 10^{-4}	90%	4607
$\gamma f_0(1710) \to \gamma K\overline{K}$	< 6.4 × 10^{-5}	90%	4576
$\gamma f_2(1270)$	< 1.3 × 10^{-4}	90%	4644
$\gamma f_4(2220) \to \gamma K^+K^-$	< 1.5 × 10^{-5}	90%	4469
$\gamma\eta(1440)$	< 8.2 × 10^{-5}	90%	4624

$\chi_{b0}(1P)$ [hh] or $\chi_{b0}(9860)$

$I^G(J^{PC}) = ?^?(0 \text{ preferred}^{++})$
J needs confirmation.

Mass $m = 9859.8 \pm 1.3$ MeV

$\chi_{b0}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\gamma\Upsilon(1S)$	<6 %	90%	391

$\chi_{b1}(1P)$ [hh] or $\chi_{b1}(9890)$

$I^G(J^{PC}) = ?^?(1^{++})$
J needs confirmation.

Mass $m = 9891.9 \pm 0.7$ MeV

$\chi_{b1}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\gamma\Upsilon(1S)$	(35±8) %	422

$\chi_{b2}(1P)$ [hh] or $\chi_{b2}(9915)$

$I^G(J^{PC}) = ?^?(2^{++})$
J needs confirmation.

Mass $m = 9913.2 \pm 0.6$ MeV

$\chi_{b2}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\gamma\,\Upsilon(1S)$	(22 ± 4) %	443

$\Upsilon(2S)$ or $\Upsilon(10023)$

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 10.02330 \pm 0.00031$ GeV
Full width $\Gamma = 43 \pm 8$ keV

$\Upsilon(2S)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\Upsilon(1S)\pi^+\pi^-$	$(18.5\ \pm0.8\ )$ %		475
$\Upsilon(1S)\pi^0\pi^0$	$(\ 8.8\ \pm1.1\ )$ %		480
$\tau^+\tau^-$	$(\ 1.7\ \pm1.6\ )$ %		4683
$\mu^+\mu^-$	$(\ 1.31\pm0.21)$ %		5011
e^+e^-	seen		5012
$\Upsilon(1S)\pi^0$	$< 8 \times 10^{-3}$	90%	531
$\Upsilon(1S)\eta$	$< 2 \times 10^{-3}$	90%	122
$J/\psi(1S)$ anything	$< 6 \times 10^{-3}$	90%	–
Radiative decays			
$\gamma\chi_{b1}(1P)$	$(\ 6.7\ \pm0.9\ )$ %		131
$\gamma\chi_{b2}(1P)$	$(\ 6.6\ \pm0.9\ )$ %		110
$\gamma\chi_{b0}(1P)$	$(\ 4.3\ \pm1.0\ )$ %		162
$\gamma f_0(1710)$	$< 5.9 \times 10^{-4}$	90%	4866
$\gamma f'_2(1525)$	$< 5.3 \times 10^{-4}$	90%	4896
$\gamma f_2(1270)$	$< 2.41 \times 10^{-4}$	90%	4931

$\chi_{b0}(2P)$ [hh] or $\chi_{b0}(10235)$

$I^G(J^{PC}) = ?^?(0 \text{ preferred}^{++})$
J needs confirmation.

Mass $m = 10.2320 \pm 0.0007$ GeV

$\chi_{b1}(2P)$ [hh] or $\chi_{b1}(10255)$

$I^G(J^{PC}) = ?^?(1 \text{ preferred}^{++})$
J needs confirmation.

Mass $m = 10.2549 \pm 0.0006$ GeV
$m_{\chi_{b1}(2P)} - m_{\chi_{b0}(2P)} = 22.9 \pm 0.6$ MeV

$\chi_{b1}(2P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\gamma\,\Upsilon(2S)$	$(22\ \ \pm4\ \ )$ %	229
$\gamma\,\Upsilon(1S)$	$(\ 7.9\pm1.1)$ %	764

$\chi_{b2}(2P)$ [hh] or $\chi_{b2}(10270)$

$I^G(J^{PC}) = ?^?(2 \text{ preferred}^{++})$
J needs confirmation.

Mass $m = 10.26835 \pm 0.00057$ GeV
$m_{\chi_{b2}(2P)} - m_{\chi_{b1}(2P)} = 13.4 \pm 0.4$ MeV
$m_{\chi_{b2}(2P)} - m_{\chi_{b0}(2P)} = 36.4 \pm 0.6$ MeV

$\chi_{b2}(2P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\gamma\,\Upsilon(2S)$	$(19\ \ \pm4\ \ )$ %	242
$\gamma\,\Upsilon(1S)$	$(\ 7.0\pm1.1)$ %	776

$\Upsilon(3S)$ or $\Upsilon(10355)$

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 10.3553 \pm 0.0005$ GeV
Full width $\Gamma = 24.3 \pm 2.9$ keV

$\Upsilon(3S)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
$\Upsilon(2S)$ anything	$(10.9\ \pm1.3\ )$ %		–
$\Upsilon(2S)\pi^+\pi^-$	$(\ 2.1\ \pm0.4\ )$ %		177
$\Upsilon(2S)\pi^0\pi^0$	$(\ 1.3\ \pm0.4\ )$ %		190
$\Upsilon(1S)\pi^+\pi^-$	$(\ 4.48\pm0.29)$ %		814
$\Upsilon(1S)\pi^0\pi^0$	$(\ 1.8\ \pm0.4\ )$ %		816
$\mu^+\mu^-$	$(\ 1.81\pm0.17)$ %		5177
e^+e^-	seen		–
Radiative decays			
$\gamma\chi_{b2}(2P)$	$(11.4\ \pm0.8\ )$ %	1.3	87
$\gamma\chi_{b1}(2P)$	$(11.3\ \pm0.6\ )$ %		100
$\gamma\chi_{b0}(2P)$	$(\ 5.4\ \pm0.6\ )$ %	1.1	123

$\Upsilon(4S)$ or $\Upsilon(10580)$

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 10.5800 \pm 0.0035$ GeV
Full width $\Gamma = 23.8 \pm 2.2$ MeV
$\Gamma_{ee} = 0.24 \pm 0.05$ keV (S = 1.7)

$\Upsilon(4S)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
e^+e^-	$(1.01\pm0.21) \times 10^{-5}$		5290
D^{*+} anything + c.c.	< 7.4 %	90%	–
ϕ anything	$< 2.3 \times 10^{-3}$	90%	–
$\Upsilon(1S)$ anything	$< 4 \times 10^{-3}$	90%	–

$\Upsilon(10860)$

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 10.865 \pm 0.008$ GeV (S = 1.1)
Full width $\Gamma = 110 \pm 13$ MeV
$\Gamma_{ee} = 0.31 \pm 0.07$ keV (S = 1.3)

$\Upsilon(10860)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
e^+e^-	$(2.8\pm0.7) \times 10^{-6}$	5432

$\Upsilon(11020)$

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 11.019 \pm 0.008$ GeV
Full width $\Gamma = 79 \pm 16$ MeV
$\Gamma_{ee} = 0.130 \pm 0.030$ keV

$\Upsilon(11020)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
e^+e^-	$(1.6\pm0.5) \times 10^{-6}$	5509

Searches for Top and Fourth Generation Hadrons

The section on "Searches for Top and Fourth Generation Hadrons" can be found immediately after the Bottom Mesons.

NOTES

In this Summary Table:

When a quantity has "(S = ...)" to its right, the error on the quantity has been enlarged by the "scale factor" S, defined as $S = \sqrt{\chi^2/(N-1)}$, where N is the number of measurements used in calculating the quantity. We do this when S > 1, which often indicates that the measurements are inconsistent. When S > 1.25, we also show in the Full Listings an ideogram of the measurements. For more about S, see the Introduction.

A decay momentum p is given for each decay mode. For a 2-body decay, p is the momentum of each decay product in the rest frame of the decaying particle. For a 3-or-more-body decay, p is the largest momentum any of the products can have in this frame.

[a] See the Note on $\pi^\pm \to \ell^\pm \nu\gamma$ and $K^\pm \to \ell^\pm \nu\gamma$ Form Factors in the Full Listings for definitions and details.

[b] See the Full Listings for the energy limits used in this measurement; low-energy γ's are not included. Measurements of $\Gamma(e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ always include decays with γ's, and measurements of $\Gamma(e^+\nu_e\gamma)$ and $\Gamma(\mu^+\nu_\mu\gamma)$ never include low-energy γ's. Therefore, since no clean separation is possible, we consider the modes with γ's to be subreactions of the modes without them, and let $[\Gamma(e^+\nu_e) + \Gamma(\mu^+\nu_\mu)]/\Gamma_{\rm total} = 100\%$.

[c] Astrophysical and cosmological arguments give limits of order 10^{-13}; see the Full Listings.

[d] See the Note on the Decay Rate $\Gamma(\eta \to \gamma\gamma)$ in the Full Listings.

[e] See the Note on η Decay Parameters in the Full Listings.

[f] The e^+e^- branching fraction is from $e^+e^- \to \pi^+\pi^-$ experiments only. The $\omega\rho$ interference is then due to $\omega\rho$ mixing only, and is expected to be small. If $e\mu$ universality holds, $\Gamma(\rho^0 \to \mu^+\mu^-) = \Gamma(\rho^0 \to e^+e^-) \times 0.99785$.

[g] This is only an educated guess; the error given is larger than the error on the average of the published values. (See the Meson Full Listings for details.)

[h] See Meson Full Listings.

[i] The definition of the slope parameter g of the $K \to 3\pi$ Dalitz plot is as follows (see also note in the Full Listings):

$$|M|^2 = 1 + g(s_3 - s_0)/m^2_{\pi^+} + \cdots .$$

[j] For more details and definitions of parameters see the Full Listings.

[k] See the Note on $\pi^\pm \to \ell^\pm \nu\gamma$ and $K^\pm \to \ell^\pm \nu\gamma$ Form Factors in the $\pi^\pm$ Full Listings for definitions and details.

[l] See the Full Listings for the energy limits used in this measurement.

[m] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.

[n] Direct-emission branching fraction.

[o] Structure-dependent part.

[p] The CP-violation parameters are defined as follows (see also note in the Full Listings):

$$\eta_{+-} = |\eta_{+-}|e^{i\phi_{+-}} = \frac{A(K^0_L \to \pi^+\pi^-)}{A(K^0_S \to \pi^+\pi^-)} = \epsilon + \epsilon'$$

$$\eta_{00} = |\eta_{00}|e^{i\phi_{00}} = \frac{A(K^0_L \to \pi^0\pi^0)}{A(K^0_S \to \pi^0\pi^0)} = \epsilon - 2\epsilon'$$

$$\delta = \frac{\Gamma(K^0_L \to \pi^-\ell^+\nu) - \Gamma(K^0_L \to \pi^+\ell^-\nu)}{\Gamma(K^0_L \to \pi^-\ell^+\nu) + \Gamma(K^0_L \to \pi^+\ell^-\nu)} ,$$

$$|\eta_{+-0}|^2 = \frac{\Gamma(K^0_S \to \pi^+\pi^-\pi^0)^{CP\ \rm viol.}}{\Gamma(K^0_L \to \pi^+\pi^-\pi^0)} ,$$

$$|\eta_{000}|^2 = \frac{\Gamma(K^0_S \to \pi^0\pi^0\pi^0)}{\Gamma(K^0_L \to \pi^0\pi^0\pi^0)} .$$

[q] ϵ'/ϵ is derived from $|\eta_{00}/\eta_{+-}|$ measurements using theoretical input on phases. Preliminary higher precision results were presented at the Lepton Photon Symp. and Conf. on High Energy Physics, Geneva (1991), but are not included in these averages. See note in the Full Listings.

[r] The value is for the sum of the charge states indicated.

[s] This is a weighted average of $D^\pm$ (44%) and D^0 (56%) branching fractions. See the $D^\pm$ Listing for $D^\pm$ and $D^0 \to \eta X$.

[t] The whole differs from the sum of the parts due to interference effects; see (in the Full Listings) COFFMAN 92B.

[u] The $D^0_1 - D^0_2$ limits are inferred from the limit on $D^0 \to \overline{D}^0 \to K^+\pi^-$. The $B^0_1 - B^0_2$ value is inferred from $B^0 \to \overline{B}^0 \to \mu^-$ anything.

[v] It is generally agreed that the $\overline{K}\pi e^+\nu_e$ decays of the D^+ and D^0 are dominantly $\overline{K}^*(892)e^+\nu_e$. In that case, these $\overline{K}\pi e^+\nu_e$ branching fractions are too large to agree with the $K^*(892)^- e^+\nu_e$ branching fraction in the Table. Our guess is that the fault lies with these $\overline{K}\pi e^+\nu_e$ branching fractions. What is lacking in order to include these results in a fit and at least get a consistent set of branching fractions is a measurement of the ratio $\Gamma(K^*(892)^- e^+\nu_e)/\Gamma(\overline{K}\pi e^+\nu_e)$ for the D^0 alone.

[w] This value is, however, in some conflict with an upper limit of 0.9% (90% CL); see the Full Listings.

[x] The sum of appropriate fractions of the next three modes.

[y] Includes all the decay modes of the ϕ, $K^*(892)$, η, ω, $\eta'(958)$, or $f_0(975)$.

[z] This is an average of the $\phi e^+\nu_e$ and $\phi\mu^+\nu_\mu$ branching fractions.

[aa] ℓ indicates e or μ mode, not sum over modes.

[bb] B^0, $B^\pm$, and B^0_s not separated.

[cc] Indirect limit from fit to precision electroweak observables. See the minireview "Constraints on m_t, M_H, and Heavy Physics from Precision Experiments" in the Full Listings.

[dd] Value is for the sum of the charge states indicated.

[ee] Includes $p\overline{p}\pi^+\pi^-\gamma$ and excludes $p\overline{p}\eta$, $p\overline{p}\omega$, $p\overline{p}\eta'$.

[ff] See $\eta(1440)$ mini-review.

[gg] J^{PC} known by production in e^+e^- via single photon annihilation. I^G is not known; interpretation of this state as a single resonance is unclear because of the expectation of substantial threshold effects in this energy region.

[hh] Spectroscopic labeling for these states is theoretical, pending experimental information.

See also the table of suggested $q\overline{q}$ quark-model assignments in the Quark Model section.

- • Indicates particles that appear in the preceding Meson Summary Table. We do not regard the other entries as being established.
- † Indicates that the value of J given is preferred, but needs confirmation.

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^{\pm}$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $\rho(770)$	$1^+(1^{--})$	• $\rho(1700)$	$1^+(1^{--})$
• $\omega(783)$	$0^-(1^{--})$	$X(1700)$	$\text{even}^+(?^?{}^+)$
• $\eta'(958)$	$0^+(0^{-+})$	• $f_0(1710)$	$0^+(0^{++})$
• $f_0(975)$	$0^+(0^{++})$	$X(1740)$	0^+
• $a_0(980)$	$1^-(0^{++})$	$\eta(1760)$	$0^+(0^{-+})$
• $\phi(1020)$	$0^-(1^{--})$	$\pi(1770)$	$1^-(0^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	$\pi(1775)$	$1^-(?^{-+})$
• $b_1(1235)$	$1^+(1^{+-})$	$f_2(1810)$	$0^+(2^{++})$
$f_0(1240)$	$0^+(0^{++})$	$X(1814)$	$1^-(?^{??})$
• $a_1(1260)$	$1^-(1^{++})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $f_2(1270)$	$0^+(2^{++})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $f_1(1285)$	$0^+(1^{++})$	$X(1910)$	$0^+(?^?{}^+)$
• $\eta(1295)$	$0^+(0^{-+})$	$X(1950)$	$?^?(?^{??})$
• $\pi(1300)$	$1^-(0^{-+})$	• $f_2(2010)$	$0^+(2^{++})$
$a_0(1320)$	$1^-(0^{++})$	$a_4(2040)$	$1^-(4^{++})$
• $a_2(1320)$	$1^-(2^{++})$	$a_3(2050)$	$1^-(3^{++})$
$h_1(1380)$	$?^-(1^{+?})$	• $f_4(2050)$	$0^+(4^{++})$
• $\omega(1390)$	$0^-(1^{--})$	$\eta(2100)$	$0^+(0^{-+})$
• $f_0(1400)$	$0^+(0^{++})$	$\pi_2(2100)$	$1^-(2^{-+})$
$\hat{\rho}(1405)$	$1^-(1^{-+})$	$\rho(2110)$	$1^+(1^{--})$
• $f_1(1420)$	$0^+(1^{++})$	$f_2(2150)$	$0^+(2^{++})$
$f_2(1430)$	$0^+(2^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $\eta(1440)$	$0^+(0^{-+})$	$f_2(2175)$	$0^+(2^{++})$
• $\rho(1450)$	$1^+(1^{--})$	$X(2200)$	$?^?(\text{even}^{++})$
• $f_1(1510)$	$0^+(1^{++})$	$f_4(2220)$	$0^+(4^{++})$
$f_2(1520)$	$0^+(2^{++})$	$\rho_3(2250)$	$1^+(3^{--})$
$f_0(1525)$	$0^+(0^{++})$	• $f_2(2300)$	$0^+(2^{++})$
• $f'_2(1525)$	$0^+(2^{++})$	$f_4(2300)$	$0^+(4^{++})$
• $f_0(1590)$	$0^+(0^{++})$	• $f_2(2340)$	$0^+(2^{++})$
• $\omega(1600)$	$0^-(1^{--})$	$\rho_5(2350)$	$1^+(5^{--})$
$X(1600)$	$2^+(2^{++})$	$a_6(2450)$	$1^-(6^{++})$
$f_2(1640)$	$0^+(2^{++})$	$f_6(2510)$	$0^+(6^{++})$
$X(1650)$	$1^-(?^{??})$	$X(3100)$	$?^?(?^{??})$
• $\omega_3(1670)$	$0^-(3^{--})$	$X(3250)$	$?^?(?^{??})$

OTHER LIGHT UNFLAVORED ($S = C = B = 0$)

$e^+e^-(1100\text{–}2200)$	$?^?(1^{--})$
$\overline{N}N(1100\text{–}3600)$	
$X(1900\text{–}3600)$	

STRANGE ($S = \pm1,\ C = B = 0$)

	$I(J^P)$
• $K^{\pm}$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K^*_0(1430)$	$1/2(0^+)$
• $K^*_2(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K^*_3(1780)$	$1/2(3^-)$
$K(1830)$	$1/2(0^-)$
$K^*_0(1950)$	$1/2(0^+)$
$K^*_2(1980)$	$1/2(2^+)$
• $K^*_4(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K^*_5(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$

CHARMED ($C = \pm1$)

• $D^{\pm}$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2010)^{\pm}$	$1/2(1^-)$
• $D^*(2010)^0$	$1/2(1^-)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_J(2440)^{\pm}$	$1/2(?^?)$
• $D^*_2(2460)^0$	$1/2(2^+)$
$D^*_J(2470)^{\pm}$	$1/2(?^?)$

CHARMED STRANGE ($C = S = \pm1$)

• $D^{\pm}_s$	$0(0^-)$
• $D^{*\pm}_s$	$?(?^?)$
• $D_{s1}(2536)^{\pm}$	$0(1^+)$
$D_{sJ}(2564)^{\pm}$	$?(?^?)$

BOTTOM ($B = \pm1$)

• $B^{\pm}$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• B^*	$1/2(1^-)$
B^0_s	$?(?^?)$
B^*_s	$?(?^?)$

HEAVY QUARK SEARCHES

	$I^G(J^{PC})$
• Top and Fourth Generation Hadrons	

$c\overline{c}$

• $\eta_c(1S) = \eta_c(2980)$	$0^+(0^{-+})$
• $J/\psi(1S) = J/\psi(3097)$	$0^-(1^{--})$
• $\chi_{c0}(1P) = \chi_{c0}(3415)$	$0^+(0^{++})$
• $\chi_{c1}(1P) = \chi_{c1}(3510)$	$0^+(1^{++})$
• $\chi_{c2}(1P) = \chi_{c2}(3555)$	$0^+(2^{++})$
$\eta_c(2S) = \eta_c(3590)$	$?^?(?^?{}^+)$
• $\psi(2S) = \psi(3685)$	$0^-(1^{--})$
• $\psi(3770)$	$?^?(1^{--})$
• $\psi(4040)$	$?^?(1^{--})$
• $\psi(4160)$	$?^?(1^{--})$
• $\psi(4415)$	$?^?(1^{--})$

$b\overline{b}$

• $\Upsilon(1S) = \Upsilon(9460)$	$?^?(1^{--})$
• $\chi_{b0}(1P) = \chi_{b0}(9860)$	$?^?(0^{++})^{\dagger}$
• $\chi_{b1}(1P) = \chi_{b1}(9890)$	$?^?(1^{++})$
• $\chi_{b2}(1P) = \chi_{b2}(9915)$	$?^?(2^{++})$
• $\Upsilon(2S) = \Upsilon(10023)$	$?^?(1^{--})$
• $\chi_{b0}(2P) = \chi_{b0}(10235)$	$?^?(0^{++})^{\dagger}$
• $\chi_{b1}(2P) = \chi_{b1}(10255)$	$?^?(1^{++})^{\dagger}$
• $\chi_{b2}(2P) = \chi_{b2}(10270)$	$?^?(2^{++})^{\dagger}$
• $\Upsilon(3S) = \Upsilon(10355)$	$?^?(1^{--})$
• $\Upsilon(4S) = \Upsilon(10580)$	$?^?(1^{--})$
• $\Upsilon(10860)$	$?^?(1^{--})$
• $\Upsilon(11020)$	$?^?(1^{--})$

NON-$q\overline{q}$ CANDIDATES

Non-$q\overline{q}$ Candidates

Baryon Summary Table

This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4-star status are included in the main Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the short table are not established as baryons. The names with masses are of baryons that decay strongly. See our 1986 edition (Physics Letters **170B**) for listings of evidence for Z baryons (KN resonances).

p	P_{11}	****	$\Delta(1232)$	P_{33}	****	Λ	P_{01}	****	Σ^+	P_{11}	****	Ξ^0	P_{11}	****
n	P_{11}	****	$\Delta(1600)$	P_{33}	***	$\Lambda(1405)$	S_{01}	****	Σ^0	P_{11}	****	Ξ^-	P_{11}	****
$N(1440)$	P_{11}	****	$\Delta(1620)$	S_{31}	****	$\Lambda(1520)$	D_{03}	****	Σ^-	P_{11}	****	$\Xi(1530)$	P_{13}	****
$N(1520)$	D_{13}	****	$\Delta(1700)$	D_{33}	****	$\Lambda(1600)$	P_{01}	***	$\Sigma(1385)$	P_{13}	****	$\Xi(1620)$		*
$N(1535)$	S_{11}	****	$\Delta(1750)$	P_{31}	*	$\Lambda(1670)$	S_{01}	****	$\Sigma(1480)$		*	$\Xi(1690)$		***
$N(1650)$	S_{11}	****	$\Delta(1900)$	S_{31}	***	$\Lambda(1690)$	D_{03}	****	$\Sigma(1560)$		**	$\Xi(1820)$	D_{13}	***
$N(1675)$	D_{15}	****	$\Delta(1905)$	F_{35}	****	$\Lambda(1800)$	S_{01}	***	$\Sigma(1580)$	D_{13}	**	$\Xi(1950)$		***
$N(1680)$	F_{15}	****	$\Delta(1910)$	P_{31}	****	$\Lambda(1810)$	P_{01}	***	$\Sigma(1620)$	S_{11}	**	$\Xi(2030)$		***
$N(1700)$	D_{13}	***	$\Delta(1920)$	P_{33}	***	$\Lambda(1820)$	F_{05}	****	$\Sigma(1660)$	P_{11}	***	$\Xi(2120)$		*
$N(1710)$	P_{11}	***	$\Delta(1930)$	D_{35}	***	$\Lambda(1830)$	D_{05}	****	$\Sigma(1670)$	D_{13}	****	$\Xi(2250)$		**
$N(1720)$	P_{13}	****	$\Delta(1940)$	D_{33}	*	$\Lambda(1890)$	P_{03}	****	$\Sigma(1690)$		**	$\Xi(2370)$		**
$N(1900)$	P_{13}	*	$\Delta(1950)$	F_{37}	****	$\Lambda(2000)$		*	$\Sigma(1750)$	S_{11}	***	$\Xi(2500)$		*
$N(1990)$	F_{17}	**	$\Delta(2000)$	F_{35}	*	$\Lambda(2020)$	F_{07}	*	$\Sigma(1770)$	P_{11}	*			
$N(2000)$	F_{15}	**	$\Delta(2150)$	S_{31}	*	$\Lambda(2100)$	G_{07}	****	$\Sigma(1775)$	D_{15}	****	Ω^-		****
$N(2080)$	D_{13}	**	$\Delta(2200)$	G_{37}	*	$\Lambda(2110)$	F_{05}	***	$\Sigma(1840)$	P_{13}	*	$\Omega(2250)^-$		***
$N(2090)$	S_{11}	*	$\Delta(2300)$	H_{39}	**	$\Lambda(2325)$	D_{03}	*	$\Sigma(1880)$	P_{11}	**	$\Omega(2380)^-$		**
$N(2100)$	P_{11}	*	$\Delta(2350)$	D_{35}	*	$\Lambda(2350)$	H_{09}	***	$\Sigma(1915)$	F_{15}	****	$\Omega(2470)^-$		**
$N(2190)$	G_{17}	****	$\Delta(2390)$	F_{37}	*	$\Lambda(2585)$		**	$\Sigma(1940)$	D_{13}	***			
$N(2200)$	D_{15}	**	$\Delta(2400)$	G_{39}	**				$\Sigma(2000)$	S_{11}	*	Λ_c^+		****
$N(2220)$	H_{19}	****	$\Delta(2420)$	$H_{3,11}$	****				$\Sigma(2030)$	F_{17}	****	$\Sigma_c(2455)$		****
$N(2250)$	G_{19}	****	$\Delta(2750)$	$I_{3,13}$	**				$\Sigma(2070)$	F_{15}	*	Ξ_c^+		***
$N(2600)$	$I_{1,11}$	***	$\Delta(2950)$	$K_{3,15}$	**				$\Sigma(2080)$	P_{13}	**	Ξ_c^0		***
$N(2700)$	$K_{1,13}$	**							$\Sigma(2100)$	G_{17}	*	Ω_c^0		*
									$\Sigma(2250)$		***			
									$\Sigma(2455)$		**	Λ_b^0		***
									$\Sigma(2620)$		**			
									$\Sigma(3000)$		*			
									$\Sigma(3170)$		*			

**** Existence is certain, and properties are at least fairly well explored.

*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.

** Evidence of existence is only fair.

* Evidence of existence is poor.

N BARYONS
($S = 0$, $I = 1/2$)

p

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 938.27231 \pm 0.00028$ MeV [a]
$= 1.007276470 \pm 0.000000012$ u
$m(\overline{p})/m(p) = 0.99999998 \pm 0.00000004$
Magnetic moment $\mu = 2.79284739 \pm 0.00000006\ \mu_N$
Electric dipole moment $d = (-4 \pm 6) \times 10^{-23}$ e-cm
Electric polarizability $\alpha = (0.70 \pm 0.26) \times 10^{-3}$ fm^3
$|q_p + q_e| < 1.0 \times 10^{-21}\ e$ [b]
Mean life $\tau > 1.6 \times 10^{25}$ years (independent of modes)
$> 10^{31} - 5 \times 10^{32}$ years [c] (mode dependent)

For N decays, p and n distinguish proton and neutron partial lifetimes. See also "Note on Proton Mean Life Limits" in the Full Listings.

p DECAY MODES	Partial mean life (10^{30} years)	Confidence level	p (MeV/c)
Antilepton + meson			
$N \to e^+\pi$	>130 (n), >550 (p)	90%	459
$N \to \mu^+\pi$	>100 (n), >270 (p)	90%	453
$N \to \nu\pi$	>100 (n), >25 (p)	90%	459
$p \to e^+\eta$	>140	90%	309
$p \to \mu^+\eta$	>69	90%	296
$n \to \nu\eta$	>54	90%	310
$N \to e^+\rho$	>58 (n), >75 (p)	90%	153
$N \to \mu^+\rho$	>23 (n), >110 (p)	90%	119
$N \to \nu\rho$	>19 (n), >27 (p)	90%	153
$p \to e^+\omega$	>45	90%	142
$p \to \mu^+\omega$	>57	90%	104
$n \to \nu\omega$	>43	90%	144
$N \to e^+K$	>1.3 (n), >150 (p)	90%	337
$p \to e^+K^0_S$	>76	90%	337
$p \to e^+K^0_L$	>44	90%	337
$N \to \mu^+K$	>1.1 (n), >120 (p)	90%	326
$p \to \mu^+K^0_S$	>64	90%	326
$p \to \mu^+K^0_L$	>44	90%	326
$N \to \nu K$	>86 (n), >100 (p)	90%	339
$p \to e^+K^*(892)^0$	>52	90%	45
$N \to \nu K^*(892)$	>22 (n), >20 (p)	90%	45
Antilepton + mesons			
$p \to e^+\pi^+\pi^-$	>21	90%	448
$p \to e^+\pi^0\pi^0$	>38	90%	449
$n \to e^+\pi^-\pi^0$	>32	90%	449
$p \to \mu^+\pi^+\pi^-$	>17	90%	425
$p \to \mu^+\pi^0\pi^0$	>33	90%	427
$n \to \mu^+\pi^-\pi^0$	>33	90%	427
$n \to e^+K^0\pi^-$	>18	90%	319
Lepton + meson			
$n \to e^-\pi^+$	>65	90%	459
$n \to \mu^-\pi^+$	>49	90%	453
$n \to e^-\rho^+$	>62	90%	154
$n \to \mu^-\rho^+$	>7	90%	120
$n \to e^-K^+$	>32	90%	340
$n \to \mu^-K^+$	>57	90%	330
Lepton + mesons			
$p \to e^-\pi^+\pi^+$	>30	90%	448
$n \to e^-\pi^+\pi^0$	>29	90%	449
$p \to \mu^-\pi^+\pi^+$	>17	90%	425
$n \to \mu^-\pi^+\pi^0$	>34	90%	427
$p \to e^-\pi^+K^+$	>20	90%	320
$p \to \mu^-\pi^+K^+$	>5	90%	279
Antilepton + photon(s)			
$p \to e^+\gamma$	>460	90%	469
$p \to \mu^+\gamma$	>380	90%	463
$n \to \nu\gamma$	>24	90%	470
$p \to e^+\gamma\gamma$	>100	90%	469
Three leptons			
$p \to e^+e^+e^-$	>510	90%	469
$p \to e^+\mu^+\mu^-$	>81	90%	457
$p \to e^+\nu\nu$	>11	90%	469
$n \to e^+e^-\nu$	>74	90%	470
$n \to \mu^+e^-\nu$	>47	90%	464
$n \to \mu^+\mu^-\nu$	>42	90%	458
$p \to \mu^+e^+e^-$	>91	90%	464
$p \to \mu^+\mu^+\mu^-$	>190	90%	439
$p \to \mu^+\nu\nu$	>21	90%	463
$p \to e^-\mu^+\mu^+$	>6.0	90%	457
$n \to 3\nu$	>0.0005	90%	470
Inclusive modes			
$N \to e^+$ anything	>0.6 (n, p)	90%	–
$N \to \mu^+$ anything	>12 (n, p)	90%	–
$N \to e^+\pi^0$ anything	>0.6 (n, p)	90%	–
$\Delta B = 2$ dinucleon modes			
The following are lifetime limits per iron nucleus.			
$pp \to \pi^+\pi^+$	>0.7	90%	–
$pn \to \pi^+\pi^0$	>2.0	90%	–
$nn \to \pi^+\pi^-$	>0.7	90%	–
$nn \to \pi^0\pi^0$	>3.4	90%	–
$pp \to e^+e^+$	>5.8	90%	–
$pp \to e^+\mu^+$	>3.6	90%	–
$pp \to \mu^+\mu^+$	>1.7	90%	–
$pn \to e^+\overline{\nu}$	>2.8	90%	–
$pn \to \mu^+\overline{\nu}$	>1.6	90%	–
$nn \to \nu_e\overline{\nu}_e$	>0.000012	90%	–
$nn \to \nu_\mu\overline{\nu}_\mu$	>0.000006	90%	–

n

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 939.56563 \pm 0.00028$ MeV [a]
$= 1.008664904 \pm 0.000000014$ u
$m_n - m_p = 1.293318 \pm 0.000009$ MeV
$= 0.001388434 \pm 0.000000009$ u
Mean life $\tau = 889.1 \pm 2.1$ s (S = 1.2)
$c\tau = 2.665 \times 10^8$ km
Magnetic moment $\mu = -1.9130427 \pm 0.0000005\ \mu_N$
Electric dipole moment $d < 12 \times 10^{-26}$ e-cm, CL = 95%
Electric polarizability $\alpha = (1.16^{+0.19}_{-0.23}) \times 10^{-3}$ fm^3
Charge $q = (-0.4 \pm 1.1) \times 10^{-21}\ e$
Mean time for $n\overline{n}$ oscillations $> 1.2 \times 10^8$ s, CL = 90% [d]

Decay parameters

$pe^-\overline{\nu}_e$ $g_A/g_V = -1.2573 \pm 0.0028$
" $A = -0.1127 \pm 0.0011$
" $\phi_{AV} = (180.07 \pm 0.18)°$

n DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$pe^-\overline{\nu}_e$		100 %		1.19
hydrogen-atom $\overline{\nu}_e$		< 3 %	95%	1.19
Charge conservation (Q) violating mode				
$p\nu_e\overline{\nu}_e$	Q	< 9×10^{-24}	90%	1.29

N(1440) P_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1430$ to 1470 (≈ 1440) MeV
Full width $\Gamma = 250$ to 450 (≈ 350) MeV
$p_{beam} = 0.61$ GeV/c $4\pi\lambda\!\!\!^-{}^2 = 31.0$ mb

N(1440) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	60–70 %	397
$N\pi\pi$	30–40 %	342
$\Delta\pi$	20–30 %	143
$N\rho$	<10 %	†
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	5–15 %	–
$p\gamma$	0.08–0.10 %	414
$n\gamma$	0.01–0.06 %	413

$N(1520)\ D_{13}$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$

Mass m = 1515 to 1530 (≈ 1520) MeV
Full width Γ = 110 to 135 (≈ 120) MeV
p_{beam} = 0.74 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 23.5 mb

N(1520) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	50–60 %	456
$N\eta$	≈ 0.1 %	149
$N\pi\pi$	40–50 %	410
$\Delta\pi$	15–30 %	228
$N\rho$	10–25 %	†
$N\ (\pi\pi)^{I=0}_{S\text{-wave}}$	<10 %	–
$p\gamma$	0.43–0.57 %	470
$n\gamma$	0.34–0.51 %	470

$N(1535)\ S_{11}$

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$

Mass m = 1520 to 1555 (≈ 1535) MeV
Full width Γ = 100 to 250 (≈ 150) MeV
p_{beam} = 0.76 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 22.5 mb

N(1535) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	35–55 %	467
$N\eta$	30–50 %	182
$N\pi\pi$	5–20 %	422
$\Delta\pi$	<10 %	242
$N\rho$	<10 %	†
$N\ (\pi\pi)^{I=0}_{S\text{-wave}}$	<10 %	–
$N(1440)\pi$	<10 %	†
$p\gamma$	0.1–0.2 %	481
$n\gamma$	0.15–0.35 %	480

$N(1650)\ S_{11}$

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$

Mass m = 1640 to 1680 (≈ 1650) MeV
Full width Γ = 145 to 190 (≈ 150) MeV
p_{beam} = 0.96 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 16.4 mb

N(1650) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	60–80 %	547
$N\eta$	≈ 1 %	346
ΛK	≈ 7 %	161
$N\pi\pi$	5–20 %	511
$\Delta\pi$	<10 %	344
$N\rho$	<15 %	†
$N\ (\pi\pi)^{I=0}_{S\text{-wave}}$	<5 %	–
$N(1440)\pi$	<5 %	147
$p\gamma$	0.04–0.16 %	558
$n\gamma$	0–0.17 %	557

$N(1675)\ D_{15}$

$I(J^P) = \frac{1}{2}(\frac{5}{2}^-)$

Mass m = 1670 to 1685 (≈ 1675) MeV
Full width Γ = 140 to 180 (≈ 150) MeV
p_{beam} = 1.01 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 15.4 mb

N(1675) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	40–50 %	563
$N\eta$	≈ 1 %	374
ΛK	≈ 0.1 %	209
$N\pi\pi$	50–60 %	529
$\Delta\pi$	50–60 %	364
$N\rho$	<10 %	†
$N\ (\pi\pi)^{I=0}_{S\text{-wave}}$	<1 %	–
$p\gamma$	~ 0.01 %	575
$n\gamma$	0.07–0.12 %	574

$N(1680)\ F_{15}$

$I(J^P) = \frac{1}{2}(\frac{5}{2}^+)$

Mass m = 1675 to 1690 (≈ 1680) MeV
Full width Γ = 120 to 140 (≈ 130) MeV
p_{beam} = 1.01 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 15.2 mb

N(1680) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	60–70 %	567
$N\eta$	not seen	379
ΛK	not seen	218
$N\pi\pi$	30–40 %	532
$\Delta\pi$	5–15 %	369
$N\rho$	5–15 %	†
$N\ (\pi\pi)^{I=0}_{S\text{-wave}}$	5–20 %	–
$p\gamma$	0.21–0.30 %	578
$n\gamma$	0.02–0.05 %	577

$N(1700)\ D_{13}$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$

Mass m = 1650 to 1750 (≈ 1700) MeV
Full width Γ = 50 to 150 (≈ 100) MeV
p_{beam} = 1.05 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 14.5 mb

N(1700) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–15 %	580
ΛK	0.1–0.3 %	250
$N\pi\pi$	85–95 %	547
$\Delta\pi$	5–70 %	385
$N\rho$	<15 %	†
$N\ (\pi\pi)^{I=0}_{S\text{-wave}}$	<60 %	–
$p\gamma$	~ 0.01 %	591

$N(1710)\ P_{11}$

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 1680 to 1740 (≈ 1710) MeV
Full width Γ = 50 to 250 (≈ 100) MeV
p_{beam} = 1.07 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 14.2 mb

N(1710) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	587
$N\eta$	20–40 %	410
ΛK	5–25 %	264
$N\pi\pi$	20–50 %	554
$\Delta\pi$	10–25 %	393
$N\rho$	5–20 %	48
$N\ (\pi\pi)^{I=0}_{S\text{-wave}}$	<25 %	–

$N(1720)\ P_{13}$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$

Mass m = 1650 to 1750 (≈ 1720) MeV
Full width Γ = 100 to 200 (≈ 150) MeV
p_{beam} = 1.09 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 13.9 mb

N(1720) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	594
$N\eta$	2–6 %	420
ΛK	3–10 %	278
$N\pi\pi$	>35 %	561
$\Delta\pi$	5–15 %	401
$N\rho$	25–75 %	104
$N\ (\pi\pi)^{I=0}_{S\text{-wave}}$	10–15 %	–

$N(2190)\ G_{17}$

$I(J^P) = \frac{1}{2}(\frac{7}{2}^-)$

Mass m = 2100 to 2200 (≈ 2190) MeV
Full width Γ = 350 to 550 (≈ 450) MeV
p_{beam} = 2.07 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 6.21 mb

N(2190) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	888
$N\eta$	1–3 %	790
ΛK	0.2–0.4 %	712
$N\pi\pi$	20–40 %	868
$N\rho$	20–40 %	683

$N(2220)\ H_{19}$

$I(J^P) = \frac{1}{2}(\frac{9}{2}^+)$

Mass m = 2180 to 2310 (≈ 2220) MeV
Full width Γ = 320 to 550 (≈ 400) MeV
p_{beam} = 2.14 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 5.97 mb

N(2220) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	905
$N\eta$	0.5–1.0 %	811

$N(2250)\ G_{19}$

$I(J^P) = \frac{1}{2}(\frac{9}{2}^-)$

Mass m = 2170 to 2310 (≈ 2250) MeV
Full width Γ = 290 to 470 (≈ 400) MeV
p_{beam} = 2.21 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 5.74 mb

N(2250) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–15 %	923
$N\eta$	1–3 %	831
ΛK	<0.6 %	754

$N(2600)\ I_{1,11}$

$I(J^P) = \frac{1}{2}(\frac{11}{2}^-)$

Mass m = 2550 to 2750 (≈ 2600) MeV
Full width Γ = 500 to 800 (≈ 650) MeV
p_{beam} = 3.12 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 3.86 mb

N(2600) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–10 %	1126

Δ BARYONS
($S=0, I=3/2$)

$\Delta(1232)\ P_{33}$

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$

Mass m = 1230 to 1234 (≈ 1232) MeV
Full width Γ = 115 to 125 (≈ 120) MeV
p_{beam} = 0.30 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 94.8 mb

Δ(1232) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	99.3–99.5 %	227
$N\gamma$	0.56–0.66 %	259

$\Delta(1600)\ P_{33}$

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$

Mass m = 1550 to 1700 (≈ 1600) MeV
Full width Γ = 250 to 450 (≈ 350) MeV
p_{beam} = 0.87 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 18.6 mb

Δ(1600) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–25 %	512
$N\pi\pi$	75–90 %	473
$\Delta\pi$	50–60 %	301
$N\rho$	5–20 %	†
$N(1440)\pi$	20–30 %	74

$\Delta(1620)\ S_{31}$

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$

Mass m = 1615 to 1675 (≈ 1620) MeV
Full width Γ = 120 to 180 (≈ 150) MeV
p_{beam} = 0.91 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 17.7 mb

Δ(1620) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	20–30 %	526
$N\pi\pi$	70–80 %	488
$\Delta\pi$	40–60 %	318
$N\rho$	20–35 %	†
$N(1440)\pi$	<10 %	107
$N\gamma$	~ 0.03 %	538

$\Delta(1700)\ D_{33}$

$I(J^P) = \frac{3}{2}(\frac{3}{2}^-)$

Mass m = 1670 to 1770 (≈ 1700) MeV
Full width Γ = 200 to 400 (≈ 300) MeV
p_{beam} = 1.05 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 14.5 mb

Δ(1700) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	580
$N\pi\pi$	80–90 %	547
$\Delta\pi$	35–55 %	385
$N\rho$	30–50 %	†
$N\gamma$	0.14–0.33 %	591

$\Delta(1900)\ S_{31}$

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$

Mass m = 1850 to 1950 (≈ 1900) MeV
Full width Γ = 140 to 240 (≈ 200) MeV
p_{beam} = 1.44 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 9.71 mb

Δ(1900) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–30 %	710
ΣK	not seen	410

$\Delta(1905)\ F_{35}$

$I(J^P) = \frac{3}{2}(\frac{5}{2}^+)$

Mass m = 1870 to 1920 (≈ 1905) MeV
Full width Γ = 280 to 440 (≈ 350) MeV
p_{beam} = 1.45 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 9.62 mb

Δ(1905) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–15 %	713
ΣK	0.1–0.3 %	415
$N\pi\pi$	85–95 %	687
$\Delta\pi$	<30 %	542
$N\rho$	55–95 %	421
$N\gamma$	0.01–0.05 %	721

$\Delta(1910)\ P_{31}$

$I(J^P) = \frac{3}{2}(\frac{1}{2}^+)$

Mass m = 1870 to 1920 ($\approx$ 1910) MeV
Full width Γ = 190 to 270 ($\approx$ 250) MeV
p_{beam} = 1.46 GeV/c $4\pi\bar{\lambda}^2$ = 9.54 mb

Δ(1910) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	15–30 %	716
ΣK	not seen	421
$N\pi\pi$	70–85 %	691
$\Delta\pi$	<5 %	545
$N\rho$	5–25 %	426
$N(1440)\pi$	50–70 %	393

$\Delta(1920)\ P_{33}$

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$

Mass m = 1900 to 1970 ($\approx$ 1920) MeV
Full width Γ = 150 to 300 ($\approx$ 200) MeV
p_{beam} = 1.48 GeV/c $4\pi\bar{\lambda}^2$ = 9.37 mb

Δ(1920) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–20 %	722
ΣK	1–3 %	431

$\Delta(1930)\ D_{35}$

$I(J^P) = \frac{3}{2}(\frac{5}{2}^-)$

Mass m = 1920 to 1970 ($\approx$ 1930) MeV
Full width Γ = 250 to 450 ($\approx$ 350) MeV
p_{beam} = 1.50 GeV/c $4\pi\bar{\lambda}^2$ = 9.21 mb

Δ(1930) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	729
ΣK	not seen	441
$N\pi\pi$	not seen	704

$\Delta(1950)\ F_{37}$

$I(J^P) = \frac{3}{2}(\frac{7}{2}^+)$

Mass m = 1940 to 1960 ($\approx$ 1950) MeV
Full width Γ = 290 to 350 ($\approx$ 300) MeV
p_{beam} = 1.54 GeV/c $4\pi\bar{\lambda}^2$ = 8.91 mb

Δ(1950) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	35–40 %	741
ΣK	0.6–0.8 %	460
$N\pi\pi$	15–40 %	716
$\Delta\pi$	15–30 %	574
$N\rho$	<10 %	469
$N\gamma$	0.08–0.17 %	749

$\Delta(2420)\ H_{3,11}$

$I(J^P) = \frac{3}{2}(\frac{11}{2}^+)$

Mass m = 2300 to 2500 ($\approx$ 2420) MeV
Full width Γ = 300 to 500 ($\approx$ 400) MeV
p_{beam} = 2.64 GeV/c $4\pi\bar{\lambda}^2$ = 4.68 mb

Δ(2420) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–15 %	1023
ΣK	0.1–0.9 %	833

Λ BARYONS
($S = -1, I = 0$)

Λ

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 1115.63 $\pm$ 0.05 MeV (S = 1.4)
Mean life τ = (2.632 $\pm$ 0.020) $\times$ 10^{-10} s (S = 1.6)
$c\tau$ = 7.89 cm
Magnetic moment μ = -0.613 ± 0.004 μ_N
Electric dipole moment d < 1.5 $\times$ 10^{-16} e-cm, CL = 95%

Decay parameters [e]

$p\pi^-$ $\alpha_- = 0.642 \pm 0.013$
" $\phi_- = (-6.5 \pm 3.5)°$
" $\gamma_- = 0.76$
" $\Delta_- = (8 \pm 4)°$
$n\pi^0$ $\alpha_0 = +0.65 \pm 0.05$

Coupling constant ratios [f]

$pe^-\bar{\nu}_e$ $g_A/g_V = -0.718 \pm 0.015$

Λ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$p\pi^-$	(64.1 $\pm$0.5) %	101
$n\pi^0$	(35.7 $\pm$0.5) %	104
$n\gamma$	(1.02$\pm$0.33) $\times 10^{-3}$	162
$p\pi^-\gamma$	[g] (8.5 $\pm$1.4) $\times 10^{-4}$	101
$pe^-\bar{\nu}_e$	(8.34$\pm$0.14) $\times 10^{-4}$	163
$p\mu^-\bar{\nu}_\mu$	(1.57$\pm$0.35) $\times 10^{-4}$	131

$\Lambda(1405)\ S_{01}$

$I(J^P) = 0(\frac{1}{2}^-)$

Mass m = 1407 $\pm$ 4 MeV
Full width Γ = 50.0 $\pm$ 2.0 MeV
Below $\bar{K}N$ threshold

Λ(1405) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Sigma\pi$	100 %	152

$\Lambda(1520)\ D_{03}$

$I(J^P) = 0(\frac{3}{2}^-)$

Mass m = 1519.5 $\pm$ 1.0 MeV [h]
Full width Γ = 15.6 $\pm$ 1.0 MeV [h]
p_{beam} = 0.39 GeV/c $4\pi\bar{\lambda}^2$ = 82.8 mb

Λ(1520) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\bar{K}$	45 $\pm$ 1%	244
$\Sigma\pi$	42 $\pm$ 1%	267
$\Lambda\pi\pi$	10 $\pm$ 1%	252
$\Sigma\pi\pi$	0.9 $\pm$ 0.1%	152
$\Lambda\gamma$	0.8 $\pm$ 0.2%	351

$\Lambda(1600)\ P_{01}$

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 1560 to 1700 ($\approx$ 1600) MeV
Full width Γ = 50 to 250 ($\approx$ 150) MeV
p_{beam} = 0.58 GeV/c $4\pi\bar{\lambda}^2$ = 41.6 mb

Λ(1600) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\bar{K}$	15–30 %	343
$\Sigma\pi$	10–60 %	336

$\Lambda(1670)\ S_{01}$

$I(J^P) = 0(\frac{1}{2}^-)$

Mass $m = 1660$ to 1680 (≈ 1670) MeV
Full width $\Gamma = 25$ to 50 (≈ 35) MeV
$p_{beam} = 0.74$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 28.5$ mb

$\Lambda(1670)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	15–25 %	414
$\Sigma\pi$	20–60 %	393
$\Lambda\eta$	15–35 %	64

$\Lambda(1690)\ D_{03}$

$I(J^P) = 0(\frac{3}{2}^-)$

Mass $m = 1685$ to 1695 (≈ 1690) MeV
Full width $\Gamma = 50$ to 70 (≈ 60) MeV
$p_{beam} = 0.78$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 26.1$ mb

$\Lambda(1690)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	20–30 %	433
$\Sigma\pi$	20–40 %	409
$\Lambda\pi\pi$	~ 25 %	415
$\Sigma\pi\pi$	~ 20 %	350

$\Lambda(1800)\ S_{01}$

$I(J^P) = 0(\frac{1}{2}^-)$

Mass $m = 1720$ to 1850 (≈ 1800) MeV
Full width $\Gamma = 200$ to 400 (≈ 300) MeV
$p_{beam} = 1.01$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 17.5$ mb

$\Lambda(1800)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	25–40 %	528
$\Sigma\pi$	seen	493
$\Sigma(1385)\pi$	seen	345
$N\overline{K}^*(892)$	seen	†

$\Lambda(1810)\ P_{01}$

$I(J^P) = 0(\frac{1}{2}^+)$

Mass $m = 1750$ to 1850 (≈ 1810) MeV
Full width $\Gamma = 50$ to 250 (≈ 150) MeV
$p_{beam} = 1.04$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 17.0$ mb

$\Lambda(1810)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	20–50 %	537
$\Sigma\pi$	10–40 %	501
$\Sigma(1385)\pi$	seen	356
$N\overline{K}^*(892)$	30–60 %	†

$\Lambda(1820)\ F_{05}$

$I(J^P) = 0(\frac{5}{2}^+)$

Mass $m = 1815$ to 1825 (≈ 1820) MeV
Full width $\Gamma = 70$ to 90 (≈ 80) MeV
$p_{beam} = 1.06$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 16.5$ mb

$\Lambda(1820)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	55–65 %	545
$\Sigma\pi$	8–14 %	508
$\Sigma(1385)\pi$	5–10 %	362

$\Lambda(1830)\ D_{05}$

$I(J^P) = 0(\frac{5}{2}^-)$

Mass $m = 1810$ to 1830 (≈ 1830) MeV
Full width $\Gamma = 60$ to 110 (≈ 95) MeV
$p_{beam} = 1.08$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 16.0$ mb

$\Lambda(1830)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	3–10 %	553
$\Sigma\pi$	35–75 %	515
$\Sigma(1385)\pi$	>15 %	371

$\Lambda(1890)\ P_{03}$

$I(J^P) = 0(\frac{3}{2}^+)$

Mass $m = 1850$ to 1910 (≈ 1890) MeV
Full width $\Gamma = 60$ to 200 (≈ 100) MeV
$p_{beam} = 1.21$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 13.6$ mb

$\Lambda(1890)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	20–35 %	599
$\Sigma\pi$	3–10 %	559
$\Sigma(1385)\pi$	seen	420
$N\overline{K}^*(892)$	seen	233

$\Lambda(2100)\ G_{07}$

$I(J^P) = 0(\frac{7}{2}^-)$

Mass $m = 2090$ to 2110 (≈ 2100) MeV
Full width $\Gamma = 100$ to 250 (≈ 200) MeV
$p_{beam} = 1.68$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 8.68$ mb

$\Lambda(2100)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	25–35 %	751
$\Sigma\pi$	~ 5 %	704
$\Lambda\eta$	<3 %	617
ΞK	<3 %	483
$\Lambda\omega$	<8 %	443
$N\overline{K}^*(892)$	10–20 %	514

$\Lambda(2110)\ F_{05}$

$I(J^P) = 0(\frac{5}{2}^+)$

Mass $m = 2090$ to 2140 (≈ 2110) MeV
Full width $\Gamma = 150$ to 250 (≈ 200) MeV
$p_{beam} = 1.70$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 8.53$ mb

$\Lambda(2110)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	5–25 %	757
$\Sigma\pi$	10–40 %	711
$\Lambda\omega$	seen	455
$\Sigma(1385)\pi$	seen	589
$N\overline{K}^*(892)$	10–60 %	524

$\Lambda(2350)\ H_{09}$

$I(J^P) = 0(\frac{9}{2}^+)$

Mass $m = 2340$ to 2370 (≈ 2350) MeV
Full width $\Gamma = 100$ to 250 (≈ 150) MeV
$p_{beam} = 2.29$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 5.85$ mb

$\Lambda(2350)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	~ 12 %	915
$\Sigma\pi$	~ 10 %	867

Σ BARYONS
$(S=-1, I=1)$

Σ^+

$I(J^P) = 1(\frac{1}{2}^+)$

Mass $m = 1189.37 \pm 0.07$ MeV (S = 2.1)
Mean life $\tau = (0.799 \pm 0.004) \times 10^{-10}$ s
$c\tau = 2.395$ cm
Magnetic moment $\mu = 2.42 \pm 0.05\ \mu_N$ (S = 3.1)
$\Gamma(\Sigma^+ \to n\ell^+\nu)/\Gamma(\Sigma^- \to n\ell^-\overline{\nu}) < 0.043$

Decay parameters [e]

$p\pi^0$	$\alpha_0 = -0.980^{+0.017}_{-0.015}$
"	$\phi_0 = (36 \pm 34)^\circ$
"	$\gamma_0 = 0.16$
"	$\Delta_0 = (187 \pm 6)^\circ$
$n\pi^+$	$\alpha_+ = 0.068 \pm 0.013$
"	$\phi_+ = (167 \pm 20)^\circ$ (S = 1.1)
"	$\gamma_+ = -0.97$
"	$\Delta_+ = (-73^{+133}_{-10})^\circ$
$p\gamma$	$\alpha_\gamma = -0.83 \pm 0.12$

Σ^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$p\pi^0$		(51.57 ± 0.30) %		189
$n\pi^+$		(48.30 ± 0.30) %		185
$p\gamma$		$(1.25 \pm 0.07) \times 10^{-3}$		225
$n\pi^+\gamma$	[g]	$(4.5 \pm 0.5) \times 10^{-4}$		185
$\Lambda e^+\nu_e$		$(2.0 \pm 0.5) \times 10^{-5}$		71
$\Delta S = \Delta Q$ (*SQ*) or Flavor-Changing neutral current (*FC*) violating modes				
$ne^+\nu_e$	*SQ*	$< 5 \times 10^{-6}$	90%	224
$n\mu^+\nu_\mu$	*SQ*	$< 3.0 \times 10^{-5}$	90%	202
pe^+e^-	*FC*	$< 7 \times 10^{-6}$		225

Σ^0

$I(J^P) = 1(\frac{1}{2}^+)$

J^P not measured; assumed to be the same as for the Σ^+ and Σ^-.
Mass $m = 1192.55 \pm 0.10$ MeV (S = 1.4)
$m_{\Sigma^-} - m_{\Sigma^0} = 4.89 \pm 0.08$ MeV (S = 1.2)
$m_{\Sigma^0} - m_\Lambda = 76.92 \pm 0.10$ MeV (S = 1.4)
Mean life $\tau = (7.4 \pm 0.7) \times 10^{-20}$ s
$c\tau = 2.22 \times 10^{-11}$ m
Transition magnetic moment $|\mu_{\Sigma\Lambda}| = 1.61 \pm 0.08\ \mu_N$

Σ^0 DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\Lambda\gamma$		100 %		74
$\Lambda\gamma\gamma$		< 3 %	90%	74
Λe^+e^-	[i]	5×10^{-3}		74

Σ^-

$I(J^P) = 1(\frac{1}{2}^+)$

Mass $m = 1197.43 \pm 0.06$ MeV (S = 1.6)
$m_{\Sigma^-} - m_{\Sigma^+} = 8.07 \pm 0.09$ MeV (S = 1.9)
Mean life $\tau = (1.479 \pm 0.011) \times 10^{-10}$ s (S = 1.3)
$c\tau = 4.434$ cm
Magnetic moment $\mu = -1.160 \pm 0.025\ \mu_N$ (S = 1.7)

Decay parameters [e]

$n\pi^-$	$\alpha_- = -0.068 \pm 0.008$
"	$\phi_- = (10 \pm 15)^\circ$
"	$\gamma_- = 0.98$
"	$\Delta_- = (249^{+12}_{-120})^\circ$

Coupling constant ratios [f]

$ne^-\overline{\nu}_e$	$g_A/g_V = 0.340 \pm 0.017$
$\Lambda e^-\overline{\nu}_e$	$g_V/g_A = 0.01 \pm 0.10$ (S = 1.5)
"	$g_{WM}/g_A = 2.4 \pm 1.7$

Σ^- DECAY MODES		Fraction (Γ_i/Γ)	p (MeV/c)
$n\pi^-$		(99.848 ± 0.005) %	193
$n\pi^-\gamma$	[g]	$(4.6 \pm 0.6) \times 10^{-4}$	193
$ne^-\overline{\nu}_e$		$(1.017 \pm 0.034) \times 10^{-3}$	230
$n\mu^-\overline{\nu}_\mu$		$(4.5 \pm 0.4) \times 10^{-4}$	210
$\Lambda e^-\overline{\nu}_e$		$(5.73 \pm 0.27) \times 10^{-5}$	79

$\Sigma(1385)\ P_{13}$

$I(J^P) = 1(\frac{3}{2}^+)$

$\Sigma(1385)^+$ mass $m = 1382.8 \pm 0.4$ MeV (S = 2.0)
$\Sigma(1385)^0$ mass $m = 1383.7 \pm 1.0$ MeV (S = 1.4)
$\Sigma(1385)^-$ mass $m = 1387.2 \pm 0.5$ MeV (S = 2.2)
$\Sigma(1385)^+$ full width $\Gamma = 35.8 \pm 0.8$ MeV
$\Sigma(1385)^0$ full width $\Gamma = 36 \pm 5$ MeV
$\Sigma(1385)^-$ full width $\Gamma = 39.4 \pm 2.1$ MeV (S = 1.7)
Below $\overline{K}N$ threshold

$\Sigma(1385)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda\pi$	88 ± 2 %	208
$\Sigma\pi$	12 ± 2 %	127

$\Sigma(1660)\ P_{11}$

$I(J^P) = 1(\frac{1}{2}^+)$

Mass $m = 1630$ to 1690 (≈ 1660) MeV
Full width $\Gamma = 40$ to 200 (≈ 100) MeV
$p_{beam} = 0.72$ GeV/c $\quad 4\pi\lambda\!\!\!^-{}^2 = 29.9$ mb

$\Sigma(1660)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	10–30 %	405
$\Lambda\pi$	seen	439
$\Sigma\pi$	seen	385

$\Sigma(1670)\ D_{13}$

$I(J^P) = 1(\frac{3}{2}^-)$

Mass $m = 1665$ to 1685 (≈ 1670) MeV
Full width $\Gamma = 40$ to 80 (≈ 60) MeV
$p_{beam} = 0.74$ GeV/c $\quad 4\pi\lambda\!\!\!^-{}^2 = 28.5$ mb

$\Sigma(1670)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	7–13 %	414
$\Lambda\pi$	5–15 %	447
$\Sigma\pi$	30–60 %	393

$\Sigma(1750)\ S_{11}$

$I(J^P) = 1(\frac{1}{2}^-)$

Mass $m = 1730$ to 1800 (≈ 1750) MeV
Full width $\Gamma = 60$ to 160 (≈ 90) MeV
$p_{beam} = 0.91$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 20.7$ mb

$\Sigma(1750)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	10–40 %	486
$\Lambda\pi$	seen	507
$\Sigma\pi$	<8 %	455
$\Sigma\eta$	15–55 %	81

$\Sigma(1775)\ D_{15}$

$I(J^P) = 1(\frac{5}{2}^-)$

Mass $m = 1770$ to 1780 (≈ 1775) MeV
Full width $\Gamma = 105$ to 135 (≈ 120) MeV
$p_{beam} = 0.96$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 19.0$ mb

$\Sigma(1775)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	37–43%	508
$\Lambda\pi$	14–20%	525
$\Sigma\pi$	2–5%	474
$\Sigma(1385)\pi$	8–12%	324
$\Lambda(1520)\pi$	17–23%	198

$\Sigma(1915)\ F_{15}$

$I(J^P) = 1(\frac{5}{2}^+)$

Mass $m = 1900$ to 1935 (≈ 1915) MeV
Full width $\Gamma = 80$ to 160 (≈ 120) MeV
$p_{beam} = 1.26$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 12.8$ mb

$\Sigma(1915)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	5–15 %	618
$\Lambda\pi$	seen	622
$\Sigma\pi$	seen	577
$\Sigma(1385)\pi$	<5 %	440

$\Sigma(1940)\ D_{13}$

$I(J^P) = 1(\frac{3}{2}^-)$

Mass $m = 1900$ to 1950 (≈ 1940) MeV
Full width $\Gamma = 150$ to 300 (≈ 220) MeV
$p_{beam} = 1.32$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 12.1$ mb

$\Sigma(1940)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	<20 %	637
$\Lambda\pi$	seen	639
$\Sigma\pi$	seen	594
$\Sigma(1385)\pi$	seen	460
$\Lambda(1520)\pi$	seen	354
$\Delta(1232)\overline{K}$	seen	410
$N\overline{K}^*(892)$	seen	320

$\Sigma(2030)\ F_{17}$

$I(J^P) = 1(\frac{7}{2}^+)$

Mass $m = 2025$ to 2040 (≈ 2030) MeV
Full width $\Gamma = 150$ to 200 (≈ 180) MeV
$p_{beam} = 1.52$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 9.93$ mb

$\Sigma(2030)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	17–23 %	702
$\Lambda\pi$	17–23 %	700
$\Sigma\pi$	5–10 %	657
ΞK	<2 %	412
$\Sigma(1385)\pi$	5–15 %	529
$\Lambda(1520)\pi$	10–20 %	430
$\Delta(1232)\overline{K}$	10–20 %	498
$N\overline{K}^*(892)$	<5 %	438

$\Sigma(2250)$

$I(J^P) = 1(?^?)$

Mass $m = 2210$ to 2280 (≈ 2250) MeV
Full width $\Gamma = 60$ to 150 (≈ 100) MeV
$p_{beam} = 2.04$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 6.76$ mb

$\Sigma(2250)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	<10 %	851
$\Lambda\pi$	seen	842
$\Sigma\pi$	seen	803

Ξ BARYONS
($S=-2, I=1/2$)

Ξ^0

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

P not yet measured; + is the quark model prediction.
Mass $m = 1314.9 \pm 0.6$ MeV
$m_{\Xi^-} - m_{\Xi^0} = 6.4 \pm 0.6$ MeV
Mean life $\tau = (2.90 \pm 0.09) \times 10^{-10}$ s
$c\tau = 8.69$ cm
Magnetic moment $\mu = -1.250 \pm 0.014\ \mu_N$

Decay parameters [e]

$\Lambda\pi^0$	$\alpha = -0.411 \pm 0.022$ (S = 2.1)
"	$\phi = (21 \pm 12)^\circ$
"	$\gamma = 0.85$
"	$\Delta = (218^{+12}_{-19})^\circ$
$\Lambda\gamma$	$\alpha = 0.4 \pm 0.4$
$\Sigma^0\gamma$	$\alpha = 0.20 \pm 0.32$

Ξ^0 DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\Lambda\pi^0$		100 %		135
$\Lambda\gamma$		$(1.06\pm0.16) \times 10^{-3}$		184
$\Sigma^0\gamma$		$(3.6\ \pm0.4\ ) \times 10^{-3}$		117
$\Sigma^+e^-\overline{\nu}_e$		$< 1.1 \times 10^{-3}$	90%	120
$\Sigma^+\mu^-\overline{\nu}_\mu$		$< 1.1 \times 10^{-3}$	90%	64
$\Delta S = \Delta Q$ (SQ) or $\Delta S = 2$ (ΔS) violating modes				
$\Sigma^-e^+\nu_e$	SQ	$< 9 \times 10^{-4}$	90%	112
$\Sigma^-\mu^+\nu_\mu$	SQ	$< 9 \times 10^{-4}$	90%	49
$p\pi^-$	ΔS	$< 4 \times 10^{-5}$	90%	299
$pe^-\overline{\nu}_e$	ΔS	$< 1.3 \times 10^{-3}$		323
$p\mu^-\overline{\nu}_\mu$	ΔS	$< 1.3 \times 10^{-3}$		309

Ξ^-

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

P not yet measured; + is the quark model prediction.
Mass $m = 1321.32 \pm 0.13$ MeV
Mean life $\tau = (1.639 \pm 0.015) \times 10^{-10}$ s
$c\tau = 4.91$ cm
Magnetic moment $\mu = -0.6507 \pm 0.0025\ \mu_N$

Decay parameters [e]

$\Lambda\pi^-$	$\alpha = -0.456 \pm 0.014$ (S = 1.8)
"	$\phi = (4 \pm 4)^\circ$
"	$\gamma = 0.89$
"	$\Delta = (188 \pm 8)^\circ$

Coupling constant ratios [f]

$\Lambda e^-\overline{\nu}_e$ $\quad g_A/g_V = -0.25 \pm 0.05$

Ξ^- DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\Lambda\pi^-$	100 %		139
$\Sigma^-\gamma$	$(2.3\pm1.0) \times 10^{-4}$		118
$\Lambda e^-\overline{\nu}_e$	$(5.5\pm0.3) \times 10^{-4}$		190
$\Lambda\mu^-\overline{\nu}_\mu$	$(3.5\pm3.5) \times 10^{-4}$		163
$\Sigma^0e^-\overline{\nu}_e$	$(8.7\pm1.7) \times 10^{-5}$		122
$\Sigma^0\mu^-\overline{\nu}_\mu$	$< 8 \times 10^{-4}$	90%	70
$\Xi^0e^-\overline{\nu}_e$	$< 2.3 \times 10^{-3}$	90%	6

$\Delta S = 2$ (ΔS) violating modes

$n\pi^-$	ΔS	$< 1.9 \times 10^{-5}$	90%	303
$n e^- \overline{\nu}_e$	ΔS	$< 3.2 \times 10^{-3}$	90%	327
$n \mu^- \overline{\nu}_\mu$	ΔS	< 1.5 %	90%	314
$p\pi^-\pi^-$	ΔS	$< 4 \times 10^{-4}$	90%	223
$p\pi^- e^- \overline{\nu}_e$	ΔS	$< 4 \times 10^{-4}$	90%	304
$p\pi^- \mu^- \overline{\nu}_\mu$	ΔS	$< 4 \times 10^{-4}$	90%	250

$\Xi(1530)$ P_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$

$\Xi(1530)^0$ mass $m = 1531.80 \pm 0.32$ MeV (S = 1.3)
$\Xi(1530)^-$ mass $m = 1535.0 \pm 0.6$ MeV
$\Xi(1530)^0$ full width $\Gamma = 9.1 \pm 0.5$ MeV
$\Xi(1530)^-$ full width $\Gamma = 9.9^{+1.7}_{-1.9}$ MeV

Ξ(1530) DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\Xi\pi$	100 %		152
$\Xi\gamma$	<4 %	90%	200

$\Xi(1690)$

$I(J^P) = \frac{1}{2}(?^?)$

Mass $m = 1690 \pm 10$ MeV [h]
Full width $\Gamma < 50$ MeV

Ξ(1690) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda\overline{K}$	seen	240
$\Sigma\overline{K}$	seen	51
$\Xi^-\pi^+\pi^-$	possibly seen	214

$\Xi(1820)$ D_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$

Mass $m = 1823 \pm 5$ MeV [h]
Full width $\Gamma = 24^{+15}_{-10}$ MeV [h]

Ξ(1820) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda\overline{K}$	large	400
$\Sigma\overline{K}$	small	320
$\Xi\pi$	small	413
$\Xi(1530)\pi$	small	234

$\Xi(1950)$

$I(J^P) = \frac{1}{2}(?^?)$

Mass $m = 1950 \pm 15$ MeV [h]
Full width $\Gamma = 60 \pm 20$ MeV [h]

Ξ(1950) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda\overline{K}$	seen	522
$\Sigma\overline{K}$	possibly seen	460
$\Xi\pi$	seen	518

$\Xi(2030)$

$I(J^P) = \frac{1}{2}(\geq \frac{5}{2}^?)$

Mass $m = 2025 \pm 5$ MeV [h]
Full width $\Gamma = 20^{+15}_{-5}$ MeV [h]

Ξ(2030) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda\overline{K}$	~ 20 %	589
$\Sigma\overline{K}$	~ 80 %	533
$\Xi\pi$	small	573
$\Xi(1530)\pi$	small	421
$\Lambda\overline{K}\pi$	small	501
$\Sigma\overline{K}\pi$	small	430

Ω BARYONS
($S = -3$, $I = 0$)

Ω^-

$I(J^P) = 0(\frac{3}{2}^+)$

J^P not yet measured; $\frac{3}{2}^+$ is the quark model prediction.
Mass $m = 1672.43 \pm 0.32$ MeV
Mean life $\tau = (0.822 \pm 0.012) \times 10^{-10}$ s
$c\tau = 2.46$ cm
Magnetic moment $\mu = -1.94 \pm 0.22\ \mu_N$

Decay parameters

ΛK^- $\alpha = -0.026 \pm 0.026$
$\Xi^0\pi^-$ $\alpha = 0.09 \pm 0.14$
$\Xi^-\pi^0$ $\alpha = 0.05 \pm 0.21$

Ω^- DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
ΛK^-	(67.8±0.7) %		211
$\Xi^0\pi^-$	(23.6±0.7) %		294
$\Xi^-\pi^0$	(8.6±0.4) %		290
$\Xi^-\pi^+\pi^-$	$(4.3^{+3.4}_{-1.3}) \times 10^{-4}$		190
$\Xi(1530)^0\pi^-$	$(6.4^{+5.1}_{-2.0}) \times 10^{-4}$		17
$\Xi^0 e^- \overline{\nu}_e$	$(5.6\pm2.8) \times 10^{-3}$		319
$\Xi^-\gamma$	$< 2.2 \times 10^{-3}$	90%	314
$\Delta S = 2$ (ΔS) violating modes			
$\Lambda\pi^-$	ΔS $< 1.9 \times 10^{-4}$	90%	449

$\Omega(2250)^-$

$I(J^P) = 0(?^?)$

Mass $m = 2252 \pm 9$ MeV
Full width $\Gamma = 55 \pm 18$ MeV

$\Omega(2250)^-$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Xi^-\pi^+K^-$	seen	531
$\Xi(1530)^0 K^-$	seen	437

CHARMED BARYONS
($C = +1$)

Λ_c^+

$I(J^P) = 0(\frac{1}{2}^+)$

J not yet measured; $\frac{1}{2}$ is the quark model prediction.
Mass $m = 2284.9 \pm 0.6$ MeV
Mean life $\tau = (1.91^{+0.15}_{-0.12}) \times 10^{-13}$ s
$c\tau = 57\ \mu$m

Decay parameters

$\Lambda\pi^+$ $\alpha = -1.03 \pm 0.29$

Λ_c^+ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
Hadronic modes with a p and one K			
$p\overline{K}^0$	(1.6±0.4) %		872
$pK^-\pi^+$	(3.2±0.7) %		822
$p\overline{K}^*(892)^0$	[j] $(8.8\pm2.9) \times 10^{-3}$		681
$\Delta(1232)^{++}K^-$	$(6.6\pm3.0) \times 10^{-3}$		709
$p\overline{K}^0\pi^+\pi^-$	(1.7±0.6) %	1.2	753
$pK^-\pi^+\pi^0$	seen		758
$pK^*(892)^-\pi^+$	seen		579
$\Delta(1232)\overline{K}^*(892)$	seen		417
$pK^-\pi^+\pi^+\pi^-$	$(7 \pm5) \times 10^{-4}$		670
Modes with a p and zero or two K's			
$p\pi^+\pi^-$	$(2.2\pm1.3) \times 10^{-3}$		926
$pf_0(975)$	[j] $(1.8\pm1.2) \times 10^{-3}$		624
$p\pi^+\pi^+\pi^-\pi^-$	$(1.2\pm0.8) \times 10^{-3}$		851
pK^+K^-	$(1.6\pm0.9) \times 10^{-3}$		615
$p\phi$	[j] $(1.3\pm0.9) \times 10^{-3}$		589

Hadronic modes with a hyperon		
Λ anything	(27 ±9) %	–
$\Lambda\pi^+$	(5.8±1.6) × 10^{-3}	863
$\Lambda\pi^+\pi^+\pi^-$	(2.1±0.5) %	806
$\Sigma^0\pi^+$	(5.5±2.6) × 10^{-3}	824
$\Sigma^\pm$ anything	(10 ±5) %	–
$\Sigma^+\pi^+\pi^-$	(10 ±8) %	803
$\Xi^- K^+\pi^+$	(4.8±1.9) × 10^{-3}	564
Semileptonic modes		
e^+ anything	(4.5±1.7) %	–
pe^+ anything	(1.8±0.9) %	–
Λe^+ anything	(1.2±0.4) %	–
$\Lambda\mu^+$ anything	(1.1±0.7) %	–

$\Sigma_c(2455)$

$I(J^P) = 1(\frac{1}{2}^+)$

J^P not confirmed; $\frac{1}{2}^+$ is the quark model prediction.

$\Sigma_c(2455)^{++}$ mass $m = 2452.7 \pm 0.7$ MeV
$\Sigma_c(2455)^+$ mass $m = 2452.9 \pm 3.1$ MeV
$\Sigma_c(2455)^0$ mass $m = 2452.5 \pm 0.8$ MeV

$\Sigma_c(2455)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda_c^+\pi$	100 %	93

Ξ_c^+

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$I(J^P)$ not confirmed; $\frac{1}{2}(\frac{1}{2}^+)$ is the quark model prediction.

Mass $m = 2466.4 \pm 2.1$ MeV
Mean life $\tau = (3.0^{+1.0}_{-0.6}) \times 10^{-13}$ s (S = 1.1)
$c\tau = 90$ μm

Ξ_c^+ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda K^-\pi^+\pi^+$	seen	786
$\Sigma^+ K^-\pi^+$	seen	810
$\Sigma^0 K^-\pi^+\pi^+$	seen	734
$\Xi^-\pi^+\pi^+$	seen	850

Ξ_c^0

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$I(J^P)$ not confirmed; $\frac{1}{2}(\frac{1}{2}^+)$ is the quark model prediction.

Mass $m = 2472.7 \pm 1.7$ MeV
$m_{\Xi_c^0} - m_{\Xi_c^+} = 6.3 \pm 2.3$ MeV
Mean life $\tau = (0.82^{+0.59}_{-0.30}) \times 10^{-13}$ s
$c\tau = 25$ μm

Ξ_c^0 DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Xi^-\pi^+$	seen	876
$\Xi^-\pi^+\pi^+\pi^-$	seen	818
$pK^-\overline{K}^*(892)^0$	seen	410

BOTTOM (BEAUTY) BARYON ($B = -1$)

Λ_b^0

$I(J^P) = 0(\frac{1}{2}^+)$

$I(J^P)$ not yet measured; $0(\frac{1}{2}^+)$ is the quark model prediction.

Mass $m = 5641 \pm 50$ MeV

Λ_b^0 DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$J/\psi(1S)\Lambda$	seen	1756
$pD^0\pi^-$	seen	2383
$\Lambda_c^+\pi^+\pi^-\pi^-$	seen	2336

NOTES

This Summary Table only includes established baryons. The Full Listings include evidence for other baryons. The masses, widths, and branching fractions for the resonances in this Table are Breit-Wigner parameters. The Full Listings also give, where available, pole parameters. See, in particular, the *Note on N and Δ Resonances.*

For most of the resonances, the parameters come from various partial-wave analyses of more or less the same sets of data, and it is not appropriate to treat the results of the analyses as independent or to average them together. Furthermore, the systematic errors on the results are not well understood. Thus, we usually only give ranges for the parameters. We then also give a best guess for the mass (as part of the name of the resonance) and for the width. The *Note on N and Δ Resonances* and the *Note on Λ and Σ Resonances* in the Full Listings review the partial-wave analyses.

When a quantity has "(S = ...)" to its right, the error on the quantity has been enlarged by the "scale factor" S, defined as $S = \sqrt{\chi^2/(N-1)}$, where N is the number of measurements used in calculating the quantity. We do this when S > 1, which often indicates that the measurements are inconsistent. When S > 1.25, we also show in the Full Listings an ideogram of the measurements. For more about S, see the Introduction.

A decay momentum p is given for each decay mode. For a 2-body decay, p is the momentum of each decay product in the rest frame of the decaying particle. For a 3-or-more-body decay, p is the largest momentum any of the products can have in this frame. For any resonance, the *nominal* mass is used in calculating p. A dagger ("†") in this column indicates that the mode is forbidden when the nominal masses of resonances are used, but is in fact allowed due to the nonzero widths of the resonances.

[*a*] The masses of the p and n are most precisely known in u (unified atomic mass units). The conversion factor to MeV, 1 u = 931.49432 ± 0.00028 MeV, is less well known than are the masses in u.

[*b*] The limit is from neutrality-of-matter experiments; it assumes $q_n = q_p + q_e$. See also the charge of the neutron.

[*c*] The first limit is geochemical and independent of decay mode. The second limit assumes the dominant decay modes are among those investigated. For antiprotons the best limit, inferred from the observation of cosmic ray $\overline{p}$'s is $\tau_{\overline{p}} > 10^7$ yrs, the cosmic-ray storage time. The best direct observation of stored antiprotons gives $\tau_{\overline{p}} > 0.28$ yrs.

[*d*] There is some controversy about whether nuclear physics and model dependence complicate the analysis for bound neutrons (from which the best limit comes). For free neutrons the best limit is $> 10^7$ s.

[*e*] The decay parameters γ and Δ are calculated from α and ϕ using

$$\gamma = \sqrt{1-\alpha^2}\cos\phi \qquad \tan\Delta = -\frac{1}{\alpha}\sqrt{1-\alpha^2}\sin\phi$$

See the Note on Baryon Decay Parameters in the neutron Full Listings.

[*f*] The parameters g_A, g_V, and g_{WM} for semileptonic modes are defined by $\overline{B}_f[\gamma_\lambda(g_V + g_A\gamma_5) + i(g_{WM}/m_{B_i})\,\sigma_{\lambda\nu}\,q^\nu]B_i$, and ϕ_{AV} is defined by $g_A/g_V = |g_A/g_V|e^{i\phi_{AV}}$. See the Note on Baryon Decay Parameters in the neutron Full Listings.

[*g*] See the Full Listings for the pion momentum range used in this measurement.

[*h*] The error given here is only an educated guess. It is larger than the error on the weighted average of the published values.

[*i*] A theoretical value using QED; see the Full Listings.

[*j*] Includes all the decay modes of the resonances.

Searches Summary Table

SEARCHES FOR FREE QUARKS, MONOPOLES, SUPERSYMMETRY, COMPOSITENESS, etc.

Free Quark Searches

All searches since 1977 have had negative results.

Magnetic Monopole Searches

Isolated candidate events have not been confirmed. Most experiments obtain negative results.

Supersymmetric Particle Searches

Limits are based on the Minimal Supersymmetric Standard Model.

Assumptions include: 1) $\widetilde{\chi}_1^0$ (or $\widetilde{\gamma}$) is lightest supersymmetric particle; 2) R-parity is conserved; 3) mass of exchanged supersymmetric particles is less than about 250 GeV (most limits are not sensitive to this requirement); 4) $m(\widetilde{f}_L) = m(\widetilde{f}_R)$, and all scalar quarks (except $\widetilde{t}_L$ and $\widetilde{t}_R$) are degenerate in mass.

See the Full Listings for a Note giving details of supersymmetry.

$\widetilde{\chi}_i^0$ — neutralinos (mixtures of $\widetilde{\gamma}$, $\widetilde{Z}^0$, and $\widetilde{H}_i^0$)

Mass $m(\widetilde{\gamma}) > 15$ GeV, CL = 90% [if $m(\widetilde{f}) = 100$ GeV (from cosmology)]
Mass $m(\widetilde{\chi}_1^0) > 18$ GeV, CL = 90% [GUT relations assumed]
Mass $m(\widetilde{\chi}_2^0) > 45$ GeV, CL = 95% [GUT relations assumed]
Mass $m(\widetilde{\chi}_3^0) > 70$ GeV, CL = 95% [GUT relations assumed]
Mass $m(\widetilde{\chi}_4^0) > 108$ GeV, CL = 95% [GUT relations assumed]

$\widetilde{\chi}_i^\pm$ — charginos (mixtures of $\widetilde{W}^\pm$ and $\widetilde{H}_i^\pm$)

Mass $m(\widetilde{\chi}_1^\pm) > 45$ GeV, CL = 95% [if $m(\widetilde{\chi}_1^0) < 28$ GeV]
Mass $m(\widetilde{\chi}_2^\pm) > 99$ GeV, CL = 95% [GUT relations assumed]

$\widetilde{\nu}$ — scalar neutrino (sneutrino)

Mass $m >$ 31.4 GeV, CL = 95% [one flavor]
Mass $m >$ 39.4 GeV, CL = 95% [three degenerate flavors]

$\widetilde{e}$ — scalar electron (selectron)

Mass $m >$ 65 GeV, CL = 95% [if $m(\widetilde{\gamma}) = 0$]
Mass $m >$ 50 GeV, CL = 95% [if $m(\widetilde{\gamma}) < 5$ GeV]
Mass $m >$ 43.5 GeV, CL = 95% [if $m(\widetilde{\chi}_1^0) < 36$ GeV]

$\widetilde{\mu}$ — scalar muon (smuon)

Mass $m >$ 45 GeV, CL = 95% [if $m(\widetilde{\chi}_1^0) < 30$ GeV]

$\widetilde{\tau}$ — scalar tau (stau)

Mass $m >$ 43 GeV, CL = 95% [if $m(\widetilde{\chi}_1^0) < 23$ GeV]

$\widetilde{q}$ — scalar quark (squark)

These limits are based on the assumption B($\widetilde{q} \to q\widetilde{g}$ or $q\widetilde{\chi}_1^0$) = 1. For the best squark mass limits reported, this assumption is unrealistic and actual limits will be somewhat lower.

Mass $m >$ 74 GeV, CL = 90% [any $m(\widetilde{q})$]
Mass $m >$ 106 GeV, CL = 90% [if $m(\widetilde{g}) = m(\widetilde{q})$]

$\widetilde{g}$ — gluino

There is some controversy about a low-mass window ($1 \lesssim m(\widetilde{g}) \lesssim 4$ GeV). Several experiments cast doubt on the existence of this window.

These limits are based on the assumption B($\widetilde{g} \to q\overline{q}\widetilde{\chi}_1^0$) = 1. For the best gluino mass limits reported, this assumption is unrealistic and actual limits will be somewhat lower.

Mass $m >$ 79 GeV, CL = 90% [any $m(\widetilde{g})$]
Mass $m >$ 106 GeV, CL = 90% [if $m(\widetilde{q}) = m(\widetilde{g})$]

Searches for Quark and Lepton Compositeness

Scale Limits Λ for Contact Interactions (the lowest dimensional interactions with four fermions)

If the Lagrangian has the form

$$\pm \frac{g^2}{2\Lambda^2}\,\overline{\psi}_L\gamma_\mu\psi_L\overline{\psi}_L\gamma^\mu\,\psi_L$$

(with $g^2/4\pi$ set equal to 1), then we define $\Lambda \equiv \Lambda_{LL}^{\pm}$. For the full definitions and for other forms, see the Note in the Listings for Quark and Lepton Compositeness in the full-sized edition of the Review of Particle Properties and the original literature.

$\Lambda_{LL}^+(eeee)$ > 1.4 TeV, CL = 95%
$\Lambda_{LL}^-(eeee)$ > 3.3 TeV, CL = 95%
$\Lambda_{LL}^+(ee\mu\mu)$ > 4.4 TeV, CL = 95%
$\Lambda_{LL}^-(ee\mu\mu)$ > 2.1 TeV, CL = 95%
$\Lambda_{LL}^+(ee\tau\tau)$ > 2.2 TeV, CL = 95%
$\Lambda_{LL}^-(ee\tau\tau)$ > 3.2 TeV, CL = 95%
$\Lambda_{LL}^+(eeqq)$ > 1.7 TeV, CL = 95%
$\Lambda_{LL}^-(eeqq)$ > 2.2 TeV, CL = 95%
$\Lambda_{LL}^+(\mu\mu qq)$ > 1.4 TeV, CL = 95%
$\Lambda_{LL}^-(\mu\mu qq)$ > 1.6 TeV, CL = 95%
$\Lambda_{LR}^+(\mu\nu_\mu e\nu_e)$ > 3.1 TeV, CL = 90%
$\Lambda_{LR}^-(\mu\nu_\mu e\nu_e)$ > 3.1 TeV, CL = 90%
$\Lambda_{LL}^+(qqqq)$ > 0.825 TeV, CL = 95%
$\Lambda_{LL}^-(qqqq)$ > 0.825 TeV, CL = 95%

Excited Leptons

The limits from $\ell^{*+}\ell^{*-}$ do not depend on λ (where λ is the $\ell\ell^*$ transition coupling). The λ-dependent limits assume chiral coupling, except for the third limit for e^* which is for nonchiral coupling. For chiral coupling, this limit corresponds to $\lambda_\gamma = \sqrt{2}$.

$e^{*\pm}$ — excited electron

Mass $m >$ 46.1 GeV, CL = 95% (from $e^{*+}e^{*-}$)
Mass $m >$ 91 GeV, CL = 95% (if $\lambda_Z > 0.5$)
Mass $m >$ 116 GeV, CL = 95% (if $\lambda_\gamma = 1$)

$\mu^{*\pm}$ — excited muon

Mass $m >$ 46.1 GeV, CL = 95% (from $\mu^{*+}\mu^{*-}$)
Mass $m >$ 91 GeV, CL = 95% (if $\lambda_Z > 1$)

$\tau^{*\pm}$ — excited tau

Mass $m >$ 46.0 GeV, CL = 95% (from $\tau^{*+}\tau^{*-}$)
Mass $m >$ 90 GeV, CL = 95% (if $\lambda_Z > 1$)

ν^* — excited neutrino

Mass $m >$ 47 GeV, CL = 95% (from $\nu^*\overline{\nu}^*$)
Mass $m >$ 91 GeV, CL = 95% (if $\lambda_Z > 1$)

q^* — excited quark

Mass $m >$ 45 GeV, CL = 95% (from $q^*\overline{q}^*$)
Mass $m >$ 88 GeV, CL = 95% (if $\lambda_Z > 1$)

Color Sextet and Octet Particles

Color Sextet Quarks (q_6)

Mass $m >$ 84 GeV, CL = 95% (Stable q_6)

Color Octet Leptons (ℓ_8)

Mass $m >$ 110 GeV, CL = 90% ($\nu_8 \to \nu g$)

Tests of Conservation Laws

In keeping with the current interest in tests of conservation laws, we collect together a Table of experimental limits on all weak and electromagnetic decays, mass differences, and moments, and on a few reactions, whose observation would violate conservation laws. The Table is given only in the full *Review of Particle Properties*, not in the Data Booklet. For the benefit of Booklet readers, we include the best limits from the Table in the following text. The Table is in two parts: "Discrete Space-Time Symmetries," *i.e.*, C, P, T, CP, and CPT; and "Number Conservation Laws," *i.e.*, lepton, baryon, hadronic flavor, and charge conservation. The references for these data can be found in the the Full Listings in the *Review*. A discussion of these tests follows.

CPT INVARIANCE

General principles of relativistic field theory require invariance under the combined transformation CPT. The simplest tests of CPT invariance are the equality of the masses and lifetimes of a particle and its antiparticle. The best test comes from the limit on the mass difference between K^0 and $\overline{K}^0$. Any such difference contributes to the CP-violating parameter ϵ. Assuming CPT invariance, ϕ_ϵ, the phase of ϵ should be very close to 44°. (See the "Note on CP Violation in K^0_L Decay" in the Full Listings.) In contrast, if the entire source of CP violation in K^0 decays were a $K^0 - \overline{K}^0$ mass difference, ϕ_ϵ would be $44° + 90°$. It is possible to deduce that [1]

$$m_{\overline{K}^0} - m_{K^0} \approx \frac{2(m_{K^0_L} - m_{K^0_S})\,|\eta|\,(\frac{2}{3}\phi_{+-} + \frac{1}{3}\phi_{00} - \phi_\epsilon)}{\sin\phi_\epsilon} \; .$$

Using our best values of the CP-violation parameters, we get $|(m_{\overline{K}^0} - m_{K^0})/m_{K^0}| \leq 4 \times 10^{-18}$ (CL = 90%). Limits can also be placed on specific CPT-violating decay amplitudes. Given the small value of $(1 - |\eta_{00}/\eta_{+-}|)$, the value of $\phi_{00} - \phi_{+-}$ provides a measure of CPT violation in $K^0_L \to 2\pi$ decay. Results from CERN [1] and Fermilab [2] indicate no CPT-violating effect.

CP AND T INVARIANCE

Given CPT invariance, CP violation and T violation are equivalent. So far the only evidence for CP or T violation comes from the measurements of η_{+-}, η_{00}, and the semileptonic decay charge asymmetry for K_L, *e.g.*, $|\eta_{+-}| = |A(K^0_L \to \pi^+\pi^-)/A(K^0_S \to \pi^+\pi^-)| = (2.268 \pm 0.023) \times 10^{-3}$ and $[\Gamma(K^0_L \to \pi^-e^+\nu) - \Gamma(K^0_L \to \pi^+e^-\overline{\nu})]/[\text{sum}] = (0.333 \pm 0.014)\%$. Other searches for CP or T violation divide into (a) those that involve weak interactions or parity violation, and (b) those that involve processes allowed by the strong or electromagnetic interactions. In class (a) the most sensitive is probably the search for an electric dipole moment of the neutron, measured to be $< 1.2 \times 10^{-25}$ e cm (95% CL). A nonzero value requires both P and T violation. Class (b) includes the search for C violation in η decay, believed to be an electromagnetic process, *e.g.*, as measured by $\Gamma(\eta \to \mu^+\mu^-\pi^0)/\Gamma(\eta \to \text{all}) < 5 \times 10^{-6}$, and searches for T violation in a number of nuclear and electromagnetic reactions.

CONSERVATION OF LEPTON NUMBERS

Present experimental evidence and the standard electroweak theory are consistent with the absolute conservation of three separate lepton numbers: electron number L_e, muon number L_μ, and tau number L_τ. Searches for violations are of the following types:

a) $\Delta L = 2$ for one type of lepton. The best limit comes from the search for neutrinoless double beta decay $(Z, A) \to (Z+2, A) + e^- + e^-$. The best laboratory limit is $t_{1/2} > 1.3 \times 10^{24}$ yr (CL=68%) for ^{76}Ge.

b) Conversion of one lepton type to another. For purely leptonic processes, the best limits are on $\mu \to e\gamma$ and $\mu \to 3e$, measured as $\Gamma(\mu \to e\gamma)/\Gamma(\mu \to \text{all}) < 5 \times 10^{-11}$ and $\Gamma(\mu \to 3e)/\Gamma(\mu \to \text{all}) < 1.0 \times 10^{-12}$. For semileptonic processes, the best limit comes from the coherent conversion process in a muonic atom, $\mu^- + (Z, A) \to e^- + (Z, A)$, measured as $\Gamma(\mu^-\text{Ti} \to e^-\text{Ti})/\Gamma(\mu^-\text{Ti} \to \text{all}) < 5 \times 10^{-12}$. Of special interest is the case in which the hadronic flavor also changes, as in $K_L \to e\mu$ and $K^+ \to \pi^+e^-\mu^+$, measured as $\Gamma(K_L \to e\mu)/\Gamma(K_L \to \text{all}) < 0.9 \times 10^{-10}$ and $\Gamma(K^+ \to \pi^+e^-\mu^+)/\Gamma(K^+ \to \text{all}) < 2.1 \times 10^{-10}$. Limits on the conversion of τ into e or μ are found in τ decay and are much less stringent than those for $\mu \to e$ conversion, *e.g.*, $\Gamma(\tau \to \mu\gamma)/\Gamma(\tau \to \text{all}) < 5.5 \times 10^{-4}$ and $\Gamma(\tau \to e\gamma)/\Gamma(\tau \to \text{all}) < 2.0 \times 10^{-4}$.

c) Conversion of one type of lepton into another type of antilepton. The case most studied is $\mu^- + (Z, A) \to e^+ + (Z-2, A)$, the strongest limit being $\Gamma(\mu^-\text{Ti} \to e^+\text{Ca})/\Gamma(\mu^-\text{Ti} \to \text{all}) < 1.7 \times 10^{-10}$.

d) Relation to neutrino mass. If neutrinos have mass, then it is expected even in the standard electroweak theory that the lepton numbers are not separately conserved, as a consequence of lepton mixing analogous to Cabibbo quark mixing. However, in this case lepton-number-violating processes such as $\mu \to e\gamma$ are expected to have extremely small probability. For small neutrino masses, the lepton-number violation would be observed first in neutrino oscillations, which have been the subject of extensive experimental searches. For example, searches for $\overline{\nu}_e$ disappearance, which we label as $\overline{\nu}_e \not\to \overline{\nu}_e$, give measured limits $\Delta(m^2) < 0.0083$ eV^2 for $\sin^2(2\theta) = 1$, and $\sin^2(2\theta) < 0.14$ for large $\Delta(m^2)$, where θ is the neutrino mixing angle. Searches for $\nu_\mu \to \nu_e$ set limits $\Delta(m^2) < 0.09$ eV^2 for $\sin^2(2\theta) = 1$, and $\sin^2(2\theta) < 0.0034$ for large $\Delta(m^2)$. For larger neutrino masses ($\gg 1$ keV), lepton-number violation is searched for by looking for anomalous decays such as $\pi \to e\nu_x$, where ν_x is a massive neutrino. If the $\Delta L = 2$ type of violation occurs, it is expected that neutrinos will have a nonzero mass of the Majorana type.

CONSERVATION OF HADRONIC FLAVORS

In strong and electromagnetic interactions, hadronic flavor is conserved, *i.e.* the conversion of a quark of one flavor (d, u, s, c, b, t) into a quark of another flavor is forbidden. In the Standard Model, the weak interactions violate these conservation laws in a manner described by the Cabibbo-Kobayashi-Maskawa mixing (see the section "Cabibbo-Kobayashi-Maskawa Mixing Matrix"). The way in which these conservation laws are violated is tested as follows:

a) $\Delta S = \Delta Q$ rule. In the semileptonic decay of strange particles, the strangeness change equals the change in charge of the hadrons. Tests come from limits on decay rates such as $\Gamma(\Sigma^+ \to ne^+\nu)/\Gamma(\Sigma^+ \to \text{all}) < 5 \times 10^{-6}$, and from a detailed analysis of $K_L \to \pi e\nu$, which yields the parameter x, measured to be (Rex, Imx) = $(0.006 \pm 0.018, -0.003 \pm 0.026)$. Corresponding rules are $\Delta C = \Delta Q$ and $\Delta B = \Delta Q$.

b) Change of flavor by two units. In the Standard Model this occurs only in second-order weak interactions. The classic example is $\Delta S = 2$ $K^0 - \overline{K}^0$ mixing, which is directly measured by $m(K_S) - m(K_L) = (3.522 \pm 0.016) \times 10^{-12}$ MeV. There is now evidence for $B^0 - \overline{B}^0$ mixing ($\Delta B = 2$), with the corresponding mass difference between the eigenstates $|m_{B^0_1} - m_{B^0_2}| = (0.72 \pm 0.14)\ \Gamma_B = (3.6 \pm 0.7) \times 10^{-10}$ MeV. No evidence exists for $D^0 - \overline{D}^0$ mixing, which is expected to be much smaller in the Standard Model.

c) Flavor-changing neutral currents. In the Standard Model the neutral-current interactions do not change flavor. The low rate $\Gamma(K_L \to \mu^+\mu^-)/\Gamma(K_L \to \text{all}) = (7.3 \pm 0.4) \times 10^{-9}$ puts limits on such interactions; the nonzero value for this rate is attributed to a combination of the weak and electromagnetic interactions. The best test should come from a limit on $K^+ \to \pi^+\nu\overline{\nu}$, which occurs in the Standard Model only as a second-order weak process with a branching fraction of (1 to 8)$\times 10^{-10}$. The current limit is $\Gamma(K^+ \to \pi^+\nu\overline{\nu})/\Gamma(K^+ \to \text{all}) < 3.4 \times 10^{-8}$. Limits for charm-changing or bottom-changing neutral currents are much less stringent: $\Gamma(D^0 \to \mu^+\mu^-)/\Gamma(D^0 \to \text{all}) < 1.1 \times 10^{-5}$ and $\Gamma(B^0 \to \mu^+\mu^-)/\Gamma(B^0 \to \text{all}) < 1.2 \times 10^{-5}$.

Revised April 1992 by T.G. Trippe and L. Wolfenstein.

1. R. Carosi *et al.*, Phys. Lett. **B237**, 303 (1990).
2. M. Karlsson *et al.*, Phys. Rev. Lett. **64**, 2976 (1990).

Tests of Conservation Laws: Discrete Space-Time Symmetries

Quantity[a]		Value[b]	Symmetry tested or violated
$\pi^0 \to \gamma\gamma\gamma/\text{all}$		$< 3.1 \times 10^{-8}$	C
$(e^+e^-)_{J=0} \to 3\gamma/2\gamma$		$< 1 \times 10^{-5}$[c]	C
$(e^+e^-)_{J=1} \to 4\gamma/3\gamma$		$< 1 \times 10^{-5}$[c]	C
$\eta \to \gamma\gamma\gamma/\text{all}$		$< 5 \times 10^{-4}$	C
$\eta \to \pi^0 e^+e^-/\text{all}$		$< 4 \times 10^{-5}$	C (single photon process)
$\eta \to \pi^0 \mu^+\mu^-/\text{all}$		$< 5 \times 10^{-6}$	C (single photon process)
$\eta \to \pi^+\pi^-\pi^0$ parameters :	left-right asymmetry	$(0.9 \pm 1.7) \times 10^{-3}$	C
	sextant asymmetry	$(1.8 \pm 1.6) \times 10^{-3}$	C
	quadrant asymmetry	$(-1.7 \pm 1.7) \times 10^{-3}$	C
$\eta \to \pi^+\pi^-\gamma$ parameters:	left-right asymmetry	$(9 \pm 4) \times 10^{-3}$	C
	β (D-wave)	0.05 ± 0.06	C
$\eta \to \pi^+\pi^-/\text{all}$		$< 1.5 \times 10^{-3}$	P and CP
e electric dipole moment		$(-3 \pm 8) \times 10^{-27}$ e cm	T and P
μ electric dipole moment		$(3.7 \pm 3.4) \times 10^{-19}$ e cm	T and P
p electric dipole moment		$(-4 \pm 6) \times 10^{-23}$ e cm	T and P
n electric dipole moment		$< 1.2 \times 10^{-25}$ e cm	T and P
Λ electric dipole moment		$< 1.5 \times 10^{-16}$ e cm	T and P
α'/A from $\mu \to e\overline{\nu}\nu$		$(0 \pm 4) \times 10^{-3}$	T
β'/A from $\mu \to e\overline{\nu}\nu$		$(2 \pm 6) \times 10^{-3}$	T
e^+ pol.$\perp$ μ spin and e^+ mom. from $\mu^+ \to e^+\overline{\nu}\nu$		0.007 ± 0.023	T
Im ξ in $K^{\pm}_{\mu 3}$ decay (from transverse μ pol.)		-0.017 ± 0.025	T
Im ξ in $K^0_{\mu 3}$ decay (from transverse μ pol.)		-0.007 ± 0.026	T
ϕ, phase of g_A/g_V for n		$(180.07 \pm 0.18)^\circ$	T (0° or 180°)
n triple correlation coefficient		$(-5 \pm 14) \times 10^{-4}$	T
$\Sigma^- \to ne^-\overline{\nu}_e$ triple correlation coefficient		0.11 ± 0.10	T
$K^\pm \to \pi^\pm\pi^+\pi^-$ rate difference/average		$(0.07 \pm 0.12)\%$	CP
$K^\pm \to \pi^\pm 2\pi^0$ rate difference/average		$(0.0 \pm 0.6)\%$	CP
$K^\pm \to \pi^\pm\pi^0\gamma$ rate difference/average		$(0.9 \pm 3.3)\%$	CP
$K^\pm \to 3\pi^\pm$ slope $(g^+ - g^-)/\text{sum}$		$(-0.70 \pm 0.53)\%$	CP
$\lvert\eta_{+-0}\rvert^2 = \Gamma(K^0_S \to \pi^+\pi^-\pi^0,\ CP \text{ viol.})/\Gamma(K^0_L \to \pi^+\pi^-\pi^0)$		< 0.12	CP
$\lvert\eta_{000}\rvert^2 = \Gamma(K^0_S \to 3\pi^0)/\Gamma(K^0_L \to 3\pi^0)$		< 0.1	CP
$K^0_L \to \pi^0\nu\overline{\nu}/\text{all}$		$< 7.6 \times 10^{-3}$	CP[d]
$\quad \to \pi^0\mu^+\mu^-/\text{all}$		$< 1.2 \times 10^{-6}$	CP[e]
$\quad \to \pi^0 e^+e^-/\text{all}$		$< 5.5 \times 10^{-9}$	CP[e]
Charge asymmetry j in $K^0_L \to \pi^+\pi^-\pi^0$		0.0011 ± 0.0008	CP
$K^0_L \to (\pi^-\mu^+\nu - \pi^+\mu^-\overline{\nu})/\text{sum}$		$(0.304 \pm 0.025)\%$	CP (violated)
$\quad \to (\pi^-e^+\nu - \pi^+e^-\overline{\nu})/\text{sum}$		$(0.333 \pm 0.014)\%$	CP (violated)
$\lvert\eta_{00}\rvert = \lvert A(K^0_L \to \pi^0\pi^0)/A(K^0_S \to \pi^0\pi^0)\rvert$		$(2.253 \pm 0.024) \times 10^{-3}$	CP (violated)
$\lvert\eta_{+-}\rvert = \lvert A(K^0_L \to \pi^+\pi^-)/A(K^0_S \to \pi^+\pi^-)\rvert$		$(2.268 \pm 0.023) \times 10^{-3}$	CP (violated)
$\lvert\epsilon'/\epsilon\rvert = (1 - \lvert\eta_{00}/\eta_{+-}\rvert)/3$		$(2.2 \pm 1.1) \times 10^{-3}$	CP (violated)[f]
ϕ_{+-} : phase of η_{+-}		$(46.6 \pm 1.2)^\circ$	CP (violated)
ϕ_{00} : phase of η_{00}		$(46.6 \pm 2.0)^\circ$	CP (violated)
$(D^0 - \overline{D}^0) \to K^+K^-$ rate difference/sum		< 0.45	CP
$[\alpha_-(\Lambda) + \alpha_+(\overline{\Lambda})]/[\alpha_-(\Lambda) - \alpha_+(\overline{\Lambda})]$		-0.03 ± 0.06	CP
$(g_{e^+} - g_{e^-})/\text{average}$		$(-0.5 \pm 2.1) \times 10^{-12}$	CPT
$(g_{\mu^+} - g_{\mu^-})/\text{average}$		$(-2.6 \pm 1.6) \times 10^{-8}$	CPT
$(\mu_p - \lvert\mu_{\overline{p}}\rvert)/\text{average}$		$(-2.6 \pm 2.9) \times 10^{-3}$	CPT
$e^+ - e^-$ mass difference/average		$< 4 \times 10^{-8}$	CPT
$\pi^+ - \pi^-$ mass difference/average		$(2 \pm 5) \times 10^{-4}$	CPT
$K^+ - K^-$ mass difference/average		$(-0.6 \pm 1.8) \times 10^{-4}$	CPT
$\lvert K^0 - \overline{K}^0\rvert$ mass difference/average		$< 4 \times 10^{-18}$	CPT[g]
$\phi_{00} - \phi_{+-}$		$(0.1 \pm 1.9)^\circ$	CPT
$p - \overline{p}$ mass difference/average		$(2 \pm 4) \times 10^{-8}$	CPT
$n - \overline{n}$ mass difference/average		$(9 \pm 5) \times 10^{-5}$	CPT
$\Lambda - \overline{\Lambda}$ mass difference/average		$(0.0 \pm 1.1) \times 10^{-4}$	CPT
$\Xi^- - \overline{\Xi}^+$ mass difference/average		$(1.1 \pm 2.7) \times 10^{-4}$	CPT
$\Omega^- - \overline{\Omega}^+$ mass difference/average		$(-1 \pm 5) \times 10^{-4}$	CPT
$W^+ - W^-$ mass difference/average		$(-2 \pm 7) \times 10^{-3}$	CPT
$\mu^+ - \mu^-$ mean life difference/average		$(2 \pm 8) \times 10^{-5}$	CPT
$\pi^+ - \pi^-$ mean life difference/average		$(6 \pm 7) \times 10^{-4}$	CPT
$K^+ - K^-$ mean life difference/average		$(1.1 \pm 0.9) \times 10^{-3}$	CPT
$\Lambda - \overline{\Lambda}$ mean life difference/average		$(4 \pm 9) \times 10^{-2}$	CPT
$\Xi^- - \overline{\Xi}^+$ mean life difference/average		(0.02 ± 0.18)	CPT
$K^\pm \to \mu^\pm\nu$ rate difference/average		$(-0.54 \pm 0.41)\%$	CPT
$K^\pm \to \pi^\pm\pi^0$ rate difference/average		$(0.8 \pm 1.2)\%$	CPT[h]

Tests of Conservation Laws: Number Conservation Laws

Quantity[a]	Value[b]	Conservation law tested
$Z \to e^{\pm}\mu^{\mp}$/all	$< 2.4 \times 10^{-5}$	Lepton family number[j]
$\to e^{\pm}\tau^{\mp}$/all	$< 3.4 \times 10^{-5}$	" " "
$\to \mu^{\pm}\tau^{\mp}$/all	$< 4.8 \times 10^{-5}$	" " "
$\mu^- \to e^-\nu_e\overline{\nu}_\mu$/all	$< 1.8 \times 10^{-2}$[k]	" " "
$\to e^-\gamma$/all	$< 5 \times 10^{-11}$	" " "
$\to e^-e^+e^-$/all	$< 1.0 \times 10^{-12}$	" " "
$\to e^-\gamma\gamma$/all	$< 7 \times 10^{-11}$	" " "
$\mu^{-\,32}\text{S} \to e^{-\,32}\text{S}/(\mu^{-\,32}\text{S} \to \nu_\mu{}^{32}\text{P}^*)$	$< 7 \times 10^{-11}$	" " "
$\mu^-\text{Ti} \to e^-\text{Ti}$/(all μ^-Ti capture)	$< 5 \times 10^{-12}$	" " "
coupling for $(\mu^+e^- \to \mu^-e^+)_{\text{bound}}$	$< 0.16\ G_F$	" " "
$\tau^- \to$ (e^- chgd. particles + μ^- chgd. particles)/all	$< 4 \times 10^{-2}$	" " "
$\to \mu^-\gamma$/all	$< 5.5 \times 10^{-4}$	" " "
$\to e^-\gamma$/all	$< 2.0 \times 10^{-4}$	" " "
$\to \mu^-\pi^0$/all	$< 8.2 \times 10^{-4}$	" " "
$\to e^-\pi^0$/all	$< 1.4 \times 10^{-4}$	" " "
$\to \mu^-K^0$/all	$< 1.0 \times 10^{-3}$	" " "
$\to e^-K^0$/all	$< 1.3 \times 10^{-3}$	" " "
$\to \mu^-\rho^0$/all	$< 3.8 \times 10^{-5}$	" " "
$\to e^-\rho^0$/all	$< 3.9 \times 10^{-5}$	" " "
$\to e^-K^*(892)^0$/all	$< 5.4 \times 10^{-5}$	" " "
$\to \mu^-K^*(892)^0$/all	$< 5.9 \times 10^{-5}$	" " "
$\to e^-\eta$/all	$< 2.4 \times 10^{-4}$	" " "
$\to e^-e^+e^-$/all	$< 2.7 \times 10^{-5}$	" " "
$\to e^-\mu^+\mu^-$/all	$< 2.7 \times 10^{-5}$	" " "
$\to e^+\mu^-\mu^-$/all	$< 1.6 \times 10^{-5}$	" " "
$\to \mu^-e^+e^-$/all	$< 2.7 \times 10^{-5}$	" " "
$\to \mu^+e^-e^-$/all	$< 1.6 \times 10^{-5}$	" " "
$\to \mu^-\mu^+\mu^-$/all	$< 1.7 \times 10^{-5}$	" " "
$\to e^-\pi^+\pi^-$/all	$< 4.2 \times 10^{-5}$	" " "
$\to \mu^-\pi^+\pi^-$/all	$< 3.9 \times 10^{-5}$	" " "
$\to e^-\pi^+K^-$/all	$< 4.2 \times 10^{-5}$	" " "
$\to e^-\pi^-K^+$/all	$< 5.8 \times 10^{-5}$	" " "
$\to \mu^-\pi^+K^-$/all	$< 7.7 \times 10^{-5}$	" " "
$\to \mu^-\pi^-K^+$/all	$< 7.7 \times 10^{-5}$	" " "
$\to e^-$ + light spinless boson/all	$< 3.2 \times 10^{-3}$	" " "
$\to \mu^-$ + light spinless boson/all	$< 6.4 \times 10^{-3}$	" " "
$\pi^+ \to \mu^+\nu_e$/all	$< 8.0 \times 10^{-3}$[ℓ]	" " "
$\to \mu^-e^+e^+\nu$/all	$< 8 \times 10^{-6}$	" " "
$\pi^0 \to \mu^+e^-$/all	$< 1.6 \times 10^{-8}$	" " "
$K^+ \to \pi^+e^+\mu^-$/all	$< 7 \times 10^{-9}$	" " "
$\to \pi^+e^-\mu^+$/all	$< 2.1 \times 10^{-10}$	" " "
$\to \mu^-\nu e^+e^+$/all	$< 2 \times 10^{-8}$	" " "
$\to \mu^+\nu_e$/all	$< 4 \times 10^{-3}$[ℓ]	" " "
$K^0_L \to e^{\pm}\mu^{\mp}$/all	$< 9.4 \times 10^{-11}$	" " "
$D^+ \to \pi^+e^{\pm}\mu^{\mp}$/all	$< 3.8 \times 10^{-3}$	" " "
$\to \pi^+e^+\mu^-$/all	$< 3.3 \times 10^{-3}$	" " "
$\to \pi^+e^-\mu^+$/all	$< 3.3 \times 10^{-3}$	" " "
$\to K^+e^+\mu^-$/all	$< 3.4 \times 10^{-3}$	" " "
$\to K^+e^-\mu^+$/all	$< 3.4 \times 10^{-3}$	" " "
$D^0 \to e^{\pm}\mu^{\mp}$/all	$< 1.0 \times 10^{-4}$	" " "
$B^+ \to \pi^+e^+\mu^-$/all	$< 6.4 \times 10^{-3}$	" " "
$\to \pi^+e^-\mu^+$/all	$< 6.4 \times 10^{-3}$	" " "
$\to K^+e^+\mu^-$/all	$< 6.4 \times 10^{-3}$	" " "
$\to K^+e^-\mu^+$/all	$< 6.4 \times 10^{-3}$	" " "
$B^0 \to e^{\pm}\mu^{\mp}$/all	$< 4 \times 10^{-5}$	" " "
ν oscillations (For other lepton mixing effects in particle decays, see the Full Listings.)		
$\Delta(m^2)$ for $\sin^2(2\theta)$=1		
$\overline{\nu}_e \not\to \overline{\nu}_e$	< 0.0083 eV^2	" " "
$\nu_\mu \to \nu_e$	< 0.09 eV^2	" " "
$\overline{\nu}_\mu \to \overline{\nu}_e$	< 0.11 eV^2	" " "
$\nu_\mu \to \nu_\tau$	< 0.9 eV^2	" " "
$\overline{\nu}_\mu \to \overline{\nu}_\tau$	< 2.2 eV^2	" " "
$\nu_\mu \not\to \nu_\mu$	< 0.23 eV^2 or > 1500 eV^2	" " "
$\nu_e \not\to \nu_e$	< 2.3 eV^2	" " "
$\overline{\nu}_\mu \not\to \overline{\nu}_\mu$	< 7 eV^2 or > 1200 eV^2	" " "
$\nu_e \to \nu_\tau$	< 9 eV^2	" " "

Cont'd on next page

Tests of Conservation Laws: Number Conservation Laws (Cont'd)

Quantity[a]	Value[b]	Conservation law tested
ν oscillations (cont'd) (For other lepton mixing effects in particle decays, see the Full Listings.)		
$\sin^2(2\theta)$ for large $\Delta(m^2)$		
$\overline{\nu}_e \not\to \overline{\nu}_e$	< 0.14	Lepton family number[j]
$\nu_\mu \to \nu_e$	< 0.0034	" " "
$\overline{\nu}_\mu \to \overline{\nu}_e$	< 0.004	" " "
$\nu_\mu \to \nu_\tau$	< 0.004	" " "
$\overline{\nu}_\mu \to \overline{\nu}_\tau$	< 0.04	" " "
$\nu_\mu \not\to \nu_\mu$	< 0.02 [$\Delta(m^2) = 100$ eV^2]	" " "
$\nu_e \not\to \nu_e$	< 0.07	" " "
$\overline{\nu}_e \to \overline{\nu}_\tau$	< 0.7	" " "
$\overline{\nu}_\mu \not\to \overline{\nu}_\mu$	< 0.02 [190 eV$^2 < \Delta(m^2) <$ 320 eV^2]	" " "
$\nu_e \to \nu_\tau$	< 0.12	" " "
$\mu^- {}^{32}\text{S} \to e^+ {}^{32}\text{Si}^*$/all	$< 9 \times 10^{-10}$	Total lepton number[m]
$\mu^- {}^{127}\text{I} \to e^+ {}^{127}\text{Sb}^{\text{stable}}$/all	$< 3 \times 10^{-10}$	" " "
$\mu^- \text{Ti} \to e^+ \text{Ca}$/all	$< 1.7 \times 10^{-10}$	" " "
$\tau^- \to e^+ \pi^- \pi^-$/all	$< 1.7 \times 10^{-5}$	" " "
$\to \mu^+ \pi^- \pi^-$/all	$< 3.9 \times 10^{-5}$	" " "
$\to e^+ \pi^- K^-$/all	$< 4.9 \times 10^{-5}$	" " "
$\to \mu^+ \pi^- K^-$/all	$< 4.0 \times 10^{-5}$	" " "
$\pi^+ \to \mu^+ \overline{\nu}_e$/all	$< 1.5 \times 10^{-3}$ [ℓ]	" " "
$K^+ \to \pi^- e^+ e^+$/all	$< 1.0 \times 10^{-8}$	" " "
$\to \pi^- \mu^+ \mu^+$/all	$< 1.5 \times 10^{-4}$	" " "
$\to \pi^- e^+ \mu^+$/all	$< 7 \times 10^{-9}$	" " "
$\to \mu^+ \overline{\nu}_e$/all	$< 3.3 \times 10^{-3}$ [ℓ]	" " "
$\to e^+ \pi^0 \overline{\nu}_e$/all	$< 3.0 \times 10^{-3}$ [ℓ]	" " "
$B^+ \to \pi^- e^+ e^+$/all	$< 3.9 \times 10^{-3}$	" " "
$\to \pi^- \mu^+ \mu^+$/all	$< 9.1 \times 10^{-3}$	" " "
$\to \pi^- e^+ \mu^+$/all	$< 6.4 \times 10^{-3}$	" " "
$\to K^- e^+ e^+$/all	$< 3.9 \times 10^{-3}$	" " "
$\to K^- \mu^+ \mu^+$/all	$< 9.1 \times 10^{-3}$	" " "
$\to K^- e^+ \mu^+$/all	$< 6.4 \times 10^{-3}$	" " "
neutrinoless double beta decay	See the Full Listings.	" " "
A few examples of proton or bound neutron decay follow. For limits on many other nucleon decay channels, see the Baryon Summary Table.		
$\tau_p/\text{BR}(p \to e^+ \pi^0)$	$> 550 \times 10^{30}$ yr	Baryon number
$\tau_n/\text{BR}(n \to e^+ \pi^-)$	$> 130 \times 10^{30}$ yr	" "
$\tau_p/\text{BR}(p \to \mu^+ \pi^0)$	$> 270 \times 10^{30}$ yr	" "
$\tau_n/\text{BR}(n \to \mu^+ \pi^-)$	$> 100 \times 10^{30}$ yr	" "
$\tau_p/\text{BR}(p \to e^+ K^0)$	$> 150 \times 10^{30}$ yr	" "
$\tau_n/\text{BR}(n \to e^+ K^-)$	$> 1.3 \times 10^{30}$ yr	" "
$\tau_p/\text{BR}(p \to \mu^+ K^0)$	$> 120 \times 10^{30}$ yr	" "
$\tau_n/\text{BR}(n \to \mu^+ K^-)$	$> 1.1 \times 10^{30}$ yr	" "
mean time for $n \to \overline{n}$ transition	> 4 yr	" "
e mean life	$> 2 \times 10^{22}$ yr	Charge
$n \to p \nu \overline{\nu}$/all	$< 9 \times 10^{-24}$	" "
Re x from $K^0 \to \pi e \nu$	0.006 ± 0.018	$\Delta S = \Delta Q$[n]
Im x from $K^0 \to \pi e \nu$	-0.003 ± 0.026	" "
$K^+ \to \pi^+ \pi^+ e^- \overline{\nu}$/all	$< 1.2 \times 10^{-8}$	" "
$\to \pi^+ \pi^+ \mu^- \overline{\nu}$/all	$< 3.0 \times 10^{-6}$	" "
$\Sigma^+ \to n e^+ \nu$/all	$< 5 \times 10^{-6}$	" "
$\to n \mu^+ \nu$/all	$< 3.0 \times 10^{-5}$	" "
$(\Sigma^+ \to n \ell^+ \nu)/(\Sigma^- \to n \ell^- \overline{\nu})$	< 0.04	" "
$\Xi^0 \to \Sigma^- e^+ \nu$/all	$< 9 \times 10^{-4}$	" "
$\to \Sigma^- \mu^+ \nu$/all	$< 9 \times 10^{-4}$	" "
$\to p e^- \overline{\nu}$/all	$< 1.3 \times 10^{-3}$	$\Delta S = 2$ forbidden[n]
$\to p \mu^- \overline{\nu}$/all	$< 1.3 \times 10^{-3}$	" "
$\to p \pi^-$/all	$< 3.4 \times 10^{-5}$	" "
$\Xi^- \to n e^- \overline{\nu}$/all	$< 3.2 \times 10^{-3}$	" "
$\to n \mu^- \overline{\nu}$/all	$< 1.5 \times 10^{-2}$	" "
$\to p \pi^- e^- \overline{\nu}$/all	$< 4 \times 10^{-4}$	" "
$\to p \pi^- \mu^- \overline{\nu}$/all	$< 4 \times 10^{-4}$	" "
$\to n \pi^-$/all	$< 1.9 \times 10^{-5}$	" "
$\to p \pi^- \pi^-$/all	$< 4 \times 10^{-4}$	" "
$\Omega^- \to \Lambda \pi^-$/all	$< 1.9 \times 10^{-4}$	" "
$m_{K_L} - m_{K_S}$	$(3.522 \pm 0.016) \times 10^{-12}$ MeV	" "

Tests of Conservation Laws: Number Conservation Laws (Cont'd)

Quantity[a]	Value[b]	Conservation law tested
$(D^0 \to \overline{D}^0 \to \mu^-$ anything$)/(D^0 \to \mu^+$ anything$)$	< 0.0056	$\Delta C = 2$ forbidden[n]
$(D^0 \to \overline{D}^0 \to K^+\pi^-)/(D^0 \to K^-\pi^+)$	< 0.0037	" "
$\lvert m_{D^0_1} - m_{D^0_2}\rvert$ (from previous limit)	$< 1.3 \times 10^{-10}$ MeV	" "
$(B^0 \to \overline{B}^0 \to \mu^-$ anything$)/(B^0 \to \mu^\pm$ anything$)$	(0.16 ± 0.04)	$\Delta B = 2$ forbidden[n]
$\lvert m_{B^0_1} - m_{B^0_2}\rvert$ (from previous limit)	$(3.6 \pm 0.7) \times 10^{-10}$ MeV	" "
$K^0_L \to \mu^+\mu^-/$all	$(7.3 \pm 0.4) \times 10^{-9}$	no flav. chng. neut. curr.[e]
$\to e^+e^-/$all	$< 1.6 \times 10^{-10}$	" " " " "
$\to \mu^+\mu^-\gamma/$all	$(2.8 \pm 2.8) \times 10^{-7}$	" " " " "
$\to e^+e^-\gamma/$all	$(9.1 \pm 0.5) \times 10^{-6}$	" " " " "
$\to \pi^0\mu^+\mu^-/$all	$< 1.2 \times 10^{-6}$	" " " " "
$\to \pi^0e^+e^-/$all	$< 5.5 \times 10^{-9}$	" " " " "
$\to \pi^0\nu\overline{\nu}/$all	$< 7.6 \times 10^{-3}$	" " " " "
$\to e^+e^-\gamma\gamma/$all	$(6.6 \pm 3.2) \times 10^{-7}$	" " " " "
$\to \pi^+\pi^-e^+e^-/$all	$< 2.5 \times 10^{-6}$	" " " " "
$\to \mu^+\mu^-e^+e^-/$all	$< 4.9 \times 10^{-6}$	" " " " "
$\to e^+e^-e^+e^-/$all	$(4 \pm 3) \times 10^{-8}$	" " " " "
$K^0_S \to \mu^+\mu^-/$all	$< 3.2 \times 10^{-7}$	" " " " "
$\to e^+e^-/$all	$< 1.0 \times 10^{-5}$	" " " " "
$\to \pi^0e^+e^-/$all	$< 4.5 \times 10^{-5}$	" " " " "
$K^+ \to \pi^+e^+e^-/$all	$(2.7 \pm 0.5) \times 10^{-7}$	" " " " "
$\to \pi^+\mu^+\mu^-/$all	$< 2.3 \times 10^{-7}$	" " " " "
$\to \pi^+\nu\overline{\nu}/$all	$< 3.4 \times 10^{-8}$	" " " " "
$D^0 \to e^+e^-/$all	$< 1.3 \times 10^{-4}$	" " " " "
$\to \mu^+\mu^-/$all	$< 1.1 \times 10^{-5}$	" " " " "
$\to \rho^0e^+e^-/$all	$< 4.5 \times 10^{-4}$	" " " " "
$\to \rho^0\mu^+\mu^-/$all	$< 8.1 \times 10^{-4}$	" " " " "
$D^+ \to \pi^+e^+e^-/$all	$< 2.5 \times 10^{-3}$	" " " " "
$\to \pi^+\mu^+\mu^-/$all	$< 2.9 \times 10^{-3}$	" " " " "
$B^0 \to \mu^+\mu^-/$all	$< 1.2 \times 10^{-5}$	" " " " "
$\to e^+e^-/$all	$< 3 \times 10^{-5}$	" " " " "
$\to K^0\mu^+\mu^-/$all	$< 4.5 \times 10^{-4}$	" " " " "
$\to K^0e^+e^-/$all	$< 3.0 \times 10^{-4}$	" " " " "
$\to K^*(892)^0e^+e^-/$all	$< 2.9 \times 10^{-4}$	" " " " "
$\to K^*(892)^0\mu^+\mu^-/$all	$< 2.3 \times 10^{-5}$	" " " " "
$B^+ \to \pi^+e^+e^-/$all	$< 3.9 \times 10^{-3}$	" " " " "
$\to \pi^+\mu^+\mu^-/$all	$< 9.1 \times 10^{-3}$	" " " " "
$\to K^+\mu^+\mu^-/$all	$< 1.5 \times 10^{-4}$	" " " " "
$\to K^+e^+e^-/$all	$< 5 \times 10^{-5}$	" " " " "
$\to K^*(892)^+e^+e^-/$all	$< 6.3 \times 10^{-4}$	" " " " "
$\to K^*(892)^+\mu^+\mu^-/$all	$< 1.1 \times 10^{-3}$	" " " " "
$B \to (e^+e^-$ anything$)/$all	$< 2.4 \times 10^{-3}$	" " " " "
$\to (\mu^+\mu^-$ anything$)/$all	$< 5 \times 10^{-5}$	" " " " "
$\Sigma^+ \to pe^+e^-/$all	$< 7 \times 10^{-6}$	" " " " "

a. Branching fractions are described by a shorthand notation, *e.g.*, "$\mu^+ \to e^+\gamma/$all" means $\Gamma(\mu^+ \to e^+\gamma)/\Gamma(\mu^+ \to$ all$)$.
b. Limits are given at the 90% confidence level, while errors are given as ± 1 standard deviation.
c. Positronium data are from A.P. Mills and S. Berko, Phys. Rev. Lett. **18**, 420 (1967); and K. Marko and A. Rich, Phys. Rev. Lett. **33**, 980 (1974). Values for 90% confidence limit are from A.P. Mills, private communication.
d. Violates CP in leading order, since the indirect CP-violating and CP-conserving contributions are expected to be suppressed.
e. Allowed by higher-order electroweak interactions.
f. Derived from measured values of $\lvert\eta_{00}\rvert$ and $\lvert\eta_{+-}\rvert$, and theoretical input on phases. See the "Note on CP Violation" in the K^0_L Full Listings.
g. Derived from measured values of ϕ_{+-}, ϕ_{00}, $\lvert\eta\rvert$, $\tau_{K^0_S}$, and $\lvert m_{K^0_L} - m_{K^0_S}\rvert$, as described in the introduction to this Table.
h. Neglecting photon channels. See, *e.g.*, A. Pais and S.B. Treiman, Phys. Rev. **D12**, 2744 (1975).
j. Lepton family number conservation means separate conservation of each of L_e, L_μ, and L_τ.
k. A test of additive vs. multiplicative lepton family number conservation.
ℓ. Derived from the analysis of neutrino oscillation experiments.
m. Violation of total lepton number conservation also implies violation of lepton family number conservation.
n. Can be violated in second-order weak interactions.

MISCELLANEOUS TABLES, FIGURES, AND FORMULAE

PHYSICAL CONSTANTS

Reviewed 1991 by B.N. Taylor. Based mainly on the "1986 Adjustment of the Fundamental Physical Constants" by E.R. Cohen and B.N. Taylor, Rev. Mod. Phys. **59**, 1121 (1987). The figures in parentheses after the values give the 1-standard-deviation uncertainties in the last digits; the uncertainties in parts per million (ppm) are given in the last column. The uncertainties of the values from a least-squares adjustment are in general correlated, and the laws of error propagation must be used in calculating additional quantities; the full variance matrix is given in the cited paper. The set of constants resulting from the 1986 adjustment has been recommended for international use by CODATA (Committee on Data for Science and Technology).

Since the 1986 adjustment, new experiments have yielded improved values for a number of constants, including the Rydberg constant R_∞, the Planck constant h, the fine-structure constant α, and the molar gas constant R, and hence also for constants directly derived from these, such as the Boltzmann constant k and Stefan-Boltzmann constant σ. The new results and their impact on the 1986 recommended values are discussed extensively in "Recommended Values of the Fundamental Physical Constants: A Status Report," B.N. Taylor and E.R. Cohen, J. Res. Natl. Inst. Stand. Technol. **95**, 497 (1990). In general, the new results give uncertainties for the affected constants that are 5 to 7 times smaller than the 1986 uncertainties, but the changes in the values themselves are smaller than twice the 1986 uncertainties. Until there are more experiments and a complete readjustment of the constants, the 1986 CODATA set, given (in part) below, remains the set of choice.

Quantity	Symbol, equation	Value	Uncert. (ppm)
speed of light	c	299 792 458 m s^{-1}	(exact)*
Planck constant	h	$6.626\,075\,5(40)\times10^{-34}$ J s	0.60
Planck constant, reduced	$\hbar \equiv h/2\pi$	$1.054\,572\,66(63)\times10^{-34}$ J s	0.60
		$= 6.582\,122\,0(20)\times10^{-22}$ MeV s	0.30
electron charge magnitude	e	$1.602\,177\,33(49)\times10^{-19}$ C $= 4.803\,206\,8(15)\times10^{-10}$ esu	0.30, 0.03
conversion constant	$\hbar c$	197.327 053(59) MeV fm	0.30
conversion constant	$(\hbar c)^2$	0.389 379 66(23) GeV^2 mbarn	0.59
electron mass	m_e	0.510 999 06(15) MeV/c^2 $= 9.109\,389\,7(54)\times10^{-31}$ kg	0.30, 0.59
proton mass	m_p	938.272 31(28) MeV/c^2 $= 1.672\,623\,1(10)\times10^{-27}$ kg	0.30, 0.59
		$= 1.007\,276\,470(12)$ u $= 1836.152\,701(37)\ m_e$	0.012, 0.020
deuteron mass	m_d	1875.613 39(57) MeV/c^2	0.30
unified atomic mass unit (u)	(mass C^{12} atom)/12 = (1 g)/N_A	931.494 32(28) MeV/c^2 $= 1.660\,540\,2(10)\times10^{-27}$ kg	0.30, 0.59
permittivity of free space	ϵ_0 } $\epsilon_0\mu_0 = 1/c^2$	$8.854\,187\,817\ldots\times10^{-12}$ F m^{-1}	(exact)
permeability of free space	μ_0 }	$4\pi\times10^{-7}$ N A^{-2} $= 12.566\,370\,614\ldots\times10^{-7}$ N A^{-2}	(exact)
fine-structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	1/137.035 989 5(61)†	0.045
classical electron radius	$r_e = e^2/4\pi\epsilon_0 m_e c^2$	$2.817\,940\,92(38)\times10^{-15}$ m	0.13
electron Compton wavelength	$\lambda\!\!\!^-_e = \hbar/m_e c = r_e\alpha^{-1}$	$3.861\,593\,23(35)\times10^{-13}$ m	0.089
Bohr radius ($m_{\rm nucleus} = \infty$)	$a_\infty = 4\pi\epsilon_0\hbar^2/m_e e^2 = r_e\alpha^{-2}$	$0.529\,177\,249(24)\times10^{-10}$ m	0.045
wavelength of 1 eV/c particle	hc/e	$1.239\,842\,44(37)\times10^{-6}$ m	0.30
Rydberg energy	$hcR_\infty = m_e e^4/2(4\pi\epsilon_0)^2\hbar^2 = m_e c^2\alpha^2/2$	13.605 698 1(40) eV	0.30
Thomson cross section	$\sigma_T = 8\pi r_e^2/3$	0.665 246 16(18) barn	0.27
Bohr magneton	$\mu_B = e\hbar/2m_e$	$5.788\,382\,63(52)\times10^{-11}$ MeV T^{-1}	0.089
nuclear magneton	$\mu_N = e\hbar/2m_p$	$3.152\,451\,66(28)\times10^{-14}$ MeV T^{-1}	0.089
electron cyclotron freq./field	$\omega^e_{\rm cycl}/B = e/m_e$	$1.758\,819\,62(53)\times10^{11}$ rad s^{-1} T^{-1}	0.30
proton cyclotron freq./field	$\omega^p_{\rm cycl}/B = e/m_p$	$9.578\,830\,9(29)\times10^{7}$ rad s^{-1} T^{-1}	0.30
gravitational constant	G_N	$6.672\,59(85)\times10^{-11}$ m^3 kg^{-1} s^{-2}	128
		$= 6.707\,11(86)\times10^{-39}\ \hbar c\ ({\rm GeV}/c^2)^{-2}$	128
standard grav. accel., sea level	g	9.806 65 m s^{-2}	(exact)
Avogadro number	N_A	$6.022\,136\,7(36)\times10^{23}$ mol^{-1}	0.59
Boltzmann constant	k	$1.380\,658(12)\times10^{-23}$ J K^{-1}	8.5
		$= 8.617\,385(73)\times10^{-5}$ eV K^{-1}	8.4
Wien displacement law constant	$b = \lambda_{\rm max}T$	$2.897\,756(24)\times10^{-3}$ m K	8.4
molar volume, ideal gas at STP	$N_A k$(273.15 K)/(1 atmosphere)	$22.414\,10(19)\times10^{-3}$ m^3 mol^{-1}	8.4
Stefan-Boltzmann constant	$\sigma = \pi^2k^4/60\hbar^3c^2$	$5.670\,51(19)\times10^{-8}$ W m^{-2} K^{-4}	34
Fermi coupling constant	$G_F/(\hbar c)^3$	$1.166\,39(2)\times10^{-5}$ GeV^{-2}	17
weak mixing angle	$\sin^2\theta_W$ ($\overline{\rm MS}$)	0.2325±0.0008	3441
$W^\pm$ boson mass	m_W	80.22±0.26 GeV/c^2	3241
Z^0 boson mass	m_Z	91.173±0.020 GeV/c^2	219
strong coupling constant	$\alpha_s(m_Z)$	0.1134±0.0035	3.1×10^4

$\pi = 3.141\,592\,653\,589\,793\,238$ $\qquad e = 2.718\,281\,828\,459\,045\,235$ $\qquad \gamma = 0.577\,215\,664\,901\,532\,861$

1 in ≡ 0.0254 m	1 barn ≡ 10^{-28} m^2	1 eV = $1.602\,177\,33(49)\times10^{-19}$ J	1 gauss (G) ≡ 10^{-4} tesla (T)
1 Å ≡ 10^{-10} m	1 dyne ≡ 10^{-5} newton (N)	1 eV/c^2 = $1.782\,662\,70(54)\times10^{-36}$ kg	0° C ≡ 273.15 K
1 fm ≡ 10^{-15} m	1 erg ≡ 10^{-7} joule (J)	$2.997\,924\,58\times10^{9}$ esu = 1 coulomb (C)	1 atmosphere ≡ 760 torr ≡ $1.013\,25\times10^{5}$ N/m^2

* The meter is now defined to be the length of the path traveled by light in 1/299792458 second. See B.W. Petley, Nature **303**, 373 (1983).

† At $Q^2 = m_e^2$. At $Q^2 \approx m_W^2$ the value is approximately 1/128.

ASTROPHYSICAL CONSTANTS

Quantity	Symbol, equation	Value
Newtonian gravitational constant	G_N	$6.672\,59(85) \times 10^{-11}$ m^3 kg^{-1} s^{-2}
astronomical unit	AU	$1.495\,978\,706\,6(2) \times 10^{11}$ m
Planck mass	$\sqrt{\hbar c/G_N}$	$1.221\,047(79) \times 10^{19}$ GeV/c^2 $= 2.176\,71(14) \times 10^{-8}$ kg
tropical year (1900)†	yr	$31\,556\,925.974\,7$ s
mean sidereal day		$23^{\rm h}\,56^{\rm m}\,04\overset{\rm s}{.}090\,53$
parsec (1 AU/1 arc sec)	pc	$3.085\,677\,580\,6 \times 10^{16}$ m
light year	ly	$0.306\,6$ pc $= 0.946 \times 10^{16}$ m
solar mass	$M_\odot$	$1.988\,92(25) \times 10^{30}$ kg
Schwarzschild radius of the sun	$2G_N M_\odot/c^2$	$2.953\,250\,074$ km
solar luminosity	$L_\odot$	$3.826(8) \times 10^{26}$ J s^{-1}
solar equatorial radius	$R_\odot$	$6.959\,9(7) \times 10^8$ m

Quantity	Symbol	Value
earth equatorial radius	$R_\oplus$	$6.378\,140 \times 10^6$ m
$v_\odot$ around center of galaxy		220 (20) km s^{-1}
solar radius in galaxy		8.5 kpc
local density of matter	$\rho_{\rm local}$	0.3 GeV/c^2 cm$^{-3$} $\approx 3 \times 10^4\ \rho_c$
Hubble parameter‡	H_0	$100\ h_0$ km s^{-1} Mpc^{-1} $h_0 \times (0.977\,81 \times 10^{10}\,{\rm yr})^{-1}$
normalized Hubble parameter‡	h_0	$0.4 < h_0 < 1$
critical density of the universe‡	$\rho_c = 3H_0^2/8\pi G_N$	$2.775\,366\,273 \times 10^{11}\ h_0^2\ M_\odot{\rm Mpc}^{-3}$ $= 1.878\,82(24) \times 10^{-29}\ h_0^2$ g cm^{-3}
density parameter of the universe‡	$\Omega_0 \equiv \rho_0/\rho_c$	$0.05 < \Omega_0 < 4$
cosmological constant	Λ	$\lvert\Lambda\rvert < 3 \times 10^{-52}$ m^{-2}
age of the universe‡	t_0	$1.5(5) \times 10^{10}$ yr

Compiled with the help of K.A. Olive, J. Primack, S. Rudaz, and E. M. Standish, Jr. Some values are taken from C.W. Allen, *Astrophysical Quantities* (Athlone Press, London, 1973) and *The Astronomical Almanac for the year 1990* (U.S. Government Printing Office, Washington, and Her Majesty's Stationery Office, London).

† Equinox to equinox; defining constant. The 1990 value is about 0.7 s less.

‡ Subscript 0 indicates present-day values.

BIG-BANG COSMOLOGY

All observational evidence to date indicates that our universe is very nearly homogeneous and isotropic. The most general space-time interval with these properties is the Friedmann-Robertson-Walker metric (with $c = 1$):

$$ds^2 = dt^2 - R^2(t)\left[\frac{dr^2}{1-\kappa r^2} + r^2\,(d\theta^2 + \sin^2\theta\,d\phi^2)\right] ,$$

where $\kappa = +1$, -1, or 0 corresponds to closed, open, or spatially flat geometries; $R(t)$ is a scale factor for distances in comoving coordinates. Einstein's equations lead to the Friedmann equation

$$H^2 \equiv \left(\frac{\dot R}{R}\right)^2 = \frac{8\pi\,G_N\,\rho}{3} - \frac{\kappa}{R^2} + \frac{\Lambda}{3} ,$$

as well as to

$$\frac{\ddot R}{R} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3}\ (\rho + 3p) ,$$

where $H(t)$ is the Hubble parameter, ρ is the total mass-energy density, p is the isotropic pressure, and Λ is the cosmological constant. (For limits on Λ, see the Table of Astrophysical Constants; we will assume here $\Lambda = 0$.) The Friedmann equation serves to define the density parameter Ω_0 (subscript 0 indicates present-day values):

$$\kappa/R_0^2 = H_0^2(\Omega_0 - 1) , \qquad \Omega_0 = \rho_0/\rho_c ;$$

and the critical density is defined as

$$\rho_c \equiv \frac{3H_0^2}{8\pi\,G_N} = 1.88 \times 10^{-26}\,h_0^2 \text{ kg m}^{-3} ,$$

with

$$H_0 = 100 h_0 \text{ km s}^{-1}\text{ Mpc}^{-1} .$$

Observational bounds give $0.4 < h_0 < 1$. The three possible values of κ, $+1$, -1, and 0, correspond to $\Omega_0 > 1$, < 1, and $= 1$, i.e., to closed, open, and flat (critical) universes. The value of Ω_0 is inferred from velocity measurements on scales greater than 100 kpc, which are all consistent with $0.1 \lesssim \Omega_0 \lesssim 0.4$. Conservative bounds are $0.05 \le \Omega_0 \le 4$. The portion of Ω in luminous matter is much smaller, $0.005 \le \Omega_{\rm lum} \le 0.02$. The excess of Ω_0 over $\Omega_{\rm lum}$ leads to the inference that most of the matter in the universe is nonluminous "dark" matter.

Energy conservation implies that $\dot\rho = -3(\dot R/R)\ (\rho + p)$, so that for a matter-dominated ($p = 0$) universe $\rho \propto R^{-3}$, while for a radiation-dominated ($p = 1/3\rho$) universe $\rho \propto R^{-4}$. Thus the less singular curvature term κ/R^2 in the Friedmann equation can be neglected at early times when R is small. Energy conservation also implies that the universe expands adiabatically, $R^3 s$ = constant, where the entropy density $s = (\rho + p)/T$ and T is temperature. The energy density of radiation can be expressed as

$$\rho_r = \frac{\pi^2 k^4}{30}\ N(T) T^4 ,$$

with $\hbar = 1$, where $N(T)$ counts the effectively massless degrees of freedom of bosons and fermions:

$$N(T) = \sum_B g_B + \frac{7}{8}\sum_F g_F .$$

For example, for $m_\mu > kT > m_e$, $N(T) = g_\gamma + 7/8\,(g_e + 3g_\nu) = 2 + 7/8\,[4 + 3(2)] = 43/4$. For $m_\pi > kT > m_\mu$, $N(T) = 57/4$.

In the early universe when $\rho \sim \rho_r$, then $\dot R \sim 1/R$, so that $R \propto t^{1/2}$ and $Ht \to 1/2$; the time-temperature relation then follows:

$$t = 2.4\,[N(T)]^{-1/2}\left(\frac{1\text{ MeV}}{kT}\right)^2 \text{ s} .$$

Today, the energy density in photons is $\rho_\gamma = (\pi^2 k^4/15) T_0^4$, where the present temperature of the microwave background is $T_0 = 2.736 \pm 0.017$K, and the number density of photons n_γ is $400\,(T_0/2.7\text{ K})^3$ cm^{-3}. For nonrelativistic matter (such as baryons) today, the energy density is $\rho_B = m_B n_B$ with $n_B \propto R^{-3}$, so that for most of the history of the universe n_B/s is constant. Today, the entropy density is related to the photon density by $s \approx 7 n_\gamma$. Big Bang nucleosynthesis calculations limit $\eta = n_B/n_\gamma$ to $2.8 \times 10^{-10} \le \eta \le 4.0 \times 10^{-10}$. The parameter η is also related to the portion of Ω in baryons

$$\Omega_B = 3.6 \times 10^7 \eta\ h_0^{-2}\ (T_0/2.7\text{ K})^3 ,$$

so that $0.01 < \Omega_b\,h_0^2 < 0.02$ and hence the universe cannot be closed by baryons.

Written December 1985 by K.A. Olive and S. Rudaz.

DARK MATTER

There is increasing evidence for the existence of large quantities of dark matter in the Universe. The most direct piece of evidence comes from the astronomical observation of the motion of visible matter (stars and regions of neutral hydrogen gas) in galaxies. The observed velocities due to rotational motion in spiral galaxies are measured to be largely independent of the distance to the center of these galaxies. In the absence of any unseen component, we would expect that the velocity falls off with increasing distance, $v^2 \approx G_N M_{\rm vis}/r$. In contrast, a flat rotation curve implies a total mass $M_{\rm tot} \approx G_N^{-1} v_{\rm obs}^2 r$ [$\approx 10^{11} M_\odot$ $(v_{\rm obs}/200$ km s$^{-1})^2$ $(r/10$ kpc)] in excess of the visible mass $M_{\rm vis}$. It can be inferred from these observations that there exists a dark matter component distributed in a (roughly) spherical halo about the galaxy. The dynamics of groups of galaxies and clusters, as well as the presence of very hot gas in elliptical galaxies require large quantities of unseen matter as well. In addition, theories of cosmological inflation predict that the density parameter of the Universe $\Omega_{\rm tot} = 1$, whereas standard Big Bang nucleosynthesis requires $\Omega_{\rm baryon} \leq 0.1$, implying the existence of nonbaryonic dark matter. Less direct evidence comes from our theoretical understanding of the growth of density perturbations as seeds for galaxy formation. Without the presence of dark matter, it is very difficult to reconcile the existence of galaxies (and quasars) at high redshifts with limits on the anisotropy of the microwave background radiation. Perturbations in baryons can grow only after the time of recombination, i.e. when the baryons decouple from the microwave background. When $\Omega_{\rm tot} = 1$ due to dark matter, matter domination occurs much earlier and dark matter perturbations grow for a longer period thus avoiding a conflict with limits on the anisotropy of the microwave background.

In our own galaxy, the distribution of the visible matter and its observed circular motion determine the local (solar neighborhood) dark matter density $\rho^{\rm DM} \approx 0.3$ GeV cm^{-3}. Regardless of the nature of the dark matter, it must behave as a collisionless gas, with a broad velocity distribution (typically assumed to be Maxwellian); $\langle v \rangle \approx \Delta v \approx 300$ km s^{-1} in our galaxy.

We do not know the identity of the dark matter nor whether there is more than one type of dark matter. Baryons are difficult to conceal and in the standard Big Bang model cannot make up all of the dark matter if $\Omega_{\rm tot} = 1$. It is also theoretically unlikely and is not at present observationally motivated that galactic halos could be made of very dim objects. There are several theoretical elementary particle candidates that could explain the existence of dark matter, of which the most commonly discussed are: a neutrino (if massive), a neutralino (from supersymmetry), and the axion (from the strong CP problem).

Regardless of the exact identity of the dark matter, its kinetic energy at the time when dark-matter domination begins determines the subsequent evolution of the density perturbations that seed galactic and large structures. If the dark matter is relativistic (hot dark matter, HDM) only the largest (supercluster) structures survive and they must fragment to form galactic structure, whereas if it is nonrelativistic (cold dark matter, CDM), structure on all scales is preserved. The large-scale distribution of matter in N-body simulations of a HDM-dominated universe is not compatible with observations (unless there are point-like density perturbations), whereas a flat CDM-dominated universe requires that the visible matter be predominantly concentrated in the denser regions of the DM distribution (biased galaxy formation).

For a cold dark matter particle species with equal particle (X) and antiparticle ($\overline{X}$) densities (except for the axions), its cosmological density at present is

$$\Omega_X h^2 \approx 1.6 \times 10^{-10} N_F^{1/2} (T_X/T_\gamma)^3 \times \left(a + \frac{1}{12} b \langle v^2 \rangle_f\right)^{-1} \langle v^2 \rangle_f^{-1} \tag{1}$$

with a, b determined from the (velocity averaged) annihilation cross section, expanded in powers of momentum, $\langle v\, \sigma_{X\overline{X}} \rangle = a + \frac{1}{6} b \langle v^2 \rangle_f$, at freezeout temperature T_f ($\langle v^2 \rangle_f = 6T_f/M_X$) at which the X's drop from thermal equilibrium (typically $T_f \approx \frac{1}{20} M_X$). In Eq. (1), N_F is the total number of relativistic degrees of freedom at T_f and (T_X/T_γ) is the ratio of the temperatures of X's and photons at T_f. In the halo of our galaxy $\langle v^2 \rangle \sim 10^{-6}$, thus $\langle v\, \sigma_{X\overline{X}} \rangle_{\rm halo}$ and Ω_X are closely related.

Several proposals or experiments exist to detect cold dark matter candidates. In the case of heavy ($M \geq 1$ GeV) particles, elastic scattering from nuclei would produce nuclear recoils with energies of $\gtrsim 1$ keV, and several techniques have been proposed to detect these recoils. The expected collision rate for a target nucleus mass m_N is:

$$R = 4.3 \text{ kg}^{-1} \text{ day}^{-1} \left(\frac{\text{GeV}^2}{m_N\, m_x}\right) \left(\frac{\sigma_{\rm el}}{10^{-38} \text{ cm}^2}\right) \times \left(\frac{\rho^{\rm DM}}{0.3 \text{ GeV cm}^{-3}}\right) \left(\frac{\langle |v_E| \rangle}{300 \text{ km s}^{-1}}\right) , \tag{2}$$

where $\langle |v_E| \rangle$ is the average velocity at which they strike the detector. Since crossing symmetry relates $\sigma_{\rm el}$ to $\sigma_{X\overline{X}}$, R is closely related to Ω_X. Dirac neutrinos and sneutrinos with masses 0.012–20 TeV have already been excluded by double-β decay experiments. Axions could be detected by their expected coherent conversion to microwave photons in a tuned cavity. Products of DM annihilation in the halo (*e.g.*, cosmic ray $\overline{p}$'s, e^+'s, γ's) and the core of the Sun (ν's) would indirectly signal the existence of particle DM. The absence of a signal in high energy solar-ν searches using underground detectors rules out sneutrinos whereas cosmic ray searches do not constrain theory so far.

Recent LEP results combined with the above experimental constraints now completely eliminate neutrinos and sneutrinos as dark matter candidates. Dirac and Majorana neutrinos and sneutrinos with masses $\lesssim 40$ GeV are excluded by LEP. This alone eliminates a Majorana neutrino, since the relic abundance for the neutrinos with masses > 40 GeV would be $\Omega h^2 \lesssim 2 \times 10^{-3}$ making them cosmologically uninteresting. It would have been possible for Dirac neutrinos to have a cosmologically interesting density for $m_\nu > 40$ GeV if there were a density asymmetry between ν and $\overline{\nu}$. However, Dirac neutrinos along with sneutrinos are eliminated by experiments using double-β decay detectors.

Written September 1989 by R. Flores and K.A. Olive. Revised November 1991.

INTERNATIONAL SYSTEM (SI) UNITS

Physical quantity	Name of unit	Symbol
Base units		
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd
Supplementary units		
plane angle	radian	rad
solid angle	steradian	sr
Derived units		
frequency	hertz	Hz
energy	joule	J
force	newton	N
pressure	pascal	Pa
power	watt	W
electric charge	coulomb	C
electric potential	volt	V
electric resistance	ohm	Ω
electric conductance	siemens	S
electric capacitance	farad	F
magnetic flux	weber	Wb
inductance	henry	H
magnetic flux density	tesla	T
luminous flux	lumen	lm
illuminance	lux	lx
activity (of a radioactive source)*	becquerel	Bq
absorbed dose (of ionizing radiation)*	gray	Gy

See *Quantities, Units, and Symbols*, report of the Symbols Committee of the Royal Society, 2^{nd} ed. (Royal Society, London, 1975).

*See "Radioactivity and radiation protection," p. III.29.

METRIC PREFIXES

10^{18}	exa	(E)
10^{15}	peta	(P)
10^{12}	tera	(T)
10^{9}	giga	(G)
10^{6}	mega	(M)
10^{3}	kilo	(k)
10^{2}	hecto	(h)
10	deca	(da)
10^{-1}	deci	(d)
10^{-2}	centi	(c)
10^{-3}	milli	(m)
10^{-6}	micro	(μ)
10^{-9}	nano	(n)
10^{-12}	pico	(p)
10^{-15}	femto	(f)
10^{-18}	atto	(a)

ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Material	Z	A	Nuclear[a] total cross section σ_T [barn]	Nuclear[b] inelastic cross section σ_I [barn]	Nuclear[c] collision length λ_T [g/cm^2]	Nuclear[c] interaction length λ_I [g/cm^2]	$\left.\frac{dE}{dx}\right\|_{min}$ [d] $\left[\frac{\text{MeV}}{\text{g/cm}^2}\right]$	Radiation length[e] X_0 [g/cm^2] () is for gas	Radiation length[e] X_0 [cm] () is for gas	Density[f] [g/cm^3] () is for gas [g/ℓ]	Refractive index n[f] () is $(n-1)\times10^6$ for gas
H_2	1	1.01	0.0387	0.033	43.3	50.8	4.12	61.28	865	0.0708(0.090)	1.112(140)
D_2	1	2.01	0.073	0.061	45.7	54.7	2.07	122.6	757	0.162(0.177)	1.128
He	2	4.00	0.133	0.102	49.9	65.1	1.94	94.32	755	0.125(0.178)	1.024(35)
Li	3	6.94	0.211	0.157	54.6	73.4	1.58	82.76	155	0.534	—
Be	4	9.01	0.268	0.199	55.8	75.2	1.61	65.19	35.3	1.848	—
C	6	12.01	0.331	0.231	60.2	86.3	1.78	42.70	18.8	2.265[g]	—
N_2	7	14.01	0.379	0.265	61.4	87.8	1.82	37.99	47.0	0.808(1.25)	1.205(300)
O_2	8	16.00	0.420	0.292	63.2	91.0	1.82	34.24	30.0	1.14(1.43)	1.22(266)
Ne	10	20.18	0.507	0.347	66.1	96.6	1.73	28.94	24.0	1.207(0.90)	1.092(67)
Al	13	26.98	0.634	0.421	70.6	106.4	1.62	24.01	8.9	2.70	—
Si	14	28.09	0.660	0.440	70.6	106.0	1.66	21.82	9.36	2.33	—
Ar	18	39.95	0.868	0.566	76.4	117.2	1.51	19.55	14.0	1.40(1.78)	1.233(283)
Ti	22	47.88	0.995	0.637	79.9	124.9	1.51	16.17	3.56	4.54	—
Fe	26	55.85	1.120	0.703	82.8	131.9	1.48	13.84	1.76	7.87	—
Cu	29	63.55	1.232	0.782	85.6	134.9	1.44	12.86	1.43	8.96	—
Ge	32	72.59	1.365	0.858	88.3	140.5	1.40	12.25	2.30	5.323	—
Sn	50	118.69	1.967	1.21	100.2	163	1.26	8.82	1.21	7.31	—
Xe	54	131.29	2.120	1.29	102.8	169	1.24	8.48	2.77	3.057(5.89)	(705)
W	74	183.85	2.767	1.65	110.3	185	1.16	6.76	0.35	19.3	—
Pt	78	195.08	2.861	1.708	113.3	189.7	1.15	6.54	0.305	21.45	—
Pb	82	207.19	2.960	1.77	116.2	194	1.13	6.37	0.56	11.35	—
U	92	238.03	3.378	1.98	117.0	199	1.09	6.00	≈0.32	≈18.95	—
Air, 20°C, 1 atm. (STP in paren.)					62.0	90.0	1.82	36.66	(30420)	0.001205(1.29)	1.000273(293)
H_2O					60.1	84.9	2.03	36.08	36.1	1.00	1.33
Shielding concrete[h]					67.4	99.9	1.70	26.7	10.7	2.5	—
SiO_2 (quartz)					67.0	99.2	1.72	27.05	12.3	2.64	1.458
H_2 (bubble chamber 26°K)					43.3	50.8	4.12	61.28	≈1000	≈ 0.063[i]	1.100
D_2 (bubble chamber 31°K)					45.7	54.7	2.07	122.6	≈900	≈ 0.140[i]	1.110
H-Ne mixture (50 mole percent)[j]					65.0	94.5	1.84	29.70	73.0	0.407	1.092
Ilford emulsion G5					82.0	134	1.44	11.0	2.89	3.815	—
NaI					94.8	152	1.32	9.49	2.59	3.67	1.775
BaF_2					92.1	146	1.35	9.91	2.05	4.89	1.56
BGO ($Bi_4Ge_3O_{12}$)					97.4	156	1.27	7.98	1.12	7.1	2.15
Polystyrene, scintillator (CH)[k]					58.4	82.0	1.95	43.8	42.4	1.032	1.581
Lucite, Plexiglas ($C_5H_8O_2$)					59.2	83.6	1.95	40.55	≈34.4	1.16–1.20	≈ 1.49
Polyethylene (CH_2)					56.9	78.8	2.09	44.8	≈47.9	0.92–0.95	—
Mylar ($C_5H_4O_2$)					60.2	85.7	1.86	39.95	28.7	1.39	—
Borosilicate glass (Pyrex)[ℓ]					66.2	97.6	1.72	28.3	12.7	2.23	1.474
CO_2					62.4	90.5	1.82	36.2	(18310)	(1.977)	(410)
Ethane C_2H_6					55.73	75.71	2.25	45.66	(34035)	0.509(1.356)[m]	(1.038)[m]
Methane CH_4					54.7	74.0	2.41	46.5	(64850)	0.423(0.717)	(444)
Isobutane C_4H_{10}					56.3	77.4	2.22	45.2	(16930)	(2.67)	(1270)
NaF					66.78	97.57	1.69	29.87	11.68	2.558	1.336
LiF					62.00	88.24	1.66	39.25	14.91	2.632	1.392
Freon 12 (CCl_2F_2) gas, 26°C, 1 atm.[n]					70.6	106	1.62	23.7	4810	(4.93)	1.001080
Silica Aerogel[o]					65.5	95.7	1.83	29.85	≈150	0.1–0.3	$1.0+0.25\rho$
NEMA G10 plate[p]					62.6	90.2	1.87	33.0	19.4	1.7	—

ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS (Cont'd)

Material	Dielectric constant ($\kappa = \epsilon/\epsilon_0$) () is $(\kappa{-}1)\times 10^6$ for gas	Young's modulus [10^6 psi]	Coeff. of thermal expansion [10^{-6}cm/cm-°C]	Specific heat [cal/g-°C]	Electrical resistivity [$\mu\Omega$cm(@°C)]	Thermal conductivity [cal/cm-°C-sec]
H_2	(253.9)	—	—	—	—	—
He	(64)	—	—	—	—	—
Li	—	—	56	0.86	8.55(0°)	0.17
Be	—	37	12.4	0.436	5.885(0°)	0.38
C	—	0.7	0.6–4.3	0.165	1375(0°)	0.057
N_2	(548.5)	—	—	—	—	—
O_2	(495)	—	—	—	—	—
Ne	(127)	—	—	—	—	—
Al	—	10	23.9	0.215	2.65(20°)	0.53
Si	11.9	16	2.8–7.3	0.162	—	0.20
Ar	(517)	—	—	—	—	—
Ti	—	16.8	8.5	0.126	50(0°)	—
Fe	—	28.5	11.7	0.11	9.71(20°)	0.18
Cu	—	16	16.5	0.092	1.67(20°)	0.94
Ge	16.0	—	5.75	0.073	—	0.14
Sn	—	6	20	0.052	11.5(20°)	0.16
Xe	—	—	—	—	—	—
W	—	50	4.4	0.032	5.5(20°)	0.48
Pt	—	21	8.9	0.032	9.83(0°)	0.17
Pb	—	2.6	29.3	0.038	20.65(20°)	0.083
U	—	—	36.1	0.028	29(20°)	0.064

Table revised April 1988 by R.W. Kenney. σ_T, σ_I, λ_T, and λ_I are energy dependent. Values quoted apply to high energy range given in footnote *a* or *b*, where energy dependence is weak.

a. σ_{total} at 80–240 GeV for neutrons ($\approx\sigma$ for protons) from Murthy *et al.*, Nucl. Phys. **B92**, 269 (1975). This scales approximately as $A^{0.77}$.

b. $\sigma_{\text{inelastic}} = \sigma_{\text{total}} - \sigma_{\text{elastic}} - \sigma_{\text{quasielastic}}$; for neutrons at 60–375 GeV from Roberts *et al.*, Nucl. Phys. **B159**, 56 (1979). For protons and other particles, see Carroll *et al.*, Phys. Lett. **80B**, 319 (1979); note that $\sigma_I(p) \approx \sigma_I(n)$. σ_I scales approximately as $A^{0.71}$.

c. Mean free path between collisions (λ_T) or inelastic interactions (λ_I), calculated from $\lambda = A/(N \times \sigma)$, where N is Avogadro's number.

d. For minimum-ionizing protons and pions from Barkas and Berger, *Tables of Energy Losses and Ranges of Heavy Charged Particles*, NASA-SP-3013 (1964). For electrons and positrons see: M.J. Berger and S.M. Seltzer, *Stopping Powers and Ranges of Electrons and Positrons* (2^{nd} Ed.), U.S. National Bureau of Standards report NBSIR 82–2550–A (1982).

e. From Y.S. Tsai, Rev. Mod. Phys. **46**, 815 (1974); X_0 data for all elements up to uranium may be found here. Corrections for molecular binding applied for H_2 and D_2. Parentheses refer to gaseous form at STP (0°C, 1 atm.).

f. Values for solids, or the liquid phase at boiling point, except as noted. Values in parentheses for gaseous phase at STP (0°C, 1 atm.). Refractive index given for sodium *D* line.

g. For pure graphite; industrial graphite density may vary 2.1–2.3 g/cm^3.

h. Standard shielding blocks, typical composition O_2 52%, Si 32.5%, Ca 6%, Na 1.5%, Fe 2%, Al 4%, plus reinforcing iron bars. The attenuation length, $\ell = 115 \pm 5$ g/cm^2, is also valid for earth (typical $\rho = 2.15$), from CERN–LRL–RHEL Shielding exp., UCRL–17841 (1968).

i. Density may vary about ±3%, depending on operating conditions.

j. Values for typical working conditions with H_2 target: 50 mole percent, 29°K, 7 atm.

k. Typical scintillator; *e.g.*, PILOT B and NE 102A have an atomic ratio H/C = 1.10.

ℓ. Main components: 80% SiO_2 + 12% B_2O_3 + 5% Na_2O.

m. Solid ethane density at −60°C; gaseous refractive index at 0°C, 546 mm pressure.

n. Used in Čerenkov counters. Values at 26°C and 1 atm. Indices of refraction from E.R. Hayes, R.A. Schluter, and A. Tamosaitis, ANL–6916 (1964).

o. $n(SiO_2) + 2n(H_2O)$ used in Čerenkov counters, ρ = density in g/cm^3. From M. Cantin *et al.*, Nucl. Instr. and Meth. **118**, 177 (1974).

p. G10-plate, typical 60% SiO_2 and 40% epoxy.

PERIODIC TABLE OF THE ELEMENTS

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1 H Hydrogen 1.00794																	2 He Helium 4.002602
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989768	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981539	14 Si Silicon 28.0855	15 P Phosph. 30.973762	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Mangan. 54.93805	26 Fe Iron 55.847	27 Co Cobalt 58.93320	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge German. 72.61	33 As Arsenic 74.92159	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybd. 95.94	43 Tc Technet. (97.9072)	44 Ru Ruthen. 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.82	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90543	56 Ba Barium 137.327	57–71 Rare earths	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.2	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.96654	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98037	84 Po Polonium (208.9824)	85 At Astatine (209.9871)	86 Rn Radon (222.0176)
87 Fr Francium (223.0197)	88 Ra Radium (226.0254)	89–103 Actinides	104 (Rf) (Ruther.)* (261.11)	105 (Ha) (Hahn.)* (262.114)	106 (263.118)	107 (262.12)	108 (265)	109 (266)									

57 La Lanthan. 138.9055	58 Ce Cerium 140.115	59 Pr Praseody. 140.90765	60 Nd Neodym. 144.24	61 Pm Prometh. (144.9127)	62 Sm Samarium 150.36	63 Eu Europium 151.965	64 Gd Gadolin. 157.25	65 Tb Terbium 158.92534	66 Dy Dyspros. 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967	Rare earths (Lanthanide series)
89 Ac Actinium (227.0278)	90 Th Thorium 232.0381	91 Pa Protactin. 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237.0482)	94 Pu Plutonium (244.0642)	95 Am Americ. (243.0614)	96 Cm Curium (247.0703)	97 Bk Berkelium (247.0703)	98 Cf Californ. (251.0796)	99 Es Einstein. (252.083)	100 Fm Fermium (257.0951)	101 Md Mendel. (258.10)	102 No Nobelium (259.1009)	103 Lr Lawrenc. (262.11)	Actinide series

*The names of elements 104 (Rutherfordium) and 105 (Hahnium) have not been universally accepted because of conflicting claims of discovery.

Revised 1991. The atomic number (top left) is the number of protons in the nucleus. The atomic mass (bottom) is weighted by isotopic abundances in the Earth's surface. Atomic massès are relative to the mass of the carbon-12 isotope, defined to be exactly 12 unified atomic mass units (u). Errors range from 1 to 9 in the last digit quoted. Relative isotopic abundances often vary considerably, both in natural and commercial samples. A number in parentheses is the mass of the longest-lived isotope of that element—no stable isotope exists. However, although Th, Pa, and U have no stable isotopes, they do have a characteristic terrestrial composition, and a meaningful weighted mass can be given. Adapted from "Atomic Weights of the Elements, 1989," Pure and Applied Chemistry **63**, 975 (1991).

ELECTRONIC STRUCTURE OF THE ELEMENTS

The electron configurations and most of the ionization energies below are taken from S. Ruben, *Handbook of the Elements*, 3^{rd} ed. (Open Court, La Salle, IL, 1985). Twenty eight of the ionization energies have been changed slightly to bring them up to date (changes from W.C. Martin and B.N. Taylor of the National Institute of Standards and Technology, January 1990). The electron configuration for, say, iron indicates an argon electronic core (see argon), plus six $3d$ electrons and two $4s$ electrons. The ionization energy is the least energy necessary to remove to infinity one electron from an *atom* of the element.

	Element		Electron configuration ($3d^5$ = five $3d$ electrons, etc.)		Ground state $^{2S+1}L_J$	Ionization energy (eV)
1	H	Hydrogen	$(1s)$		$^2S_{1/2}$	13.60
2	He	Helium	$(1s)^2$		$^1S_0$	24.59
3	Li	Lithium	(He) $(2s)$		$^2S_{1/2}$	5.39
4	Be	Beryllium	(He) $(2s)^2$		$^1S_0$	9.32
5	B	Boron	(He) $(2s)^2$ $(2p)$		$^2P_{1/2}$	8.30
6	C	Carbon	(He) $(2s)^2$ $(2p)^2$		$^3P_0$	11.26
7	N	Nitrogen	(He) $(2s)^2$ $(2p)^3$		$^4S_{3/2}$	14.53
8	O	Oxygen	(He) $(2s)^2$ $(2p)^4$		$^3P_2$	13.62
9	F	Fluorine	(He) $(2s)^2$ $(2p)^5$		$^2P_{3/2}$	17.42
10	Ne	Neon	(He) $(2s)^2$ $(2p)^6$		$^1S_0$	21.56
11	Na	Sodium	(Ne) $(3s)$		$^2S_{1/2}$	5.14
12	Mg	Magnesium	(Ne) $(3s)^2$		$^1S_0$	7.65
13	Al	Aluminum	(Ne) $(3s)^2$ $(3p)$		$^2P_{1/2}$	5.99
14	Si	Silicon	(Ne) $(3s)^2$ $(3p)^2$		$^3P_0$	8.15
15	P	Phosphorus	(Ne) $(3s)^2$ $(3p)^3$		$^4S_{3/2}$	10.49
16	S	Sulfur	(Ne) $(3s)^2$ $(3p)^4$		$^3P_2$	10.36
17	Cl	Chlorine	(Ne) $(3s)^2$ $(3p)^5$		$^2P_{3/2}$	12.97
18	Ar	Argon	(Ne) $(3s)^2$ $(3p)^6$		$^1S_0$	15.76
19	K	Potassium	(Ar) $(4s)$		$^2S_{1/2}$	4.34
20	Ca	Calcium	(Ar) $(4s)^2$		$^1S_0$	6.11
21	Sc	Scandium	(Ar) $(3d)$ $(4s)^2$	T	$^2D_{3/2}$	6.56
22	Ti	Titanium	(Ar) $(3d)^2$ $(4s)^2$	r e	$^3F_2$	6.83
23	V	Vanadium	(Ar) $(3d)^3$ $(4s)^2$	a l	$^4F_{3/2}$	6.75
24	Cr	Chromium	(Ar) $(3d)^5$ $(4s)$	n e	$^7S_3$	6.77
25	Mn	Manganese	(Ar) $(3d)^5$ $(4s)^2$	s m	$^6S_{5/2}$	7.43
26	Fe	Iron	(Ar) $(3d)^6$ $(4s)^2$	i e	$^5D_4$	7.90
27	Co	Cobalt	(Ar) $(3d)^7$ $(4s)^2$	t n	$^4F_{9/2}$	7.88
28	Ni	Nickel	(Ar) $(3d)^8$ $(4s)^2$	i t	$^3F_4$	7.64
29	Cu	Copper	(Ar) $(3d)^{10}(4s)$	o s	$^2S_{1/2}$	7.73
30	Zn	Zinc	(Ar) $(3d)^{10}(4s)^2$	n	$^1S_0$	9.39
31	Ga	Gallium	(Ar) $(3d)^{10}(4s)^2$ $(4p)$		$^2P_{1/2}$	6.00
32	Ge	Germanium	(Ar) $(3d)^{10}(4s)^2$ $(4p)^2$		$^3P_0$	7.90
33	As	Arsenic	(Ar) $(3d)^{10}(4s)^2$ $(4p)^3$		$^4S_{3/2}$	9.82
34	Se	Selenium	(Ar) $(3d)^{10}(4s)^2$ $(4p)^4$		$^3P_2$	9.75
35	Br	Bromine	(Ar) $(3d)^{10}(4s)^2$ $(4p)^5$		$^2P_{3/2}$	11.81
36	Kr	Krypton	(Ar) $(3d)^{10}(4s)^2$ $(4p)^6$		$^1S_0$	14.00
37	Rb	Rubidium	(Kr) $(5s)$		$^2S_{1/2}$	4.18
38	Sr	Strontium	(Kr) $(5s)^2$		$^1S_0$	5.69
39	Y	Yttrium	(Kr) $(4d)$ $(5s)^2$	T	$^2D_{3/2}$	6.22
40	Zr	Zirconium	(Kr) $(4d)^2$ $(5s)^2$	r e	$^3F_2$	6.63
41	Nb	Niobium	(Kr) $(4d)^4$ $(5s)$	a l	$^6D_{1/2}$	6.76
42	Mo	Molybdenum	(Kr) $(4d)^5$ $(5s)$	n e	$^7S_3$	7.09
43	Tc	Technetium	(Kr) $(4d)^6$ $(5s)$	s m	$^6D_{9/2}$	7.28
44	Ru	Ruthenium	(Kr) $(4d)^7$ $(5s)$	i e	$^5F_5$	7.36
45	Rh	Rhodium	(Kr) $(4d)^8$ $(5s)$	t n	$^4F_{9/2}$	7.46
46	Pd	Palladium	(Kr) $(4d)^{10}$	i t	$^1S_0$	8.34
47	Ag	Silver	(Kr) $(4d)^{10}(5s)$	o s	$^2S_{1/2}$	7.58
48	Cd	Cadmium	(Kr) $(4d)^{10}(5s)^2$	n	$^1S_0$	8.99

ELECTRONIC STRUCTURE OF THE ELEMENTS (Cont'd)

49	In	Indium	(Kr) $(4d)^{10}(5s)^2$ $(5p)$			$^2P_{1/2}$	5.79
50	Sn	Tin	(Kr) $(4d)^{10}(5s)^2$ $(5p)^2$			$^3P_0$	7.34
51	Sb	Antimony	(Kr) $(4d)^{10}(5s)^2$ $(5p)^3$			$^4S_{3/2}$	8.64
52	Te	Tellurium	(Kr) $(4d)^{10}(5s)^2$ $(5p)^4$			$^3P_2$	9.01
53	I	Iodine	(Kr) $(4d)^{10}(5s)^2$ $(5p)^5$			$^2P_{3/2}$	10.45
54	Xe	Xenon	(Kr) $(4d)^{10}(5s)^2$ $(5p)^6$			$^1S_0$	12.13
55	Cs	Cesium	(Xe) $(6s)$			$^2S_{1/2}$	3.89
56	Ba	Barium	(Xe) $(6s)^2$			$^1S_0$	5.21
57	La	Lanthanum	(Xe) $(5d)$ $(6s)^2$			$^2D_{3/2}$	5.58
58	Ce	Cerium	(Xe) $(4f)^2$ $(6s)^2$	R		$^3H_4$	5.54
59	Pr	Praseodymium	(Xe) $(4f)^3$ $(6s)^2$	a		$^4I_{9/2}$	5.46
60	Nd	Neodymium	(Xe) $(4f)^4$ $(6s)^2$	r		$^5I_4$	5.52
61	Pm	Promethium	(Xe) $(4f)^5$ $(6s)^2$	e		$^6H_{5/2}$	5.55
62	Sm	Samarium	(Xe) $(4f)^6$ $(6s)^2$			$^7F_0$	5.64
63	Eu	Europium	(Xe) $(4f)^7$ $(6s)^2$	e		$^8S_{7/2}$	5.67
64	Gd	Gadolinium	(Xe) $(4f)^7$ $(5d)$ $(6s)^2$	a		$^9D_2$	6.15
65	Tb	Terbium	(Xe) $(4f)^9$ $(6s)^2$	r		$^6H_{15/2}$	5.86
66	Dy	Dysprosium	(Xe) $(4f)^{10}$ $(6s)^2$	t		$^5I_8$	5.94
67	Ho	Holmium	(Xe) $(4f)^{11}$ $(6s)^2$	h		$^4I_{15/2}$	6.02
68	Er	Erbium	(Xe) $(4f)^{12}$ $(6s)^2$	s		$^3H_6$	6.11
69	Tm	Thulium	(Xe) $(4f)^{13}$ $(6s)^2$			$^2F_{7/2}$	6.18
70	Yb	Ytterbium	(Xe) $(4f)^{14}$ $(6s)^2$			$^1S_0$	6.25
71	Lu	Lutetium	(Xe) $(4f)^{14}(5d)$ $(6s)^2$	T		$^2D_{3/2}$	5.43
72	Hf	Hafnium	(Xe) $(4f)^{14}(5d)^2$ $(6s)^2$	r	e	$^3F_2$	6.83
73	Ta	Tantalum	(Xe) $(4f)^{14}(5d)^3$ $(6s)^2$	a	l	$^4F_{3/2}$	7.89
74	W	Tungsten	(Xe) $(4f)^{14}(5d)^4$ $(6s)^2$	n	e	$^5D_0$	7.98
75	Re	Rhenium	(Xe) $(4f)^{14}(5d)^5$ $(6s)^2$	s	m	$^6S_{5/2}$	7.88
76	Os	Osmium	(Xe) $(4f)^{14}(5d)^6$ $(6s)^2$	i	e	$^5D_4$	8.7
77	Ir	Iridium	(Xe) $(4f)^{14}(5d)^7$ $(6s)^2$	t	n	$^4F_{9/2}$	9.1
78	Pt	Platinum	(Xe) $(4f)^{14}(5d)^9$ $(6s)$	i	t	$^3D_3$	9.0
79	Au	Gold	(Xe) $(4f)^{14}(5d)^{10}(6s)$	o	s	$2S_{1/2}$	9.23
80	Hg	Mercury	(Xe) $(4f)^{14}(5d)^{10}(6s)^2$	n		$^1S_0$	10.44
81	Tl	Thallium	(Xe) $(4f)^{14}(5d)^{10}(6s)^2(6p)$			$^2P_{1/2}$	6.11
82	Pb	Lead	(Xe) $(4f)^{14}(5d)^{10}(6s)^2(6p)^2$			$^3P_0$	7.42
83	Bi	Bismuth	(Xe) $(4f)^{14}(5d)^{10}(6s)^2(6p)^3$			$^4S_{3/2}$	7.29
84	Po	Polonium	(Xe) $(4f)^{14}(5d)^{10}(6s)^2(6p)^4$			$^3P_2$	8.42
85	At	Astatine	(Xe) $(4f)^{14}(5d)^{10}(6s)^2(6p)^5$			$^2P_{3/2}$	9.65
86	Rn	Radon	(Xe) $(4f)^{14}(5d)^{10}(6s)^2(6p)^6$			$^1S_0$	10.75
87	Fr	Francium	(Rn) $(7s)$			$^2S_{1/2}$	3.97
88	Ra	Radium	(Rn) $(7s)^2$			$^1S_0$	5.28
89	Ac	Actinium	(Rn) $(6d)$ $(7s)^2$			$^2D_{3/2}$	5.17
90	Th	Thorium	(Rn) $(6d)^2$ $(7s)^2$			$^3F_2$	6.08
91	Pa	Protactinium	(Rn) $(5f)^2$ $(6d)$ $(7s)^2$	A		$^4K_{11/2}$	5.89
92	U	Uranium	(Rn) $(5f)^3$ $(6d)$ $(7s)^2$	c		$^5L_6$	6.19
93	Np	Neptunium	(Rn) $(5f)^4$ $(6d)$ $(7s)^2$	t		$^6L_{11/2}$	6.27
94	Pu	Plutonium	(Rn) $(5f)^6$ $(7s)^2$	i		$^7F_0$	6.06
95	Am	Americium	(Rn) $(5f)^7$ $(7s)^2$	n		$^8S_{7/2}$	5.99
96	Cm	Curium	(Rn) $(5f)^7$ $(6d)$ $(7s)^2$	i		$^9D_2$	6.02
97	Bk	Berkelium	(Rn) $(5f)^8$ $(6d)$ $(7s)^2$	d		$^8G_{15/2}$	6.23
98	Cf	Californium	(Rn) $(5f)^{10}$ $(7s)^2$	e		$^5I_8$	6.30
99	Es	Einsteinium	(Rn) $(5f)^{11}$ $(7s)^2$	s		$^4I_{15/2}$	6.42
100	Fm	Fermium	(Rn) $(5f)^{12}$ $(7s)^2$			$^3H_6$	6.50
101	Md	Mendelevium	(Rn) $(5f)^{13}$ $(7s)^2$			$^2F_{7/2}$	6.58
102	No	Nobelium	(Rn) $(5f)^{14}$ $(7s)^2$			$^1S_0$	6.65
103	Lr	Lawrencium	(Rn) $(5f)^{14}(6d)$ $(7s)^2$			$^2D_{3/2}$	
104	Rf	Rutherfordium	(Rn) $(5f)^{14}(6d)^2$ $(7s)^2$				

HIGH-ENERGY COLLIDER PARAMETERS: e^+e^- Colliders (I)

The numbers here were received from representatives of the colliders in 1991. Quantities are, where appropriate, r.m.s. H and V indicate horizontal and vertical directions. Many of the numbers of course change over the lifetime of a collider; only the latest values are given here.

	SPEAR (SLAC)	DORIS (DESY)	CESR (Cornell)	PETRA (DESY)	PEP (SLAC)
Physics start date	1972	1973	1979	1978	1980
Physics end date	1990	--	—	1986	1990
Maximum beam energy (GeV)	4	5.6	6	23.4	15
Luminosity (10^{30}cm^{-2}s^{-1})	10 at 3 GeV	33 at 5.3 GeV	200 at 5.3 GeV (250 in 1992)	24 at 17.5 GeV	60
Time between collisions (μs)	0.75	0.965	0.36	3.8	2.44
Crossing angle (μ rad)	0	0	0	0	0
Energy spread (units 10^{-3})	1	1.2 at 5 GeV	0.6 at 5.3 GeV	1.1 at 17.5 GeV	1
Bunch length (cm)	$\sigma_z \approx 4$	$\sigma \sim 2$ at 5 GeV	1.7	$\sigma \sim 1.3$ at 17.5 GeV	$\sigma_z = 2$
Beam radius (10^{-6} m)	H: 700 V: 50	H: 540 V: $\sim$ 30 } at 5 GeV	H: 500 V: 11	H: 430 V: 13 } at 17.5 GeV	H: 340 V: 14
Free space at interaction point (m)	±2.5	±1.2	±2.2 (±0.6 to REC quads)	±4.5	±3.7
Luminosity lifetime (hr)	≈ 3	1.0–1.5	3–4	4 at 17.5 GeV	4
Filling time (min)	15	1–2	10	20	15
Acceleration period (s)	≤ 100	—	—	—	≤ 100
Injection energy (GeV)	2.5	up to 5.6	6	7	15
Transverse emittance ($10^{-9}\pi$ rad-m)	$H \approx 430$	H: 500 V: 5–50 } at 5 GeV	H: 240 V: 8	H: 140 V: 2	$H \approx 120$
β^*, amplitude function at interaction point (m)	H: 1.2 V: 0.08	H: 0.59/12.3 V: 0.04/0.79	H: 1.0 V: 0.018	H: 1.3 V: 0.08	H: 1.0 V: 0.05
Beam-beam tune shift per crossing (units 10^{-4})	300	≤ 280 (space charge limit at 5.3 GeV)	320	H: 160 V: 400 } at 17.5 GeV	550
RF frequency (MHz)	358	500	500	500	352
Particles per bunch (units 10^{10})	15	27	20	26	35
Bunches per ring per species	1	1	7	2	3
Average beam current per species (mA)	30	45 at 5.3 GeV	90	11 at 17.5 GeV	21
Circumference (km)	0.234	0.2892	0.768	2.304	2.2
Interaction regions	2	2	1	4	1
Utility insertions	18	10	2	4	5
Magnetic length of dipole (m)	2.35	3.2/1.1	1.6–6.6	5.38	5.4
Length of standard cell (m)	11.4	13.2	16	14.4	14.35
Phase advance per cell (deg)	H: 79 V: 90	H: 140 V: 50	45–90 (no standard cell)	H: 47 V: 40	H: 56 V: 33
Dipoles in ring	36	H: 28 V: 6	86	224	192
Quadrupoles in ring	46	68	106	360	248
Peak magnetic field (T)	1.1	1.5	0.3 normal 0.8 high field } at 8 GeV	0.4 at 23 GeV	0.36

HIGH-ENERGY COLLIDER PARAMETERS: e^+e^- Colliders (II)

The numbers here were received from representatives of the colliders in 1991. Numbers are subject to change. Quantities are, where appropriate, r.m.s. H, V, and s.c. indicate horizontal and vertical directions, and superconducting.

	BEPC (China)	VEPP-4M (Novosibirsk)	TRISTAN (KEK)	SLC (SLAC)	LEP (CERN)
Physics start date	1989	1992	1987	1989	1989
Maximum beam energy (GeV)	2.2	6	32	50	55
Luminosity (10^{30}cm^{-2}s^{-1})	10	50	35	0.1 to 0.5	11
Time between collisions (μs)	0.8	—	5	8300	22
Crossing angle (μ rad)	0	0	0	0	0
Energy spread (units 10^{-3})	0.58	1	1.6	3	1.0
Bunch length (cm)	5.2	5	1.2	0.1	1.8
Beam radius (10^{-6} m)	H: 926 V: 61	H: 1000 V: 30	H: 310 V: 8	2–3	H: 200 V: 8
Free space at interaction point (m)	±2.5	±2	±4.5	±2.8	±3.5
Luminosity lifetime (hr)	7–10	2	2–3	—	12
Filling time (min)	40	15	20	—	90
Acceleration period (s)	120	150	200	—	320
Injection energy (GeV)	1.1–1.4	2	8	50	20
Transverse emittance ($10^{-9}\pi$ rad-m)	H: 660 V: 43	H: 400 V: 20	H: 100 at 29 GeV	H: 0.6 V: 0.4	H: 52 V: 2.1
β^*, amplitude function at interaction point (m)	H: 1.3 V: 0.085	H: 0.75 V: 0.05	H: 1.0 V: 0.04	0.01	H: 1.00 V: 0.04
Beam-beam tune shift per crossing (units 10^{-4})	350	500	400	—	400
RF frequency (MHz)	199.53	180	508.5808	—	352.2
Particles per bunch (units 10^{10})	26	15	24	4.5 e^- 3.5 e^+	41.6
Bunches per ring per species	1	2	2	1	$4e^+ + 4e^-$
Average beam current per species (mA)	52	40	7.5	0.001	2
Circumference or length (km)	0.2404	0.366	3.02	1.45 +1.47	26.66
Interaction regions	2	1	4	1	4
Utility insertions	4	1	8	—	4
Magnetic length of dipole (m)	1.6	2	5.86	2.5	11.66/pair
Length of standard cell (m)	6.6	7.2	16.1	5.2	79
Phase advance per cell (deg)	≈ 60	65	60	108	60
Dipoles in ring	40 + 4 weak	78	264 +8 weak	460+440	3280+24 inj. + 64 weak
Quadrupoles in ring	68	150	400	—	520+288 + 8 s.c.
Peak magnetic field (T)	0.9028	0.6	0.47 at 30 GeV	0.597	0.135

HIGH-ENERGY COLLIDER PARAMETERS: e^+e^- Colliders (III)

Proposed e^+e^- colliders. The numbers here were received from representatives of the colliders in 1991. Numbers are subject to change and many are only estimates; those in parentheses are for later upgrades. Quantities are, where appropriate, r.m.s. H and V indicate horizontal and vertical directions.

	τ-CHARM (Spain)	TRISTAN-B (KEK)	CESR-B (Cornell)	PEP-II (SLAC)	VLEPP, INP (Serpukhov)
Physics start date	1997	1996	1996	1996	1998
Maximum beam energy (GeV)	2.5	8×3.5	8×3.5 (6 GeV c.m. max)	9×3.1 (6.3 GeV c.m. max)	250 ($\rightarrow$500$\rightarrow$1000)
Luminosity (10^{30}cm^{-2}s^{-1})	1000	2000 ($\rightarrow$1000)	3000	3000	3000 ($\rightarrow$6000$\rightarrow$10000)
Time between collisions (μs)	0.04	0.01 ($\rightarrow$0.002)	0.01	0.0042	—
Crossing angle (μ rad)	0	0 ($\rightarrow \pm$25,000)	$\pm$12,000	0	5000
Energy spread (units 10^{-3})	0.5	0.7	0.84/0.60	0.6/1.0	1–100
Bunch length (cm)	0.6	0.5	1.0	1.0	0.075
Beam radius (10^{-6} m)	H: 280 V: 14	H: 140 V: 1.4	H: 370 V: 5	H: 190 V: 7.6	H: 1 ($\rightarrow 1.3 \rightarrow 2$) V: 0.007 ($\rightarrow 0.003 \rightarrow 0.001$)
Free space at interaction point (m)	$\pm$0.8	$\pm$0.2 m, +300 – 500 mrad cone	$\pm$0.4 m, $\pm$300 mrad cone	$\pm$0.2 m, $\pm$300 mrad cone	$\pm$1.2
Luminosity lifetime (hr)	2	3	3	2	—
Filling time (min)	< 1 (topping up)	6 ($\rightarrow$13) topping up	< 1 (topping up)	3 (topping up)	—
Acceleration period (s)	—	—	—	—	0.0067
Injection energy (GeV)	1.5–2.5	8/3.5	3–8	2.8–10	3.5
Transverse emittance ($10^{-9}\pi$ rad-m)	H: 127 V: 6.4	H: 19 V: 0.19	H: 130 V: 2	H: 48 & 96 V: 1.9 & 3.9	H: 0.2 ($\rightarrow 0.4 \rightarrow 0.8$) V: 300($\rightarrow 50 \rightarrow 6$) $\times 10^{-6}$
β^*, amplitude function at interaction point (m)	H: 0.20 V: 0.01	H: 1.0 V: 0.01	H: 1.0 V: 0.015	H: 0.75 & 0.375 V: 0.03 & 0.015	H: 5×10^{-3} V: 10^{-4}
Beam-beam tune shift per crossing (units 10^{-4})	400	500	300	300	—
RF frequency (MHz)	400	508	500	476	1.4×10^4
Particles per bunch (units 10^{10})	15	1.3/3.2	6/14	4.1/5.9	10–20
Bunches per ring per species	30	1024 ($\rightarrow$5120)	230	1658	1
Average beam current per species (mA)	600	220/520 ($\rightarrow$1100/2600)	870/1980	1480/2140	0.003
Circumference or length (km)	0.36	3.02	0.765	2.2	2×3 ($\rightarrow$2×6$\rightarrow$2×12)
Interaction regions	1 (2 possible)	1	1	1 (2 possible)	1
Utility insertions	2	3	2	5	—
Magnetic length of dipole (m)	—	2.56/0.42	0.9–6.6	5.4/0.45	—
Length of standard cell (m)	—	19	16	15.125	1.2
Phase advance per cell (deg)	—	90	45–90 (no standard cell)	60/80	20–90
Dipoles in ring	—	224	89/212	212/208	—
Quadrupoles in ring	—	343/341	103/105	272/300	20,000
Peak magnetic field (T)	—	0.3/0.85	0.6	0.18/0.75	—

HIGH-ENERGY COLLIDER PARAMETERS: pp, $\bar{p}p$ and ep Colliders

The numbers here were received from representatives of the colliders in 1991. Numbers are subject to change, and many are only estimates. Quantities are, where appropriate, r.m.s. H, V, and s.c. indicate horizontal and vertical directions, and superconducting.

	$Sp\bar{p}S$ (CERN)	TEVATRON (Fermilab)	HERA (DESY)	UNK (Serpukhov)	LHC (CERN)			SSC (USA)
Physics start date	1981	1987	1990	1997	1998			2000
Particles collided	$p\bar{p}$	$p\bar{p}$	ep	pp	pp	Pb Pb	ep	pp
Maximum beam energy (TeV)	0.315 (0.45 in pulsed mode)	0.9–1.0	e: 0.026 p: 0.82	0.4 (3)	7.7	631	e: 0.06 p: 7.7	20
Luminosity (10^{30}cm^{-2}s^{-1})	6	2 (1989) 10 (1993)	16	1000	1.7×10^4	0.002	280	1000, $\beta^* = 0.5$ m 55, $\beta^* = 10$ m
Time between collisions (μs)	3.8	3.5	0.096	0.165	0.015	0.105	0.165	0.016678
Crossing angle (μ rad)	0	0	0	0	200	200	0	75
Energy spread (units 10^{-3})	0.35	0.15	e: 0.91 p: 0.2	±1 (±0.3)	0.1	0.2	0.1	0.058
Bunch length (cm)	20	50	e: 0.83 p: 8.5	70 (40)	7.5	7.5	e: 0.93 p: 7.5	6.0
Beam radius (10^{-6} m)	p: $73(H), 36(V)$ $\bar{p}$: $55(H), 27(V)$	36	e: $280(H), 37(V)$ p: $265(H), 84(V)$	70	15	12	122 (H) 37 (V)	4.8, $\beta^* = 0.5$ m 21.7, $\beta^* = 10$ m
Free space at interaction point (m)	16	±6.5	±5.5	±8	40	40	15	±20, $\beta^* = 0.5$ m ±120, $\beta^* = 10$ m
Luminosity lifetime (hr)	15	15–40	>3	10	11	11	24	$\sim$24
Filling time (min)	0.5	8	e: 15 p: 20	20	7	30	40	$\sim$60
Acceleration period (s)	10	44	—	100	1200			1000
Injection energy (TeV)	0.026	0.15	e: 0.014 p: 0.040	0.065 (0.4)	0.450		e: 0.02 p: 0.450	2
Transverse emittance ($10^{-9}\pi$ rad-m)	p: 9 $\bar{p}$: 5	p: 2.6 $\bar{p}$: 2.6	e: $39(H), 2(V)$ p: $7(H), 7(V)$	18 (2.3)	0.45	0.31	e: $17.5(H), 5.1(V)$ p: 0.45	0.047
β^*, amplitude function at interaction point (m)	0.6 (H) 0.15 (V)	0.50	e: $2(H), 0.70(V)$ p: $10(H), 1.0$ (V)	0.2 (1.5)	0.5	0.5	e: $0.85(H), 0.26(V)$ p: $33(H), 3.0(V)$	0.5 at 2 IR's 10 at 2 IR's
Beam-beam tune shift per crossing (units 10^{-4})	50	p: 35 $\bar{p}$: 50	e: $190(H), 210(V)$ p: $12(H)$, $9(V)$	50	34		e: 500 p: $46(H), 14(V)$	$\beta^* = 0.5$ m: 8 head on, 13 long range
RF frequency (MHz)	100+200	53	e: 499.7 p: 208.2/52.05	200	400	400	e: 352 p: 400	359.75
Particles per bunch (units 10^{10})	p: 15 $\bar{p}$: 8	p: 10 $\bar{p}$: 7	e: 3.65 p: 10	30	10	0.006	e: 9.2 p: 30	0.84
Bunches per ring per species	6	6	210	348	4725	800	508	17,424
Average beam current per species (mA)	p: 6 $\bar{p}$: 3	p: 4.6 $\bar{p}$: 3.2	e: 58 p: 163	240	850	7.4	e: 84 p: 273	73
Circumference (km)	6.911	6.28	6.336	20.772	26.659			87.12
Interaction regions	2	2 high $\mathcal{L}$	3	4	3	1	1	Maximum 8 total, 4 simultaneous
Utility insertions	—	4	4	2	2			2
Magnetic length of dipole (m)	6.26	6.12	e: 9.23 p: 8.82	5.8	9.00			Mostly 14.98
Length of standard cell (m)	64	59.5	e: 23.5 p: 47	91.8	97.96			180
Phase advance per cell (deg)	90	67.8	e: 60 p: 90	82.5	90			90
Dipoles in ring	744	774	e: 396 p: 416	2204 (2192)	1792			H: 8662 V: 276 } 2 rings
Quadrupoles in ring	232	216	e: 580 p: 280	560 (474)	560			2188 } 2 rings
Magnet type	H type with bent-up coil ends	s.c. $\cos\theta$ warm iron	e: C-shaped p: s.c., collared, cold iron	H type (s.c.)	s.c. 2 in 1 cold iron			s.c. $\cos\theta$ cold iron
Peak magnetic field (T)	1.4 (2 in pulsed mode)	4.4	e: 0.274 p: 4.65	0.67 (5)	10			6.60
$\bar{p}$ source accum. rate (hr^{-1})	6×10^{10}	5×10^{10}	—	—	—			—
Max. no. $\bar{p}$ in accum. ring	1.2×10^{12}	1×10^{12}	—	—	—			—

PASSAGE OF PARTICLES THROUGH MATTER

(1) Maximum energy transfer: The maximum kinetic energy that a point-charge particle with mass M and momentum $p = \gamma\beta cM$ can impart to a stationary unbound electron (mass m_e) is

$$T_{\max} = \frac{2m_ec^2\,\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2} \,. \tag{1}$$

This kinetic energy appears several times in the following. It is usual [1] to make the low-energy approximation $T_{\max} = 2m_ec^2\,\beta^2\gamma^2$, valid for $2\gamma m_e/M \ll 1$. For a pion, the error thus introduced into dE/dx reaches 1% at 20 GeV. However, if the energy transfer is much in excess of 1 MeV then the impact parameter is smaller than the "pion radius," so that our point-charge assumption is invalid. We use the low-energy approximation with the understanding that form-factor corrections are necessary if the energy transfer is large.

(2) Energy loss for ionizing particles: Moderately relativistic charged particles other than electrons lose energy in matter primarily by ionization. If the velocity βc is larger than that of orbital electrons ($\sim \alpha c$) and small enough that radiative effects do not dominate, then the mean rate of energy loss is given by the Bethe-Bloch equation [2],

$$-\frac{dE}{dx} = 4\pi N_A\, r_e^2\, m_ec^2\, z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\left(\frac{2m_ec^2\gamma^2\beta^2}{I}\right) - \beta^2 - \frac{\delta}{2}\right] \,. \tag{2}$$

Here the particle has charge ze and is passing through an element with atomic number Z and atomic weight A; m_e and r_e are the mass and the classical radius of the electron; and the product $4\pi N_A\, r_e^2\, m_ec^2$ equals 0.3071 MeV $\text{cm}^2\,\text{g}^{-1}$. The *ionization constant* I is approximately $16\,Z^{0.9}$ eV for $Z > 1$, but measurements and calculations which include atomic configuration effects yield results that differ by as much as 10% from this value. Hydrogen is the most sensitive to atomic effects: I is 15 eV for atomic hydrogen, 19.2 eV for H_2 gas, and 21.8 eV for liquid hydrogen [3].

In Eq. (2), dx is measured in mass per unit area, *e.g.*, in g cm^{-2}. Except in hydrogen, particles of the same velocity have very similar rates of energy loss in different materials; there is a slow decrease in the rate of energy loss with increasing Z.

Plots of dE/dx and ranges obtained by integrating $(dE/dx)^{-1}$ are given in following section.

The enhanced transverse electric field of a relativistic incident particle is shielded by the charge density of atomic electrons, reducing the rate of energy loss. This *density effect* is represented by δ in Eq. (2). For very energetic particles, δ approaches $2\ln\gamma$ plus a constant [4]. As a result, the quantity in the square brackets in Eq. (2) increases asymptotically as $\ln\gamma$ instead of $2\ln\gamma$. The correction depends upon the chemical composition and density of the medium.

The first term in the square brackets of Eq. (2) is given more precisely by $\ln(2m_ec^2\gamma^2\beta^2T_{\max}/I^2)^{1/2}$, and so in the absence of corrections the logarithmic term is in error by a few percent at several hundred GeV. At low incident-particle speeds ($\beta/z \approx \alpha$), atomic shell corrections and higher-order QED corrections also introduce errors of this magnitude. Thus Eq. (2) is only good to a few percent at any velocity, and the literature should be consulted by those with more demanding needs [2,5,6].

For particles moving more slowly than atomic electrons, the above discussion is inapplicable. At velocities $\alpha z \gtrsim \beta \gtrsim 10^{-3}$ or slightly lower, the total energy-loss rate is proportional to β, and non-ionizing nuclear recoil energy loss contributes substantially to the total [7]. For protons in silicon, $|dE/dx| = 61.2\,\beta$ GeV $\text{cm}^2\,\text{g}^{-1}$ for $\beta < 0.005$; the peak occurs at $\beta = 0.0126$, where $|dE/dx| = 522$ MeV $\text{cm}^2\,\text{g}^{-1}$. In neutron-scattering experiments, light output in scintillator has been observed for recoil protons with energies as low as 30 eV [8].

At velocities $\beta \gtrsim z/137$, $|dE/dx|$ initially falls as $1/\beta^2$, then reaches a broad minimum at $\gamma \approx 3.2$ almost independently of the medium. In practical cases, most relativistic particles (*e.g.*, cosmic-ray muons) have energy loss rates close to this minimum, and are said to be *minimum ionizing* particles, or mip's. The energy loss rate rises slowly for $\gamma > 4$, with the quantity in the square brackets of Eq. (2) first increasing as $2\ln\gamma$. The density effect gradually limits the slope to $\ln\gamma$. Much of the relativistic rise can be attributed to large energy transfers to a few electrons. If these escape or are otherwise accounted for separately, the energy deposited in an absorbing layer (in contrast to the energy lost by the particle) approaches a constant value, the *Fermi plateau* (see Sec. 3 below). At extreme energies (*e.g.*, 400 GeV for muons or pions in iron), radiative effects become important. These are especially relevant for high-energy muons, as discussed in Sec. (9).

The quantity $(dE/dx)\delta x$ is the *mean* energy loss via interaction with electrons in a layer of the medium with thickness δx. For finite δx, there are fluctuations in the actual energy loss. The distribution is skewed toward high values (the Landau tail) [9]. Only for a thick layer $[(dE/dx)\delta x \gg 2m_ec^2\,\beta^2\gamma^2]$ is the distribution nearly Gaussian. The large fluctuations in the energy loss are due to the small number of collisions involving large energy transfers. The fluctuations are smaller for the so-called restricted energy loss rate, as discussed in Sec. 3 below.

In a mixture or compound, the rate of energy loss is approximately

$$\frac{dE}{dx} = \sum f_i\, \frac{dE}{dx}\bigg|_i \,, \tag{3}$$

where f_i is the fraction by weight of the ith element and $dE/dx|_i$ is the mean rate of energy loss (in g cm^{-2}) in this element. Atomic corrections to this additivity rule are discussed in Ref. 3. These are neglected in many widely used computer codes.

Energy loss by electrons and positrons has been excluded from this discussion, since radiative effects (bremsstrahlung and pair production) usually contribute more than ionization. This important case is discussed below, and the relative contributions of various electron energy-loss processes in lead are shown in a figure given in the section "Photon and Electron Attenuation Plots."

(3) Restricted energy loss rates for relativistic ionizing particles: Fluctuations in energy loss are due mainly to the production of a few high-energy knock-on electrons. Practical detectors often measure the energy *deposited*, not the energy *lost.* When energy is carried off by energetic knock-on electrons, it is more appropriate to consider the mean energy loss excluding energy transfers greater than some cutoff $E_{\max}$. The *restricted energy loss rate* is [2].

$$-\frac{dE}{dx}\bigg|_{\le E_{\max}} = 4\pi N_A\, r_e^2\, m_ec^2\, z^2 \frac{Z}{A}\frac{1}{\beta^2} \times \left[\ln\left(\frac{\sqrt{2m_e\,c^2\,\beta^2\,\gamma^2\,E_{\max}}}{I}\right) - \frac{\beta^2}{2} - \frac{\delta}{2}\right] \,. \tag{4}$$

This differs from Eq. (2) only in that $E_{\max}$ rather than $T_{\max}$ appears in the logarithmic term and that β^2 is divided by 2. Distributions about the mean do not exhibit such a large Landau tail as does the distribution of $-dE/dx$ [Eq. (2)]. The density effect causes the restricted energy loss rate to approach a constant, the Fermi plateau value, at very high energies.

(4) Energetic knock-on electrons (δ rays): The distribution of secondary electrons with kinetic energies $T \gg I$ is given by [1]

$$\frac{d^2N}{dTdx} = \frac{1}{2}\,4\pi N_A\, r_e^2\, m_ec^2\, z^2 \frac{Z}{A}\,\frac{1}{\beta^2}\,\frac{F}{T^2} \tag{5}$$

for $I \ll T \le T_{\max}$, where $T_{\max}$ is given by Eq. (1). The factor F is spin-dependent, but is about unity for $T \ll T_{\max}$. It is evaluated for spins 0, 1/2, and 1 in Rossi [1]. For incident electrons, the indistinguishability of projectile and target means that the range of T extends only to half the kinetic energy of the incident particle. Additional formulae are given in Ref. 10. Equation (5) is inaccurate for T close to I: for $2I \lesssim T \lesssim 10I$, the $1/T^2$ dependence above becomes approximately $T^{-\eta}$, with $3 \lesssim \eta \lesssim 5$ [11].

(5) Ionization yields: Physicists frequently relate total energy loss to the number of ion pairs produced near the particle's track. This relation becomes complicated for relativistic particles due to the wandering of energetic knock-on electrons whose ranges exceed the dimensions of the fiducial volume. For a qualitative appraisal of the nonlocality of energy deposition in various media by such

PASSAGE OF PARTICLES THROUGH MATTER (Cont'd)

modestly energetic knock-on electrons, see Ref. 12. The mean local energy dissipation per local ion pair produced, W, while essentially constant for relativistic particles, increases at slow particle speeds [13]. For gases, W can be surprisingly sensitive to trace amounts of various contaminants [13]. Furthermore, ionization yields in practical cases may be greatly influenced by such factors as subsequent recombination [14].

(6) Multiple scattering through small angles: A charged particle traversing a medium is deflected by many small-angle scatters. Most of this deflection is due to Coulomb scattering from nuclei, and hence the effect is called multiple Coulomb scattering. (However, for hadronic projectiles, the strong interactions also contribute to multiple scattering.) The Coulomb scattering distribution is well represented by the theory of Molière [15]. It is roughly Gaussian for small deflection angles, but at larger angles (greater than a few θ_0, defined below) it behaves like Rutherford scattering, having larger tails than does a Gaussian distribution.

If we define

$$\theta_0 = \theta^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{2}}\,\theta^{\rm rms}_{\rm space} \; . \tag{6}$$

then it is sufficient for many applications to use a Gaussian approximation for the central 98% of the projected angular distribution, with a width given by [16,17]

$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038\ln(x/X_0)\Big] \; . \tag{7}$$

Here p, βc, and z are the momentum, velocity, and charge number of the incident particle, and x/X_0 is the thickness of the scattering medium in radiation lengths (defined below). This value of θ_0 is from a fit to Molière distribtuion [15] for singly charged particles with $\beta = 1$ for all Z, and is accurate to 11% or better for $10^{-3} < x/X_0 < 100$.

Lynch and Dahl have extended this phenomenological approach, fitting Gaussian distributions to a variable fraction of the Molière distribution for arbitrary scatterers [17], and achieve accuracies of 2% or better.

The nonprojected (space) and projected (plane) angular distributions are given approximately by [15]

$$\frac{1}{2\pi\,\theta_0^2}\,\exp\left(-\frac{\theta^2_{\rm space}}{2\theta_0^2}\right)\,d\Omega \; , \tag{8}$$

$$\frac{1}{\sqrt{2\pi}\,\theta_0}\,\exp\left(-\frac{\theta^2_{\rm plane}}{2\theta_0^2}\right)\,d\theta_{\rm plane} \; , \tag{9}$$

where θ is the deflection angle. In this approximation, $\theta^2_{\rm space} \approx (\theta^2_{{\rm plane},x} + \theta^2_{{\rm plane},y})$, where the x and y axes are orthogonal to the direction of motion, and $d\Omega \approx d\theta_{{\rm plane},x}\,d\theta_{{\rm plane},y}$. Deflections into $\theta_{{\rm plane},x}$ and $\theta_{{\rm plane},y}$ are independent and identically distributed.

Figure 1 shows other quantities sometimes used to describe multiple Coulomb scattering. They are

$$\psi^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,\theta^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,\theta_0 \; ,$$

$$y^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,x\,\theta^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,x\,\theta_0 \; ,$$

$$s^{\rm rms}_{\rm plane} = \frac{1}{4\sqrt{3}}\,x\,\theta^{\rm rms}_{\rm plane} = \frac{1}{4\sqrt{3}}\,x\,\theta_0 \; . \tag{10}$$

All the quantitative estimates in this section apply only in the limit of small $\theta^{\rm rms}_{\rm plane}$ and in the absence of large-angle scatters. The random variables s, ψ, y, and θ in a given plane are distributed in a correlated fashion (see the section on Probability, Statistics, and Monte Carlo for the definition of the correlation coefficient). Obviously, $y \approx x\psi$. In addition, y and θ have the correlation coefficient $\rho_{y\theta} = \sqrt{3}/2 \approx 0.87$. For Monte Carlo generation of a joint $(y_{\rm plane}, \theta_{\rm plane})$ distribution, or for other calculations, it may be most convenient to work with

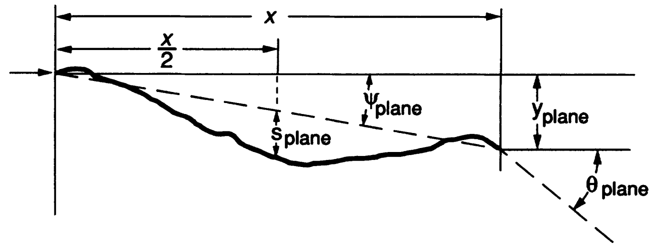

Fig. 1. Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

independent Gaussian random variables (z_1, z_2) with mean zero and variance one, and then set

$$\begin{aligned} y_{\rm plane} &= z_1\,x\,\theta_0(1-\rho^2_{y\theta})^{1/2}/\sqrt{3} + z_2\,\rho_{y\theta}x\,\theta_0/\sqrt{3} \\ &= z_1\,x\,\theta_0/\sqrt{12} + z_2\,x\,\theta_0/2 \; ; \\ \theta_{\rm plane} &= z_2\,\theta_0 \; . \end{aligned} \tag{11}$$

Note that the second term for $y_{\rm plane}$ equals $x\,\theta_{\rm plane}/2$ and represents the displacement that would have occurred had the deflection $\theta_{\rm plane}$ all occurred at the single point $x/2$.

For heavy ions the multiple Coulomb scattering has been measured and compared with various theoretical distributions [18].

(7) Radiation length and associated quantities: In dealing with electrons and photons at high energies, it is convenient to measure the thickness of the material in units of the radiation length X_0. This is the mean distance over which a high-energy electron loses all but $1/e$ of its energy by bremsstrahlung, and is the appropriate scale length for describing high-energy electromagnetic cascades. X_0 has been calculated and tabulated by Y.S. Tsai [19]. His formula is less than straightforward, but can be approximated by [20]

$$X_0 = \frac{716.4\ \text{g cm}^{-2}\,A}{Z(Z+1)\ln(287/\sqrt{Z})} \; , \tag{12}$$

where Z and A are the atomic number and weight of the medium. Results obtained with this formula agree with Tsai's values to better than 2.5% for all elements except helium, where the result is about 5% low. The radiation length in a mixture or compound may be approximated by

$$\frac{1}{X_0} = \sum \frac{f_i}{X_i} \; , \tag{13}$$

where f_i and X_i are the fraction by weight and the radiation length for the ith element.

Radiative energy losses scale nearly proportionally to incident energy, while the ionization varies only logarithmically. The two are equal at the *critical energy* E_c, which for electrons is given approximately by [21]

$$E_c = \frac{800\ \text{MeV}}{Z + 1.2} \; . \tag{14}$$

In an electromagnetic cascade, E_c defines the dividing line between shower multiplication and energy dissipation by ionization.

The transverse development of electromagnetic showers in different materials scales fairly accurately with the *Molière radius* R_M, given by [22]

$$R_M = X_0\,E_s/E_c \; , \tag{15}$$

where $E_s = \sqrt{4\pi/\alpha}\ m_e c^2 = 21.2$ MeV. In a material containing a weight fraction f_i of the element with critical energy E_{ci} and radiation length X_i, the Molière radius is given by

$$\frac{1}{R_M} = \frac{1}{E_s}\sum \frac{f_i\,E_{ci}}{X_i} \; . \tag{16}$$

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For very high-energy photons, the total e^+e^- pair-production cross section is approximately

$$\sigma = \tfrac{7}{9}(A/X_0 N_A) \ , \tag{17}$$

where A is the atomic weight of the material and N_A is Avogadro's number. Equation (17) is accurate to within a few percent down to energies as low as 1 GeV. The cross section decreases at lower energies, as shown in the figure "Fractional Energy Loss for Electrons and Positrons in Lead." As the energy decreases, a number of other processes become important, as is shown in the figures "Contributions to the Photon Cross Section in Carbon and Lead."

(8) Electromagnetic cascades: When a high-energy electron or photon is incident on a thick absorber, it initiates an electromagnetic cascade as pair production and bremsstrahlung generate more electrons and photons with lower energy. The longitudinal development is governed by the high-energy part of the cascade, and therefore scales as the radiation length in the material. Electron energies eventually fall below the critical energy, and then dissipate their energy by ionization and excitation rather than by the generation of more shower particles. In describing shower behavior, it is therefore convenient to introduce the scale variables

$$t = x/X_0$$
$$y = E/E_c \ , \tag{18}$$

so that distance is measured in units of radiation length and energy in units of critical energy.

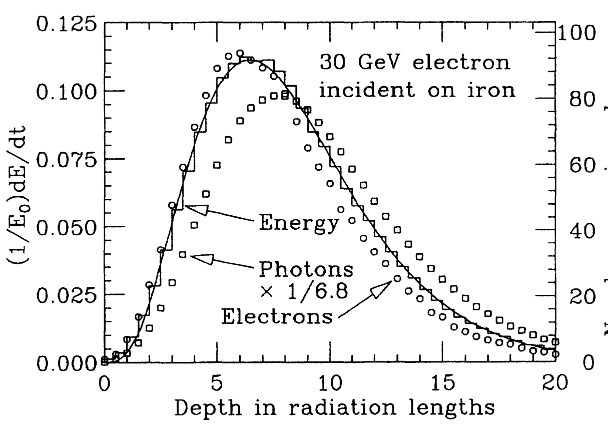

Fig. 2. An EGS4 simulation of a 30 GeV electron-induced cascade in iron. The histogram shows fractional energy deposition per radiation length, and the curve is a gamma-function fit to the distribution. Circles indicate the number of electrons with total energy greater than 1.5 MeV crossing planes at $X_0/2$ intervals (scale on right) and the squares the number of photons with $E \geq 1.5$ MeV crossing the planes (scaled down to have same area as the electron distribution).

Longitudinal profiles for an EGS4 [23] simulation of a 30 GeV electron-induced cascade in iron are shown in Fig. 2. The number of particles crossing a plane (very close to Rossi's Π function [1]) is sensitive to the cutoff energy, here chosen as a total energy of 1.5 MeV for both electrons and photons. The electron number falls off more quickly than energy deposition. This is because, with increasing depth, a larger fraction of the cascade energy is carried by photons. Exactly what a calorimeter measures depends on the device, but it is not likely to be exactly any of the profiles shown. In gas counters it may be very close to the electron number, but in glass Čerenkov detectors and other devices with "thick" sensitive regions it is closer to the energy deposition (total track length). In such detectors the signal is proportional to the "detectable" track length T_d, which is in general less than the total track length T. Practical devices are sensitive to electrons with energy above some detection threshold E_d, and $T_d = T\,F(E_d/E_c)$. An analytic form for $F(E_d/E_c)$ obtained by Rossi [1] is given by Fabjan [24]; see also Amaldi [25].

The mean longitudinal profile of the energy deposition in an electromagnetic cascade is reasonably well described by a gamma distribution [26]:

$$\frac{dE}{dt} = E_0\, b\, \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)} \tag{19}$$

The maximum $t_{\rm max}$ occurs at $(a-1)/b$. We have made fits to shower profiles in elements ranging from carbon to uranium, at energies from 1 GeV to 100 GeV. The energy deposition profiles are well described by Eq. (19) with

$$t_{\rm max} = (a-1)/b = 1.0 \times (\ln y + C_i) \ , \qquad i = e, \gamma \ , \tag{20}$$

where $C_e = -0.5$ for electron-induced cascades and $C_\gamma = +0.5$ for photon-induced cascades. The results are very similar for the electron number profiles, but there is some dependence on the atomic number of the medium. A similar form for the electron number maximum was obtained by Rossi in the context of his "Approximation B," [1] (see Fabjan's review in Ref. 24), but with $C_e = -1.0$ and $C_\gamma = -0.5$; we regard this as superseded by the EGS4 result.

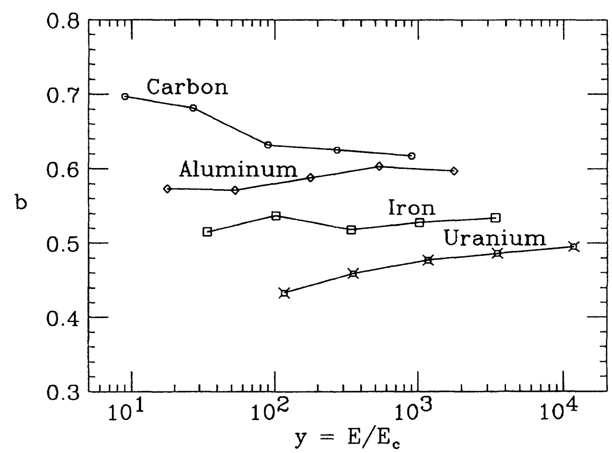

Fig. 3. Fitted values of the scale factor b for energy deposition profiles obtained with EGS4 for a variety of elements for incident electrons with $1 \leq E_0 \leq 100$ GeV. Values obtained for incident photons are essentially the same.

The "shower length" $X_s = X_0/b$ is less conveniently parametrized, since b depends upon both Z and incident energy, as shown in Fig. 3. As a corollary of this Z dependence, the number of electrons crossing a plane near shower maximum is underestimated using Rossi's approximation for carbon and seriously overestimated for uranium. Essentially the same b values are obtained for incident electrons and photons.

To use Eq. (19), one finds $t_{\rm max} = (a-1)/b$ from Eq. (20), then finds a either by assuming $b \approx 0.5$ or by finding a more accurate value from Fig. 3.

The gamma distribution is very flat near the origin, while the EGS4 cascade (or a real cascade) increases more rapidly. As a result Eq. (19) fails badly for about the first two radiation lengths; it was necessary to exclude this region in making fits.

Because fluctuations are important, Eq. (19) should be used only in applications where average behavior is adequate. Grindhammer *et al.* have developed fast simulation algorithms in which the variance and correlation of a and b are obtained by fitting Eq. (19) to individually simulated cascades, then generating profiles for cascades using a and b chosen from the correlated distributions [27].

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Measurements of the lateral distribution in electromagnetic cascades are shown in Refs. 22 and 28. On the average, only 10% of the energy lies outside the cylinder with radius R_M. About 99% is contained inside of $3.5R_M$, but at this radius and beyond composition effects become important and the scaling with R_M fails. The distributions are characterized by a narrow core, and broaden as the shower develops. They are often represented as the sum of two Gaussians, and Grindhammer [27] describes them with the function

$$f(r) = \frac{2r\,R^2}{(r^2+R^2)^2}\ , \tag{21}$$

where R is a phenomenological function of x/X_0 and $\ln E$.

(9) Muon energy loss at high energy: At high enough energies, radiative processes become more important than ionization for all charged particles. For muons and pions in materials such as iron, this "critical energy" occurs at several hundred GeV. For energetic muons found in cosmic rays or produced at the newest accelerators, radiative effects dominate. These processes are characterized by small cross sections, hard spectra, large energy fluctuations, and the associated generation of electromagnetic and (in the case of photonuclear interactions) hadronic showers. As a consequence, at these energies the treatment of energy loss as a uniform and continuous process is for many purposes inadequate.

It is convenient to write the average rate of muon energy loss as [29]

$$-dE/dx = a(E) + b(E)\,E\ . \tag{22}$$

Here $a(E)$ is the ionization energy loss given by Eq. (2), and $b(E)$ is the sum of e^+e^- pair production, bremsstrahlung, and photonuclear contributions. To the approximation that these slowly-varying functions are constant, the mean range x_0 of a muon with initial energy E_0 is given by

$$x_0 \approx (1/b)\ln(a + bE_0)\ . \tag{23}$$

Figure 4 shows contributions to $b(E)$ for iron. Since $a(E) \approx 0.002$ GeV g^{-1} cm^2, $b(E)E$ dominates the energy loss above several hundred GeV, where $b(E)$ is nearly constant. The rate of energy loss for muons in hydrogen, uranium, and iron is shown in Fig. 5 [30].

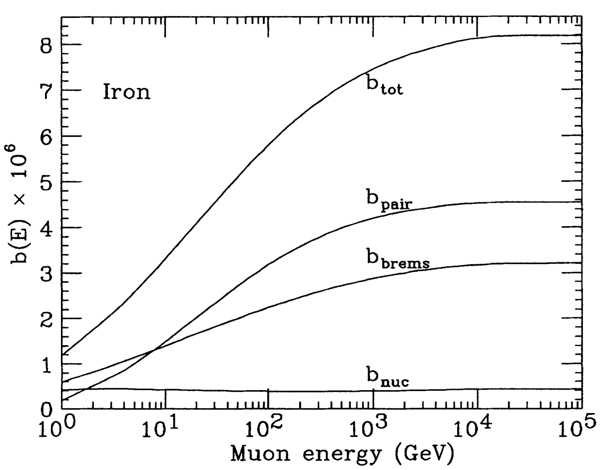

Fig. 4. Contributions to the fractional energy loss by muons in iron due to e^+e^- pair production, bremsstrahlung, and photonuclear interactions, as obtained from Lohmann *et al.* [30].

QED calculations of cross sections for bremsstrahlung and e^+e^- pair production have long been known, but were much improved around 1970 to meet the needs of cosmic ray physics [31–35]. Rozental showed that the screened atomic electron contribution could be included by replacing Z^2 with $Z(Z+1.2)$ in the nuclear bremsstrahlung cross sections and by $Z(Z+1.3)$ in the case of e^+e^-

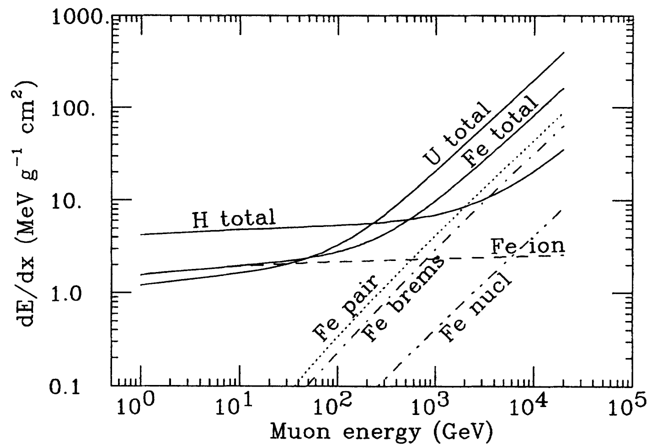

Fig. 5. The average energy loss of a muon in hydrogen, iron, and uranium as a function of muon energy. Contributions to dE/dx in iron from ionization and the processes shown in Fig. 4 are also shown.

pair production [36], and that other corrections might reduce the cross section by as much as 5%. We take this as the present uncertainty. Cross sections for both processes have been evaluated independently by Tsai [19].

A comparison of various improvements to the Bethe-Heitler formula is given by Wright [37]. For muon energies above 100 GeV, $\mu^+\mu^-$ pair production is also possible. This process is potentially troublesome because it can lead to charge misassignment, but it contributes less than 0.01% to the the total energy loss [30].

Photonuclear interactions account for about 5% of the total energy loss of high-energy muons in iron, and for about 2% in uranium [38]. The losses are concentrated in rare, relatively hard events.

These radiative cross sections are expressed as functions of the fractional energy loss ν. The bremsstrahlung cross section goes roughly as $1/\nu$ over most of the range, while for the pair production case the distribution goes as ν^{-3} to ν^{-2} (see Ref. 39). "Hard" losses are therefore more probable in bremsstrahlung, and in fact energy losses due to pair production may very nearly be treated as continuous. The momentum distribution of an incident 1 TeV/c muon beam after it crosses 3 m of iron is shown in Fig. 6. The most probable loss is 9 GeV, or 3.8 MeV g^{-1}cm^2. The full width at half maximum is 7 GeV/c, or 0.7%. The radiative tail is almost entirely due to bremsstrahlung; this includes most of the 10% that lost more than 2.8% of their energy. Most of the 3.3% that lost more than 10% of their incident energy experienced photonuclear interactions. The latter can exceed nominal detector resolution [40], necessitating the reconstruction of lost energy. Electromagnetic and hadronic cascades in detector materials can obscure muon tracks in detector planes and reduce tracking efficiency [41].

(10) Čerenkov and transition radiation [42,43,44]: A charged particle radiates if its velocity is greater than the local phase velocity of light (Čerenkov radiation) or if it crosses suddenly from one medium to another with different optical properties (transition radiation). Neither process is important for energy loss, but both are used in high-energy physics detectors.

Čerenkov Radiation. The half-angle θ_c of the Čerenkov cone for a particle with velocity βc in a medium with index of refraction n is

$$\begin{aligned}\theta_c &= \arccos(1/n\beta)\\ &\approx \sqrt{2(1-1/n\beta)}\quad \text{for small } \theta_c, \textit{e.g.} \text{ in gases.}\end{aligned} \tag{24}$$

The threshold velocity β_t is $1/n$, and $\gamma_t = 1/(1-\beta_t^2)^{1/2}$. Therefore, $\beta_t\gamma_t = 1/(2\delta+\delta^2)^{1/2}$, where $\delta = n-1$. Values of δ for various commonly used gases are given as a function of pressure and

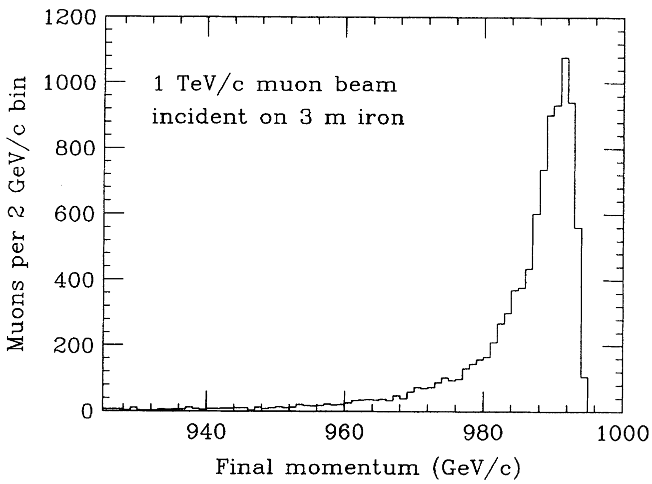

Fig. 6. The momentum distribution of 1 TeV/c muons after traversing 3 m of iron, as obtained with Van Ginniken's TRAMU muon transport code [39].

wavelength in Ref. 45. For values at atmospheric pressure, see our Table of Atomic and Nuclear Properties. Data for other commonly used materials are given in Ref. 46.

The number of photons produced per unit path length of a particle with charge ze and per unit energy interval of the photons is

$$\begin{aligned}\frac{d^2N}{dEdx} &= \frac{\alpha z^2}{\hbar c}\sin^2\theta_c = \frac{\alpha^2 z^2}{r_e\, m_e c^2}\left(1 - \frac{1}{\beta^2 n^2(E)}\right) \\ &\approx 370 \sin^2\theta_c(E)\ \mathrm{eV}^{-1}\mathrm{cm}^{-1} \qquad (z=1)\ ,\end{aligned} \tag{25}$$

or, equivalently,

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)\ . \tag{26}$$

The index of refraction is a function of photon energy E, as is the sensitivity of the transducer used to detect the light. For practical use, Eq. (25) must be multiplied by the the transducer response function and integrated over the region for which $\beta\, n(E) > 1$. Further details are given in the discussion of Čerenkov detectors in the Detectors section.

Transition Radiation. The energy radiated when a particle with charge ze crosses the boundary between vacuum and a medium with plasma frequency ω_p is

$$I = \alpha z^2 \gamma\hbar\omega_p/3\ , \tag{27}$$

where

$$\begin{aligned}\hbar\omega_p &= \sqrt{4\pi N_e r_e^3}\ m_e c^2/\alpha \\ &= \sqrt{4\pi N_e a_\infty^3}\ 2\times 13.6\ \mathrm{eV}\ .\end{aligned} \tag{28}$$

Here N_e is the electron density in the medium, r_e is the classical electron radius, and a_∞ is the Bohr radius. For styrene and similar materials, $\sqrt{4\pi N_e a_\infty^3} \approx 0.8$, so that $\hbar\omega_p \approx 20$ eV. The typical emission angle is $1/\gamma$.

The radiation spectrum is logarithmically divergent at low energies and decreases rapidly for $\hbar\omega/\gamma\hbar\omega_p > 1$. About half the energy is emitted in the range $0.1 \le \hbar\omega/\gamma\hbar\omega_p \le 1$. For a particle with $\gamma = 10^3$, the radiated photons are in the soft x-ray range 2 to 20 eV. The γ dependence of the emitted energy thus comes from the hardening of the spectrum rather than from an increased quantum yield. For a typical radiated photon energy of $\gamma\hbar\omega_p/4$, the quantum yield is

$$\begin{aligned}N_\gamma &\approx \frac{1}{2}\,\frac{\alpha z^2\gamma\hbar\omega_p}{3}\Big/\frac{\gamma\hbar\omega_p}{4} \\ &\approx \tfrac{2}{3}\alpha z^2 \approx 0.5\% \times z^2\ .\end{aligned} \tag{29}$$

More precisely, the number of photons with energy $\hbar\omega > \hbar\omega_0$ is given by [47]

$$N_\gamma(\hbar\omega > \hbar\omega_0) = \frac{\alpha z^2}{\pi}\left[\left(\ln\frac{\gamma\hbar\omega_p}{\hbar\omega_0} - 1\right)^2 + \frac{\pi^2}{12}\right]\ , \tag{30}$$

within corrections of order $(\hbar\omega_0/\gamma\hbar\omega_p)^2$. The number of photons above a fixed energy $\hbar\omega_0 << \gamma\hbar\omega_p$ thus grows as $(\ln\gamma)^2$, but the number above a fixed fraction of $\gamma\hbar\omega_p$ (as in the example above) is constant. For example, for $\hbar\omega > \gamma\hbar\omega_p/10$, $N_\gamma = 2.519\,\alpha z^2/\pi = 0.59\% \times z^2$.

The yield can be increased by using a stack of plastic foils with gaps between. However, interference can be important, and the soft x rays are readily absorbed in the foils. The first problem can be overcome by choosing thicknesses and spacings large compared to the "formation length" $D = \gamma c/\omega_p$, which in practical situations is tens of μm. Other practical problems are discussed in the Detectors section.

Revised April 1990 with the help of O. Dahl, R. Hagstrom, W.R. Nelson, and S.I. Parker.

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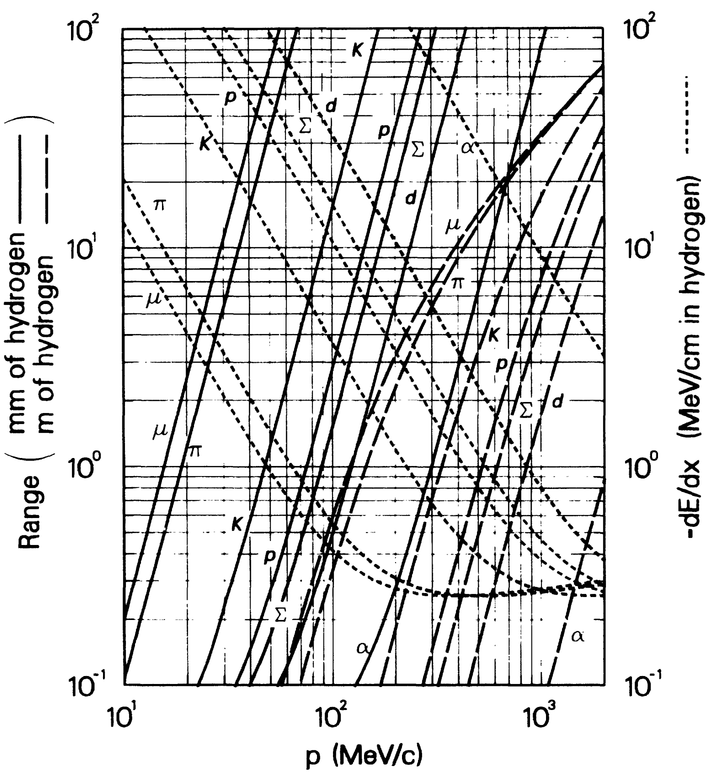
MEAN RANGE AND ENERGY LOSS

Mean Range and Energy Loss in Liquid Hydrogen

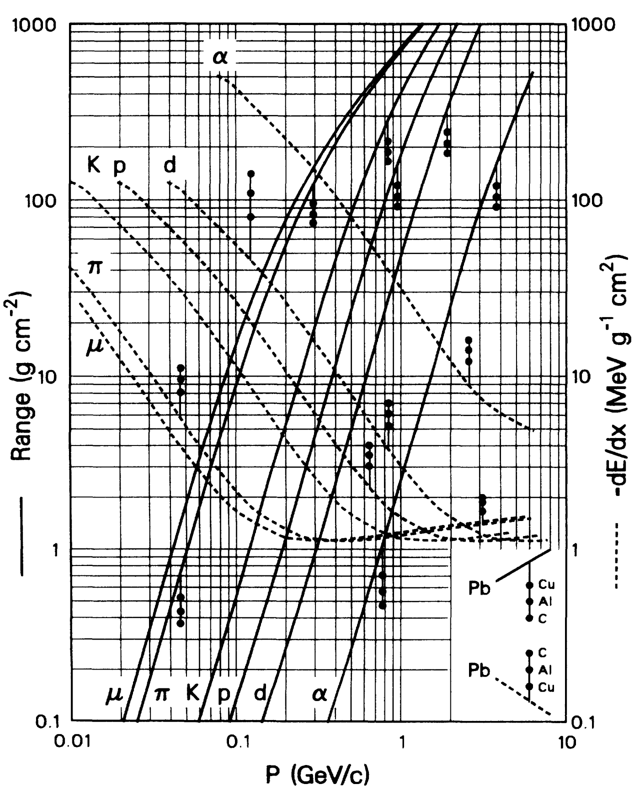


Range and energy loss in liquid hydrogen, based on Bethe-Bloch equation [See Sec. (1) of Passage of Particles Through Matter], using an average ionization potential for H_2 of $I = 20.0$ eV. , which is an approximate average of the experimental result of Garbincius and Hyman [Phys. Rev. **A2**, 1834 (70)] and the theoretical result of Ford and Browne [Phys. Rev. **A7**, 418 (73)]. Bubble chamber conditions are chosen to be those of Garbincius and Hyman: parahydrogen of density = 0.0625 g/cm^3 (note: range $\propto 1/\text{density}$), with vapor-pressure 60.8 lb/in^2 (absolute) and temperature 26.2°K. The functional dependence of the Bethe-Bloch equation is not experimentally verified to better than about ±1% over large momentum ranges. It should be noted that the number of bubbles per cm of a track in a bubble chamber is nearly proportional to $1/\beta^2$, not dE/dx. For the linear portions of the range curves, $R \propto p^{3.6}$. *Scaling law for particles of other mass or charge (except electrons):* for a given medium, the range R_b of any beam particle with mass M_b, charge z_b, and momentum p_b is given in terms of the range R_a of any other particle with mass M_a, charge z_a, and momentum $p_a = p_b M_a/M_b$ (i.e., having the same velocity) by the expression:

$$R_b\,(M_b,\ z_b,\ p_b) =$$

$$\left(\frac{M_b/M_a}{z_b^2/z_a^2}\right) R_a\,(M_a,\ z_a,\ p_a = p_b M_a/M_b)\ .$$

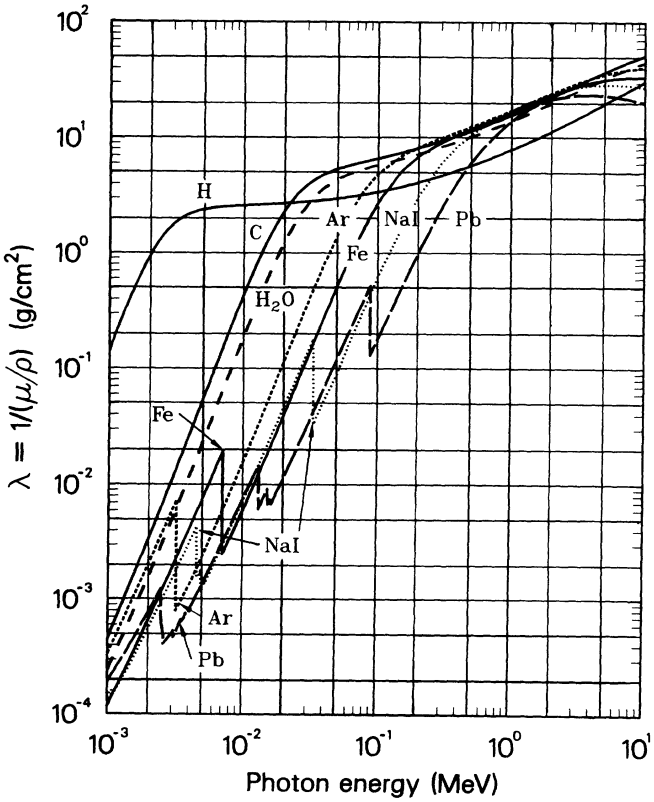
Mean Range and Energy Loss in Lead, Copper, Aluminum, and Carbon



Mean range and energy loss due to ionization for the indicated particles in Pb, with scaling to Cu, Al, and C shown, using Bethe-Bloch equation [See Sec. (1) of Passage of Particles Through Matter] with corrections. Calculated by M.J. Berger, using ionization potentials and density effect corrections as discussed in M.J. Berger and S.M. Seltzer, "Stopping Powers and Ranges of Electrons and Positrons," (2^{nd} ed.), U.S. National Bureau of Standards Report NBSIR 82-2550-A (1982). The average ionization potentials (I) assumed were: Pb (823 eV), Cu (322 eV), Al (166 eV), and C (78.0 eV). Figure indicates total path length; observed range may be smaller (by ~ 1–2% in heavy elements) due to multiple scattering, primarily from small energy-loss collisions with nuclei. The functional forms have not been experimentally verified to better than roughly ±1%. For higher energies refer to discussion by Cobb ["A Study of Some Electromagnetic Interactions of High Velocity Particles with Matter," University of Oxford Report HEP/T/55 (1973)] and by Turner ["Penetration of Charged Particles in Matter: A Symposium," National Academy of Sciences, Washington D.C. (1970), p. 48]. For lower energies neither data nor theory are well understood. Scaling to other beam particles is, to a good approximation, described by the formula in the previous figure caption.

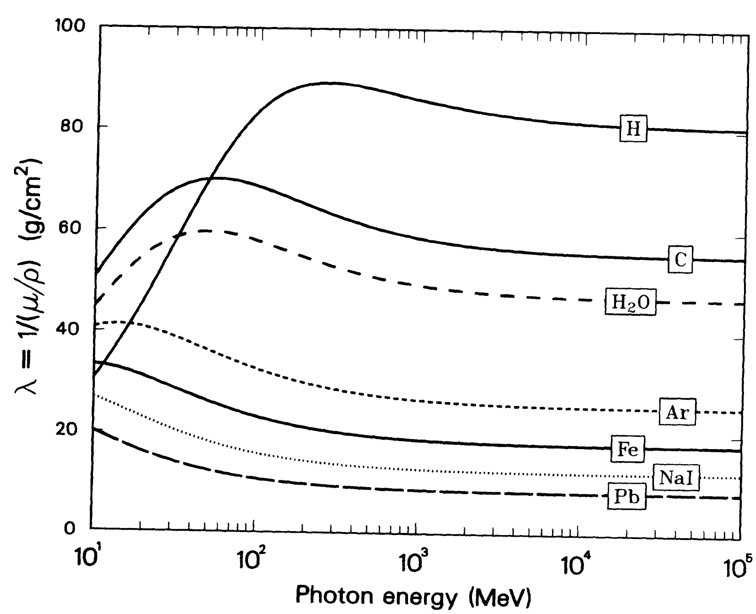
PHOTON AND ELECTRON ATTENUATION

Photon Attenuation Length



The photon mass attenuation length $\lambda = 1/(\mu/\rho)$ (also known as mfp, mean free path) for various absorbers as a function of photon energy, where μ is the mass attenuation coefficient. For a homogeneous medium of density ρ, the intensity I remaining after traversal of thickness t is given by the expression $I = I_0 \exp(-t\rho/\lambda)$. The accuracy is a few percent. Interpolation to other Z should be done in the cross section $\sigma = A/\lambda N_A$ cm²/atom, where A is the atomic weight of the absorber material in grams and N_A is the Avogadro number. For a chemical compound or mixture, use $(1/\lambda)_{\text{eff}} \approx \sum w_i (1/\lambda)_i$, accurate to a few percent, where w_i is the proportion by weight of the i^{th} constituent. See next page for high-energy range. The processes responsible for attenuation are given in a following figure. Not all of these processes necessarily result in detectable attenuation. For example, coherent Rayleigh scattering off an atom may occur at such low momentum transfer that the change in energy and momentum of the photon may not be significant. From Hubbell, Gimm, and Øverbø, J. Phys. Chem. Ref. Data **9**, 1023 (80). See also J.H. Hubbell, Int. J. of Applied Rad. and Isotopes **33**, 1269 (82). Data courtesy J.H. Hubbell.

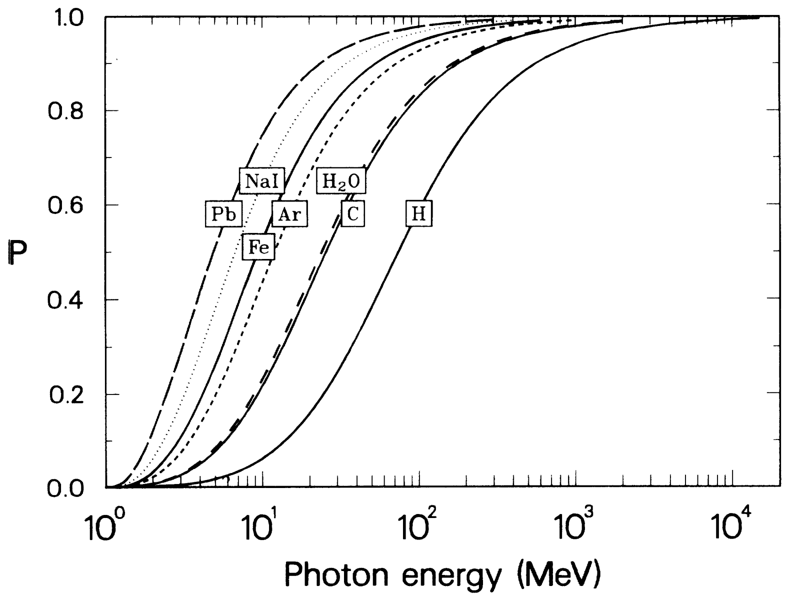
Photon Attenuation Length (High Energy)



The photon mass attenuation length, high-energy range (note that ordinate is linear scale). See previous figure caption for details. The attenuation length is constant beyond the range shown for at least two decades in energy.

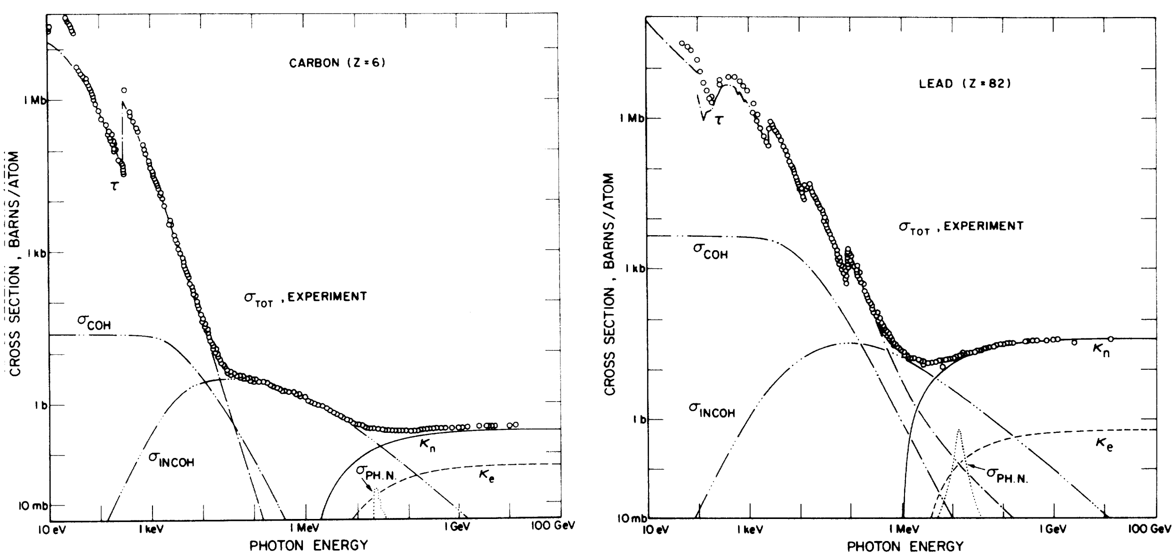
PHOTON AND ELECTRON ATTENUATION (Cont'd)

Photon Pair Conversion Probability



Probability P that a photon interaction will result in conversion to an e^+e^- pair. Except for a few-percent contribution from photonuclear absorption around 10 or 20 MeV, essentially all other interactions result in Compton scattering off an atomic electron. For a photon attenuation length λ (g/cm^2) (upper figure), the probability that a given photon will produce an electron pair (without first Compton scattering) in thickness t (cm) of absorber of density ρ (g/cm^3) is $P[1 - \exp(-t\rho/\lambda)]$.

Contributions to Photon Cross Section in Carbon and Lead



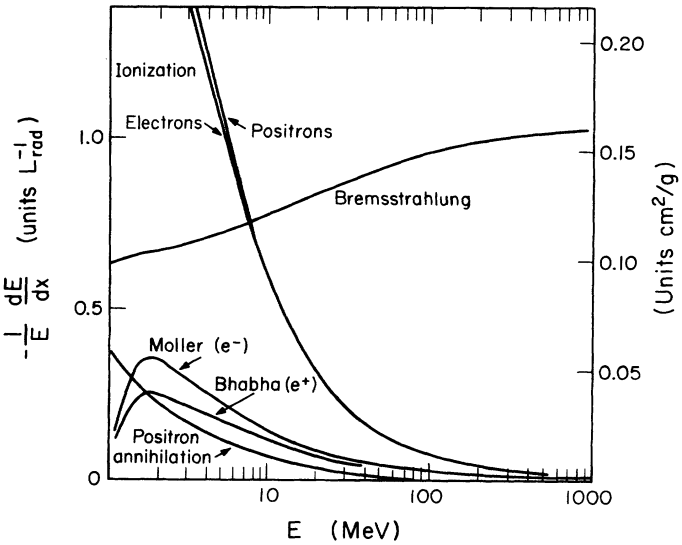
Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes.

τ = Atomic photo-effect (electron ejection, photon absorption)
$\sigma_{\rm COH}$ = Coherent scattering (Rayleigh scattering—atom neither ionized nor excited)
$\sigma_{\rm INCOH}$ = Incoherent scattering (Compton scattering off an electron)
κ_n = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{\rm PH.N.}$ = Photonuclear absorption (nuclear absorption, usually followed by emission of a neutron or other particle)

From Hubbell, Gimm, and Øverbø, J. Phys. Chem. Ref. Data **9**, 1023 (80). The photon total cross section is assumed approximately flat for at least two decades beyond the energy range shown. Figures courtesy J.H. Hubbell.

PHOTON AND ELECTRON ATTENUATION (Cont'd)

Fractional Energy Loss for Electrons and Positrons in Lead



Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization when the energy loss per collision is below 0.255 MeV, and as Moller (Bhabha) scattering when it is above. Adapted from Fig. 3.2 from Messel and Crawford, *Electron-Photon Shower Distribution Function Tables for Lead, Copper, and Air Absorbers*, Pergamon Press, 1970. Messel and Crawford use $L_r(\mathrm{Pb}) = 5.82\ \mathrm{g/cm^2}$, but we have modified the figures to reflect the value given in the Table of Atomic and Nuclear Properties of Materials, namely $L_r(\mathrm{Pb}) = 6.4\ \mathrm{g/cm^2}$. The development of electron-photon cascades is approximately independent of absorber when the results are expressed in terms of inverse radiation lengths (i.e., scale on left of plot).

COSMIC RAY FLUXES

The fluxes of particles of different types depend at the $\sim 10\%$ level on the latitude, their energy, and the conditions of measurement. Some typical sea-level values [1] for charged particles are given below:

I_v flux per unit solid angle per unit horizontal area about vertical direction

$$\equiv j(\theta = 0, \phi)[\theta = \text{zenith angle}, \phi = \text{azimuthal angle}] ;$$

J_1 total flux crossing unit horizontal area from above

$$\equiv \int_{\theta \leq \pi/2} j(\theta, \phi)\ \cos\theta\ d\Omega\ [d\Omega = \sin\theta\ d\theta\ d\phi] ;$$

J_2 total flux from above (impinging on a sphere of unit cross-sectional area)

$$\equiv \int_{\theta \leq \pi/2} j(\theta, \phi)\ d\Omega .$$

	Total Intensity	Hard Component	Soft Component
I_v	1.1×10^2	0.8×10^2	$0.3 \times 10^2\ \mathrm{m^{-2}\ s^{-1}\ sterad^{-1}}$
J_1	1.8×10^2	1.3×10^2	$0.5 \times 10^2\ \mathrm{m^{-2}\ s^{-1}}$
J_2	2.4×10^2	1.7×10^2	$0.7 \times 10^2\ \mathrm{m^{-2}\ s^{-1}}$

Very approximately, about 75% of all particles at sea level are penetrating, and are muons (the dominant portion of the hard component at sea level). The sea-level vertical flux ratio for protons to muons (both charges together) is about 3.5% at 1 GeV/c, decreasing to about 0.5% at 10 GeV/c.

The muon flux at sea level has a mean energy of 2 GeV and a differential spectrum falling as E^{-2}, steepening smoothly to $E^{-3.6}$ above a few TeV. The angular distribution is $\cos^2\theta$, changing to $\sec\theta$ at energies above a TeV, where θ is the zenith angle at production. The $\pm$ charge ratio is 1.25–1.30. The mean energy of muons originating in the atmosphere is roughly 300 GeV at slant depths $\gtrsim$ a few hundred meters. Beyond slant depths of $\sim$ 10 km water-equivalent, the muons are due primarily to in-the-earth neutrino interactions (roughly 1/8 interaction $\mathrm{ton^{-1}\ year^{-1}}$ for $E_\nu > 300$ MeV, $\sim$ constant throughout the earth) [2]. Muons from this source arrive with a mean energy of 20 GeV, and have a flux of $2 \times 10^{-9}\ \mathrm{m^{-2}\ s^{-1}\ sterad^{-1}}$ in the vertical direction and about twice that in the horizontal [3], down at least as far as the deepest mines.

Updated April 1986.

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PARTICLE DETECTORS

In this section we give various parameters for common detector components. The quoted numbers are usually based on typical devices, and should be regarded only as rough approximations for new designs. A more detailed discussion of detectors can be found in Ref. 1. In Table 1 are given typical spatial and temporal resolutions of common detectors.

Table 1. Typical detector characteristics.

Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10 to 150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	$\geq$ 300 μm[b,c]	50 ns	200 ns
Drift chamber	50 to 300 μm	2 ns[d]	100 ns
Scintillator	—	150 ps	10 ns
Emulsion	1 μm	—	—
Silicon strip	pitch[e] / 3 to 7	f	f
Silicon pixel	2 μm[g]	f	f

[a] Multiple pulsing time.
[b] 300 μm is for 1 mm pitch.
[c] Delay line cathode readout can give $\pm$150 μm parallel to anode wire.
[d] For two chambers.
[e] The highest resolution ("7") is obtained for small-pitch detectors ($\lesssim$25 μm) with pulse-height-weighted center finding.
[f] Limited at present by properties of the readout electronics. (Time resolution of $\leq$ 15 ns is planned for the SDC silicon tracker.)
[g] Analog readout of 34 μm pitch, monolithic pixel detectors.

(1) Plastic scintillators

The photon yield in the frequency range of practical photomultiplier tubes is $\approx$ 1 photon per 100 eV of charged particle ionization energy loss in plastic scintillator [2]. One must take into account the light collection efficiency ($\lesssim$10% for typical 1-cm-thick scintillator), the attenuation length (1 to 4 m for typical scintillators [3]), and the quantum efficiency of the photomultiplier cathode ($\lesssim$25% when folded with a typical scintillator emission spectrum).

(2) Inorganic scintillators

Table 2 gives a partial list of commonly-used inorganic scintillators in high-energy and nuclear physics [4–11]. These scintillating crystals are generally used where high density and good energy resolution are required. In a crystal which contains nearly all of the energy deposited by an incident particle, the energy resolution is determined largely, but not totally, by the light output. The table gives the light output of the various materials relative to NaI, which has an intrinsic light output of about 40000 photons per MeV of energy deposit. The detected signal is usually quoted in terms of photoelectrons per MeV produced by a given photodetector. The relationship between photons/MeV produced and p.e.'s/MeV detected involves factors for light collection efficiency (typically 10–50%, depending on geometry) and the quantum efficiency of the detector ($\sim$ 15–20% for photomultiplier tubes and $\sim$ 70% for silicon photodiodes for visible wavelengths). The quantum efficiency of the detector is usually highly wavelength dependent and should be matched to the particular crystal of interest to give the highest quantum yield at the wavelength corresponding to the peak of the scintillation emission. The comparison of the light output given in Table 2 is for a standard photomultiplier tube with a bialkali photocathode. For scintillators which emit in the UV, a detector with a quartz window should be used.

Table 2. Properties of several inorganic crystal scintillators.

	NaI(Tl)	BGO	BaF_2	CsI(Tl)	CsI(pure)
Density (g/cm^3)	3.67	7.13	4.89	4.53	4.53
Radiation length (cm)	2.59	1.12	2.05	1.85	1.85
Molière radius (cm)	4.5	2.4	3.4	3.8	3.8
dE/dx (MeV/cm) (per mip)	4.8	9.2	6.6	5.6	5.6
Nucl. int. length (cm)	41.4	22.0	29.9	36.5	36.5
Decay time (ns)	250	300	0.7^f / 620^s	1000	$10, 36^f$ / $\sim 1000^s$
Peak emission λ (nm)	410	480	220^f / 310^s	565	305^f / $\sim 480^s$
Refractive index	1.85	2.20	1.56	1.80	1.80
Relative light output	1.00	0.15	0.05^f / 0.20^s	0.40	0.10^f / 0.02^s
Hygroscopic	very	no	slightly	somewhat	somewhat

f = fast component, s = slow component

(3) Čerenkov detectors

Čerenkov detectors utilize one or more of the properties of Čerenkov radiation discussed in the Passages of Particles through Matter section: the existence of a *threshold* for radiation; the dependence of the Čerenkov cone half-angle θ_c on the *velocity* of the particle; the dependence of the *number of emitted photons* on the particle's velocity. The presence of the refractive index n in the relations allows tuning these quantities for a particular experimental application (*e.g.*, using pressurized gas and/or various liquids as radiators).

The number of photoelectrons (p.e.'s) detected in a given device or channel is

$$N_{\rm p.e.} = L\frac{\alpha^2 z^2}{r_e\, m_e c^2}\int \epsilon_{\rm coll}(E)\,\epsilon_{\rm det}(E)\sin^2\theta_c(E)dE\ ,$$

where L is the path length in the radiator, $\epsilon_{\rm coll}$ is the efficiency for collecting the Čerenkov light, $\epsilon_{\rm det}$ is the quantum efficiency of the transducer (photomultiplier or equivalent), and $\alpha^2/(r_e\, m_e c^2) =$ 370 cm^{-1}eV^{-1}. The quantities $\epsilon_{\rm coll}$, $\epsilon_{\rm det}$, and θ_c are all functions of the photon energy E, although in typical detectors θ_c (or, equivalently, the index of refraction) is nearly constant over the useful range of photocathode sensitivity. In this case,

$$N_{\rm p.e.} \approx LN_0\left\langle \sin^2\theta_c\right\rangle$$

with

$$N_0 = \frac{\alpha^2 z^2}{r_e\, m_e c^2}\int \epsilon_{\rm coll}\,\epsilon_{\rm det} dE\ .$$

We take $z = 1$, the usual case in high-energy physics, in the following discussion.

Threshold Čerenkov detectors make a simple yes/no decision based on whether the particle is above/below the Čerenkov threshold velocity $\beta_t = 1/n$. Careful designs give $\langle\epsilon_{\rm coll}\rangle \gtrsim 90\%$. For a photomultiplier with a typical bialkali cathode, $\int \epsilon_{\rm det} dE \approx 0.27$, so that

$$N_{\rm p.e.}/L \approx 90\ {\rm cm}^{-1}\left\langle \sin^2\theta_c\right\rangle \qquad (i.e.,\ N_0 = 90\ {\rm cm}^{-1})\ .$$

Suppose, for example, that n is chosen so that the threshold for species a is p_t; that is, at this momentum species a has velocity $\beta_a = 1/n$. A second, lighter, species b with the same momentum has velocity β_b, so $\cos\theta_c = \beta_a/\beta_b$, and

$$\frac{N_{\rm p.e.}}{L} \approx 90\ {\rm cm}^{-1}\frac{m_a^2 - m_b^2}{p_t^2 + m_a^2}\ .$$

For K/π separation at $p = 1$ GeV/c, $N_{\rm p.e.}/L \approx 16$ cm^{-1} for π's and (by design) 0 for K's.

PARTICLE DETECTORS (Cont'd)

For limited path lengths $N_{\rm p.e.}$ can be small, and some minimum number is required to trigger external electronics. The overall efficiency of the device is controlled by Poisson fluctuations, which can be especially critical for separation of species where one particle type is dominant [12].

A related class of detectors uses the number of observed photoelectrons (or the calibrated pulse height) to discriminate between species or to set probabilities for each particle species [13].

Differential Čerenkov detectors exploit the dependence of θ_c on β, using optical focusing and/or geometrical masking to select particles having velocities in a specified region. With careful design, a velocity resolution of $\sigma_\beta/\beta \approx 10^{-4}$–$10^{-5}$ can be obtained [12,14].

Ring-Imaging Čerenkov detectors use all three properties of Čerenkov radiation in both small-aperture and 4π geometries. They are principally used as hypothesis-testing rather than yes/no devices; that is, the probability of various identification possibilities is established from θ_c and $N_{\rm p.e.}$ for a particle of known momentum. In most cases the optics map the Čerenkov cone onto a circle at the photodetector, often with distortions which must be understood.

The 4π devices [15,16] typically have both liquid (C_6F_{14}, $n = 1.276$) and gas (C_5F_{12}, $n = 1.0017$) radiators, the light from the latter being focused by mirrors. They achieve 3 σ separation of $e/\pi/K/p$ over wide ranges, as shown in Table 3. Great attention to detail, especially with the minimization of UV-absorbing impurities, is required to get $\langle\epsilon_{\rm coll}\rangle \gtrsim 50\%$.

Table 3. Momentum range for 3σ separation in the SLD ring-imaging Čerenkov detector.

Particle pair	Momentum range for 3 σ separation
e/π	$p \lesssim 5$ GeV/c
π/K	$0.23 \lesssim p \lesssim 20$ GeV/c
K/p	$0.82 \lesssim p \lesssim 30$ GeV/c

The phototransducer is typically a TPC/wire-chamber combination sensitive to single photoelectrons and having charge division or pads. This construction permits three-dimensional reconstruction of photoelectron origins, which is important for transforming the Čerenkov cone into a ring. Single photoelectrons are generated by doping the TPC gas (for instance, ethane/methane in some proportion) with $\sim 0.05\%$ TMAE [tetrakis(dimethylamino)ethylene] [17], leading to photon absorption lengths along the Čerenkov cone of ~ 30 mm. The readout wires must be equipped with special structures (blinds or wire gates) to prevent photon feedback from avalanches generating cross-talk photoelectrons in the TPC. Drift-gas purity must be maintained to assure mean drift lengths of the order of meters without recombination (*i.e.*, lifetimes of $\gtrsim$ 100 μs at typical drift velocities of $\gtrsim$ 4 cm/μs). The net $\langle\epsilon_{\rm det}\rangle$'s reach 30%, with the limitation being the TMAE quantum efficiency.

Photon energy cutoffs are set by the TMAE ($E > 5.4$ eV), the UV transparency of fused silica glass ($E < 7.4$ eV), and the C_6F_{14} ($E < 7.1$ eV). With effort one gets $50 \le N_0 \le 100$ for complete rings using liquid or gas. This includes losses due to electrostatic shielding wires and window/mirror reflections, but not gross losses caused by total internal reflection or inadequate coverage by the TPC's.

Such numbers allow determination of ring radii to $\sim$0.5% (liquid) and $\sim$2% (gas), leading to the particle species separations quoted above. Since the separation efficiencies may have "holes" as a function of p, detailed calculations are necessary.

(4) Transition radiation detectors (TRD's)

It is evident from the discussion in the Passages of Particles Through Matter section that transition radiation (TR) only becomes useful for particle detectors when the Lorentz factor $\gamma \gtrsim 10^3$. In practice, TRD's are used to provide e/π separation when $p \gtrsim 1$ GeV/c. (The momentum is usually measured elsewhere in the detector.) Since a soft x ray is radiated with about 1% probability per boundary crossing, practical detectors use radiators with several hundred interfaces, *e.g.* foils of lithium or plastic in a gas. Absorption inside the radiator and interference effects between interfaces are important [18,19].

A practical detector is composed of several similar modules, each consisting of a radiator and an x-ray detector. The radiator is made of foils or fibers of a low-Z material (for low absorption) in a low-Z gas such as helium. The x-ray detector is usually a wire chamber operated with a xenon-rich mixture in order to obtain a high conversion efficiency. As transition radiation is emitted at small angles, the chamber usually detects the sum of the ionization of the particle and of converted TR photons. The discrimination between electrons and pions can be based on the charges measured in each set, or on more sophisticated methods using pulse-shape analysis. The TRD in the D0 experiment serves as an example [20,21].

The major factor in the performance of a TRD is its overall length. Very roughly, the pion rejection factor for a detector with 90% electron efficiency is $10^{(L/20\ \rm cm)}$, where L is the overall length of a radiator with foils. Radiators with fibers are easier to build, but generally provide a rejection factor which is at least a factor of two lower.

(5) Silicon photodiodes and particle detectors

Silicon detectors are p-n junction diodes operated at reverse bias. This forms a sensitive region depleted of mobile charge and sets up an electric field that sweeps charge liberated by radiation to the electrodes. The thickness of the depleted region is

$$W = \sqrt{\frac{2\epsilon\,(V + V_{bi})}{ne}} = \sqrt{2\rho\epsilon(V + V_{bi})}\ ,$$

where V = external bias voltage
V_{bi} = "built-in" voltage(≈ 0.8 V for resistivities typically used in detectors
n = doping concentration
e = electron charge
ϵ = dielectric constant = $11.9\ \epsilon_0 \approx 1$ pF/cm
ρ = resistivity (typically 1–10 kΩ cm)
μ = charge carrier mobility
= 1350 cm^2 V^{-1} s^{-1} for electrons (n-type material)
= 450 cm^2 V^{-1} s^{-1} for holes (p-type material)

or

$$W = 0.5\ \mu{\rm m} \times \sqrt{\rho(V + V_{bi})} \quad \text{for } n\text{-type material, and}$$

$$W = 0.3\ \mu{\rm m} \times \sqrt{\rho(V + V_{bi})} \quad \text{for } p\text{-type material,}$$

where V is in volts and ρ is in Ω cm.

The corresponding capacitance per unit area is

$$C = \frac{\epsilon}{W} \approx 1\,[\text{pF/cm}]\,\frac{1}{W}\ .$$

In strip detectors the capacitance is dominated by the strip-to-strip fringing capacitance of $\sim$ 1–1.5 pF cm^{-1} of strip length at a strip pitch of 25–50 μm.

About 3.6 eV is required to create an electron-hole pair. For minimum-ionizing particles, the most probable charge deposition in a 300 μm thick silicon detector is about 4 fC (25000 electrons). Readily available photodiodes have quantum efficiences > 70% for wavelengths between 600 nm and 1 μm. UV extended photodiodes have useful efficiency down to 200 nm. In applications in which photodiodes detect light from scintillators, care must be taken so that signal from the scintillator is larger than that produced by particles going through the photodiode.

Collection time decreases with increased depletion voltage, and can be reduced further by operating the detector with "overbias," *i.e.*, a bias voltage exceeding the value required to fully deplete the device. The collection time is limited by velocity saturation at high fields; at an average field of 10^4 V/cm, the collection times is about 15 ps/μm for electrons and 30 ps/μm for holes. In typical strip detectors of 300 μm thickness, electrons are collected within about 8 ns, and holes within about 25 ns.

PARTICLE DETECTORS (Cont'd)

Position resolution is limited by transverse diffusion during charge collection (typically 5 μm for 300 μm thickness) and by knock-on electrons. Resolutions of 3–4 μm (rms) have been obtained in beam tests. In magnetic fields, the Lorentz drift can increase the spatial spread appreciably (see "Hall effect" in semiconductor textbooks).

Radiation damage occurs through two basic mechanisms:

1. Bulk damage due to displacement of atoms from their lattice sites. This leads to increased leakage current, carrier trapping, and changes in doping concentration. Displacement damage depends on the nonionizing energy loss, *i.e.,* particle type and energy. The dose should be specified as a fluence of particles of a specific type and energy.
2. Surface damage due to charge build-up in surface layers, which leads to increased surface leakage currents. In strip detectors the inter-strip isolation is affected. The effects of charge build-up are strongly dependent on the device structure and on fabrication details. Since the damage is determined directly by the absorbed energy, the dose should be specified in these units (rad or Gray).

The increase in leakage current due to bulk damage is $\Delta i = \alpha\phi$ per unit volume, where ϕ is the particle fluence and α the damage coefficient ($\alpha \approx 2 \times 10^{-17}$ A/cm for minimum ionizing protons and pions after long-term annealing; roughly the same value applies for 1 MeV neutrons). The doping concentration in n-type silicon changes as $n = n_0\exp(-\delta\phi) - \beta\phi$, where n_0 is the initial donor concentration, $\delta \approx 6 \times 10^{14}$ cm^2 determines donor removal, and $\beta \approx 0.03$ cm^{-1} describes acceptor creation. This leads to an initial increase in resisitivity until type-inversion changes the net doping from n to p. At this point the resistivity decreases, with a corresponding increase in depletion voltage. The safe operating limit of depletion voltage ultimately limits the detector lifetime. Strip detectors have remained functional at fluences beyond 10^{14} cm^{-2} for minimum ionizing protons. At this damage level, charge loss due to recombination and trapping also seems to become significant.

(6) Proportional and drift chambers

Proportional chamber wire instability The limit on the voltage V for a wire tension T, due to mechanical effects when the electrostatic repulsion of adjacent wires exceeds the restoring force of wire tension, is given by (MSKA) [22]

$$V \le \frac{s}{\ell C}\sqrt{4\pi\epsilon_0 T} \ ,$$

where s, ℓ, and C are the wire spacing, length, and capacitance per unit length. An approximation to C for chamber half-gap t and wire diameter d (good for $s \lesssim t$) gives [23]

$$V \lesssim 59T^{1/2}\left[\frac{t}{\ell} + \frac{s}{\pi\ell}\ln\left(\frac{s}{\pi d}\right)\right] \ ,$$

where V is in kV, and T is in grams-weight equivalent.

Proportional and drift chamber potentials The potential distributions and fields in a proportional or drift chamber can usually be calculated with good accuracy from the exact formula for the potential around an array of parallel line charges q (coul/m) along z and located at $y = 0$, $x = 0, \pm s, \pm 2s, \ldots,$

$$V(x,y) = -\frac{q}{4\pi\epsilon_0}\ln\left\{4\left[\sin^2\left(\frac{\pi x}{s}\right) + \sinh^2\left(\frac{\pi y}{s}\right)\right]\right\} \ .$$

Errors from the presence of cathodes, mechanical defects, TPC-type edge effects, etc., are usually small and are beyond the scope of this review.

(7) Calorimeters

Electromagnetic calorimeters. The development of electromagnetic showers is discussed in the "Passage of Particles Through Matter" section. Formulae are given for the approximate description of average showers, but since the physics of electromagnetic showers is well understood, detailed and reliable Monte Carlo simulation is possible. EGS4 has emerged as the standard [24].

The resolution of sampling calorimeters (hadronic and electromagnetic) is usually dominated by sampling fluctuations, leading to fractional resolution σ/E scaling inversely as the square root of the incident energy. Homogenous calorimeters, such as solid NaI(Tl), will in general not have resolution varying as $1/\sqrt{E}$. At high energies deviations from $1/\sqrt{E}$ occur because of noise, pedestal fluctuations, nonuniformities, calibration errors, and incomplete shower containment. Such effects are usually included by adding a constant term to σ/E, either in quadrature or (incorrectly) directly. In the case of the hadronic cascades discussed below, noncompensation also contributes to the constant term.

In Table 4 we give resolution as measured in detectors using typical EM calorimeter technologies. In almost all cases the installed calorimeters yield worse resolution than test beam prototypes for a variety of practical reasons. Where possible actual detector performance is given. For a fixed number of radiation lengths, the FWHM in sandwich detectors would be expected to be proportional to $\sqrt{t}$ for t (= plate thickness) ≥ 0.2 radiation lengths [25].

Given sufficient transverse granularity early in the calorimeter, position resolution of the order of a millimeter can be obtained.

Table 4. Resolution of typical electromagnetic calorimeters. E is in GeV.

Detector	Resolution
NaI(Tl) (Crystal Ball [26]; 20 X_0)	$2.7\%/E^{1/4}$
Lead glass (OPAL [27])	$5\%/\sqrt{E}$
Lead-liquid argon (NA31 [28]; 80 cells: 27 X_0, 1.5 mm Pb + 0.6 mm Al + 0.8 mm G10 + 4 mm LA)	$7.5\%/\sqrt{E}$
Lead-scintillator sandwich (ARGUS [29], LAPP-LAL [30])	$9\%/\sqrt{E}$
Lead-scintillator spaghetti (CERN test module) [31]	$13\%/\sqrt{E}$
Proportional wire chamber (MAC; 32 cells: 13 X_0, 2.5 mm typemetal + 1.6 mm Al) [32]	$23\%/\sqrt{E}$

Hadronic calorimeters [33,34]. The length scale appropriate for hadronic cascades is the nuclear interaction length, given very roughly by

$$\lambda_I \approx 35 \text{ g cm}^{-2} A^{1/3} \ .$$

Longitudinal energy deposition profiles are characterized by a sharp peak near the first interaction point (from the fairly local deposition of EM energy resulting from π^0's produced in the first interaction), followed by a more gradual development with a maximum at

$$x/\lambda_I \equiv t_{\max} \approx 0.2\ln(E/1\text{ GeV}) + 0.7$$

as measured from the front of the detector.

The depth required for containment of a fixed fraction of the energy also increases logarithmically with incident particle energy. The thickness of iron required for 95% and 99% containment of cascades induced by single hadrons is shown in Fig. 1 [35]. Two of the sets of data are from large neutrino experiments, while the third is from a commonly used parametrization. Depths as measured in nuclear interaction lengths presumably scale to other materials. From the same data it can be concluded that the requirement that 95% of the energy in 95% of the showers be contained requires 40 to 50 cm (2.4 to 3.0 λ_I) more material material than for an average 95% containment.

The transverse dimensions of hadronic showers also scale as λ_I, although most of the energy is contained in a narrow core.

The energy deposit in a hadronic cascade consists of a prompt EM component due to π^0 production and a slower component mainly due to low-energy hadronic activity. In general, these energy depositions are converted to electrical signals with different efficiencies. The ratio of the conversion efficiencies is usually called the intrinsic e/h ratio. If $e/h = 1.0$ the calorimeter is said to be *compensating.* If it differs from

PARTICLE DETECTORS (Cont'd)

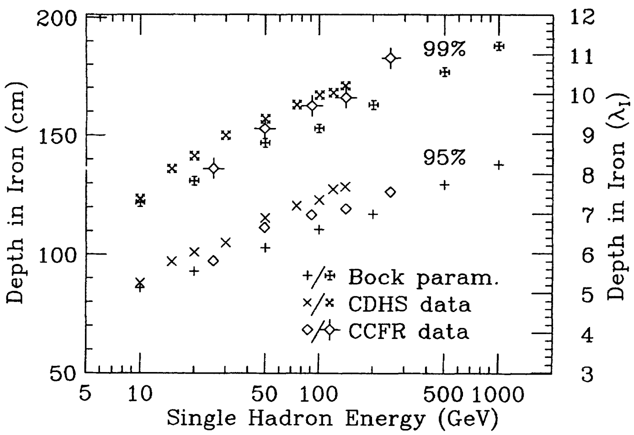

Fig. 1. Required calorimeter thickness for 95% and 99% hadronic cascade containment in iron, on the basis of data from two large neutrino detectors and the parametrization of Bock *et al.* [35].

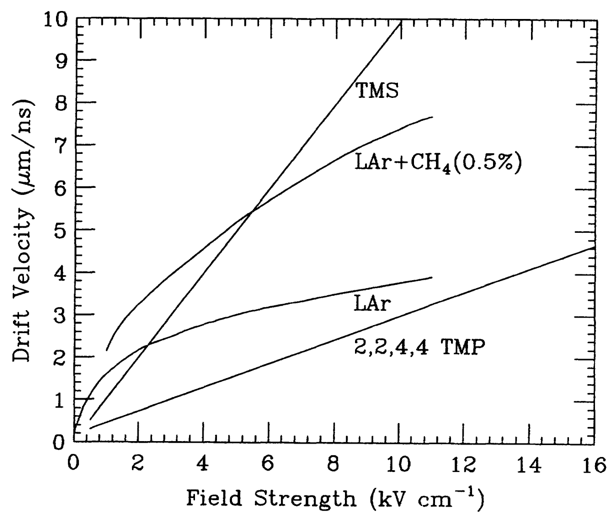

Fig. 2. Electron drift velocity as a function of field strength for commonly used liquids.

unity by more than 5% or 10%, detector performance is compromised because of fluctuations in the π^0 content of the cascades. Problems include:

a) A skewed signal distribution;

b) A response ratio for electrons and hadrons (the "e/π ratio") which is different from unity and depends upon energy;

c) A nonlinear response to hadrons (the response per GeV is proportional to the reciprocal of e/π);

d) A constant contribution to detector resolution, almost proportional to the degree of noncompensation. The coefficient relating the constant term to $|1 - e/h|$ is 14% according to FLUKA simulations, and 21% according to Wigman's calculations [33].

In most cases e/h is greater than unity, particularly if little hydrogen is present or if the gate time is short. This is because much of the low-energy hadronic energy is "hidden" in nuclear binding energy release, low-energy spallation products, etc. Partial correction for these losses occurs in a sampling calorimeter with thick plates, because a disproportionate fraction of electromagnetic energy is deposited in the inactive region. For this reason, it is very unlikely that a fully sensitive detector such as BGO or glass can be made compensating.

Compensation has been demonstrated in calorimeters with 2.5 mm scintillator sheets sandwiched between 3 mm depleted uranium plates [37] or 10 mm lead plates [38]; resolutions σ/E of $0.34/\sqrt{E}$ and $0.44/\sqrt{E}$ were obtained for these cases (E in GeV). The former was shown to be linear to within 2% over three orders of magnitude in energy, with approximately Gaussian signal distributions.

<u>dE/dx resolution in argon.</u> Particle identification by dE/dx is dependent on the width of the distribution. For relativistic incident particles with charge e in a multiple-sample Ar gas counter with no lead [39],

$$\left.\frac{dE}{dx}\right|_{\rm FWHM} \Big/ \left.\frac{dE}{dx}\right|_{\rm most\ probable} = 0.96\, N^{-0.46}\, (xp)^{-0.32} ,$$

where N = number of samples, x = thickness per sample (cm), p = pressure (atm.). Most commonly used chamber gases (except Xe) give approximately the same resolution.

<u>Free electron drift velocities in liquid ionization chambers</u> [40–43] Velocity as a function of electric field strength is given in Fig. 2.

(8) Measurement of particle momenta in a uniform magnetic field [44]

The trajectory of a particle with momentum p (in GeV/c) and charge ze in a constant magnetic field $\vec{B}$ is a helix, with radius of curvature R and pitch angle λ. The radius of curvature and momentum component perpendicular to $\vec{B}$ are related by

$$p \cos\lambda = 0.3\, z\, B\, R ,$$

where B is in tesla and R is in meters.

The distribution of measurements of the curvature $k \equiv 1/R$ is approximately Gaussian. The curvature error for a large number of uniformly spaced measurements on the trajectory of a charged particle in a uniform magnetic field can be approximated by

$$(\delta k)^2 = (\delta k_{\rm res})^2 + (\delta k_{\rm ms})^2 ,$$

where δk = curvature error
$\delta k_{\rm res}$ = curvature error due to finite measurement resolution
$\delta k_{\rm ms}$ = curvature error due to multiple scattering.

If many (≥ 10) uniformly spaced position measurements are made along a trajectory in a uniform medium,

$$\delta k_{\rm res} = \frac{\epsilon}{L'^2}\sqrt{\frac{720}{N+5}} .$$

If a vertex constraint is applied at the origin of the track, the coefficient under the radical becomes 320.

where N = number of points measured along track
L' = the projected length of the track onto the bending plane
ϵ = measurement error for each point, perpendicular to the trajectory.

The contribution due to multiple Coulomb scattering is approximately

$$\delta k_{\rm ms} \approx \frac{(0.016)({\rm GeV}/c)z}{Lp\beta\cos^2\lambda}\sqrt{\frac{L}{X_0}} ,$$

where p = momentum (GeV/c)
z = charge of incident particle in units of e
L = the total track length
X_0 = radiation length of the scattering medium (in units of length; the X_0 defined elsewhere must be multiplied by density)
β = the kinematic variable v/c.

PARTICLE DETECTORS (Cont'd)

More accurate approximations for multiple scattering may be found in the section on Passage of Particles Through Matter (following). The contribution to the curvature error is given approximately by $\delta k_{\rm ms} \approx 8 s^{\rm rms}_{\rm plane}/L^2$, where $s^{\rm rms}_{\rm plane}$ is defined there.

(9) Superconducting solenoids for collider detectors

Basic (approximate) equations: In all cases SI units are assumed, so that B is in tesla, E is in joules, dimensions are in meters, and $\mu_0 = 4\pi \times 10^{-7}$.

Magnetic field. The magnetic field at the center of a solenoid of length L and radius R, having N total turns and a current I is

$$B(0,0) = \frac{\mu_0 N I}{\sqrt{L^2 + 4R^2}} \ .$$

Stored energy. The energy stored in the magnetic field of any magnet is calculated by integrating B^2 over all space:

$$E = (1/2\mu_0) \int B^2 dV \ .$$

For a solenoid with an iron flux return in which the magnetic field is $< 2T$, the field in the aperture is approximately uniform and equal to $\mu_0 N I/L$. If the thickness of the coil is small, (which is the case if it is superconducting), then

$$E \simeq (\pi/2\mu_0) B^2 R^2 L \ .$$

Cost of a superconducting solenoid [45]:

$$\text{Cost (in M\$)} = 0.523\,[(E/(1\text{MJ})]^{0.662}$$

Magnetostatic computer programs. It is too difficult to solve the Biot-Savart equation for a magnetic circuit which includes iron components and so iterative computer programs are used. These include POISSON, TOSCA [46], and ANSYS [47].

Scaling laws for thin solenoids:

For a detector in which the calorimetry is outside the aperture of the solenoid, the coil must be thin in terms of radiation and absorption lengths. This usually means that the coil is superconducting and that the vacuum vessel encasing it is of minimum real thickness and fabricated of a material with long radiation length. There are two major contributers to the thickness of a thin solenoid:

1. The conductor, consisting of the current-carrying superconducting material (usually Cu/Nb-Ti) and the quench protecting stabilizer (usually aluminum), is wound on the inside of a structural support cylinder (usually aluminum also). This package typically represents about 60% of the total thickness in radiation lengths. The thickness scales approximately as $B^2 R$.
2. Approximately another 25% of the thickness of the magnet comes from the outer cylindrical shell of the vacuum vessel. Since this shell is susceptible to buckling collapse, its thickness is determined by the diameter, length, and the modulus of the material of which it is fabricated. When designing this shell to a typical standard, the real thickness is

$$t = P_c D^{2.5}[(L/D) - 0.45(t/D)^{0.5}]/2.6 Y^{0.4} \ ,$$

where t = shell thickness (in), D = shell diameter (in), L = shell length (in), Y = modulus of elasticity (psi), and P_c = design collapse pressure (= 30 psi). For most large-diameter detector solenoids, the thickness to within a few percent is given by [48]

$$t = P_c D^{2.5}(L/D)/2.6 Y^{0.4} \ .$$

Properties of collider detector solenoids:

The physical dimensions, central field, stored energy and thickness in radiation lengths normal to the beam line of the superconducting solenoids associated with the major colliders are given in Table 5.

Table 5. Properties of superconducting collider detector solenoids.

Experiment–Lab	Field (T)	Bore Dia (m)	Length (m)	Energy (MJ)	Thickness (X_0)
CDF-Fermilab	1.5	2.86	5.07	30	0.86
Topaz–KEK	1.2	2.72	5.4	19.5	0.70
Venus–KEK	0.75	3.4	5.64	12	0.52
Cleo II–Cornell	1.5	2.9	3.8	25	2.5
Aleph–CERN	1.5	5.0	7.0	130	1.7
Delphi–CERN	1.2	5.2	7.4	109	4.0
H1–DESY	1.2	5.2	5.75	120	1.2
Zeus–DESY	1.8	1.72	2.85	10.5	0.9

The ratio of stored energy to cold mass (E/M) is a useful performance measure. One would like the cold mass to be as small as possible to minimize the thickness, but temperature rise during a quench must also be minimized. Ratios as large as 8 kJ/kg may be possible (final temperature of 80 K after a fast quench with homogenous energy dump), but some contingency is desirable. This quantity is shown as a function of total stored energy for some major collider detectors in Fig. 3.

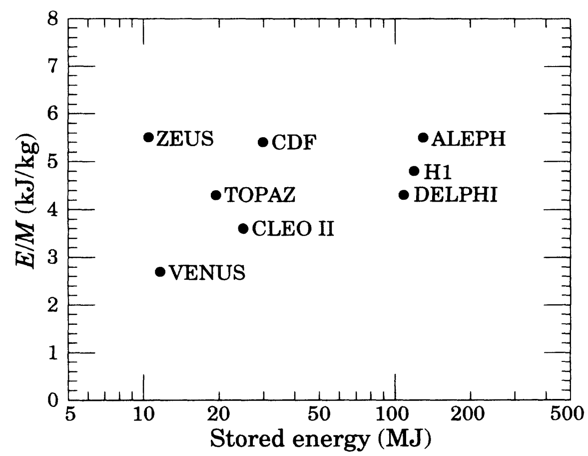

Fig. 3. Ratio of stored energy to cold mass for existing thin detector solenoids.

(10) Radiation levels in detectors at hadron colliders

An SSC Central Design Group task force made a study of radiation levels to be expected in SSC detectors [49]. Its model assumed

- The machine luminosity at $\sqrt{s} = 40$ TeV is $\mathcal{L} = 10^{33}$ cm^{-2}s^{-1}, and the $p-p$ inelastic cross section is $\sigma_{\rm inel} = 100$ mb. This luminosity is effectively achieved for 10^7 s yr^{-1}. The interaction rate is thus 10^8 s^{-1}, or 10^{15} yr^{-1};
- All radiation comes from $p-p$ collisions at the interaction point;
- The charged particle distribution is (a) flat in pseudorapidity for $|\eta| < 6$ and (b) has a momentum distribution whose perpendicular component is independent of rapidity, which is taken as independent of pseudorapidity:

$$\frac{d^2 N_{\rm ch}}{d\eta\, dp_\perp} = H\, f(p_\perp)$$

  (where $p_\perp = p \sin\theta$). Integrals involving $f(p_\perp)$ are simplified by replacing $f(p_\perp)$ by $\delta(p_\perp - \langle p_\perp \rangle)$; in the worst case this approximation introduces an error of less than 10%;
- Gamma rays from π^0 decay are as abundant as charged particles. They have approximately the same η distribution, but half the mean momentum;

PARTICLE DETECTORS (Cont'd)

- At the SSC ($\sqrt{s}$ = 40 TeV), $H \approx 7.5$ and $\langle p_\perp \rangle \approx 0.6$ GeV/c; assumed values at other energies are given in Table 7. Together with the model discussed above, these values are thought to describe particle production to within a factor of two or better.

It then follows that the flux of charged particles from the interaction point passing through a normal area da located a distance $r_\perp$ from the beam line is given by

$$\frac{dN_{\rm ch}}{da} = \frac{1.2 \times 10^8\,{\rm s}^{-1}}{r_\perp^2} \ .$$

In a typical organic material, a relativistic charged particle flux of 3×10^9 cm^{-2} produces an ionizing radiation dose of 1 Gy, where 1 Gy $\equiv$ 1 joule kg^{-1} (= 100 rads). The above result may thus be rewritten as dose rate,

$$\dot{D} = \frac{0.4 \text{ MGy yr}^{-1}}{(r_\perp/1 \text{ cm})^2} \ .$$

If a magnetic field is present, "loopers" may increase this dose rate by a factor of two.

In a medium in which cascades can develop, the ionizing dose or neutron fluence is proportional to $dN_{\rm ch}/da$ multiplied by $\langle E \rangle^\alpha$, where $\langle E \rangle$ is the mean energy of the particles going through da and the power α is slightly less than unity. Since $E \approx p = p_\perp / \sin\theta$ and $r_\perp = r \sin\theta$, the above expression for $dN_{\rm ch}/da$ becomes

$$\text{Dose or fluence}^{**} = \frac{A}{r^2}\cosh^{2+\alpha}\eta = \frac{A}{r^2 \sin^{2+\alpha}\theta} \ .$$

The constant A contains the total number of interactions $\sigma_{\rm inel}\int \mathcal{L}dt$, so the ionizing dose or neutron flux at another accelerator scales as $\sigma_{\rm inel}\int \mathcal{L}dt\, H \langle p_\perp \rangle^\alpha$.

The dose or fluence in a calorimeter scales as $1/r^2$, as does the neutron fluence inside a central cavity with characteristic dimension r.

Under all conditions so far studied, the neutron spectrum shows a broad log-normal distribution peaking at just under 1 MeV. In a 2 m radius central cavity of a detector with coverage down to $|\eta| = 3$, the average neutron flux is 2×10^{12} cm^{-2}yr^{-1}, including secondary scattering contributions.

Values of A and α are given in Table 6 for several relevant situations. Examples of scaling to other accelerators are given in Table 7. It should be noted that the assumption that all radiation comes from the interaction point does not apply to the present generation of accelerators.

The constant A includes factors evaluated with cascade simulation programs as well as constants describing particle production at the interaction point. It is felt that each could introduce an error as large as a factor of two in the results.

Table 6. Coefficients $A/(100\text{ cm})^2$ and α for the evaluation of calorimeter radiation levels at cascade maxima under SSC nominal operating conditions. At a distance r and angle θ from the interaction point the annual fluence or dose is $A/(r^2 \sin^{2+\alpha}\theta)$.

Quantity	$A/(100\text{ cm})^2$	Units	$\langle p_\perp \rangle$	α
Neutron flux	1.5×10^{12}	cm^{-2}yr^{-1}	0.6 GeV/c	0.67
Dose rate from photons	124	Gy yr^{-1}	0.3 GeV/c	0.93
Dose rate from hadrons	29	Gy yr^{-1}	0.6 GeV/c	0.89

Table 7. A rough comparison of beam-collision induced radiation levels at the Tevatron, UNK, high-luminosity LHC, and SSC.

	Tevatron	UNK-3	LHC	SSC
$\sqrt{s}$ (TeV)	1.8	6	16	40
$\mathcal{L}_{\rm nom}$ (cm^{-2}s^{-1})	2×10^{30}	4×10^{32}	4×10^{34} [a]	1×10^{33}
$\sigma_{\rm inel}$	59 mb	80 mb	86 mb	100 mb
H	4.1	4.5	6.3	7.5
$\langle p_\perp \rangle$ (GeV/c)	0.46	0.52	0.55	0.60
Relative dose rate [b]	5×10^{-4}	0.2	27	1

[a] High-luminosity option.
[b] Proportional to $\mathcal{L}_{\rm nom}\,\sigma_{\rm inel}\,H\,\langle p_\perp \rangle^{0.7}$

Updated 1992 by D.G. Coyne, R.W. Fast, R.D. Kephart, B. Mansoulie, H.F.W. Sadrozinski, H.G. Spieler, and C.L. Woody

** *Dose* is the time integral of *dose rate*, and *fluence* is the time integral of *flux*.

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RADIOACTIVITY & RADIATION PROTECTION

The International Commission on Radiation Units and Measurements (ICRU) recommends the use of SI units. Therefore we list SI units first, followed by cgs (or other common) units in parentheses, where they differ.

• **Unit of activity** = becquerel (curie):
 1 Bq = 1 disintegration s^{-1} [= $1/(3.7 \times 10^{10})$ Ci]

• **Unit of absorbed dose**= gray (rad):
 1 Gy = 1 joule kg^{-1} (= 10^4 erg g^{-1} = 100 rad)
 = 6.24×10^{12} MeV kg^{-1} deposited energy

• **Unit of exposure**, the quantity of x- or γ- radiation at a point in space integrated over time, in terms of charge of either sign produced by showering electrons in a small volume of air about the point:
 = 1 coul kg^{-1} of air (roentgen; 1 $R = 2.58 \times 10^{-4}$ coul kg^{-1})
 = 1 esu cm^{-3}(= 87.8 erg released energy per g of air)

Implicit in the definition is the assumption that the small test volume is embedded in a sufficiently large uniformly irradiated volume that the number of secondary electrons entering the volume equals the number leaving. This unit is somewhat historical, but appears on many measuring instruments.

• **Unit of equivalent dose** (for biological damage) = sievert [= 100 rem (**r**oentgen **e**quivalent for **m**an)]: Equivalent dose in Sv = absorbed dose in grays × w_R, where w_R (radiation weighting factor, formerly the quality factor Q) expresses long-term risk (primarily cancer and leukemia) from low-level chronic exposure. It depends upon the type of radiation and other factors, as follows [1]:

Radiation	w_R
X- and γ-rays, all energies	1
Electrons and muons, all energies	1
Neutrons < 10 keV	5
10–100 keV	10
> 100 keV to 2 MeV	20
2–20 MeV	10
> 20 MeV	5
Protons (other than recoils) > 2 MeV	5
Alphas, fission fragments, & heavy nuclei	20

• **Natural annual background**, all sources: Most world areas, whole-body equivalent dose rate ≈ (0.4–4) mSv (40–400 millirems). Can range up to 50 mSv (5 rems) in certain areas. U.S. average ≈ 3.6 mSv, including ≈ 2 mSv (≈ 200 mrem) from inhaled natural radioactivity, mostly radon and radon daughters (0.1–0.2 mSv in open areas. Average is for a typical house and varies by more than an order of magnitude. It can be more than two orders of magnitude higher in poorly ventilated mines).

• **Cosmic ray background** in counters (Earth's surface): ~ 1 min^{-1} cm^{-2} sr. For more accurate estimates and details, see the Cosmic Rays section.

• **Fluxes** (per cm^2) to deposit one Gy, assuming uniform irradiation:
 ≈ (**charged particles**) $6.24 \times 10^9/(dE/dx)$, where dE/dx (MeV g^{-1} cm^2), the energy loss per unit length, may be obtained from the Mean Range and Energy Loss figures.
 ≈ 3.5×10^9 cm^{-2} minimum-ionizing singly-charged particles in carbon.
 ≈ (**photons**) $6.24 \times 10^9/[Ef/\lambda]$, for photons of energy E (MeV), attenuation length λ (g cm^{-2}) (see Photon Attenuation Length figure), and fraction $f \lesssim 1$ expressing the fraction of the photon's energy deposited in a small volume of thickness $\ll \lambda$ but large enough to contain the secondary electrons.
 ≈ 2×10^{11} photons cm^{-2} for 1 MeV photons on carbon ($f \approx 1/2$).
 (Quoted fluxes are good to about a factor of 2 for all materials.)

• **Recommended limits to exposure (whole-body dose):***
 CERN: 15 mSv yr^{-1}
 U.K.: 15 mSv yr^{-1}
 U.S.: 50 mSv yr^{-1} (5 rem yr^{-1})†

• **Lethal dose**: Whole-body dose from penetrating ionizing radiation resulting in 50% mortality in 30 days (assuming no medical treatment) 2.5–3.0 Gy (250–300 rads), as measured internally on body longitudinal center line. Surface dose varies due to variable body attenuation and may be a strong function of energy.

For a recent review, see E. Pochin, *Nuclear Radiation: Risks and Benefits* (Clarendon Press, Oxford, 1983).

Revised Sept. 1991 with assistance from N.A. Greenhouse.

* The ICRP recomendation [1] is 20 mSv yr^{-1} averaged over 5 years, with the dose in any one year ≤ 50 mSv.

† Many laboratories in the U.S. and elsewhere set lower limits.

1. ICRP Publication 60, *1990 Recommendation of the International Commission on Radiological Protection* Pergamon Press (1991).

COMMONLY USED RADIOACTIVE SOURCES

Nuclide	Half-life	Type of decay	Particle Energy (MeV)	Particle Prob.	Photon Energy (MeV)	Photon Prob.
$^{22}_{11}$Na	2.602 y	β^+, EC	0.545	90%	0.511	Annih.
					1.275	100%
$^{54}_{25}$Mn	0.855 y	EC			0.835	100%
					Cr K X rays	24%
$^{55}_{26}$Fe	2.73 y	EC			Mn K X rays:	
					0.00589	24%
					0.00649	2.9%
$^{57}_{27}$Co	0.745 y	EC			0.014	10%
					0.122	86%
					0.136	11%
					Fe K X rays	55%
$^{60}_{27}$Co	5.271 y	β^-	0.316	100%	1.173	100%
					1.333	100%
$^{68}_{32}$Ge	0.742 y	EC			Ga K X rays	44%
$\to ^{68}_{31}$Ga		β^+, EC	1.899	90%	0.511	Annih.
					1.077	3%
$^{90}_{38}$Sr	28.5 y	β^-	0.546	100%		
$\to ^{90}_{39}$Y		β^-	2.283	100%		
$^{106}_{44}$Ru	1.020 y	β^-	0.039	100%		
$\to ^{106}_{45}$Rh		β^-	3.541	79%	0.512	21%
					0.622	10%
$^{109}_{48}$Cd	1.267 y	EC	0.063 e^-	41%	0.088	3.6%
			0.084 e^-	45%	Ag K X rays	100%
			0.087 e^-	9%		
$^{113}_{50}$Sn	0.315 y	EC	0.364 e^-	29%	0.392	64%
			0.388 e^-	6%	In K X rays	98%
$^{137}_{55}$Cs	30.0 y	β^-	0.514 e^-	94%	0.662	85%
			1.176 e^-	6%		
$^{133}_{56}$Ba	10.54 y	EC	0.045 e^-	50%	0.081	34%
			0.075 e^-	6%	0.356	62%
					Cs K X rays	124%
$^{207}_{83}$Bi	32.2 y	EC	0.481 e^-	2%	0.569	98%
			0.975 e^-	7%	1.063	75%
			1.047 e^-	2%	1.770	7%
					Pb K X rays	75%
$^{228}_{90}$Th	1.913 y	6α:	5.341 to 8.785		0.239	44%
		$3\beta^-$:	0.334 to 2.246		0.583	31%
					2.614	36%
($\to ^{224}_{88}$Ra $\to ^{220}_{86}$Rn $\to ^{216}_{84}$Po $\to ^{212}_{82}$Pb $\to ^{212}_{83}$Bi $\to ^{212}_{84}$Po)						
$^{241}_{95}$Am	432.7 y	α	5.443	13%	0.060	36%
			5.486	85%	Np L X rays	39%
$^{241}_{95}$Am/Be	432.7 y	6×10^{-5} neutrons (4–8 MeV) and				
		$4 \times 10^{-5}\gamma$'s (4.43 MeV) per Am decay				
$^{244}_{96}$Cm	18.11 y	α	5.763	24%	Pu L X rays	$\sim 9\%$
			5.805	76%		
$^{252}_{98}$Cf	2.645 y	α (97%)	6.076	15%		
			6.118	82%		
		Fission (3.1%)				
		≈ 20 γ's/fission; 80% < 1 MeV				
		≈ 4 neutrons/fission; $\langle E_n \rangle = 2.14$ MeV				

Updated April 1989 by E. Browne and V. Shirley.
"Prob." is the probability per decay of a given emission; because of cascades these may total more than 100%. Only principal emissions are listed. EC means electron capture, and e^- means monoenergetic internal conversion (Auger) electron. The intensity of 0.511 MeV e^+e^- annihilation photons depends upon the number of stopped positrons. Endpoint $\beta^\pm$ energies are listed. In some cases when energies are closely spaced, the γ-ray values are approximate weighted averages. Radiation from short-lived daughter isotopes is included where relevant.

Half-lives, energies, and intensities are from E. Browne and R.B. Firestone, *Table of Radioactive Isotopes* (John Wiley & Sons, New York, 1986) or recent *Nuclear Data Sheets*.
Neutrons are from *Neutron Sources for Basic Physics and Applications* (Pergamon Press, 1983).

PROBABILITY, STATISTICS, AND MONTE CARLO

1. PROBABILITY

1.1 General

If x is the outcome of an observation, we define the probability of x as the relative frequency with which x occurs out of a (possibly hypothetical) large set of similar observations. If x may take any value from a *continuous* range, we write $f(x;\theta)\,dx$ as the probability of observing x between x and $x+dx$. The function $f(x;\theta)$ is the *probability density function* (p.d.f.) for the *random variable* x, which may depend upon a parameter θ. If x can take on only one of a set of *discrete* values (*e.g.*, the non-negative integers), then $f(x;\theta)$ is itself a probability, but we still refer to it as a p.d.f. The p.d.f. is always normalized to unit area (unit sum, if discrete). Both x and θ may have multiple components and are then usually written as column vectors. If θ is unknown and we wish to estimate its value from a given set of data x, we may use statistics (Section 2).

The *cumulative distribution function* $F(a)$ expresses the probability that $x \le a$:

$$F(a) = \int_{-\infty}^{a} f(x)\,dx \ . \tag{1.1}$$

Here and in what follows, if x is discrete-valued, the integral is replaced by a sum. The endpoint a is expressly included in the integral or sum. Then $0 \le F(x) \le 1$, $F(x)$ is nondecreasing, and $\text{Prob}(a < x \le b) = F(b) - F(a)$. If x is discrete, $F(x)$ is flat except at allowed values of x, where it has a discontinuous jump equal to $f(x)$.

Any function of random variables is itself a random variable, with (in general) a different p.d.f. The *expectation value* of any function $u(x)$ is

$$\boldsymbol{E}[u(x)] = \int_{-\infty}^{\infty} u(x)\,f(x)\,dx \ . \tag{1.2}$$

The expectation value is said to exist only if it is finite. For x and y any two random variables, $\boldsymbol{E}(x+y) = \boldsymbol{E}(x) + \boldsymbol{E}(y)$. For c and k constants, $\boldsymbol{E}(cx+k) = c\boldsymbol{E}(x) + k$.

The nth moment of a distribution is given by

$$\alpha_n = \boldsymbol{E}(x^n) \ , \tag{1.3a}$$

and the nth moment about the mean by

$$m_n = \boldsymbol{E}[(x-\alpha_1)^n] \ . \tag{1.3b}$$

The most commonly used are the mean and variance:

$$\mu \equiv \alpha_1 \tag{1.4a}$$

$$\sigma^2 \equiv \text{Var}(x) \equiv m_2 = \alpha_2 - \mu^2 \ . \tag{1.4b}$$

The mean is the location of the "center of mass" of the distribution of x and the variance is a measure of the square of its width. Note that $\text{Var}(cx+k) = c^2\text{Var}(x)$.

Any odd moment about the mean is a measure of skewness; the simplest of these is the dimensionless coefficient of skewness $\gamma_1 = m_3/\sigma^3$.

In addition to the mean, another useful indicator of the x *location* near which most of the probability is likely to concentrate is the *median* x_{med}. This is that value of x such that $F(x_{\text{med}}) = 1/2$, *i.e.*, exactly half of the probability lies above and half lies below x_{med}. For a given *sample* of events, x_{med} is that observed x such that half the events have larger x and half have smaller x (as closely as possible, not counting any that have the same x as the median). If this lies between two observed x values, the sample median is set by convention to be halfway between them. If the p.d.f. for x has the form $f(x-\mu)$ and μ is both mean and median, then for a large number of events N the variance of the median approaches $1/[4Nf^2(0)]$, provided $f(0) > 0$.

Let x and y be two random variables with joint p.d.f. $f(x,y)$. The *marginal* p.d.f. of, for example, x, expressing the p.d.f. for x with y unobserved, is

$$f_1(x) = \int_{-\infty}^{\infty} f(x,y)\,dy \tag{1.5}$$

and similarly for $f_2(y)$. If y is fixed, the *conditional* p.d.f. for x given the fixed y is given by

$$f(x|y) = f(x,y)/f_2(y) \ . \tag{1.6}$$

The x mean is

$$\mu_x = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x\,f(x,y)\,dx\,dy = \int_{-\infty}^{\infty} x\,f_1(x)\,dx \tag{1.7}$$

and similarly for y. The *correlation* between x and y is a measure of the dependence of one on the other:

$$\rho_{xy} = \boldsymbol{E}\left[(x-\mu_x)(y-\mu_y)\right]/\sigma_x\,\sigma_y \equiv \text{Cov}[x,y]/\sigma_x\,\sigma_y \ , \tag{1.8}$$

where σ_x, σ_y are defined in analogy with Eq. (1.4b); it can be shown that $-1 \le \rho_{xy} \le 1$. The symbol "Cov" represents the covariance of x and y, a 2-variable analogue to the variance, Eq. (1.4b). Two random variables are *independent* if and only if

$$f(x,y) = f_1(x)\,f_2(y) \ . \tag{1.9}$$

If x and y are independent then $\rho_{xy} = 0$; the converse is not necessarily true except for Gaussian-distributed x and y. If x and y are independent, $\boldsymbol{E}[u(x)\,v(y)] = \boldsymbol{E}[u(x)]\,\boldsymbol{E}[v(y)]$ and $\text{Var}(x+y) = \text{Var}(x)+\text{Var}(y)$; otherwise, $\text{Var}(x+y) = \text{Var}(x)+\text{Var}(y)+2\text{Cov}[x,y]$ and $\boldsymbol{E}[u\,v]$ does not factor.

In a *change of continuous random variables* from, *e.g.*, $\vec{x} \equiv (x_1,\ldots,x_n)$, with p.d.f. $f(x_1,\ldots,x_n)$, to $\vec{y} \equiv (y_1,\ldots,y_n)$, a one-to-one function of the x's, the p.d.f. $g(y_1,\ldots,y_n)$ is found by substitution for $(x_1,\ldots,x_n)$ in f followed by multiplication by the absolute value of the Jacobian of the transformation:

$$g(\vec{y}) = f\left[w_1(\vec{y}),\ldots,w_n(\vec{y})\right]|J| \ . \tag{1.10}$$

The functions w_i express the *reverse* transformation $x_i = w_i(\vec{y})$ for $i = 1,\ldots,n$, and $|J|$ is the absolute value of the determinant of the square matrix $J_{ij} = \partial x_i/\partial y_j$. Such transformations must always preserve the number of random variables, n. To transform to fewer variables, first perform (1.10) and then use Eq. (1.5) to eliminate unwanted variables. If the transformation from $\vec{x}$ to $\vec{y}$ is not one-to-one, the situation is more complex and a unique solution may not exist. To change variables for discrete random variables simply substitute; no Jacobian is necessary because in that case f is a probability rather than a probability density. If f depends upon a parameter set θ, we can change to a different parameter set $\phi = \phi(\theta)$ by simple substitution; no Jacobian is used.

1.2 Characteristic functions [1]

The characteristic function $\phi(u)$ associated with the p.d.f. $f(x)$ is essentially its Fourier transform, or the expectation value of $\exp(iux)$,

$$\phi(u) = \boldsymbol{E}(e^{iux}) = \int e^{iux} f(x)dx \ . \tag{1.11}$$

It is sufficiently useful to deserve special attention, and several of its properties follow.

We note from Eqs. (1.3a) and (1.11) that the nth moment of the distribution $f(x)$ is given by

$$i^{-n}\frac{d^n\phi}{du^n}\bigg|_{u=0} = \int x^n f(x)dx = \alpha_n \ . \tag{1.12}$$

As a result, it is often easy to calculate all the moments of a distribution defined by $\phi(u)$ even when the inversion is not available.

If $f_1(x)$ and $f_2(y)$ have characteristic functions $\phi_1(u)$ and $\phi_2(u)$, then the characteristic function of the weighted sum $ax+by$ is $\phi_1(au)\phi_2(bu)$.

Let the (partial) characteristic function corresponding to the conditional p.d.f. $f_2(x|z)$ be $\phi_2(u|z)$, and the p.d.f. of z be $f_1(z)$. The characteristic function after integration over the conditional value is

$$\phi(u) = \int \phi_2(u|z)\,f_1(z)dz \ . \tag{1.13}$$

Suppose we can write ϕ_2 in the form

$$\phi_2(u|z) = A(u)e^{ig(u)z} \ . \tag{1.14}$$

PROBABILITY, STATISTICS, AND MONTE CARLO (Cont'd)

Then

$$\phi(u) = A(u)\phi_1(g(u)) \ . \tag{1.15}$$

The semi-invariants κ_n are defined by

$$\phi(u) = \exp\left(\sum_1^{\infty} \frac{\kappa_n}{n!}(iu)^n\right) \ . \tag{1.16}$$

The α_n's, m_n's, and κ_n's are related algebraically, and the first few are familiar:

$$\begin{aligned} &\kappa_1 = \alpha_1 \ (= \mu, \text{ the mean}) \\ &\kappa_2 = m_2 \ = \alpha_2 - \alpha_1^2 \ (= \sigma^2, \text{ the variance}) \\ &\kappa_3 = m_3 = \alpha_3 - 3\alpha_1\alpha_2 + 2\alpha_1^2 \ . \end{aligned} \tag{1.17}$$

1.3 Examples of probability density functions

We describe a few p.d.f.'s commonly encountered in physics applications. Tables for most of these distributions, relations among them, and further information may be found in Refs. 1–6. Monte Carlo techniques for generating each of them may be found in Section 3.3 below.

1.3.1 Uniform distribution (continuous)

This p.d.f. assumes equal probability density for any x in an allowed range $[a, b]$:

$$\begin{aligned} f(x) &= 1/(b-a) \ , \qquad && a \le x \le b \\ &= 0, && \text{otherwise;} \end{aligned} \tag{1.18}$$

$$E(x) = (b+a)/2 \ ; \qquad \mathrm{Var}(x) = (b-a)^2/12 \ . \tag{1.19}$$

1.3.2 Binomial distribution (discrete)

Any random process with exactly two possible outcomes is a *Bernoulli* process. If the process is repeated n times independently, and if the probability of obtaining a certain outcome (a "success") in each trial is p, then the probability of obtaining exactly r successes is given by the binomial distribution:

$$f(r; n, p) = \binom{n}{r} p^r q^{n-r} = \frac{n!}{r!(n-r)!}\, p^r q^{n-r} \ , \qquad r = 0, 1, 2, \ldots, n \ , \tag{1.20}$$

where $q = 1 - p$ and the order in which the successes and failures come is assumed irrelevant.

$$E(r) = np \ ; \ \mathrm{Var}(r) = npq \ . \tag{1.21}$$

If r successes are observed in n_r Bernoulli trials with probability p of success, and if s successes are observed in n_s similar trials, then $t = r + s$ is also binomial with $n_t = n_r + n_s$.

1.3.3 Poisson distribution (discrete)

The Poisson distribution with mean μ is:

$$f(n; \mu) = \frac{\mu^n e^{-\mu}}{n!} \ , \ n = 0, 1, 2, \ldots \ . \tag{1.22}$$

The observed result of a Poisson process is a non-negative integer n; the parameter μ is any non-negative real number. The Poisson distribution describes the population of events in any interval of x (*e.g.*, space or time) whenever: (a) the number of events in any interval of x is independent of that in any other non-overlapping interval; (b) in any small Δx, the probability of one event is $\lambda\Delta x$ and the probability of two or more vanishes at least as fast as $(\Delta x)^2$, as $\Delta x \to 0$; and (c) λ does not depend on x. Then $\mu \equiv \lambda x$;

$$E(n) = \mu \ ; \ \mathrm{Var}(n) = \mu \ . \tag{1.23}$$

When μ is large ($\gtrsim 7$ or 8), it is often useful to approximate the distribution of n by a Gaussian distribution of mean μ and variance $\sigma^2 = \mu$, as though n were a continuous variable. Two or more Poisson processes (*e.g.*, *signal* + *background*, with parameters μ_S and μ_B, respectively) which independently contribute amounts n_S and n_B to a given measurement will produce an observed number $n = n_S + n_B$, which is distributed according to a new Poisson distribution with parameter $\mu = \mu_S + \mu_B$.

1.3.4 Normal or Gaussian distribution (continuous)

The Gaussian distribution is

$$f(x;\, \mu, \sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} \ , \ -\infty < x < \infty \ ; \tag{1.24}$$

$$E(x) = \mu \ ; \ \mathrm{Var}(x) = \sigma^2 \ . \tag{1.25}$$

The characteristic function of a Gaussian p.d.f. with mean m and variance σ^2 is

$$\phi(u) = e^{imu - \frac{1}{2}\sigma^2 u^2} \ , \tag{1.26}$$

so the Gaussian is that unique distribution for which all semi-invariants beyond the second vanish.

For x and y independent and normally distributed, $z = x + y$ obeys $f(z;\, \mu_x + \mu_y,\, \sigma_x^2 + \sigma_y^2)$.

The integrated probability for x to fall in the range $\mu - \sigma$ to $\mu + \sigma$ is 0.683. Other measures of width commonly encountered are: probable error (central region containing 0.50 of the probability) $= \mu \pm 0.67\sigma$; mean absolute deviation; $E[|x - \mu|] = 0.80\sigma$; rms deviation $= \sigma$; half-width at half-maximum $= 1.18\sigma$.

The Gaussian gets its importance in large part from the *central limit theorem*: if a continuous random variable x is distributed according to *any* p.d.f. with finite mean and variance, then the sample mean, $\overline{x}_n$ of n observations of x will have a p.d.f. that approaches a Gaussian as n increases. Therefore the end result $\sum^n x_i \equiv n\overline{x}_n$ of a large number of small fluctuations x_i will be distributed as a Gaussian, even if the x_i themselves are not.

The cumulative distribution (1.1) for a Gaussian with $\mu = 0$ and $\sigma^2 = 1$ is given by the *error function*, erf(a), through the following ugly relation:

$$F(a; 0, 1) = 0.5\left[1 + \mathrm{erf}(a/\sqrt{2})\right] \ . \tag{1.27}$$

The function erf(a) is tabulated in Ref. 2 and is available as a FORTRAN function on many computers [caution: other definitions of erf(a) are sometimes used]; for mean μ and variance σ^2 replace a by $[(a - \mu)/\sigma]$.

For $\vec{x}$ a set of n (not necessarily independent) Gaussian random variables x_i arranged into a column vector, their joint p.d.f. is the *multivariate Gaussian*:

$$f(\vec{x}; \vec{\mu}, V) = \frac{1}{(2\pi)^{n/2}} |V|^{-1/2} \times \exp\left[-\frac{1}{2}(\vec{x} - \vec{\mu})^T V^{-1} (\vec{x} - \vec{\mu})\right] \ , \ |V| \neq 0 \ , \tag{1.28a}$$

where V is the *covariance matrix* of the x's, $V_{ii} = \mathrm{Var}(x_i)$ and $V_{ij} = E[(x_i - \mu_i)(x_j - \mu_j)] \equiv \rho_{ij}\, \sigma_i \sigma_j$, and $|V|$ is the determinant of V. The quantity ρ_{ij} is the correlation coefficient for x_i and x_j; $|\rho_{ij}|^2 \le 1$. For $n = 2$ this becomes

$$f(x_1, x_2;\, \mu_1, \mu_2, \sigma_1, \sigma_2, \rho) = \frac{1}{2\pi\, \sigma_1 \sigma_2 \sqrt{1 - \rho^2}} \times \exp\left\{\frac{-1}{2(1-\rho^2)}\left[\frac{(x_1 - \mu_1)^2}{\sigma_1^2} - \frac{2\rho(x_1 - \mu_1)(x_2 - \mu_2)}{\sigma_1\sigma_2} + \frac{(x_2 - \mu_2)^2}{\sigma_2^2}\right]\right\} \ . \tag{1.28b}$$

The special case $\sigma_1 = \sigma_2$ and $\rho = 0$ is called the *Rayleigh distribution.* If V is singular, there is a linear relation among some variables; in this case one usually wants to eliminate completely dependent variables and work in a smaller number of dimensions. The marginal distribution of any x_i is a Gaussian with mean μ_i and variance V_{ii}. V is $n \times n$, symmetric, and positive definite. Therefore for any vector $\vec{X}$, the quadratic form $\vec{X}^T V^{-1} \vec{X} = c$ traces an n-dimensional ellipsoid as $\vec{X}$ varies for any given $c > 0$. If $X_i = (x_i - \mu_i)/\sigma_i$, then c is a random variable obeying the $\chi^2(n)$ distribution, which is discussed in the following section. The probability that $\vec{X}$ corresponding to a set of Gaussian random variables $\vec{x}_i$ lies *outside* the ellipsoid characterized by a given value of $c (= \chi^2)$ is given by Eq. (1.31) and may be read

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from Fig. 1. For example, the "s-standard-deviation ellipsoid" occurs at $c = s^2$. For the two-variable case ($n = 2$) the point $\vec{X}$ lies outside the one-standard-deviation ellipsoid with 61% probability, so both X_1 and X_2 lie inside the ellipsoid with 39% probability. This assumes that μ_i and σ_i are correct. For $X_i = x_i/\sigma_i$, the ellipsoids of constant χ^2 have the same size and orientation but are centered at $\vec{\mu}$. The use of these ellipsoids as indicators of probable error is described in Sec. 2.4.1.

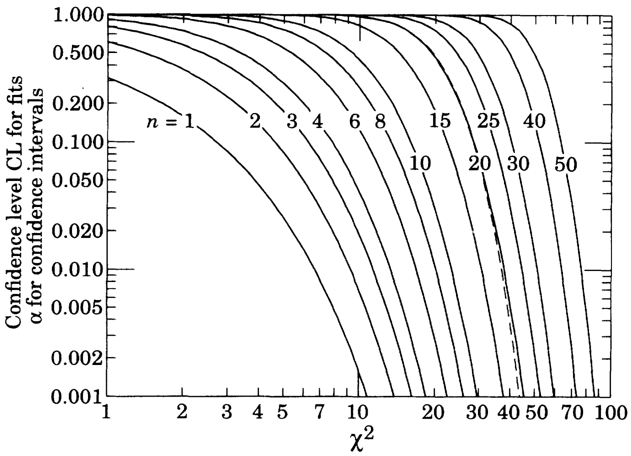

Fig. 1. χ^2 confidence level vs χ^2 for n degrees of freedom, as defined in Eq. (1.31). The curve for a given n expresses the probability that a value at least as large as χ^2 will be obtained in an experiment; *e.g.*, for $n = 10$, a value $\chi^2 \gtrsim 18$ will occur in 5% of a very large number of experiments. For a fit, CL is a measure of goodness-of-fit in that a good fit to a correct model is expected to yield a low χ^2 (Sec. 2.3.3). For a confidence interval, α measures the probability that the interval *does not* cover the true value of the quantity being estimated (Sec. 2.4). The dashed curve for $n = 20$ is calculated using the approximation of Eq. (1.32).

It is a characteristic of the multivariate Gaussian that $\rho_{ij} = 0$ is necessary and sufficient for x_i and x_j to be independent. For a given covariance matrix V, there always exist nonsingular $n \times n$ matrices H such that $HH^T = V$; H is usually upper or lower triangular in the most efficient algorithms. Then $\vec{z} = H^{-1}(\vec{x} - \vec{\mu})$ is a vector of n independent Gaussian random variables with zero mean and with covariance matrix equal to the identity.

1.3.5 The χ^2 distribution (continuous)

If $x_1, \ldots, x_n$ are independent Gaussian distributed random variables, the sum $z = \sum^n (x_i - \mu_i)^2/\sigma_i^2$ is distributed as a χ^2 with n *degrees of freedom* [$\chi^2(n)$]:

$$f(z;\, n) = \frac{1}{2^{n/2}\Gamma(n/2)}\, z^{n/2-1}\, e^{-z/2} \;, \quad z \geq 0 \;; \tag{1.29}$$

$$\boldsymbol{E}(z) = n \;;\; \mathrm{Var}(z) = 2n \;. \tag{1.30}$$

Under a linear transformation to n *dependent* Gaussian variables x_i', the χ^2 at each transformed point retains its value; then $z = \vec{X}'^T\, V^{-1}\, \vec{X}'$ as in the previous section. For a set of z_i, each of which is $\chi^2(n_i)$, $\sum z_i$ is a new random variable which is $\chi^2\,(\sum n_i)$.

Fig. 1 shows the Confidence Level (CL) obtained by integrating the tail of the function given in Eq. (1.29) for n degrees of freedom:

$$\mathrm{CL}(\chi^2) = \int_{\chi^2}^{\infty} f(z;\, n)\, dz \;; \tag{1.31}$$

this area is shown schematically in Fig. 2. It is equal to 1.0 minus the cumulative distribution function $F(z = \chi^2;\, n)$. It is useful in evaluating the consistency of data with a model (see Sec. 2): The CL is the probability that a random repeat of the given experiment would observe a *worse* χ^2, assuming the correctness of the model. It is also useful for confidence intervals for statistical estimators (Sec. 2.4), when one is interested in the unshaded area of Fig. 2.

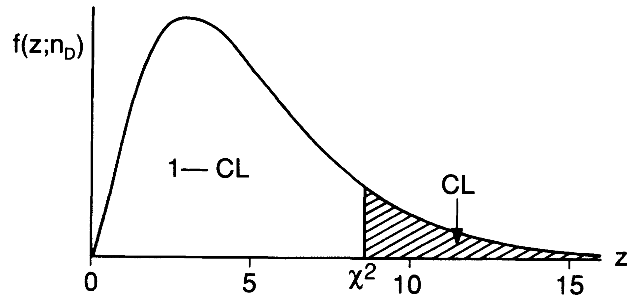

Fig. 2. Schematic illustration of the confidence level integral given in Eq. (1.31).

Since the mean of the χ^2 distribution is equal to the number of degrees of freedom, one expects to obtain $\chi^2 \approx n$ in a "reasonable" experiment. While caution is necessary because of the skewness of the distribution, the "reduced χ^2" $\equiv \chi^2/n$ is therefore a useful quantity. Figure 3 shows χ^2/n for useful CL's as a function of n. It contains the same information as Fig. 1, but is easier to read.

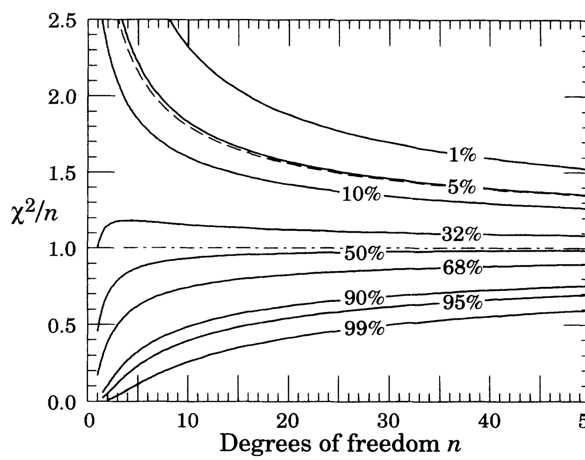

Fig. 3. Confidence limits as a function of the "reduced χ^2" $\equiv \chi^2/n$ and the number of degrees of freedom n. Curves are labeled by the probability of a measurement resulting in a value of χ^2/n greater than that given on the y axis; *e.g.*, for $n = 10$, a value $\chi^2/n \gtrsim 1.8$ will occur in 5% of a very large number of experiments. The dashed curve for CL = 5% is calculated using the approximation of Eq. (1.32).

It is commonly stated that for large n the CL is approximately given by [1,7]

$$\mathrm{CL} \approx \frac{1}{\sqrt{2\pi}} \int_y^{\infty} e^{-x^2/2} dx \;, \tag{1.32}$$

where $y = \sqrt{2\chi^2} - \sqrt{2n-1}$. This approximation was used to draw the dashed curves in Fig. 1 (for $n = 20$) and Fig. 3 (for CL = 5%). However, all of the functions and their inverses are now readily available in standard mathematical libraries (such as IMSL, used to generate these Figures), and so the approximation (and even such figures and tables) plays only a secondary role in practical problems.

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1.3.6 Student's *t* (continuous)

Suppose that x and $x_1, \ldots, x_n$ are independent and normal with mean 0 and variance 1. We then define $z = \sum_1^n x_i^2$, and

$$t = x/\sqrt{z/n} \; . \tag{1.33}$$

The variable z thus belongs to a $\chi^2(n)$ distribution. Then t is distributed according to a Student's t distribution with n degrees of freedom:

$$f(t;\, n) = \frac{1}{\sqrt{n\pi}} \frac{\Gamma[(n+1)/2]}{\Gamma(n/2)} \left(1 + \frac{t^2}{n}\right)^{-(n+1)/2} , \tag{1.34}$$

$$-\infty < t < \infty \; ,$$

and

$$\boldsymbol{E}(t) = 0 \;\text{ for } n > 1 \; ; \;\; \text{Var}(t) = \frac{n}{n-2} \;\text{ for } n > 2 \; . \tag{1.35}$$

Here $\Gamma(k)$ is the gamma function, equal to $(k-1)!$ if k is an integer. Student's t distribution resembles a Gaussian distribution with wide tails. As $n \to \infty$, the distribution approaches a Gaussian, and if $n = 1$, the distribution is *Cauchy*, or *Breit-Wigner*. The mean is finite for $n > 1$ and the variance is finite for $n > 2$, so for $n = 1$ or $n = 2$, t does not obey the central limit theorem.

As an example, consider the *sample mean* $\overline{x} = \sum x_i/n$ and the *sample variance* $s^2 = \sum(x_i - \overline{x})^2/(n-1)$ for normally distributed random variables x_i with unknown mean μ and variance σ^2. The sample mean has a Gaussian distribution with a variance σ^2/n, so the variable $(\overline{x} - \mu)/\sqrt{\sigma^2/n}$ is normal with mean 0 and variance 1. Similarly, $(n-1)\, s^2/\sigma^2$ is independent of this and is χ^2 distributed with $n-1$ degrees of freedom. The ratio

$$t = \frac{(\overline{x} - \mu)/\sqrt{\sigma^2/n}}{\sqrt{(n-1)\; s^2/\sigma^2\; (n-1)}} = \frac{\overline{x} - \mu}{\sqrt{s^2/n}} \tag{1.36}$$

distributes as $f(t;\, n-1)$. The unknown true variance σ^2 cancels, and t can be used to test the probability that the true mean is some particular value μ.

The distribution (1.34) is written such that n is not required to be an integer. A Student's t distribution with nonintegral $n > 0$ is useful in certain applications.

1.3.7 The gamma distribution (continuous)

If a process generating events as a function of x (*e.g.*, space or time) satisfies conditions (a)–(c) of the Poisson distribution, then the x distance from an arbitrary starting point (which may be some particular event) to the k^{th} event is belongs to a *gamma* distribution:

$$f(x;\, \lambda, k) = \frac{x^{k-1}\, \lambda^k\, e^{-\lambda x}}{\Gamma(k)} \; , \; 0 < x < \infty \; . \tag{1.37}$$

$\Gamma(k)$ is the gamma function, equal to $(k-1)!$ if k is an integer. The Poisson parameter μ is λ per unit x;

$$\boldsymbol{E}(x) = k/\lambda \; ; \; \text{Var}(x) = k/\lambda^2 \; . \tag{1.38}$$

The special case $k = 1$ is called the *exponential* distribution. A sum of k' exponential random variables x_i is distributed as $f(\sum x_i;\, \lambda, k')$. Eq. (1.37) allows $k > 0$ to be nonintegral. If $\lambda = 1/2$ and $k = n/2$, the gamma and $\chi^2(n)$ distributions are identical.

2. STATISTICS

2.1 General

A probability density function with known parameters enables us to predict the frequency with which a random variable will take on a particular value (if discrete) or lie in a given range (if continuous). In *parametric* statistics we have the opposite problem of estimating the parameters of the p.d.f. from a set of actual observations.

We refer to the true p.d.f. as the *population*; the data form a *sample* from this population. A *statistic* is any function of the data, plus known constants, which does not depend upon any of the unknown parameters. A statistic is a random variable if the data have random errors. An *estimator* is any statistic whose value is intended as a meaningful guess for the value of an unknown parameter; we denote estimators with hats, *e.g.*, $\widehat{\theta}$.

Often it is possible to construct more than one reasonable estimator. Let θ represent the true value of a parameter to be estimated; θ is a vector if there is more than one parameter. Then if $\widehat{\theta}$ is an estimator for θ, desirable properties for $\widehat{\theta}$ are: (a) *Unbiased*; bias $b = \boldsymbol{E}(\widehat{\theta}) - \theta$, where the expectation value is taken over a hypothetical set of similar experiments in which $\widehat{\theta}$ is constructed the same way. The bias may be due to statistical properties of the estimator or to *systematic* errors in the experiment. If we can estimate the average bias b we usually subtract it from $\widehat{\theta}$ to obtain a new $\widehat{\theta}' \equiv \widehat{\theta} - b$. However, b may depend upon θ or other unknowns, in which case we usually try to choose an estimator which minimizes its average size. (b) *Minimum variance*; the minimum possible value of $\text{Var}(\widehat{\theta})$ is given by the Rao-Cramér-Frechet bound:

$$\text{Var}_{\min} = \left[1 + \partial b/\partial\theta\right]^2 / I(\theta) \; ; \tag{2.1}$$

$$I(\theta) = \boldsymbol{E}\left\{ \left[\frac{\partial}{\partial\theta} \sum_{i=1}^{n} \ln f(x_i;\, \theta) \right]^2 \right\} .$$

The sum is over all data and b is the bias, if any; the x_i are assumed independent and distributed as $f(x_i; \theta)$, and the allowed range of x must not depend upon θ. The ratio $\epsilon = \text{Var}_{\min}/\text{Var}(\widehat{\theta})$ is the *efficiency*. An *efficient* estimator (with $\epsilon = 1$) exists only for certain cases. The square root of the variance expresses the expected spread of $\widehat{\theta}$ about its average value, as would be observed in a large number of repeats of the same measurement. (c) *Minimum mean-squared error* (mse); mse $= \boldsymbol{E}[(\widehat{\theta} - \theta)^2] = V(\widehat{\theta}) + b^2$. The mse combines the error due to any bias quadratically with the variance, which expresses only the spread about $\boldsymbol{E}(\widehat{\theta})$, as distinct from θ, the true value. (d) *Robust*; a robust estimator is not sensitive to errors in our assumptions, *e.g.*, to departures from the assumed p.d.f. due to such factors as noise.

These criteria (and others) allow us to evaluate any procedure for obtaining $\widehat{\theta}$. In many cases these criteria conflict. The bias, variance, and mse may depend on the unknown θ. In this case the optimum prescription for $\widehat{\theta}$ may depend on the range in which we assume θ to lie.

Following are techniques in common use for obtaining estimators and their standard errors $\sigma(\widehat{\theta}) = \sqrt{\text{Var}(\widehat{\theta})}$. When the conditions of the central limit theorem are satisfied, the interval $\widehat{\theta} \pm \sigma(\widehat{\theta})$ forms a 68.3% *confidence interval*. This is a random interval in that its endpoints depend upon the randomly sampled data; its meaning here will be taken to be that in 68.3% of all similar experiments the interval will include the true value θ. One should be aware that in most practical cases the central limit theorem is only approximately satisfied and accordingly confidence intervals which depend on that are only approximate. Confidence intervals are discussed in Section 2.4 below.

2.2 Data with a common mean

(1) Suppose we have a set of N independent measurements y_i assumed to be unbiased measurements of the same unknown quantity μ with a common, but unknown, variance σ^2 resulting from measurement error. Then

$$\widehat{\mu} = \frac{1}{N} \sum_{i=1}^{N} y_i \tag{2.2}$$

$$\widehat{\sigma}^2 = \frac{1}{N-1} \sum_{i=1}^{N} (y_i - \widehat{\mu})^2 = \frac{N}{N-1} \left(\boldsymbol{E}(y^2) - \widehat{\mu}^2\right) \tag{2.3}$$

are unbiased estimators of μ and σ^2. The variance of $\widehat{\mu}$ is σ^2/N. If the common p.d.f. of the y_i is Gaussian, these statistics are independent. Then, for large N, the variance of $\widehat{\sigma}^2$ is $2\sigma^4/N$. If the y_i are Gaussian or N is large enough that the central limit theorem applies, then $\widehat{\mu}$ is an efficient estimator for μ. Otherwise $\widehat{\mu}$ is sometimes subject to large fluctuations, *e.g.*, if the p.d.f. for y_i has long tails. In this case the median of the y_i may be a more *robust* estimator for μ, provided the median and mean are expected to lie at the same point in the p.d.f. for y. For Gaussian y, the median has asymptotic (large-N) efficiency

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$2/\pi \approx 0.64$. The Student's t distribution provides an example in which there are large tails. In this case, for large N the efficiency of the sample median relative to the sample mean is (∞, ∞, 1.62, 1.12, 0.96, 0.80, 0.64) for (1, 2, 3, 4, 5, 8, ∞) degrees of freedom.

If σ^2 is known, $\widehat{\mu}$ as given in Eq. (2.2) is still the best estimator for μ; if μ is known, substitute it for $\widehat{\mu}$ in Eq. (2.3) and replace $N-1$ by N, to obtain a somewhat better estimator $\widehat{\sigma}^2$.

(2) If the y_i have different, known, variances σ_i^2, then

$$\widehat{\mu} = \frac{1}{w}\sum^{N} w_i\, y_i\ , \tag{2.4}$$

is an unbiased estimator for μ with smaller variance than Eq. (2.2), where $w_i = 1/\sigma_i^2$ and $w = \sum w_i$. The variance of $\widehat{\mu}$ is $1/w$.

2.3 The method of maximum likelihood

2.3.1 General

"From a theoretical point of view, the most important general method of estimation so far known is the *method of maximum likelihood*." [1]. We suppose that a set of independently measured quantities $\vec{x}$ came from a p.d.f. $f(\vec{x};\,\vec{\theta})$, where $\vec{\theta}$ is an unknown set of parameters. The method of maximum likelihood consist of finding the set of values of $\vec{\theta}$, $\widehat{\theta}$, which maximizes the joint probability density for all the data, given by

$$\mathcal{L}(\vec{\theta}) = \prod_i f(\vec{x}_i;\,\vec{\theta})\ , \tag{2.5}$$

where $\mathcal{L}$ is called the likelihood. It is usually easier to work with $\ln\mathcal{L}$, and since both are maximized for the same set of $\vec{\theta}$, it is sufficient to solve the *likelihood equation*

$$\frac{\partial \ln\mathcal{L}}{\partial\theta_n} = 0\ . \tag{2.6}$$

The solution is called the *maximum likelihood estimate* of $\vec{\theta}$. The importance of the approach is shown by the following proposition, proved in Ref. 1:

If an efficient estimate $\widehat{\theta}$ of $\vec{\theta}$ exists, the likelihood equation will have a unique solution equal to $\widehat{\theta}$.

In evaluating $\mathcal{L}$, it is important that any normalization factors in the f's which involve $\vec{\theta}$ be included. However, we will only be interested in the maximum of $\mathcal{L}$ and in ratios of $\mathcal{L}$ at different $\vec{\theta}$'s; hence any multiplicative factors which do not involve the parameters we want to estimate may be dropped; this includes factors which depend on the data but not on $\vec{\theta}$.

If the solution to Eq. (2.6) is at a maximum, $\partial\ln\mathcal{L}/\partial\theta_n$ will have negative slope in its vicinity. In many practical problems, one often uses nonlinear algorithms for finding the maximum, and must be alert to various possibilities for error: (a) Eq. (2.6) may yield a minimum, therefore one must check the second derivative; (b) there may be more than one maximum—one must try to find the global maximum; (c) the global maximum may lie at a boundary of the physical region, in which case Eq. (2.6) will not find it.

If an unbiased, efficient estimator exists, this method will find it. If $\partial\ln\mathcal{L}/\partial\theta_n$ is linear in the vicinity of the root, an efficient estimator is guaranteed; other efficient cases are discussed in the literature. For large data samples, the central limit theorem will usually assure this condition in some significant neighborhood of zero; hence the estimator is usually efficient in that case, provided certain conditions are met (*e.g.*, that the solution does not lie on a boundary). In this case, in the neighborhood of the maximum $\ln\mathcal{L}$ is a downward-curving parabola and $\mathcal{L}$ is proportional to a Gaussian.

The results of two or more experiments may be combined by forming the product of the $\mathcal{L}$'s, or the sum of the $\ln\mathcal{L}$'s.

Under a one-to-one change of parameters from $\vec{\theta}$ to $\vec{\phi} = \vec{\phi}(\vec{\theta})$, the maximum likelihood estimate is simply $\widehat{\phi} = \vec{\phi}(\widehat{\theta})$, given the solution for $\widehat{\theta}$ for $\vec{\theta}$. That is, the maximum likelihood solution for $\vec{\phi}$ is found by simple substitution of $\widehat{\theta}$ into the transformation equation. It is possible that the new solution $\widehat{\phi}$ will be a biased solution for the true value of $\vec{\phi}$ even if $\widehat{\theta}$ is not biased, and vice-versa. In the asymptotic limit (of large amounts of data) both $\widehat{\theta}$ and $\widehat{\phi}$ will (usually) converge to unbiased solutions, but at different rates.

Except in special cases like the least-squares method, the value of the likelihood function at the solution does not necessarily tell us whether the final fit was a sensible description of the data or not. To evaluate this, one may: (a) prepare histograms of the data projected on various axes and make χ^2 (or other) comparisons with the fitted model projected upon the same axes; and/or (b) do numerous Monte Carlo simulations of the experiment under the hypothesis that the fitted parameters are correct, fit each of these, and compare the experimental likelihood (or $\ln\mathcal{L}$) with those obtained from these simulations. If the experimental likelihood is lower than that of some agreed-upon fraction of these results, one should question the appropriateness of the p.d.f. f. At the same time one can check for bias in the solution.

2.3.2 Error estimates

The covariance matrix V may be estimated from

$$V_{nm} = \left(\boldsymbol{E}\left[-\frac{\partial^2\ln\mathcal{L}}{\partial\theta_n\,\partial\theta_m}\bigg|_{\widehat{\theta}}\right]\right)^{-1}\ . \tag{2.7}$$

If $\partial\ln\mathcal{L}/\partial\theta_n$ is linear, the "expectation" operation in Eq. (2.7) has no effect because the second derivative of $\ln\mathcal{L}$ is constant. Otherwise, it may be approximated by taking the average of the quantity in square brackets over a range of θ_n and θ_m near the solution. For complex cases it may be more practical to evaluate s-standard-deviation errors from the contour

$$\ln\mathcal{L}(\vec{\theta}) = \ln\mathcal{L}_{\rm max} - s^2/2\ , \tag{2.8}$$

where $\ln\mathcal{L}_{\rm max}$ is the value of $\ln\mathcal{L}$ at the solution point (compare with $\chi^2(\vec{a}') = \chi^2_{\rm min} + 1$ and the discussion in the least-squares case, below). The extreme limits of this contour parallel to the θ_n axis give an approximate s-standard-deviation confidence interval in θ_n. These intervals may not be symmetric and they may even consist of two or more disjoint intervals. This procedure gives one-standard-deviation errors in θ_n equal to $\sqrt{V_{nn}}$ of Eq. (2.7) if the estimator is efficient. If it is not efficient, the level of confidence implied by the value of s is only approximate.

2.3.3 Method of least squares

By far the most common case of the maximum likelihood approach is the *method of least squares.* We suppose a set of N measurements at points x_i. The ith measurement y_i is assumed to be chosen from a Gaussian distribution with mean $F(x_i;\,\vec{a})$ and variance σ_i^2. Then

$$-\tfrac{1}{2}\ln\mathcal{L} \equiv \chi^2 = \sum_1^N \frac{(y_i - F(x_i;\,\vec{a}))^2}{\sigma_i^2}\ . \tag{2.9}$$

Finding the set of parameters $\vec{a}$ which maximizes $\mathcal{L}$ is equivalent to finding the set which minimizes χ^2.

At the outset it should be said that the method of least squares is sometimes applied in cases where the distribution is not Gaussian or not known to be Gaussian. In such cases it can still be used, but it is then not a special case of the maximum likelihood method, and the theorems having to do with that approach no longer apply.

In many practical cases one further restricts the problem to the situation in which $F(x_i;\,\vec{a})$ is a linear function of the a_m's,

$$F(x_i;\,\vec{a}) = \sum_n a_n\, f_n(x)\ , \tag{2.10}$$

where the f_n are k linearly independent functions (*e.g.*, 1, x, x^2, ..., or Legendre polynomials) which are single-valued over the allowed range of x. We require $k \le N$, and at least k of the x_i must be distinct. We wish to estimate the linear coefficients a_n. Later we will discuss the nonlinear case.

If the point errors $\epsilon_i = y_i - F(x_i;\,\vec{a})$ are Gaussian, then the minimum χ^2 will be distributed as a χ^2 random variable with $n = N - k$ degrees of freedom. We can then evaluate the goodness-of-fit (confidence level) from Figs. 1 or 3, as per the earlier discussion. The confidence level expresses the probability that a *worse* fit would be obtained in a large number of similar experiments under the assumptions that: (a) the model $y = \sum a_n\, f_n$ is correct and (b) the errors ϵ_i are Gaussian and unbiased with variance

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σ_i^2. If this probability is larger than an agreed-upon value (0.001, 0.01, or 0.05 are common choices), the data are *consistent* with the assumptions; otherwise we may want to find improved assumptions. As for the converse, most people do not regard a model as being truly *inconsistent* unless the probability is as low as that corresponding to four or five standard deviations for a Gaussian (6×10^{-3} or 6×10^{-5}; see Sec. 2.4.1). If the ϵ_i are not Gaussian, the method of least squares still gives an answer, but the goodness-of-fit test would have to be done using the correct distribution of the random variable which is still called "χ^2."

Finding the minimum of χ^2 in the linear case is straightforward:

$$-\frac{1}{2}\frac{\partial\chi^2}{\partial a_m} = \sum_i f_m(x_i)\left(\frac{y_i - \sum_n a_n\, f_n(x_i)}{\sigma_i^2}\right)$$
$$= \sum_i \frac{y_i\, f_m(x_i)}{\sigma_i^2} - \sum_n a_n \sum_i \frac{f_n(x_i)\, f_m(x_i)}{\sigma_i^2} . \qquad (2.11)$$

With the definitions

$$g_m = \sum_i y_i\, f_m(x_i)/\sigma_i^2 \qquad (2.12)$$

and

$$\left(V_{\widehat{a}}^{-1}\right)_{mn} = \sum_i f_n(x_i)\, f_m(x_i)/\sigma_i^2 , \qquad (2.13)$$

the k-element column vector of solutions $\widehat{a}$, for which $\partial\chi^2/\partial a_m = 0$ for all m, is given by

$$\widehat{a} = V_{\widehat{a}}\, \vec{g} . \qquad (2.14)$$

More generally, the measured y_i's are not independent. Then the set of σ_i^2's must be replaced by the $N \times N$ covariance matrix V_y. Then, if H is the $N \times k$ matrix with element $H_{in} = f_n(x_i)$, the solution $\widehat{a}$ is given by the solution to the *normal equation*

$$(H^T\, V_y^{-1}\, H)\, \widehat{a} = H^T\, V_y^{-1}\, \vec{y} , \qquad (2.15a)$$

or, formally,

$$\widehat{a} = (H^T\, V_y^{-1}\, H)^{-1}\, H^T\, V_y^{-1}\, \vec{y} \equiv D\vec{y} , \qquad (2.15b)$$

where $\vec{y}$ is the N-element vector of measured y_i's. The normal equations may be solved by numerical methods much more computationally efficient than brute application of Eq. (2.15b). In particular, $H^T\, V_y^{-1}\, H$ is sometimes singular or nearly singular. In such cases there is at least one f_n which may be expressed as a linear combination of others (or nearly so) when evaluated at the data points. The best procedure is usually to drop such functions from the expansion (or set $\widehat{a}_n = 0$). See Press [8], Maindonald [9], or Basilevsky [10] for discussions.

In terms of the $k \times N$ matrix D, the standard covariance matrix for the $\widehat{a}$ is estimated by

$$V_{\widehat{a}} = D\, V_y\, D^T . \qquad (2.16)$$

If the measured y_i's are independent, V_y is diagonal with ii^{th} element σ_i^2 and $V_{\widehat{a}}$ is obtained from Eq. (2.13) above.

The expected covariance [see Eq. (1.8)] of $\widehat{a}_n$ and $\widehat{a}_m$ is estimated by

$$\boldsymbol{E}\Big[(a_n - \widehat{a}_n)(a_m - \widehat{a}_m)\Big] = (V_{\widehat{a}})_{nm} . \qquad (2.17)$$

Even when the y_i's are independent (diagonal V_y), $\widehat{a}_n$ and $\widehat{a}_m$ may not be (nondiagonal $V_{\widehat{a}}$). For the model function $y = \sum a_n\, f_n(x)$, the estimated variance of an interpolated or extrapolated value of y at a point x is

$$\boldsymbol{E}\left[(y - \widehat{y})^2\right] = \sigma^2(y)$$
$$= \sum_{n,m} (V_{\widehat{a}})_{nm}\, f_n(x)\, f_m(x) . \qquad (2.18)$$

If y is not linear in the fitting parameters a_n, or if the errors σ_i depend upon y and therefore on a_n, the solution vector may have to be found by iteration of Eqs. (2.12)–(2.14) or Eq. (2.15b). The same results may be obtained by numerical techniques from the sum of squares, χ^2, directly, if we have a reasonable first guess $\vec{a}_0$ for the solution vector:

$$\widehat{a} = \vec{a}_0 - \left(\frac{\partial^2\chi^2}{\partial a^2}\right)^{-1}_{\vec{a}_0} \cdot \left.\frac{\partial\chi^2}{\partial a}\right|_{\vec{a}_0} \qquad (2.19a)$$

and

$$V_{\widehat{a}} = 2\left(\frac{\partial^2\chi^2}{\partial a^2}\right)^{-1}_{\widehat{a}} , \qquad (2.19b)$$

where $\partial\chi^2/\partial a$ is a k-element vector whose n^{th} element is $\partial\chi^2/\partial a_n$, $\partial^2\chi^2/\partial a^2$ is a $k \times k$ matrix with mn^{th} element $\partial^2\chi^2/(\partial a_m \cdot \partial a_n)$, and all derivatives are to be evaluated at the points indicated. If "χ^2" is a true χ^2, the second-derivative matrix is independent of $\vec{a}$; therefore the shape of the χ^2 as a function of $\vec{a}$ is a paraboloid and Eq. (2.19a) will give the solution immediately. Otherwise one may need to iterate Eq. (2.19a) to arrive at a solution (Newton-Raphson method).

Note that in Eq. (2.15b), one needs only a matrix proportional to V_y to find $\widehat{a}$. Hence, for example, if the variances σ_i^2 of the errors are unknown but assumed equal and independent, and $\boldsymbol{E}(\epsilon_i) = 0$, one can still solve for $\widehat{a}$. One cannot, however, solve for $V_{\widehat{a}}$ or evaluate goodness-of-fit. These can be estimated from the *residuals*, $r_i = \widehat{y}(x_i) - y_i$, where $\widehat{y}(x_i)$ is the fitted curve at x_i, because study of the r_i enables one to estimate V_y. In addition, the residuals can be used to look for evidence of bias such as trends in the data not incorporated in the model [3].

Note that the errors on the solution $\widehat{a}$ are independent of the value of χ^2 at minimum—they depend only upon the shape about the minimum. Eq. (2.19b) implies that one-standard-deviation limits on the elements of $\widehat{a}$ are given by the set of $\vec{a}'$ such that

$$\chi^2(\vec{a}') = \chi^2_{\rm min} + 1 ; \qquad (2.20)$$

compare with Eq. (2.8) for the general maximum-likelihood case. This equation, which defines a contour in $\vec{a}$-space, is often convenient for estimating errors in applications of least-squares techniques to *nonlinear* cases, where the second derivative [Eq. (2.19b)] may be a rapidly varying function of $\vec{a}$. In general, contours at s standard deviations may be found by replacing the 1 in Eq. (2.20) by s^2. If the problem is highly nonlinear, all such contours are at best only approximations to desired exact confidence regions which would have some given probability of covering the true value of $\vec{a}$. It may be that Eq. (2.20) will define a set of disjoint regions. In addition, iteration of Eq. (2.19a) may require sophisticated techniques [8] to reach convergence in a practical amount of computation. For example, in cases involving many variables in $\vec{a}$, especially if the correlations are not small, simplex or other techniques which do not involve explicit calculation of derivatives are often to be preferred. Such techniques are designed to find their way through complicated nonlinear problems without diverging to infinite $\vec{a}$ (unless the minimum is actually at infinity).

Least-squares estimation requires that an error matrix V_y be known (a matrix proportional to V_y will suffice to find an estimator). For counting experiments it is therefore necessary to group the data in bins in order to associate a Poisson error with each bin. In this case y_i is the bin height and the error depends on the expectation value of the theory in each bin, N_i^{th}, as estimated by the best fit of the model. Thus the requirements of the Gauss-Markov theorem are not satisfied, since the errors are not fixed. Many experimenters arrange the bins to contain enough expected events (say $\gtrsim 7$ or 8) that the Gaussian approximation to the Poisson (Sec. 1.3.3) is accurate, in which case the expected error is the square root of the theoretical height and "χ^2" is approximately a true χ^2. If an approximate error is used, based on the actual observed height $N_i^{\rm obs}$ rather than the theoretical height N_i^{th}, the Gauss-Markov conditions would be satisfied except that a bias favoring downward fluctuations will occur.

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This is because a fluctuation in the data which goes down from the true expectation value will be assigned a smaller error and therefore a greater weight than an equal fluctuation upward. For bins with few events, a procedure that converges to the above when N_i^{th} is large and yields correct error estimates for all N_i^{th} is to define

$$\chi^2 = \sum_i \left[2(N_i^{th} - N_i^{\rm obs}) + 2N_i^{\rm obs}\ln(N_i^{\rm obs}/N_i^{th})\right] . \tag{2.21}$$

This assumes that $N_i^{\rm obs}$ is the outcome of a Poisson process, with Poisson parameter $\mu = N_i^{th}$, in the i^{th} bin. In bins where $N_i^{\rm obs} = 0$, the second term is zero. For any N_i^{th}, s-standard-deviation error estimates are constructed as in Eq. (2.20) and subsequent discussion. If we drop the requirement that χ^2 converge to a true χ^2 for large numbers of events in each bin, then minimizing "χ^2" $= 2\sum_i[N_i^{th} - N_i^{\rm obs}\ln(N_i^{th})]$ will give the same answer and errors, with slightly faster execution, as the above.

In the more general maximum likelihood case, the small-number distributions are well known and there are no corresponding requirements concerning large numbers or even of binning.

Example: straight-line fit

For the case of a *straight-line fit*, $y(x) = a_1 + a_2\,x$, one obtains, for independent measurements y_i, the following estimates of a_1 and a_2,

$$\begin{aligned} \widehat{a}_1 &= (S_y\,S_{xx} - S_x\,S_{xy})/D\ , \\ \widehat{a}_2 &= (S_1\,S_{xy} - S_x\,S_y)/D\ , \end{aligned} \tag{2.22}$$

where

$$S_1,\, S_x,\, S_y,\, S_{xx},\, S_{xy} = \sum(1,\, x_i,\, y_i,\, x_i^2,\, x_i\,y_i)/\sigma_i^2\ , \tag{2.23}$$

respectively, and

$$D = S_1\,S_{xx} - S_x^2\ .$$

The covariance matrix of the fitted parameters is:

$$\begin{pmatrix} V_{11} & V_{12} \\ V_{12} & V_{22} \end{pmatrix} = \frac{1}{D}\begin{pmatrix} S_{xx} & -S_x \\ -S_x & S_1 \end{pmatrix}\ . \tag{2.24}$$

The estimated variance of an interpolated or extrapolated value of y at point x is:

$$(\,\widehat{y} - y_{\rm true})^2\Big|_{\rm est} = \frac{1}{S_1} + \frac{S_1}{D}\left(x - \frac{S_x}{S_1}\right)^2\ . \tag{2.25}$$

2.4 Errors and confidence intervals

2.4.1 Gaussian errors

If the data are such that the distribution of the estimator(s) satisfies the central limit theorem discussed in Sec. 1.3.4, the Gaussian distribution is the basis of the error analysis. If there is more than one parameter being estimated, the multivariate Gaussian is used. We define a *confidence interval* as being an interval constructed from the data to have probability *at least* $1-\alpha$ (α is called the *confidence coefficient*) of covering the true value of θ. For the univariate case with known σ,

$$1-\alpha = \int_{\widehat{\mu}-\delta}^{\widehat{\mu}+\delta} f(x;\,\widehat{\mu},\,\sigma^2)\,dx \tag{2.26}$$

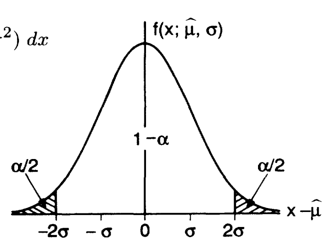

Fig. 4. Illustration of a two standard-deviation confidence interval (unshaded) for a measurement of a single quantity with Gaussian errors. Integrated probabilities, defined by α, are as shown.

is the probability that the true value of μ will fall within $\pm\delta$ ($\delta > 0$) of the measured $\widehat{\mu}$. This interval will cover μ in a fraction $1-\alpha$ of all similar measurements. Fig. 4 shows a $\delta = 2\sigma$ confidence interval unshaded. The choice $\delta = \sqrt{\mathrm{Var}(\,\widehat{\mu}\,)} \equiv \sigma$ gives an interval called the *standard error* which has $1-\alpha = 68.33\%$ if σ is known. Other frequently used choices for δ, in terms of α are:

α (%)	δ	α (%)	δ
31.73	1σ	20	1.28σ
4.55	2σ	10	1.64σ
0.27	3σ	5	1.96σ
6.3×10^{-3}	4σ	1	2.58σ
5.7×10^{-5}	5σ	0.1	3.29σ
2.0×10^{-7}	6σ	0.01	3.89σ

For other δ, find α as the ordinate of Fig. 1 on the $n = 1$ curve at $\chi^2 = (\delta/\sigma)^2$. We can set a one-sided (upper or lower) limit by excluding above $\widehat{\mu}+\delta$ (or below $\widehat{\mu}-\delta$); α's for such limits are 1/2 the values in the table above.

Note that we have increased confidence that the interval covers the true value as $1-\alpha$ increases, or χ^2 increases. We must be careful to distinguish this case from the other major use of Fig. 1, evaluation of goodness-of-fit (Sec. 2.3.3). In that case we have increased confidence in the fit as χ^2 decreases. In an attempt to reduce possible confusion in this discussion, we will use the α notation (which corresponds to notation used in hypothesis testing [3]) when discussing confidence intervals and CL notation when discussing goodness-of-fit. Elsewhere in this Review, where the confusion between fit confidence level and interval (usually an upper or lower limit) confidence level does not arise, we follow the common practice of using "CL" to refer to the confidence level of the interval. This CL is understood to represent $1-\alpha$.

If the variance σ^2 of the estimator is not known, but must be estimated from the data, then we need to incorporate the error in $\widehat{\sigma}$ into our confidence interval using Student's t distribution. If we have N data points with which we estimate k parameters, the Gaussian approximation is adequate for $N-k \gg 1$. Otherwise replace δ by a factor $T\widehat{\sigma}$, T being defined by

$$1-\alpha = \int_{-T}^{T} f(x;N-k)\,dx\ , \tag{2.27}$$

where f is defined in Eq. (1.34). T is tabulated in Ref. 2 and here:

	α (%)					
$N-k$	31.67	10.00	5.00	4.55	1.00	0.27
1	1.84	6.31	12.71	13.97	63.66	235.78
2	1.32	2.92	4.30	4.53	9.92	19.21
3	1.20	2.35	3.18	3.31	5.84	9.22
4	1.14	2.13	2.78	2.87	4.60	6.62
5	1.11	2.01	2.57	2.65	4.03	5.51
10	1.05	1.81	2.23	2.28	3.17	3.96
20	1.03	1.72	2.09	2.13	2.85	3.42
∞	1.00	1.64	1.96	2.00	2.58	3.00

For multivariate θ we must consider pairwise correlations. Assuming a multivariate Gaussian, Eq. (1.28a), and subsequent discussion the standard error ellipse for the pair $(\,\widehat{\theta}_m, \widehat{\theta}_n)$ may be drawn as in Fig. 5.

The minimum χ^2 or maximum likelihood solution is at $(\,\widehat{\theta}_m, \widehat{\theta}_n)$. The standard errors σ_m and σ_n are defined as shown, where the ellipse is at a constant value of $\chi^2 = \chi^2_{\rm min} + 1$ or $\ln\mathcal{L} = \ln\mathcal{L}_{\rm max} - 1/2$. The angle of the major axis of the ellipse is given by

$$\tan 2\phi = \frac{2\rho_{mn}\,\sigma_m\,\sigma_n}{\sigma_m^2 - \sigma_n^2}\ . \tag{2.28}$$

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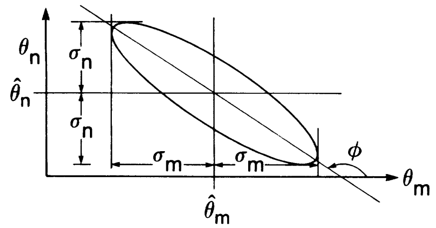

Fig. 5. Standard error ellipse for the estimators $\widehat{\theta}_m$ and $\widehat{\theta}_n$. In this case the correlation is negative.

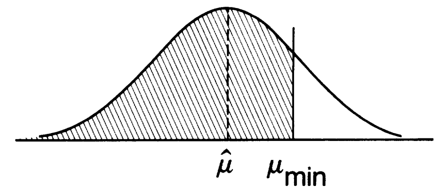

Fig. 6. An example of a bounded physical region with Gaussian errors. In this case the estimator $\widehat{\mu}$ has fallen within the unphysical region due to random error.

For non-Gaussian or nonlinear cases, one may construct an analogous contour from the same χ^2 or $\ln \mathcal{L}$ relations. Any other parameters $\widehat{\theta}_\ell, \ell \neq m, n$, must be allowed freely to find their optimum values for every trial point.

For any unbiased procedure (*e.g.*, least squares or maximum likelihood) being used to estimate k parameters θ_i, $i = 1, \ldots, k$, the probability $1 - \alpha$ that the true values of all k lie within the s-standard deviation ellipsoid may be found from Fig. 1. Read the ordinate as α; the correct value of α occurs on the $n = k$ curve at $\chi^2 = s^2$. For example, for $k = 2$, the probability that the true values of θ_1 and θ_2 simultaneously lie within the one-standard-deviation error ellipse ($s = 1$), centered on $\widehat{\theta}_1$ and $\widehat{\theta}_2$, is 39%. This probability only assumes Gaussian errors, unbiased estimators, and that the model describing the data in terms of the θ_i is correct.

2.4.2 Gaussian errors—bounded physical region

In certain statistical problems the true value of the parameter to be estimated, μ, is constrained to lie within a bounded *physical region* (*e.g.*, the mass of a neutrino is bounded from below by 0). However, due to random measurement error, real measured values may or may not occur inside the physical region. For this case no completely satisfactory approach exists, but here we suggest a technique for obtaining limits within the physical region approximately at specified confidence levels. The "classical" statistical techniques of the previous section can still be used for confidence intervals at some exact α. However, such limits are useful mainly in the statistical sense where it is assumed that no bound exists. In bad cases, the limit may exclude the physical region entirely, or extend into it a small distance and create the false impression of a powerful limit close to the edge of the physical region.

We assume a measurement x, which represents one observation (or the result of combining multiple measurements as in Sec. 2.2) from a Gaussian of true (but unknown) mean μ and known, fixed, variance σ^2. We *estimate* μ by $\widehat{\mu} = x$ and attempt to construct a confidence interval for μ from the resultant Gaussian, as above. If $\widehat{\mu}$ or a significant portion of the probability lies in the unphysical region (Fig. 6), the result, while statistically perfectly correct as stated, is physically unsatisfactory.

If we assume μ is bounded from below by $\mu_{\rm min}$ (the argument for μ bounded from above is similar), we may estimate a reasonable upper limit for μ at the $1 - \alpha$ (*e.g.*, 90% or 95%) level by the following procedure: (1) *renormalize* the Gaussian probability distribution for x such that the integral of Eq. (1.24) with $\mu = \widehat{\mu}$ over x from $\mu_{\rm min}$ to infinity (i.e., over the physical region), unshaded in the figure below, is equal to 1.0; (2) find the value μ_1 such that the integral over x of the renormalized distribution from $\mu_{\rm min}$ to μ_1 is equal to the desired value of $1 - \alpha$; (3) set μ_1 to be the desired upper limit with confidence $1 - \alpha$. In fact, it can be shown that this is *conservative*, in the sense that the probability that this interval actually covers the true value of μ is $\geq 1 - \alpha$

The "classical" approach as described above can be derived formally by the application of Bayes' theorem with the explicit assumption that all values of the parameter are equally probable. This means, for example, that limits on m^2 are different than limits on m. A recent treatment is given by James and Roos [11].

For $\mu - \mu_{\rm min} \gg \sigma$, this technique, which may be applied for any measured x (physical or unphysical), converges smoothly to that of the previous section since x is then effectively confined to the physical region.

One should exercise caution for values of x which lie many standard deviations outside the physical region. It may be that the particular probability model (Gaussian with variance σ^2) may not be a correct description of the measurement process (*e.g.*, the true variance may have unanticipated components and be $> \sigma^2$, or there may be a bias), in which case confidence levels of this sort will not be correct.

If $\widehat{\mu} < \mu_{\rm min}$, some authors prefer to use a fixed upper limit calculated for $\widehat{\mu} = \mu_{\rm min}$ or $\widehat{\mu} = \mu_{\rm min} + \sigma$, rather than allow the upper limit to decrease as $\widehat{\mu}$ decreases. In any case, averaging of experiments requires that $\widehat{\mu}$ and its variance be quoted, in addition to any upper limits, even if $\widehat{\mu}$ is unphysical.

2.4.3 Poisson processes—upper limits

Because the outcome of a Poisson process is an integral number of events, n_0, it is usually not possible to set confidence intervals for the true Poisson parameter μ at a certain exact α. For large n_0 an approximate interval can be set using the Gaussian approximation, Sec. 1.3.3, and the techniques of Sec. 2.4.1.

For small n_0 we can define an upper limit N for μ as being that value of μ such that it would be at least $1 - \alpha$ (*e.g.*, 90% or 95%) probable that a random observation of n would then lie above the observed n_0. Thus

$$1 - \alpha = \sum_{n=n_0+1}^{\infty} f(n;\, N)\ ; \qquad \alpha = \sum_{n=0}^{n_0} f(n;\, N)\ . \tag{2.29}$$

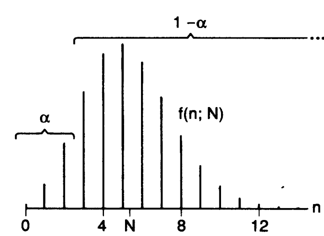

Fig. 7. Illustration of Eq. (2.29) Poisson probabilities for an assumed mean of N. With an observed count $n_0 = 2$, $N = 5.3$ as shown gives summed probability $1 - \alpha = 90\%$.

Fig. 7 illustrates the case with $n_0 = 2$ and $1 - \alpha = 90\%$, for which it may be shown that $N = 5.3$. For any given n_0 and desired α we can obtain N from the χ^2 Confidence Level figure because of a relation between the Poisson and the χ^2: read the ordinate as α, find χ^2 on the curve for $n = 2(n_0 + 1)$; then $N = \chi^2/2$. Some useful values are:

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Poisson upper limits N for n_0 observed events

n_0	$\alpha =$ 10%	$\alpha =$ 5%	n_0	$\alpha =$ 10%	$\alpha =$ 5%
0	2.30	3.00	6	10.53	11.84
1	3.89	4.74	7	11.77	13.15
2	5.32	6.30	8	13.00	14.44
3	6.68	7.75	9	14.21	15.71
4	7.99	9.15	10	15.41	16.96
5	9.27	10.51			

The meaning of these upper limits is that, for a given true μ, the probability is *at least* $1-\alpha$ that one will observe n_0 which will result in N which is $\geq \mu$. The probability for that to occur may be higher than $1-\alpha$; for example, if $\mu \leq 2.30$ a "90%" upper limit will actually exceed μ 100% of the time. Note from Eq. (2.29) that for $n_0 = 0$, $N = \ln[1/(1-\alpha)]$.

2.4.4 Poisson processes with background [12]

If we observe n_0 events in a Poisson process which has two components, signal and background, estimating a limit on the signal is more complicated. Let μ_S be the unknown mean (the Poisson parameter) for the signal and μ_B be the mean for the sum of all backgrounds. Assume μ_B is known with negligible error; however we don't know n_B, the actual number of events resulting from the background. We do know that $n_B \leq n_0$. If $\mu_B + \mu_S$ is large, the Gaussian approximation to the Poisson distribution (see Sec. 1.3.3) is usually adequate, and one can define confidence intervals or limits as above, assuming $\widehat{n}_B \approx \mu_B$ and therefore $\widehat{\mu}_S = n_0 - \mu_B$ with variance equal to n_0 (larger than $\widehat{\mu}_S$ to allow for the error in $\widehat{n}_B$).

Otherwise an upper limit can be defined by extension of the argument of the preceding section. Let N be the desired upper limit on μ_S with confidence coefficient α. Set N to be that value of μ_S such that any random repeat of the current experiment with $\mu_S = N$ and the same μ_B would observe *more* than n_0 events in total *and* would have $n_B \leq n_0$, all with probability $1-\alpha$. For any assumed N and μ_B we can calculate this probability:

$$1-\alpha = 1 - \frac{e^{-(\mu_B+N)} \displaystyle\sum_{n=0}^{n_0} \frac{(\mu_B+N)^n}{n!}}{e^{-\mu_B} \displaystyle\sum_{n=0}^{n_0} \frac{\mu_B^n}{n!}} . \tag{2.30}$$

We adjust N to obtain a desired α. For $\mu_B = 0$ this converges to (2.29). As in that case (see the last paragraph of Section 2.4.3) this gives a *conservative* upper limit in that for any given true μ_S we get a true probability $\geq 1-\alpha$ that $N \geq \mu_S$, averaged over a large set of identically performed experiments. For $\alpha = 0.10$, Fig. 8 shows N as a function of n_0 and μ_B.

Averaging of experiments and other comparisons require that n_0 and μ_B be quoted and the technique used for upper limit extraction be given.

If $\mu_B \gg n_0$ the experimenter should question the probability of observing n_B as that n_0. If this is very small the background, μ_B, may not have been calculated properly and the upper limit for μ_S obtained under those assumptions may be too low. For example, in Fig. 8, the dashed portions of the curves lie in the region where n_0 is expected to exceed the observed value 99% of the time (or more), even in the complete absence of signal. In these regions one should be cautious about accepting the results of the measurement.

As in the Gaussian case (2.4.2), whenever $n_0 < \mu_B$ some experimenters may prefer to use N calculated as if $n_0 \approx \mu_B$ rather than the smaller value obtained from the observed n_0.

2.5 Propagation of errors

Suppose we have a set of N random variables y_i which may be direct measurements or derived estimators $\widehat{\theta}$, and we have a covariance matrix $V(y)$ for these. We can make a transformation to a different

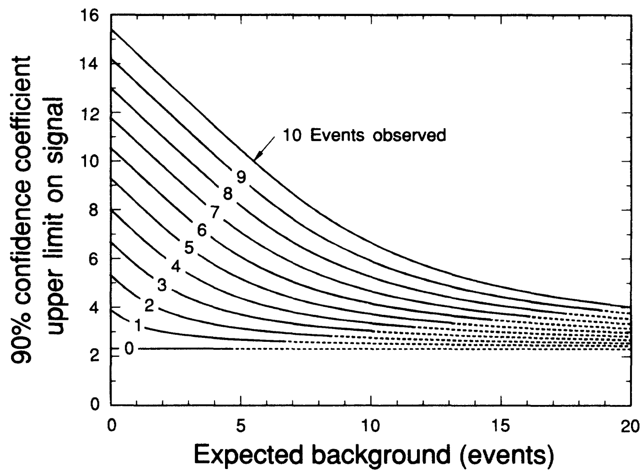

Fig. 8. 90% confidence coefficient upper limit on the number of signal events as a function of the expected number of background events. For example, if the expected background is 8 events and 5 events are observed, then the signal is 4.0 (approximately) or less with 90% confidence. Dashed portions indicate regions where it is to be expected that the number observed would exceed the number actually observed $\geq$ 99% of the time, even in the complete absence of signal.

set of variables $f_j \equiv f_j(y)$, $j = 1, \ldots, M$ $(M \leq N)$ and obtain best estimates for the f_j from

$$\widehat{f}_j \approx f_j(\widehat{y}) + \frac{1}{2} \sum_{k,n}^{N} V_{kn}(\widehat{y}) \left[\frac{\partial^2 f_j}{\partial y_k \, \partial y_n} \right]_{\widehat{y}} \tag{2.31}$$

with covariance matrix

$$V_{ij}(\widehat{f}) \approx \sum_{n,m} \left. \frac{\partial f_i}{\partial y_n} \right|_{\widehat{y}} \left. \frac{\partial f_j}{\partial y_m} \right|_{\widehat{y}} V_{nm}(\widehat{y}) . \tag{2.32}$$

For a single-valued function f of a single measurement y with variance σ^2 (i.e., $M = 1, N = 1$), this becomes

$$\begin{aligned} \widehat{f} &\approx f(\widehat{y}) + \frac{1}{2}\sigma^2 f''(\widehat{y}) \\ V(\widehat{f}) &\approx \sigma^2 [f'(\widehat{y})]^2 , \end{aligned} \tag{2.33}$$

where the primes denote differentiation with respect to y, evaluated at $\widehat{y}$.

These approximations are based on a Taylor expansion of f about the true value of y. If f is approximately linear in y over a range of roughly $\widehat{y}_i \pm \sigma(y_i)$, the approximation is good and the second-order terms in (2.31) and (2.33) can be neglected. This is what is usually done. However, if linearity is badly violated (*e.g.*, $f \propto 1/y$ and $\widehat{y}$ is no more than a few σ from zero), it should be recognized that propagation of errors will give very approximate results. In such cases $\widehat{f} \approx f(\widehat{y})$ may be a biased estimator for f even if $\widehat{y}$ is unbiased for y, and the second-order terms in (2.31) and (2.33) will help to reduce that bias.

3. MONTE CARLO TECHNIQUES

Monte Carlo techniques are used to simulate on a computer random behavior which is too complex to be derived analytically. Most calculations are based upon *pseudorandom* numbers, a reproducible sequence of numbers generated on the open interval (0,1) in such a way that they satisfy various statistical tests for a uniform distribution, with independent numbers. (Caution: some commercial random number generators fill the *closed* interval [0,1]. The occurrence of 0 or 1 can sometimes cause problems for the algorithms below). No such numbers are truly uniform and independent. Many commercial random number generators sacrifice randomness in favor of speed. It is not rare that unforeseen correlations will introduce non-negligible errors in the results. A useful test for this is to recompute the same results with a different algorithm for the pseudorandom numbers. To improve the performance of an existing generator one may use the *Bays-Durham algorithm* [see Ref. 8 for discussion]: (a) Initialize by generating and storing N (*e.g.*, $N = 97$) random numbers in an array v, using the available generator. Generate a new random number u and save it. (b) On the next call, use this u as an address $j = 1+$ (integer part of Nu) to select v_j as the random number to be returned. Also save this v_j as u for the next call. Replace v_j in the array with a new random number using the available generator. On the next call, go to (b).

A second problem sometimes encountered in computations requiring long sequences of random numbers is that all pseudorandom number generators will eventually begin over and repeat the same sequence. One may choose algorithms which minimize the number used. One may also use two or three different generators in different parts of the program.

Monte Carlo simulations of complex processes break them down into a sequence of steps. At each step a particular outcome is chosen from a set of possibilities according to a certain p.d.f. To do this we must transform our uniform random numbers into random numbers sampled from different distributions on different ranges.

Two techniques are in wide use to do this. We will discuss only single variable cases; multiple variable cases use straightforward extensions of these techniques. We assume we are in possession of a random number u chosen from a uniform distribution on (0,1).

3.1 Inverse transform method

If the desired probability density function is $f(x)$ on the range $-\infty < x < \infty$, its cumulative distribution function (expressing the probability that $x \le a$) is given by Eq. (1.1). If a is chosen with probability density $f(a)$, then the integrated probability up to point a, $F(a)$, is itself a random variable which will occur with uniform probability density on $[0, 1]$. Ignoring the endpoints, we can then find a unique x distributed as $f(x)$ for $f(x)$ *continuous*, for a given u if we set

$$u = F(x) \ , \tag{3.1}$$

provided we can find an inverse of F, defined by

$$x = F^{-1}(u) \ , \tag{3.2}$$

as is illustrated in Fig. 9

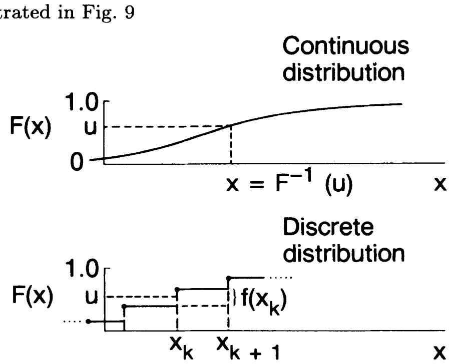

Fig. 9. Use of a random number u chosen from a uniform distribution (0,1) to find a random number x from a distribution with cumulative distribution function $F(x)$.

For a *discrete* distribution, $F(x)$ will have a discontinuous jump of size $f(x_k)$ at each allowed $x_k, k = 1, 2, \cdots$. Choose u from a uniform distribution on (0,1) as before. Find x_k such that

$$F(x_{k-1}) < u \le F(x_k) \equiv \text{Prob } (x \le x_k) = \sum_{i=1}^{k} f(x_i) \ ; \tag{3.3}$$

then x_k is the value we seek (note: $F(x_0) \equiv 0$).

3.2 Acceptance-rejection method (Von Neumann)

Very commonly an analytic form for $F(x)$ is unknown or too complex to work with, so that obtaining an inverse as in Eq. (3.2) is impractical. We suppose that for any given value of x the probability density function $f(x)$ can be computed and further that enough is known about $f(x)$ that we can enclose it entirely inside a shape which is C times an easily generated distribution $h(x)$ as illustrated in Fig. 10.

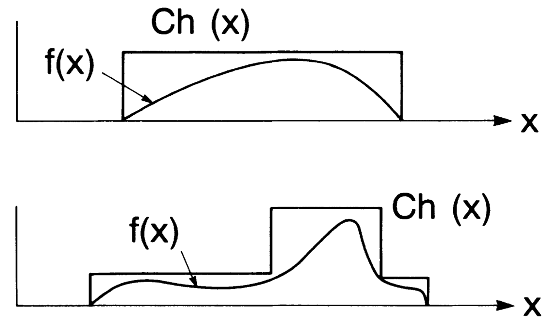

Fig. 10. Illustration of the acceptance-rejection method. Random points are chosen inside the upper bounding figure, and rejected if the ordinate exceeds $f(x)$. Lower figure illustrates importance sampling.

Frequently $h(x)$ is uniform or is a normalized sum of uniform distributions. Note that both $f(x)$ and $h(x)$ must be normalized to unit area and therefore the proportionality constant $C > 1$. To generate $f(x)$, first generate a candidate x according to $h(x)$. Calculate $f(x)$ and the height of the envelope $C\,h(x)$; generate u and *test* if $uC\,h(x) \le f(x)$. If so, accept x; if not reject x and try again. If we regard x and $uC\,h(x)$ as the abscissa and ordinate of a point in a two-dimensional plot, these points will populate the entire area $C\,h(x)$ in a smooth manner; then we accept those which fall under $f(x)$. The efficiency is the ratio of areas, which must equal $1/C$; therefore we must keep C as close as possible to 1.0. Therefore we try to choose $C\,h(x)$ to be as close to $f(x)$ as convenience dictates, as in the lower part of Fig. 10. This practice is called *importance sampling*, because we generate more trial values of x in the region where $f(x)$ is most important.

3.3 Algorithms

Many algorithms for generating common distributions are given by Rubinstein (1981) [13], Devroye (1986) [14], Press (1986) [8], Walck (1987) [15], and Everett (1983) [16]; a few of these are reproduced here. For many distributions alternative algorithms exist, varying in complexity, speed, and accuracy. For time-critical applications, these algorithms may be coded in-line to remove the significant overhead often encountered in making function calls. Variables named "u" are assumed to be independent and uniform on (0,1).

3.3.1 Sine and cosine of random angle

Generate u_1 and u_2. Then $v_1 = 2u_1 - 1$ is uniform on $(-1,1)$, and $v_2 = u_2$ is uniform on (0,1). Calculate $r^2 = v_1^2 + v_2^2$. If $r^2 > 1$, start over. Otherwise, the sine (S) and cosine (C) of a random angle are given by

$$S = 2v_1v_2/r^2 \quad \text{and} \quad C = (v_1^2 - v_2^2)/r^2 \ .$$

3.3.2 Gaussian distribution

If u_1 and u_2 are uniform on (0,1), then

$$z_1 = \sin 2\pi u_1 \sqrt{-2\ln u_2} \quad \text{and} \quad z_2 = \cos 2\pi u_1 \sqrt{-2\ln u_2}$$

are independent and Gaussian distributed with mean 0 and $\sigma = 1$.

There are many faster variants of this basic algorithm. For example, construct $v_1 = 2u_1 - 1$ and $v_2 = 2u_2 - 1$, which are uniform on $(-1,1)$.

PROBABILITY, STATISTICS, AND MONTE CARLO (Cont'd)

Calculate $r^2 = v_1^2 + v_2^2$, and if $r^2 > 1$ start over. If $r^2 < 1$, it is uniform on (0,1). Then

$$z_1 = v_1 \sqrt{\frac{-2\ln r^2}{r^2}} \quad \text{and} \quad z_2 = v_2 \sqrt{\frac{-2\ln r^2}{r^2}}$$

are independent numbers chosen from a normal distribution with mean 0 and variance 1. $z_i' = \mu + \sigma z_i$ distributes with mean μ and variance σ^2.

For a multivariate Gaussian it often is simplest to find a transformation matrix H as described at the end of Sec. 1.3.4 and generate n independent z_i's with zero means and unit variances; then return $\overrightarrow{x} = H\overrightarrow{z} + \overrightarrow{\mu}$. For $n = 2$ it is convenient to choose H such that $x_1 = z_1\sigma_1 + \mu_1$ and
$x_2 = V_{12}\, x_1/\sigma_1^2 + z_2\left[(\sigma_1^2\,\sigma_2^2 - V_{12}^2)/\sigma_1^2\right]^{1/2} + \mu_2$, where $\sigma_i^2 = V_{ii}$.

3.3.3 $\chi^2(n)$ distribution

For n even, generate $n/2$ uniform numbers u_i; then

$$y = -2\ln\left(\prod_{i=1}^{n/2} u_i\right) \quad \text{is} \quad \chi^2(n)\ .$$

For n odd, generate $(n-1)/2$ uniform numbers u_i and one Gaussian z as in 3.3.2; then

$$y = -2\ln\left(\prod_{i=1}^{(n-1)/2} u_i\right) + z^2 \quad \text{is} \quad \chi^2(n)\ .$$

For $n \gtrsim 30$ the much faster Gaussian approximation for the χ^2 may be preferable: generate z as in 3.3.2 and use $y = \left[z + \sqrt{2n-1}\right]^2/2$; if $z < -\sqrt{2n-1}$ reject and start over.

3.3.4 Binomial distribution

If $p \leq 1/2$ in Eq. (1.20), iterate until a successful choice is made: begin with $k = 1$; compute $P_k = q^n$ [for $k \neq 1$ use $P_k \equiv f(r_k; n, p)$, Eq. (1.20)] and store P_k into B; generate u. If $u \leq B$ accept $r_k = k - 1$ and stop; otherwise increment k by 1 and compute next P_k and add to B; generate a new u and repeat. If we arrive at $k = n + 1$, stop and accept $r_{n+1} = n$. If $p > 1/2$ it will be more efficient to generate r from $f(r; n, q)$, i.e., with p and q interchanged, and then set $r_k = n - r$.

3.3.5 Poisson distribution

Iterate until a successful choice is made: Begin with $k = 1$ and set $A = 1$ to start. Generate u. Replace A with uA; if now $A < \exp(-\mu)$, where μ is the Poisson parameter, accept $n_k = k - 1$ and stop. Otherwise increment k by 1, generate a new u and repeat, always starting with the value of A left from the previous try. For large $\mu(\gtrsim 10)$ it may be satisfactory (and much faster) to approximate the Poisson distribution by a Gaussian distribution [Sec. 1.3.4] and generate z from $f(z;0,1)$; then accept $x = \max(0, [\mu + z\sqrt{\mu} - 0.5])$ where [ ] signifies the greatest integer $\leq$ the expression.

3.3.6 Student's *t* distribution

For $n > 0$ degrees of freedom (n not necessarily integer), generate x from a Gaussian with mean 0 and $\sigma^2 = 1$ according to the method of 3.3.2. Next generate y, an independent gamma random variate with $k = n/2$ degrees of freedom. Then $z = x\sqrt{2n}/\sqrt{y}$ is distributed as a t with n degrees of freedom.

For the special case $n = 1$, the *Breit-Wigner* distribution, generate u_1 and u_2; set $v_1 = 2u_1 - 1$ and $v_2 = 2u_2 - 1$. If $v_1^2 + v_2^2 \leq 1$ accept $z = v_1/v_2$ as a Breit-Wigner distribution with unit area, center at 0.0, and FWHM 2.0. Otherwise start over. For center M_0 and FWHM Γ, use $W = z\Gamma/2 + M_0$.

Revised April 1992.

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ELECTROMAGNETIC RELATIONS

Quantity	Gaussian CGS	SI
Charge: Electron charge e: Potential: Magnetic field:	$2.997\ 924\ 58 \times 10^9$ esu $4.803\ 206\ 8 \times 10^{-10}$ esu (1/299.792 458) statvolt (ergs/esu) 10^4 gauss $= 10^4$ dyne/esu	$= 1$ C $= 1$ A s $= 1.602\ 177\ 33 \times 10^{-19}$ C $= 1$ V $= 1$ J C^{-1} $= 1$ T $= 1$ N A^{-1}m^{-1}
Lorentz force:	$\mathbf{F} = q\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right)$	$\mathbf{F} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$
Maxwell equations:	$\nabla \cdot \mathbf{D} = 4\pi\rho$ $\nabla \times \mathbf{H} - \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t} = \frac{4\pi}{c}\mathbf{J}$ $\nabla \cdot \mathbf{B} = 0$ $\nabla \times \mathbf{E} + \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = 0$	$\nabla \cdot \mathbf{D} = \rho$ $\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J}$ $\nabla \cdot \mathbf{B} = 0$ $\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$
Materials: Permitivity of free space: Permeability of free space:	$\mathbf{D} = \epsilon\mathbf{E}, \quad \mathbf{H} = \mathbf{B}/\mu$ 1 1	$\mathbf{D} = \epsilon\mathbf{E}, \quad \mathbf{H} = \mathbf{B}/\mu$ $\epsilon_0 = 8.854\ 187\ldots \times 10^{-12}$ F m^{-1} $\mu_0 = 4\pi \times 10^{-7}$ N A^{-2}
Fields from potentials:	$\mathbf{E} = -\nabla V - \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t}$ $\mathbf{B} = \nabla \times \mathbf{A}$	$\mathbf{E} = -\nabla V - \frac{\partial \mathbf{A}}{\partial t}$ $\mathbf{B} = \nabla \times \mathbf{A}$
Static potentials: (coulomb gauge)	$V = \sum_{\text{charges}} \frac{q_i}{r_i} = \int \frac{\rho(\mathbf{r}')}{\lvert\mathbf{r} - \mathbf{r}'\rvert}\, d^3x'$ $\mathbf{A} = \frac{1}{c}\sum_{\text{currents}} \frac{\mathbf{I}_i}{r_i} = \frac{1}{c}\int \frac{\mathbf{J}(\mathbf{r}')}{\lvert\mathbf{r} - \mathbf{r}'\rvert}\, d^3x'$	$V = \frac{1}{4\pi\epsilon_0}\sum_{\text{charges}} \frac{q_i}{r_i} = \frac{1}{4\pi\epsilon_0}\int \frac{\rho(\mathbf{r}')}{\lvert\mathbf{r} - \mathbf{r}'\rvert}\, d^3x'$ $\mathbf{A} = \frac{\mu_0}{4\pi}\sum_{\text{currents}} \frac{\mathbf{I}_i}{r_i} = \frac{\mu_0}{4\pi}\int \frac{\mathbf{J}(\mathbf{r}')}{\lvert\mathbf{r} - \mathbf{r}'\rvert}\, d^3x'$
Relativistic transformations: ($\mathbf{v}$ is the velocity of the primed frame as seen in the unprimed frame)	$\mathbf{E}'_\parallel = \mathbf{E}_\parallel$ $\mathbf{E}'_\perp = \gamma(\mathbf{E}_\perp + \frac{1}{c}\mathbf{v} \times \mathbf{B})$ $\mathbf{B}'_\parallel = \mathbf{B}_\parallel$ $\mathbf{B}'_\perp = \gamma(\mathbf{B}_\perp - \frac{1}{c}\mathbf{v} \times \mathbf{E})$	$\mathbf{E}'_\parallel = \mathbf{E}_\parallel$ $\mathbf{E}'_\perp = \gamma(\mathbf{E}_\perp + \mathbf{v} \times \mathbf{B})$ $\mathbf{B}'_\parallel = \mathbf{B}_\parallel$ $\mathbf{B}'_\perp = \gamma(\mathbf{B}_\perp - \frac{1}{c^2}\mathbf{v} \times \mathbf{E})$

$\frac{1}{4\pi\epsilon_0} = c^2 \times 10^{-7}$ N A^{-2} $= 8.987\ 55\ldots \times 10^9$ F m^{-1} ; $\quad \frac{\mu_0}{4\pi} = 10^{-7}$ N A^{-2} ; $\quad c = \frac{1}{\sqrt{\mu_0\epsilon_0}} = 2.997\ 924\ 58 \times 10^8$ m s^{-1}

ELECTROMAGNETIC RELATIONS (Cont'd)

Impedances (SI units)

ρ = resistivity at room temperature in $10^{-8}\,\Omega$ m:

~ 1.7 for Cu	~ 5.5 for W
~ 2.4 for Au	~ 73 for SS 304
~ 2.8 for Al	~ 100 for Nichrome

(Al alloys may have double the Al value.)

For alternating currents, instantaneous current I, voltage V, angular frequency ω:

$$V = V_0\, e^{j\omega t} = ZI \ .$$

Impedance of self-inductance L: $Z = j\omega L$.

Impedance of capacitance C: $Z = 1/j\omega C$.

Impedance of free space: $Z = \sqrt{\mu_0/\epsilon_0} = 376.7\ \Omega$.

Impedance per unit length of a flat conductor of width w (high frequency, ν):

$$Z = \frac{(1+j)\,\rho}{w\,\delta}\ , \quad \text{where } \delta = \text{effective skin depth}\ ;$$

$$\delta = \sqrt{\frac{\rho}{\pi\nu\mu}} \approx \frac{6.6\ \text{cm}}{\sqrt{\nu\,(\text{Hz})}} \quad \text{for Cu}\ .$$

Capacitance $\widehat{C}$ and inductance $\widehat{L}$ per unit length (SI units)

Flat rectangular plates of width w, separated by $d \ll w$:

$$\widehat{C} = \epsilon\,\frac{w}{d}\ ; \quad \widehat{L} = \mu\,\frac{d}{w}\ ;$$

$$\frac{\epsilon}{\epsilon_0} = 2 \text{ to } 6 \text{ for plastics; 4 to 8 for porcelain, glasses.}$$

Coaxial cable of inner radius r_1, outer radius r_2:

$$\widehat{C} = \frac{2\pi\,\epsilon}{\ln\,(r_2/r_1)}\ ; \quad \widehat{L} = \frac{\mu}{2\pi}\,\ln\,(r_2/r_1)\ .$$

Transmission lines (no loss):

Impedance: $Z = \sqrt{\widehat{L}/\widehat{C}}$.

Velocity: $v = 1/\sqrt{\widehat{L}\,\widehat{C}} = 1/\sqrt{\mu\,\epsilon}$.

Synchrotron radiation (CGS units)

For a particle of charge e, velocity $v = \beta c$, and energy $E = \gamma mc^2$, traveling in a circular orbit of radius R, the energy loss per revolution δE is

$$\delta E = \frac{4\pi}{3}\,\frac{e^2}{R}\,\beta^3\,\gamma^4\ .$$

For high-energy electrons or positrons ($\beta \approx 1$), this becomes

$$\delta E\ (\text{in MeV}) \approx 0.0885\ [E(\text{in GeV})]^4/R(\text{in m})\ .$$

For $\gamma \gg 1$, the energy radiated per revolution into the photon energy interval $d(\hbar\omega)$ is

$$dI = \frac{8\pi}{9}\alpha\,\gamma\,F(\omega/\omega_c)\,d(\hbar\omega)\ ,$$

where $\alpha = e^2/\hbar c$ is the fine-structure constant and

$$\omega_c = \frac{3\gamma^3 c}{2R}$$

is the critical frequency. The normalized function $F(y)$ is

$$F(y) = \frac{9}{8\pi}\sqrt{3}\,y \int_y^\infty K_{5/3}(x)\ dx\ ,$$

where $K_{5/3}(x)$ is a modified Bessel function of the third kind. For electrons or positrons,

$$\hbar\omega_c\,(\text{in keV}) \approx 2.22\ [E(\text{in GeV})]^3/R(\text{in m})\ .$$

Fig. 1 shows $F(y)$ over the important range of y.

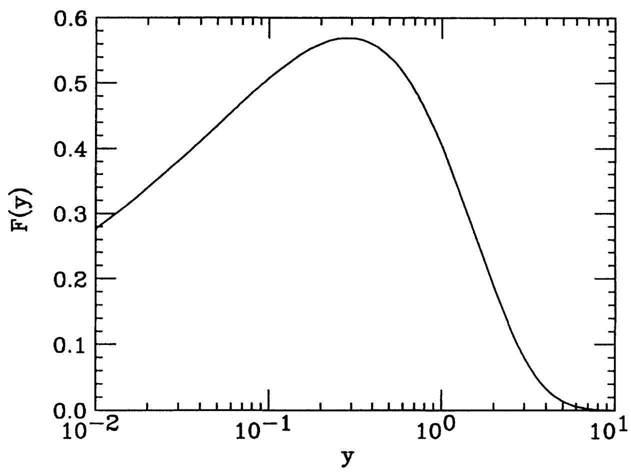


Fig. 1. The normalized synchrotron radiation spectrum $F(y)$.

For $\gamma \gg 1$ and $\omega \ll \omega_c$,

$$\frac{dI}{d(\hbar\omega)} \approx 3.3\alpha\,(\omega R/c)^{1/3}\ ,$$

whereas for $\gamma \gg 1$ and $\omega \gtrsim 3\omega_c$,

$$\frac{dI}{d(\hbar\omega)} \approx \sqrt{\frac{3\pi}{2}}\,\alpha\,\gamma\left(\frac{\omega}{\omega_c}\right)^{1/2} e^{-\omega/\omega_c}\left[1 + \frac{55}{72}\frac{\omega_c}{\omega} + \ldots\right]\ .$$

The radiation is confined to angles $\lesssim 1/\gamma$ relative to the instantaneous direction of motion.

See J.D. Jackson, *Classical Electrodynamics*, 2nd edition (John Wiley & Sons, New York, 1975) for more formulae and details. In his book, Jackson uses a definition of ω_c that is twice as large as the customary one given above.

CLEBSCH-GORDAN COEFFICIENTS, SPHERICAL HARMONICS, AND d FUNCTIONS

Note: A $\sqrt{\ }$ is to be understood over every coefficient; e.g., for -8/15 read $-\sqrt{8/15}$.

Notation:

	J	J	...
	M	M	...
m_1 m_2			
m_1 m_2	Coefficients		
. .			

$$Y_1^0 = \sqrt{\frac{3}{4\pi}}\cos\theta$$

$$Y_1^1 = -\sqrt{\frac{3}{8\pi}}\sin\theta\, e^{i\phi}$$

$$Y_2^0 = \sqrt{\frac{5}{4\pi}}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)$$

$$Y_2^1 = -\sqrt{\frac{15}{8\pi}}\sin\theta\cos\theta\, e^{i\phi}$$

$$Y_2^2 = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\sin^2\theta\, e^{2i\phi}$$

$$Y_\ell^{-m} = (-1)^m Y_\ell^{m*}$$

$$d^\ell_{m,0} = \sqrt{\frac{4\pi}{2\ell+1}}\, Y_\ell^m\, e^{-im\phi}$$

$$\langle j_1 j_2 m_1 m_2 | j_1 j_2 J M\rangle = (-1)^{J-j_1-j_2}\langle j_2 j_1 m_2 m_1 | j_2 j_1 J M\rangle$$

1/2 × 1/2

m_1 m_2	1 +1
+1/2 +1/2	1

m_1 m_2	1 0	0 0
+1/2 -1/2	1/2	1/2
-1/2 +1/2	1/2	-1/2

m_1 m_2	1 -1
-1/2 -1/2	1

1 × 1/2

m_1 m_2	3/2 +3/2
+1 +1/2	1

m_1 m_2	3/2 +1/2	1/2 +1/2
+1 -1/2	1/3	2/3
0 +1/2	2/3	-1/3

m_1 m_2	3/2 -1/2	1/2 -1/2
0 -1/2	2/3	1/3
-1 +1/2	1/3	-2/3

m_1 m_2	3/2 -3/2
-1 -1/2	1

2 × 1/2

m_1 m_2	5/2 +5/2
+2 1/2	1

m_1 m_2	5/2 +3/2	3/2 +3/2
+2 -1/2	1/5	4/5
+1 +1/2	4/5	-1/5

m_1 m_2	5/2 +1/2	3/2 +1/2
+1 -1/2	2/5	3/5
0 +1/2	3/5	-2/5

m_1 m_2	5/2 -1/2	3/2 -1/2
0 -1/2	3/5	2/5
-1 +1/2	2/5	-3/5

m_1 m_2	5/2 -3/2	3/2 -3/2
-1 -1/2	4/5	1/5
-2 +1/2	1/5	-4/5

m_1 m_2	5/2 -5/2
-2 -1/2	1

3/2 × 1/2

m_1 m_2	2 +2
+3/2 +1/2	1

m_1 m_2	2 +1	1 +1
+3/2 -1/2	1/4	3/4
+1/2 +1/2	3/4	-1/4

m_1 m_2	2 0	1 0
+1/2 -1/2	1/2	1/2
-1/2 +1/2	1/2	-1/2

m_1 m_2	2 -1	1 -1
-1/2 -1/2	3/4	1/4
-3/2 +1/2	1/4	-3/4

m_1 m_2	2 -2
-3/2 -1/2	1

2 × 1

m_1 m_2	3 +3
+2 +1	1

m_1 m_2	3 +2	2 +2
+2 0	1/3	2/3
+1 +1	2/3	-1/3

m_1 m_2	3 +1	2 +1	1 +1
+2 -1	1/15	1/3	3/5
+1 0	8/15	1/6	-3/10
0 +1	6/15	-1/2	1/10

m_1 m_2	3 0	2 0	1 0
+1 -1	1/5	1/2	3/10
0 0	3/5	0	-2/5
-1 +1	1/5	-1/2	3/10

m_1 m_2	3 -1	2 -1	1 -1
0 -1	6/15	1/2	1/10
-1 0	8/15	-1/6	-3/10
-2 +1	1/15	-1/3	3/5

m_1 m_2	3 -2	2 -2
-1 -1	2/3	1/3
-2 0	1/3	-2/3

m_1 m_2	3 -3
-2 -1	1

1 × 1

m_1 m_2	2 +2
+1 +1	1

m_1 m_2	2 +1	1 +1
+1 0	1/2	1/2
0 +1	1/2	-1/2

m_1 m_2	2 0	1 0	0 0
+1 -1	1/6	1/2	1/3
0 0	2/3	0	-1/3
-1 +1	1/6	-1/2	1/3

m_1 m_2	2 -1	1 -1
0 -1	1/2	1/2
-1 0	1/2	-1/2

m_1 m_2	2 -2
-1 -1	1

3/2 × 1

m_1 m_2	5/2 +5/2
+3/2 +1	1

m_1 m_2	5/2 +3/2	3/2 +3/2
+3/2 0	2/5	3/5
+1/2 +1	3/5	-2/5

m_1 m_2	5/2 +1/2	3/2 +1/2	1/2 +1/2
+3/2 -1	1/10	2/5	1/2
+1/2 0	3/5	1/15	-1/3
-1/2 +1	3/10	-8/15	1/6

m_1 m_2	5/2 -1/2	3/2 -1/2	1/2 -1/2
+1/2 -1	3/10	8/15	1/6
-1/2 0	3/5	-1/15	-1/3
-3/2 +1	1/10	-2/5	1/2

m_1 m_2	5/2 -3/2	3/2 -3/2
-1/2 -1	3/5	2/5
-3/2 0	2/5	-3/5

m_1 m_2	5/2 -5/2
-3/2 -1	1

$$d^j_{m',m} = (-1)^{m-m'} d^j_{m,m'} = d^j_{-m,-m'}$$

3/2 × 3/2

m_1 m_2	3 +3
+3/2 +3/2	1

m_1 m_2	3 +2	2 +2
+3/2 +1/2	1/2	1/2
+1/2 +3/2	1/2	-1/2

m_1 m_2	3 +1	2 +1	1 +1
+3/2 -1/2	1/5	1/2	3/10
+1/2 +1/2	3/5	0	-2/5
-1/2 +3/2	1/5	-1/2	3/10

m_1 m_2	3 0	2 0	1 0	0 0
+3/2 -3/2	1/20	1/4	9/20	1/4
+1/2 -1/2	9/20	1/4	-1/20	-1/4
-1/2 +1/2	9/20	-1/4	-1/20	1/4
-3/2 +3/2	1/20	-1/4	9/20	-1/4

m_1 m_2	3 -1	2 -1	1 -1
+1/2 -3/2	1/5	1/2	3/10
-1/2 -1/2	3/5	0	-2/5
-3/2 +1/2	1/5	-1/2	3/10

m_1 m_2	3 -2	2 -2
-1/2 -3/2	1/2	1/2
-3/2 -1/2	1/2	-1/2

m_1 m_2	3 -3
-3/2 -3/2	1

2 × 3/2

m_1 m_2	7/2 +7/2
+2 +3/2	1

m_1 m_2	7/2 +5/2	5/2 +5/2
+2 +1/2	3/7	4/7
+1 +3/2	4/7	-3/7

m_1 m_2	7/2 +3/2	5/2 +3/2	3/2 +3/2
+2 -1/2	1/7	16/35	2/5
+1 1/2	4/7	1/35	-2/5
0 3/2	2/7	-18/35	1/5

m_1 m_2	7/2 +1/2	5/2 +1/2	3/2 +1/2	1/2 +1/2
+2 -3/2	1/35	6/35	2/5	2/5
+1 -1/2	12/35	5/14	0	-3/10
0 1/2	18/35	-3/35	-1/5	1/5
-1 3/2	4/35	-27/70	2/5	-1/10

m_1 m_2	7/2 -1/2	5/2 -1/2	3/2 -1/2	1/2 -1/2
+1 -3/2	4/35	27/70	2/5	1/10
0 -1/2	18/35	3/35	-1/5	-1/5
-1 1/2	12/35	-5/14	0	3/10
-2 3/2	1/35	-6/35	2/5	-2/5

m_1 m_2	7/2 -3/2	5/2 -3/2	3/2 -3/2
0 -3/2	2/7	18/35	1/5
-1 -1/2	4/7	-1/35	-2/5
-2 1/2	1/7	-16/35	2/5

m_1 m_2	7/2 -5/2	5/2 -5/2
-1 -3/2	4/7	3/7
-2 -1/2	3/7	-4/7

m_1 m_2	7/2 -7/2
-2 -3/2	1

2 × 2

m_1 m_2	4 +4
+2 +2	1

m_1 m_2	4 +3	3 +3
+2 +1	1/2	1/2
+1 +2	1/2	-1/2

m_1 m_2	4 +2	3 +2	2 +2
+2 0	3/14	1/2	2/7
+1 1	4/7	0	-3/7
0 2	3/14	-1/2	2/7

m_1 m_2	4 +1	3 +1	2 +1	1 +1
+2 -1	1/14	3/10	3/7	1/5
+1 0	3/7	1/5	-1/14	-3/10
0 1	3/7	-1/5	-1/14	3/10
-1 2	1/14	-3/10	3/7	-1/5

m_1 m_2	4 0	3 0	2 0	1 0	0 0
+2 -2	1/70	1/10	2/7	2/5	1/5
+1 -1	8/35	2/5	1/14	-1/10	-1/5
0 0	18/35	0	-2/7	0	1/5
-1 1	8/35	-2/5	1/14	1/10	-1/5
-2 2	1/70	-1/10	2/7	-2/5	1/5

m_1 m_2	4 -1	3 -1	2 -1	1 -1
+1 -2	1/14	3/10	3/7	1/5
0 -1	3/7	1/5	-1/14	-3/10
-1 0	3/7	-1/5	-1/14	3/10
-2 1	1/14	-3/10	3/7	-1/5

m_1 m_2	4 -2	3 -2	2 -2
0 -2	3/14	1/2	2/7
-1 -1	4/7	0	-3/7
-2 0	3/14	-1/2	2/7

m_1 m_2	4 -3	3 -3
-1 -2	1/2	1/2
-2 -1	1/2	-1/2

m_1 m_2	4 -4
-2 -2	1

d functions

$$d^{1/2}_{1/2,1/2} = \cos\frac{\theta}{2} \qquad d^{1/2}_{1/2,-1/2} = -\sin\frac{\theta}{2}$$

$$d^1_{1,1} = \frac{1+\cos\theta}{2} \qquad d^1_{1,0} = -\frac{\sin\theta}{\sqrt{2}} \qquad d^1_{1,-1} = \frac{1-\cos\theta}{2} \qquad d^1_{0,0} = \cos\theta$$

$$d^{3/2}_{3/2,3/2} = \frac{1+\cos\theta}{2}\cos\frac{\theta}{2}$$

$$d^{3/2}_{3/2,1/2} = -\sqrt{3}\,\frac{1+\cos\theta}{2}\sin\frac{\theta}{2}$$

$$d^{3/2}_{3/2,-1/2} = \sqrt{3}\,\frac{1-\cos\theta}{2}\cos\frac{\theta}{2}$$

$$d^{3/2}_{3/2,-3/2} = -\frac{1-\cos\theta}{2}\sin\frac{\theta}{2}$$

$$d^{3/2}_{1/2,1/2} = \frac{3\cos\theta-1}{2}\cos\frac{\theta}{2}$$

$$d^{3/2}_{1/2,-1/2} = -\frac{3\cos\theta+1}{2}\sin\frac{\theta}{2}$$

$$d^2_{2,2} = \left(\frac{1+\cos\theta}{2}\right)^2 \qquad d^2_{2,1} = -\frac{1+\cos\theta}{2}\sin\theta \qquad d^2_{2,0} = \frac{\sqrt{6}}{4}\sin^2\theta$$

$$d^2_{2,-1} = -\frac{1-\cos\theta}{2}\sin\theta \qquad d^2_{2,-2} = \left(\frac{1-\cos\theta}{2}\right)^2$$

$$d^2_{1,1} = \frac{1+\cos\theta}{2}(2\cos\theta-1) \qquad d^2_{1,0} = -\sqrt{\frac{3}{2}}\sin\theta\cos\theta \qquad d^2_{1,-1} = \frac{1-\cos\theta}{2}(2\cos\theta+1)$$

$$d^2_{0,0} = \left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)$$

Sign convention is that of Wigner (*Group Theory*, Academic Press, New York, 1959), also used by Condon and Shortley (*The Theory of Atomic Spectra*, Cambridge Univ. Press, New York, 1953), Rose (*Elementary Theory of Angular Momentum*, Wiley, New York, 1957), and Cohen (*Tables of the Clebsch-Gordan Coefficients*, North American Rockwell Science Center, Thousand Oaks, Calif., 1974). The signs and numbers in the current tables have been calculated by computer programs written independently by Cohen and at LBL. (Table extended April 1974.)

SU(3) ISOSCALAR FACTORS AND REPRESENTATION MATRICES

The most commonly used SU(3) isoscalar factors, corresponding to the singlet, octet, and decuplet content of $8 \otimes 8$ and $10 \otimes 8$, are shown at the right. The notation uses particle names to identify the coefficients, so that the pattern of relative couplings may be seen at a glance. We illustrate the use of the coefficients by example. See J.J de Swart, Rev. Mod. Phys. **35**, 916 (1963) for detailed explanations and phase conventions.

A $\sqrt{\ }$ is to be understood over every integer in the matrices; the exponent 1/2 on each matrix is a reminder of this. For example, the $\Xi \to \Omega K$ element of our $10 \to 10 \otimes 8$ matrix is $-\sqrt{6}/\sqrt{24} = -1/2$.

Intramultiplet relative decay strengths may be read directly from our matrices. Thus, the ratio of the partial widths for $\Omega^* \to \Xi\overline{K}$ and $\Delta \to N\pi$ is, from the $10 \to 8 \times 8$ matrix,

$$\frac{\Gamma(\Omega^* \to \Xi\overline{K})}{\Gamma(\Delta \to N\pi)} = \frac{12}{6} \times \text{(phase space factors)} .$$

Supplying isospin Clebsch-Gordan coefficients, we obtain, *e.g.*,

$$\frac{\Gamma(\Omega^{*-} \to \Xi^0 K^-)}{\Gamma(\Delta^+ \to p\pi^0)} = \frac{1/2}{2/3} \times \frac{12}{6} \times p.s.f. = \frac{3}{2} \times p.s.f.$$

Partial widths for $8 \to 8 \otimes 8$ involve a linear superposition of 8_1 (symmetric) and 8_2 (antisymmetric) couplings. For example,

$$\Gamma(\Xi^* \to \Xi\pi) \sim \left(-\sqrt{\frac{9}{20}}\, g_1 + \sqrt{\frac{3}{12}}\, g_2\right)^2 .$$

The relations between g_1 and g_2 (with de Swart's normalization) and the standard D and F couplings that appear in the interaction Lagrangian,

$$\mathcal{L} = -\sqrt{2}\, D\, Tr\left([\overline{B}, B]_+ M\right) + \sqrt{2}\, F\, Tr\left([\overline{B}, B]_- M\right) ,$$

are

$$D = \frac{\sqrt{30}}{40}\, g_1 , \qquad F = \frac{\sqrt{6}}{24}\, g_2 .$$

Thus, for example,

$$\Gamma(\Xi^* \to \Xi\pi) \sim (F - D)^2 \sim (1 - 2\alpha)^2 ,$$

where $\alpha \equiv D/(D + F)$.

When acting upon a representation of dimension d, the generators of SU(3) transformations, λ_a (a = 1, 8), are $d \times d$ matrices that obey the following commutation and anticommutation relationships:

$$[\lambda_a, \lambda_b] = 2 i f_{abc} \lambda_c$$

$$\{\lambda_a, \lambda_b\} = \frac{4}{3}\delta_{ab} I + 2 d_{abc}\lambda_c ,$$

where I is the $d \times d$ unit matrix. The f_{abc} are odd under the permutation of any pair of indices, while the d_{abc} are even. The nonzero elements are

$1 \to 8 \otimes 8$

$$(\Lambda) \to (N\overline{K} \;\; \Sigma\pi \;\; \Lambda\eta \;\; \Xi K) = \frac{1}{\sqrt{8}} (2 \;\; 3 \;\; -1 \;\; -2)^{1/2}$$

$8_1 \to 8 \otimes 8$

$$\begin{pmatrix} N \\ \Sigma \\ \Lambda \\ \Xi \end{pmatrix} \to \begin{pmatrix} N\pi \;\; N\eta \;\; \Sigma K \;\; \Lambda K \\ N\overline{K} \;\; \Sigma\pi \;\; \Lambda\pi \;\; \Sigma\eta \;\; \Xi K \\ N\overline{K} \;\; \Sigma\pi \;\; \Lambda\eta \;\; \Xi K \\ \Sigma\overline{K} \;\; \Lambda\overline{K} \;\; \Xi\pi \;\; \Xi\eta \end{pmatrix} = \frac{1}{\sqrt{20}} \begin{pmatrix} 9 & -1 & -9 & -1 & \\ -6 & 0 & 4 & 4 & -6 \\ 2 & -12 & -4 & -2 & \\ 9 & -1 & -9 & -1 & \end{pmatrix}^{1/2}$$

$8_2 \to 8 \otimes 8$

$$\begin{pmatrix} N \\ \Sigma \\ \Lambda \\ \Xi \end{pmatrix} \to \begin{pmatrix} N\pi \;\; N\eta \;\; \Sigma K \;\; \Lambda K \\ N\overline{K} \;\; \Sigma\pi \;\; \Lambda\pi \;\; \Sigma\eta \;\; \Xi K \\ N\overline{K} \;\; \Sigma\pi \;\; \Lambda\eta \;\; \Xi K \\ \Sigma\overline{K} \;\; \Lambda\overline{K} \;\; \Xi\pi \;\; \Xi\eta \end{pmatrix} = \frac{1}{\sqrt{12}} \begin{pmatrix} 3 & 3 & 3 & -3 & \\ 2 & 8 & 0 & 0 & -2 \\ 6 & 0 & 0 & 6 & \\ 3 & 3 & 3 & -3 & \end{pmatrix}^{1/2}$$

$10 \to 8 \otimes 8$

$$\begin{pmatrix} \Delta \\ \Sigma \\ \Xi \\ \Omega \end{pmatrix} \to \begin{pmatrix} N\pi \;\; N\eta \\ N\overline{K} \;\; \Sigma\pi \;\; \Lambda\pi \;\; \Sigma\eta \;\; \Xi K \\ \Sigma\overline{K} \;\; \Lambda\overline{K} \;\; \Xi\pi \;\; \Xi\eta \\ \Xi\overline{K} \end{pmatrix} = \frac{1}{\sqrt{12}} \begin{pmatrix} -6 & 6 & & & \\ -2 & 2 & -3 & 3 & 2 \\ 3 & -3 & 3 & 3 & \\ 12 & & & & \end{pmatrix}^{1/2}$$

$8 \to 10 \otimes 8$

$$\begin{pmatrix} N \\ \Sigma \\ \Lambda \\ \Xi \end{pmatrix} \to \begin{pmatrix} \Delta\pi \;\; \Sigma K \\ \Delta\overline{K} \;\; \Sigma\pi \;\; \Sigma\eta \;\; \Xi K \\ \Sigma\pi \;\; \Xi K \\ \Sigma\overline{K} \;\; \Xi\pi \;\; \Xi\eta \;\; \Omega K \end{pmatrix} = \frac{1}{\sqrt{15}} \begin{pmatrix} -12 & 3 & & \\ 8 & -2 & -3 & 2 \\ -9 & 6 & & \\ 3 & -3 & -3 & 6 \end{pmatrix}^{1/2}$$

$10 \to 10 \otimes 8$

$$\begin{pmatrix} \Delta \\ \Sigma \\ \Xi \\ \Omega \end{pmatrix} \to \begin{pmatrix} \Delta\pi \;\; \Delta\eta \;\; \Sigma K \\ \Delta\overline{K} \;\; \Sigma\pi \;\; \Sigma\eta \;\; \Xi K \\ \Sigma\overline{K} \;\; \Xi\pi \;\; \Xi\eta \;\; \Omega K \\ \Xi\overline{K} \;\; \Omega\eta \end{pmatrix} = \frac{1}{\sqrt{24}} \begin{pmatrix} 15 & 3 & -6 & \\ 8 & 8 & 0 & -8 \\ 12 & 3 & -3 & -6 \\ 12 & -12 & & \end{pmatrix}^{1/2}$$

abc	f_{abc}	abc	d_{abc}	abc	d_{abc}
123	1	118	$1/\sqrt{3}$	355	1/2
147	1/2	146	1/2	366	−1/2
156	−1/2	157	1/2	377	−1/2
246	1/2	228	$1/\sqrt{3}$	448	$-1/(2\sqrt{3})$
257	1/2	247	−1/2	558	$-1/(2\sqrt{3})$
345	1/2	256	1/2	668	$-1/(2\sqrt{3})$
367	−1/2	338	$1/\sqrt{3}$	778	$-1/(2\sqrt{3})$
458	$\sqrt{3}/2$	344	1/2	888	$-1/\sqrt{3}$
678	$\sqrt{3}/2$				

In the fundamental 3-dimensional representation, the λ_a's are

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \quad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

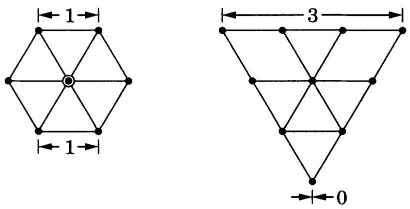
$$\lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

SU(N) MULTIPLETS AND YOUNG DIAGRAMS

This note tells (1) how SU(n) particle multiplets are identified or labeled, (2) how to find the number of particles in a multiplet from its label, (3) how to draw the Young diagram for a multiplet, and (4) how to use Young diagrams to determine the overall multiplet structure of a composite system, such as a 3-quark or a meson-baryon system.

In much of the literature, the word "representation" is used where we use "multiplet," and "tableau" is used where we use "diagram."

(1) Multiplet labels—An SU(n) multiplet is uniquely identified by a string of (n−1) nonnegative integers: $(\alpha, \beta, \gamma, \ldots)$. Any such set of integers specifies a multiplet. For an SU(2) multiplet such as an isospin multiplet, the single integer α is the number of *steps* from one end of the multiplet to the other (i.e., it is one fewer than the number of particles in the multiplet). In SU(3), the two integers α and β are the numbers of steps across the top and bottom levels of the multiplet diagram. Thus the labels for the SU(3) octet and decuplet



are (1,1) and (3,0). For larger n, the interpretation of the integers in terms of the geometry of the multiplets, which exist in an (n−1)-dimensional space, is not so readily apparent.

The label for the SU(n) singlet is $(0, 0, \ldots, 0)$. In a flavor SU(n), the n quarks together form a $(1, 0, \ldots, 0)$ multiplet, and the n antiquarks belong to a $(0, \ldots, 0, 1)$ multiplet. These two multiplets are *conjugate* to one another, which means their labels are related by $(\alpha, \beta, \ldots) \leftrightarrow (\ldots, \beta, \alpha)$.

(2) Number of particles—The number of particles in a multiplet, $N = N(\alpha, \beta, \ldots)$, is given as follows (note the pattern of the equations).

In SU(2), $N = N(\alpha)$ is

$$N = \frac{(\alpha + 1)}{1} \, .$$

In SU(3), $N = N(\alpha, \beta)$ is

$$N = \frac{(\alpha + 1)}{1} \cdot \frac{(\beta + 1)}{1} \cdot \frac{(\alpha + \beta + 2)}{2} \, .$$

In SU(4), $N = N(\alpha, \beta, \gamma)$ is

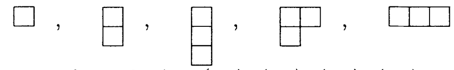
$$N = \frac{(\alpha{+}1)}{1} \cdot \frac{(\beta{+}1)}{1} \cdot \frac{(\gamma{+}1)}{1} \cdot \frac{(\alpha{+}\beta{+}2)}{2} \cdot \frac{(\beta{+}\gamma{+}2)}{2} \cdot \frac{(\alpha{+}\beta{+}\gamma{+}3)}{3} \, .$$

Note that there is no factor with $(\alpha + \gamma + 2)$: only a *consecutive* sequence of the label integers appears in any factor. One more example should make the pattern clear for any SU(n). In SU(5), $N = N(\alpha, \beta, \gamma, \delta)$ is

$$N = \frac{(\alpha{+}1)}{1} \cdot \frac{(\beta{+}1)}{1} \cdot \frac{(\gamma{+}1)}{1} \cdot \frac{(\delta{+}1)}{1} \cdot \frac{(\alpha{+}\beta{+}2)}{2} \cdot \frac{(\beta{+}\gamma{+}2)}{2} \times \frac{(\gamma{+}\delta{+}2)}{2} \cdot \frac{(\alpha{+}\beta{+}\gamma{+}3)}{3} \cdot \frac{(\beta{+}\gamma{+}\delta{+}3)}{3} \cdot \frac{(\alpha{+}\beta{+}\gamma{+}\delta{+}4)}{4} \, .$$

From the symmetry of these equations, it is clear that multiplets that are conjugate to one another have the same number of particles, but so can other multiplets. For example, the SU(4) multiplets (3,0,0) and (1,1,0) each have 20 particles. Try the equations and see.

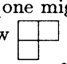
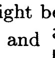
(3) Young diagrams—A Young diagram consists of an array of boxes (or some other symbol) arranged in one or more *left-justified* rows, with each row being *at least as long* as the row beneath. The correspondence between a diagram and a multiplet label is: The top row juts out α boxes to the right past the end of the second row, the second row juts out β boxes to the right past the end of the third row, etc. A diagram in SU(n) has at most n rows. There can be any number of "completed" columns of n boxes buttressing the left of a diagram; these don't affect the label. Thus in SU(3) the diagrams



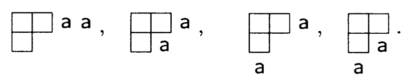
represent the multiplets (1,0), (0,1), (0,0), (1,1), and (3,0). In any SU(n), the quark multiplet is represented by a single box, the antiquark multiplet by a column of (n−1) boxes, and a singlet by a completed column of n boxes.

(4) Coupling multiplets together—The following recipe tells how to find the multiplets that occur in coupling two multiplets together. To couple together more than two multiplets, first couple two, then couple a third with each of the multiplets obtained from the first two, etc.

First a definition: A sequence of the letters $a, b, c, \ldots$ is *admissible* if at any point in the sequence at least as many a's have occurred as b's, at least as many b's have occurred as c's, etc. Thus *abcd* and *aabcb* are admissible sequences and *abb* and *acb* are not. Now the recipe:

(a) Draw the Young diagrams for the two multiplets, but in one of the diagrams replace the boxes in the first row with a's, the boxes in the second row with b's, etc. Thus, to find the multiplets that occur in the coupling of two SU(3) octets (one might be the π-meson octet, the other the baryon octet), we draw  and . The *unlettered* diagram forms the *upper left-hand corner* of all the enlarged diagrams constructed below.

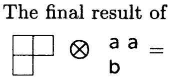
(b) Add the a's from the lettered diagram to the right-hand ends of the rows of the unlettered diagram to form all possible legitimate Young diagrams that have no more than one a per column. In general, there will be several distinct diagrams, and all the a's appear in each diagram. At this stage, the calculation of the coupling of the two SU(3) octets look as follows:

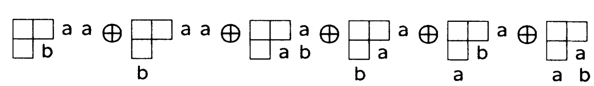


(c) Use the b's to further enlarge the diagrams already obtained, subject to the same rules. Then throw away any diagram in which the sequence of letters formed by reading *right to left* in the first row, then the second row, etc., is not admissible.

(d) Proceed as in (c) with the c's (if any), etc.

The final result of the coupling of the two octets is:





Here only the diagrams with admissible sequences of a's and b's and with fewer than four rows (since $n = 3$) have been kept. In terms of multiplet labels, the above may be written

$$(1,1) \otimes (1,1) = (2,2) \oplus (3,0) \oplus (0,3) \oplus (1,1) \oplus (1,1) \oplus (0,0) \, .$$

In terms of numbers of particles, it may be written

$$\mathbf{8} \otimes \mathbf{8} = \mathbf{27} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1} \, .$$

The product of the numbers on the left here is equal to the sum on the right. (See also the section on the Quark Model.)

KINEMATICS

Throughout this section units are used in which $\hbar = c = 1$. The following conversions are useful: $\hbar c$ = 197.3 MeV fermi, $(\hbar c)^2$ = 0.3894 $(\text{GeV})^2$ mb.

A. LORENTZ TRANSFORMATIONS

The energy E and 3-momentum $\vec{p}$ of a particle of mass m form a 4-vector $p = (E, \vec{p})$ whose square $p^2 \equiv E^2 - |\vec{p}|^2 = m^2$. The velocity of the particle is $\vec{\beta} = \vec{p}/E$. The energy and momentum $(E^*, \vec{p}^*)$ viewed from a frame moving with velocity $\vec{\beta}_f$ are given by

$$\begin{pmatrix} E^* \\ p_\parallel^* \end{pmatrix} = \begin{pmatrix} \gamma_f & -\gamma_f\beta_f \\ -\gamma_f\beta_f & \gamma_f \end{pmatrix} \begin{pmatrix} E \\ p_\parallel \end{pmatrix} , \quad p_\perp^* = p_\perp , \tag{A.1}$$

where $\gamma_f = (1-\beta_f^2)^{-1/2}$ and $p_\perp$ $(p_\parallel)$ are the components of $\vec{p}$ perpendicular (parallel) to $\vec{\beta}_f$. The scalar product of two 4-vectors $p_1 \cdot p_2 = E_1E_2 - \vec{p}_1 \cdot \vec{p}_2$ is invariant (frame independent).

In the collision of two particles of masses m_1 and m_2 the total center-of-mass energy is

$$E_{\text{cm}} = (p_1+p_2)^{1/2} = \left[(E_1+E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2\right]^{1/2} ,$$

$$= \left[m_1^2 + m_2^2 + 2E_1E_2(1-\beta_1\beta_2\cos\theta)\right]^{1/2} , \tag{A.2}$$

where θ is the angle between the particles. In the frame where one particle (of mass m_2) is at rest (lab frame),

$$E_{\text{cm}} = (m_1^2 + m_2^2 + 2E_{1\,\text{lab}}\, m_2)^{1/2} . \tag{A.3}$$

The velocity in the lab of the center-of-mass frame is

$$\vec{\beta}_{\text{cm}} = \vec{p}_{1\,\text{lab}}/(E_{1\,\text{lab}} + m_2) , \tag{A.4}$$

and

$$\gamma_{\text{cm}} = (E_{1\,\text{lab}} + m_2)/E_{\text{cm}} .$$

B. CENTER OF MASS ENERGY AND MOMENTUM

A beam of particles with mass m and momentum p_{beam} is incident on a fixed target consisting of particles with mass M. The energy of the beam particles E_{beam}, the center-of-mass energy E_{cm}, and center of mass momentum of one of the particles p_{cm} are given by

$$E_{\text{beam}} = \sqrt{p_{\text{beam}}^2 + m^2}$$

$$E_{\text{cm}} = \sqrt{m^2 + 2E_{\text{beam}}M + M^2}$$

$$p_{\text{cm}} = p_{\text{beam}}\frac{M}{E_{\text{cm}}} .$$

For example, if a 0.80 GeV/c kaon beam is incident on a proton target, the center of mass energy is 1.699 GeV and the center of mass momentum of either particle is 0.442 GeV/c. It is also useful to note that

$$E_{\text{cm}}\, dE_{\text{cm}} = M\, dE_{\text{beam}} = M\,\beta_{\text{beam}}\, dp_{\text{beam}} .$$

C. LORENTZ INVARIANT AMPLITUDES

The invariant amplitude $-i\mathcal{M}$ for a scattering or decay process is determined in perturbation theory by a set of Feynman diagrams. The convention of Bjorken and Drell is used except that fermion spinors are normalized so that $u\bar{u} = 2m$. As an example, the S-matrix for $2 \to 2$ scattering is related to $\mathcal{M}$ by

$$\langle p_1'p_2'\,|S|\,p_1p_2\rangle = I - i(2\pi)^4\,\delta^4(p_1+p_2-p_1'-p_2')$$

$$\times \frac{\mathcal{M}(p_1,\,p_2;\,p_1',\,p_2')}{(2E_1)^{1/2}\,(2E_2)^{1/2}\,(2E_1')^{1/2}\,(2E_2')^{1/2}} . \tag{C.1}$$

The state normalization is such that

$$\langle p'|p\rangle = (2\pi)^3\delta^3(\vec{p} - \vec{p}\,') . \tag{C.2}$$

D. PARTICLE DECAYS

The partial decay rate of a particle of mass M into n bodies in its rest frame is given in terms of the Lorentz invariant matrix element $\mathcal{M}$ by

$$d\Gamma = \frac{(2\pi)^4}{2M}\,|\mathcal{M}|^2\, d\Phi_n\,(P;\,p_1,\,\ldots,\,p_n), \tag{D.1}$$

where $d\Phi_n$ is an element of n-body phase space given by

$$d\Phi_n(P;\,p_1,\,\ldots,\,p_n) = \delta^4\,(P - \sum_{i=1}^{n} p_i)\,\prod_{i=1}^{n}\frac{d^3p_i}{(2\pi)^3 2E_i} . \tag{D.2}$$

This phase space can be generated recursively, viz.

$$d\Phi_n(P;\,p_1,\,\ldots,\,p_n) = d\Phi_j(q;\,p_1,\,\ldots,\,p_j) \tag{D.3}$$

$$\times\; d\Phi_{n-j+1}\,(P;\,q,\,p_{i+1},\,\ldots,\,p_n)(2\pi)^3 dq^2 ,$$

where $q^2 = (\sum_{i=j+1}^n E_i)^2 - \left|\sum_{i=j+1}^n \vec{p}_i\right|^2$. This form is particularly useful in the case where a particle decays into another particle which subsequently decays.

D.1 Survival probability:

If a particle of mass M has mean proper lifetime τ $(= 1/\Gamma)$ and has momentum $(E, \vec{p})$, then the probability that it lives for a time t_0 or greater before decaying is given by

$$P(t_0) = e^{-t_0\,\Gamma/\gamma} = e^{-Mt_0\,\Gamma/E} , \tag{D.4}$$

and the probability that it travels a distance x_0 or greater is

$$P(x_0) = e^{-Mx_0\,\Gamma/|\vec{p}|} . \tag{D.5}$$

D.2 Two-body decays:

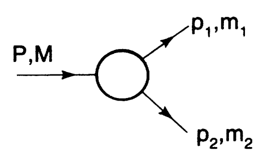


Fig. 1. Variable definitions for two-body decays.

In the rest frame of a particle of mass M, decaying into 2 particles labeled 1 and 2,

$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M} ,$$

$$|\vec{p}_1| = |\vec{p}_2| \tag{D.6}$$

$$= \frac{\left[\left(M^2 - (m_1+m_2)^2\right)\left(M^2 - (m_1-m_2)^2\right)\right]^{1/2}}{2M} ,$$

and

$$d\Gamma = \frac{1}{32\pi^2}\,|\mathcal{M}|^2\,\frac{|\vec{p}_1|}{M^2}\,d\Omega , \tag{D.7}$$

where $d\Omega = d\phi_1 d(\cos\theta_1)$ is the solid angle of particle 1.

D.3 Three-body decays:

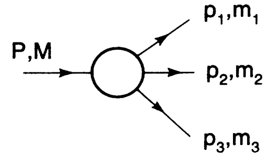


Fig. 2. Variable definitions for three-body decays.

KINEMATICS (Cont'd)

Defining $p_{ij} = p_i + p_j$, $m_{ij}^2 = p_{ij}^2$, then $m_{12}^2 + m_{23}^2 + m_{13}^2 = M^2 + m_1^2 + m_2^2 + m_3^2$ and $m_{12}^2 = (P - p_3)^2 = M^2 + m_3^2 - 2ME_3$. The relative orientation of the three final-state particles is fixed if their energies are known. Their momenta can therefore be specified by giving three Euler angles (α, β, γ) which specify the orientation of the final system relative to the initial particle. Then

$$d\Gamma = \frac{1}{(2\pi)^5} \frac{1}{16M} |\mathcal{M}|^2 \, dE_1 \, dE_2 \, d\alpha \, d\cos\beta \, d\gamma \; . \tag{D.8}$$

Alternatively

$$d\Gamma = \frac{1}{(2\pi)^5} \frac{1}{16M^2} |\mathcal{M}|^2 \, |\vec{p}_1^{\,*}| \, |\vec{p}_3| \, dm_{12} \, d\Omega_1^* \, d\Omega_3 \; , \tag{D.9}$$

where $(|\vec{p}_1^{\,*}|, \Omega_1^*)$ is the momentum of particle 1 in the rest frame of 1 and 2, and Ω_3 is the angle of particle 3 in the rest frame of the decaying particle. $|\vec{p}_1^{\,*}|$ and $|\vec{p}_3|$ are given by

$$|\vec{p}_1^{\,*}| = \frac{\left[\left(m_{12}^2 - (m_1 + m_2)^2\right)\left(m_{12}^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2m_{12}} \; ,$$

and

$$|\vec{p}_3| = \frac{\left[\left(M^2 - (m_{12} + m_3)^2\right)\left(M^2 - (m_{12} - m_3)^2\right)\right]^{1/2}}{2M} \; . \tag{D.10}$$

[Compare with Eq. (D.6).]

Integrating over the angles in Eq. (D.8) (this is only possible if the decaying particle is a scalar or we average over its spin states; otherwise $\mathcal{M}$ depends on α, β, and γ) gives

$$\begin{aligned} d\Gamma &= \frac{1}{(2\pi)^3} \frac{1}{8M} |\mathcal{M}|^2 \, dE_1 \, dE_2 \\ &= \frac{1}{(2\pi)^3} \frac{1}{32M^3} |\mathcal{M}|^2 \, dm_{12}^2 \, dm_{23}^2 \; . \end{aligned} \tag{D.11}$$

This is the standard form for the Dalitz plot.

D.3.1 Dalitz plot:

If m_{12}^2 is fixed then the range of m_{13}^2 is determined by its values when $\vec{p}_1$ is parallel or antiparallel to $\vec{p}_3$.

$$(m_{13}^2)_{\max} = (E_1^* + E_3^*)^2 - \left(\sqrt{E_1^{*2} - m_1^2} - \sqrt{E_3^{*2} - m_3^2}\right)^2 \; ,$$

$$(m_{13}^2)_{\min} = (E_1^* + E_3^*)^2 - \left(\sqrt{E_1^{*2} - m_1^2} + \sqrt{E_3^{*2} - m_3^2}\right)^2 \; ,$$

where $E_3^* = (M^2 - m_{12}^2 - m_3^2)/(2m_{12})$ and $E_1^* = (m_{12}^2 + m_1^2 - m_2^2)/(2m_{12})$. The scatter plot in m_{12}^2 and m_{13}^2 has uniform phase space density [see Eq. (D.11)] and is called a Dalitz plot.

A nonuniformity in the plot gives immediate information on $|\mathcal{M}|^2$. For example, in the case of $D \to K\pi\pi$, bands appear when $m_{(K\pi)} = m_{K^*(892)}$, reflecting the appearance of the decay chain $D \to K^*(892)\pi \to K\pi\pi$.

D.4 Kinematic limits:

In a three-body decay the maximum of $|\vec{p}_3|$, [given by Eq. (D.10)], is achieved when $m_{12} = m_1 + m_2$, i.e., particles 1 and 2 have the same vector velocity in the rest frame of the decaying particle. If, in addition, $m_3 > m_1, m_2$, then $|\vec{p}_3|_{\max} > |\vec{p}_1|_{\max}$, $|\vec{p}_2|_{\max}$.

D.5 Multibody decays:

The above results may be generalized to final states containing any number of particles by combining some of the particles into "effective particles" and treating the final states as 2 or 3 "effective particle" states. Thus, if $p_{ijk\ldots} = p_i + p_j + p_k + \ldots$, then

$$m_{ijk\ldots} = \sqrt{p^2{}_{ijk\ldots}} \; ,$$

and $m_{ijk\ldots}$ may be used in place of *e.g.*, m_{12} in the relations in Sec. D.3 or D.3.1 above.

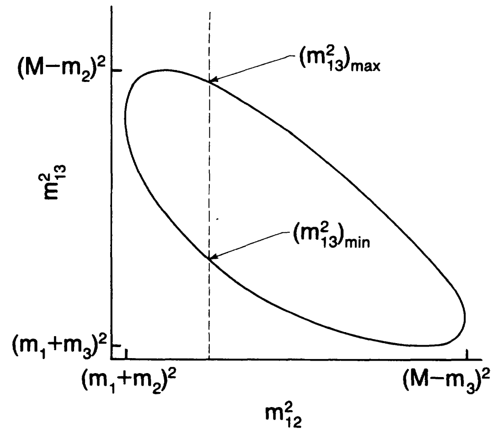


Fig. 3. Dalitz plot for a three-body final state. Four-momentum conservation restricts events to the interior of the closed curve.

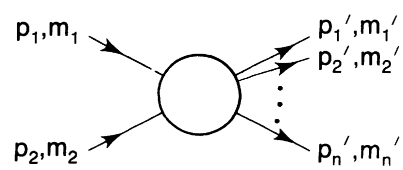


Fig. 4. Variable definitions for production of an n-body final state.

E. CROSS SECTIONS

The differential cross section is given by

$$d\sigma = \frac{(2\pi)^4 |\mathcal{M}|^2}{4\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}} \times d\Phi_n(p_1 + p_2; \, p_3, \ldots, p_{n+2}) \; . \tag{E.1}$$

[See Eq. (D.2).] In the rest frame of m_2(lab),

$$\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2} = m_2 p_{1\,\text{lab}} \; ;$$

while in the center-of-mass frame

$$\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2} = p_{1\text{cm}} \sqrt{s} \; .$$

E.1 Two-body reactions:

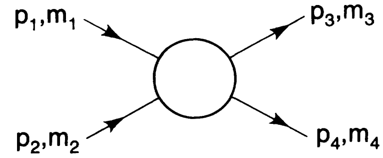


Fig. 5. Variable definitions for a two-body final state.

KINEMATICS (Cont'd)

Two particles of momenta p_1 and p_2 and masses m_1 and m_2 scatter to particles of momenta p_3 and p_4 and masses m_3 and m_4; the Lorentz invariant Mandelstam variables are defined by

$$\begin{aligned} s &= (p_1+p_2)^2 = (p_3+p_4)^2 \\ &= m_1^2 + 2E_1E_2 - 2\vec{p}_1\cdot\vec{p}_2 + m_2^2 , \\ t &= (p_1-p_3)^2 = (p_2-p_4)^2 \\ &= m_1^2 - 2E_1E_3 + 2\vec{p}_1\cdot\vec{p}_3 + m_3^2 , \\ u &= (p_1-p_4)^2 = (p_2-p_3)^2 \\ &= m_1^2 - 2E_1E_4 + 2\vec{p}_1\cdot\vec{p}_4 + m_4^2 , \end{aligned} \tag{E.2}$$

and they satisfy

$$s+t+u = m_1^2+m_2^2+m_3^2+m_4^2 .$$

The two-body cross section may be written as

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s}\,\frac{1}{|\vec{p}_{1\mathrm{cm}}|^2}\,|\mathcal{M}|^2 . \tag{E.3}$$

In the center-of-mass frame

$$\begin{aligned} t &= (E_{1\mathrm{cm}} - E_{3\mathrm{cm}})^2 - (p_{1\mathrm{cm}} - p_{3\mathrm{cm}})^2 \\ &\quad -4p_{1\mathrm{cm}}\,p_{3\mathrm{cm}}\,\sin^2(\theta_{\mathrm{cm}}/2) \\ &= t_0 - 4p_{1\mathrm{cm}}\,p_{3\mathrm{cm}}\,\sin^2(\theta_{\mathrm{cm}}/2) , \end{aligned} \tag{E.4}$$

where θ_{cm} is the angle between particle 1 and 3.

$$\begin{aligned} t_{\mp} &= \left[\frac{m_1^2-m_3^2-m_2^2+m_4^2}{2\sqrt{s}}\right]^2 \\ &\quad -\left\{\left[\left(\frac{s+m_1^2-m_2^2}{2\sqrt{s}}\right)^2 - m_1^2\right]^{1/2} \right. \\ &\quad \left. \mp\left[\left(\frac{s+m_3^2-m_4^2}{2\sqrt{s}}\right)^2 - m_3^2\right]^{1/2}\right\}^2 . \end{aligned} \tag{E.5}$$

Note that t_- (t_+) is the largest (smallest) value of t for $2\to 2$ scattering processes and that t_+ is always negative. In the literature the notation $t_{\min}$ $(t_{\max})$ for t_- (t_+) is sometimes used. This usage should be discouraged since $t_- > t_+$. The center-of-mass energies and momenta of the incoming particles are

$$E_{\mathrm{cm}} = \frac{s+m_1^2-m_2^2}{2\sqrt{s}} , \tag{E.6}$$

$$\begin{aligned} p_{\mathrm{cm}} &= \frac{\left[\left(s-(m_1+m_2)^2\right)\left(s-(m_1-m_2)^2\right)\right]^{1/2}}{2\sqrt{s}} \\ &= \frac{p_{1\,\mathrm{lab}}m_2}{\sqrt{s}} , \end{aligned} \tag{E.7}$$

Here the subscript lab refers to the frame where particle 2 is at rest. [For other relations see Eqs. (A2–A4).]

E.2 Inclusive reactions:

Choose some direction (usually the beam direction) for the z-axis; then the energy and momentum of a particle can be written as

$$E = m_\perp\cosh y\ ,\ p_x\ ,\ p_y\ ,\ p_z = m_\perp \sinh y\ ,$$

where $m_\perp$ is the transverse mass

$$m_\perp^2 = m^2 + p_x^2 + p_y^2 ,$$

and the rapidity y is defined by

$$\begin{aligned} y &= \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \\ &= \ln\left(\frac{E+p_z}{m_\perp}\right) = \tanh^{-1}\left(\frac{p_z}{E}\right) . \end{aligned} \tag{E.8}$$

Under a boost in the z-direction to a frame with velocity β, $y\to y+\tanh^{-1}\beta$. Hence the shape of the rapidity distribution dN/dy is invariant. The invariant cross section may also be rewritten

$$E\frac{d^3\sigma}{dp^3} = \frac{d^3\sigma}{dy\,dp_\perp^2} .$$

Feynman's x variable is given by

$$x = \frac{p_z}{p_{z\max}} \approx \frac{E+p_z}{(E+p_z)_{\max}} ;$$

in the center-of-mass frame,

$$x \approx \frac{2p_{z\mathrm{cm}}}{\sqrt{s}} \approx \frac{2m_\perp \sinh y_{\mathrm{cm}}}{\sqrt{s}} . \tag{E.9}$$

For y_{cm} such that $e^{-2y_{\mathrm{cm}}} \ll 1$,

$$x \approx \frac{m_\perp}{\sqrt{s}}e^{y_{\mathrm{cm}}}$$

and

$$(y_{\mathrm{cm}})_{\max} = \ln\left(\sqrt{s}/m\right) .$$

The definition of rapidity [Eq. (E.8)] may be expanded to obtain

$$\begin{aligned} y &= \frac{1}{2}\ln\frac{\cos^2(\theta/2)+m^2/4p^2+\ldots}{\sin^2(\theta/2)+m^2/4p^2+\ldots} \\ &\approx -\ln\tan(\theta/2) \equiv \eta \end{aligned} \tag{E.10}$$

if the particle has zenith angle θ. The pseudorapidity η defined by the second line is approximately equal to the rapidity y for $p\gg m$ and $\theta \gg 1/\gamma$, and in any case can be measured when the mass and momentum of the particle is unknown. From the definition one can obtain the identities

$$\sinh\eta = \cot\theta$$

$$\cosh\eta = 1/\sin\theta$$

$$\tanh\eta = \cos\theta .$$

E.3 Partial waves:

The amplitude in the center of mass for elastic scattering of spinless particles may be expanded in Legendre polynomials

$$f(k,\theta) = \frac{1}{k}\sum_\ell (2\ell+1)a_\ell P_\ell(\cos\theta) , \tag{E.11}$$

where k is the c.m. momentum, θ is the c.m. scattering angle, $a_\ell = (\eta_\ell e^{2i\delta_\ell}-1)/2i$, $0\le\eta_\ell\le 1$, and δ_ℓ is the phase shift of the ℓ^{th} partial wave. For purely elastic scattering, $\eta_\ell = 1$. The differential cross section is

$$\frac{d\sigma}{d\Omega} = |f(k,\theta)|^2 .$$

The optical theorem states that

$$\sigma_{\mathrm{tot}} = \frac{4\pi}{k}\mathrm{Im}\,f(k,0) , \tag{E.12}$$

and the cross section in the ℓ^{th} partial wave is therefore bounded:

$$\sigma_\ell = \frac{4\pi}{k^2}(2\ell+1)|a_\ell|^2 \le \frac{4\pi(2\ell+1)}{k^2} . \tag{E.13}$$

The partial-wave amplitude a_ℓ can be displayed in an Argand plot.

The usual Lorentz invariant matrix element $\mathcal{M}$ (see Sec. C above) for the elastic process is related to $f(k,\theta)$ by

$$\mathcal{M} = -8\pi\sqrt{s}\,f(k,\theta) ,$$

so

$$\sigma_{\mathrm{tot}} = -\frac{1}{2k\sqrt{s}}\,\mathrm{Im}\,\mathcal{M}(t=0) , \tag{E.14}$$

where s and t are the center-of-mass energy squared and momentum transfer squared, respectively (see Sec. D.1).

KINEMATICS (Cont'd)

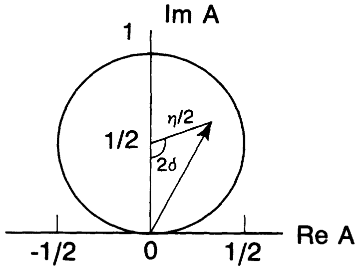


Fig. 6. Argand plot for the display of a partial-wave amplitude as a function of energy.

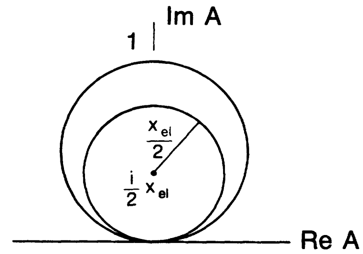


Fig. 7. Argand plot for a resonance.

E.3.1 Resonances:
The Breit-Wigner form for a_ℓ with a resonance at c.m. energy E_R, elastic width $\Gamma_{\rm el}$, and total width $\Gamma_{\rm tot}$ is

$$a_\ell = \frac{\Gamma_{\rm el}/2}{E_R - E - i\Gamma_{\rm tot}/2} \ , \tag{E.15}$$

where E is the c.m. energy. This gives a circle in the Argand plot with center $ix_{\rm el}/2$ and radius $x_{\rm el}/2$, where the elasticity $x_{\rm el} = \Gamma_{\rm el}/\Gamma_{\rm tot}$. The amplitude has a pole at $E = E_R - i\Gamma_{\rm tot}/2$.

The Breit-Wigner cross section for a spin-J resonance produced in the collision of particles of spin S_1 and S_2 is

$$\sigma_{BW}(E) = \frac{(2J+1)}{(2S_1+1)(2S_2+1)} \frac{\pi}{k^2} \frac{B_{\rm in}B_{\rm out}\Gamma^2_{\rm tot}}{(E-E_R)^2 + \Gamma^2_{\rm tot}/4} \ ,$$

where k is the c.m. momentum, E is the c.m. energy, and $B_{\rm in}$ and $B_{\rm out}$ are the branching fractions of the resonance into the entrance and exit channels. The $2S+1$ factors are the multiplicities of the incident spin states, so they are replaced by 2 for photons, *etc.* This expression is valid only for a particle of narrow width. If the width is not small, $\Gamma_{\rm tot}$ cannot be treated as a constant independent of E. There are many other forms for σ_{BW}, all of which are equivalent to the one given here in the narrow-width case. Some of these forms may be more appropriate if the resonance is broad.

The relativistic Breit-Wigner form corresponding to Eq. (E.15) is:

$$a_\ell = \frac{-m\Gamma_{\rm el}}{s - m^2 + im\Gamma_{\rm tot}} \ .$$

A better form incorporates the known kinematic dependences, replacing $m\Gamma_{\rm tot}$ by $\sqrt{s}\,\Gamma_{\rm tot}(s)$, where $\Gamma_{\rm tot}(s)$ is the width the resonance particle would have if its mass were $\sqrt{s}$, and correspondingly $m\Gamma_{\rm el}$ by $\sqrt{s}\,\Gamma_{\rm el}(s)$ where $\Gamma_{\rm el}(s)$ is the partial width in the incident channel for a mass $\sqrt{s}$:

$$a_\ell = \frac{-\sqrt{s}\,\Gamma_{\rm el}(s)}{s - m^2 + i\sqrt{s}\,\Gamma_{\rm tot}(s)} \ .$$

For the Z boson, all the decays are to particles whose masses are small enough to be ignored, so on dimensional grounds $\Gamma_{\rm tot}(s) = \sqrt{s}\,\Gamma_0/m_Z$, where Γ_0 defines the width of the Z, and $\Gamma_{\rm el}(s)/\Gamma_{\rm tot}(s)$ is constant. A full treatment of the line shape requires consideration of dynamics, not just kinematics. For the Z this is done by calculating the radiative corrections in the Standard Model.

Revised April 1992 with the assistance of R. Cahn.

CROSS-SECTION FORMULAE FOR SPECIFIC PROCESSES

A. LEPTOPRODUCTION

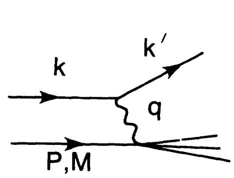


Fig. 1. Kinematic quantities for description of lepton-nucleon scattering. k and k' are the four-momenta of incoming and outgoing leptons, P is the four-momentum of a nucleon with mass M. The exchanged particle is a γ, $W^\pm$, or Z^0; it transfers four-momentum $q = k - k'$ to the target.

Invariant quantities:

$\nu = \dfrac{q \cdot P}{M} = E - E'$ is the lepton's energy loss in the lab (in earlier literature sometimes $\nu = q \cdot P$). Here, E and E' are the initial and final lepton energies in the lab.

$Q^2 = -q^2 = 2(EE' - \vec{k} \cdot \vec{k}\,') - m_\ell^2 - m_{\ell'}^2$ where $m_\ell(m_{\ell'})$ is the initial (final) lepton mass. If $EE'\sin^2(\theta/2) \gg m_\ell^2,\ m_{\ell'}^2$, then

$\approx 4EE'\sin^2(\theta/2)$, where θ is the lepton's scattering angle in the lab.

$x = \dfrac{Q^2}{2M\nu}$ In the parton model, x is the fraction of the target nucleon's momentum carried by the struck quark. See section on QCD.

$y = \dfrac{q \cdot P}{k \cdot P} = \dfrac{\nu}{E}$ is the fraction of the lepton's energy lost in the lab.

$W^2 = (P+q)^2 = M^2 + 2M\nu - Q^2$ is the mass squared of the system recoiling against the lepton.

$$s = (k+P)^2 = \frac{Q^2}{xy} + M^2$$

A.1 Leptoproduction cross sections:

$$\frac{d^2\sigma}{dx\,dy} = \nu\,(s - M^2)\,\frac{d^2\sigma}{d\nu\,dQ^2} = \frac{2\pi\,M\nu}{E'}\,\frac{d^2\sigma}{d\Omega_{\rm lab}\,dE'}$$
$$= x(s - M^2)\,\frac{d^2\sigma}{dx\,dQ^2} \ .$$

CROSS-SECTION FORMULAE FOR SPECIFIC PROCESSES (Cont'd)

A.2 Electroproduction structure functions:

The neutral-current process, $eN \to eX$, is parity conserving at low Q^2 and can be written in terms of two structure functions $F_1^{\rm NC}(x,Q^2)$ and $F_2^{\rm NC}(x,Q^2)$:

$$\frac{d^2\sigma}{dx\,dy} = \frac{4\pi\,\alpha^2(s-M^2)}{Q^4}\left[(1-y)\,F_2^{\rm NC} + y^2\,xF_1^{\rm NC} - \frac{M^2}{(s-M^2)}\,xy\,F_2^{\rm NC}\right] .$$

The charged-current processes, $e^-N \to \nu X$, $\nu N \to e^-X$, and $\overline{\nu}N \to e^+X$, are parity violating and can be written in terms of three structure functions $F_1^{\rm CC}(x,Q^2)$, $F_2^{\rm CC}(x,Q^2)$, and $F_3^{\rm CC}(x,Q^2)$:

$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F^2\,(s-M^2)}{2\pi}\,\frac{M_W^4}{(Q^2+M_W^2)^2} \tag{A.1}$$

$$\times\left\{\left[1-y-\frac{M^2xy}{(s-M^2)}\right]F_2^{\rm CC} + \frac{y^2}{2}\,2x\,F_1^{\rm CC} + (y-\frac{y^2}{2})\,x\,F_3^{\rm CC}\right\} .$$

A.3 The QCD parton model:

In the QCD parton model, the structure functions defined above can be expressed in terms of parton distribution functions. The quantity $f_i(x,Q^2)dx$ is the probability that a parton of type i (quark, antiquark, or gluon), carries a momentum fraction between x and $x+dx$ of the nucleon's momentum in a frame where the nucleon's momentum is large. For the cross section corresponding to the *neutral-current process* $ep \to eX$, we have for $s \gg M^2$ (in the case where the incoming electron is either left- (L) or right- (R) handed):

$$\frac{d^2\sigma}{dx\,dy} = \frac{\pi\alpha^2}{sx^2\,y^2}\left[\sum_q (x\,f_q\,(x,\,Q^2) + x\,f_{\overline{q}}\,(x,\,Q^2)\right] \times\left[A_q + (1-y)^2\,B_q\right] .$$

Here the index q refers to a quark flavor (i.e., u, d, s, c, b, or t), and

$$A_q = \left(-q_q + g_{Lq}\,g_{Le}\,\frac{Q^2}{Q^2+M_Z^2}\right)^2 + \left(-q_q + g_{Rq}\,g_{Re}\,\frac{Q^2}{Q^2+M_Z^2}\right)^2 ,$$

$$B_q = \left(-q_q + g_{Rq}\,g_{Le}\,\frac{Q^2}{Q^2+M_Z^2}\right)^2 + \left(-q_q + g_{Lq}\,g_{Re}\,\frac{Q^2}{Q^2+M_Z^2}\right)^2 .$$

Here q_q is the charge of flavor q. For a left-handed electron, $g_{Re}=0$ and $g_{Le} = (-1/2+\sin^2\theta_W)/(\sin\theta_W\cos\theta_W)$, while for a right-handed one, $g_{Le}=0$ and $g_{Re} = (\sin^2\theta_W)/(\sin\theta_W\cos\theta_W)$. For the quarks, $g_{Lq} = (T_3 - q_q\sin^2\theta_W)/(\sin\theta_W\cos\theta_W)$, and $g_{Rq} = (-q_q\sin^2\theta_W)\,/\,(\sin\theta_W\cos\theta_W)$.

For neutral-current *neutrino (antineutrino) scattering*, the same formula applies with g_{Le} replaced by $g_{L\nu} = 1/(2\sin\theta_W\cos\theta_W)$ ($g_{L\overline{\nu}}=0$) and g_{Re} replaced by $g_{R\nu}=0$ [$g_{R\overline{\nu}} = -1/(2\sin\theta_W\cos\theta_W)$].

In the case of the *charged-current processes* $e_L^-p \to \nu X$ and $\overline{\nu}p \to e^+X$, Eq. (A.1) applies with

$$F_2 = 2xF_1 = 2x\Big[f_u(x,Q^2) + f_c(x,Q^2) + f_t(x,Q^2) + f_{\overline{d}}\,(x,Q^2) + f_{\overline{s}}\,(x,Q^2) + f_{\overline{b}}\,(x,Q^2)\Big] ,$$

$$F_3 = 2x\Big[f_u(x,Q^2) + f_c(x,Q^2) + f_t(x,Q^2) - f_{\overline{d}}\,(x,Q^2) - f_{\overline{s}}\,(x,Q^2) - f_{\overline{b}}\,(x,Q^2)\Big] .$$

For the process $\nu p \to e^-X$:

$$F_2 = 2xF_1 = 2x\Big[f_d(x,Q^2) + f_s(x,Q^2) + f_b(x,Q^2) + f_{\overline{u}}\,(x,Q^2) + f_{\overline{c}}\,(x,Q^2) + f_{\overline{t}}\,(x,Q^2)\Big] ,$$

$$F_3 = 2x\Big[f_d(x,Q^2) + f_s(x,Q^2) + f_b(x,Q^2) - f_{\overline{u}}\,(x,Q^2) - f_{\overline{c}}\,(x,Q^2) - f_{\overline{t}}\,(x,Q^2)\Big] .$$

B. e^+e^- ANNIHILATION

For pointlike spin-1/2 fermions in the c.m., the differential cross section for $e^+e^- \to f\overline{f}$ via single photon annihilation is

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\,\beta\,\left[1+\cos^2\theta + (1-\beta^2)\sin^2\theta\right]Q_f^2 ,$$

where β is the velocity of the final state fermion in the center of mass and Q_f is the charge of the fermion in units of the proton charge. For $\beta \to 1$,

$$\sigma = \frac{4\pi\alpha^2}{3s}\,Q_f^2 = \frac{86.8\,Q_f^2\;nb}{s({\rm GeV}^2)} .$$

At higher energies the Z^0 (mass M_Z and width Γ_Z) must be included, and the differential cross section for $e^+e^- \to f\overline{f}$ becomes

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\,\beta\,\Bigg[Q_f^2[1+\cos^2\theta+(1-\beta^2)\,\sin^2\theta] -2Q_f\,\chi_1\left\{VV_f\,[1+\cos^2\theta+(1-\beta^2)\,\sin^2\theta] - 2a_f\,\beta\cos\theta\right\} +\chi_2\Big\{V_f^2\,(1+V^2)\,[1+\cos^2\theta+(1-\beta^2)\,\sin^2\theta] +\beta^2\,a_f^2(1+V^2)\,[1+\cos^2\theta] - 8\beta\,VV_f\,a_f\cos\theta\Big\}\Bigg] ,$$

$$\chi_1 = \frac{1}{16\sin^2\theta_W\cos^2\theta_W}\,\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+\Gamma_Z^2M_Z^2} ,$$

$$\chi_2 = \frac{1}{256\sin^4\theta_W\cos^4\theta_W}\,\frac{s^2}{(s-M_Z^2)^2+\Gamma_Z^2M_Z^2} ,$$

$$V = -1+4\sin^2\theta_W ,$$

$$a_f = 2T_{3f} ,$$

$$V_f = 2T_{3f} - 4Q_f\sin^2\theta_W ,$$

where the subscript f refers to the particular fermion and

$T_3 = +1/2$ for ν_e, ν_μ, ν_τ, u, c, t,

$T_3 = -1/2$ for e^-, μ^-, τ^-, d, s, b.

C. e^+e^- TWO-PHOTON PROCESS

In the equivalent photon approximation, the cross section for $e^+e^- \to e^+e^-X$ is related to the cross section for $\gamma\gamma \to X$ by

$$d\sigma_{e^+e^-\to e^+e^-X}\,(s) = \eta^2\int_0^1 d\omega\,f(\omega)\,d\sigma_{\gamma\gamma\to X}\,(\omega s) ,$$

where

$$\eta \approx \frac{\alpha}{2\pi}\,\ln\left(\frac{s}{4m_e^2}\right)$$

CROSS-SECTION FORMULAE FOR SPECIFIC PROCESSES (Cont'd)

and

$$f(\omega) = \frac{1}{\omega}\left[(2+\omega)^2 \ln\frac{1}{\omega} - 2(1-\omega)(3+\omega)\right] .$$

The factor η arises from integrating over the mass squared of the virtual photon. For the production of a resonance, form factors suppress contributions from very virtual photons, so in the standard formula for production of a resonance of mass m_R and spin $J \neq 1$, namely,

$$\sigma(e^+e^- \to e^+e^- R) = \eta^2 \, \frac{(2J+1)\, 8\pi^2\, \Gamma(R\to\gamma\gamma)}{s m_R}\, f(\frac{m_R^2}{s}) ,$$

it would be better to use

$$\eta \approx \frac{\alpha}{2\pi} \ln\left(\frac{m_V^2}{4m_e^2}\right) ,$$

where m_V is the mass of the vector (ρ, ϕ, $\cdots$) that enters into the form factor.

D. INCLUSIVE HADRONIC REACTIONS

One-particle inclusive cross sections $E(d^3\sigma)/(d^3p_i)$ for the production of a particle of momentum p_i are conveniently expressed in terms of rapidity (see above) and the momentum $p_\perp$ transverse to the beam direction (defined in the center-of-mass frame)

$$\frac{d^3\sigma}{dy\, d^2p_\perp} = E\,\frac{d^3\sigma}{d^3p} .$$

In the case of processes where $p_\perp$ is large or the mass of the produced particle is large (here large means greater than 10 GeV), the parton model can be used to calculate the rate. Symbolically

$$\sigma_{\text{hadronic}} = \sum_{ij} \int f_i(x_1,\, Q^2)\, f_j(x_2,\, Q^2)\, dx_1\, dx_2\, \widehat{\sigma}_{\text{partonic}} ,$$

where $f_i(x,\, Q^2)$ is the parton distribution introduced above and Q is a typical momentum transfer in the partonic process and $\widehat{\sigma}$ is the partonic cross section. Two examples will help to clarify. The production of a W^+ in pp reactions at rapidity y in the center-of-mass frame is given by

$$\begin{aligned}\frac{d\sigma}{dy} &= \frac{G_F\, \pi\sqrt{2}}{3} \\ &\times \tau\Bigg[\cos^2\theta_c\Big(u(x_1\,,\ M_W^2)\, \overline{d}\,(x_2, M_W^2) \\ &\quad + u(x_2\,,\ M_W^2)\, \overline{d}\,(x_1, M_W^2)\Big) \\ &\quad + \sin^2\theta_c\Big(u(x_1\,,\ M_W^2)\, \overline{s}\,(x_2\,,\ M_W^2) \\ &\quad + s(x_2, M_W^2)\, \overline{u}\,(x_1, M_W^2)\Big)\Bigg] ,\end{aligned}$$

where $x_1 = \sqrt{\tau}\, e^{y}$, $x_2 = \sqrt{\tau}\, e^{-y}$, and $\tau = M_W^2/s$. Similarly the production of a jet in pp (or $p\overline{p}$) collisions is given by

$$\begin{aligned}\frac{d^3\sigma}{d^2p_\perp\, dy} &= \sum_{ij}\int f_i(x_1\,,\ p_\perp^2)\, f_j(x_2, p_\perp^2) \\ &\times \left[\widehat{s}\,\frac{d\widehat{\sigma}}{d\widehat{t}}\right]_{ij} dx_1\, dx_2\, \delta(\widehat{s} + \widehat{t} + \widehat{u}) ,\end{aligned} \qquad \text{(D.1)}$$

where the summation is over quarks, gluons, and antiquarks. Here

$$s = (p_1 + p_2)^2 ,$$
$$t = (p_1 - p_{\text{jet}})^2 ,$$
$$u = (p_2 - p_{\text{jet}})^2 ,$$

p_1 and p_2 are the momenta of the incoming p and p (or $\overline{p}$) and $\widehat{s}$, $\widehat{t}$, and $\widehat{u}$ are s, t, and u with $p_1 \to x_1 p_1$ and $p_2 \to x_2 p_2$. The partonic cross section $\widehat{s}\,[(d\widehat{\sigma})/(d\widehat{t})]$ can be found in Ref. 1. Example: for the process $gg \to q\overline{q}$,

$$\widehat{s}\,\frac{d\sigma}{dt} = 3\alpha_s^2\, \frac{(\widehat{t}^{\,2} + \widehat{u}^2)}{8\widehat{s}} \left[\frac{4}{9\,\widehat{t}\,\widehat{u}} - \frac{1}{\widehat{s}^{\,2}}\right] .$$

The prediction of Eq. (D.1) is compared to data from the UA1 and UA2 collaborations in a figure labeled "Jet Production in pp and $\overline{p}p$ Interactions" in the Plots of Cross Sections and Related Quantities section.

E. ONE-PARTICLE INCLUSIVE DISTRIBUTIONS

In order to describe one-particle inclusive production in e^+e^- annihilation or deep inelastic scattering, it is convenient to introduce a fragmentation function $D_i^h\,(z,Q^2)/z$ which is the probability that a parton of type i and momentum p will fragment into a hadron of type h and momentum zp. The Q^2 evolution is predicted by QCD and is similar to that of the parton distribution functions (see section on Quantum Chromodynamics). The $D_i^h(z,Q^2)$ are normalized so that

$$\sum_h \int D_i^h\,(z,Q^2) dz = 1 .$$

If the contributions of the Z boson and three-jet events are neglected, the cross section for producing a hadron h in e^+e^- annihilation is given by

$$\frac{1}{\sigma_{\text{had}}}\frac{d\sigma}{dz} = \frac{\sum_i e_i^2\, D_i^h\,(z,Q^2)}{\sum_i e_i^2} ,$$

where e_i is the charge of quark-type i, σ_{had} is the total hadronic cross section, and the momentum of the hadron is $zE_{\text{cm}}/2$.

In the case of deep inelastic muon scattering, the cross section for producing a hadron of energy E_h is given by

$$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma}{dz} = \frac{\sum_i e_i^2\, q_i(x,Q^2)\, D_i^h(z,Q^2)}{\sum_i e_i^2\, q_i(x,Q^2)} ,$$

where $E_h = \nu z$. (For the kinematics of deep inelastic scattering, see section D.2 of the Kinematics section of this Review.) The fragmentation functions for light and heavy quarks have a different z dependence; the former peak near $z = 0$. They are illustrated in a figure in the section on Plots of Cross Sections and Related Quantities.

1. G.F. Owens, F. Reya, and M. Glück, Phys. Rev. **D18**, 1501 (1978).

QUANTUM CHROMODYNAMICS

A. THE QCD LAGRANGIAN

Quantum Chromodynamics (QCD), the gauge field theory which describes the interactions of colored quarks and gluons, is one of the components of the SU(3)×SU(2)×U(1) Standard Model. The Lagrangian is (up to gauge-fixing terms)

$$L_{\rm QCD} = -\frac{1}{4} F^{(a)}_{\mu\nu}\, F^{(a)\mu\nu} + i \sum_q \overline{\psi}^i_q\, \gamma^\mu\, (D_\mu)_{ij}\, \psi^j_q - \sum_q m_q\, \overline{\psi}^i_q\, \psi_{qi}\ ,$$

$$F^{(a)}_{\mu\nu} = \partial_\mu\, A^a_\nu - \partial_\nu\, A^a_\mu + g_s\, f_{abc}\, A^b_\mu\, A^c_\nu\ ,$$

$$(D_\mu)_{ij} = \delta_{ij}\, \partial_\mu - i g_s \sum_a \frac{\lambda^a_{i,j}}{2} A^a_\mu\ , \qquad \text{(A.1)}$$

where g_s is the QCD coupling constant, and the f_{abc} are the structure constants of the SU(3) algebra (the λ matrices and values for f_{abc} can be found in "SU(3) Isoscalar Factors and Representation Matrices"). The $\psi^i_q(x)$ are the 4-component Dirac spinors associated with each quark field of color i and flavor q and the $A^a_\mu(x)$ are the (8) Yang-Mills (gluon) fields. A complete list of the Feynman rules which derive from this Lagrangian, together with some useful color-algebra identities, can be found in Ref. 1.

The principle of "asymptotic freedom" (see below) determines that the renormalized QCD coupling is small only at high energies, and it is only in this domain that high-precision tests—similar to those in QED—can be performed using perturbation theory. Nonetheless, there has in recent years been much progress in understanding and quantifying the predictions of QCD in the nonperturbative domain, for example in soft hadronic processes and on the lattice. [2] This short review will concentrate on QCD at short distances (large momentum transfers), where perturbation theory is the standard tool.

B. THE QCD COUPLING AND RENORMALIZATION SCHEME

The renormalization scale dependence of the effective QCD coupling $\alpha_s = g_s^2/4\pi$ is controlled by the β-function:

$$\mu \frac{\partial \alpha_s}{\partial \mu} = -\frac{\beta_0}{2\pi}\, \alpha_s^2 - \frac{\beta_1}{8\pi^2}\, \alpha_s^3 - \cdots\ ,$$

$$\beta_0 = 11 - \frac{2}{3} n_f\ ,$$

$$\beta_1 = 102 - \frac{38}{3} n_f\ , \qquad \text{(B.1)}$$

and n_f is the number of quarks with mass less than the energy scale μ. In solving this differential equation for α_s, a constant of integration is introduced. This constant is the one fundamental constant of QCD that must be determined from experiment. The most sensible choice for this constant is the value of α_s at a fixed reference scale μ_0, but it is more conventional to introduce the dimensional parameter Λ. The definition of Λ is arbitrary. One way to define it (adopted here) is to write a solution of Eq. (B.1) as an expansion in inverse powers of $\ln(\mu^2)$:

$$\alpha_s(\mu) = \frac{12\pi}{(33 - 2n_f)\, \ln(\mu^2/\Lambda^2)} \times \left[1 - \frac{6(153 - 19n_f)}{(33-2n_f)^2}\, \frac{\ln\left[\ln(\mu^2/\Lambda^2)\right]}{\ln(\mu^2/\Lambda^2)}\right] + \cdots\ . \qquad \text{(B.2)}$$

The next term in this expansion is

$$\mathcal{O}\left(\frac{\ln^2\left[\ln(\mu^2/\Lambda^2)\right]}{\ln^3(\mu^2/\Lambda^2)}\right)\ .$$

This solution illustrates the *asymptotic freedom* property: $\alpha_s \to 0$ as $\mu \to \infty$. Alternative definitions of Λ are possible. For example, the solution of Eq. (B.1) with the β-function truncated at the second order:

$$\frac{1}{\alpha_s} + b_1\, \ln\left(\frac{b_1\, \alpha_s}{1 + b_1\, \alpha_s}\right) = b_0\, \ln\frac{\mu}{\Lambda}\ ,$$

$$b_0 = \frac{\beta_0}{2\pi}\ , \quad b_1 = \frac{\beta_1}{4\pi\beta_0}\ . \qquad \text{(B.3)}$$

can be used. For a given value of $\alpha_s(\mu = 5\ \text{GeV})$ one finds that (Λ[Eq. (B.2)] − Λ[Eq. (B.3)]) varies by 5 to 22 MeV as Λ goes from 120 to 350 MeV, while for $\alpha_s(\mu = 30\ \text{GeV})$ it varies by 3 to 11 MeV over the same Λ range.

In the above discussion we have ignored quark-mass effects, *i.e.*, we have assumed an idealized situation where quarks of mass greater than μ are neglected completely. In this picture, the β-function coefficients change by discrete amounts as flavor thresholds are crossed when integrating the differential equation for α_s. It follows that, for a relationship such as Eq. (B.2) to remain valid for all values of μ, Λ must also change discretely through flavor thresholds. This leads to the concept of a different Λ for each range of μ corresponding to an effective number of massless quarks: $\Lambda \to \Lambda^{(n_f)}$. This is the standard convention. It follows that when comparing measured Λ values, account must be taken of the effective number of quark flavors in each experiment. In practice, it is straightforward to relate the different $\Lambda^{(n_f)}$ using the above expressions. For example, one finds [3] (the meaning of $\overline{\rm MS}$ will be explained below)

$$\Lambda^{(4)}_{\overline{\rm MS}} \approx \Lambda^{(5)}_{\overline{\rm MS}} \left[\frac{m_b}{\Lambda^{(5)}_{\overline{\rm MS}}}\right]^{2/25} \left[2\, \ln\left(\frac{m_b}{\Lambda^{(5)}_{\overline{\rm MS}}}\right)\right]^{963/14375}$$

$$\Lambda^{(4)}_{\overline{\rm MS}} \approx \Lambda^{(3)}_{\overline{\rm MS}} \left[\frac{\Lambda^{(3)}_{\overline{\rm MS}}}{m_c}\right]^{2/25} \left[2\, \ln\left(\frac{m_c}{\Lambda^{(3)}_{\overline{\rm MS}}}\right)\right]^{-107/1875} \qquad \text{(B.4)}$$

Note that these differences are numerically very significant; for example, if $\Lambda^{(5)}_{\overline{\rm MS}} = 200$ MeV, the corresponding $\Lambda^{(4)}_{\overline{\rm MS}} = 293$ MeV. Data from Deep Inelastic scattering are in a range of energy where the bottom quark is not readily excited and hence these experiments quote $\Lambda^{(4)}_{\overline{\rm MS}}$. Most data from PEP, PETRA, TRISTAN, and LEP quote a value of $\Lambda^{(5)}_{\overline{\rm MS}}$ since these data are in an energy range where the bottom quark is light compared to the available energy. We have converted it to $\Lambda^{(4)}_{\overline{\rm MS}}$ as required.

We turn now to a discussion of renormalization-scheme dependence in QCD. Although necessarily rather technical, this discussion is vital to understanding how Λ values can be measured and compared. See the review by Duke and Roberts [4] for further details.

Consider a "typical" QCD cross section which, when calculated perturbatively, starts at $\mathcal{O}(\alpha_s)$:

$$\sigma = A_1\, \alpha_s + A_2\, \alpha_s^2 + \cdots\ . \qquad \text{(B.5)}$$

The coefficients A_1, A_2 come from calculating the appropriate Feynman diagrams. In performing such calculations various divergences arise, and these must be regulated in a consistent way. This requires a particular renormalization scheme (RS). The most commonly used one is the modified minimal subtraction ($\overline{\rm MS}$) scheme [5]. This involves continuing momentum integrals from 4 to 4–2ϵ dimensions and then subtracting off the resulting $1/\epsilon$ poles and also ($\ln 4\pi - \gamma_E$), which is another artifact of continuing the dimension. (Here γ_E is the Euler-Mascheroni constant.) To preserve the dimensionless nature of the coupling, a mass scale μ must also be introduced: $g \to \mu^\epsilon g$. The finite coefficients A_i thus obtained depend implicitly on the renormalization convention used and explicitly on the scale μ.

The first two coefficients (β_0, β_1) in Eq. (B.1) are independent of the choice of RS's. In contrast, the coefficients of terms proportional to α_s^n for $n > 3$ *are* RS-dependent. Although the value of Λ, defined as above, does depend on the convention, it is straightforward to relate the different Λ's corresponding to different RS's. It has become conventional to use the $\overline{\rm MS}$ scheme for calculating QCD cross sections beyond leading order.

QUANTUM CHROMODYNAMICS (Cont'd)

The fundamental theorem of RS dependence is straightforward. Physical quantities, in particular the cross section, calculated to all orders in perturbation theory, do not depend on the RS. It follows that a truncated series *does* exhibit RS dependence. In practice, all QCD cross sections are known either to leading or to next-to-leading order, and it is only the latter, which have reduced RS dependence, that are useful for precision tests. At second order the RS dependence is completely given by one condition which can be taken to be the value of the renormalization scale μ. One therefore has to address the question of what is the "best" choice for μ. There is no definite answer to this question—higher-order corrections do not "fix" the scale, rather they render the theoretical predictions less sensitive to its variation.

One could imagine that choosing a scale μ characteristic of the typical energy scale in the process would be most appropriate. More byzantine choices are the scale for which the next-to-leading-order correction vanishes ("Fastest Apparent Convergence [6]") or the scale for which the next-to-leading-order prediction is stationary [7].

An important corollary is that if the higher-order corrections are naturally small, then the additional uncertainties introduced by the μ dependence are likely to be less than the experimental measurement errors. There are some processes, however, for which the choice of scheme (*i.e.* the value of μ) *can* influence the extracted value of $\Lambda_{\overline{\rm MS}}$. There is no resolution to this problem other than to try to calculate even more terms in the perturbation series.

In the cases where the higher-order corrections to a process are known and are large, some caution should be exercised when quoting the value of α_s. In what follows we will attempt to indicate the size of the theoretical uncertainties on the extracted value of α_s. There are two simple ways to determine this error. First, we can estimate it by comparing the value of $\alpha_s(\mu)$ obtained by fitting data using the QCD formula to highest known order in α_s, and then comparing it with the value obtained using the next-to-highest-order formula (μ is chosen as the typical energy scale in the process). The corresponding Λ's are then obtained by evolving $\alpha_s(\mu)$ to $\mu = m_Z$ using Eq. (B.1) to the same order in α_s as the fit, and then converting to $\Lambda^{(4)}$ using Eq. (B.4). Alternatively, we can vary the value of μ over a reasonable range, extracting a value of Λ for each choice of μ. In either case, if the perturbation series is well behaved, the resulting error on Λ will be small.

C. QCD IN DEEP INELASTIC SCATTERING

The original and still one of the most powerful quantitative tests of perturbative QCD is the breaking of Bjorken scaling in deep inelastic lepton-hadron scattering. In the leading-logarithm approximation the measured structure functions $F_i(x,Q^2)$ are related to the quark distribution functions $q_i(x,Q^2)$ according to the naive parton model by the formulae in "Cross-Section Formulae for Specific Processes" (in that section, q_i is denoted by the notation f_q). In describing the way in which scaling is broken in QCD, it is convenient to define nonsinglet and singlet quark distributions:

$$F^{NS} = q_i - q_j \qquad F^S = \sum_i (q_i + \overline{q}_i) \ . \tag{C.1}$$

The nonsinglet structure functions have nonzero values of flavor quantum numbers such as isospin or baryon number. The variation with Q^2 of these is described by the so-called Altarelli-Parisi equations [8]:

$$\begin{aligned} Q^2\,\frac{\partial F^{NS}}{\partial Q^2} &= \frac{\alpha_s(|Q|)}{2\pi} P^{qq} * F^{NS} \\ Q^2\,\frac{\partial}{\partial Q^2}\begin{pmatrix} F^S \\ G \end{pmatrix} &= \frac{\alpha_s(|Q|)}{2\pi}\begin{pmatrix} P^{qq} & 2n_f P^{qg} \\ P^{gq} & P^{gg} \end{pmatrix} * \begin{pmatrix} F^S \\ G \end{pmatrix} \end{aligned} \tag{C.2}$$

where $*$ denotes a convolution integral:

$$f * g = \int_x^1 \frac{dy}{y}\, f(y)\, g\left(\frac{x}{y}\right) \ . \tag{C.3}$$

The leading-order Altarelli-Parisi splitting functions are

$$\begin{aligned} P^{qq} &= \frac{4}{3}\left[\frac{1+x^2}{1-x}\right]_+ + 2\delta(1-x) \ , \\ P^{qg} &= \frac{1}{2}\left[x^2 + (1-x)^2\right] \ , \\ P^{gq} &= \frac{4}{3}\left[\frac{1+(1-x)^2}{x}\right] \ , \\ P^{gg} &= 6\left[\frac{1-x}{x} + x(1-x) + \left(\frac{x}{1-x}\right)_+ + \frac{11}{12}\delta(1-x)\right] \\ &\quad -\frac{n_f}{3}\delta(1-x) \ . \end{aligned} \tag{C.4}$$

Here the gluon distribution $G(x,Q^2)$ has been introduced and $1/(1-x)_+$ means

$$\int_0^1 dx \frac{f(x)}{(1-x)_+} = \int_0^1 dx\, \frac{f(x) - f(1)}{(1-x)} \ .$$

The precision of contemporary experimental data demands that higher-order corrections also be included [9]. The above results are for massless quarks. Algorithms exist for the inclusion of nonzero quark masses [10]. At low Q^2 values there are also important "higher-twist" contributions of the form:

$$F_i(x,Q^2) = F_i^{(LT)}\,(x,Q^2) + \frac{F_i^{(HT)}(x,Q^2)}{Q^2} + \cdots \ . \tag{C.5}$$

These corrections are numerically important only for $Q^2 < \mathcal{O}(10\,{\rm GeV}^2)$ except for x very close to 1.

A detailed review of the current status of the experimental data can be found, for example, in Ref. 11, and only a brief summary will be presented here. There is a problem in that some sets of data do not agree with each other and some have a poor fit to QCD. Recent data from the CCFRR collaboration [12] on neutrino scattering do not agree with the older CDHSW results [13]. In scattering off an isoscalar target, the parton model predicts that $F_2(eN) = 5/18 F_2(\nu N)$. The new CCFRR data satisfy this when compared to the data from BCDMS whereas the CDHSW data do not. There has been a long standing problem in that the muon scattering results from EMC [14] and BCDMS [15] have significant systematic disagreements. The overlap with the older measurements at SLAC [16] is not sufficient to completely resolve the discrepancy. New data from the NMC collaboration [17] agree quite well with BCDMS but are in disagreement at the 15% level with the older EMC results for $x < 0.2$. We shall only include determinations of Λ from the recent results; the previous edition of this review should be consulted for the earlier data.

From Eq. (C.2), it is clear that a nonsinglet structure function offers in principle the most precise test of the theory, since the Q^2 evolution is independent of the unmeasured gluon distribution. Recently a measurement of Λ has been made using F_3 in neutrino scattering [12]. The result is $\Lambda^{(4)}_{\overline{\rm MS}} = 179 \pm 36 \pm 54$ MeV. The errors are statistical and systematic but do not include (theoretical) errors arising from the choice of μ^2. Measurements involving singlet-dominated structure functions such as F_2 result in correlated measurements of $\Lambda^{(4)}_{\overline{\rm MS}}$ and the gluon distribution. By utilizing high-statistics data at large x ($>$ 0.25) and large Q^2, where F_2 behaves like an nonsinglet and F_3 at smaller x a nonsinglet fit can be performed with better statistical precision and hence the error on the measured value of $\Lambda^{(4)}_{\overline{\rm MS}}$ is much

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reduced. CCFRR gives $\Lambda^{(4)}_{\overline{\rm MS}} = 213 \pm 29 \pm 41$ MeV [12] from $F_2(\nu N)$ and $F_3(\nu N)$. There is an additional uncertainty of ± 59 MeV from the choice of scale. A reanalysis of EMC [18] data give $\Lambda^{(4)}_{\overline{\rm MS}} = 211 \pm 80 \pm 80$ MeV from $F_2(\nu N)$. Finally a combined analysis [19] of SLAC [16] and BCDMS [15] data gives $\Lambda^{(4)}_{\overline{\rm MS}} = 263 \pm 42 \pm 55$ MeV. Here the systematic error is an estimate of the uncertainty due to the choice of Q^2 used in the argument of α_s and in the scale at which the structure functions (factorization scale) used in the QCD calculation are evaluated.

The results from Refs. 12, 18, and 19 can be combined to give $\Lambda^{(4)}_{\overline{\rm MS}} = 238 \pm 30 \pm 60$ MeV. Here the former error is a combination of statistical and systematic errors and the second error is due to the scale uncertainty.

Typically, Λ is extracted from the data by parameterizing the parton densities in a simple analytic way at some Q_0^2, evolving to higher Q^2 using the next-to-leading-order evolution equations, and fitting globally to the measured structure functions to obtain $\Lambda^{(4)}_{\overline{\rm MS}}$. Thus an important by-product of such studies is the extraction of parton densities at a fixed reference value of Q_0^2. These can then be evolved in Q^2 and used as input for phenomenological studies in hadron-hadron collisions (see below). To avoid having to evolve from the starting Q_0^2 value each time, a parton density is required; it is useful to have available a simple analytic approximation to the densities valid over a range of x and Q^2 values. Such parameterizations are available in the literature [20]. A package is available in the from the CERN computer library that includes an exhaustive set of fits [21]. Some of these fits are obsolete. In using a parameterization to predict event rates, a next-to-leading order fit must be used if the process being calculated is known to next-to-leading order in QCD perturbation theory. In such a case there is an additional scheme dependence; this scheme dependence is reflected in the $O(\alpha_s)$ corrections that appear in the relations between the structure functions and the quark distribution functions. There are two common schemes, a deep inelastic scheme where there are no order α_s corrections in the formula for $F_2(x, Q^2)$ and the minimal subtraction scheme. It is important, when these next-to-leading order fits are used in other processes (see below), that the same scheme is used in the calculation of the partonic rates.

The average is obtained from the above values using the method discussed in the text.

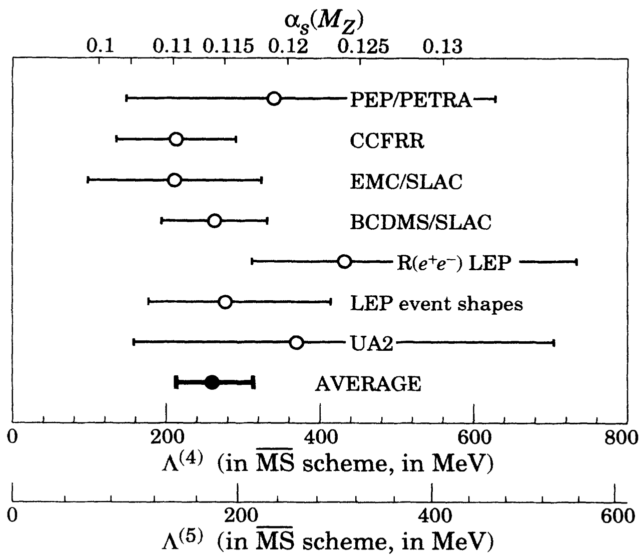

Fig. 1. Summary of the values of $\Lambda^{(4)}_{\overline{\rm MS}}$, $\alpha_s(M_Z)$ and $\Lambda^{(5)}_{\overline{\rm MS}}$ from various processes. Where the experiment quotes separate systematic and statistical errors, these have been combined in quadrature. The PEP/PETRA average is from Ref. 22. The three results from deep inelastic scattering are CCFRR [12], SLAC/BCDMS [19], and EMC/SLAC [18]. The result from R at LEP is from the ratio of the hadronic to leptonic width of the Z discussed in the text. The value at LEP from event shapes is the average given in Ref. 23 and the UA2 result is from W/Z production Ref. 24.

D. QCD IN HIGH ENERGY HADRON COLLISIONS

There are many ways in which perturbative QCD can be tested in high-energy hadron colliders. The quantitative tests are only useful if the process in question has been calculated beyond leading order in QCD perturbation theory. The production of hadrons with large transverse momentum in hadron-hadron collisions provides a direct probe of the scattering of quarks and gluons: $qq \to qq$, $qg \to qg$, $gg \to gg$, etc. The present generation of $p\overline{p}$ colliders provide center-of-mass energies which are sufficiently high that these processes can be unambiguously identified in two-jet production at large transverse momentum. Recent higher-order QCD calculations of the jet rates [25] and shapes are in impressive agreement with data [26]. As an example, the figure on "Jet Production in pp and $p\overline{p}$ Interactions" in "Plots of Cross Sections and Related Quantities" shows the inclusive jet cross section at zero pseudorapidity as a function of the jet transverse momentum for $p\overline{p}$ collisions. The QCD prediction combines the parton distributions with the leading-order $2 \to 2$ parton scattering amplitudes. Data are also available on the angular distribution of jets; these are also in agreement with QCD expectations [27,28].

QCD corrections to Drell-Yan type cross sections (*i.e.*, the production in hadron collisions by quark-antiquark annihilation of lepton pairs of invariant mass Q from virtual photons, or of real W or Z bosons) are known [29]. These $\mathcal{O}(\alpha_s)$ QCD corrections are sizable and approximately constant over the lepton-pair mass range probed by experiments. Thus

$$\sigma_{DY} \approx \sigma^{(0)}_{DY}\left[1 + \frac{\alpha_s(Q^2)}{2\pi}C + \cdots\right] . \qquad \text{(D.1)}$$

It is interesting to note that the corresponding correction to W and Z production, as measured at $p\overline{p}$ colliders, has essentially the same theoretical form and is of order 30%. Total W and Z production are known accurately enough to be sensitive to such 30% effects and provide yet another test of the theory.

The production of W and Z bosons and photons at large transverse momentum can also be used to determine α_s. The leading-order QCD subprocesses are $q\overline{q} \to \gamma g$ and $qg \to \gamma q$. If the parton distributions are taken from other processes and a value of $\Lambda^{(4)}_{\overline{\rm MS}}$ assumed, then an absolute prediction is obtained. Conversely, the data can be used to extract information on quark and gluon distributions and on the value of $\Lambda^{(4)}_{\overline{\rm MS}}$. The next-to-leading-order QCD corrections corrections are known [30,31] (for photons) and for W/Z production [32], and so a precision test is possible in principle. Recently, the UA2 collaboration [24] has extracted a value of $\alpha_s(m_W) = 0.123 \pm 0.01 \pm 0.013$ from an analysis of W production.

E. QCD IN HEAVY QUARKONIUM DECAY

Under the assumption that the hadronic and leptonic decay widths of heavy $Q\overline{Q}$ resonances can be factorized into a nonperturbative part—dependent on the confining potential—and a calculable perturbative part, the ratios of partial decay widths allow measurements of α_s at the heavy quark mass scale. The most precise data come from the decay widths of the 1^{--} $J/\psi(1S)$ and Υ resonances. Potential model dependences cancel from the ratios of decay widths. For more discussion of this subject, see the QCD review in the previous edition.

F. PERTURBATIVE QCD IN e^+e^- COLLISIONS

The total cross section for $e^+e^- \to$ hadrons is obtained (at low values of $\sqrt{s}$) by multiplying the muon-pair cross section by the factor $R = 3\Sigma_q e_q^2$. The higher-order QCD corrections to this quantity have been calculated, and the results can be expressed in terms of the

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factor:

$$R = R^{(0)}\left[1 + \frac{\alpha_s}{\pi} + C_2\left(\frac{\alpha_s}{\pi}\right)^2 + C_3\left(\frac{\alpha_s}{\pi}\right)^3 + \cdots\right] , \qquad \text{(F.1)}$$

where $C_2 = 1.411$ and $C_3 = -12.8$ [33].

$R^{(0)}$ can be obtained from the formula for $d\sigma/d\Omega$ for $e^+e^- \to f\bar{f}$ by integrating over Ω. The formula is given in "Cross-Section Formulae for Specific Processes," Section B. This result is strictly only correct in the zero-quark-mass limit. The $\mathcal{O}(\alpha_s)$ corrections are also known for massive quarks [34].

A comparison of the theoretical prediction of Eq. (F.1) (corrected for the b-quark mass) with all the available data (including those from TRISTAN at $\sqrt{s} = 50$ GeV) except that from LEP has been performed by the CELLO collaboration [35]. The result is a correlated measurement of α_s and $\sin^2\theta_W$. Fixing $\sin^2\theta_W$ at the world-average value of 0.23 then gives:

$$\alpha_s(34 \text{ GeV}) = 0.148 \pm 0.018 . \qquad \text{(F.2)}$$

The principal advantage of determining α_s from R in e^+e^- annihilation is that there is no dependence on fragmentation models, jet algorithms, etc. The size of the order α_s^3 term is of order 40% of that of the order α_s^2 and 3% of the order α_s. If the order α_s^3 term is not included a fit to the data yields $\alpha_s(34 \text{ GeV}) = 0.144 \pm 0.018$, indicating that the theoretical uncertainty is smaller than the experimental error.

Measurements of the ratio of hadronic to leptonic width of the Z at LEP Γ_h/Γ_μ probe the same quantity as R. Using the average of $\Gamma_h/\Gamma_\mu = 20.92 \pm 0.11$ and $\sin^2\theta_W = 0.2325 \pm 0.0008$ gives $\alpha_s(M_Z) = 0.124 \pm 0.016$.

The traditional method of determining α_s in e^+e^- annihilation is from measuring quantities that are sensitive to the relative rates of two-, three-, and four-jet events. In addition to simply counting jets, there are many possible choices of such "shape variables": thrust [36], energy-energy correlations [37], planar triple-energy correlations [38], average jet mass, etc. All of these are infrared safe, which means they can be reliably calculated in perturbation theory. The starting point for all these quantities is the multijet cross section. For example at order α_s, for the process $e^+e^- \to qqg$:

$$\frac{1}{\sigma}\,\frac{d^2\sigma}{dx_1 dx_2} = \frac{2\alpha_s}{3\pi}\,\frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)} , \qquad \text{(F.3)}$$

where

$$x_i = \frac{2E_i}{\sqrt{s}}$$

are the center-of-mass energy fractions of the final-state (massless) quarks. A distribution in a "three-jet" variable, such as those listed above, is obtained by integrating this differential cross section over an appropriate phase space region for a fixed value of the variable. The order α_s^2 corrections to this process have been computed as well as the 4-jet final states such as $e^+e^- \to qqgg$.

There are many methods used by the LEP groups [39,40,41,42] to determine α_s from the event topology. The jet-counting algorithm originally introduced by the JADE collaboration [43] has been used by the LEP groups . Here particles of momenta p_i and p_j are combined into a pseudo-particle of momentum $p_i + p_j$ if the invariant mass of the pair is less than $y_0\sqrt{s}$. The process is then iterated until no more pairs of particles or pseudo-particles remain. The remaining number is then defined to be the number of jets in the event and can be compared to the QCD prediction.

There are theoretical ambiguities in the way that this process is carried out; quarks and gluons are massless whereas the observed hadrons are not. So that the massive jets that result from this scheme (the so-called E-0 scheme) cannot be compared directly to the massless jets of perturbative QCD. Different recombination schemes have been tried, for example combining 3-momenta and then rescaling the energy of the cluster so that it remains massless (p scheme), and these result in the same data giving a slightly different value [44] of α_s. These differences can be used to determine a systematic error.

In addition, since what is observed is hadrons rather than quarks and gluons, a model is needed to describe the evolution of a partonic final state into one involving hadrons so that detector corrections can be applied. The second-order matrix elements are combined with a parton fragmentation model. This model can then be used to correct the data for a direct comparison with the parton calculation. The different hadronization models that are used [45,46,47,48] model the dynamics that are controlled by nonperturbative QCD effects which we cannot yet calculate. The differences between these models contribute to the systematic errors. The systematic errors from recombination schemes and fragmentation effects dominate over the statistical and other errors of the LEP experiments. The OPAL collaboration [44] quotes $\alpha_s(M_Z) = 0.118 \pm 0.008$, the included experimental errors being ± 0.003. The total error also includes an error (± 0.003 in the $p-$scheme) for varying the scale μ from M_Z down to the value that gives the best fit to the data ($\sim 0.4M_Z$). The various schemes proposed for theoretically determining the value of μ all result in smaller values.

Measurements of the energy-energy correlations have also been performed at LEP. In a recent paper the DELPHI collaboration [49] has used eight of the shape variables to determine $\alpha_s(M_Z) = 0.112 \pm 0.002(expt) \pm 0.003(hadron) \pm 0.006(scale)$. The errors are those inherent in the experiment (*expt*), those from hadronization Monte-Carlos (*hadron*) and from the choice of μ (*scale*).

The various measurements of event shapes at LEP can be combined to give a value of $\alpha_s(M_Z) = 0.115 \pm 0.008$ [23]. This is an unweighted average of the LEP results. The error is dominantly systematic arising from hadronization and scale uncertainties.

In addition to the measurements at LEP there are results from e^+e^- annihilation at lower energies. For example, the TASSO collaboration [50] uses the energy-energy correlation and quotes α_s (44 GeV) $= 0.143 \pm 0.014$ for the Lund fragmentation model [45] and α_s (44 GeV) $= 0.129 \pm 0.012$ for the Ali model [46], after the fragmentation models have been fitted to the data at $\sqrt{s} = 44$ GeV. A compilation of all this available data and a complete list of references can be found in Ref. 51. A "world-average" is [22]

$$\alpha_s(34 \text{ GeV}) = 0.14 \pm 0.02 , \qquad \text{(F.4)}$$

with the error being the spread between the different experiments including the fragmentation uncertainty, but not that due to choice of μ. Notice that this value of α_s is in agreement with the value obtained from the measurement of R described above. Since these results are essentially completely independent, the associated $\Lambda^{(4)}_{\overline{\rm MS}}$ values are displayed separately in Fig. 1.

There are many other ways in which QCD can be tested in electron-positron collisions. Mention should be made in particular of the interesting and important results from "two-photon" processes. For a comprehensive review of the data, see Ref. 52. Paramount among these is the measurement of the photon structure function in collisions involving a highly virtual and an almost real photon.

In contrast to hadronic structure functions, the photon structure function increases linearly [53] with log Q^2, and a measurement of the absolute size at large Q^2 provides information about Λ. However, the exact situation is complicated and somewhat controversial. The theoretical situation is reviewed in some detail in Ref. 54. The TPC/2-gamma collaboration [55] quotes two values of $\Lambda^{(4)}_{\overline{\rm MS}} = 215 \pm 55$ and 119 ± 34 MeV, depending upon how the nonperturbative component of the photon structure function is parameterized. The AMY collaboration at TRISTAN [56] has also measured the photon structure function and claims that the data are consisted with $\Lambda = 200$ MeV. These determinations of α_s are less precise than those given above.

All the data on the photon structure function (see Fig. 1) are consistent with [57]

$$\Lambda^{(4)}_{\overline{\rm MS}} = 180^{+100}_{-90} \text{ MeV} . \qquad \text{(F.5)}$$

The higher-order QCD corrections correspond approximately to a shift of 20% in the photon structure function and hence in α_s.

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G. CONCLUSIONS

In this short review we have focused on those high-energy processes which currently offer the most quantitative tests of perturbative QCD. Emphasis has been given to the recent data from LEP and deep inelastic scattering. The values of $\Lambda^{(4)}_{\overline{\rm MS}}$ for $n_f = 4$ given in Fig. 1 are all consistent with each other. A "world average" is obtained as follows. The average of the three deep inelastic measurements ($\Lambda^{(4)}_{\overline{\rm MS}} = 238 \pm 30 \pm 60$ MeV) is combined with the values from event shapes at LEP, PEP/PETRA, from the hadronic width of the Z, and from UA2. The theoretical and experimental errors on each of these values is combined before the average is taken. The result is $\alpha_s(M_Z) = 0.1134 \pm 0.0035$, corresponding to $\Lambda^{(4)}_{\overline{\rm MS}} = 260^{+54}_{-46}$ MeV or $\Lambda^{(5)}_{\overline{\rm MS}} = 175^{+41}_{-34}$ MeV. The remarks in Sec. B concerning different Λ's for different effective n_f values should be remembered. With the exception of the value arising from the measured hadronic width of the Z, all of the results here are such that the dominant errors are systematic. While these systematic errors are different for different processes, a significant reduction in them is not likely in the near future. Jet production data from high-energy hadron collisions, while not yet in the precision measurement class, demonstrate in a very clear way the scattering of quarks and gluons over many orders of magnitude in cross section.

The need for brevity has meant that many other important topics in QCD phenomenology have had to be omitted from this review. One should mention in particular the study of exclusive processes (form factors, elastic scattering, ...), the behavior of quarks and gluons in nuclei, the spin properties of the theory and the importance of polarized scattering data, the interface of soft and hard QCD as manifest, for example, by minijet production and hard diffractive processes, and QCD effects in hadron spectroscopy.

After this review was completed, a paper [58] was received that uses a lattice calculation of the splitting between the $1s$ and $1p$ states in charmonium to determine α_s. The result quoted is $\alpha_s(M_Z) = 0.105 \pm 0.004$.

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STANDARD MODEL OF ELECTROWEAK INTERACTIONS

The standard electroweak model is based on the gauge group [1] SU(2) × U(1), with gauge bosons W^i_μ, $i = 1,2,3$, and B_μ for the SU(2) and U(1) factors, respectively, and the corresponding gauge coupling constants g and g'. The left-handed fermion fields $\psi_i = \begin{pmatrix} \nu_i \\ \ell^-_i \end{pmatrix}$ and $\begin{pmatrix} u_i \\ d'_i \end{pmatrix}$ of the i^{th} fermion family transform as doublets under SU(2), where $d'_i \equiv \sum_j V_{ij}\, d_j$, and V is the Cabibbo-Kobayashi-Maskawa mixing matrix.** The right-handed fields are SU(2) singlets. In the minimal model there are three fermion families and a single complex Higgs doublet $\phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$.

After spontaneous symmetry breaking the Lagrangian is

$$\begin{aligned}\mathcal{L}_F = &\sum_i \overline{\psi}_i \left(i\, \partial\!\!\!/ - m_i - \frac{g m_i H}{2M_W} \right) \psi_i \\ &- \frac{g}{2\sqrt{2}} \sum_i \overline{\psi}_i\, \gamma^\mu\, (1-\gamma^5)(T^+\, W^+_\mu + T^-\, W^-_\mu)\, \psi_i \\ &- e \sum_i q_i\, \overline{\psi}_i\, \gamma^\mu\, \psi_i\, A_\mu \\ &- \frac{g}{2\cos\theta_W} \sum_i \overline{\psi}_i\, \gamma^\mu (V^i - A^i \gamma^5)\, \psi_i\, Z_\mu \ . \end{aligned} \qquad (1)$$

$\theta_W \equiv \tan^{-1}(g'/g)$ is the weak angle; $e = g\sin\theta_W$ is the positron electric charge; and $A \equiv B\cos\theta_W + W^3 \sin\theta_W$ is the (massless) photon field. $W^\pm \equiv (W^1 \mp iW^2)/\sqrt{2}$ and $Z \equiv -B\sin\theta_W + W^3\cos\theta_W$ are the massive charged and neutral weak boson fields, respectively. T^+ and T^- are the weak isospin raising and lowering operators. The vector and axial couplings are

$$\begin{aligned} V^i &\equiv t_{3L}(i) - 2q_i \sin^2\theta_W \\ A^i &\equiv t_{3L}(i)\ , \end{aligned} \qquad (2)$$

where $t_{3L}(i)$ is the weak isospin of fermion i (+1/2 for u_i and ν_i; −1/2 for d_i and e_i) and q_i is the charge of ψ_i in units of e.

The second term in $\mathcal{L}_F$ represents the charged-current weak interaction [2]. For example, the coupling of a W to an electron and a neutrino is

$$-\frac{e}{2\sqrt{2}\sin\theta_W} \left[W^-_\mu\ \overline{e}\, \gamma^\mu (1-\gamma^5)\nu + W^+_\mu\ \overline{\nu}\, \gamma^\mu\, (1-\gamma^5) e \right] \ . \qquad (3)$$

For momenta small compared to M_W, the second term gives rise to the effective four-fermion interaction with the Fermi constant given (at tree level, i.e., lowest order in perturbation theory) by $G_F/\sqrt{2} = g^2/8M_W^2$. CP violation is incorporated in the Standard Model by a single observable phase in V_{ij}. The third term in $\mathcal{L}_F$ describes electromagnetic interactions (QED), and the last is the weak neutral-current interaction.

In Eq. (1), m_i is the mass of the i^{th} fermion ψ_i. For the quarks these are the current masses. For the light quarks, a typical estimate [3] gives $m_u \approx 5.6 \pm 1.1$ MeV, $m_d \approx 9.9 \pm 1.1$ MeV, $m_s \approx 199 \pm 33$ MeV, and $m_c \approx 1.35 \pm 0.05$ GeV (these are running masses evaluated at 1 GeV). For the heavier quarks $m_b \approx 5$ GeV (the "pole" mass), and $m_t > \mathcal{O}(91)$ GeV.

H is the physical neutral Higgs scalar which is the only remaining part of ϕ after spontaneous symmetry breaking. The Yukawa coupling of H to ψ_i, which is flavor diagonal in the minimal model, is $gm_i/2M_W$. The H mass is not predicted by the model. Experimental limits are given in the Higgs section. In nonminimal models there are additional charged and neutral scalar Higgs particles [4].

Renormalization and radiative corrections: The Standard Model has three parameters (not counting M_H and the fermion masses and mixings). A particularly useful set is: (a) the fine structure constant $\alpha = 1/137.036$,† determined from the quantum Hall effect, (b) the Fermi constant, $G_F = 1.16639 \times 10^{-5}$ GeV^{-2}, determined from the muon lifetime formula:

$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} \left(1 - 8\frac{m_e^2}{m_\mu^2}\right) \left(1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2}\right) [1 + \mathcal{O}(\alpha)]\ , \qquad (4)$$

and (c) $\sin^2\theta_W$, determined from neutral-current processes, the W and Z masses, and Z-pole observables [5]. The value of $\sin^2\theta_W$ depends on the renormalization prescription. A useful (on-shell) scheme [6] is to take the tree-level formula $\sin^2\theta_W = 1 - M_W^2/M_Z^2$ as the definition of the renormalized $\sin^2\theta_W$ to all orders in perturbation theory. Another scheme, less dependent on m_t, uses the modified minimal subtraction ($\overline{\text{MS}}$) quantity $\sin^2\widehat{\theta}_W(\mu)$, where μ is conveniently chosen to be M_Z for electroweak processes. The two definitions are related by $\sin^2\widehat{\theta}_W(M_Z) = C(m_t, M_H)\sin^2\theta_W$, where $C = 1.009$ (1.054) for $m_t = 100$ (200) GeV, $M_H = 250$ GeV. The dominant (quadratic) m_t dependence is given by $C \sim 1 + \rho_t/\tan^2\theta_W$, where $\rho_t = 3G_F m_t^2/8\sqrt{2}\pi^2 \simeq 0.0031\ (m_t/100\ \text{GeV})^2$. Alternatively, one can take M_Z rather than $\sin^2\theta_W$ as the third fundamental parameter.

STANDARD MODEL OF ELECTROWEAK INTERACTIONS (Cont'd)

Experiments are now at such a level of precision that complete $\mathcal{O}(\alpha)$ radiative corrections must be applied. These corrections are conveniently divided into two classes:

1. QED diagrams involving the emission of real photons or the exchange of virtual photons in loops, but not including vacuum polarization diagrams. These graphs yield finite and gauge-invariant contributions to observable processes. However, they are dependent on energies, experimental cuts, etc., and must be calculated individually for each experiment.
2. Electroweak corrections, including $\gamma\gamma$, γZ, ZZ, and WW vacuum polarization diagrams, as well as vertex corrections, box graphs, etc., involving virtual W's and Z's. Many of these corrections are absorbed into the renormalized Fermi constant defined in Eq. (4). Others modify the tree-level expressions for neutral-current amplitudes in several ways [5].

In addition, the tree-level expressions for M_W and M_Z are modified:

$$M_W = \frac{A_0}{\sin\theta_W(1-\Delta r_s)^{1/2}}$$

$$M_Z = \frac{M_W}{\rho_s^{1/2}\cos\theta_W} \tag{5}$$

where $A_0 = (\pi\alpha/\sqrt{2}G_F)^{1/2} = 37.2803$ GeV. The radiative correction parameters Δr_s and ρ_s are scheme-dependent. In the on-shell scheme, $\rho_s \equiv 1$ and $\Delta r_s \equiv \Delta r$ is predicted to be 0.0608 ± 0.0009 for $m_t = 100$ GeV and to be 0.0222 for $m_t = 200$ GeV (both for $M_H = 250$ GeV). In $\overline{\text{MS}}$, $\Delta r_s \equiv \Delta\widehat{r}_W = 0.0695 \pm 0.0009$ (0.0722), while $\rho_s \equiv \widehat{\rho} = 1.003$ (1.015) for $m_t = 100$ (200) GeV. The quadratic m_t dependence is given by $\widehat{\rho} \simeq 1 + \rho_t$, $\Delta r \simeq \Delta r_o - \rho_t/\tan^2\theta_W$, $\Delta\widehat{r}_W \simeq \Delta r_0$, where $\Delta r_0 \simeq 1 - \alpha/\alpha(M_Z) \simeq 0.07$. If M_Z is regarded as fundamental, then

$$\sin^2\theta_W = \frac{1}{2}\left[1 - \left(1 - \frac{4A_0^2}{\rho_s M_Z^2(1-\Delta r_s)}\right)^{1/2}\right] \tag{6}$$

is a derived parameter, and $M_W = \rho_s^{1/2} M_Z \cos\theta_W$.

Cross section and asymmetry formulas: It is convenient to write the four-fermion interactions relevant to ν-hadron, νe, and parity-violating e-hadron neutral-current processes in a form that is valid in an arbitrary gauge theory (assuming massless left-handed neutrinos). One has

$$-\mathcal{L}^{\nu\text{Hadron}} = \frac{G_F}{\sqrt{2}}\,\overline{\nu}\,\gamma^\mu\,(1-\gamma^5)\nu \times \sum_i \left[\epsilon_L(i)\,\overline{q}_i\,\gamma_\mu(1-\gamma^5)q_i + \epsilon_R(i)\,\overline{q}_i\,\gamma_\mu(1+\gamma^5)q_i\right] , \tag{7}$$

$$-\mathcal{L}^{\nu e} = \frac{G_F}{\sqrt{2}}\,\overline{\nu}_\mu\,\gamma^\mu(1-\gamma^5)\nu_\mu\,\overline{e}\,\gamma_\mu(g_V^e - g_A^e\gamma^5)e \tag{8}$$

(for $\nu_e e$ or $\overline{\nu}_e e$, the charged-current contribution must be included), and

$$-\mathcal{L}^{e\text{Hadron}} = -\frac{G_F}{\sqrt{2}} \times \sum_i \left[C_{1i}\,\overline{e}\,\gamma_\mu\,\gamma^5\,e\,\overline{q}_i\,\gamma^\mu\,q_i + C_{2i}\,\overline{e}\,\gamma_\mu\,e\,\overline{q}_i\,\gamma^\mu\,\gamma^5\,q_i\right] . \tag{9}$$

(One must add the parity-conserving QED contribution.)

The Standard Model expressions for $\epsilon_{L,R}(i)$, $g^e_{V,A}$, and C_{ij} are given in Table 1.

A precise determination of $\sin^2\theta_W$, which depends only very weakly on m_t and M_H, is obtained from deep inelastic neutrino scattering from (approximately) isoscalar targets. The ratio $R_\nu \equiv \sigma^{NC}_{\nu N}/\sigma^{CC}_{\nu N}$ of neutral- to charged-current cross sections has been measured to 1% accuracy by the CDHS [7] and CHARM [8] collaborations [9,10], so it is important to obtain theoretical expressions for R_ν and $R_{\overline{\nu}} \equiv \sigma^{NC}_{\overline{\nu}N}/\sigma^{CC}_{\overline{\nu}N}$ (as functions of $\sin^2\theta_W$) to comparable accuracy.

Table 1. Standard Model expressions for the neutral-current parameters for ν-hadron, νe, and e-hadron processes. If radiative corrections are ignored, $\rho = \kappa = 1$, $\lambda = 0$. At $\mathcal{O}(\alpha)$ in the on-shell scheme, $\rho^{NC}_{\nu N} = 1.0026$, $\kappa_{\nu N} = 1.0049$, $\lambda_{u_L} = -0.0031$, $\lambda_{d_L} = -0.0025$, and $\lambda_{u_R} = 1/2\,\lambda_{d_R} = 3.8 \times 10^{-5}$ for $m_t = 100$ GeV, $M_H = 250$ GeV, $M_Z = 91.173$ GeV, and $\langle Q^2\rangle = 20$ GeV^2. For νe scattering, $\kappa_{\nu e} = 1.0044$ and $\rho_{\nu e} = 1.0072$ (at $\langle Q^2\rangle = 0.$). For atomic parity violation, $\rho'_{eq} = 0.9824$ and $\kappa'_{eq} = 1.012$. For the SLAC polarized electron experiment, $\rho'_{eq} = 0.973$, $\kappa'_{eq} = 1.010$, $\rho_{eq} = 0.995$, and $\kappa_{eq} = 1.04$ after incorporating additional QED corrections, while $\lambda_{2u} = -0.013$, $\lambda_{2d} = 0.003$. For $m_t = 200$ GeV the $\rho(\kappa)$ values should be increased by 0.010 (0.048). The dominant m_t dependence is given by $\rho \sim 1 + \rho_t$, while $\kappa \sim 1 + \rho_t/\tan^2\theta_W$ (on-shell) or $\kappa \sim 1(\overline{\text{MS}})$.

Quantity	Standard Model Expression
$\epsilon_L(u)$	$\rho^{NC}_{\nu N}\left(\frac{1}{2} - \frac{2}{3}\kappa_{\nu N}\sin^2\theta_W + \lambda_{uL}\right)$
$\epsilon_L(d)$	$\rho^{NC}_{\nu N}\left(-\frac{1}{2} + \frac{1}{3}\kappa_{\nu N}\sin^2\theta_W + \lambda_{dL}\right)$
$\epsilon_R(u)$	$\rho^{NC}_{\nu N}\left(-\frac{2}{3}\kappa_{\nu N}\sin^2\theta_W + \lambda_{uR}\right)$
$\epsilon_R(d)$	$\rho^{NC}_{\nu N}\left(\frac{1}{3}\kappa_{\nu N}\sin^2\theta_W + \lambda_{dR}\right)$
g^e_V	$\rho_{\nu e}\left(-\frac{1}{2} + 2\kappa_{\nu e}\sin^2\theta_W\right)$
g^e_A	$\rho_{\nu e}\left(-\frac{1}{2}\right)$
C_{1u}	$\rho'_{eq}\left(-\frac{1}{2} + \frac{4}{3}\kappa'_{eq}\sin^2\theta_W\right)$
C_{1d}	$\rho'_{eq}\left(\frac{1}{2} - \frac{2}{3}\kappa'_{eq}\sin^2\theta_W\right)$
C_{2u}	$\rho_{eq}\left(-\frac{1}{2} + 2\kappa_{eq}\sin^2\theta_W\right) + \lambda_{2u}$
C_{2d}	$\rho_{eq}\left(\frac{1}{2} - 2\kappa_{eq}\sin^2\theta_W\right) + \lambda_{2d}$

Fortunately, most of the uncertainties from the strong interactions and neutrino spectra cancel in the ratio.

A simple zeroth-order approximation is

$$R_\nu = g_L^2 + g_R^2 r$$

$$R_{\overline{\nu}} = g_L^2 + \frac{g_R^2}{r} , \tag{10}$$

where

$$g_L^2 \equiv \epsilon_L(u)^2 + \epsilon_L(d)^2 \approx \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W$$

$$g_R^2 \equiv \epsilon_R(u)^2 + \epsilon_R(d)^2 \approx \frac{5}{9}\sin^4\theta_W , \tag{11}$$

and $r \equiv \sigma^{CC}_{\overline{\nu}N}/\sigma^{CC}_{\nu N}$ is the ratio of $\overline{\nu}$ and ν charged-current cross sections, which can be measured directly. [In the simple parton model, ignoring hadron energy cuts, $r \approx (\frac{1}{3} + \epsilon)/(1 + \frac{1}{3}\epsilon)$, where $\epsilon \sim 0.125$ is the ratio of the fraction of the nucleon's momentum carried by antiquarks to that carried by quarks.] In practice, Eq. (10) must be corrected for quark mixing, the s and c seas, c-quark threshold effects, nonisoscalar target effects, W-Z propagator differences, and radiative corrections (which lower the extracted value of $\sin^2\theta_W$ by ~ 0.009). Details of the neutrino spectra, experimental cuts, x and Q^2 dependence of structure functions, and longitudinal structure functions enter only at the level of these corrections and therefore lead to very small uncertainties. The largest theoretical uncertainty is associated with the c threshold, which mainly affects σ^{CC}. Using the slow rescaling prescription [5] the central value of $\sin^2\theta_W$ varies as 0.013 [m_c(GeV)$-$1.3], where m_c is the effective mass. For $m_c = 1.3^{+0.4}_{-0.3}$ GeV

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(determined from ν-induced dimuon production [11]) this contributes ± 0.004 to the total theoretical uncertainty $\Delta \sin^2\theta_W \sim \pm 0.005$. This would require a high-energy neutrino beam for improvement. (The experimental uncertainty is ± 0.003).

The laboratory cross section for $\nu_\mu e \to \nu_\mu e$ or $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ elastic scattering is

$$\frac{d\sigma_{\nu_\mu,\overline{\nu}_\mu}}{dy} = \frac{G_F^2 m_e E_\nu}{2\pi} \times \left[(g_V^e \pm g_A^e)^2 + (g_V^e \mp g_A^e)^2(1-y)^2 - (g_V^{e2} - g_A^{e2})\frac{y\, m_e}{E_\nu}\right] , \tag{12}$$

where the upper (lower) sign refers to $\nu_\mu(\overline{\nu}_\mu)$, and $y \equiv E_e/E_\nu$ [which runs from 0 to $(1 + m_e/2E_\nu)^{-1}$] is the ratio of the kinetic energy of the recoil electron to the incident ν or $\overline{\nu}$ energy. For $E_\nu \gg m_e$ this yields a total cross section

$$\sigma = \frac{G_F^2\, m_e\, E_\nu}{2\pi}\left[(g_V^e \pm g_A^e)^2 + \tfrac{1}{3}(g_V^e \mp g_A^e)^2\right] . \tag{13}$$

The most accurate leptonic measurements [12–14] of $\sin^2\theta_W$ are from the ratio $R \equiv \sigma_{\nu_\mu e}/\sigma_{\overline{\nu}_\mu e}$ in which many of the systematic uncertainties cancel. Radiative corrections (other than m_t effects) are small compared to the precision of present experiments and have negligible effect on the extracted $\sin^2\theta_W$. The cross sections for $\nu_e e$ and $\overline{\nu}_e e$ may be obtained from Eq. (12) by replacing $g^e_{V,A}$ by $g^e_{V,A} + 1$, where the 1 is due to the charged-current contribution.

The SLAC polarized-electron experiment [15] measured the parity-violating asymmetry

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} , \tag{14}$$

where $\sigma_{R,L}$ is the cross section for the deep-inelastic scattering of a right- or left-handed electron: $e_{R,L}N \to e$X. In the quark parton model

$$\frac{A}{Q^2} = a_1 + a_2\,\frac{1-(1-y)^2}{1+(1-y)^2} , \tag{15}$$

where $Q^2 > 0$ is the momentum transfer and y is the fractional energy transfer from the electron to the hadrons. For the deuteron or other isoscalar target, one has, neglecting the s quark and antiquarks,

$$a_1 = \frac{3G_F}{5\sqrt{2}\pi\alpha}\left(C_{1u} - \tfrac{1}{2}C_{1d}\right) \approx \frac{3G_F}{5\sqrt{2}\pi\alpha}\left(-\tfrac{3}{4} + \tfrac{5}{3}\sin^2\theta_W\right)$$

$$a_2 = \frac{3G_F}{5\sqrt{2}\pi\alpha}\left(C_{2u} - \tfrac{1}{2}C_{2d}\right) \approx \frac{9G_F}{5\sqrt{2}\pi\alpha}\left(\sin^2\theta_W - \tfrac{1}{4}\right) . \tag{16}$$

Radiative corrections (other than m_t effects) lower the extracted value of $\sin^2\theta_W$ by $\sim$ 0.005.

Experiments measuring atomic parity violation [16] are now quite precise, and the uncertainties associated with atomic wave functions are relatively small (especially for cesium, for which the theoretical uncertainty is $\sim 1\%$ [17]). For heavy atoms one determines the "weak charge"

$$Q_W = -2\left[C_{1u}\,(2Z+N) + C_{1d}(Z+2N)\right] \approx Z(1 - 4\sin^2\theta_W) - N . \tag{17}$$

Radiative corrections increase the extracted $\sin^2\theta_W$ by ~ 0.008.

The forward-backward asymmetry for $e^+e^- \to \ell\overline{\ell}$, $\ell = \mu$ or τ, is defined as

$$A_{FB} \equiv \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} , \tag{18}$$

where $\sigma_F(\sigma_B)$ is the cross section for ℓ^- to travel forward (backward) with respect to the e^- direction. A_{FB} and R, the total cross section relative to pure QED, are given by

$$R = F_1 \qquad A_{FB} = 3F_2/4F_1 , \tag{19}$$

where

$$F_1 = 1 - 2\chi_0\, V^e\, V^\ell\, \cos\delta_R + \chi_0^2\left(V^{e2} + A^{e2}\right)\left(V^{\ell 2} + A^{\ell 2}\right)$$

$$F_2 = -2\chi_0\, A^e\, A^\ell\, \cos\delta_R + 4\chi_0^2\, A^e\, A^\ell\, V^e\, V^\ell , \tag{20}$$

where

$$\tan\delta_R = \frac{M_Z\Gamma_Z}{M_Z^2 - s}$$

$$\chi_0 = \frac{G_F}{2\sqrt{2}\pi\alpha}\frac{sM_Z^2}{\left[(M_Z^2 - s)^2 + M_Z^2\Gamma_Z^2\right]^{1/2}} \tag{21}$$

and $\sqrt{s}$ is the CM energy. Eq. (20) is valid at tree level. If the data are radiatively corrected for QED effects (as described above), then the remaining electroweak corrections can be incorporated [18] (in an approximation adequate for existing PEP, PETRA, and TRISTAN data) by replacing χ_0 by $\chi(s) \equiv (1+\rho_t)\chi_0(s)\alpha/\widehat{\alpha}(s)$, where $\widehat{\alpha}(s)$ is the running QED coupling, and evaluating V in the $\overline{\rm MS}$ scheme. Formulas for $e^+e^- \to$ *hadrons* may be found in Ref. 19.

At SLC and LEP, A_{FB} for $e^+e^- \to \overline{f}f$ at the Z pole will be measured to high precision for $f = \mu, \tau, s, c, b$ [20–25]. Similarly, the left-right asymmetry

$$A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} , \tag{22}$$

where $\sigma_L(\sigma_R)$ is the cross section for a left- (right)-handed incident electron, may be measured very precisely. At tree level and neglecting terms of order $(\Gamma_Z/M_Z)^2$, one has

$$A_{FB} \approx 3\eta_f\,\frac{\eta_e + 1/2(P_e)}{1 + 2P_e\eta_e} \qquad A_{LR} \approx 2\eta_e , \tag{23}$$

where P_e is the initial e^- polarization and

$$\eta_f \equiv \frac{V^f A^f}{V^{f2} + A^{f2}} . \tag{24}$$

Unlike A_{FB}, A_{LR} is especially sensitive to $\sin^2\theta_W$, and is insensitive to QED radiative corrections. Precise measurements of the τ polarization $P_\tau = 2\eta_\tau$ can also be obtained. The tree-level expressions for the (QED-corrected) asymmetries are an excellent first approximation if the vector couplings V^f are expressed in terms of $\sin^2\widehat{\theta}_W(M_Z)$ in the $\overline{\rm MS}$ scheme.

***W* and *Z* decays** [20–27]: The partial decay width for gauge bosons to decay into massless fermions $f_1\overline{f}_2$ is

$$\Gamma(W^+ \to e^+\nu_e) = \frac{G_F M_W^3}{6\sqrt{2}\pi} \approx 226 \pm 2 \text{ MeV}$$

$$\Gamma(W^+ \to u_i\overline{d}_i) = \frac{CG_F M_W^3}{6\sqrt{2}\pi}\,|V_{ij}|^2 \approx (702 \pm 7)\,|V_{ij}|^2 \text{ MeV} \tag{25}$$

$$\Gamma(Z \to \psi_i\overline{\psi}_i) = \frac{CG_F M_Z^3}{6\sqrt{2}\pi}\left[V^{i2} + A^{i2}\right]$$

$$\approx \begin{cases} 166.2 \pm 0.1\ (167.8)\text{ MeV } (\nu\overline{\nu}), & 83.5 \pm 0.1\ (84.1)\text{ MeV } (e^+e^-), \\ 295.3 \pm 0.3\ (300.0)\text{ MeV } (u\overline{u}), & 381.4 \pm 0.3\ (386.9)\text{ MeV } (d\overline{d}), \end{cases}$$

where the first (second) values are for m_t = 100 (200) GeV and M_H = 250 GeV, and the quoted errors are from $M_{W,Z}$. For leptons $C = 1$, while for quarks $C = 3\left(1 + \alpha_s(M_V)/\pi + 1.405\alpha_s^2/\pi^2\right)$, where the 3 is due to color and the factor in parentheses is a QCD correction, which introduces an additional uncertainty of $\sim 0.3\%$ in the hadronic widths [6,28]. Corrections to Eq. (25) for massive fermions are given in Refs. 6 and 28. Here the numerical values assume $M_W = 80.22 \pm 0.26$ GeV, $M_Z = 91.173 \pm 0.020$ GeV, and $\alpha_s \approx 0.115 \pm 0.008$. Expressing the widths in terms of $G_F M^3_{W,Z}$ incorporates the bulk of the low-energy radiative corrections [6,28]. The $Z \to f\overline{f}$ widths have an additional QED correction $1 + 3\alpha\, q_f^2/4\pi$. In the $\overline{\rm MS}$ scheme, most of the electroweak corrections are described by multiplying the lowest-order Γ_Z expressions by a factor $\rho_Z \simeq 1 + \rho_t$.

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Additional small effects are included in the numbers. Vertex corrections in $Z \to b\bar{b}$ can be approximated by $A^b \to A^b + \rho_t/3$, $V^b \to V^b + \rho_t/3$ [28].

For 3-fermion families the total widths are

$$\Gamma_Z \approx 2.478 \pm 0.002\ (2.504)\ \text{GeV}$$
$$\Gamma_W \approx 2.08 \pm 0.02\ \text{GeV}\ . \qquad (26)$$

for $m_t = 100$ (200) GeV. QCD introduces an additional uncertainty of ≈ 5 MeV in Γ_Z. (Fermion masses have been included in Γ_Z). This is to be compared with the experimental results [20–27]: $\Gamma_Z = 2.487 \pm 0.010$ GeV and $\Gamma_W = 2.12 \pm 0.11$ GeV.

Experimental results: Fits to the Z-line shape yield M_Z, Γ_Z, and the peak (QED-corrected) cross sections

$$\sigma_p^f = \frac{12\pi}{M_Z^2} \frac{\Gamma_{e\bar{e}}\,\Gamma_{f\bar{f}}}{\Gamma_Z^2} \qquad (27)$$

for $e^+e^- \to f\bar{f}$ [20–25]. The values of the principle Z-pole observables are listed in Table 2, along with the Standard Model predictions for $M_Z = 91.173 \pm 0.020$, $m_t = 150^{+23}_{-26}$ GeV (for $M_H = 250$ GeV), and 50 GeV $< M_H <$ 1 TeV. The values and predictions of M_W [26], M_W/M_Z [27], and the Q_W for cesium [16,17] are also listed. The agreement is remarkable. The only hints of a discrepancy are in $A_{FB}(b)$ and Q_W, but even these agree at $\sim 1\frac{1}{2}\sigma$. The observables in Table 2 (including correlations on the LEP observables), as well as all low-energy neutral-current data [5], are used in the global fits described below. The parameter $\sin^2\theta_W$ can be determined from the Z-pole observables and M_W, and from a variety of neutral-current processes spanning a very wide Q^2 range. The results [5], shown in Table 3, are in impressive agreement with each other, indicating the quantitative success of the Standard Model.

The best fit to all data yields $\sin^2\hat{\theta}_W(M_Z) = 0.2337 \pm 0.0003$ for the weak angle in the $\overline{\text{MS}}$ scheme for $m_t = 100$ GeV and yields 0.2310 ± 0.0003 for $m_t = 200$ GeV, both for $M_H = 250$ GeV. In all fits the errors include full statistical, systematic, and theoretical uncertainties. The result is dominated by M_Z, with the error reflecting both ΔM_Z (± 0.0002) and the low-energy uncertainty of ± 0.0009 in Δr (± 0.0003). In the on-shell scheme $\sin^2\theta_W$ is more sensitive to m_t [29]. One obtains $\sin^2\theta_W = 0.2315 \pm 0.0003$ (0.2191 ± 0.0003) for $m_t = 100$ (200) GeV.

The derived $\sin^2\theta_W$ is sensitive to the isospin breaking [5] associated with a large m_t, as can be seen in Fig. 1. Consistency of the

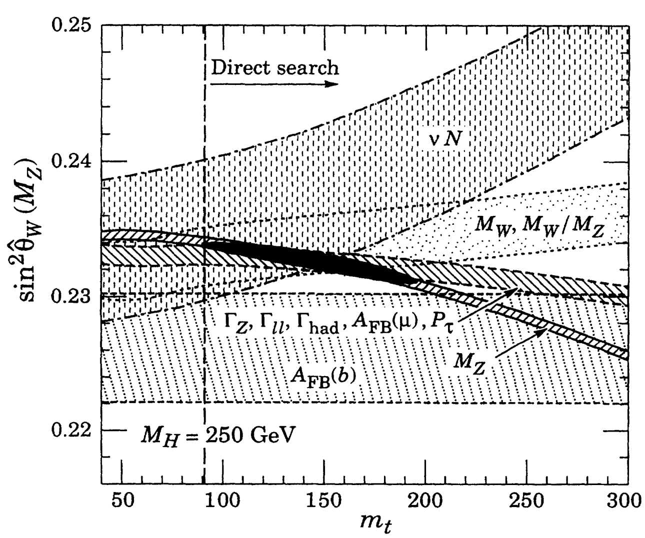

Fig. 1. One standard deviation uncertainties in $\sin^2\hat{\theta}_W$ as a function of m_t, the direct constraint $m_t > 91$ GeV [30], and the 90% CL region in $\sin^2\hat{\theta}_W - m_t$ allowed by all data, assuming $M_H = 250$ GeV.

Table 2. Principal LEP and other recent observables, compared with the Standard Model predictions for $M_Z = 91.173 \pm 0.020$ GeV, 50 GeV $< M_H <$ 1 TeV, and the global best fit value $m_t = 150^{+23}_{-26}$ GeV (for $M_H = 250$ GeV). The LEP averages of the ALEPH [21], DELPHI [22], L3 [23], and OPAL [24] results include common systematic errors [25]. $\Gamma_{\ell\ell}$ is the average of Γ_{ee}, $\Gamma_{\mu\mu}$, and $\Gamma_{\tau\tau}$; Γ_{had} is the width into hadrons. The invisible width Γ_{inv} corresponds to $N_\nu = 3.00 \pm 0.05$ light neutrino flavors. $\bar{g}_A$ and $\bar{g}_V$ are effective leptonic couplings determined from $A_{FB}(\mu)$ and $\Gamma_{\ell\ell}$ ($\bar{g}_A$ is not independent). At tree level, $\bar{g}_A = A^e$, $\bar{g}_V = V^e$. $A_{FB}(b)$ is corrected for $B\overline{B}$ oscillations. The second error in Q_W (for cesium) is theoretical [17]. In the Standard Model predictions, the first uncertainty is from M_Z and Δr, while the second is from m_t and M_H. There is an additional QCD error of ~ 5 MeV in Γ_Z and Γ_{had}.

Quantity	Value	Standard Model
M_Z (GeV)	91.173 ± 0.020	input
Γ_Z (GeV)	2.487 ± 0.010	$2.488 \pm 0.002 \pm 0.006$
$\Gamma_{\ell\ell}$ (MeV)	83.0 ± 0.6	$83.7 \pm 0.1 \pm 0.2$
Γ_{had} (MeV)	1736 ± 11	$1737 \pm 2 \pm 4$
Γ_{inv} (MeV)	502 ± 9	$501 \pm 0.3 \pm 1$
$\bar{g}_A^2$	0.2492 ± 0.0012	$0.2513 \pm 0.0002 \pm 0.0004$
$\bar{g}_V^2$	0.0012 ± 0.0003	$0.0011 \pm 0 \pm 0.0001$
P_τ	0.134 ± 0.035	$0.136 \pm 0.003 \pm 0.006$
$A_{FB}(b)$	0.126 ± 0.022	$0.091 \pm 0.002 \pm 0.004$
M_W (GeV)	80.22 ± 0.26	$80.21 \pm 0.03 \pm 0.16$
M_W/M_Z	0.8798 ± 0.0028	$0.8798 \pm 0.0002 \pm 0.0017$
Q_W [16,17]	$-71.04 \pm 1.58 \pm 0.88$	$-73.21 \pm 0.08 \pm 0.03$

$\sin^2\theta_W$ values derived from the various reactions requires [5] $m_t < 194$ GeV at 90% CL ($m_t < 201$ GeV at 95% CL) for $M_H \leq 1000$ GeV. (Similar limits hold for the mass splittings between fourth-generation quarks or leptons.)

When m_t is left as a free parameter one obtains $\sin^2\hat{\theta}_W(M_Z) = 0.2325 \pm 0.0008$ ($\overline{\text{MS}}$), or $\sin^2\theta_W = 0.2259 \pm 0.0029$ (on-shell), and $m_t = 150^{+23}_{-26} \pm 16$ GeV. The $\sin^2\theta_W$ errors include m_t and M_H (assuming 50 GeV $< M_H <$ 1 TeV). The central value and first error in m_t is for $M_H = 250$ GeV, while the second error is from M_H. The fits cannot significantly constrain M_H until m_t is known independently. The $\sin^2\hat{\theta}_W(M_Z)$ value is in striking agreement with the prediction 0.233 ± 0.003 of grand unified theories based on the minimal supersymmetric extension of the Standard Model, but disagree with the prediction 0.211 ± 0.002 of nonsupersymmetric unified theories.

One can also determine the radiative correction parameters Δr [Eq. (5)]: one obtains $\Delta r = 0.049 \pm 0.009$ and $\Delta\hat{r}_W = 0.063 \pm 0.007$, where the error includes m_t and M_H. The data also yield $\alpha_s(M_Z) = 0.127 \pm 0.015$ (mainly from $\Gamma_{\text{had}}/\Gamma_{\ell\ell}$), in excellent agreement with the value 0.115 ± 0.008 obtained from event shapes and jet studies [31].

Deviations from the Standard Model: The Z-pole, W mass, and neutral-current data can be used to search for and set limits on deviations from the Standard Model. For example, the relation in Eq. (5) between M_W and M_Z is modified if there are Higgs multiplets with weak isospin $> 1/2$ with significant vacuum expectation values. In order to calculate to higher orders in such theories one must define a set of four fundamental renormalized parameters. It is convenient to take these as α, G_F, M_Z, and M_W, since M_W and M_Z are directly measurable. Then $\sin^2\theta_W$ and ρ_0 can be considered dependent

STANDARD MODEL OF ELECTROWEAK INTERACTIONS (Cont'd)

Table 3. Values obtained for $\sin^2\widehat{\theta}_W(M_Z)$ in the $\overline{\text{MS}}$ scheme from various reactions. The values in the top line of the second column assume m_t = 100 GeV and M_H = 250 GeV. When two errors are shown, the first is experimental and the second (in square brackets) is theoretical. In the other cases they are combined. The numbers in parentheses (second line) are for m_t = 200 GeV. (The results extrapolate roughly linearly in this range.) The values in the third column are for the global best fit value $m_t = 150^{+23}_{-26}$ GeV (for M_H = 250 GeV), and the uncertainties include the effect of 50 GeV $< M_H <$ 1 TeV.

Reaction	$\sin^2\widehat{\theta}_W\ (M_Z)$ m_t = 100 (200) GeV	$\sin^2\widehat{\theta}_W\ (M_Z)$ $m_t = 150^{+23}_{-26}$ GeV
M_Z	$0.2339 \pm 0.0002 \pm [0.0003]$ (0.2307)	0.2326 ± 0.0008
$M_W, M_W/M_Z$	0.2331 ± 0.0022 (0.2346)	0.2340 ± 0.0022
Γ_Z	0.2332 ± 0.0008 (0.2319)	0.2326 ± 0.0009
$\Gamma_{\ell\ell}$	0.2350 ± 0.0015 (0.2334)	0.2342 ± 0.0015
$A_{FB}(\mu)$	0.2319 ± 0.0022 (0.2321)	0.2320 ± 0.0022
P_τ	0.233 ± 0.005 (0.233)	0.233 ± 0.005
$A_{FB}(b)$	0.226 ± 0.004 (0.226)	0.226 ± 0.004
Deep inelastic (isocalar)	$0.234 \pm 0.003 \pm [0.005]$ (0.240)	0.237 ± 0.006
$\nu_\mu(\overline{\nu}_\mu)p \to \nu_\mu(\overline{\nu}_\mu)p$	0.212 ± 0.032 (0.212)	0.212 ± 0.032
$\nu_\mu(\overline{\nu}_\mu)e \to \nu_\mu(\overline{\nu}_\mu)e$	0.231 ± 0.010 (0.230)	0.231 ± 0.010
atomic parity violation	$0.224 \pm 0.007 \pm [0.004]$ (0.221)	0.223 ± 0.008
SLAC eD	0.222 ± 0.018 (0.223)	0.222 ± 0.018
All data	0.2337 ± 0.0003 (0.2310)	0.2325 ± 0.0008

parameters defined by

$$\sin^2\theta_W \equiv A_0^2/M_W^2(1-\Delta r_s) \tag{28}$$

and

$$\rho_0 \equiv M_W^2/(M_Z^2\cos^2\theta_W\rho_s)\ . \tag{29}$$

Provided that the new physics which yields $\rho_0 \neq 1$ is a small perturbation which does not significantly affect the radiative corrections, ρ_0 can be regarded as a phenomenological parameter which multiplies G_F in Eqs. (7)–(9), (21), and Γ_Z in Eq. (25). (Also, the expression for M_Z in Eq. (5) is divided by $\sqrt{\rho_0}$; the M_W formula is unchanged.) The allowed regions in the $\rho_0 - \sin^2\theta_W$ plane for m_t = 100 GeV are shown in Fig. 2. ρ_0 could be determined very precisely if m_t were known. One obtains $\rho_0 = 1.004 \pm 0.002$ (0.995) for m_t = 100 (200) GeV and M_H = 250 GeV. However, ρ_o and m_t are strongly correlated because the quadratic m_t dependence enters all observables (except the $Zb\overline{b}$ vertex) in the combination $\rho_{\text{eff}} = \rho_0(1+\rho_t)$, which is determined to be 1.007 ± 0.002. Fortunately, m_t and ρ_0 can be separated by the subleading ($\ln m_t$) terms in $\Delta\widehat{r}_W$ and $\widehat{\rho}$ and by the vertex corrections in the $Z \to b\overline{b}$ width (and thus in Γ_Z). A fit to all data with m_t free and 50 GeV $< M_H <$ 1 TeV yields [5]

$$\rho_0 = 0.995 \pm 0.013$$
$$\sin^2\widehat{\theta}_W(M_Z) = 0.2325 \pm 0.0008\ , \tag{30}$$

consistent with $\rho_0 = 1$. Also, $m_t <$ 331 (353) GeV at 90 (95)% CL, even allowing for arbitrary ρ_0.

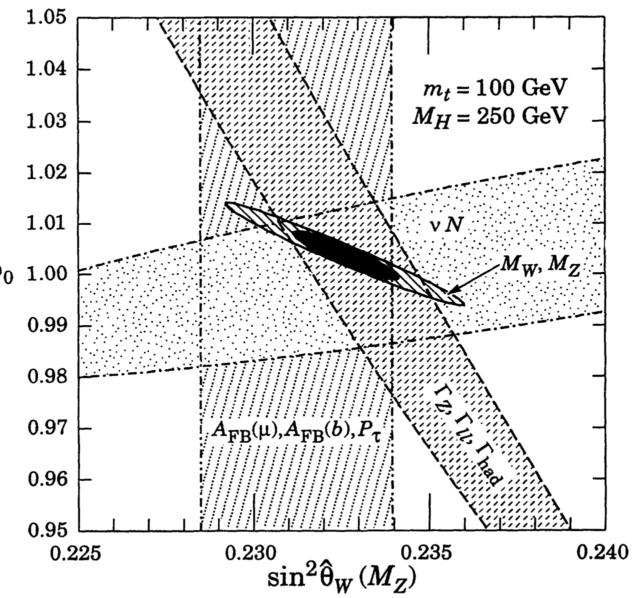

Fig. 2. The allowed regions in $\sin^2\widehat{\theta}_W - \rho_0$ at 90% CL for various reactions for m_t = 100 GeV.

Most of the parameters relevant to ν-hadron, νe, e-hadron, and e^+e^- processes are now determined uniquely and precisely from the data in "model independent" fits (i.e., fits which allow for an arbitrary electroweak gauge theory). The values for the parameters defined in Eqs. (7)–(9)are given in Table 4 along with the predictions of the Standard Model. The agreement is excellent. The low-energy e^+e^- results are difficult to present in a model-independent way because Z-propagator effects are non-negligible at TRISTAN, PETRA, and PEP energies. However, assuming e-μ-τ universality, the lepton asymmetries imply [19] $4(A^e)^2 = 0.99 \pm 0.05$, in good agreement with the Standard Model prediction +1. The much more precisely measured Z-pole parameters in Table 2 are in excellent agreement with the Standard Model.

This section prepared Sept. 1991 by P. Langacker.

** Constraints on V are discussed in the section on the Cabibbo-Kobayashi-Maskawa mixing matrix.

† α is dependent upon the energy scale of the process in which it is measured. This value is appropriate for low energy. At energies of order M_W the value 1/128 is applicable.

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STANDARD MODEL OF ELECTROWEAK INTERACTIONS (Cont'd)

Table 4. Values of the model-independent neutral-current parameters, compared with the Standard Model prediction using $M_Z = 91.173$ GeV for $m_t = 100$ (200) GeV. There is a second $g^e_{V,A}$ solution, given approximately by $g^e_V \leftrightarrow g^e_A$, which is eliminated by e^+e^- data under the assumption that the neutral current is dominated by the exchange of a single Z. θ_i, $i = L$ or R, is defined as $\tan^{-1}[\epsilon_i(u)/\epsilon_i(d)]$.

Quantity	Experimental Value	Standard Model Prediction	Correlation	
$\epsilon_L(u)$	0.329 $\pm$0.015	0.342 (0.347)		
$\epsilon_L(d)$	−0.437 $\pm$0.012	−0.426 (−0.431)		non-
$\epsilon_R(u)$	−0.178 $\pm$0.013	−0.156 (−0.156)		Gaussian
$\epsilon_R(d)$	−0.023 $^{+0.077}_{-0.047}$	0.078 (0.078)		
g_L^2	0.2990$\pm$0.0042	0.299 (0.307)		
g_R^2	0.0321$\pm$0.0034	0.030 (0.030)		small
θ_L	2.50 $\pm$0.035	2.46 (2.46)		
θ_R	4.58 $^{+0.44}_{-0.27}$	5.18 (5.18)		
g^e_A	−0.516 $\pm$0.025	−0.504 (−0.509)		−0.05
g^e_V	−0.041 $\pm$0.020	−0.035 (−0.039)		
C_{1u}	−0.215 $\pm$0.047	−0.184 (−0.190)	−0.995	− 0.79
C_{1d}	0.360 $\pm$0.041	0.338 (0.343)		0.79
$C_{2u} - \frac{1}{2}C_{2d}$	−0.03 $\pm$0.13	−0.042 (−0.052)		

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THE CABIBBO-KOBAYASHI-MASKAWA MIXING MATRIX

In the Standard Model with SU(2) × U(1) as the gauge group of electroweak interactions, both the quarks and leptons are assigned to be left-handed doublets and right-handed singlets. The quark mass eigenstates are not the same as the weak eigenstates, and the matrix relating these bases was defined for six quarks and given an explicit parametrization by Kobayashi and Maskawa [1] in 1973. It generalizes the four-quark case, where the matrix is parametrized by a single angle, the Cabibbo angle [2].

By convention, the three charge 2/3 quarks (u, c, and t) are unmixed, and all the mixing is expressed in terms of a 3 × 3 unitary matrix V operating on the charge −1/3 quarks (d, s, b):

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} . \qquad (1)$$

The values of individual matrix elements can in principle all be determined from weak decays of the relevant quarks, or, in some cases, from deep inelastic neutrino scattering. Using the constraints discussed below together with unitarity, and assuming only three generations, the 90% confidence limits on the magnitude of the elements of the complete matrix are:

$$\begin{pmatrix} 0.9747 \text{ to } 0.9759 & 0.218 \text{ to } 0.224 & 0.002 \text{ to } 0.007 \\ 0.218 \text{ to } 0.224 & 0.9735 \text{ to } 0.9751 & 0.032 \text{ to } 0.054 \\ 0.003 \text{ to } 0.018 & 0.030 \text{ to } 0.054 & 0.9985 \text{ to } 0.9995 \end{pmatrix} . \qquad (2)$$

The ranges shown are for the individual matrix elements. The constraints of unitarity connect different elements, so choosing a specific value for one element restricts the range of the others.

There are several parametrizations of the Cabibbo-Kobayashi-Maskawa matrix. In view of the need for a "standard" parametrization in the literature, we advocate:

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \qquad (3)$$

proposed by Chau and Keung [3]. The choice of rotation angles follows earlier work of Maiani [4], and the placement of the phase follows that of Wolfenstein [5]. The notation used is that of Harari and Leurer [6] who, along with Fritzsch and Plankl [7], proposed this parametrization as a particular case of a form generalizable to an arbitrary number of "generations." The general form was also put forward by Botella and Chau [8]. Here $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$, with i and j being "generation" labels, $\{i, j = 1, 2, 3\}$. In the limit $\theta_{23} = \theta_{13} = 0$ the third generation decouples, and the situation reduces to the usual Cabibbo mixing of the first two generations with θ_{12} identified with the Cabibbo angle [2]. The real angles θ_{12}, θ_{23}, θ_{13} can all be made to lie in the first quadrant by an appropriate redefinition of quark field phases. Then all s_{ij} and c_{ij} are positive, $|V_{us}| = s_{12}c_{13}$, $|V_{ub}| = s_{13}$, and $|V_{cb}| = s_{23}c_{13}$. As c_{13} is known to deviate from unity only in the fifth decimal place, $|V_{us}| = s_{12}$, $|V_{ub}| = s_{13}$, and $|V_{cb}| = s_{23}$ to an excellent approximation. The phase δ_{13} lies in the range $0 \le \delta_{13} < 2\pi$, with non-zero values generally breaking CP invariance for the weak interactions. The generalization to the n generation case contains $n(n-1)/2$ angles and $(n-1)(n-2)/2$ phases [6,7,8]. The range of matrix elements in Eq. (2) corresponds to 90% CL limits on the angles of $s_{12} = 0.218$ to 0.224, $s_{23} = 0.032$ to 0.054, and $s_{13} = 0.002$ to 0.007.

Kobayashi and Maskawa [1] originally chose a parametrization involving the four angles, θ_1, θ_2, θ_3, δ:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} c_1 & -s_1c_3 & -s_1s_3 \\ s_1c_2 & c_1c_2c_3-s_2s_3e^{i\delta} & c_1c_2s_3+s_2c_3e^{i\delta} \\ s_1s_2 & c_1s_2c_3+c_2s_3e^{i\delta} & c_1s_2s_3-c_2c_3e^{i\delta} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} , \qquad (4)$$

where $c_i = \cos\theta_i$ and $s_i = \sin\theta_i$ for $i = 1, 2, 3$. In the limit $\theta_2 = \theta_3 = 0$, this reduces to the usual Cabibbo mixing with θ_1 identified (up to a sign) with the Cabibbo angle [2]. Slightly different forms of the Kobayashi-Maskawa parametrization are found in the literature. The C-K-M matrix used in the 1982 Review of Particle Properties is obtained by letting $s_1 \to -s_1$ and $\delta \to \delta + \pi$ in the matrix given above. An alternative is to change Eq. (4) by $s_1 \to -s_1$ but leave δ unchanged. With this change in s_1, the angle θ_1 becomes the usual Cabibbo angle, with the "correct" sign (i.e. $d' = d\cos\theta_1 + s\sin\theta_1$) in the limit $\theta_2 = \theta_3 = 0$. The angles θ_1, θ_2, θ_3 can, as before, all be taken to lie in the first quadrant by adjusting quark field phases. Since all these parametrizations are referred to as "the" Kobayashi-Maskawa form, some care about which one is being used is needed when the quadrant in which δ lies is under discussion.

Other parametrizations, mentioned above, are due to Maiani [4] and to Wolfenstein [5]. The latter emphasizes the relative sizes of the matrix elements by expressing them in powers of the Cabibbo angle. Still other parametrizations [9] have come into the literature in connection with attempts to define "maximal CP violation". No physics can depend on which of the above parametrizations (or any other) is used as long as a single one is used consistently and care is taken to be sure that no other choice of phases is in conflict.

Our present knowledge of the matrix elements comes from the following sources:

(1) Nuclear beta decay, when compared to muon decay, gives [10–13]

$$|V_{ud}| = 0.9744 \pm 0.0010 . \qquad (5)$$

This includes refinements in the analysis of the radiative corrections, especially the order $Z\alpha^2$ effects, which have brought the ft-values from low and high Z Fermi transitions into good agreement.

(2) Analysis of K_{e3} decays yields [14]

$$|V_{us}| = 0.2196 \pm 0.0023 . \qquad (6)$$

The isospin violation between K^+_{e3} and K^0_{e3} decays has been taken into account, bringing the values of $|V_{us}|$ extracted from these two decays into agreement at the 1% level of accuracy. The analysis of hyperon decay data has larger theoretical uncertainties because of first order SU(3) symmetry breaking effects in the axial-vector couplings, but due account of symmetry breaking [15] applied to the WA2 data [16] gives a corrected value [17] of 0.222 ± 0.003. We average these two results to obtain:

$$|V_{us}| = 0.2205 \pm 0.0018 . \qquad (7)$$

(3) The magnitude of $|V_{cd}|$ may be deduced from neutrino and antineutrino production of charm off valence d quarks. The dimuon production cross sections of the CDHS group [18] yield $\overline{B}_c|V_{cd}|^2 = 0.41 \pm 0.07 \times 10^{-2}$, where $\overline{B}_c$ is the semileptonic branching fraction of the charmed hadrons produced. The corresponding value from a recent Tevatron experiment [19] is $\overline{B}_c|V_{cd}|^2 = 0.534^{+0.052}_{-0.078} \times 10^{-2}$. Averaging these two results gives $\overline{B}_c|V_{cd}|^2 = 0.47 \pm 0.05 \times 10^{-2}$. Supplementing this with measurements of the semileptonic branching fractions of charmed mesons [20], weighted by a production ratio of $D^0/D^+ = (60 \pm 10)/(40 \mp 10)$, to give $\overline{B}_c = 0.113 \pm 0.015$, yields

$$|V_{cd}| = 0.204 \pm 0.017 \qquad (8)$$

(4) Values of $|V_{cs}|$ from neutrino production of charm are dependent on assumptions about the strange quark density in the parton-sea. The most conservative assumption, that the strange-quark sea does not exceed the value corresponding to an SU(3) symmetric sea, leads to a lower bound [18], $|V_{cs}| > 0.59$. It is more advantageous to proceed analogously to the method used for extracting $|V_{us}|$ from K_{e3} decay; namely, we compare the experimental value for the width of D_{e3} decay with the expression [21] that follows from the standard weak interaction amplitude:

$$\Gamma(D \to \overline{K}e^+\nu_e) = |f_+^D(0)|^2\, |V_{cs}|^2\, (1.54 \times 10^{11}\ \mathrm{s}^{-1}) . \qquad (9)$$

Here $f_+^D(q^2)$, with $q = p_D - p_K$, is the form factor relevant to D_{e3} decay; its variation has been taken into account with the parametrization $f_+^D(t)/f_+^D(0) = M^2/(M^2 - t)$ and $M = 2.1$ GeV/c^2, a form and mass consistent with Mark III and E691 measurements [22,23]. Combining data on branching ratios for $D_{\ell 3}$ decays from Mark III, E691, ARGUS, and CLEO experiments [22–24] with accurate values [25] for τ_{D^+} and τ_{D^0}, gives the value $(0.75 \pm 0.15) \times 10^{11}\ \mathrm{s}^{-1}$ for $\Gamma(D \to \overline{K}e^+\nu_e)$. Therefore

$$|f_+^D(0)|^2\, |V_{cs}|^2 = 0.49 \pm 0.10 . \qquad (10)$$

THE CABIBBO-KOBAYASHI-MASKAWA MIXING MATRIX (Cont'd)

A very conservative assumption is that $|f_+^D(0)| < 1$, from which it follows that $|V_{cs}| > 0.62$. Calculations of the form factor either performed [26,27] directly at $q^2 = 0$, or done [28] at the maximum value of $q^2 = (m_D - m_K)^2$ and interpreted at $q^2 = 0$ using the measured q^2 dependence, yield $f_+^D(0) = 0.7 \pm 0.1$. It follows that

$$|V_{cs}| = 1.00 \pm 0.20 \ . \tag{11}$$

The constraint of unitarity when there are only three generations gives a much tighter bound (see below).

(5) The ratio $|V_{ub}/V_{cb}|$ can be obtained from the semileptonic decay of B mesons by fitting to the lepton energy spectrum as a sum of contributions involving $b \to u$ and $b \to c$. The relative overall phase space factor between the two processes is calculated from the usual four-fermion interaction with one massive fermion (c quark or u quark) in the final state. The value of this factor depends on the quark masses, but is roughly one-half (in suppressing $b \to c$ compared to $b \to u$). Both the CLEO [29] and ARGUS [30] collaborations have reported evidence for $b \to u$ transitions in semileptonic B decays. The interpretation of the result in terms of $|V_{ub}/V_{cb}|$ depends fairly strongly on the theoretical model used to generate the lepton energy spectrum, especially for $b \to u$ transitions [27,28,31]. Combining the experimental and theoretical uncertainties, we quote

$$|V_{ub}/V_{cb}| = 0.10 \pm 0.03 \ . \tag{12}$$

(6) The magnitude of V_{cb} itself can be determined if the measured semileptonic bottom hadron partial width is assumed to be that of a b quark decaying through the usual $V - A$ interaction:

$$\Gamma(b \to c\ell\overline{\nu}_\ell) = \frac{\mathrm{BF}(b \to c\ell\overline{\nu}_\ell)}{\tau_b} = \frac{G_F^2\, m_b^5}{192\pi^3} F(m_c/m_b)\, |V_{cb}|^2 \ , \tag{13}$$

where τ_b is the b lifetime and $F(m_c/m_b)$ is the phase space factor noted above as approximately one-half. Most of the error on $|V_{cb}|$ derived from Eq. (13) is not from the experimental uncertainties, but in the theoretical uncertainties in choosing a value of m_b and in the use of the quark model to represent inclusively semileptonic decays which, at least for the B meson, are dominated by a few exclusive channels. Instead we use the model-independent treatment in the heavy quark effective theory [32], where, in the case of $B \to D^*$ transitions, the decay rates at zero recoil are fixed by a normalization condition, with vanishing $1/m_q$ corrections [33]. From data of the ARGUS [34] and CLEO [35] experiments, we quote a value [36] derived from the decay of $\overline{B} \to D^*\ell\overline{\nu}_\ell$ of

$$|V_{cb}| = 0.043 \pm 0.007 \tag{14}$$

that is deduced using a B-lifetime of (1.28 ± 0.06) ps [37]. The central value and the error are now comparable to what is obtained from the inclusive semileptonic decays, but ultimately, with more data, exclusive semileptonic decays should provide the most accurate value of $|V_{cb}|$.

The results for three generations of quarks, from Eqs. (5), (7), (8), (11), (12), and (14) plus unitarity, are summarized in the matrix in Eq. (2). The ranges given there are different from those given in Eqs. (5)–(14) (because of the inclusion of unitarity), but are consistent with the one standard deviation errors on the input matrix elements.

The data do not preclude there being more than three generations. Moreover, the entries deduced from unitarity might be altered when the C-K-M matrix is expanded to accommodate more generations. Conversely, the known entries restrict the possible values of additional elements if the matrix is expanded to account for additional generations. For example, unitarity and the known elements of the first row require that any additional element in the first row have a magnitude $|V_{ub'}| < 0.07$. When there are more than three generations the allowed ranges (at 90% CL) of the matrix elements connecting the first three generations are

$$\begin{pmatrix} 0.9728 \text{ to } 0.9757 & 0.218 \text{ to } 0.224 & 0.002 \text{ to } 0.007 & \cdots \\ 0.179 \text{ to } 0.228 & 0.864 \text{ to } 0.975 & 0.032 \text{ to } 0.054 & \cdots \\ 0 \text{ to } 0.14 & 0 \text{ to } 0.45 & 0 \text{ to } 0.9995 & \cdots \\ \vdots & \vdots & \vdots & \end{pmatrix},$$

where we have used unitarity (for the expanded matrix) and Eqs. (5), (7), (8), (11), (12), and (14).

Further information on the angles requires theoretical assumptions. For example, $B_d - \overline{B}_d$ mixing, if it originates from short distance contributions to ΔM_B dominated by box diagrams involving virtual t quarks, gives information on $V_{tb}V_{td}^*$ once hadronic matrix elements and the t quark mass are known. A similar comment holds for $V_{tb}V_{ts}^*$ and $B_s - \overline{B}_s$ mixing.

Direct and indirect information on the C-K-M matrix is neatly summarized in terms of the "unitarity triangle." The name arises since unitarity of the 3×3 C-K-M matrix applied to the first and third columns yields

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \ . \tag{15}$$

In the parametrization adopted above, V_{cb} is real and V_{cd} is real to a very good approximation. Setting cosines of small angles to unity, Eq. (15) becomes

$$V_{ub}^* + V_{td} = |V_{cd}V_{cb}| \ . \tag{16}$$

The unitarity triangle is just a geometrical presentation of this equation in the complex plane [38].

CP-violating processes will involve the phase in the C-K-M matrix, assuming that the observed CP violation is solely related to a nonzero value of this phase. This allows additional constraints to be imposed. More specifically, a necessary and sufficient condition for CP violation with three generations can be formulated in a parametrization-independent manner in terms of the non-vanishing of the determinant of the commutator of the mass matrices for the charge $2e/3$ and charge $-e/3$ quarks [39]. CP violating amplitudes or differences of rates all are proportional to the C-K-M factor in this quantity. This is the product of factors $s_{12}s_{13}s_{23}c_{12}c_{13}^2c_{23}s_{\delta_{13}}$ in the parametrization adopted above, and is $s_1^2 s_2 s_3 c_1 c_2 c_3 s_\delta$ in that of Ref. 1. With the approximation of setting cosines to unity, this is just twice the area of the unitarity triangle. While hadronic matrix elements whose values are imprecisely known generally now enter, the constraints from CP violation in the neutral kaon system are tight enough to very much restrict the range of angles and the phase of the C-K-M matrix. For CP-violating asymmetries of neutral B mesons decaying to CP eigenstates, there is a direct relationship between the magnitude of the asymmetry in a given decay and $\sin 2\phi$, where ϕ is an appropriate angle of the unitarity triangle [38].

The combination of all the direct and indirect information can be used to find the overall constraints on the C-K-M matrix and thence the implications for future measurements of CP violation in the B system [40].

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QUARK MODEL

A. QUANTUM NUMBERS

Each quark has spin 1/2 and baryon number 1/3. Table 1 gives the additive quantum numbers (other than baryon number) of the quarks. Our convention is that the *flavor* of a quark (I_z, S, C, B, or T) has the same sign as its *charge*. With this convention, any flavor carried by a *charged* meson has the same sign as its charge; *e.g.*, the strangeness of the K^+ is $+1$, the bottomness of the B^+ is $+1$, and the charm and strangeness of the D_s^- are each -1.

Table 1. Additive quantum numbers of the three generations of quarks.

Property \ Quark	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I_z – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	-1	0	0	0
C – charm	0	0	0	$+1$	0	0
B – bottomness	0	0	0	0	-1	0
T – topness	0	0	0	0	0	$+1$

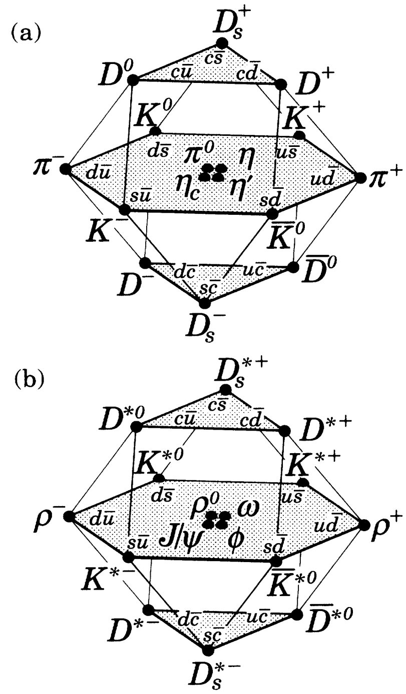


Fig. 1. The SU(4) hexadecuplets for the (a) pseudoscalar and (b) vector mesons made up of u, d, s, and c $q\bar{q}'$ combinations. The nonets mesons occupy the central planes, to which the $c\bar{c}$ members have been added. The neutral mesons at the center of these planes are mixtures of $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, and $c\bar{c}$ states.

B. MESONS

Nearly all known mesons can be understood as bound states of a quark q and an antiquark $\bar{q}'$ (the flavors of q and q' may be different). If the orbital angular momentum of the $q\bar{q}'$ state is L, then the parity $P = (-1)^{L+1}$. A state $q\bar{q}$ of a quark and its own antiquark is also an eigenstate of charge conjugation with $C = (-1)^{L+S}$, where the spin $S = 0$ or 1. The $L = 0$ states are the pseudoscalars, $J^P = 0^-$, and the vectors, $J^P = 1^-$. Assignments for some known $q\bar{q}'$ states are given in Table 2. States in the "normal" spin-parity series, $P = (-1)^J$, must, according to the above, have $S = 1$ and hence $CP = +1$. Thus mesons with normal spin-parity and $CP = -1$ are forbidden in the $q\bar{q}'$ quark model. The $J^{PC} = 0^{--}$ state is forbidden as well. Mesons with such J^{PC} may exist, but would lie outside the $q\bar{q}'$ model.

The nine possible $q\bar{q}'$ combinations containing u, d, and s quarks group themselves into an octet and a singlet:

$$\mathbf{3} \otimes \overline{\mathbf{3}} = \mathbf{8} \oplus \mathbf{1}$$

States with the same IJ^P and additive quantum numbers can mix (if they are eigenstates of charge conjugation, they must also have the same value of C). Thus the $I = 0$ member of the ground-state pseudoscalar octet mixes with the corresponding pseudoscalar singlet to produce the η and η'. These appear as members of a nonet, which is shown as the middle plane in Fig. 1(a). Similarly, the ground-state vector nonet appears as the middle plane in Fig. 1(b).

A fourth quark such as charm can be included in this scheme by extending the symmetry to SU(4), as shown in Fig. 1. Bottom could be included in this way instead of charm, but if both are included the figure becomes four-dimensional.

For the pseudoscalar mesons, the Gell-Mann-Okubo formula is

$$m_\eta^2 = \frac{1}{3}(4m_K^2 - m_\pi^2) ,$$

assuming no octet-singlet mixing. However, the octet η_8 and singlet η_1 mix because of SU(3) breaking. The physical states η and η' are given by

$$\eta = \eta_8 \cos\theta_P - \eta_1 \sin\theta_P$$

$$\eta' = \eta_8 \sin\theta_P + \eta_1 \cos\theta_P .$$

These combinations diagonalize the mass-squared matrix

$$M^2 = \begin{pmatrix} M_{11}^2 & M_{18}^2 \\ M_{18}^2 & M_{88}^2 \end{pmatrix} ,$$

where $M_{88}^2 = \frac{1}{3}(4m_K^2 - m_\pi^2)$. It follows that

$$\tan^2\theta_P = \frac{M_{88}^2 - m_\eta^2}{m_{\eta'}^2 - M_{88}^2} .$$

The sign of θ_P is meaningful in the quark model. If

$$\eta_1 = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$$

$$\eta_8 = (u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6} ,$$

then the matrix element M_{18}^2, which is due mostly to the strange quark mass, is negative. From the relation

$$\tan\theta_P = \frac{M_{88}^2 - m_\eta^2}{M_{18}^2} ,$$

we find $\theta_P < 0$. However, we note that caution is suggested in the use of the η-η' mixing-angle formulas, as they are extremely sensitive to SU(3) breaking. If we allow $M_{88}^2 = \frac{1}{3}(4m_K^2 - m_\pi^2)\,(1+\Delta)$, the mixing angle is determined by

$$\tan^2\theta_P = 0.0319(1 + 17\Delta)$$

$$\theta_P = -10.1^\circ(1 + 8.5\Delta)$$

to first order in Δ. A small breaking of the Gell-Mann-Okubo relation can produce a major modification of θ_P.

For the vector mesons we replace $\pi \to \rho$, $K \to K^*$, $\eta \to \phi$, and $\eta' \to \omega$, so

$$\phi = \omega_8 \cos\theta_V - \omega_1 \sin\theta_V$$

$$\omega = \omega_8 \sin\theta_V + \omega_1 \cos\theta_V .$$

QUARK MODEL (Cont'd)

Table 2. Suggested $q\bar{q}$ quark-model assignments for most of the known mesons. Some assignments, especially for the 0^{++} multiplet and for some of the members of the higher multiplets, are controversial. Only the states with both I and all flavors = 0 and the neutral states with $I = 1$ are eigenstates of charge conjugation C. Mesons in bold face are included in the Meson Summary Table. Of the light mesons in the Summary Table, the $f_1(1420)$, $f_0(1590)$, $f_2(1520)$, $f_2(1720)$, $f_2(2300)$, $f_2(2340)$, and the two peaks in the $\eta(1440)$ entry are not in this table. It is especially hard to find a place for the first four of these f mesons or for one of the $\eta(1440)$ peaks in the $q\bar{q}$ model. See the 'Note on Non-$q\bar{q}$ Mesons' in the Meson Listings.

$N\ ^{2S+1}L_J$	J^{PC}	$u\bar{d}$, $u\bar{u}$, $d\bar{d}$ $I=1$	$u\bar{u}$, $d\bar{d}$, $s\bar{s}$ $I=0$	$c\bar{c}$ $I=0$	$b\bar{b}$ $I=0$	$\bar{s}u$, $\bar{s}d$ $I=1/2$	$c\bar{u}$, $c\bar{d}$ $I=1/2$	$c\bar{s}$ $I=0$	$\bar{b}u$, $\bar{b}d$ $I=1/2$
$1\ ^1S_0$	0^{-+}	**π**	**η, η'**	**η_c**		**K**	**D**	**D_s**	**B**
$1\ ^3S_1$	1^{--}	**ρ**	**ω, ϕ**	**$J/\psi(1S)$**	**$\Upsilon(1S)$**	**$K^*(892)$**	**$D^*(2010)$**	**$D_s^*(2110)$**	**$B^*(5330)$**
$1\ ^1P_1$	1^{+-}	**$b_1(1235)$**	**$h_1(1170)$**, $h_1(1380)$			**K_{1B}**‡	**$D_1(2420)$**	**$D_{s1}(2536)$**	
$1\ ^3P_0$	0^{++}	**$a_0(980)$**	**$f_0(1400)$, $f_0(975)$**	**$\chi_{c0}(1P)$**	**$\chi_{b0}(1P)$**	**$K_0^*(1430)$**			
$1\ ^3P_1$	1^{++}	**$a_1(1260)$**	**$f_1(1285)$, $f_1(1510)$**	**$\chi_{c1}(1P)$**	**$\chi_{b1}(1P)$**	**K_{1A}**‡			
$1\ ^3P_2$	2^{++}	**$a_2(1320)$**	**$f_2(1270)$, $f_2'(1525)$**	**$\chi_{c2}(1P)$**	**$\chi_{b2}(1P)$**	**$K_2^*(1430)$**	**$D_2^*(2460)$**		
$1\ ^1D_2$	2^{-+}	**$\pi_2(1670)$**							
$1\ ^3D_1$	1^{--}	**$\rho(1700)$**	**$\omega(1600)$**	**$\psi(3770)$**		**$K^*(1680)$**†			
$1\ ^3D_2$	2^{--}					**$K_2(1770)$**			
$1\ ^3D_3$	3^{--}	**$\rho_3(1690)$**	**$\omega_3(1670)$, $\phi_3(1850)$**			**$K_3^*(1780)$**			
$1\ ^3F_4$	4^{++}	$a_4(2040)$	**$f_4(2050)$**, $f_4(2220)$			**$K_4^*(2045)$**			
$2\ ^1S_0$	0^{-+}	**$\pi(1300)$**	**$\eta(1295)$**	$\eta_c(2S)$		$K(1460)$			
$2\ ^3S_1$	1^{--}	**$\rho(1450)$**	**$\omega(1390)$, $\phi(1680)$**	**$\psi(2S)$**	**$\Upsilon(2S)$**	**$K^*(1410)$**†			
$2\ ^3P_2$	2^{++}		$f_2(1810)$, **$f_2(2010)$**		**$\chi_{b2}(2P)$**	$K_2^*(1980)$			
$3\ ^1S_0$	0^{-+}	$\pi(1770)$	**$\eta(1760)$**			$K(1830)$			

†The $K^*(1410)$ could be replaced by the $K^*(1680)$ as the $2\ ^3S_1$ state.

‡ The K_{1A} and K_{1B} are nearly 45° mixed states of the $K_1(1270)$ and $K_1(1400)$.

For "ideal mixing," $\phi = s\bar{s}$, $\tan\theta_V = 1/\sqrt{2}$, so $\theta_V = 35.3°$. Experimentally, θ_V is near 35°, the sign being determined by a formula analogous to that for $\tan\theta_P$. Following this procedure we find the mixing angles given in Table 3.

Table 3. Singlet-octet mixing for the pseudoscalar, vector, and tensor mesons. The sign conventions are given in the text. The value of $\theta_{\rm quad}$ is obtained from the equations in the text, and $\theta_{\rm lin}$ is obtained by replacing m^2 by m throughout. Of the two isosinglets, the mostly octet one is listed first.

J^{PC}	Nonet Members	$\theta_{\rm quad}$	$\theta_{\rm lin}$
0^{-+}	π, K, η, η'	$-10°$	$-23°$
1^{--}	ρ, $K^*(892)$, ϕ, ω	$39°$	$36°$
2^{++}	$a_2(1320)$, $K_2^*(1430)$, $f_2'(1525)$, $f_2(1270)$	$28°$	$26°$
3^{--}	$\rho_3(1690)$, $K_3^*(1780)$, $\phi_3(1850)$, $\omega_3(1670)$	$29°$	$28°$

In the quark model, the coupling of neutral mesons to two photons is proportional to $\sum_i Q_i^2$, where Q_i is the charge of the i-th quark. This provides an alternative characterization of mixing. For example, defining

$$\text{Amp}\,[P \to \gamma(k_1)\,\gamma(k_2)] = M\epsilon^{\mu\nu\alpha\beta}\,\epsilon^*_{1\mu}\,k_{1\nu}\,\epsilon^*_{2\alpha}\,k_{2\beta}\ ,$$

where $\epsilon_{i\lambda}$ is the λ component of the polarization vector of the i^{th} photon, one finds

$$\frac{M(\eta\to\gamma\gamma)}{M(\pi^0\to\gamma\gamma)} = \frac{1}{\sqrt{3}}(\cos\theta_P - 2\sqrt{2}\sin\theta_P) = \frac{1.73\pm0.18}{\sqrt{3}}$$

$$\frac{M(\eta'\to\gamma\gamma)}{M(\pi^0\to\gamma\gamma)} = 2\sqrt{2/3}\left(\cos\theta_P + \frac{\sin\theta_P}{2\sqrt{2}}\right) = (0.78\pm0.04)2\sqrt{2/3}\ .$$

These data favor $\theta_P \approx -20°$, which is compatible with the quadratic mass mixing formula with $\approx 12\%$ SU(3) breaking in M_{88}^2.

QUARK MODEL (Cont'd)

C. BARYONS

All the established baryons are apparently 3-quark (qqq) states, and each such state is an SU(3) color singlet, a completely antisymmetric state of the three possible colors. Since the quarks are fermions, the state function for any baryon must be antisymmetric under interchange of any two equal-mass quarks (up and down quarks in the limit of isospin symmetry). Thus the state function may be written as

$$|\, qqq \,\rangle_A = |\, \text{color} \,\rangle_A \times |\, \text{space, spin, flavor} \,\rangle_S \ ,$$

where the subscripts S and A indicate symmetry or antisymmetry under interchange of any two of the equal-mass quarks. Note the contrast with the state function for the three nucleons in ^{3}H or ^{3}He:

$$|\, NNN \,\rangle_A = |\, \text{space, spin, isospin} \,\rangle_A \ .$$

This difference has major implications for internal structure, magnetic moments, etc. (For a nice discussion, see Ref. 1.)

The "ordinary" baryons are made up of d, u, and s quarks. The three flavors imply an approximate flavor SU(3), which requires that baryons made of these quarks belong to the multiplets on the right side of

$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10}_S \oplus \mathbf{8}_M \oplus \mathbf{8}_M \oplus \mathbf{1}_A$$

(see the section on SU(n) Multiplets and Young Diagrams). Here the subscripts indicate symmetric, mixed-symmetry, or antisymmetric states under interchange of any two quarks. The **1** is a *sud* state (Λ_1) and the octet contains a similar state (Λ_8). If these have the same spin and parity they can mix. An example is the mainly octet D_{03} $\Lambda(1690)$ and mainly singlet D_{03} $\Lambda(1520)$. In the ground state multiplet, the SU(3) flavor singlet Λ is forbidden by Fermi statistics. The mixing formalism is the same as for η-η' or ϕ-ω (see above), except that for baryons the mass M instead of M^2 is used. The section SU(3) Isoscalar Factors shows how relative decay rates in, say, $\mathbf{10} \to \mathbf{8} \otimes \mathbf{8}$ decays may be calculated. A summary of results of fits to the observed baryon masses and decay rates for the best-known SU(3) multiplets is given in Appendix II of our 1982 edition [2].

Figures 2(a) and 2(b) show the (badly broken) SU(4) multiplets that have as their "ground floors" the SU(3) octet that contains the nucleons and the SU(3) decuplet that contains the $\Delta(1232)$. All the particles in a given SU(4) multiplet have the same spin and parity. The only charmed baryons that have been discovered each contain one charmed quark. These belong to the first floor of the multiplet shown in Fig. 2(a), which consists of two SU(3) multiplets: a $\overline{\mathbf{3}}$ which contains the Λ_c and Ξ_c, both of which decay weakly, and a **6** that contains the $\Sigma_c(2455)$, which decays strongly into $\Lambda_c\pi$. A second Ξ_c and a Ω_c^0 remain to be discovered to fill out the **6**, and a host of other baryons with one or more charmed quarks are still needed to fill out the SU(4) multiplets shown in Fig. 2. Furthermore, *every* N or Δ baryon resonance "starts" a multiplet like those shown in Figs. 2(a) and 2(b). Analogous SU(4) structures can be made by substituting b for c. If both are present, the figures are four-dimensional.

For the "ordinary" baryons, flavor and spin may be combined in an approximate flavor-spin SU(6) in which the six basic states are $d\uparrow$, $d\downarrow$, $\cdots$, $s\downarrow$ ($\uparrow$, $\downarrow$ = spin up, down). Then the baryons belong to the multiplets on the right side of

$$\mathbf{6} \otimes \mathbf{6} \otimes \mathbf{6} = \mathbf{56}_S \oplus \mathbf{70}_M \oplus \mathbf{70}_M \oplus \mathbf{20}_A \ .$$

These SU(6) multiplets decompose into flavor SU(3) multiplets as follows:

$$\mathbf{56} = {}^4\mathbf{10} \oplus {}^2\mathbf{8}$$

$$\mathbf{70} = {}^2\mathbf{10} \oplus {}^4\mathbf{8} \oplus {}^2\mathbf{8} \oplus {}^2\mathbf{1}$$

$$\mathbf{20} = {}^2\mathbf{8} \oplus {}^4\mathbf{1} \ ,$$

where the superscript $(2S+1)$ gives the net spin S of the quarks for each particle in the SU(3) multiplet. The $J^P = 1/2^+$ octet containing the nucleon and the $J^P = 3/2^+$ decuplet containing the $\Delta(1232)$ together make up the "ground-state" 56-plet in which the orbital angular momenta between the quark pairs are zero (so that the spatial part of the state function is trivially symmetric). The **70** and **20** require some excitation of the spatial part of the state function in order to make the overall state function symmetric. States with nonzero orbital angular momenta are classified in SU(6)⊗O(3) supermultiplets. Physical baryons with the same quantum numbers do not belong to a single supermultiplet, since SU(6) is broken by spin-dependent interactions, differences in quark masses, etc.; nevertheless, the SU(6)⊗O(3) basis provides a suitable framework for describing baryon state functions.

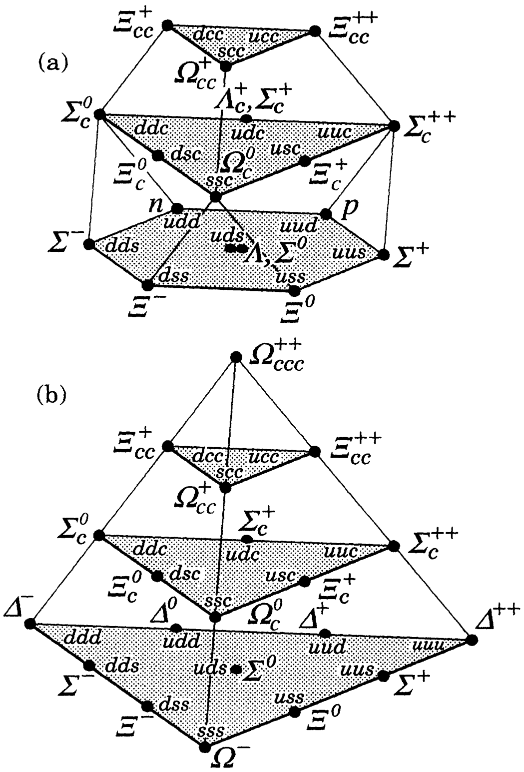


Fig. 2. SU(4) multiplets of baryons made of u, d, s, and c quarks. (a) The 20-plet with an SU(3) octet. (b) The 20-plet with an SU(3) decuplet.

It is convenient to classify the baryons into bands that have the same number N of quanta of excitation. Each band consists of a number of supermultiplets, specified by (D, L_N^P), where D is the dimensionality of the SU(6) representation, L is the total quark orbital angular momentum, and P is the total parity. Supermultiplets contained in bands up to $N = 12$ are given in Ref. 3. The $N = 0$ band, which contains the nucleon and $\Delta(1232)$, consists only of the $(56,0_0^+)$ supermultiplet. The $N = 1$ band consists only of the $(70,1_1^-)$ multiplet and contains the negative-parity baryons with masses below about 1.9 GeV. The $N = 2$ band contains five supermultiplets: $(56,0_2^+)$, $(70,0_2^+)$, $(56,2_2^+)$, $(70,2_2^+)$, and $(20,1_2^+)$. Baryons belonging to the $(20,1_2^+)$ supermultiplet are not ever likely to be observed, since a coupling from the ground-state baryons requires a two-quark excitation. Selection rules are similarly responsible for the fact that many other baryon resonances have not been observed [4].

In Table 4, quark-model assignments are given for many of the established baryons whose SU(6)⊗O(3) compositions are relatively unmixed. Note that the unestablished resonances $\Sigma(1480)$, $\Sigma(1560)$, $\Sigma(1580)$, $\Sigma(1770)$, and $\Xi(1620)$ in our Baryon Full Listings are too low in mass to be accommodated in most modern quark models [4,5].

Quark models for baryons are extensively reviewed in Ref. 6.

QUARK MODEL (Cont'd)

Table 4. Quark-model assignments for some of the known baryons in terms of a flavor-spin SU(6) basis. Only the dominant representation is listed. Assignments for some states, especially for $\Lambda(1810)$, $\Lambda(2350)$, $\Xi(1820)$, and $\Xi(2030)$, are merely educated guesses.

J^P	(D,L_N^P)	S	Octet members				Singlets
1/2$^+$	$(56,0_0^+)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
1/2$^+$	$(56,0_2^+)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
1/2$^-$	$(70,1_1^-)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
3/2$^-$	$(70,1_1^-)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
1/2$^-$	$(70,1_1^-)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
3/2$^-$	$(70,1_1^-)$	3/2	$N(1700)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
5/2$^-$	$(70,1_1^-)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$	
1/2$^+$	$(70,0_2^+)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
3/2$^+$	$(56,2_2^+)$	1/2	$N(1720)$	$\Lambda(1890)$	$\Sigma(?)$	$\Xi(?)$	
5/2$^+$	$(56,2_2^+)$	1/2	$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$	$\Xi(2030)$	
7/2$^-$	$(70,3_3^-)$	1/2	$N(2190)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	$\Lambda(2100)$
9/2$^-$	$(70,3_3^-)$	3/2	$N(2250)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
9/2$^+$	$(56,4_4^+)$	1/2	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	
			Decuplet members				
3/2$^+$	$(56,0_0^+)$	3/2	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$	
1/2$^-$	$(70,1_1^-)$	1/2	$\Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
3/2$^-$	$(70,1_1^-)$	1/2	$\Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
5/2$^+$	$(56,2_2^+)$	3/2	$\Delta(1905)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
7/2$^+$	$(56,2_2^+)$	3/2	$\Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$	
11/2$^+$	$(56,4_4^+)$	3/2	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	

D. DYNAMICS

Many specific quark models exist, but most contain basically the same set of dynamical ingredients. These include:

i) Using a confining interaction, which is generally spin-independent.
ii) Adding a spin-dependent interaction, modeled after the effects of gluon exchange in QCD. For example, in the S-wave states, there is a spin-spin hyperfine interaction of the form

$$H_{HF} = -\alpha_S M \sum_{i>j} (\vec{\sigma}\lambda^A)_i(\vec{\sigma}\lambda^A)_j \ ,$$

where M is a constant with units of energy; λ^A, $A = 1,\cdots,8$, is the set of SU(3) unitary spin matrices, defined in the "SU(3) Isoscalar Factors and Representation Matrices" section; and the sum runs over constituent quarks or antiquarks. Spin-orbit interactions, although allowed, seem to be small.
iii) Taking the strange quark mass to be somewhat larger than the up and down quark masses in order to split the SU(3) multiplets.
iv) In the case of isoscalar mesons, an interaction is needed for mixing $q\overline{q}$ configurations of different flavors (*e.g.*, $u\overline{u} \leftrightarrow d\overline{d}, s\overline{s}$) in a manner which is generally chosen to be flavor independent.

These four ingredients provide the basic mechanisms which determine the hadron spectrum.

1. F.E. Close, in *Quarks and Nuclear Forces* (Springer-Verlag, 1982), p. 56.
2. Particle Data Group, Phys. Lett. **111B** (1982).
3. R.H. Dalitz and L.J. Reinders, in *Hadron Structure as Known from Electromagnetic and Strong Interactions, Proceedings of the Hadron '77 Conference* (Veda, 1979), p. 11.
4. N. Isgur and G. Karl, Phys. Rev. **D18**, 4187 (1978); ibid. **D19**, 2653 (1979); ibid. **D20**, 1191 (1979); and K.-T. Chao, N. Isgur, and G. Karl, Phys. Rev. **D23**, 155 (1981).
5. C.P. Forsyth and R.E. Cutkosky, Z. Phys. **C18**, 219 (1983).
6. A.J.G. Hey and R.L. Kelly, Phys. Reports **96**, 71 (1983). Also see S. Gasiorowicz and J.L. Rosner, Am. J. Phys. **49**, 954 (1981).

NAMING SCHEME FOR HADRONS

1. Introduction

We introduced in the 1986 edition [1] a new naming scheme for the hadrons. Changes from older terminology affected mainly the heavier mesons made of u, d, and s quarks. Otherwise, the only important change to known hadrons was that the $F^{\pm}$ became the $D_s^{\pm}$. None of the lightest pseudoscalar or vector mesons changed names, nor did the $c\overline{c}$ or $b\overline{b}$ mesons (we do, however, now use χ_c for the $c\overline{c}$ χ states), nor did any of the established baryons. The Summary Tables give both the new and old names whenever a change has occurred.

We follow custom and use spectroscopic names such as $\Upsilon(1S)$ as the primary name for most of those ψ, Υ, and χ states whose spectroscopic identity is known. We use the form $\Upsilon(9460)$ as an alternate, and as the primary name when the spectroscopic identity is not known.

2. "Neutral-flavor" mesons ($S = C = B = T = 0$)

Table I shows the naming scheme for mesons having the strangeness and all heavy-flavor quantum numbers equal to zero. The scheme is designed for all mesons, whether ordinary or exotic. (This isn't quite true. We haven't proposed names for mesons whose charge Q, strangeness S, or other additive quantum numbers can't be matched by a $q\overline{q}$ state. For example, we have no name for a meson with $Q = 2$, or for one with $Q = -1$ and $S = +1$.) First, we assign names to those states with quantum numbers compatible with being $q\overline{q}$ states. The rows of the Table give the possible $q\overline{q}$ content. The columns give the possible parity/charge-conjugation states, $PC = -+, +-, --$, and $++$; these combinations correspond one-to-one with the angular-momentum state $^{2S+1}L_J$ of the $q\overline{q}$ system being $^1(L\ \text{even})_J$, $^1(L\ \text{odd})_J$, $^3(L\ \text{even})_J$, or $^3(L\ \text{odd})_J$. The relations between the quantum numbers are $P = (-1)^{L+1}$, $C = (-1)^{L+S}$, and $G = (-1)^{L+S+I}$, where of course the C quantum number is only relevant to neutral mesons.

Table I. Symbols for mesons with the strangeness and all heavy-flavor quantum numbers equal to zero.

	$J^{PC} =$	0^{-+}, 2^{-+}, ⋮	1^{+-}, 3^{+-}, ⋮	1^{--}, 2^{--}, ⋮	0^{++}, 1^{++}, ⋮
$q\overline{q}$ content	$^{2S+1}L_J =$	$^1(L\,\text{even})_J$	$^1(L\,\text{odd})_J$	$^3(L\,\text{even})_J$	$^3(L\,\text{odd})_J$
$u\overline{d}, u\overline{u}-d\overline{d}, d\overline{u}$	$(I=1)$	π	b	ρ	a
$d\overline{d}+u\overline{u}$ and/or $s\overline{s}$	$(I=0)$	η, η'	h, h'	ω, ϕ	f, f'
$c\overline{c}$		η_c	h_c	$\psi^{\dagger}$	χ_c
$b\overline{b}$		η_b	h_b	Υ	χ_b
$t\overline{t}$		η_t	h_t	θ	χ_t

†The J/ψ remains the J/ψ.

NAMING SCHEME FOR HADRONS (Cont'd)

The entries in the Table give the particle symbols. The spin J is added to the symbol as a subscript except for pseudoscalar and vector mesons, and the mass is added in parentheses for any meson that decays strongly. However, for the lightest meson resonances, we sometimes omit the mass, as in ρ for $\rho(770)$, ϕ for $\phi(1020)$, etc.

Experimental determination of the mass, quark content (where relevant), and quantum numbers I, J, P, and C (or G) of a meson thus fixes its symbol. Conversely, these properties may be inferred unambiguously from the symbol.

If the main symbol cannot be assigned because the quantum numbers are unknown, X is used. Sometimes it is not known whether a meson is mainly the isospin-0 mix of $u\overline{u}$ and $d\overline{d}$ or is mainly $s\overline{s}$. A prime (or symbol ϕ) may be used to distinguish two such mixing states.

Names are assigned for the anticipated $t\overline{t}$ mesons.

Gluonium states or other mesons that are not $q\overline{q}$ states are, if the quantum numbers are *not* exotic, to be named just as are the $q\overline{q}$ mesons. Such states will probably be difficult to distinguish from $q\overline{q}$ states and will likely mix with them and our scheme makes no attempt to distinguish the "mostly gluonium" or "mostly $q\overline{q}$" nature.

An "exotic" meson with J^{PC} quantum numbers that a $q\overline{q}$ system cannot have, namely $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \cdots$, would use the same symbol as does an ordinary meson with all the same quantum numbers as the exotic meson except for the C parity. Then a caret or "hat" is added to the symbol: for example, an isospin-1 0^{--} meson would be a $\widehat{\pi}$, an isospin-0 1^{-+} meson would be an $\widehat{\omega}$.

The results of all this are as follows. Established mesons whose names changed slightly in 1986 are:

Old name	New name	Old name	New name
$H(1170)$	$h_1(1170)$	$A_2(1320)$	$a_2(1320)$
$B(1235)$	$b_1(1235)$	$f'(1525)$	$f_2'(1525)$
$A_1(1270)$	$a_1(1260)$	$\omega(1670)$	$\omega_3(1670)$
$f(1270)$	$f_2(1270)$		

Established mesons whose names changed completely are:

Old name	New name	Old name	New name
$S(975)$	$f_0(975)$	$A_3(1680)$	$\pi_2(1670)$
$\delta(980)$	$a_0(980)$	$g(1690)$	$\rho_3(1690)$
$D(1285)$	$f_1(1285)$	$\theta(1690)$	$f_0(1710)$
$\epsilon(1300)$	$f_0(1400)$	$X(1850)$	$\phi_3(1850)$
$E(1420)$	$f_1(1420)$	$h(2030)$	$f_4(2050)$
$\iota(1440)$	$\eta(1440)$		

The old $S(975)$, $D(1285)$, $\epsilon(1300)$, $E(1420)$, $\theta(1690)$, and $h(2030)$ all became f mesons; the new scheme revealed that they all have $PC = ++$ and are $^3(L\text{ odd})_J$ states.

3. Mesons with nonzero S, C, B, and/or T

Since the strangeness or a heavy flavor of these mesons is nonzero, none of them are eigenstates of charge conjugation, and in each of them one of the quarks is heavier than the other. The rules are:

(1) The main symbol is an upper-case italic letter indicating the heavier quark as follows:

$$s \to \overline{K} \qquad c \to D \qquad b \to \overline{B} \qquad t \to T\ .$$

We use the convention that *the flavor and the charge of a quark have the same sign.* Thus the strangeness of the s quark is negative, the charm of the c quark is positive, and the bottom of the b quark is negative. In addition, I_3 of the u and d quarks are positive and negative, respectively. The effect of this convention is as follows: *Any flavor carried by a charged meson has the same sign as its charge.* Thus the K^+, D^+, and B^+ have positive strangeness, charm, and bottom, respectively, and all have positive I_3. The D_s^+ has positive charm *and* strangeness. Furthermore, the $\Delta(\text{flavor}) = \Delta Q$ rule, best known for the kaons, applies to every flavor.

(2) If the lighter quark is not a u or a d quark, its identity is given by a subscript.

(3) If the spin-parity is in the "normal" series, $J^P = 0^+, 1^-, 2^+, \cdots$, a superscript "*" is added.

(4) The spin is added as a subscript unless the meson is a pseudoscalar or a vector.

Thus the pseudoscalar and vector K, K^*, D, D^*, and B mesons did not change names. Established mesons whose names did change were:

Old name	New name	Old name	New name
$Q_1(1280)$	$K_1(1270)$	$L(1770)$	$K_2(1770)$
$Q_2(1400)$	$K_1(1400)$	$K^*(1780)$	$K_3^*(1780)$
$\kappa(1350)$	$K_0^*(1430)$	$K^*(2060)$	$K_4^*(2045)$
$K^*(1430)$	$K_2^*(1430)$	F	D_s

Most notably, the F (the $c\overline{s}$ state) became the D_s.

4. Baryons

The symbols N, Δ, Λ, Σ, Ξ, and Ω used for 30 years for the baryons made of light quarks (u, d, and s quarks) tell the isospin and quark content, and the same information is conveyed by the symbols now used for the baryons containing one or more heavy quarks (c, b, and t quarks). The rules are:

(1) Baryons with *three* u and/or d quarks are N's (isospin 1/2) or Δ's (isospin 3/2).

(2) Baryons with *two* u and/or d quarks are Λ's (isospin 0) or Σ's (isospin 1). If the third quark is a c, b, or t quark, its identity is given by a subscript.

(3) Baryons with *one* u or d quark are Ξ's (isospin 1/2). One or two subscripts are used if one or both of the remaining quarks are heavy: thus Ξ_c, Ξ_{cc}, Ξ_b, etc.

(4) Baryons with *no* u or d quarks are Ω's (isospin 0), and subscripts indicate any heavy-quark content.

In short, the number of u plus d quarks together with the isospin determine the main symbol, and subscripts indicate any content of heavy quarks. A Σ always has isospin 1, an Ω always has isospin 0, etc.

---

1. Particle Data Group: M. Aguilar-Benitez *et al.*, Phys. Lett. **170B** (1986).

MONTE CARLO PARTICLE NUMBERING SCHEME

Most particle physics Monte Carlo and analysis systems use a numbering scheme to represent particles. The lack of standardization of such schemes inhibits interfacing different programs. The following table proposes a standard numbering scheme. Some of the properties of this scheme are:

1. Quarks and leptons are ordered by family, and within the family, by isospin. This puts the u and d in the opposite order than is often used in other numbering schemes. In our scheme we call the highest numbered quark the heaviest quark.
2. For multiple quark systems (mesons, baryons, and diquarks), the rightmost digit is generally $L = 2J + 1$. (The K_S^0 and K_L^0 are exceptions.) Particles with $J > 4$ have not been assigned numbers.
3. Mesons are represented by the form NML and baryons by $NMKL$, where N, M, and K are quark numbers.
4. For these systems the heaviest quark is usually on the left and the quarks are in decreasing mass order from left to right. One exception to this convention is the K_L^0-K_S^0 pair. A second exception is for the Λ's for which we invert the up and down quarks to distinguish the Λ from the Σ^0.
5. The other exception to this mass order rule is for some N's and Δ's. For N's, the u and d quark are reversed for spins 3/2 and 7/2. For Δ's, they are reversed for spins 1/2 and 5/2. The quarks are in the normal decreasing order when $I + J$ is odd.
6. Mesons, and only mesons, have the third digit nonzero and the fourth digit zero. (We designate the rightmost digit as the first digit.)
7. Only baryons and diquarks have the fourth digit nonzero.
8. Only quarks and diquarks have the second digit equal to zero.
9. Particles have positive numbers; each antiparticle has the negative of its counterpart.
10. The particle-antiparticle convention is the one used by the Particle Data Group, so that the K^+ and B^+ are particles.
11. The above rules imply that for mesons (as opposed to anti-mesons), when the number of the leftmost (heaviest) quark is even, it is a quark, and when the number of the leftmost quark is odd, it is an antiquark.
12. The gluon has two numbers. Its official number is 21 to place it with the other gauge bosons. Its number is also 9 so that a glueball is specified as 99.
13. The fifth digit is used to differentiate different particles with the same quark content and spin.
14. Although isospin is not manifest in this scheme, the isospin of any hadron can be determined from the number. Mesons with $11L$ are isospin 1 and those with $22L$ are isospin 0. For nonstrange baryons, if the quarks are in the normal decreasing order, then $I + J$ is odd, otherwise $I + J$ is even. If a strange baryon does not have the normal decreasing quark order, it has $I = 0$.

More details about the motivation behind, and properties of, this scheme can be found in Ref. 1. Although this scheme has the advantage that a particle's number has considerable physics content, it has the disadvantage that it is not compact. An algorithm that translates this scheme into a more compact scheme is needed for its implementation. Contact the Berkeley Particle Data Group for further information on such an algorithm.

A list of particle numbers follows.

Written April 1988 by G.R. Lynch and T.G. Trippe.

1. T.G. Trippe and G.R. Lynch, "Particle I.D. Numbers, Decay Tables, and Other Possible Contributions of the Particle Data Group to Monte Carlo Standards," LBL-24287, in *Proceedings of the Workshop on Detector Simulation for the SSC* (August 1987).

QUARKS

d	1
u	2
s	3
c	4
b	5
t	6

GAUGE AND HIGGS BOSONS

γ	22
W	24
Z	23
g	21 and 9
H_1^0	25
H_2^0	35
H_3^0	36
H^+	37

LEPTONS

ν_e	12
ν_μ	14
ν_τ	16
e	11
μ	13
τ	15

DIQUARKS

$(dd)_1$	1103
$(ud)_0$	2101
$(ud)_1$	2103
$(uu)_1$	2203
$(sd)_0$	3101
$(sd)_1$	3103
$(su)_0$	3201
$(su)_1$	3203

MESONS

π^+	211
π^0	111
η	221
$\rho(770)$	113, 213
$\omega(783)$	223
$\eta'(958)$	331
$f_0(975)$	10221
$a_0(980)$	10111, 10211
$\phi(1020)$	333
$h_1(1170)$	10223
$b_1(1235)$	10113, 10213
$a_1(1260)$	20113, 20213
$f_2(1270)$	225
$f_1(1285)$	20223
$\eta(1295)$	20221
$\pi(1300)$	20111, 20211

MESONS (Cont'd)

$a_2(1320)$	115, 215
$\omega(1390)$	50223
$f_0(1400)$	30221
$f_1(1420)$	30223
$\eta(1440)$	40221
$\rho(1450)$	40113, 40213
$f_1(1510)$	40223
$f_2'(1525)$	335
$f_0(1590)$	50221
$\omega(1600)$	60223
$\omega_3(1670)$	227
$\pi_2(1670)$	10115, 10215
$\phi(1680)$	10333
$\rho_3(1690)$	117, 217
$\rho(1700)$	30113, 30213
$f_0(1710)$	60221
$\phi_3(1850)$	337
$f_2(2010)$	20225
$f_4(2050)$	229
$f_2(2300)$	30225
$f_2(2340)$	40225
K^+	321
K^0	311
K_S^0	310
K_L^0	130

MONTE CARLO PARTICLE NUMBERING SCHEME (Cont'd)

MESONS (Cont'd)

$K^*(892)$	313, 323
$K_1(1270)$	10313, 10323
$K_1(1400)$	20313, 20323
$K^*(1410)$	30313, 30323
$K_0^*(1430)$	10311, 10321
$K_2^*(1430)$	315, 325
$K^*(1680)$	40313, 40323
$K_2(1770)$	10315, 10325
$K_3^*(1780)$	317, 327
$K_4^*(2045)$	319, 329
D^+	411
D^0	421
$D^*(2010)^+$	413
$D^*(2010)^0$	423
$D_1(2420)^0$	10423
$D_2^*(2460)^0$	425
D_s^+	431
D_s^{*+}	433
$D_{s1}(2536)^+$	10433
B^+	521
B^0	511
B^*	513, 523
$\eta_c(1S)$	441
$J/\psi(1S)$	443
$\chi_{c0}(1P)$	10441
$\chi_{c1}(1P)$	10443
$\chi_{c2}(1P)$	445
$\psi(2S)$	20443
$\psi(3770)$	30443
$\psi(4040)$	40443
$\psi(4160)$	50443
$\psi(4415)$	60443
$\Upsilon(1S)$	553
$\chi_{b0}(1P)$	551
$\chi_{b1}(1P)$	10553
$\chi_{b2}(1P)$	555
$\Upsilon(2S)$	20553
$\chi_{b0}(2P)$	10551
$\chi_{b1}(2P)$	70553
$\chi_{b2}(2P)$	10555
$\Upsilon(3S)$	30553
$\Upsilon(4S)$	40553
$\Upsilon(10860)$	50553
$\Upsilon(11020)$	60553

BARYONS

p	P_{11}	2212
n	P_{11}	2112
$N(1440)$	P_{11}	12112, 12212
$N(1520)$	D_{13}	1214, 2124
$N(1535)$	S_{11}	22112, 22212
$N(1650)$	S_{11}	32112, 32212

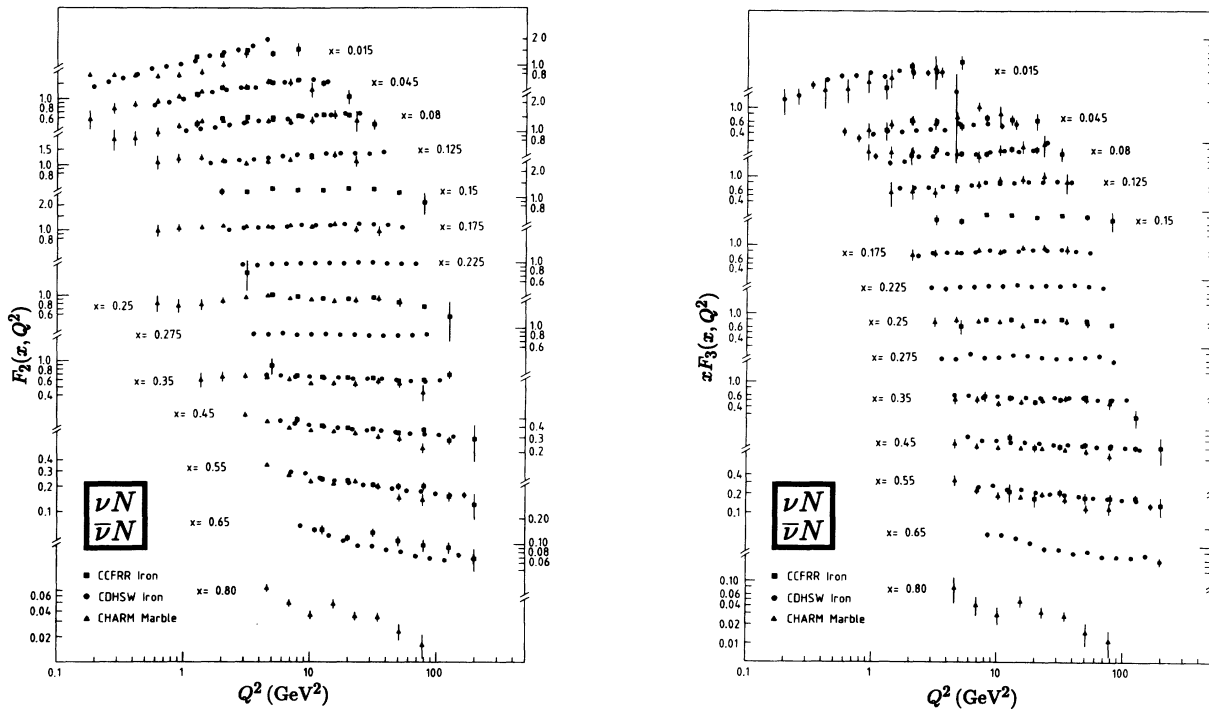
BARYONS (Cont'd)

$N(1675)$	D_{15}	2116, 2216
$N(1680)$	F_{15}	12116, 12216
$N(1700)$	D_{13}	21214, 22124
$N(1710)$	P_{11}	42112, 42212
$N(1720)$	P_{13}	31214, 32124
$N(2190)$	G_{17}	1218, 2128
$\Delta(1232)$	P_{33}	1114, 2114, 2214, 2224
$\Delta(1600)$	P_{33}	31114, 32114, 32214, 32224
$\Delta(1620)$	S_{31}	1112, 1212, 2122, 2222
$\Delta(1700)$	D_{33}	11114, 12114, 12214, 12224
$\Delta(1900)$	S_{31}	11112, 11212, 12122, 12222
$\Delta(1905)$	F_{35}	1116, 1216, 2126, 2226
$\Delta(1910)$	P_{31}	21112, 21212, 22122, 22222
$\Delta(1920)$	P_{33}	21114, 22114, 22214, 22224
$\Delta(1930)$	D_{35}	11116, 11216, 12126, 12226
$\Delta(1950)$	F_{37}	1118, 2118, 2218, 2228
Λ	P_{01}	3122
$\Lambda(1405)$	S_{01}	13122
$\Lambda(1520)$	D_{03}	3124
$\Lambda(1600)$	P_{01}	23122
$\Lambda(1670)$	S_{01}	33122
$\Lambda(1690)$	D_{03}	13124
$\Lambda(1800)$	S_{01}	43122
$\Lambda(1810)$	P_{01}	53122
$\Lambda(1820)$	F_{05}	3126
$\Lambda(1830)$	D_{05}	13126
$\Lambda(1890)$	P_{03}	23124
$\Lambda(2100)$	G_{07}	3128
$\Lambda(2110)$	F_{05}	23126
Σ^+	P_{11}	3222
Σ^0	P_{11}	3212
Σ^-	P_{11}	3112
$\Sigma(1385)$	P_{13}	3114, 3214, 3224
$\Sigma(1660)$	P_{11}	13112, 13212, 13222
$\Sigma(1670)$	D_{13}	13114, 13214, 13224
$\Sigma(1750)$	S_{11}	23112, 23212, 23222
$\Sigma(1775)$	D_{15}	3116, 3216, 3226
$\Sigma(1915)$	F_{15}	13116, 13216, 13226
$\Sigma(1940)$	D_{13}	23114, 23214, 23224
$\Sigma(2030)$	F_{17}	3118, 3218, 3228
Ξ^0	P_{11}	3322
Ξ^-	P_{11}	3312
$\Xi(1530)$	P_{13}	3314, 3324
$\Xi(1820)$	D_{13}	13314, 13324
Ω^-		3334
Λ_c^+		4122
$\Sigma_c(2455)$		4112, 4212, 4222
Ξ_c^+		4322
Ξ_c^0		4312
Ω_c^0		4332
Λ_b^0		5122

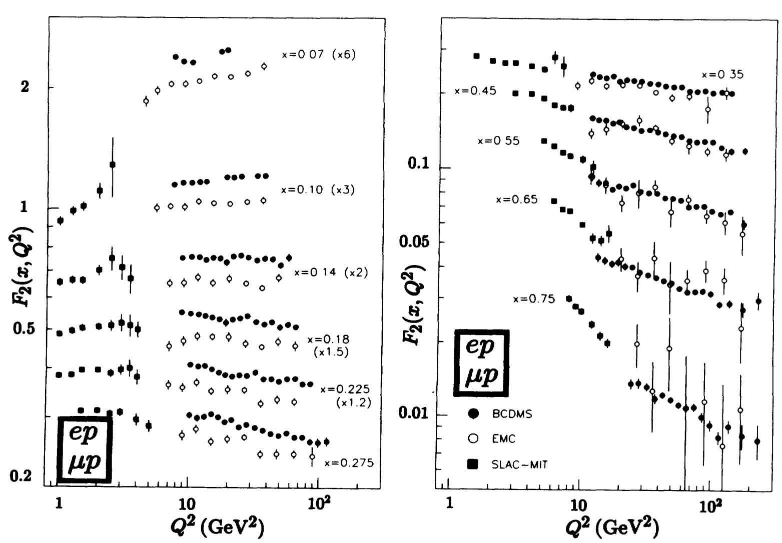
PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES

NOTE: THE FIGURES IN THIS SECTION ARE INTENDED TO SHOW THE "BEST" OR "MOST REPRESENTATIVE" DATA IN THE OPINION OF THE COMPILER. THEY ARE NOT NECESSARILY COMPLETE COMPILATIONS OF ALL THE WORLD'S RELIABLE DATA

Structure Functions



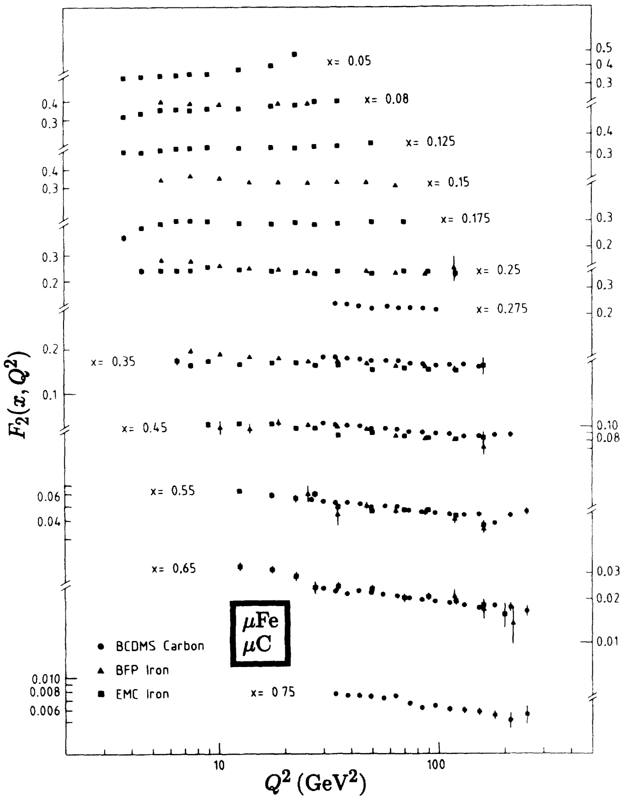
The nucleon structure functions F_2 and xF_3 measured in charged-current neutrino and antineutrino scattering on iron (CCFRR, CDHSW) and marble (CHARM) targets, versus Q^2, for fixed bins of x. Closed symbols are read on the right-hand scale, open symbols (appearing for alternate x values) on the left-hand scale. Only statistical errors are shown. $R = \sigma_L/\sigma_T = 0$ is used in the CHARM data, and a QCD-inspired parametrization for R is assumed in the CCFRR and CDHSW data. The CHARM measurements have not been corrected for the recalibration of the total neutrino and antineutrino cross sections in the CERN neutrino beam which was completed after the publication of these data. References: **CCFRR**—D.B. MacFarlane *et al.*, Z. Phys. **C26**, 1 (1984); **CDHSW**—P. Berge *et al.*, Z. Phys. **C49**, 187 (1991); **CHARM**—F. Bergsma *et al.*, Phys. Lett. **123B**, 269 (1983) and Phys. Lett. **141B**, 129 (1984).



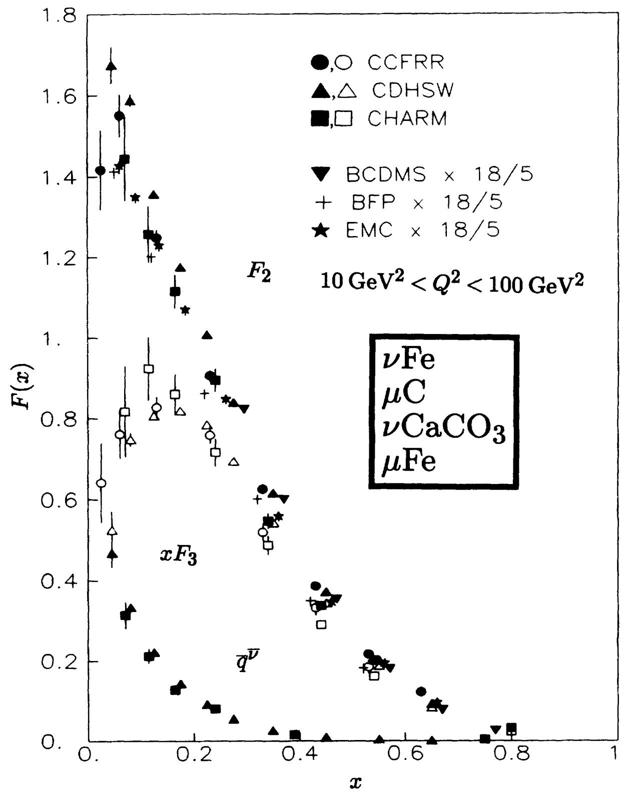
The proton structure function F_2^p measured in electromagnetic scattering of electrons (SLAC-MIT) and muons (BCDMS, EMC) on hydrogen targets, versus Q^2, for fixed bins of x. The data have been multiplied by the factors shown on the left-hand figure for convenience in plotting. Only statistical errors are shown. $R = \sigma_L/\sigma_T = 0.21$ is assumed in the SLAC-MIT data, $R = 0$ in the EMC data, and a QCD prediction for R in the BCDMS data. Where necessary, the SLAC-MIT and EMC data were interpolated to the x bins of the BCDMS data. Note that there are no SLAC-MIT data in the lowest x bin. References: **SLAC-MIT**—A. Bodek *et al.*, Phys. Rev. **D20**, 1471 (1979); **EMC**—J.J. Aubert *et al.*, Nucl. Phys. **B259**, 189 (1985); **BCDMS**—A.C. Benvenuti *et al.*, Phys. Lett. **B223**, 485 (1989).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

Structure Functions



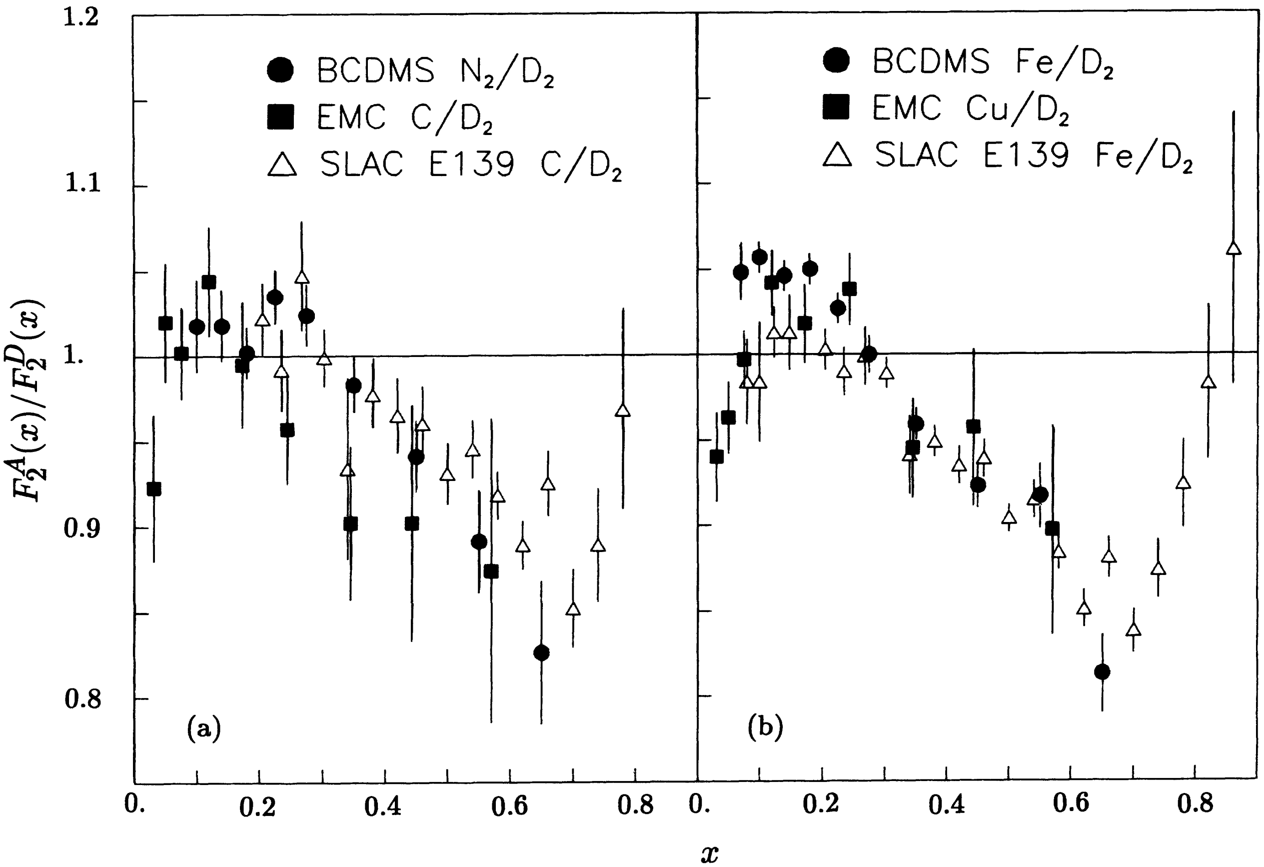
The nucleon structure function F_2 measured in electromagnetic scattering of muons on iron (BFP, EMC) and carbon (BCDMS) targets, versus Q^2, for fixed bins in x. For x of 0.05, 0.125, 0.175, 0.275, 0.45, and 0.65 use the right-hand scale; for all other bins of x, use the left-hand scale. Only statistical errors are shown. $R = \sigma_L/\sigma_T = 0$ is used in the BFP and a QCD prediction for R is assumed in the BCDMS and EMC data. References: **BCDMS**—A.C. Benvenuti *et al.*, Phys. Lett. **B195**, 91 (1987); **BFP**—P.D. Meyers *et al.*, Phys. Rev. **D34**, 1265 (1986); **EMC**—J.J. Aubert *et al.*, Nucl. Phys. **B272**, 158 (1986).



The structure functions F_2, xF_3, and $\overline{q}^{\overline{\nu}}$ measured in different experiments on isoscalar targets as functions of Bjorken x. The CCFRR, CDHSW, BFP, and EMC data were taken with iron targets; the CHARM data with a marble ($CaCO_3$) target; and the BCDMS data with a carbon target. Only statistical errors are shown. The CHARM and BFP collaborations assume $R = \sigma_L/\sigma_T = 0$, whereas a QCD prediction for R is assumed in the analysis of the CCFRR, CDHSW, BCDMS, and EMC data. The electromagnetic structure function $F_2^{\mu N}$ is compared to the charged-current structure function $F_2^{\nu N}$ correcting for the average squared quark charge 5/18. No corrections have been applied for the difference between the strange and charmed quark sea. References: **CCFRR**—D.B. MacFarlane *et al.*, Z. Phys. **C26**, 1 (1984); **CDHSW**—P. Berge *et al.*, Z. Phys. **C49**, 187 (1991); **CHARM**—F. Bergsma *et al.*, Phys. Lett. **123B**, 269 (1983) and Phys. Lett. **141B**, 129 (1984); **BCDMS**—A.C. Benvenuti *et al.*, Phys. Lett. **B195**, 91 (1987); **BFP**—P.D. Meyers *et al.*, Phys. Rev. **D34**, 1265 (1986); **EMC**—J.J. Aubert *et al.*, Nucl. Phys. **B272**, 158 (1986).

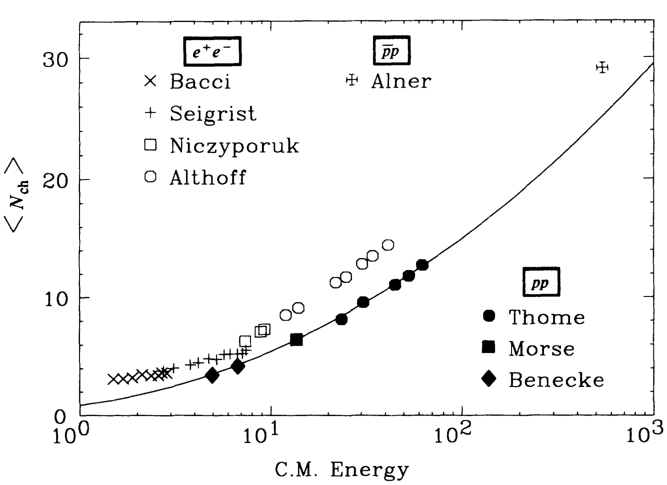
PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

"EMC" Effect



The ratio of nucleon structure functions $F_2^{\mathrm{A}}(x)/F_2^{\mathrm{D}}(x)$ for nuclear targets A compared to deuterium D, measured in deep inelastic electron (SLAC-E139) and muon (BCDMS, EMC) scattering: (a) medium-weight targets (A = N, C), (b) heavy targets (A = Fe, Cu). Only statistical errors are shown. The SLAC-E139 data were evaluated as cross section ratios $\sigma^{\mathrm{A}}/\sigma^{\mathrm{D}}$ but are equal to structure function ratios if $R = \sigma_L/\sigma_T$ is independent of A. References: **BCDMS**—G. Bari *et al.*, Phys. Lett. **163B**, 282 (1985); and A.C. Benvenuti *et al.*, Phys. Lett. **B189**, 483 (1987); **EMC**—J. Ashman *et al.*, Phys. Lett. **B202**, 603 (1988); **SLAC-E139**—R.G. Arnold *et al.*, Phys. Rev. Lett. **52**, 727 (1984); and SLAC-PUB-3257 (1983).

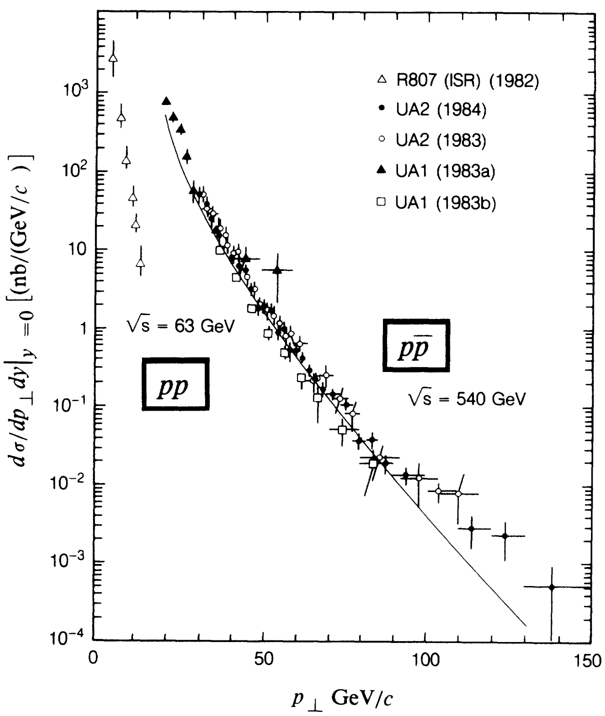
Average e^+e^-, pp, and $\bar{p}p$ Multiplicity



Average multiplicity as a function of $\sqrt{s}$ for $p\bar{p}$ at the S$\bar{p}p$S for pp at the ISR, (open circles) and for e^+e^-. Solid curve is a fit by Thomé *et al.* to their data (solid circles) with the form $\langle N_{ch}\rangle = 0.88 + 0.44 \ln\ s + 0.118\ (\ln\ s)^2$. e^+e^- data points have been combined to reduce overlap; errors (not shown) are dominated by 10%–25% systematic effects. References: $p\bar{p}$—G.J. Alner *et al.*, Phys. Lett. **138B**, 304 (1984); pp—W. Thomé *et al.*, Nucl. Phys. **B129**, 365 (1977); W.M. Morse *et al.*, Phys. Rev. **D15**, 66 (1977); and J. Benecke *et al.*, Nucl. Phys. **B76**, 29 (1974); e^+e^-—ADONE: C. Bacci *et al.*, Phys. Lett. **86B**, 234 (1979); MARK II: J.L. Siegrist *et al.*, Phys. Rev. **D26**, 969 (1982); LENA: B. Niczyporuk *et al.*, Z. Phys. **C9**, 1 (1981); and TASSO: M. Althoff *et al.*, Z. Phys. **C229**, 307 (1984).

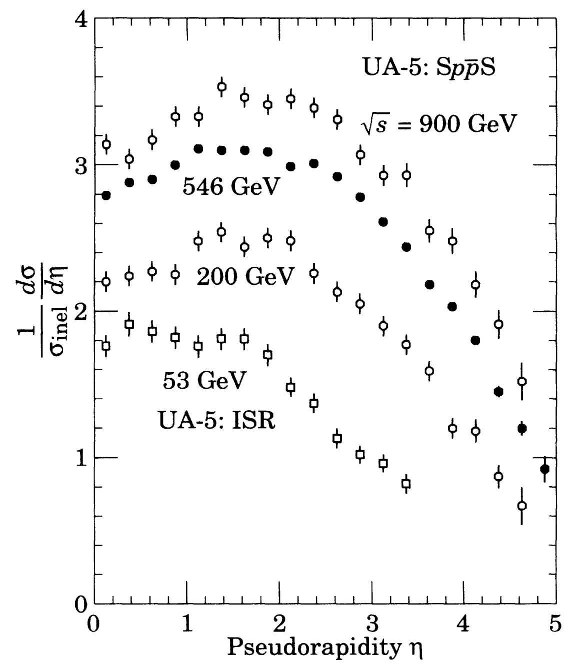
PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

Jet Production in pp and $\bar{p}p$ Interactions



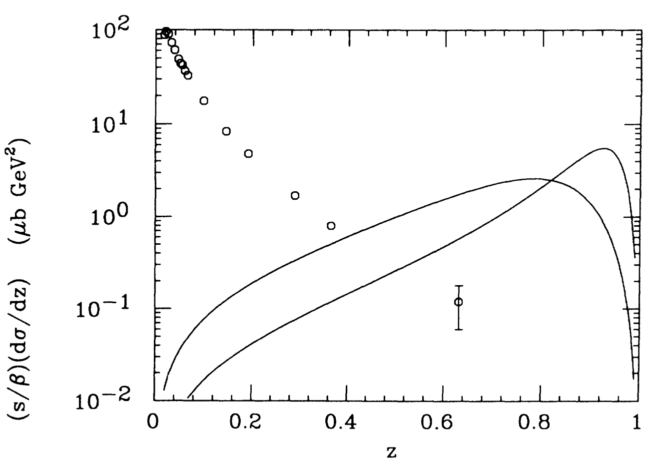
Differential cross sections for observation of a single jet of rapidity $y = 0$ as a function of the jet transverse momentum. ISR (pp) and S$\bar{p}p$S collider ($\bar{p}p$) data compared. Error bars include a contribution due to estimated systematic error in defining jet direction and p_T. Solid curve: QCD prediction; refer to the "Cross-Section Formulae for Specific Processes" section and the "Quantum Chromodynamics" section in the full-sized edition. References: **ISR**—T. Akesson *et al.*, Phys. Lett. **118B**, 185 (1982); **UA2**—P. Bagnaia *et al.*, Phys. Lett. **138B**, 430 (1984); and P. Bagnaia *et al.*, Z. Phys. **C20**, 117 (1983); **UA1**—G. Arnison *et al.*, Phys. Lett. **123B**, 115 (1983a); and G. Arnison *et al.*, Phys. Lett. **132B**, 144 (1983b).

Pseudorapidity Distributions in $\bar{p}p$ Interactions



Charge particle pseudorapidity distributions in $p\bar{p}$ collisions for 53 GeV $\leq \sqrt{s} \leq$ 900 GeV. The number per pseudorapidity interval is about 10% higher if the rate is normalized excluding singly diffractive events rather than to the total inelastic rate. S$p\bar{p}$S data are from G.J. Alner *et al.*, Z. Phys. **C33**, 1 (1986), and ISR data are from K. Alpgård *et al.*, Phys. Lett. **112B**, 193 (1982).

Fragmentation Function



The cross section $(s/\beta)\ d\sigma/dz$ versus z for producing a hadron h in e^+e^- annihilation, measured in different experiments, for fixed energies $Q^2 = s$. This quantity is closely related to the fragmentation function $D_i^h(z, Q^2)$ as discussed in the "Cross-Section Formulae for Specific Processes" section. Note that we use $z = (E + p_\parallel)_{\rm hadron}/(E + p_\parallel)_{\rm quark}$, whereas some experiments use $z' = E_{\rm hadron}/E_{\rm beam}$ or $z'' = p_{\rm hadron}/(E^2_{\rm beam} - m^2_{\rm had})^{1/2}$. The data are shown for pions (singlet term) measured by the TPC at 29 GeV; they actually used z'' — for $z > 0.05$ the difference between z and z'' can be neglected at those energies. The data for heavy quarks are frequently parametrized by the Peterson *et al.* form, $D(z) = Nz(1-z)^2/[(1-z)^2 + \epsilon_i z]^2$. The parameter ϵ for quark type i depends on $\sqrt{s}$ and upon the heavy quark mass. At $\sqrt{s} \sim 30$ GeV, $\epsilon_b = 0.006 \pm 0.002$, $\epsilon_c = 0.06^{+0.03}_{-0.015}$. Curves corresponding to these values (N is chosen arbitrarily) are shown on the figure. References: C. Peterson *et al.*, Phys. Rev. **D27**, 105 (1983); **TPC**—H. Aihara *et al.*, Z. Phys. **C27**, 495 (1985); and J. Chrin, Z. Phys. **C36**, 163 (1987).

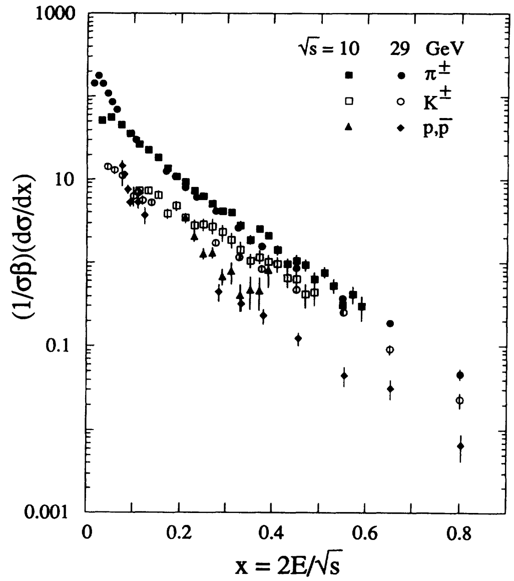
PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

Quark Fragmentation in Electron-Positron Annihilation

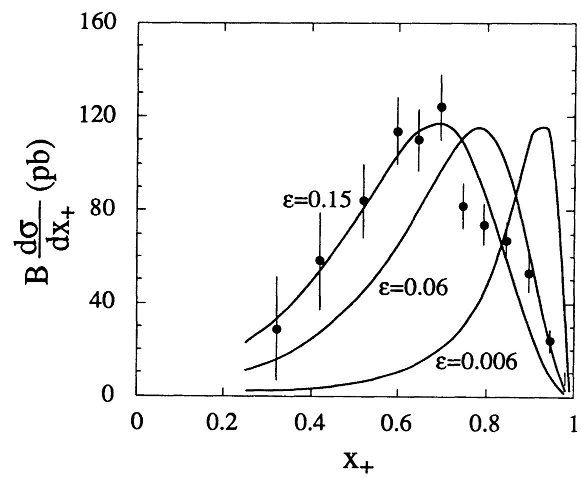
Average Hadron Multiplicities in e^+e^- Annihilation Events

	Particle	$\sqrt{s} \approx 10$ GeV	$\sqrt{s} = 29$ GeV
Pseudoscalar mesons	π^+	6.6 ± 0.2	10.3 ± 0.4
	π^0	3.2 ± 0.3	5.6 ± 0.3
	K^+	0.90 ± 0.04	1.48 ± 0.09
	K^0	0.91 ± 0.05	1.42 ± 0.07
	η	0.19 ± 0.06	0.60 ± 0.08
	$\eta\prime(958)$	—	0.26 ± 0.10
	D^+	0.16 ± 0.03	0.17 ± 0.03
	D^0	0.37 ± 0.06	0.45 ± 0.07
Vector mesons	$\rho(770)^0$	0.50 ± 0.09	0.81 ± 0.08
	$K^*(892)^+$	0.45 ± 0.08	0.64 ± 0.05
	$K^*(892)^0$	0.38 ± 0.09	0.56 ± 0.06
	$\phi(1020)$	0.045 ± 0.007	0.085 ± 0.011
	$D^*(2010)^+$	0.22 ± 0.04	0.43 ± 0.07
	$D^*(2010)^0$	0.23 ± 0.06	0.27 ± 0.11
Tensor mesons	$f_2(1270)$	—	0.14 ± 0.04
	$K_2^*(1430)^+$	—	0.09 ± 0.03
	$K_2^*(1430)^0$	—	0.12 ± 0.06
Baryons	p	0.28 ± 0.03	0.58 ± 0.05
	Λ	0.080 ± 0.013	0.214 ± 0.012
	Σ^0	0.023 ± 0.008	—
	$\Delta(1232)^{++}$	0.040 ± 0.010	—
	Ξ^-	0.0059 ± 0.0008	0.0178 ± 0.0036
	$\Sigma(1385)^{\pm}$	0.0107 ± 0.0020	0.035 ± 0.009
	Ω^-	0.0007 ± 0.0004	0.015 ± 0.007

Average hadron multiplicity per e^+e^- annihilation event at $\sqrt{s} \approx 10$ GeV. and $\sqrt{s} = 29$ GeV. The rates given include decay products from resonances with $c\tau, 10$ cm, and include charge conjugated states. References: W. Hofmann, Ann. Rev. Nucl. and Part. Sci. **38**, 279 (1988); and H.D. Saxon, in *High Energy Electron Positron Physics,* World Sci., p. 540 (1988); R. Marshall, RAL-89-021 (1989).

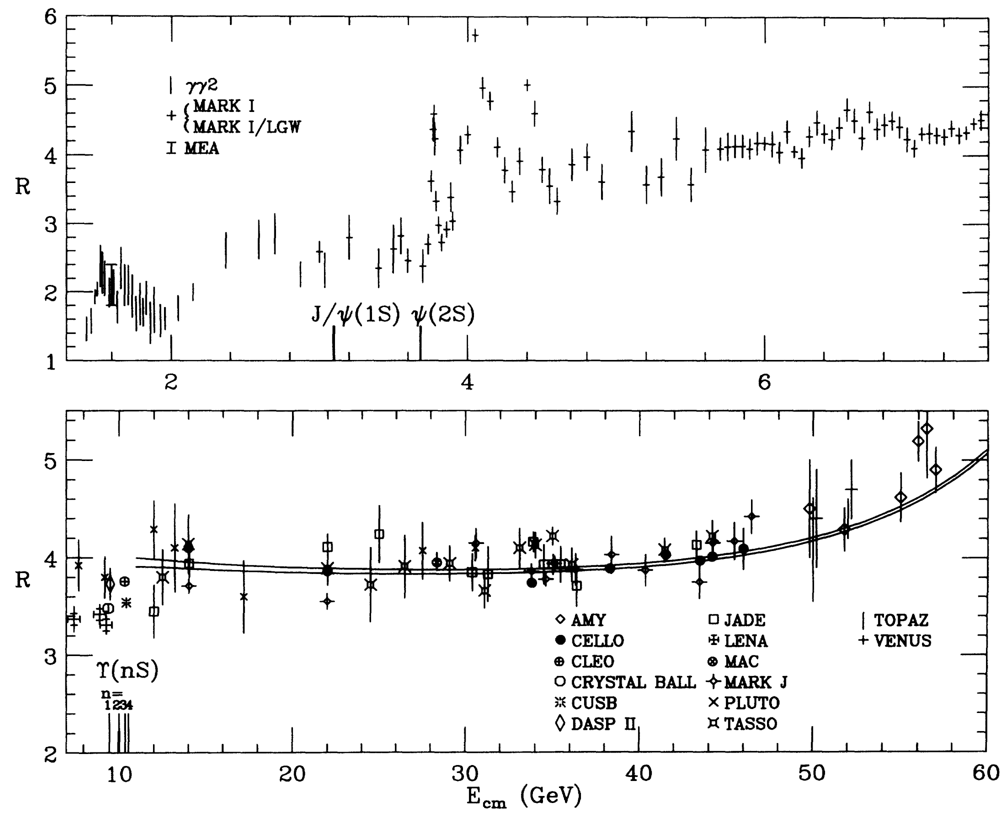


Fragmentation into light hadrons: Inclusive cross sections $(1/\sigma\beta)(d\sigma/dx)$ for production of charged hadrons (π, K, p) in e^+e^- annihilation at $\sqrt{s} \approx 10$ GeV and $\sqrt{s} = 29$ GeV, normalized to the total hadronic cross section, as a function of $x = 2E\sqrt{s}$. References: H. Aihara *et al.*, Phys. Rev. Lett. **61**, 1263 (1988); and H. Albrecht *et al.*, Z. Phys. **C44**, 547 (1989).



Heavy quark fragmentation: Inclusive cross section for the production of $D^*(2010)^+$ mesons in e^+e^- annihilation at $\sqrt{s} \approx 10$ GeV, as a function of the scaling variable $x_+ = (E+p)/(E+p)_{\text{kinem. limit}}$. Also shown is the Peterson *et al.* form, $d\sigma/dz \sim z(1-z)^2/[(1-z)^2+\epsilon z]^2$, for $\epsilon = 0.15$. We note that instead of the scaling variable x or x_+, some experiments prefer to define a scaling variable z as $z = (E+p_{\|})_{\text{had.}}/(E+p)_{\text{quark}}$, correcting for gluon radiation before the final fragmentation. With this definition at $\sqrt{s} \approx 30$ GeV, $\langle z_C\rangle = 0.67 \pm 0.03$ $\langle z_B\rangle = 0.83 \pm 0.03$, corresponding to $\epsilon_C = 0.06^{+0.03}_{-0.02}$ and $\epsilon_B = 0.006 \pm 0.002$. The corresponding Peterson shapes are included here. References: D. Bortoletto *et al.*, Phys. Rev. **D37**, 1719 (1988); J. Chrin, Z. Phys. **C36**, 163 (1987); and C. Peterson *et al.*, Phys. Rev. **D27**, 105 (1983).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

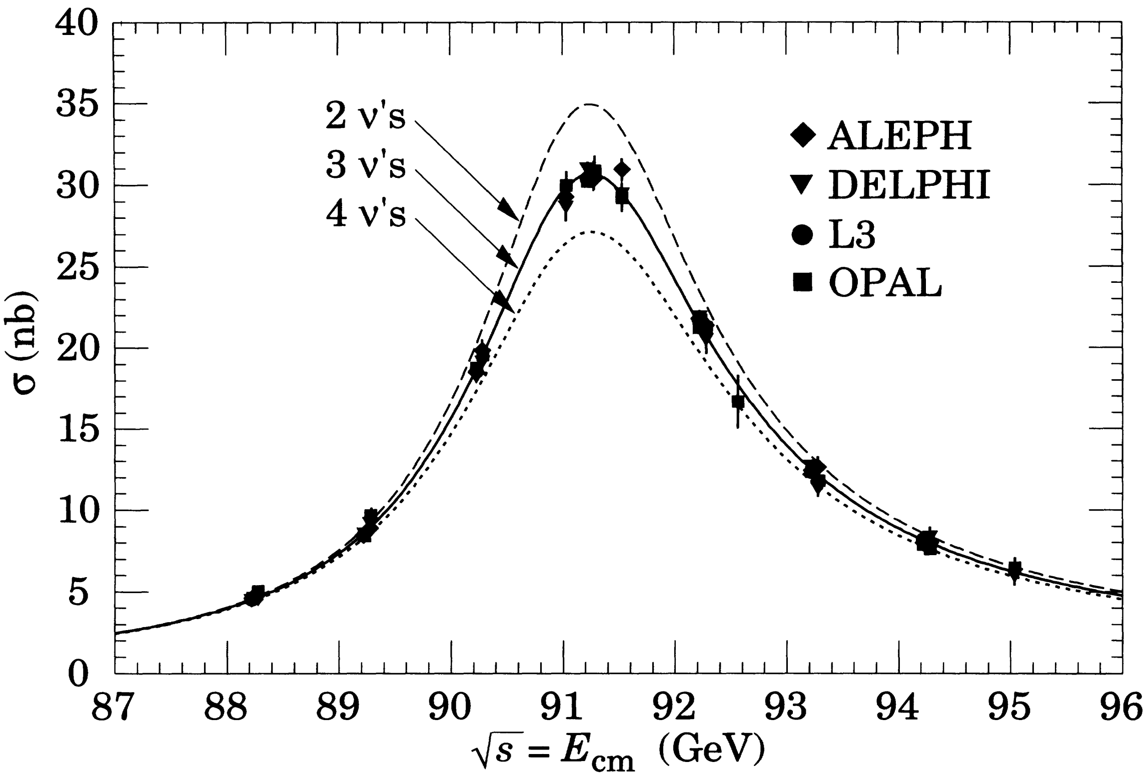


Selected measurements of $R \equiv \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$, where the annihilation in the numerator proceeds via one photon or via the Z^0. Measurements in the vicinity of the Z^0 mass are shown in the following figure. The denominator is the calculated QED single-photon process; see the section on Cross-Section Formulae for Specific Processes. Radiative corrections and, where important, corrections for two-photon processes and τ production have been made. Note that the ADONE data ($\gamma\gamma 2$ and MEA) is for ≥ 3 hadrons. The points in the $\psi(3770)$ region are from the MARK I—Lead Glass Wall experiment. To preserve clarity only a representative subset of the available measurements is shown—references to additional data are included below. Also for clarity, some points have been combined or shifted slightly ($< 4\%$) in $E_{\rm cm}$, and some points with low statistical significance have been omitted. Systematic normalization errors are not included; they range from ~5–20%, depending on experiment. We caution that especially the older experiments tend to have large normalization uncertainties. Note the suppressed zero. The horizontal extent of the plot symbols has no significance. The positions of the $J/\psi(1S)$, $\psi(2S)$, and the four lowest Υ vector-meson resonances are indicated. Two curves are overlaid for $E_{\rm cm} > 11$ GeV, showing the theoretical prediction for R, including higher order QCD [M. Dine and J. Sapirstein, Phys. Rev. Lett. **43**, 668 (1979)] and electroweak corrections. The Λ values are for 5 flavors in the $\overline{\rm MS}$ scheme and are $\Lambda^{(5)}_{\overline{\rm MS}} = 60$ MeV (lower curve) and $\Lambda^{(5)}_{\overline{\rm MS}} = 250$ MeV (upper curve). References (including several references to data not appearing in the figure and some references to preliminary data):

AMY: T. Mori *et al.*, Phys. Lett. **B218**, 499 (1989);
CELLO: H.-J. Behrend *et al.*, Phys. Lett. **144B**, 297 (1984); and H.-J. Behrend *et al.*, Phys. Lett. **183B**, 400 (1987);
CLEO: R. Giles *et al.*, Phys. Rev. **D29**, 1285 (1984); and D. Besson *et al.*, Phys. Rev. Lett. **54**, 381 (1985);
CUSB: E. Rice *et al.*, Phys. Rev. Lett. **48**, 906 (1982);
CRYSTAL BALL: A. Osterheld *et al.*, SLAC-PUB-4160; and Z. Jakubowski *et al.*, Z. Phys. **C40**, 49 (1988);
DASP: R. Brandelik *et al.*, Phys. Lett. **76B**, 361 (1978);
DASP II: Phys. Lett. **116B**, 383 (1982);
DCI: G. Cosme *et al.*, Nucl. Phys. **B152**, 215 (1979);
DHHM: P. Bock *et al.* (DESY-Hamburg-Heidelberg-MPI München Collab.), Z. Phys. **C6**, 125 (1980);
γγ2: C. Bacci *et al.*, Phys. Lett. **86B**, 234 (1979);
HRS: D. Bender *et al.*, Phys. Rev. **D31**, 1 (1985);
JADE: W. Bartel *et al.*, Phys. Lett. **129B**, 145 (1983); and W. Bartel *et al.*, Phys. Lett. **160B**, 337 (1985);
LENA: B. Niczyporuk *et al.*, Z. Phys. **C15**, 299 (1982).
MAC: E. Fernandez *et al.*, Phys. Rev. **D31**, 1537 (1985);
MARK J: B. Adeva *et al.*, Phys. Rev. Lett. **50**, 799 (1983); and B. Adeva *et al.*, Phys. Rev. **D34**, 681 (1986);
MARK I: J.L. Siegrist *et al.*, Phys. Rev. **D26**, 969 (1982);
MARK I + Lead Glass Wall: P.A. Rapidis *et al.*, Phys. Rev. Lett. **39**, 526 (1977); and P.A. Rapidis, thesis, SLAC-Report-220 (1979);
MARK II: J. Patrick, Ph.D. thesis, LBL-14585 (1982);
MEA: B. Esposito *et al.*, Lett. Nuovo Cimento **19**, 21 (1977);
PLUTO: A. Bäcker, thesis Gesamthochschule Siegen, DESY F33-77/03 (1977); C. Gerke, thesis, Hamburg Univ. (1979); Ch. Berger *et al.*, Phys. Lett. **81B**, 410 (1979); and W. Lackas, thesis, RWTH Aachen, DESY Pluto-81/11 (1981);
TASSO: R. Brandelik *et al.*, Phys. Lett. **113B**, 499 (1982); and M. Althoff *et al.*, Phys. Lett. **138B**, 441 (1984);
TOPAZ: I. Adachi *et al.*, Phys. Rev. Lett. **60**, 97 (1988);
and **VENUS**: H. Yoshida *et al.*, Phys. Lett. **198B**, 570 (1987).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

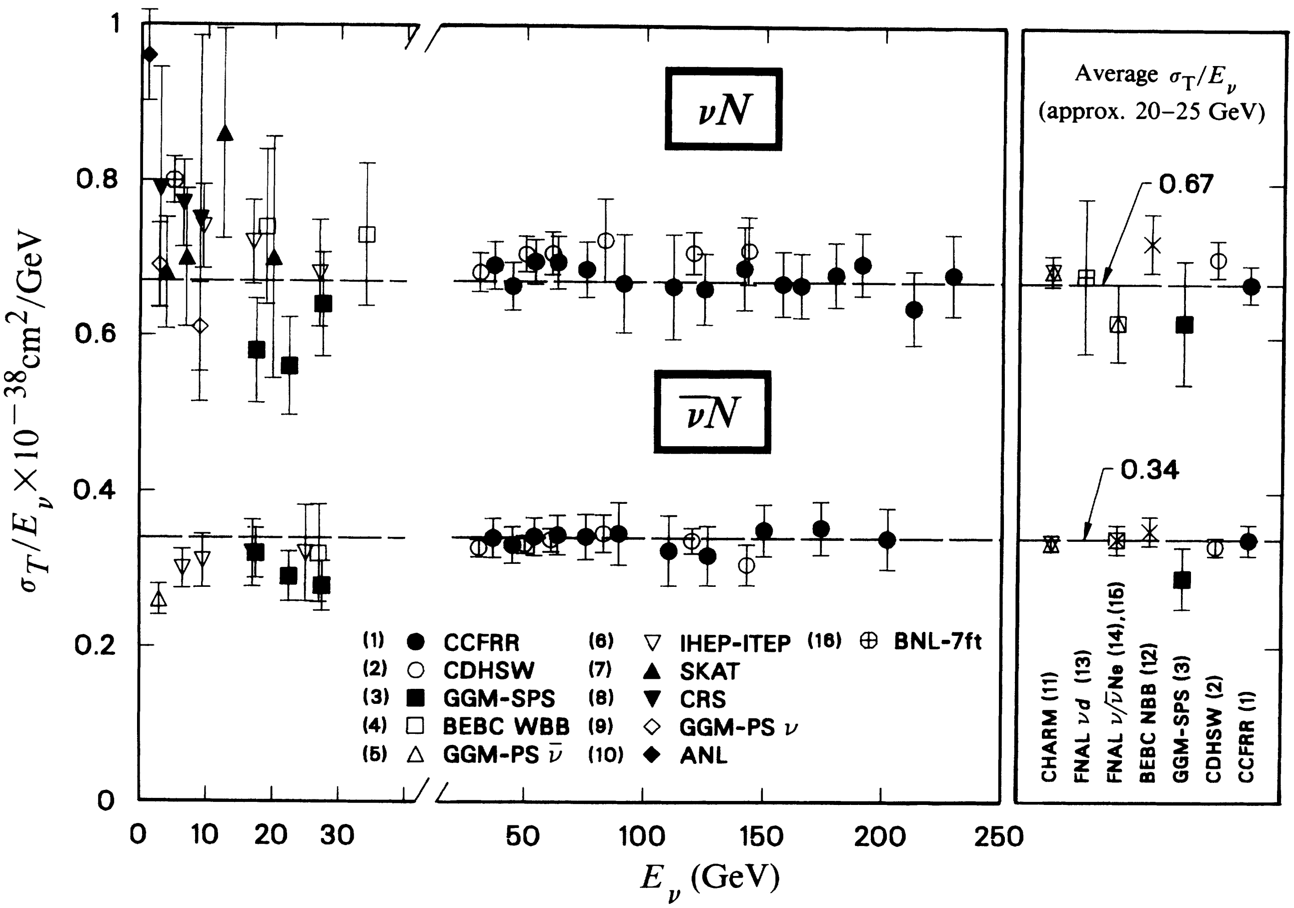
e^+e^- Annihilation Cross Section in Vicinity of M_Z



Data from the Mark II, ALEPH, DELPHI, L3, and OPAL Collaborations (Refs. 1–4) for the cross section in e^+e^- annihilation into hadronic final states as a function of c.m. energy near the Z. LEP detectors obtained data at the same energies; some of the points are obscured by overlap. The curves show the predictions of the Standard Model with three species (solid curve) and four species (dashed curve) of light neutrinos. The asymmetry of the curves is produced by initial-state radiation.

1. ALEPH—D. Decamp *et al.*, Z. Phys. **C53**, 1 (1992).
2. DEPHI—P. Abreu *et al.*, Nucl. Phys. **B367**, 511 (1992).
3. L3—B. Adeva *et al.*, Z. Phys. **C51**, 179 (1991).
4. OPAL—G. Alexander *et al.*, Z. Phys. **C52**, 175 (1991).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)



σ_T/E_ν for the muon neutrino and antineutrino charged-current total cross section as a function of neutrino energy. The error bars include both statistical and systematic errors. The straight lines are averages for the CCFRR measurement. Note the change in the energy scale between 30 and 50 GeV. The data points on the right give averages for other high energy measurements. Courtesy M.H. Shaevitz, Columbia University (Nevis Laboratory).

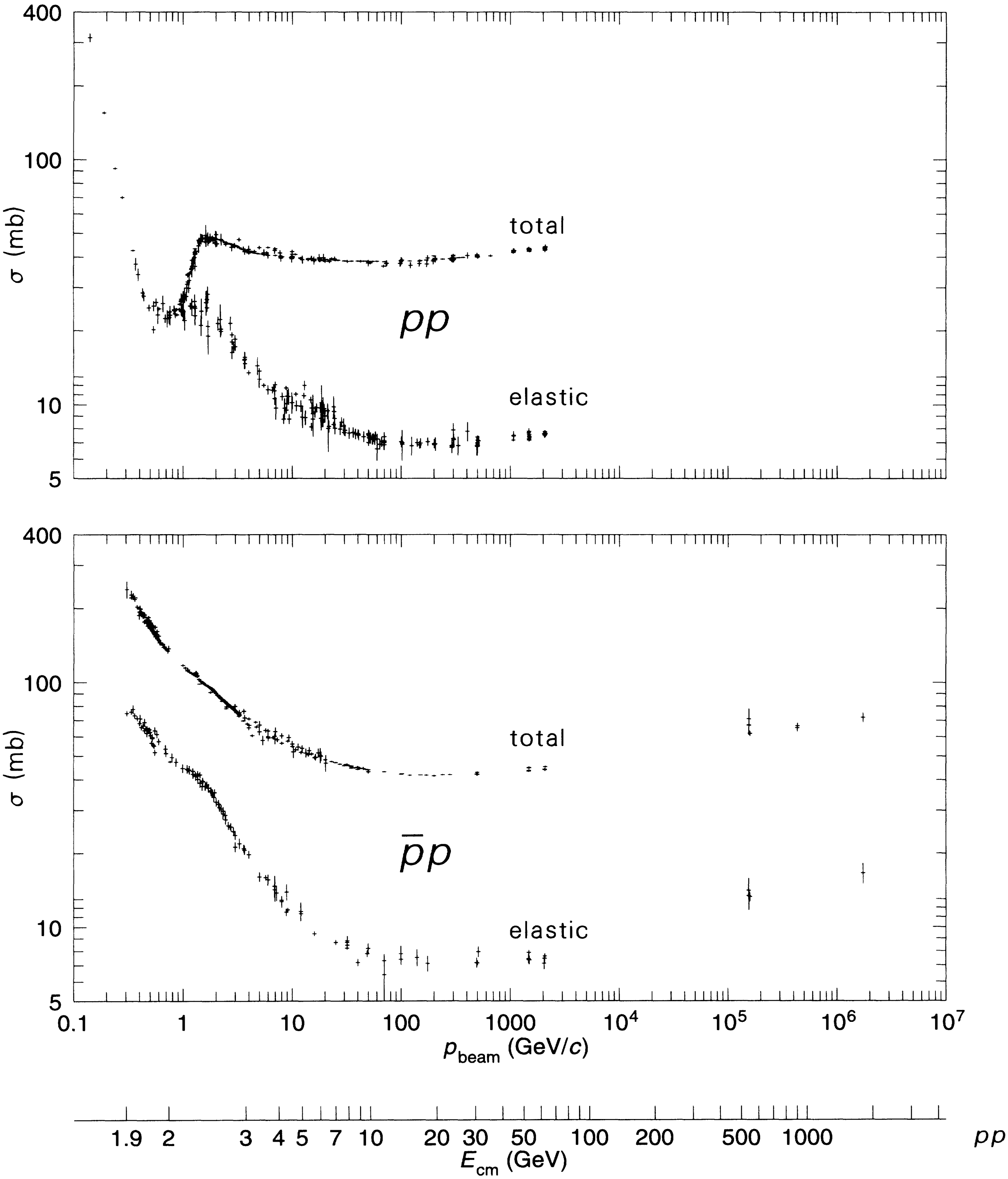
(1) D.B. MacFarlane *et al.*, Z. Phys. **C26**, 1 (1984);
(2) P. Berge *et al.*, Z. Phys. **C35**, 443 (1987);
(3) J. Morfin *et al.*, Phys. Lett. **104B**, 235 (1981);
(4) D.C. Colley *et al.*, Z. Phys. **C2**, 187 (1979);
(5) O. Erriquez *et al.*, Phys. Lett. **80B**, 309 (1979);
(6) A.S. Vovenko *et al.*, Sov. Jour. Nucl. Phys. **30**, 527 (1979);
(7) D.S. Baranov *et al.*, Phys. Lett. **81B**, 255 (1979);
(8) C. Baltay *et al.*, Phys. Rev. Lett. **44**, 916 (1980);
(9) S. Ciampolillo *et al.*, Phys. Lett. **84B**, 281 (1979);
(10) S.J. Barish *et al.*, Phys. Rev. **D19**, 2521 (1979);
(11) J.V. Allaby *et al.*, Z. Phys. **C38**, 403 (1988), E_ν = 10–160 GeV;
(12) P. Bosetti *et al.*, Phys. Lett. **110B**, 167 (1982), E_ν = 20–200 GeV, as revised in M. Aderholz *et al.*, Phys. Lett. **173B**, 211 (1986);
(13) T. Kitagaki *et al.*, Phys. Rev. Lett. **49**, 98 (1982), E_ν = 10–200 GeV;
(14) N.J. Baker *et al.*, Phys. Rev. Lett. **51**, 735 (1983), E_ν = 10–240 GeV;
(15) G.N. Taylor *et al.*, Phys. Rev. Lett. **51**, 739 (1983), E_ν = 5–250 GeV;
(16) N.J. Baker *et al.*, Phys. Rev. **D25**, 617 (1982), E_ν = 1.6–10 GeV.

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

Extensively revised 1991 by A. Baldini, V. Flaminio, and O. Yushchenko. The CERN-HERA and COMPAS Groups have made least-squares fits to many high-energy cross sections. The parametrization is $\sigma(p) = A + Bp^n + C\ln^2(p) + D\ln(p)$, where σ is in mb and p is in GeV/c. The best-fit coefficients A, B, C, and D, and the exponent n are tabulated below; where indicated, not all the terms in $\sigma(p)$ are included in the fit. The errors on the parameters are highly correlated since the terms in $\sigma(p)$ are far from orthogonal. Also given is the range of momentum over which the fit was done; extrapolation outside this range is likely to give incorrect results.

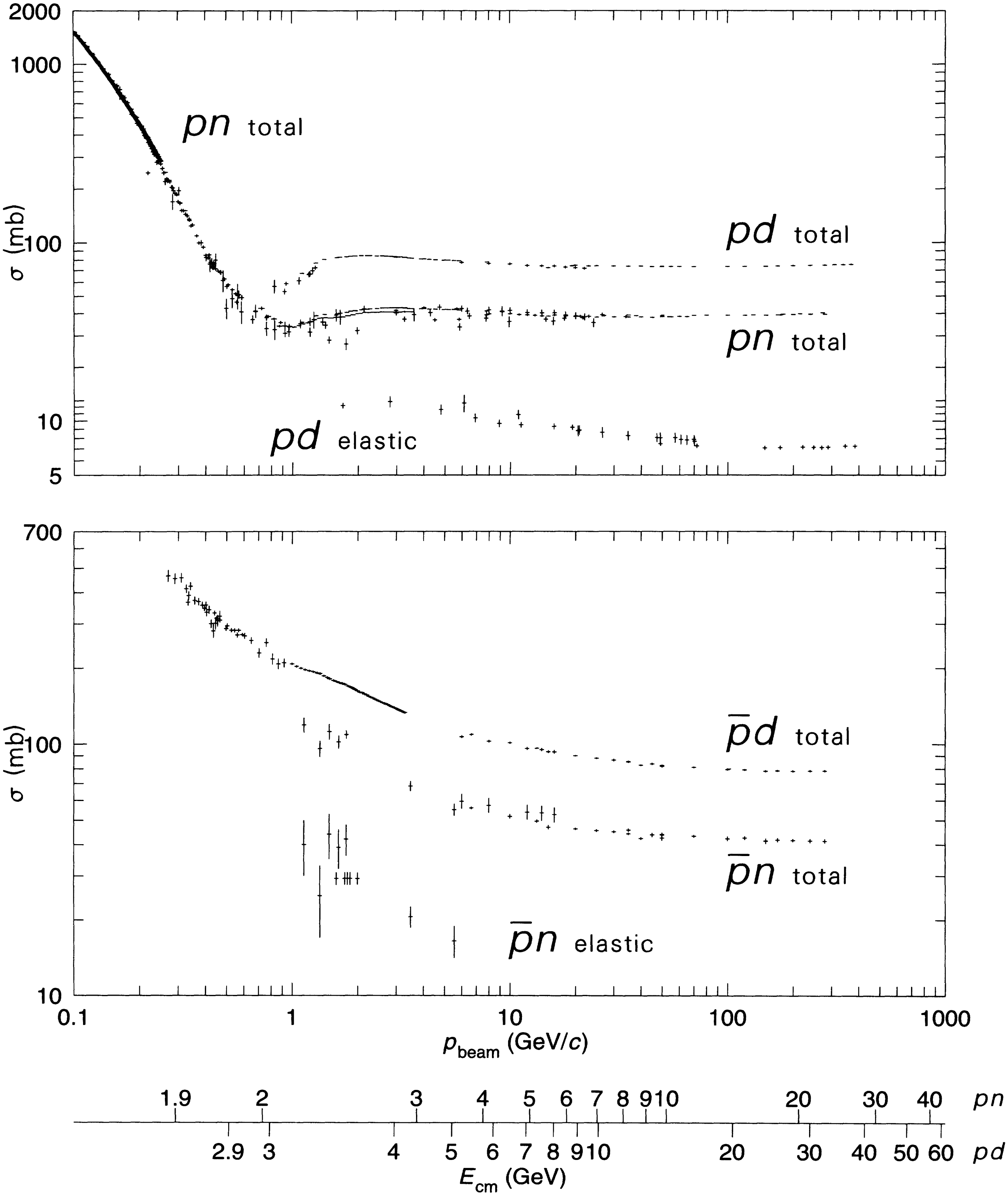
Reaction	Momentum range (GeV/c)	Fitted parameters A	B	n	C	D
γp total	3.0–183	0.147 ± 0.001	—	—	0.0022 ± 0.0001	-0.0170 ± 0.0007
γd total	2.0–17.8	0.300 ± 0.005	—	—	0.0095 ± 0.0020	-0.057 ± 0.007
$\pi^+ p$ total	4.0–340	16.4 ± 1.2	19.3 ± 0.8	-0.42 ± 0.05	0.19 ± 0.02	—
$\pi^+ p$ elastic	2.0–200	—	11.4 ± 0.3	-0.4 ± 0.2	0.079 ± 0.005	—
$\pi^- p$ total	2.5–370	33.0 ± 1.2	14.0 ± 1.8	-1.36 ± 0.29	0.456 ± 0.049	-4.03 ± 0.48
$\pi^- p$ elastic	2.0–360	1.76 ± 0.42	11.2 ± 0.3	-0.64 ± 0.07	0.043 ± 0.011	—
$\pi^\pm d$ total	2.5–370	56.8 ± 3.6	42.2 ± 8.4	-1.45 ± 0.38	0.65 ± 0.14	-5.39 ± 1.43
$K^+ p$ total	2.0–310	18.1 ± 0.1	—	—	0.26 ± 0.03	-1.0 ± 0.1
$K^+ p$ elastic	2.0–175	5.0 ± 1.2	8.1 ± 1.5	-1.8 ± 0.7	0.16 ± 0.06	-1.3 ± 0.5
$K^+ n$ total	2.0–310	18.7 ± 0.2	—	—	0.21 ± 0.02	-0.89 ± 0.14
$K^+ d$ total	2.0–310	34.2 ± 1.2	7.9 ± 3.8	-2.1 ± 1.1	0.346 ± 0.074	-0.99 ± 0.61
$K^- p$ total	3.0–310	32.1 ± 0.2	—	—	0.66 ± 0.01	-5.6 ± 0.1
$K^- p$ elastic	3.0–175	7.3 ± 0.1	—	—	0.29 ± 0.01	-2.40 ± 0.09
$K^- n$ total	1.8–310	25.2 ± 0.5	—	—	0.38 ± 0.03	-2.9 ± 0.3
$K^- d$ total	3.0–310	57.6 ± 0.4	—	—	1.17 ± 0.03	-9.5 ± 0.2
pp total	3.0–2100	48.0 ± 0.1	—	—	0.522 ± 0.005	-4.51 ± 0.05
pp elastic	2.0–2100	11.9 ± 0.8	26.9 ± 1.7	-1.21 ± 0.11	0.169 ± 0.021	-1.85 ± 0.26
pn total	3.0–370	47.30 ± 0.17	—	—	0.513 ± 0.023	-4.27 ± 0.15
pd total	3.0–370	91.3 ± 0.2	—	—	1.05 ± 0.03	-8.8 ± 0.2
pd elastic	2.0–384	16.1 ± 0.7	—	—	0.32 ± 0.04	-3.4 ± 0.4
$\bar{p}p$ total	5.0–1.73×10^6	38.4 ± 4.4	77.6 ± 2.8	-0.64 ± 0.07	0.26 ± 0.05	-1.2 ± 0.9
$\bar{p}p$ elastic	5.0–1.73×10^6	10.2 ± 0.7	52.7 ± 1.8	-1.16 ± 0.05	0.125 ± 0.014	-1.28 ± 0.20
$\bar{p}n$ total	1.1–280	—	133.6 ± 4.6	-0.70 ± 0.03	-1.22 ± 0.13	13.7 ± 0.7
$\bar{p}n$ elastic	1.1–5.55	36.5 ± 1.5	—	—	—	-11.9 ± 1.8
$\bar{p}d$ total	2.0–280	112 ± 13	125 ± 8	-1.08 ± 0.15	1.14 ± 0.49	-12.4 ± 4.9
Λp total	0.6–21	30.4 ± 2.7	—	—	—	1.6 ± 1.0
Λp elastic	0.6–24	12.3 ± 0.9	—	—	—	-2.4 ± 0.5

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)



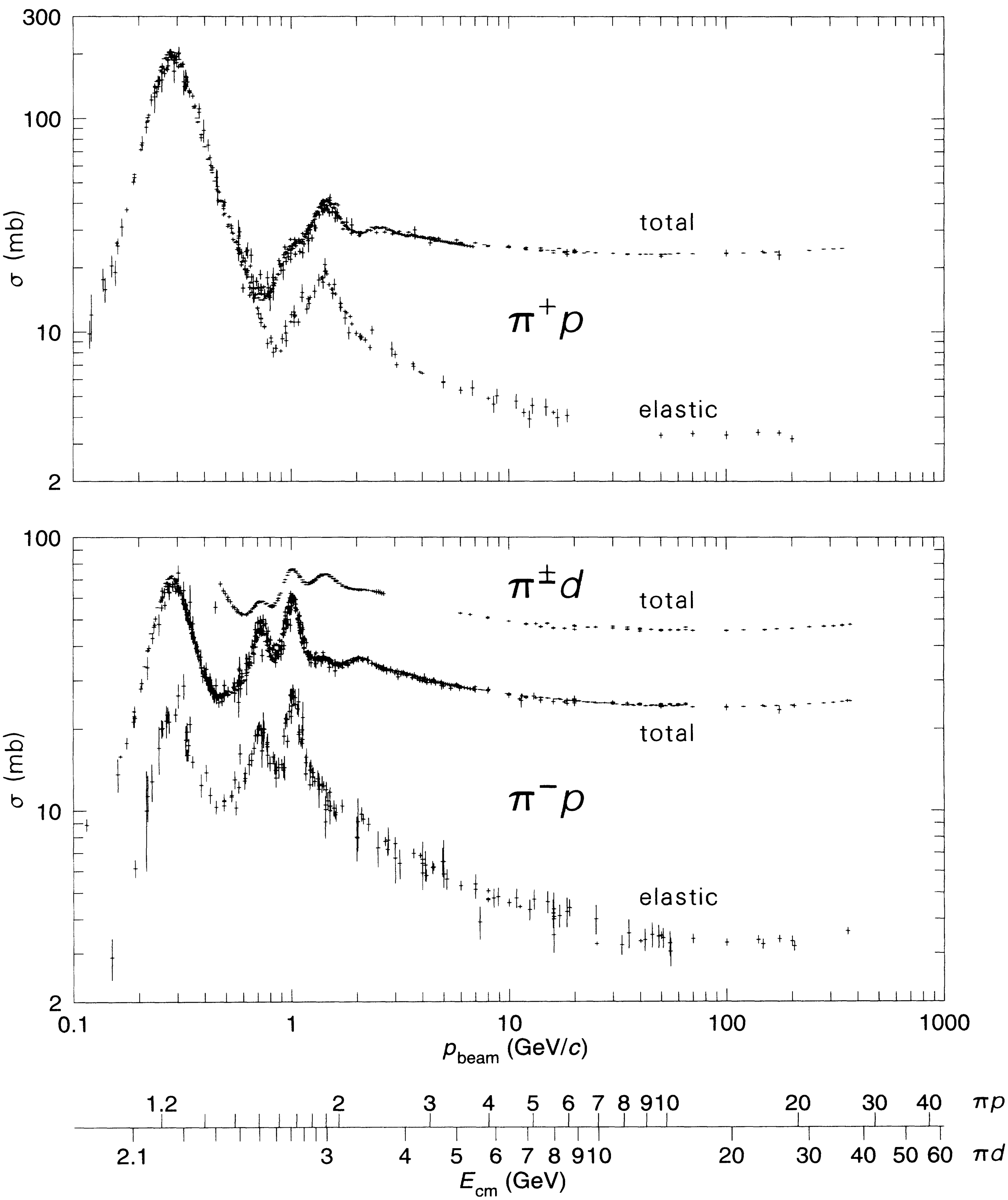
Hadronic total and elastic cross sections vs. laboratory beam momentum and total center-of-mass energy. Data courtesy A. Baldini, V. Flaminio, W.G. Moorhead, and D.R.O. Morrison, CERN; and COMPAS Group, IHEP, Serpukhov, USSR. See *Total Cross Sections for Reactions of High Energy Particles*, Landolt-Börnstein, New Series Vol. **I/12 a** and **I/12 b**, ed. H. Schopper (1988).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)



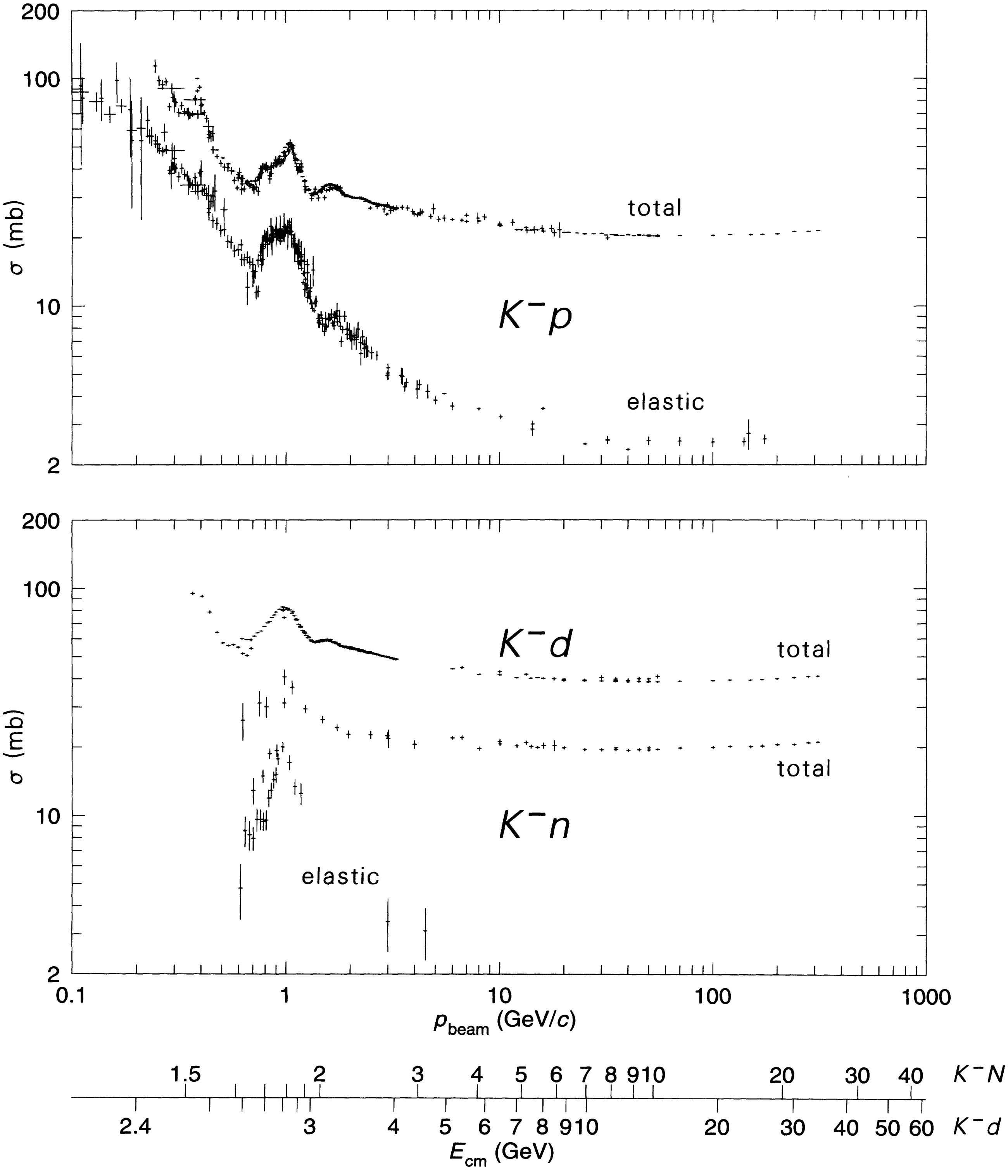
Hadronic total and elastic cross sections vs. laboratory beam momentum and total center-of-mass energy. Data courtesy A. Baldini, V. Flaminio, W.G. Moorhead, and D.R.O. Morrison, CERN; and COMPAS Group, IHEP, Serpukhov, USSR. See *Total Cross Sections for Reactions of High Energy Particles*, Landolt-Börnstein, New Series Vol. **I/12 a** and **I/12 b**, ed. H. Schopper (1988).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

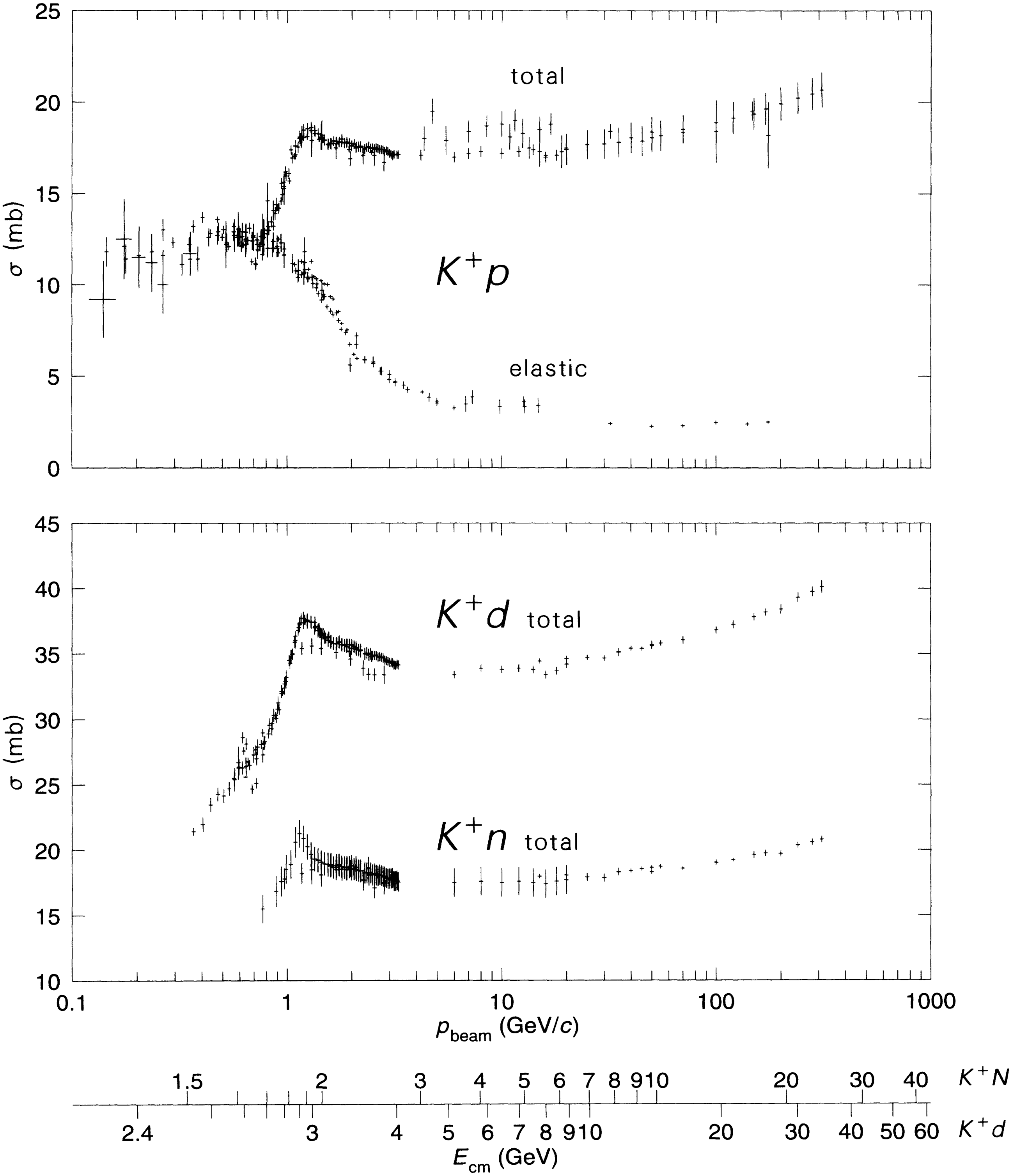


Hadronic total and elastic cross sections vs. laboratory beam momentum and total center-of-mass energy. Data courtesy A. Baldini, V. Flaminio, W.G. Moorhead, and D.R.O. Morrison, CERN; and COMPAS Group, IHEP, Serpukhov, USSR. See *Total Cross Sections for Reactions of High Energy Particles*, Landolt-Börnstein, New Series Vol. **I/12 a** and **I/12 b**, ed. H. Schopper (1988).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

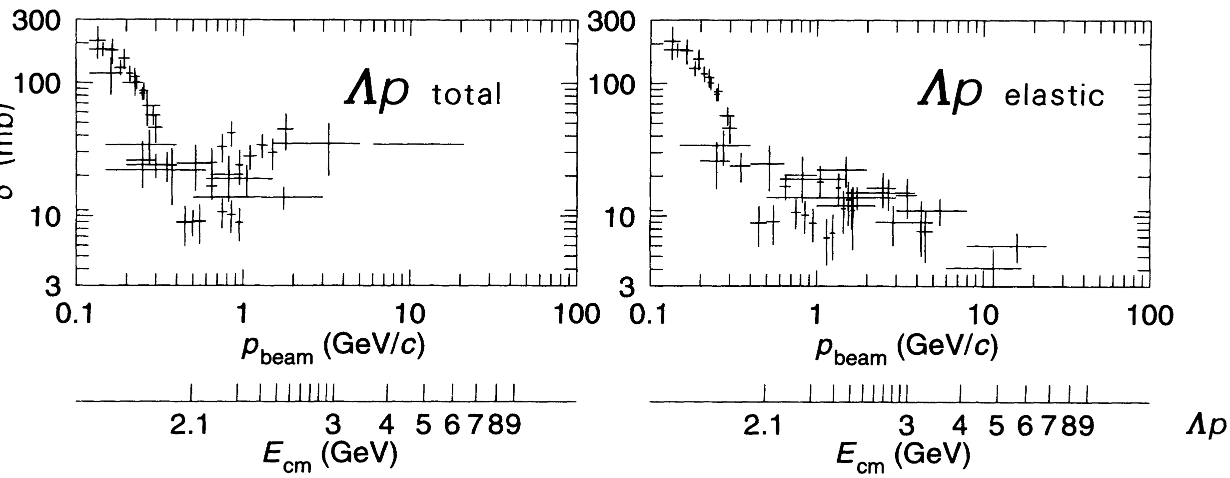


Hadronic total and elastic cross sections vs. laboratory beam momentum and total center-of-mass energy. Data courtesy A. Baldini, V. Flaminio, W.G. Moorhead, and D.R.O. Morrison, CERN; and COMPAS Group, IHEP, Serpukhov, USSR. See *Total Cross Sections for Reactions of High Energy Particles*, Landolt-Börnstein, New Series Vol. **I/12 a** and **I/12 b**, ed. H. Schopper (1988).

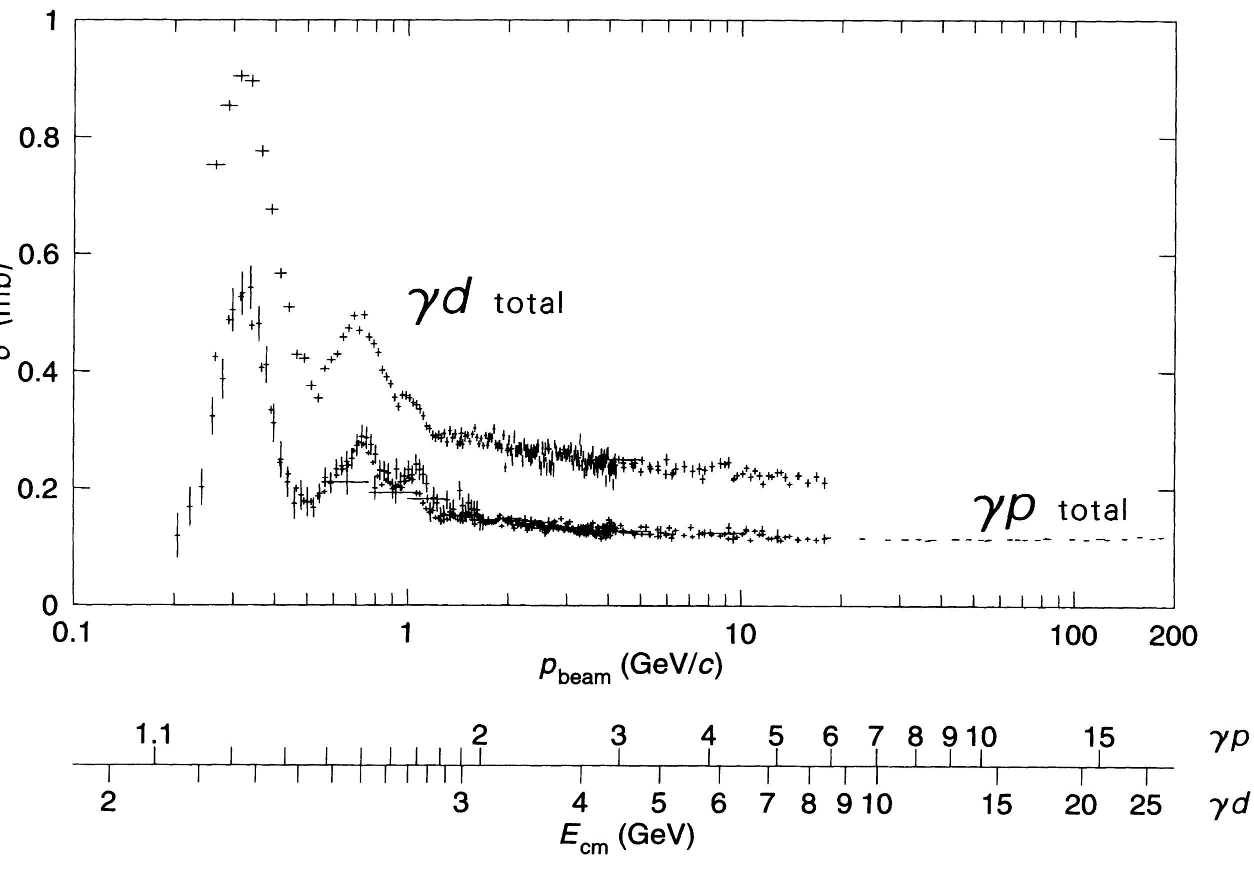


Hadronic total and elastic cross sections vs. laboratory beam momentum and total center-of-mass energy. Data courtesy A. Baldini, V. Flaminio, W.G. Moorhead, and D.R.O. Morrison, CERN; and COMPAS Group, IHEP, Serpukhov, USSR. See *Total Cross Sections for Reactions of High Energy Particles*, Landolt-Börnstein, New Series Vol. **I/12 a** and **I/12 b**, ed. H. Schopper (1988).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)



Λp total and elastic cross sections vs. laboratory beam momentum and total center-of-mass energy. Data courtesy A. Baldini, V. Flaminio, W.G. Moorhead, and D.R.O. Morrison, CERN; and COMPAS Group, IHEP, Serpukhov, USSR. See *Total Cross Sections for Reactions of High Energy Particles*, Landolt-Börnstein, New Series Vol. **I/12 a** and **I/12 b**, ed. H. Schopper (1988).



Photon cross sections vs. laboratory beam momentum and total center-of-mass energy. Data courtesy A. Baldini, V. Flaminio, W.G. Moorhead, and D.R.O. Morrison, CERN; COMPAS Group, IHEP, Serpukhov, USSR; and G.M. Lewis, Glasgow. See *Total Cross Sections for Reactions of High Energy Particles*, Landolt-Börnstein, New Series Vol. **I/12 a** and **I/12 b**, ed. H. Schopper (1988).

INTRODUCTION TO THE FULL LISTINGS

Illustrative Key to the Full Listings

Name of particle. "Old" name used before 1986 renaming scheme also given if different. See the section "Naming Scheme for Hadrons" for details.

Quantity tabulated below.

Top line gives our best value (and error) of quantity tabulated here, based on weighted average of measurements used. Could also be from fit, best limit, estimate, or other evaluation. See next page for details.

Footnote number linking measurement to text of footnote.

Number of events *above background.*

Measured value used in averages, fits, limits, etc.

Error in measured value (often statistical only; followed by systematic if separately known; the two are combined in quadrature for averaging and fitting.)

Measured value *not used* in averages, fits, limits, etc. See the Introductory Text for explanations.

Top "data point" indicates average. Width of error bar (and shaded pattern below) is ±error on average, scaled by "scale factor" S.

Value and error for each experiment.

Partial decay mode (labeled by Γ_i).

Branching ratio.

Our best value (and error) of quantity tabulated, as determined from constrained fit (using *all significant* measured branching ratios for this particle).

Weighted average of measurements of this ratio only.

Footnote (referring to LYNCH 81).

Confidence level for measured upper limit.

References, ordered inversely by year, then author.

"Document id" used on data entries above.

Journal, report, preprint, etc. (See abbreviations on next page.)

$a_0(1200)$ $\quad I^G(J^{PC}) = 1^-(0^{++})$

OMITTED FROM SUMMARY TABLE

Evidence not compelling, may be a kinematic effect.

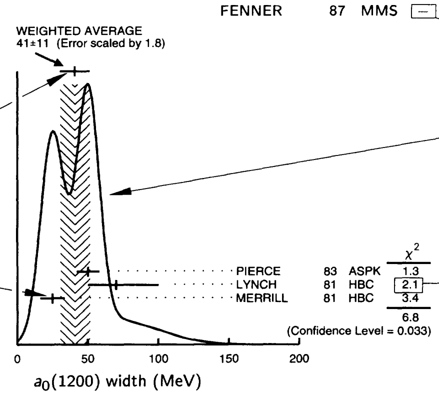
$a_0(1200)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1206± 7 OUR AVERAGE						
1210± 8±9	3000	FENNER	87	MMS	−	3.5 $\pi^- p$
1198±10		PIERCE	83	ASPK	+	2.1 $K^- p$
1216±11±9	1500	[1] MERRILL	81	HBC	0	3.2 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1192±16	200	LYNCH	81	HBC	±	2.7 $\pi^- p$

[1] Systematic error was added quadratically by us in our 1986 edition.

$a_0(1200)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
41±11 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.						
50± 8		PIERCE	83	ASPK	+	2.1 $K^- p$
70^{+30}_{-20}	200	LYNCH	81	HBC	±	2.7 $\pi^- p$
25± 5±7		MERRILL	81	HBC	0	3.2 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<60		FENNER	87	MMS	−	3.5 $\pi^- p$



$a_0(1200)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	3π	(65.2±1.3) %	S=1.7
Γ_2	$K\overline{K}$	(34.8±1.3) %	S=1.7
Γ_3	$\eta\pi^\pm$	< 4.9 × 10^{-4}	CL=95%

$a_0(1200)$ BRANCHING RATIOS

$\Gamma(3\pi)/\Gamma_{total}$ $\qquad \Gamma_1/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.652±0.013 OUR FIT Error includes scale factor of 1.7.					
0.643±0.010 OUR AVERAGE					
0.64 ±0.01	PIERCE	83	ASPK	+	2.1 $K^- p$
0.74 ±0.06	MERRILL	81	HBC	0	3.2 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.48 ±0.15	[2] LYNCH	81	HBC	±	2.7 $\pi^- p$

[2] Data has questionable background subtraction.

$\Gamma(K\overline{K})/\Gamma_{total}$ $\qquad \Gamma_2/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.348±0.013 OUR FIT Error includes scale factor of 1.7.					
0.35 ±0.05	PIERCE	83	ASPK	+	2.1 $K^- p$

$\Gamma(K\overline{K})/\Gamma(3\pi)$ $\qquad \Gamma_2/\Gamma_1$

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.535±0.030 OUR FIT Error includes scale factor of 1.7.					
0.50 ±0.03	MERRILL	81	HBC	0	3.2 $K^- p$

$\Gamma(\eta$ (neutral decay) $\pi^\pm)/\Gamma_{total}$ $\qquad 0.71\Gamma_3/\Gamma$

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
<3.5	95	PIERCE	83	ASPK	+	2.1 $K^- p$

$a_0(1200)$ REFERENCES

FENNER	87	PRL 55 14	+Watson, Willis, Zorn	(SLAC)
PIERCE	83	PL 123B 230		(FNAL) IJP
LYNCH	81	PR D24 610	+Jones+	(CLEO Collab.)
MERRILL	81	PRL 47 143	+Armstrong, Harper, Rittenberg, Wagman	(SACL, CERN)

Particle quantum numbers (where known).

Indicates particle omitted from Particle Properties Summary Table, implying particle's existence is not confirmed.

General comments on particle.

"Document id" for this result; full reference given below.

Measurement technique. (See abbreviations on next page.)

Scale factor > 1 indicates possibly inconsistent data.

Reaction producing particle, or general comments.

"Change bar" indicates result added or changed since previous edition.

Charge(s) of particle(s) detected.

Ideogram to display possibly inconsistent data. Curve is sum of Gaussians, one for each experiment (area of Gaussian = 1/error; width of Gaussian = ±error). See Introductory Text for discussion.

Contribution of experiment to χ^2 (if no entry present, experiment not used in calculating χ^2 or scale factor because of very large error).

Our best value for branching fraction as determined from data averaging, fitting, evaluating, limit selection, etc. This list is basically a compact summary of results in the Branching Ratio section below.

Branching ratio in terms of partial decay mode(s) Γ_i above.

Partial list of author(s) in addition to first author.

Quantum number determinations in this reference.

Institution(s) of author(s). (See abbreviations on next page.)

Abbreviations Used in the Full Listings

Indicator of Procedure Used to Obtain Our Result

OUR AVERAGE	From a weighted average of selected data.
OUR FIT	From a constrained or overdetermined multiparameter fit of selected data.
OUR EVALUATION	Not from a direct measurement, but evaluated from measurements of other quantities.
OUR ESTIMATE	Based on the observed range of the data. Not from a formal statistical procedure.
OUR LIMIT	For special cases where the limit is evaluated by us from measured ratios or other data. Not from a direct measurement.

Measurement Techniques (i.e., Detectors and Methods of Analysis)

ACCM	ACCMOR Collaboration
AEMS	Argonne effective mass spectrometer
ALEP	ALEPH – CERN LEP detector
AMY	AMY detector at KEK-TRISTAN
ARG	ARGUS detector at DORIS
ASP	Anomalous single-photon detector
ASPK	Automatic spark chambers
ASTE	ASTERIX detector at LEAR
ASTR	Astronomy
B845	BNL experiment 845 detector
BAKS	Baksan underground scintillation telescope
BC	Bubble chamber
BDMP	Beam dump
BEBC	Big European bubble chamber at CERN
BIS2	BIS-2 spectrometer at Serpukhov
BONA	Bonanza nonmagnetic detector at DORIS
BPWA	Barrelet-zero partial-wave analysis
CALO	Calorimeter
CBAL	Crystal Ball detector at SLAC-SPEAR or DORIS
CBAR	Crystal Barrel detector at CERN-LEAR
CBOX	Crystal Box at LAMPF
CC	Cloud chamber
CCD	Charge-coupled device
CDF	Collider detector at Fermilab
CDHS	CDHS neutrino detector at CERN
CELL	CELLO detector at DESY
CHM2	CHARM-II neutrino detector (glass) at CERN
CHRM	CHARM neutrino detector (marble) at CERN
CIBS	CERN-IHEP boson spectrometer
CLE2	CLEO II detector at CESR.
CLEO	Cornell magnetic detector at CESR
CMD	Cryogenic magnetic detector at VEPP-2M, Novosibirsk
CNTR	Counters
COSM	Cosmology and astrophysics
CSB2	Columbia U. - Stony Brook BGO calorimeter inserted in NaI array
CUSB	Columbia U. - Stony Brook segmented NaI detector at CESR
DASP	DESY double-arm spectrometer
DBC	Deuterium bubble chamber
DLCO	DELCO detector at SLAC-SPEAR or SLAC-PEP
DLPH	DELPHI detector at LEP
DM1	Magnetic detector no. 1 at Orsay DCI collider
DM2	Magnetic detector no. 2 at Orsay DCI collider
DPWA	Energy-dependent partial-wave analysis
DUD	Deep Underground Detector (IMB)
EHS	Four-pi detector at CERN
ELEC	Electronic combination
EMC	European muon collaboration detector at CERN
EMUL	Emulsions
F731	FNAL E-731 Spectrometer-Calorimeter
FBC	Freon bubble chamber
FIT	Fit to previously existing data
FMPS	Fermilab Multiparticle Spectrometer
FRAB	ADONE $B\overline{B}$ group detector
FRAG	ADONE $\gamma\gamma$ group detector
FRAM	ADONE MEA group detector
FREJ	FREJUS Collaboration – modular flash chamber detector (calorimeter)
GAM2	IHEP hodoscope Cerenkov γ calorimeter GAMS-2000
GAM4	CERN hodoscope Cerenkov γ calorimeter GAMS-4000
GGM	CERN Gargamelle bubble chamber
GOLI	CERN Goliath spectrometer
HBC	Hydrogen bubble chamber
HDBC	Hydrogen and deuterium bubble chambers
HEBC	Helium bubble chamber
HEPT	Helium proportional tubes
HLBC	Heavy-liquid bubble chamber
HOME	Homestake underground scintillation detector
HPW	Harvard-Pennsylvania-Wisconsin detector
HRS	SLAC high-resolution spectrometer
HYBR	Hybrid: bubble chamber + electronics
IMB	Irvine-Michigan-Brookhaven underground Cherenkov detector
IMB3	Irvine-Michigan-Brookhaven underground Cherenkov detector
INDU	Magnetic induction
IPWA	Energy-independent partial-wave analysis
JADE	JADE detector at DESY
KAM2	KAMIOKANDE-II underground Cherenkov detector
KAMI	KAMIOKANDE underground Cherenkov detector
KOLR	Kolar Gold Field underground detector
L3	L3 detector at LEP
LASS	Large-angle superconducting solenoid spectrometer at SLAC
LEBC	Little European bubble chamber at CERN
LENA	Nonmagnetic lead-glass NaI detector at DORIS
MAC	MAC detector at PEP/SLAC
MBR	Molecular beam resonance technique
MD1	Magnetic detector at VEEP-4, Novosibirsk
MDRP	Millikan drop measurement
MICA	Underground mica deposits
MLEV	Magnetic levitation
MMS	Missing mass spectrometer
MPS	Multiparticle spectrometer at BNL
MPS2	Multiparticle spectrometer upgrade at BNL
MPSF	Multiparticle spectrometer at Fermilab
MPWA	Model-dependent partial-wave analysis
MRK1	SLAC Mark-I detector
MRK2	SLAC Mark-II detector
MRK3	SLAC Mark-III detector
MRKJ	Mark-J detector at DESY
MRS	Magnetic resonance spectrometer
NA31	CERN NA31 Spectrometer-Calorimeter
ND	NaI detector at VEPP-2M, Novosibirsk
NEUL	Neuland large-angle neutrino spectrometer
NICE	Serpukhov nonmagnetic precision spectrometer
NMR	Nuclear magnetic resonance
NUSX	Mont Blanc NUSEX underground detector
OBLX	OBELIX detector at LEAR
OLYA	Detector at VEPP-2M and VEPP-4, Novosibirsk
OMEG	CERN OMEGA spectrometer
OPAL	OPAL detector at LEP
OSPK	Optical spark chamber
PBC	Propane bubble chamber
PLAS	Plastic detector
PLUT	DESY PLUTO detector
PWA	Partial-wave analysis
REDE	Resonance depolarization
RVUE	Review of previous data
SAGE	US - Russian Gallium Experiment
SFM	CERN split-field magnet
SHF	SLAC Hybrid Facility Photon Collaboration
SIGM	Serpukhov CERN-IHEP magnetic spectrometer (SIGMA)
SILI	Silicon detector
SOUD	Soudan underground detector
SPEC	Spectrometer
SPRK	Spark chamber
STRC	Streamer chamber
TASS	DESY TASSO detector
THEO	Theoretical or heavily model-dependent result
THY	Theory
TOF	Time-of-flight
TOPZ	TOPAZ detector at KEK-TRISTAN
TPC	TPC detector at PEP/SLAC
TPS	Tagged photon spectrometer at Fermilab
TRAP	Penning trap
UA1	UA1 detector at CERN
UA2	UA2 detector at CERN
UA5	UA5 detector at CERN
VES	Vertex Spectrometer Facility at 70 GeV IHEP accelerator
VNS	VENUS detector at KEK-TRISTAN
WIRE	Wire chamber
XEBC	Xenon bubble chamber

Abbreviations Used in the Full Listings *(Cont'd)*

Conferences

Conferences are generally referred to by the location at which they were held (e.g., HAMBURG, TORONTO, CORNELL, BRIGHTON, etc.).

Journals

AA	Astronomy and Astrophysics
ADVP	Advances in Physics
AFIS	Anales de Fisica
ANP	Annals of Physics
ANYAS	Annals New York Academy of Science
AP	Atomic Physics
APAH	Acta Phys. Acad. Hungarica
APJ	Astrophysical Journal
APP	Acta Physica Polonica
ARNPS	Annual Review of Nuclear and Particle Science
ARNS	Annual Review of Nuclear Science
BAPS	Bulletin of the American Physical Society
BASUP	Bulletin of the Academy of Science, USSR (Physics)
CJP	Canadian Journal of Physics
CNPP	Comments on Nuclear and Particle Physics
CZJP	Czechoslovak Journal of Physics
DANS	Doklady Akademii nauk SSSR
EPL	Europhysics Letters
IJMP	Int. Journal of Modern Physics
JAP	Journal of Applied Physics
JETP	English Translation of Soviet Physics ZETF
JETPL	English Translation of Soviet Physics ZETF Letters
JINR	Joint Inst. for Nuclear Research
JP	Journal of Physics (A,B,G)
JPCRD	Journal of Physical and Chemical Reference Data
JPSJ	Journal of the Physical Society of Japan
LNC	Letters to Nuovo Cimento
MNRA	Monthly Notices of the Royal Astronomical Society
MPL	Modern Physics Letters
NAT	Nature
NC	Nuovo Cimento
NIM	Nuclear Instruments and Methods
NP	Nuclear Physics
NPBPS	Nuclear Physics B Proceedings Supplement
PDAT	Physik Daten
PL	Physics Letters
PN	Particles and Nuclei
PPSL	Proc. of the Physical Society of London
PR	Physical Review
PRAM	Pramana
PRL	Physical Review Letters
PRPL	Physics Reports (Physics Letters C)
PRSE	Proc. of the Royal Society of Edinburgh
PRSL	Proc. of the Royal Society of London
PS	Physica Scripta
PTP	Progress of Theoretical Physics
RA	Radiochimica Acta
RMP	Reviews of Modern Physics
RNC	La Rivista del Nuovo Cimento
RPP	Reports on Progress in Physics
RRP	Revue Romaine de Physique
SCI	Science
SJNP	Soviet Journal of Nuclear Physics
SPD	Soviet Physics Doklady (Magazine)
SPU	Soviet Physics - Uspekhi
YAF	Yadernaya Fisika
ZETF	Zhurnal Eksp. i Teor. Fiziki
ZETFP	Zhurnal Eksp. i Teor. Fiziki, Pis'ma v Redakts
ZNAT	Zeitschrift fur Naturforschung
ZPHY	Zeitschrift fur Physik

Institutions

AACH	Technische Univ. Aachen	Aachen, Germany
AARH	Univ. of Aarhus	Aarhus, Denmark
ABO	Abo Akademi	Abo, Finland
ADEL	Adelphi Univ.	Garden City, NY, USA
ADLD	Adelaide Univ.	Adelaide, Australia
AERE	Atomic Energy Research Estab.	Harwell, Berks., England
AFRR	Armed Forces Radiobiology Research Inst.	Bethesda, MD, USA
AICH	Aichi Univ. of Education	Kariya, Aichi Pref., Japan
AIKH	Nationaal Inst voor Kernfysica en Hoge-Energiefysica	Amsterdam, Netherlands
AKIT	Akita Univ.	Akita, Japan
ALAH	Univ. of Alabama at Huntsville	Huntsville, AL, USA
ALBA	State Univ. of New York at Albany	Albany, NY, USA
ALBE	Alberta Univ.	Edmonton, AB, Canada
AMHT	Amherst College	Amherst, MA, USA
AMST	Univ. of Amsterdam	Amsterdam, Netherlands
ANIK	Amsterdam NIKHEF	Amsterdam, Netherlands
ANKA	Middle East Technical Univ.	Ankara, Turkey
ANL	Argonne National Lab.	Argonne, IL, USA
ANSM	St. Anselm College	Manchester, NH, USA
ARIZ	Univ. of Arizona	Tucson, AZ, USA
ARZS	Arizona State Univ.	Tempe, AZ, USA
ASCI	USSR Academy of Sciences	Moscow, Russia (USSR)
AST	Academia Sinica	Taipei, Taiwan
ATEN	Nuclear Research Centre Demokritos	Athens, Greece
ATHU	Univ. of Athens	Athens, Greece
AUCK	Univ. of Auckland	Auckland, New Zealand
BAKU	Phys. Inst., Azerbaijanian Acad. Sci.	Baku, Azerbaijan (USSR)
BARC	Univ. de Barcelona	Barcelona, Spain
BARI	Univ. di Bari	Bari, Italy
BART	Bartol Research Foundation	Swarthmore, PA, USA
BASL	Univ. of Basel	Basel, Switzerland
BAYR	Univ. Bayreuth	Bayreuth, Germany
BCEN	CEN, Bordeaux-Gradignan	Bordeaux, France
BCIP	Central Inst. of Physics	Bucharest, Romania
BEIJ	Beijing Univ.	Beijing, China
BELG	Inst. Interuniv. des Sciences Nucleaires	Bruxelles, Belgium
BELL	Bell Labs.	Murray Hill, NJ, USA
BERG	Univ. of Bergen	Bergen, Norway
BERL	Inst. Hochenergiephys. DAW	Berlin-Zeuthen, Germany
BERN	Univ. Bern	Bern, Switzerland
BGNA	Univ. di Bologna	Bologna, Italy
BGUN	Ben Gurion Univ. of the Negev	Beer Sheva, Israel
BHAB	Bhabha Atomic Research Center	Bombay, India
BHEP	Inst. of High Energy Physics	Beijing, China
BIEL	Univ. Bielefeld	Bielefeld, Germany
BING	State Univ. of New York at Binghamton	Binghamton, NY, USA
BIRM	Birmingham Univ.	Birmingham, England
BLSU	Bloomsburg State Univ.	Bloomsburg, PA, USA
BNL	Brookhaven National Lab.	Upton, L.I., NY, USA
BOCH	Ruhr-Universitat Bochum	Bochum, Germany
BOHR	Niels Bohr Inst.	Copenhagen, Denmark
BOIS	Boise State Univ.	Boise, ID, USA
BOMB	Univ. of Bombay	Bombay, India
BONN	Univ. Bonn	Bonn, Germany
BORD	Univ. de Bordeaux	Bordeaux, France
BOST	Boston Univ.	Boston, MA, USA
BRAN	Brandeis Univ.	Waltham, MA, USA
BRAT	Univ. of Bratislava	Bratislava, Czechoslovakia
BRCO	Univ. of British Columbia	Vancouver, BC, Canada
BRIS	H. H. Wills Physics Lab., Univ. of Bristol	Bristol, England
BROW	Brown Univ.	Providence, RI, USA
BRTD	Bartol Research Foundation	Newark, DE, USA
BRUN	Brunel Univ.	Uxbridge, Middlesex, England
BRUX	Univ. Libre de Bruxelles	Bruxelles, Belgium
BUCH	Bucharest State Univ.	Bucharest, Romania
BUDA	Central Research Inst. of Physics	Budapest, Hungary
BUFF	State Univ. of New York at Buffalo	Buffalo, NY, USA
BURE	Inst. des Hautes Etudes Scientifiques	Bures-sur-Yvette, France
CAEN	Lab. de Physique Corpusculaire	Caen, France
CAGL	Cagliari Univ.	Cagliari, Italy
CAIR	Cairo University	Cairo, Egypt

Abbreviations Used in the Full Listings *(Cont'd)*

CAIW	Carnegie Inst. of Washington	Washington, DC, USA
CAMB	Cambridge Univ.	Cambridge, England
CAMP	Inst. de Fisica, Univ. Estadual de Campinas	Sao Paulo, Brazil
CANB	Australian National Univ.	Canberra, Australia
CAPI	Societe Generale Direction des Marches de capitaux	Paris, France
CARA	Univ. Central de Venezuela	Caracas, Venezuela
CARL	Carleton Univ.	Ottawa, ON, Canada
CASE	Case Western Reserve Univ.	Cleveland, OH, USA
CAST	China Center of Advanced Science and Technology	Beijing, China
CATA	Univ. of Catania	Catania, Italy
CATH	Catholic Univ. of America	Washington, DC, USA
CAVE	Cavendish Lab., Cambridge Univ.	Cambridge, England
CBER	Univ. Claude Bernard	Lyon, France
CBNM	Joint Research Center, Central Bureau for Nuclear Measurements	Greel, Belgium
CCAC	Community College of Allegheny County	Pittsburgh, PA, USA
CDEF	College de France	Paris, France
CEA	Cambridge Electron Accelerator	Cambridge, MA, USA
CENG	CEN, Grenoble	Grenoble, France
CERN	European Organization for Nuclear Research	Geneva, Switzerland
CHIB	Chiba Univ.	Chiba, Japan
CHIC	Univ. of Chicago	Chicago, IL, USA
CINC	Univ. of Cincinnati	Cincinnati, OH, USA
CINV	Centro de Investigacio y de Estudios Avanzados del IPN	Mexico, Mexico
CIT	Calif. Inst. of Technology	Pasadena, CA, USA
CLER	Univ. de Clermont-Ferrand	Clermont-Ferrand, France
CLEV	Cleveland State Univ.	Cleveland, OH, USA
CMNS	Comenius Univ.	Bratislava, Czechoslovakia
CMU	Carnegie-Mellon Univ.	Pittsburgh, PA, USA
CNRC	National Research Council of Canada	Ottawa, ON, Canada
COLO	Univ. of Colorado	Boulder, CO, USA
COLU	Columbia Univ.	New York, NY, USA
CORN	Cornell Univ.	Ithaca, NY, USA
COSU	Colorado State Univ.	Fort Collins, CO, USA
CRAC	Inst. for Nuclear Research	Cracow, Poland
CRNL	Chalk River National Labs	Chalk River, ON, Canada
CSNZ	Dipt. di Fisica dell'Universita	Cosenza, Italy
CSOK	Central State Univ.	Edmond, OK, USA
CUNY	City Univ. of New York	New York, NY, USA
CURI	Laboratoire Joliot-Curie	Paris, France
CUT	Chalmers Univ. of Technology	Goteborg, Sweden
DALH	Dalhausie Univ.	Halifax, NS, Canada
DARE	Daresbury Nuclear Physics Lab.	Daresbury, England
DARM	Inst. fur Kernphsik	Darmstadt, Germany
DELA	Univ. of Delaware	Newark, DE, USA
DELH	Univ. of Delhi	Delhi, India
DESY	Deutsches Elektronen-Synchrotron	Hamburg, Germany
DOE	U.S. Department of Energy	Washington, DC, USA
DORT	Univ. Dortmund	Dortmund, Germany
DUKE	Duke Univ.	Durham, NC, USA
DURH	Univ. of Durham	Durham, England
DUUC	University College	Dublin, Ireland
EDIN	Univ. of Edinburgh	Edinburgh, Scotland
EFI	Enrico Fermi Inst. for Nuclear Studies	Chicago, IL, USA
ELMT	Elmhurst College	Elmhurst, IL, USA
ENSP	Ecole Normale Superieure	Paris, France
EOTV	Eotvos Univ.	Budapest, Hungary
EPOL	Ecole Polytechnique	Palaiseau, France
ERLA	Univ. Erlangen-Nurnberg	Erlangen, Germany
ETH	Swiss Federal Inst. of Technology	Zurich, Switzerland
FERR	Dipartimento di Fisica dell'Universita'	Ferrara, Italy
FIRZ	Univ. di Firenze	Firenze, Italy
FISK	Fisk Univ.	Nashville, TN, USA
FLOR	Univ. of Florida	Gainsville, FL, USA
FNAL	Fermi National Accelerator Lab.	Batavia, IL, USA
FOM	Foundation for Fundamental Research on Matter	Utrecht, Netherlands
FRAN	Univ. of Frankfort	Frankfort, Germany
FRAS	Lab. Nazionali del C.N.E.N.	Frascati, Italy
FREI	Univ. of Freiburg	Freiburg, Germany
FRIB	Univ. of Fribourg	Fribourg, Switzerland
FSU	Florida State Univ.	Tallahassee, FL, USA
FUKI	Fukui Univ.	Fukui, Japan
FUKU	Fukushima Univ.	Fukushima, Japan
GENO	Univ. di Genova	Genova, Italy
GEOR	Georgian Academy of Sciences	Tbilisi, Georgia (USSR)
GESC	General Electric Research and Development Center	Schenectady, NY, USA
GEVA	Univ. de Geneve	Geneva, Switzerland
GIFU	Gifu Univ.	Gifu, Japan
GLAS	Univ. of Glasgow	Glasgow, Scotland
GMAS	George Mason Univ.	Fairfax, VA, USA
GOET	Goettingen Univ.	Goettingen, Germany
GOML	Gomel State Univ.	Gomel, Byelorussia (USSR)
GRAZ	Univ. Graz	Graz, Austria
GRON	Univ. van Groningen	Groningen, Netherlands
GSCO	Geological Survey of Canada	Ottawa, ON, Canada
GSI	Gesellschaft fur Schwerionenforschung	Darmstadt, Germany
GUEL	Guelph Univ.	Guelph, ON, Canada
GWU	George Washington Univ.	Washington, DC, USA
GYEO	Gyeongsang National Univ.	Jinju, Korea
HAIF	Technion — Israel Inst. of Technology	Haifa, Israel
HAMB	Univ. Hamburg	Hamburg, Germany
HANN	Hannover Tech. Univ.	Hannover, Germany
HARC	Houston Advanced Research Center	The Woodlands, TX, USA
HARV	Harvard Univ.	Cambridge, MA, USA
HAWA	Univ. of Hawaii	Honolulu, HI, USA
HEBR	Hebrew Univ.	Jerusalem, Israel
HEID	Univ. Heidelberg	Heidelberg, Germany
HELS	Helsingin Yliopisto	Helsinki, Finland
HIRO	Hiroshima Univ.	Hiroshima, Japan
HITJ	Hiroshima Shudo Univ. Inst. of Tech.	Hiroshima, Japan
HOUS	Univ. of Houston	Houston, TX, USA
HPC	Hewlett-Packard Corp.	Cupertino, CA, USA
HSCA	Harvard-Smithsonian Inst. for Astrophysics	Cambridge, MA, USA
IAS	Inst. for Advanced Study	Princeton, NJ, USA
IASD	Inst. of Advanced Studies	Dublin, Ireland
IBAR	Ibaraki Univ., Mito	Ibaraki-ken, Japan
IBCT	Ibaraki College of Technology	Ibaraki, Japan
IBM	International Business Machines	Palo Alto, CA, USA
IBMY	IBM Watson Res. Center	Yorktown Heights, NY, USA
IBS	Inst. for Boson Studies, Pasadena	Pasadena, CA, USA
ICRR	Inst. for Cosmic Ray Research	Tokyo, Japan
ICTP	International Center for Theoretical Physics	Trieste, Italy
IFIC	Instituto de Fisica Corpuscular	Valencia, Spain
IFRJ	Inst. de Fisica, Rio de Janeiro	Rio de Janeiro, Brazil
IIT	Illinois Inst. of Technology	Chicago, IL, USA
ILL	Univ. of Illinois	Urbana, IL, USA
ILLC	Univ. of Illinois at Chicago	Chicago, IL, USA
ILLG	Inst. Laue-Langevin	Grenoble, France
IND	Indiana Univ.	Bloomington, IN, USA
INEL	Idaho National Engineering Lab.	Idaho Falls, ID, USA
INFN	Ist. Nazionale di Fisica Nucleare	Italy
INNS	Phys. Inst., Univ. Innsbruck	Innsbruck, Austria
INRM	Inst. for Nuclear Research	Moscow, Russia (USSR)
INRU	Inst. of Nuclear Research, Academy of Science of the Ukrainian SSR	Uzhgorod, Ukraine (USSR)

Abbreviations Used in the Full Listings *(Cont'd)*

INUS	Inst. for Nuclear Study at Tokyo Univ.	Tokyo, Japan
IOFF	Ioffe Inst. of Physics and Technology	St. Petersburg, Russia (USSR)
IOWA	Univ. of Iowa	Iowa City, IA, USA
IPCR	Inst. of Physical and Chemical Research	Saitama-ken, Japan
IPN	Inst. de Physique Nucleaire	Orsay, France
IPNP	Inst. de Physique Nucleaire	Paris, France
IRAD	Inst. du Radium	Paris, France
ISNG	Inst. des Sciences Nucleaires, Univ. de Grenoble	Grenoble, France
ISU	Iowa State Univ.	Ames, IA, USA
ITEP	Inst. for Theoretical and Experimental Physics	Moscow, Russia (USSR)
ITHA	Ithaca College	Ithaca, NY, USA
ITPU	Inst. for Theoretical Physics	Utrecht, Netherlands
IUPU	Indiana Univ. — Purdue Univ. at Indianapolis	Indianapolis, IN, USA
JADA	Jadavpur Univ.	Calcutta, India
JAGL	Jagellonian Univ.	Cracow, Poland
JHU	Johns Hopkins Univ.	Baltimore, MD, USA
JINR	Joint Inst. for Nuclear Research	Dubna, Russia (USSR)
JULI	Kernforschungsanlage, Julich	Julich, Germany
KAGO	Kagoshima Univ.	Kagoshima, Japan
KANS	Univ. of Kansas	Lawrence, KS, USA
KARL	Univ. Karlsruhe	Karlsruhe, Germany
KAZA	Kazakh Academy of Science	Alma-Ata, Kazakhstan (USSR)
KEK	National Lab for High Energy Physics, Japan	Tsukuba-gun, Japan
KENT	Kent Univ. at Cantebury, Kent	Cantebury, England
KEYN	Open Univ.	Milton Keynes, England
KHAR	Phys.-Tech. Inst., Acad. Sci., Ukr.,	Kharkov, Ukraine (USSR)
KIAE	Kurchatov Inst. of Atomic Energy	Moscow, Russia (USSR)
KIAM	Keldysk Inst. of Applied Math	Moscow, Russia (USSR)
KIEV	Physical-Technical Inst.	Kiev, Ukraine (USSR)
KINK	Kinki Univ.	Osaka, Japan
KNTY	Univ. of Kentucky	Lexington, KY, USA
KOBE	Kobe Univ.	Kobe, Japan
KOSI	Inst. of Exp. Phys., Slovak Acad. Sci.	Kosice, Czechoslovakia
KYOT	Kyoto Univ.	Kyoto, Japan
LALO	Linear Accelerator Lab, Orsay	Orsay, France
LANC	Lancaster Univ.	Lancaster, England
LANL	U.C. Los Alamos National Lab.	Los Alamos, NM, USA
LAPP	Lab. d'Annecy de Physique des Particules	Annecy, France
LASL	U.C. Los Alamos Scientific Lab.	Los Alamos, NM, USA
LAUS	Univ. of Lausanne	Lausanne, Switzerland
LAVL	Laval Univ.	Quebec, PQ, Canada
LBL	U.C. Lawrence Berkeley Lab.	Berkeley, CA, USA
LCGT	Lab. di Cosmo-Geofisica del CNR	Torino, Italy
LEBD	Lebedev Physics Inst.	Moscow, Russia (USSR)
LECE	Universita di Lecce	Lecce, Italy
LEED	Univ. of Leeds	Leeds, England
LEHI	Lehigh Univ.	Bethlehem, PA, USA
LEHM	Herbert H. Lehman College	Bronx, NY, USA
LEID	Inst. Lorentz	Leiden, Netherlands
LEMO	Le Moyne College	Syracuse, NY, USA
LENI	Inst. of Nuclear Physics, USSR Acad. Sci.	St. Petersburg, Russia (USSR)
LIBH	Lab. Interuniv. Belge Hautes Energies	Bruxelles, Belgium
LINZ	Linz Inst. fur Physik, Kepler Hoch.	Linz, Austria
LISB	Univ. de Lisboa	Lisboa, Codex, Portugal
LIVP	Liverpool Univ.	Liverpool, England
LLL	Lawrence Livermore Lab.	Livermore, CA, USA
LLNL	Lawrence Livermore National Lab.	Livermore, CA, USA
LOCK	Lockheed Research Lab	Palo Alto, CA, USA
LOIC	Imperial College of Science and Technology	London, England
LOQM	Queen Mary College	London, England
LOUC	University College	London, England
LOWC	Westfield College	London, England
LPNP	Lab. de Physique Nucleaire et Hautes Energies	Paris, France
LPTP	Lab. de Physique Theor. et Hautes Energies	Paris, France
LRL	U.C. Lawrence Berkeley Lab.	Berkeley, CA, USA
LSU	Louisiana State Univ.	Baton Rouge, LA, USA
LUND	Univ. of Lund	Lund, Sweden
LVLN	Univ. Catholique de Louvain	Louvain-La-Neuve, Belgium
LYON	Univ. de Lyon	Villeurbanne, France
MADE	Inst. de Estructura de la Materia	Madrid, Spain
MADR	C.I.E.M.A.T.	Madrid, Spain
MADU	Univ. Autonome de Madrid	Madrid, Spain
MANI	Univ. of Manitoba	Winnipeg, MB, Canada
MANZ	Univ. Mainz	Mainz, Germany
MARS	Centre National de la Recherche Scientifique	Marseille, France
MASA	Univ. of Massachusetts	Amherst, MA, USA
MASB	Univ. of Massachusetts	Boston, MA, USA
MCGI	McGill Univ.	Montreal, PQ, Canada
MCHS	Univ. Manchester	Manchester, England
MCMS	McMaster Univ.	Hamilton, ON, Canada
MEIS	Meisei Univ.	Hino, Tokyo, Japan
MELB	Univ. of Melbourne	Parkville, Australia
MHCO	Mount Holyoke College	South Hadley, MA, USA
MICH	Univ. of Michigan	Ann Arbor, MI, USA
MILA	Univ. di Milano	Milano, Italy
MINN	Univ. of Minnesota	Minneapolis, MN, USA
MISS	Univ. of Mississippi	University, MI, USA
MIT	Massachusetts Inst. of Technology	Cambridge, MA, USA
MIU	Maharishi International Univ.	Fairfield, IA, USA
MIYA	Miyazaki University	Miyazaki, Japan
MNSK	Acad. Sci. Byelorussian SSR	Minsk, Byelorussia (USSR)
MONP	Univ. de Montpellier	Montpellier, France
MONS	Univ. de l'Etat, Mons	Mons, Belgium
MONT	Univ. de Montreal	Montreal, PQ, Canada
MOSU	Moscow State Univ.	Moscow, Russia (USSR)
MPCM	Max Planck Inst. fur Chemie	Mainz, Germany
MPEI	Moscow Phys. Eng. Inst.	Moscow, Russia (USSR)
MPHY	Max Planck Inst. fur Physics	Mainz, Germany
MPIH	Max Planck Inst. fur Kernphysik	Heidelberg, Germany
MPIM	Max Planck Inst. fur Physik-Astrophysik	Munich, Germany
MSU	Michigan State Univ.	East Lansing, MI, USA
MTHO	Mt. Holyoke College	South Hadley, MA, USA
MULH	Centre Univ. du Haut-Rhin	Mulhouse, France
MUNI	Univ. of Munich	Munich, Germany
MUNT	Tech. Univ. Munchen	Garching, Germany
MURA	Midwestern Univ. Research Assoc.	Stroughton, WI, USA
NAAS	North American Aviation Science Center	Thousand Oaks, CA, USA
NAGO	Nagoya Univ.	Nagoya, Japan
NAPL	Univ. di Napoli	Napoli, Italy
NASA	NASA, Goddard Space Flight Center	Greenbelt, MD, USA
NBS	U.S. National Bureau of Standards	Gaithersburg, MD, USA
NBSB	U.S. National Bureau of Standards	Boulder, CO, USA
NCAR	National Center for Atmospheric Research	Boulder, CO, USA
NDAM	Univ. of Notre Dame	Notre Dame, IN, USA
NEAS	Northeastern Univ.	Boston, MA, USA
NEUC	Univ. de Neuchatel	Neuchatel, Switzerland
NIHO	College of Industrial Technology, Nihon Univ.	Chiba, Japan
NIIG	Univ. of Niigata	Niigata, Japan
NIJM	R. K. Univ. Nijmegen	Nijmegen, Netherlands
NIRS	National Inst. of Radiological Sciences	Chiba, Japan

Abbreviations Used in the Full Listings *(Cont'd)*

NIST	National Inst. Standards Tech	Gaithersburg, MD, USA
NIU	Northern Illinois Univ.	DeKalb, IL, USA
NMSU	New Mexico State Univ.	Las Cruces, NM, USA
NORD	Nordisk Inst. for Teor. Atomfysik	Copenhagen, Denmark
NOTT	Nottingham Univ.	Nottingham, England
NOVO	Inst. of Nuclear Physics	Novosibirsk, Russia (USSR)
NPOL	Northern Polytechnic	London, England
NRL	Naval Research Laboratory	Washington, DC, USA
NSF	U.S. National Science Foundation	Washington, DC, USA
NTUA	National Technical Univ.	Athens, Greece
NWES	Northwestern Univ.	Evanston, IL, USA
NYU	New York Univ.	New York, NY, USA
OBER	Oberlin College	Oberlin, OH, USA
OHIO	Ohio Univ.	Athens, OH, USA
OKAY	Okayama Univ.	Okayama, Japan
OKLA	Univ. of Oklahoma	Norman, OK, USA
OKSU	Oklahoma State Univ.	Stillwater, OK, USA
OREG	Univ. of Oregon	Eugene, OR, USA
ORNL	Oak Ridge National Lab.	Oak Ridge, TN, USA
ORSA	Univ. de Paris, Fac. des Sci.	Orsay, France
ORST	Oregon State	Corvalis, OR, USA
OSAK	Osaka Univ.	Osaka, Japan
OSKC	Osaka City Univ.	Osaka, Japan
OSLO	Oslo Univ.	Oslo, Norway
OSU	Ohio State Univ.	Columbus, OH, USA
OTTA	Univ. of Ottawa	Ottawa, ON, Canada
OXF	Oxford Univ.	Oxford, England
PADO	Univ. di Padova	Padova, Italy
PARI	Univ. Paris (unspecified division)	Paris, France
PARM	Univ. di Parma	Parma, Italy
PASC	Univ. Blaise Pascal	Aubiere, France
PATR	Univ. of Patras	Patras, Greece
PAVI	Univ. di Pavia	Pavia, Italy
PENN	Univ. of Pennsylvania	Philadelphia, PA, USA
PGIA	Univ. di Perugia	Perugia, Italy
PHIL	Philipps Univ.	Marburg, Germany
PINP	Inst. of Nuclear Physics, USSR Acad. Sci.	St. Petersburg, Russia (USSR)
PISA	Univ. di Pisa	Pisa, Italy
PITT	Univ. of Pittsburgh	Pittsburgh, PA, USA
PLAT	State Univ. of New York at Plattsburgh	Plattsburgh, NY, USA
PLRM	Ist. di Fisica dell'Universita	Palermo, Italy
PNL	Pacific Northwest Lab.	Richland, WA, USA
PPA	Princeton-Penn. Proton Accelerator	Princeton, NJ, USA
PRAG	Inst. of Physics, CSAV	Prague, Czechoslovakia
PRIN	Princeton Univ.	Princeton, NJ, USA
PSI	Paul Scherrer Institute (was SIN)	Villigen, Switzerland
PSLL	Physical Science Lab.	Las Cruces, NM, USA
PSU	Pennsylvania State University	University Park, PA, USA
PUCB	Pontificia Univ. Catolica	Rio de Janeiro, Brazil
PUEB	Universida AUtomata de Puebla	Puebla, Mexico
PURD	Purdue Univ.	Lafayette, IN, USA
QUKI	Queens Univ.	Kingston, ON, Canada
RAL	Rutherford Appleton Lab. (formerly RL)	Chilton, Did., Berks., England
REGE	Univ. Regensburg	Regensburg, Germany
REHO	Weizmann Inst. of Science	Rehovoth, Israel
RHBL	Royal Holloway and Bedford New College	London, England
RHEL	Rutherford High Energy Lab.	Chilton, Did., Berks., England
RHLC	Royal Holloway College	Englefield Green, England
RICE	William Marsh Rice Univ.	Houston, TX, USA
RISC	Rockwell International Science Center	Thousand Oaks, CA, USA
RISL	Univ. Research Reactor	Risley, Warrington, UK
RISO	Research Estab. Riso	Roskilde, Denmark
RL	Rutherford Lab. (formerly RHEL)	Chilton, Did., Berks., England
RMCS	Royal Military College of Science	Shrivenham, England
ROCH	Univ. of Rochester	Rochester, NY, USA
ROCK	Rockefeller Univ.	New York, NY, USA
ROMA	Univ. di Roma	Roma, Italy
ROSE	Rose Polytechnic Inst.	Terre Haute, IN, USA
RPI	Rensselaer Polytechnic Inst.	Troy, NY, USA
RUTG	Rutgers Univ.	New Brunswick, NJ, USA
SACL	Centre d'Etudes Nucleaires Saclay	Gif-sur-Yvette, France
SAGA	Saga Univ.	Saga, Japan
SANI	Ist. Superiore di Sanita	Roma, Italy
SATR	Lab. National Saturne	Gif-sur-Yvette, France
SAVO	Univ. Savoie	Chambery, France
SBER	San Bernardino State College	San Bernardino, CA, USA
SCOT	Scottish Univ. Research and REactor Center	East Kilbride, Glasgow, UK
SCUC	Univ. of South Carolina	Columbia, SC, USA
SEAT	Seattle Pacific College	Seattle, WA, USA
SEIB	Research Center Seibersdorf	Vienna, Austria
SEOU	Korea Univ.	Seoul, Korea
SERP	Inst. of High Energy Physics	Serpukov, Russia (USSR)
SETO	Seton Hall Univ.	South Orange, NJ, USA
SFLA	Univ. of South Florida	Tampa, FL, USA
SFRA	Simon Fraser U.	Burnaby, BC, Canada
SFSU	San Francisco State Univ.	San Francisco, CA, USA
SHEF	Univ. of Sheffield	Sheffield, England
SHMP	Univ. of Southampton	Southampton, England
SIEG	Gesamthochschule Siegen	Huttental, Germany
SIN	Swiss Inst. of Nuclear Research	Villigen, Switzerland
SLAC	Stanford Linear Accelerator Center	Stanford, CA, USA
SLOV	Slovak Academy of Sciences	Bratislava, Czechoslovakia
SMAS	Southeastern Massachusetts Univ.	North Dartmouth, MA, USA
SMCJ	Saitama College of Health	Saitama, Japan
SOFI	Bulgarian Acad. of Sci.	Sofia, Bulgaria
SOFU	Sofia University	Sofia, Bulgaria
SSCL	Superconducting Super Collider Laboratory	Dallas, TX, USA
SSL	Space Sciences Laboratory, UCB	Berkeley, CA, USA
STAN	Stanford Univ.	Stanford, CA, USA
STEV	Stevens Inst. of Technology	Hoboken, NJ, USA
STLO	St. Louis Univ.	St. Louis, MO, USA
STOC	Research Institute of Physics	Stockholm, Sweden
STOH	Stockholm Univ.	Stockholm, Sweden
STON	State Univ. of New York at Stony Brook	Stony Brook, L.I., NY, USA
STRB	Centre des Recherches Nucleaires	Strasbourg, France
STSI	Space Telescope Science Inst.	Baltimore, MD, USA
STUT	Univ. Stuttgart	Stuttgart, Germany
SUGI	Sugiyama Jogaku-en University	Aichi, Japan
SURR	Univ. of Surrey	Guildford, Surrey, England
SUSS	Univ. of Sussex	Falmer, Brighton, England
SYDN	Univ. of Sydney	Sydney, Australia
SYRA	Syracuse Univ.	Syracuse, NY, USA
TAJK	Inst. of Physics and Engineering, Tadzhik Acad. of Sci.	Dushanbe,Tadzhikistan (USSR)
TAMU	Texas A and M Univ.	College Station, TX, USA
TATA	Tata Inst. of Fundamental Research	Bombay, India
TBIL	Tbilisi State Univ.	Tbilisi, Georgia (USSR)
TELA	Univ. of Tel-Aviv	Tel-Aviv, Israel
TELE	Teledyne-Brown Engineering	Huntsville, AL, USA
TEMP	Temple Univ.	Philadelphia, PA, USA
TENN	Univ. of Tennessee	Knoxville, TN, USA
TEXA	Univ. of Texas	Austin, TX, USA
TEXD	Univ. of Texas at Dallas	Dallas, TX, USA
TGAK	Tokyo Gakugei University	Tokyo, Japan
TGU	Tohoku Gakuin Univ.	Miyagi, Japan
THES	Univ. of Thessaloniki	Thessaloniki, Greece
TINP	Acad. Sci., Inst. Nucl. Physics, Tashkent	Ulugbek, Uzbekistan (USSR)
TINT	Tokyo Inst. of Technology	Tokyo, Japan
TISA	Inst. for Space and Astronautical Sci.	Tokyo, Japan

Abbreviations Used in the Full Listings *(Cont'd)*

TMSK	Nuclear Physics Inst., Tomsk Polytech Inst.	Tomsk, Russia (USSR)
TMTC	Tokyo Metropolitan Technology College	Tokyo, Japan
TMU	Tokyo Metropolitan Univ.	Tokyo, Japan
TNIH	Atomic Energy Research Inst. Nihon Univ.	Tokyo, Japan
TNTO	Univ. of Toronto	Toronto, ON, Canada
TOHO	Tohoku Univ.	Sendai, Japan
TOKU	Univ. of Tokushima	Tokushima, Japan
TOKY	Univ. of Tokyo	Tokyo, Japan
TORI	Univ. di Torino	Torino, Italy
TPTI	Acad. Sci., Physical-Tech. Inst., Tashkent	Tashkent, Uzbekistan (USSR)
TRIK	Rikkyo Univ.	Tokyo, Japan
TRIN	Trinity College	Dublin, Ireland
TRIU	TRIUMF, Univ. of British Columbia	Vancouver, BC, Canada
TRST	Univ. di Trieste	Trieste, Italy
TSAP	Univ. of Tsukuba, Inst. of Applied Phys.	Ibaraki-ken, Japan
TSKP	Univ. of Tsukuba, Inst. of Phys.	Ibaraki-ken, Japan
TSUK	Univ. of Tsukuba	Tsukuba, Japan
TTAM	Tamagawa Univ.	Tokyo, Japan
TUAT	Tokyo Unov. of Agric. Tech.	Tokyo, Japan
TUFT	Tufts Univ.	Medford, MA, USA
TUW	Tech. Univ. Wien	Wien, Austria
TWAS	Waseda Univ.	Tokyo, Japan
UBEL	Univ. of Belgrade	Belgrade, Serbia, Yugoslavia
UCB	Univ. of Calif. at Berkeley	Berkeley, CA, USA
UCD	Univ. of Calif. at Davis	Davis, CA, USA
UCI	Univ. of Calif. at Irvine	Irvine, CA, USA
UCLA	Univ. of Calif. at Los Angeles	Los Angeles, CA, USA
UCND	Union Carbide Nuclear Division	Oak Ridge, TN, USA
UCR	Univ. of Calif. at Riverside	Riverside, CA, USA
UCSB	Univ. of Calif. at Santa Barbara	Santa Barbara, CA, USA
UCSC	Univ. of Calif. at Santa Cruz	Santa Cruz, CA, USA
UCSD	Univ. of Calif. at San Diego	La Jolla, CA, USA
UDCF	Univ. de Clermont-Ferrand	Aubiere, France
UMD	Univ. of Maryland	College Park, MD, USA
UNC	Univ. of North Carolina	Greensboro, NC, USA
UNCC	Univ. of North Carolina	Chapel Hill, NC, USA
UNCS	Union College	Schenectady, NY, USA
UNH	Univ. of New Hampshire	Durham, NH, USA
UNM	Univ. of New Mexico	Albuquerque, NM, USA
UOEH	Univ. of Occupational and Environmental Health	Kitakyushu, Japan
UPNJ	Upsala College	East Orange, NJ, USA
UPPS	Gustaf Werner Inst.	Uppsala, Sweden
UPR	Univ. of Puerto Rico	Piedras, Puerto Rico

URI	Univ. of Rhode Island	Kingston, RI, USA
USC	Univ. of Southern California	Los Angeles, CA, USA
USCR	Univ. of South Carolina	Columbia, SC, USA
USF	University of San Francisco	San Francisco, CA, USA
USIE	University of Siegen	Siegen, Germany
USTL	Univ. Scientifique et Technologique du Languedoc	Montpellier, France
UTAH	Univ. of Utah	Salt Lake City, UT, USA
UTRE	Univ. of Utrecht	Utrecht, Netherlands
UTRO	Univ. of Trondheim	Dragvoll, Norway
VALE	Univ. de Valencia	Valencia, Spain
VALP	Valparaiso Univ.	Valparaiso, IN, USA
VAND	Vanderbilt Univ.	Nashville, TN, USA
VASS	Vassar College	Poughkeepsie, NY, USA
VICT	Univ. of Victoria	Victoria, BC, Canada
VIEN	Inst. for High Energy Physics, A. A. S.	Vienna, Austria
VIRG	Univ. of Virginia	Charlottesville, VA, USA
VPI	Virginia Polytechnic Inst./State Univ.	Blacksburg, VA, USA
VRIJ	Vrije Univ.	Amsterdam, Netherlands
WAKM	Wakayama Medical College	Wakayama, Japan
WARS	Univ. of Warsaw	Warsaw, Poland
WASE	Sci. and Eng. Research Lab, Waseda Univ.	Tokyo, Japan
WASH	Univ. of Washington	Seattle, WA, USA
WAYN	Wayne State Univ.	Detroit, MI, USA
WESL	Wesleyan Univ.	Middletown, CT, USA
WIEN	Univ. Wien	Wien, Austria
WILL	College of William and Mary	Williamsburg, VA, USA
WINR	Warsaw Inst. of Nuclear Research	Warsaw, Poland
WISC	Univ. of Wisconsin	Madison, WI, USA
WITW	Univ. of the Witwatersrand, Schonland Research Centre	Johannesburg, S. Africa
WMIU	Western Michigan Univ.	Kalamazoo, MI, USA
WONT	Univ. of Western Ontario	London, Canada
WOOD	Woodstock College	Woodstock, MD, USA
WUPG	Gesamthochschule Wuppertal	Wuppertal, Germany
WUPP	Univ. Wuppertal	Wuppertal, Germany
WURZ	Univ. Wurzburg	Wurzburg, Germany
WUSL	Washington Univ.	St. Louis, MO, USA
WYOM	Univ. of Wyoming	Laramie, WY, USA
YALE	Yale Univ.	New Haven, CT, USA
YCC	Yokohama College of Commerce	Yokohama, Japan
YERE	Yerevan Physics Inst.	Yerevan, Armenia (USSR)
YOKO	Yokohama Univ.	Yokohama, Japan
YORK	York Univ.	Toronto, ON, Canada
ZAGR	Inst. Rudjer Boskovic	Zagreb, Croatia (Yugoslavia)
ZARA	Univ. of Zaragosa	Zaragosa, Spain
ZEEM	Zeeman Lab., Univ. of Amsterdam	Amsterdam, Netherlands
ZURI	Univ. Zurich	Zurich, Switzerland

IV.8

GAUGE AND HIGGS BOSONS

Notes in the Gauge and Higgs Boson Listings

GAUGE AND HIGGS BOSONS

γ

$I(J^{PC}) = 0,1(1^{--})$

γ MASS

For a review of the photon mass, see BYRNE 77.

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
$<3 \times 10^{-33}$		CHIBISOV	76		Galactic mag. field
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<6 \times 10^{-22}$	99.7	DAVIS	75		Jupiter magfield
$<7.3 \times 10^{-22}$		HOLLWEG	74		Alfven waves
$<6 \times 10^{-23}$		[1] FRANKEN	71		Low freq. res. cir.
$<1 \times 10^{-20}$		WILLIAMS	71	CNTR	Tests Gauss law
$<2.3 \times 10^{-21}$		GOLDHABER	68		Satellite data
$<6 \times 10^{-21}$		[1] PATEL	65		Satellite data
$<6 \times 10^{-21}$		GINTSBURG	64		Satellite data

[1] Validity questionable. See criticism in KROLL 71 and GOLDHABER 71.

γ CHARGE

VALUE (10^{-32} e)	DOCUMENT ID		TECN	COMMENT
<2	COCCONI	88	TOF	Pulsar f_1, f_2 TOF

REFERENCES FOR γ

COCCONI	88	PL B206 705		(CERN)
BYRNE	77	Ast.Sp.Sci. 46 115		(LOIC)
CHIBISOV	76	SPU 19 624		(LEBD)
DAVIS	75	PRL 35 1402	+Goldhaber, Nieto	(CIT, STON, LASL)
HOLLWEG	74	PRL 32 961		(NCAR)
FRANKEN	71	PRL 26 115	+Ampulski	(MICH)
GOLDHABER	71	RMP 43 277	+Nieto	(STON, BOHR, UCSB)
KROLL	71	PRL 26 1395		(SLAC)
WILLIAMS	71	PRL 26 721	+Faller, Hill	(WESL)
GOLDHABER	68	PRL 21 567	+Nieto	(STON)
PATEL	65	PL 14 105		(DUKE)
GINTSBURG	64	Sov. Astr. AJ7 536		(ASCI)

W

$J = 1$

W MASS

The fit uses the W and Z mass, mass difference, and mass ratio measurements.

VALUE (GeV)	EVTS	DOCUMENT ID		TECN	COMMENT
80.22± 0.26 OUR FIT					
80.1 ± 0.4 OUR AVERAGE					
80.84± 0.22±0.83	2065	[1] ALITTI	92B	UA2	$E_{cm}^{p\bar{p}}$= 630 GeV
79.91± 0.39	1722	[2] ABE	90G	CDF	$E_{cm}^{p\bar{p}}$= 1800 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
80.79± 0.31±0.84		[3] ALITTI	90B	UA2	$E_{cm}^{p\bar{p}}$= 546,630 GeV
80.0 ± 3.3 ±2.4	22	[4] ABE	89I	CDF	$E_{cm}^{p\bar{p}}$= 1800 GeV
82.7 ± 1.0 ±2.7	149	[5] ALBAJAR	89	UA1	$E_{cm}^{p\bar{p}}$= 546,630 GeV
$81.8 {}^{+6.0}_{-5.3} \pm 2.6$	46	[6] ALBAJAR	89	UA1	$E_{cm}^{p\bar{p}}$= 546,630 GeV
89 ± 3 ±6	32	[7] ALBAJAR	89	UA1	$E_{cm}^{p\bar{p}}$= 546,630 GeV
80.2 ± 0.6 ±1.4	251	[8] ANSARI	87	UA2	Repl. by ALITTI 90B
81.2 ± 1.0 ±1.4	119	[8] APPEL	86	UA2	Repl. by ANSARI 87
$83.5 {}^{+1.1}_{-1.0} \pm 2.7$	86	[9] ARNISON	86	UA1	Repl. by ALBAJAR 89
$81. {}^{+6.}_{-7.}$	14	[10] ARNISON	84D	UA1	Repl. by ALBAJAR 89
83.1 ± 1.9 ±1.3	37	BAGNAIA	84	UA2	Repl. by ALITTI 90B
81. ± 5.	6	ARNISON	83	UA1	Repl. by ARNISON 83D
80.9 ± 2.9	27	ARNISON	83D	UA1	Repl. by ARNISON 86
81.0 ± 2.8		BAGNAIA	83	UA2	Repl. by BAGNAIA 84
$80. {}^{+10.}_{-6.}$	4	BANNER	83B	UA2	Repl. by ALITTI 90B

[1] ALITTI 92B result has two contributions to the systematic error (±0.83); one (±0.81) cancels in $m(W)/m(Z)$ and one (±0.17) is noncancelling. These were added in quadrature. We choose the ALITTI 92B value without using the LEP $m(Z)$ value, because we perform our own combined fit.

[2] ABE 90G result from $W \rightarrow e\nu$ is 79.91 ± 0.35 ± 0.24±0.19(scale) GeV and from $W \rightarrow \mu\nu$ is 79.90 ± 0.53 ± 0.32 ± 0.08(scale) GeV.

[3] There are two contributions to the systematic error (±0.84): one (±0.81) which cancels in $m(W)/m(Z)$ and one (±0.21) which is non-cancelling. These were added in quadrature.

[4] ABE 89I systematic error dominated by the uncertainty in the absolute energy scale.

[5] ALBAJAR 89 result is from a total sample of 299 $W \rightarrow e\nu$ events.

[6] ALBAJAR 89 result is from a total sample of 67 $W \rightarrow \mu\nu$ events.

[7] ALBAJAR 89 result is from $W \rightarrow \tau\nu$ events.

[8] There are two contributions to the systematic error (±1.4): one (±1.3) which cancels in $m(W)/m(Z)$ and one (±0.5) which is non-cancelling. These were added in quadrature.

[9] This is enhanced subsample of 172 total events.

[10] Using $W^{\pm} \rightarrow \mu^{\pm}\nu$.

$W^+ - W^-$ MASS DIFFERENCE

VALUE (GeV)	EVTS	DOCUMENT ID		TECN	COMMENT
−0.19±0.58	1722	ABE	90G	CDF	$E_{cm}^{p\bar{p}}$= 1800 GeV

W WIDTH

The widths labelled "extracted value" are obtained by measuring $R = \sigma(W \rightarrow e\nu)/\sigma(Z \rightarrow e^+e^-)$ which is equal to $[\sigma(W)/\sigma(Z)]$ $[\Gamma(W \rightarrow e\nu)/\Gamma(Z \rightarrow ee)]$ $\Gamma(Z)/\Gamma(W)$. The bracketed quantities can be calculated with plausible reliability. $\Gamma(W)$ is then extracted by using a value of $\Gamma(Z)$ measured at LEP.

VALUE (GeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
2.12±0.11 OUR AVERAGE						
$2.10 {}^{+0.14}_{-0.13} \pm 0.09$		3559	[11] ALITTI	92	UA2	Extracted value
$2.18 {}^{+0.26}_{-0.24} \pm 0.04$			[12] ALBAJAR	91	UA1	Extracted value
2.12±0.20			[13] ABE	90	CDF	Extracted value
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2.30±0.19±0.06			[14] ALITTI	90C	UA2	Extracted value
<5.4	90	149	[15] ALBAJAR	89	UA1	$E_{cm}^{p\bar{p}}$= 546,630 GeV
$2.8 {}^{+1.4}_{-1.5} \pm 1.3$		149	[15] ALBAJAR	89	UA1	$E_{cm}^{p\bar{p}}$= 546,630 GeV
<7	90	251	ANSARI	87	UA2	$E_{cm}^{p\bar{p}}$= 546,630 GeV
<7	90	119	APPEL	86	UA2	$E_{cm}^{p\bar{p}}$= 546,630 GeV
<6.5	90	86	[16] ARNISON	86	UA1	Repl. by ALBAJAR 89
<7	90	27	ARNISON	83D	UA1	Repl. by ARNISON 86

[11] ALITTI 92 measured $R = 10.4^{+0.7}_{-0.6} \pm 0.3$. The values of $\sigma(Z)$ and $\sigma(W)$ come from $O(\alpha_s^2)$ calculations using $m(W) = 80.14 \pm 0.27$ GeV, and $m(Z) = 91.175 \pm 0.021$ GeV along with the corresponding value of $\sin^2\theta_W = 0.2274$. They use $\sigma(W)/\sigma(Z) = 3.26 \pm 0.07 \pm 0.05$ and $\Gamma(Z) = 2.487 \pm 0.010$ GeV.

[12] ALBAJAR 91 measured $R = 9.5^{+1.1}_{-1.0}$ (stat. + syst.). $\sigma(W)/\sigma(Z)$ is calculated in QCD at the parton level using $m(W) = 80.18 \pm 0.28$ GeV and $m(Z) = 91.172 \pm 0.031$ GeV along with $\sin^2\theta_W = 0.2322 \pm 0.0014$. They use $\sigma(W)/\sigma(Z) = 3.23 \pm 0.05$ and $\Gamma(Z) = 2.498 \pm 0.020$ GeV.

[13] ABE 90 extract $\Gamma(W) = 2.19 \pm 0.20$ by using the value $\Gamma(Z) = 2.57 \pm 0.07$ GeV. However, in ABE 91C they update their analysis with a new LEP value $\Gamma(Z) = 2.496 \pm 0.016$; the value $\Gamma(W) = 2.12 \pm 0.20$ above reflects this update. They measured $R = 10.2 \pm 0.8 \pm 0.4$, assumed $\sin^2\theta_W = 0.229 \pm 0.007$, and took predicted values $\sigma(W)/\sigma(Z) = 3.23 \pm 0.03$ and $\Gamma(W \rightarrow e\nu)/\Gamma(Z \rightarrow ee) = 2.70 \pm 0.02$. This yields $\Gamma(W)/\Gamma(Z) = 0.85 \pm 0.08$. The quoted error for $\Gamma(W)$ includes systematic uncertainties. $E_{cm}^{p\bar{p}} = 1800$ GeV.

[14] ALITTI 90C used the same technique as described for ABE 90. They measured $R = 9.38^{+0.82}_{-0.72} \pm 0.25$, obtained $\Gamma(W)/\Gamma(Z) = 0.902 \pm 0.074 \pm 0.024$. Using $\Gamma(Z) = 2.546 \pm 0.032$ GeV, they obtained the $\Gamma(W)$ value quoted above and the limits $\Gamma(W) < 2.56$ (2.64) GeV at the 90% (95%) CL. $E_{cm}^{p\bar{p}} = 546{,}630$ GeV.

[15] ALBAJAR 89 result is from a total sample of 299 $W \rightarrow e\nu$ events.

[16] If systematic error is neglected, result is $2.7^{+1.4}_{-1.5}$ GeV. This is enhanced subsample of 172 total events.

W ANOMALOUS MAGNETIC MOMENT ($\Delta\kappa$)

The full magnetic moment is given by $\mu_W = e(1+\kappa+\lambda)/2m(W)$. In the Standard Model, at tree level, $\kappa = 1$ and $\lambda = 0$. Some papers have defined $\Delta\kappa = 1-\kappa$ and assume that $\lambda = 0$. Note that the electric quadrupole moment is given by $-e(\kappa-\lambda)/m^2(W)$. A description of the parameterization of these moments and additional references can be found in HAGIWARA 87 and BAUR 88. The parameter Λ appearing in the theoretical limits below is a regularization cutoff which roughly corresponds to the energy scale where the structure of the W boson becomes manifest.

VALUE ($e/2m(W)$)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[17] ALITTI	92C	UA2
	[18] SAMUEL	92	THEO
	[19] SAMUEL	91	THEO
	[20] GRIFOLS	88	THEO
	[21] GROTCH	87	THEO
	[22] VANDERBIJ	87	THEO
	[23] GRAU	85	THEO
	[24] SUZUKI	85	THEO
	[25] HERZOG	84	THEO

[17] ALITTI 92C measure $\kappa = 1^{+2.6}_{-2.2}$ and $\lambda = 0^{+1.7}_{-1.8}$ in $p\overline{p} \rightarrow e\nu\gamma + X$ at $\sqrt{s} = 630$ GeV. At 95%CL they report $-3.5 < \kappa < 5.9$ and $-3.6 < \lambda < 3.5$.

[18] SAMUEL 92 use preliminary CDF and UA2 data and find $-2.4 < \kappa < 3.7$ at 96%CL and $-3.1 < \kappa < 4.2$ at 95%CL respectively. They use data for $W\gamma$ production and radiative W decay.

[19] SAMUEL 91 use preliminary CDF data for $p\overline{p} \rightarrow W\gamma X$ to obtain $-11.3 \leq \Delta\kappa \leq 10.9$. Note that their $\kappa = 1-\Delta\kappa$.

[20] GRIFOLS 88 uses deviation from ρ parameter to set limit $\Delta\kappa \lesssim 65\ (M_W^2/\Lambda^2)$.

[21] GROTCH 87 finds the limit $-37 < \Delta\kappa < 73.5$ (90% CL) from the experimental limits on $e^+e^- \rightarrow \nu\overline{\nu}\gamma$ assuming three neutrino generations and $-19.5 < \Delta\kappa < 56$ for four generations. Note their $\Delta\kappa$ has the opposite sign as our definition.

[22] VANDERBIJ 87 uses existing limits to the photon structure to obtain $|\Delta\kappa| < 33\ (m(W)/\Lambda)$. In addition VANDERBIJ 87 discusses problems with using the ρ parameter of the Standard Model to determine $\Delta\kappa$.

[23] GRAU 85 uses the muon anomaly to derive a coupled limit on the anomalous magnetic dipole and electric quadrupole (λ) moments $1.05 > \Delta\kappa\ \ln(\Lambda/m(W)) + \lambda/2 > -2.77$. In the Standard Model $\lambda = 0$.

[24] SUZUKI 85 uses partial-wave unitarity at high energies to obtain $|\Delta\kappa| \lesssim 190\ (m(W)/\Lambda)^2$. From the anomalous magnetic moment of the muon, SUZUKI 85 obtains $|\Delta\kappa| \lesssim 2.2/\ln(\Lambda/m(W))$. Finally SUZUKI 85 uses deviations from the ρ parameter and obtains a very qualitative, order-of-magnitude limit $|\Delta\kappa| \lesssim 150\ (m(W)/\Lambda)^4$ if $|\Delta\kappa| \ll 1$.

[25] HERZOG 84 consider the contribution of W-boson to muon magnetic moment including anomalous coupling of $WW\gamma$. Obtain a limit $-1 < \Delta\kappa < 3$ for $\Lambda \gtrsim 1$ TeV.

W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$e^+\nu$	(10.5 ± 0.9) %	
Γ_2	$e^+\nu\gamma$	[a] < 1.1 %	90%
Γ_3	$\mu^+\nu$	(10.5 ± 1.9) %	
Γ_4	$\mu^+\nu\gamma$		
Γ_5	$\tau^+\nu$	(10.6 ± 1.6) %	
Γ_6	$\pi^\pm\gamma$	$< 5 \times 10^{-4}$	95%

[a] See the Listings below for the γ energy range used in this measurement.

W BRANCHING RATIOS

$\Gamma(e^+\nu)/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.105±0.009 OUR AVERAGE				
0.106±0.0096	2426	[26] ABE 91C	CDF	$E_{cm}^{p\overline{p}}$= 1800 GeV
$0.10\ \pm0.014\ ^{+0.02}_{-0.03}$	248	[27] ANSARI 87C	UA2	$E_{cm}^{p\overline{p}}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	299	[28] ALBAJAR 89	UA1	$E_{cm}^{p\overline{p}}$= 546,630 GeV
seen	119	APPEL 86	UA2	$E_{cm}^{p\overline{p}}$= 546,630 GeV
seen	172	ARNISON 86	UA1	Repl. by ALBAJAR 89

[26] ABE 91C result is from a measurement of $\sigma B(W \rightarrow e\nu)/\sigma B(Z \rightarrow e^+e^-)$, the theoretical prediction for the cross section ratio, and the experimental knowledge of $\Gamma(Z \rightarrow e^+e^-)/\Gamma(Z \rightarrow \text{all})$.

[27] The first error was obtained by adding the statistical and systematic experimental uncertainties in quadrature. The second error reflects the dependence on theoretical prediction of total W cross section: σ(546 GeV) $= 4.7^{+1.4}_{-0.7}$ nb and σ(630 GeV) $= 5.8^{+1.8}_{-1.0}$ nb. See ALTARELLI 85B.

[28] ALBAJAR 89 experiment determines values of branching ratio times production cross section.

$\Gamma(e^+\nu\gamma)/\Gamma(e^+\nu)$ — Γ_2/Γ_1

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.1	90	1	[29] ARNISON 84	UA1	$E_{cm}^{p\overline{p}}$= 546 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none in 119 $W \rightarrow e\nu$ evts		0	APPEL 86	UA2	$E_{cm}^{p\overline{p}}$= 546,630 GeV

[29] After accounting for selection efficiency and geometric acceptance, and requiring $E_T(\gamma) > 10$ GeV. ARNISON 84 $W \rightarrow e\nu\gamma$ one event in 52 $W \rightarrow e\nu$ events is consistent with QED Bremsstrahlung. Mass not restricted to W mass.

$\Gamma(\mu^+\nu)/\Gamma(e^+\nu)$ — Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.00±0.14±0.08	67	ALBAJAR 89	UA1	$E_{cm}^{p\overline{p}}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.24^{+0.6}_{-0.4}$	14	ARNISON 84D	UA1	Repl. by ALBAJAR 89

$\Gamma(\mu^+\nu\gamma)/\Gamma_{total}$ — Γ_4/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
none in 18 $W \rightarrow \mu\nu$ evts	0	[30] ARNISON 84	UA1	$E_{cm}^{p\overline{p}}$= 546 GeV

[30] Mass not restricted to W mass.

$\Gamma(\tau^+\nu)/\Gamma(e^+\nu)$ — Γ_5/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.00 ±0.12 OUR AVERAGE				
0.995±0.112±0.083	198	ALITTI 91C	UA2	$E_{cm}^{p\overline{p}}$= 630 GeV
1.02 ±0.20 ±0.12	32	ALBAJAR 89	UA1	$E_{cm}^{p\overline{p}}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.02 ±0.20 ±0.10	32	ALBAJAR 87	UA1	Repl. by ALBAJAR 89

$\Gamma(\pi^\pm\gamma)/\Gamma(e^+\nu)$ — Γ_6/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<4.9 $\times 10^{-3}$	95	[31] ALITTI 92D	UA2	$E_{cm}^{p\overline{p}}$= 630 GeV
<0.058	95	[32] ALBAJAR 90	UA1	$E_{cm}^{p\overline{p}}$= 546, 630 GeV

[31] ALITTI 92D limit is 3.8×10^{-3} at 90%CL.
[32] ALBAJAR 90 obtain < 0.048 at 90%CL.

REFERENCES FOR W

ALITTI	92	PL B (to be pub.) CERN-PPE/91-162	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92B	PL B (to be pub.) CERN-PPE/91-163	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92C	PL B (to be pub.) CERN-PPE/91-216	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92D	PL B (to be pub.) CERN-PPE/91-208	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
SAMUEL	92	PL B (to be pub.)	+Li, Sinha, Sinha, Sundaresan	(OKSU, CARL)
ABE	91C	PR D44 29	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ALBAJAR	91	PL B253 503	+Albrow, Allkofer, Ankoviak, Apsimon+	(UA1 Collab.)
ALITTI	91C	ZPHY C52 209	+Ambrosini, Ansari, Autiero+	(UA2 Collab.)
SAMUEL	91	PRL 67 9	+Li, Sinha, Sinha, Sundaresan	(OKSU, CARL)
Also	91C	PRL 67 2920 erratum		
ABE	90	PRL 64 152	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
Also	91C	PR D44 29	Abe, Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	90G	PRL 65 2243	+Amidei, Apollinari, Atac+	(CDF Collab.)
Also	91B	PR D43 2070	Abe, Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ALBAJAR	90	PL B241 283	+Albrow, Allkofer+	(UA1 Collab.)
ALITTI	90B	PL B241 150	+Ansari, Ansorge, Autiero+	(UA2 Collab.)
ALITTI	90C	ZPHY C47 11	+Ansari, Ansorge, Bagnaia+	(UA2 Collab.)
ABE	89I	PRL 62 1005	+Amidei, Apollinari, Ascoli, Atac+	(CDF Collab.)
ALBAJAR	89	ZPHY C44 15	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
BAUR	88	NP B308 127	+Zeppenfeld	(FSU, WISC)
GRIFOLS	88	IJMP A3 225	+Peris, Sola	(BARC, DESY)
Also	87	PL B197 437	Grifols, Peris, Sola	(BARC, DESY)
ALBAJAR	87	PL B185 233	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
ANSARI	87	PL B186 440	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
ANSARI	87C	PL B194 158	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
GROTCH	87	PR D36 2153	+Robinett	(PSU)
HAGIWARA	87	NP B282 253	+Peccei, Zeppenfeld, Hikasa	(KEK, UCLA, FSU)
VANDERBIJ	87	PR D35 1088	van der Bij	(FNAL)
APPEL	86	ZPHY C30 1	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
ARNISON	86	PL 166B 484	+Albrow, Allkofer, Astbury+	(UA1 Collab.) J
ALTARELLI	85B	ZPHY C27 617	+Ellis, Martinelli	(CERN, FNAL, FRAS)
GRAU	85	PL 154B 283	+Grifols	(BARC)
SUZUKI	85	PL 153B 289		(LBL)
ARNISON	84	PL 135B 250	+Astbury, Aubert, Bacci+	(UA1 Collab.)
ARNISON	84D	PL 134B 469	+Astbury, Aubert, Bacci+	(UA1 Collab.)
BAGNAIA	84	ZPHY C24 1	+Banner, Battiston, Blech+	(UA2 Collab.)
HERZOG	84	PL 148B 355		(WISC)
Also	84B	PL 155B 468 erratum	Herzog	(WISC)
ARNISON	83	PL 122B 103	+Astbury, Aubert, Bacci+	(UA1 Collab.)
ARNISON	83D	PL 129B 273	+Astbury, Aubert, Bacci+	(UA1 Collab.)
BAGNAIA	83	PL 129B 130	+Banner, Battiston, Bloch+	(UA2 Collab.)
BANNER	83B	PL 122B 476	+Battiston, Bloch, Bonaudi+	(UA2 Collab.)

Z

$J = 1$

NOTE ON THE Z MASS

(by S. Willenbrock, Brookhaven National Laboratory)

The Z-boson mass values reported below are determined by fitting the e^+e^- cross section near the Z-boson resonance to a Breit-Wigner formula, including the background from single-photon exchange, and correcting for initial-state radiation. The Z-boson propagator is represented by a term in the amplitude proportional to

$$\frac{1}{s - M_Z^2 + is\Gamma_Z/M_Z} \ ,$$

where the energy dependence of the imaginary part is motivated by gauge field theory.

Fundamentally, an unstable particle, such as the Z boson, is associated with a (complex) pole in the S matrix; the pole position is process independent and gauge invariant. The mass,

M, and width, Γ, of an unstable particle are defined in terms of the position of the pole in the s plane; conventionally,

$$s_0 = (M - \frac{i}{2}\Gamma)^2 \ .$$

M does not correspond to the Breit-Wigner resonance parameter M_Z; rather,

$$M = M_Z\left[1 - \frac{3}{8}\frac{\Gamma_Z^2}{M_Z^2} + \mathcal{O}\left(\frac{\Gamma_Z^4}{M_Z^4}\right)\right] \ ,$$

i.e., M is 25 MeV less than the Z-boson mass values reported here.[1–3] The difference between the two masses is greater than the experimental uncertainty in M_Z. The width, Γ, lies 1.2 MeV below Γ_Z; this difference is much less than the experimental uncertainty in Γ_Z.

References

1. S. Willenbrock and G. Valencia, Phys. Lett. **B259**, 373 (1991).
2. R. Stuart, Phys. Lett. **B262**, 113 (1991).
3. A. Sirlin, Phys. Rev. Lett. **67**, 2127 (1991).

Z MASS

The fit uses the W and Z mass, mass difference, and mass ratio (see below) measurements. The Z-boson mass listed here corresponds to a Breit-Wigner resonance parameter. The value is 25 MeV greater than the real part of the position of the pole (in the energy plane) in the Z-boson propagator.

VALUE (GeV)	EVTS	DOCUMENT ID		TECN	COMMENT
91.173±0.020 OUR FIT					
91.173±0.020 OUR AVERAGE					
91.182±0.009±0.02	190k	[1] DECAMP	92B	ALEP	$E^{ee}_{\rm cm}$= 88–94 GeV
91.177±0.010±0.02	150k	[1] ABREU	91F	DLPH	$E^{ee}_{\rm cm}$= 88–94 GeV
91.181±0.010±0.02	125k	[1] ADEVA	91E	L3	$E^{ee}_{\rm cm}$= 88–94 GeV
91.161±0.009±0.02	184k	[1] ALEXANDER	91F	OPAL	$E^{ee}_{\rm cm}$= 88–94 GeV
90.9 ±0.3 ±0.2	188	[2] ABE	89C	CDF	$E^{p\overline{p}}_{\rm cm}$= 1800 GeV
91.14 ±0.12	480	[3] ABRAMS	89B	MRK2	$E^{ee}_{\rm cm}$= 89–93 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
91.74 ±0.28 ±0.93	156	[4] ALITTI	92B	UA2	$E^{p\overline{p}}_{\rm cm}$= 630 GeV
91.175±0.021		[5] LEP	92	RVUE	$E^{ee}_{\rm cm}$= 88–94 GeV
91.171±0.030±0.030	11k	[6] ABREU	90	DLPH	$E^{ee}_{\rm cm}$= 88–95 GeV
89.2 $^{+2.1}_{-1.8}$		[7] ADACHI	90F	RVUE	$E^{ee}_{\rm cm}$< 61.4 GeV
91.160±0.024±0.030	17k	[6] ADEVA	90C	L3	$E^{ee}_{\rm cm}$= 88–95 GeV
91.161±0.013±0.030		[6,8] ADEVA	90I	L3	$E^{ee}_{\rm cm}$= 88–95 GeV
91.154±0.021±0.030	28k	[6] AKRAWY	90E	OPAL	$E^{ee}_{\rm cm}$= 88–95 GeV
91.49 ±0.35 ±0.93		[4] ALITTI	90B	UA2	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
91.182±0.026±0.030	20k	[6] DECAMP	90D	ALEP	$E^{ee}_{\rm cm}$= 88–95 GeV
91.193±0.016±0.030	62.5k	[6] DECAMP	90P	ALEP	$E^{ee}_{\rm cm}$= 88–95 GeV
93.1 ±1.0 ±3.0	24	[9,10] ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
90.7 $^{+5.2}_{-4.8}$ ±3.2	14	[11] ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
89.3 ±1.5		[12] DAGOSTINI	89	RVUE	$E^{ee}_{\rm cm}$< 57 GeV
88.6 $^{+2.0}_{-1.8}$		[13] MORI	89	RVUE	$E^{ee}_{\rm cm}$ ≤ 57 GeV

[1] The systematic error (0.02) is an error in common to the 4 LEP experiments.
[2] First error of ABE 89 is combination of statistical and systematic contributions; second is mass scale uncertainty.
[3] ABRAMS 89B uncertainty includes 35 MeV due to the absolute energy measurement.
[4] Enters fit through W/Z mass ratio below. The ALITTI 92B systematic error (±0.93) has two contributions: one (±0.92) cancels in $m(W)/m(Z)$ and one (±0.12) is noncancelling. These were added in quadrature.
[5] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.
[6] The systematic error (0.03) is an error in common to the 4 LEP experiments.
[7] ADACHI 90F combine TOPAZ data with PEP and PETRA data to get mass value.
[8] ADEVA 90I result from a simultaneous fit to hadron and muon data.
[9] Enters fit through Z-W mass difference below.
[10] ALBAJAR 89 result is from a total sample of 33 $Z \to e^+e^-$ events.
[11] ALBAJAR 89 result is from a total sample of 19 $Z \to \mu^+\mu^-$ events.
[12] DAGOSTINI 89 result assumes $\sin^2\theta_W = 0.231$ and m(top) = 60 GeV. Result lowered by 1 GeV for m(top) = 180 GeV. Fit uses data from TRISTAN and lower energy experiments.
[13] MORI 89 result is from all then existing measurements of R below the Z region including AMY, VENUS, and TOPAZ at TRISTAN plus data from PEP, PETRA, CESR, and DORIS. Assuming $\Gamma(Z)$ = 2.5 GeV and Δr = 0.070.

W/Z MASS RATIO

The fit uses the W and Z mass, mass difference, and mass ratio measurements.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.8798±0.0028 OUR FIT					
0.8813±0.0036±0.0019	156	[14] ALITTI	92B	UA2	$E^{p\overline{p}}_{\rm cm}$= 630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.8831±0.0048±0.0026		[14] ALITTI	90B	UA2	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV

[14] Scale error cancels in this ratio.

Z − W MASS DIFFERENCE

The fit uses the W and Z mass, mass difference, and mass ratio measurements.

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.96±0.26 OUR FIT				
10.4 ±1.4 ±0.8	ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
11.3 ±1.3 ±0.9	ANSARI	87	UA2	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV

Z WIDTH

The fit is calculated using the Z width, $\Gamma(e^+e^-)$, $\Gamma(\mu^+\mu^-)/\Gamma$(hadrons), $\Gamma(\tau^+\tau^-)/\Gamma$(hadrons), B(hadrons), and other quantities with lesser statistical significance. We believe that this set is the most free of systematic errors and of correlations.

VALUE (GeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2.487±0.010 OUR FIT					
2.487±0.010 OUR AVERAGE					
2.484±0.017±0.005	190k	[15] DECAMP	92B	ALEP	$E^{ee}_{\rm cm}$= 88–94 GeV
2.465±0.019±0.005	150k	[15] ABREU	91F	DLPH	$E^{ee}_{\rm cm}$= 88–94 GeV
2.501±0.017±0.005	125k	[15] ADEVA	91E	L3	$E^{ee}_{\rm cm}$= 88–94 GeV
2.492±0.016±0.005	184k	[15] ALEXANDER	91F	OPAL	$E^{ee}_{\rm cm}$= 88–94 GeV
3.8 ±0.8 ±1.0	188	ABE	89C	CDF	$E^{p\overline{p}}_{\rm cm}$= 1800 GeV
2.42 $^{+0.45}_{-0.35}$	480	[16] ABRAMS	89B	MRK2	$E^{ee}_{\rm cm}$= 89–93 GeV
2.7 $^{+1.2}_{-1.0}$ ±1.3	24	[17] ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
2.7 ±2.0 ±1.0	25	[18] ANSARI	87	UA2	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.487±0.010		[19] LEP	92	RVUE	$E^{ee}_{\rm cm}$= 88–94 GeV
2.511±0.065	11k	ABREU	90	DLPH	$E^{ee}_{\rm cm}$= 88–95 GeV
2.539±0.054	17k	ADEVA	90C	L3	$E^{ee}_{\rm cm}$= 88–95 GeV
2.492±0.025	89k	ADEVA	90I	L3	$E^{ee}_{\rm cm}$= 88–95 GeV
2.536±0.045	28k	AKRAWY	90E	OPAL	$E^{ee}_{\rm cm}$= 88–95 GeV
2.541±0.056	20k	DECAMP	90D	ALEP	$E^{ee}_{\rm cm}$= 88–95 GeV
2.497±0.031±0.005	62.5k	[15] DECAMP	90P	ALEP	$E^{ee}_{\rm cm}$= 88–95 GeV

[15] The systematic error (0.005) is an error in common to the 4 LEP experiments.
[16] ABRAMS 89B uncertainty includes 50 MeV due to the miniSAM background subtraction error.
[17] ALBAJAR 89 result is from a total sample of 33 $Z \to e^+e^-$ events.
[18] Quoted values of ANSARI 87 are from direct fit. Ratio of Z and W production gives either $\Gamma(Z) < (1.09 \pm 0.07) \times \Gamma(W)$, CL = 90% or $\Gamma(Z) = (0.82^{+0.19}_{-0.14} \pm 0.06) \times \Gamma(W)$. Assuming Standard-Model value $\Gamma(W)$ = 2.65 GeV then gives $\Gamma(Z) < 2.89 \pm 0.19$ or $= 2.17^{+0.50}_{-0.37} \pm 0.16$.
[19] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.

Z DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	e^+e^-	(3.345±0.025) %	
Γ_2	$\mu^+\mu^-$	(3.34 ±0.04) %	S=1.3
Γ_3	$\tau^+\tau^-$	(3.32 ±0.04) %	
Γ_4	$\ell^+\ell^-$	(3.337±0.022) %	S=1.1
Γ_5	$\nu\overline{\nu}$ (or other invisible modes)	(20.2 ±0.4) %	
Γ_6	hadrons	(69.80 ±0.33) %	
Γ_7	$(u\overline{u} + c\overline{c})/2$	(13.3 ±3.5) %	
Γ_8	$(d\overline{d} + s\overline{s} + b\overline{b})/3$	(14.4 ±2.4) %	
Γ_9	$c\overline{c}$	(12.6 ±2.1) %	
Γ_{10}	$b\overline{b}$	(15.2 ±1.0) %	
Γ_{11}	$\pi^0\gamma$	< 1.4 $\times 10^{-4}$	CL=95%
Γ_{12}	$\eta\gamma$	< 5.1 $\times 10^{-5}$	CL=95%
Γ_{13}	$\eta'(958)\gamma$	< 4.2 $\times 10^{-5}$	CL=95%

Γ_{14}	$\gamma\gamma$		$<$ 1.4	$\times 10^{-4}$	CL=95%
Γ_{15}	$\gamma\gamma\gamma$		$<$ 6.6	$\times 10^{-5}$	CL=95%
Γ_{16}	$\pi^{\pm} W^{\mp}$		$<$ 7	$\times 10^{-5}$	CL=95%
Γ_{17}	$\rho^{\pm} W^{\mp}$		$<$ 8.3	$\times 10^{-5}$	CL=95%
Γ_{18}	$J/\psi(1S)$ X		(4.5 $\pm$1.1)	$\times 10^{-3}$	
Γ_{19}	$D^*(2010)^{\pm}$ X		(18.1 $\pm$3.5)	%	
Γ_{20}	anomalous γ + hadrons		[a] $<$ 3.2	$\times 10^{-3}$	CL=95%
Γ_{21}	$e^+e^-\gamma$		[a] $<$ 5.2	$\times 10^{-4}$	CL=95%
Γ_{22}	$\mu^+\mu^-\gamma$		[a] $<$ 5.6	$\times 10^{-4}$	CL=95%
Γ_{23}	$\tau^+\tau^-\gamma$		[a] $<$ 7.3	$\times 10^{-4}$	CL=95%
Γ_{24}	$e^{\pm}\mu^{\mp}$	LF	$<$ 2.4	$\times 10^{-5}$	CL=95%
Γ_{25}	$e^{\pm}\tau^{\mp}$	LF	$<$ 3.4	$\times 10^{-5}$	CL=95%
Γ_{26}	$\mu^{\pm}\tau^{\mp}$	LF	$<$ 4.8	$\times 10^{-5}$	CL=95%

[a] See the Listings below for the γ energy range used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to the total width, a partial width, and 7 branching ratios uses 31 measurements and one constraint to determine 6 parameters. The overall fit has a $\chi^2 = 12.3$ for 26 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta p_i \delta p_j \rangle / (\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	0				
x_3	0	16			
x_5	−7	−48	−48		
x_6	0	39	40	−99	
Γ	−54	0	0	4	0
	x_1	x_2	x_3	x_5	x_6

	Mode	Rate (GeV)	Scale factor
Γ_1	e^+e^-	0.0832$\pm$0.0005	
Γ_2	$\mu^+\mu^-$	0.0831$\pm$0.0011	1.2
Γ_3	$\tau^+\tau^-$	0.0826$\pm$0.0010	
Γ_5	$\nu\overline{\nu}$ (or other invisible modes)	0.502 $\pm$0.009	
Γ_6	hadrons	1.736 $\pm$0.011	

Z PARTIAL WIDTHS

The fit is calculated using the Z width, $\Gamma(e^+e^-)$, $\Gamma(\mu^+\mu^-)/\Gamma$(hadrons), $\Gamma(\tau^+\tau^-)/\Gamma$(hadrons), B(hadrons), and other quantities with lesser statistical significance. We believe that this set is the most free of systematic errors and of correlations.

$\Gamma(e^+e^-)$ — Γ_1

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
83.2 ±0.5 OUR FIT				
83.2 ±0.5 OUR AVERAGE				
83.8 ±0.9	6947	DECAMP	92B ALEP	E^{ee}_{cm}= 88–94 GeV
82.4 ±1.1 ±0.5	2772	ABREU	91F DLPH	E^{ee}_{cm}= 88–94 GeV
83.3 ±1.1	4175	ADEVA	91E L3	E^{ee}_{cm}= 88–94 GeV
82.9 ±1.0	5507	ALEXANDER	91F OPAL	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
83.20±0.55		[20] LEP	92 RVUE	E^{ee}_{cm}= 88–94 GeV

[20] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.

$\Gamma(\mu^+\mu^-)$ — Γ_2

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
83.1 ±1.1 OUR FIT Error includes scale factor of 1.2.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
81.4 ±1.4	6691	DECAMP	92B ALEP	E^{ee}_{cm}= 88–94 GeV
83.35±0.86		[21] LEP	92 RVUE	E^{ee}_{cm}= 88–94 GeV
86.9 ±1.9 ±0.9	3428	ABREU	91F DLPH	E^{ee}_{cm}= 88–94 GeV
84.5 ±2.0	3245	ADEVA	91E L3	E^{ee}_{cm}= 88–94 GeV
83.2 ±1.5	7240	ALEXANDER	91F OPAL	E^{ee}_{cm}= 88–94 GeV

[21] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.

$\Gamma(\tau^+\tau^-)$ — Γ_3

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
82.6 ±1.0 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
82.4 ±1.6	6260	DECAMP	92B ALEP	E^{ee}_{cm}= 88–94 GeV
82.76±1.02		[22] LEP	92 RVUE	E^{ee}_{cm}= 88–94 GeV
82.7 ±2.1 ±1.1	2345	ABREU	91F DLPH	E^{ee}_{cm}= 88–94 GeV
84.0 ±2.7	2540	ADEVA	91E L3	E^{ee}_{cm}= 88–94 GeV
82.7 ±1.9	5559	ALEXANDER	91F OPAL	E^{ee}_{cm}= 88–94 GeV

[22] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.

$\Gamma(\ell^+\ell^-)$ — $(\frac{1}{3}\Gamma_1+\frac{1}{3}\Gamma_2+\frac{1}{3}\Gamma_3)$

Our fit is an average of e^+e^-, $\mu^+\mu^-$, and $\tau^+\tau^-$, whereas the LEP numbers shown are the result of a fit requiring lepton universality.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
83.0 ±0.6 OUR FIT Error includes scale factor of 1.1.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
83.1 ±0.7	20k	DECAMP	92B ALEP	E^{ee}_{cm}= 88–94 GeV
83.24±0.42		[23] LEP	92 RVUE	E^{ee}_{cm}= 88–94 GeV
83.4 ±0.8	10k	ABREU	91F DLPH	E^{ee}_{cm}= 88–94 GeV
83.6 ±0.8	10k	ADEVA	91E L3	E^{ee}_{cm}= 88–94 GeV
83.0 ±0.7	18k	ALEXANDER	91F OPAL	E^{ee}_{cm}= 88–94 GeV

[23] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.

Γ(hadrons) — Γ_6

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1736±11 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1744±15	165k	DECAMP	92B ALEP	E^{ee}_{cm}= 88–94 GeV
1740±12		[24] LEP	92 RVUE	E^{ee}_{cm}= 88–94 GeV
1726±19	124k	ABREU	91F DLPH	E^{ee}_{cm}= 88–94 GeV
1742±19	115k	ADEVA	91E L3	E^{ee}_{cm}= 88–94 GeV
1739±17	166k	ALEXANDER	91F OPAL	E^{ee}_{cm}= 88–94 GeV

[24] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included. Assumes lepton universality.

$\Gamma(\nu\overline{\nu}$ (or other invisible modes)) — Γ_5

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
502± 9 OUR FIT			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
491±13	DECAMP	92B ALEP	E^{ee}_{cm}= 88–94 GeV
498± 8	[25] LEP	92 RVUE	E^{ee}_{cm}= 88–94 GeV
488±17	ABREU	91F DLPH	E^{ee}_{cm}= 88–94 GeV
508±17	ADEVA	91E L3	E^{ee}_{cm}= 88–94 GeV
504±15	ALEXANDER	91F OPAL	E^{ee}_{cm}= 88–94 GeV

[25] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included. Assumes lepton universality.

Z BRANCHING RATIOS

The fit is calculated using the Z width, $\Gamma(e^+e^-)$, $\Gamma(\mu^+\mu^-)/\Gamma$(hadrons), $\Gamma(\tau^+\tau^-)/\Gamma$(hadrons), B(hadrons), and other quantities with lesser statistical significance. We believe that this set is the most free of systematic errors and of correlations.

$\Gamma(e^+e^-)/\Gamma$(hadrons) — Γ_1/Γ_6

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0479 ±0.0004 OUR FIT				
0.037 $^{+0.016}_{-0.012}$	12	[26] ABRAMS	89D MRK2	E^{ee}_{cm}= 89–93 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.04840±0.00077	6947	[27] DECAMP	92B ALEP	E^{ee}_{cm}= 88–94 GeV
0.0478 ±0.0005	19k	[28] LEP	92 RVUE	E^{ee}_{cm}= 88–94 GeV
0.0472 ±0.0011 ±0.0004	2772	[29] ABREU	91F DLPH	E^{ee}_{cm}= 88–94 GeV
0.0476 ±0.0009 ±0.0005	4175	[30] ADEVA	91E L3	E^{ee}_{cm}= 88–94 GeV
0.0476 ±0.0009	5507	[31] ALEXANDER	91F OPAL	E^{ee}_{cm}= 88–94 GeV
0.0472 ±0.0061	127	[32] DECAMP	90B ALEP	E^{ee}_{cm}= 90–92 GeV
0.0448 ±0.0030 ±0.0012	323	DECAMP	90D ALEP	E^{ee}_{cm}= 88–95 GeV
0.0494 ±0.0015	2k	[33] DECAMP	90P ALEP	E^{ee}_{cm}= 88–95 GeV

[26] ABRAMS 89D have included both statistical and systematic uncertainties in their quoted errors.
[27] DECAMP 92B give the inverse quantity as 20.66 ± 0.33 and we have inverted.
[28] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.
[29] ABREU 91F report $\Gamma(ee)$ = 82.4 ± 1.1 ± 0.5 MeV and provided us with this branching ratio from the same data and analysis.
[30] ADEVA 91E report B(ee) = 3.33 ± 0.04% and $\Gamma(ee)$ = 83.3 ± 1.1 MeV and provided us with this branching ratio from the same data and analysis.
[31] ALEXANDER 91F report $\Gamma(ee)$ = 82.9 ± 1.0 MeV and provided us with this branching ratio from the same data and analysis.
[32] DECAMP 90B have added statistical and systematic errors in quadrature.
[33] DECAMP 90P quote the inverse quantity as 20.23 ± 0.61 and we have inverted.

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.03345±0.00025 OUR FIT				
0.046 ±0.009 $^{+0.008}_{-0.014}$	39	[34] ANSARI 87C	UA2	$E^{p\overline{p}}_{cm}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.03345±0.00020	19k	[35] LEP 92	RVUE	E^{ee}_{cm}= 88–94 GeV
0.0331 ±0.0018	263	[36] AARNIO 90	DLPH	E^{ee}_{cm}= 88–95 GeV
0.0319 ±0.0013 ±0.0005	651	[37] ADEVA 90D	L3	E^{ee}_{cm}= 88–94 GeV
0.0338 ±0.0005 ±0.0004	1991	[38] ADEVA 90J	L3	E^{ee}_{cm}= 88–94 GeV
0.0342 ±0.0015 ±0.0011	103	AKRAWY 90	OPAL	E^{ee}_{cm}= 89–93 GeV
0.0320 ±0.0009	908	[39] AKRAWY 90E	OPAL	E^{ee}_{cm}= 88–95 GeV
0.034 ±0.004 ±0.003	95	[40] ADEVA 89	L3	E^{ee}_{cm}= 89–93 GeV

[34] ANSARI 87C result is for branching ratio times cross section. The first error is obtained by adding the statistical and systematic experimental uncertanties in quadrature. The second error reflects the dependence on theoretical prediction of total Z cross section: σ(546 GeV) = $1.3^{+0.4}_{-0.2}$ nb and σ(630 GeV) = $1.7^{+0.5}_{-0.3}$ nb. See ALTARELLI 85B.

[35] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.

[36] AARNIO 90 result is from $\Gamma(ee)$ = 83.2 ± 3.0 ± 2.4 MeV.

[37] ADEVA 90D result is from $\Gamma(ee)$ = 81.1 ± 2.8 ± 1.2 ± 0.7 MeV.

[38] ADEVA 90J report $\Gamma(ee)$ = 84.3 ± 1.3 ± 1.0; we divide by their Γ(total) = 2.494 ± 0.025 GeV.

[39] AKRAWY 90E result is from $\Gamma(ee)$ = 81.2 ± 2.6 MeV and includes both statistical and systematic errors.

[40] ADEVA 89 result is from $\Gamma(ee)$ = 88 ± 9 ± 7 MeV.

$\Gamma(\mu^+\mu^-)/\Gamma(\text{hadrons})$ — Γ_2/Γ_6

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0479 ±0.0005 OUR FIT Error includes scale factor of 1.4.				
0.0479 ±0.0005 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.				
0.04704±0.00064	6691	[41] DECAMP 92B	ALEP	E^{ee}_{cm}= 88–94 GeV
0.0498 ±0.0009 ±0.0004	3428	[42] ABREU 91F	DLPH	E^{ee}_{cm}= 88–94 GeV
0.0482 ±0.0009 ±0.0004	3245	[43] ADEVA 91E	L3	E^{ee}_{cm}= 88–94 GeV
0.0478 ±0.0007	7240	[44] ALEXANDER 91F	OPAL	E^{ee}_{cm}= 88–94 GeV
0.053 $^{+0.020}_{-0.015}$	13	[45] ABRAMS 89D	MRK2	E^{ee}_{cm}= 89–93 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0479 ±0.0004	21k	[46] LEP 92	RVUE	E^{ee}_{cm}= 88–94 GeV
0.0503 ±0.0010 ±0.005	2475	[47] ABREU 91	DLPH	E^{ee}_{cm}= 91.2 GeV
0.0433 ±0.0060	117	[48] DECAMP 90B	ALEP	E^{ee}_{cm}= 90–92 GeV
0.0480 ±0.0026 ±0.0005	380	DECAMP 90D	ALEP	E^{ee}_{cm}= 88–95 GeV
0.0465 ±0.012	2k	[49] DECAMP 90P	ALEP	E^{ee}_{cm}= 88–95 GeV
0.056 ±0.006 ±0.002	97	[50] ADEVA 89	L3	E^{ee}_{cm}= 89–93 GeV

[41] DECAMP 92B give the inverse quantity as 21.26 ± 0.29 and we have inverted.

[42] ABREU 91F report $\Gamma(\mu\mu)$ = 86.9 ± 1.9 ± 0.9 MeV and provided us with this branching ratio from the same data and analysis.

[43] ADEVA 91E report $B(\mu\mu)$ = 3.38 ± 0.08% and $\Gamma(\mu\mu)$ = 84.5 ± 2.0 MeV and provided us with this branching ratio from the same data and analysis.

[44] ALEXANDER 91F report $\Gamma(\mu\mu)$ = 83.2 ± 1.5 MeV and provided us with this branching ratio from the same data and analysis.

[45] ABRAMS 89D have included both statistical and systematic uncertainties in their quoted errors.

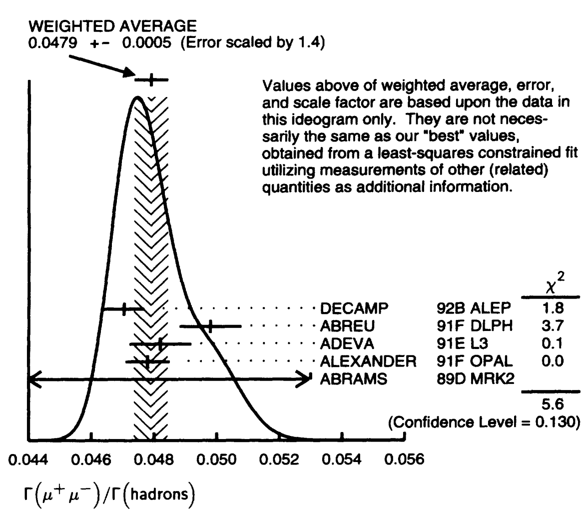
[46] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.

[47] ABREU 91 also obtain $[\Gamma(e)\Gamma(\mu)]^{1/2}$ = 85.0 ± 0.9 ± 0.8 MeV, assuming $m(Z)$ = 91.181 GeV and $\Gamma(Z)$ = 2.455 GeV. They quote the inverse quantity as 19.89 ± 0.40 ± 0.19 and we have inverted.

[48] DECAMP 90B have added statistical and systematic errors in quadrature.

[49] DECAMP 90P quote the inverse quantity as 21.52 ± 0.55 and we have inverted.

[50] ADEVA 89 result gives $\Gamma(\mu\mu)$ = 92 ± 6 MeV.



$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0334 ±0.0004 OUR FIT Error includes scale factor of 1.3.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.03351±0.00034	21k	[51] LEP 92	RVUE	E^{ee}_{cm}= 88–94 GeV
0.036 ±0.002 ±0.001	97	[52] ADEVA 90	L3	E^{ee}_{cm}= 89–93 GeV
0.0345 ±0.0023	484	[53] ADEVA 90D	L3	E^{ee}_{cm}= 88–94 GeV
0.0334 ±0.0004 ±0.0004	1352	[54] ADEVA 90G	L3	E^{ee}_{cm}= 88–94 GeV
0.0326 ±0.0018	585	[55] AKRAWY 90E	OPAL	E^{ee}_{cm}= 88–95 GeV

[51] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.

[52] ADEVA 90 result is from $\Gamma(\mu\mu)$ = 92 ± 5 ± 3 MeV. They assume e-μ universality.

[53] ADEVA 90D result is from $\Gamma(\mu\mu)$ = 87.6 ± 5.6 MeV. Error includes systematics. $\sqrt{\Gamma(ee)\Gamma(\mu\mu)}$ = 84.3 ± 2.4 ± 1.2.

[54] ADEVA 90G report $[\Gamma(ee)\Gamma(\mu\mu)]^{1/2}$ = 83.3 ± 1.3 ± 0.9 MeV and $\Gamma(\mu\mu)$ = 82.3 ± 2.3 ± 1.7; above number is obtained using their $\Gamma(Z)$ = 2.494 ± 0.025 GeV.

[55] AKRAWY 90E result is from $\Gamma(\mu\mu)$ = 82.6 ± 5.8 MeV and includes both statistical and systematic errors.

$\Gamma(\tau^+\tau^-)/\Gamma(\text{hadrons})$ — Γ_3/Γ_6

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0476 ±0.0005 OUR FIT				
0.0476 ±0.0005 OUR AVERAGE				
0.04762±0.00082	6260	[56] DECAMP 92B	ALEP	E^{ee}_{cm}= 88–94 GeV
0.0473 ±0.0011 ±0.0006	2345	[57] ABREU 91F	DLPH	E^{ee}_{cm}= 88–94 GeV
0.0480 ±0.0010 ±0.0010	2540	[58] ADEVA 91E	L3	E^{ee}_{cm}= 88–94 GeV
0.0475 ±0.0010	5559	[59] ALEXANDER 91F	OPAL	E^{ee}_{cm}= 88–94 GeV
0.066 $^{+0.021}_{-0.017}$	21	[60] ABRAMS 89D	MRK2	E^{ee}_{cm}= 89–93 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0476 ±0.0005	17k	[61] LEP 92	RVUE	E^{ee}_{cm}= 88–94 GeV
0.0483 ±0.0051	130	[62] DECAMP 90B	ALEP	E^{ee}_{cm}= 90–92 GeV
0.047 ±0.0021 ±0.0011	534	DECAMP 90D	ALEP	E^{ee}_{cm}= 88–95 GeV
0.0472 ±0.0012	2k	[63] DECAMP 90P	ALEP	E^{ee}_{cm}= 88–95 GeV

[56] DECAMP 92B give the inverse quantity as 21.00 ± 0.36 and we have inverted.

[57] ABREU 91F report $\Gamma(\tau\tau)$ = 82.7 ± 2.1 ± 1.1 MeV and provided us with this branching ratio from the same data and analysis.

[58] ADEVA 91E report $B(\tau\tau)$ = 3.36 ± 0.11% and $\Gamma(\tau\tau)$ = 84.0 ± 2.7 MeV and provided us with this branching ratio from the same data and analysis.

[59] ALEXANDER 91F report $\Gamma(\tau\tau)$ = 82.7 ± 1.9 MeV and provided us with this branching ratio from the same data and analysis.

[60] ABRAMS 89D have included both statistical and systematic uncertainties in their quoted errors.

[61] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.

[62] DECAMP 90B have added statistical and systematic errors in quadrature.

[63] DECAMP 90P quote the inverse quantity as 21.17 ± 0.54 and we have inverted.

$\Gamma(\tau^+\tau^-)/\Gamma_{total}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0332 ±0.0004 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.03328±0.00040	17k	[64] LEP 92	RVUE	E^{ee}_{cm}= 88–94 GeV
0.032 ±0.002 ±0.002	83	[65] ADEVA 90	L3	E^{ee}_{cm}= 89–93 GeV
0.0335 ±0.0006 ±0.0006	1169	[66] ADEVA 90J	L3	E^{ee}_{cm}= 88–94 GeV
0.0338 ±0.0025	506	[67] AKRAWY 90E	OPAL	E^{ee}_{cm}= 88–95 GeV

[64] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.

[65] ADEVA 90 result is from $\Gamma(\tau\tau)$ = 84 ± 5 ± 4 MeV. They assume e-τ universality.

[66] ADEVA 90J report $[\Gamma(ee)\Gamma(\tau\tau)]^{1/2}$ = 83.9 ± 1.4 ± 1.4 and $\Gamma(\tau\tau)$ = 83.5 ± 2.7 ± 2.5 MeV; above number is obtained using their $\Gamma(Z)$ = 2.494 ± 0.025 GeV.

[67] AKRAWY 90E result is from $\Gamma(\tau\tau)$ = 85.7 ± 7.1 MeV and includes both statistical and systematic errors.

$\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-)$ — Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.999±0.014 OUR FIT Error includes scale factor of 1.2.				
1.04 ±0.30 ±0.08	19	ALBAJAR 89	UA1	$E^{p\overline{p}}_{cm}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.054±0.033	3k	ABREU 91F	DLPH	E^{ee}_{cm}= 88–94 GeV
0.96 ±0.12 ±0.05	101	AKRAWY 90	OPAL	E^{ee}_{cm}= 89–93 GeV
seen	1	ARNISON 83C	UA1	Repl. by ALBAJAR 89

$\Gamma(\tau^+\tau^-)/\Gamma(e^+e^-)$ — Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.993±0.014 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.003±0.035	2k	ABREU 91F	DLPH	E^{ee}_{cm}= 88–94 GeV
1.7 $^{+0.9}_{-0.7}$ ±0.1	13	ALITTI 91C	UA2	$E^{p\overline{p}}_{cm}$= 630 GeV
0.97 ±0.13 ±0.08	87	AKRAWY 90	OPAL	E^{ee}_{cm}= 89–93 GeV

$\Gamma(\ell^+\ell^-)/\Gamma(\text{hadrons})$ $(\frac{1}{3}\Gamma_1+\frac{1}{3}\Gamma_2+\frac{1}{3}\Gamma_3)/\Gamma_6$

Our fit is an average of e^+e^-, $\mu^+\mu^-$, and $\tau^+\tau^-$, whereas the LEP numbers shown are the result of a fit requiring lepton universality.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.04781±0.00029 OUR FIT Error includes scale factor of 1.1.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.04762±0.00045	20k	[68] DECAMP 92B	ALEP	E^{ee}_{cm}= 88–94 GeV
0.04787±0.00030	57k	[69] LEP 92	RVUE	E^{ee}_{cm}= 88–94 GeV
0.04831±0.00058±0.00033	10k	[70] ABREU 91F	DLPH	E^{ee}_{cm}= 88–94 GeV
0.0480 ±0.0007	10k	[71] ADEVA 91E	L3	E^{ee}_{cm}= 88–94 GeV
0.0477 ±0.0005	18k	[72] ALEXANDER 91F	OPAL	E^{ee}_{cm}= 88–94 GeV
0.0476 ±0.0014		[73] ADEVA 90I	L3	E^{ee}_{cm}= 88–95 GeV
0.0460 $^{+0.0014}_{-0.0015}$	1946	[74] AKRAWY 90M	OPAL	E^{ee}_{cm}= 88–95 GeV
0.0480 ±0.0009	6.5k	[75] DECAMP 90P	ALEP	E^{ee}_{cm}= 88–95 GeV

[68] DECAMP 92B give the inverse quantity as 21.00 ± 0.20 and we have inverted.
[69] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.
[70] ABREU 91F give the inverse quantity as 20.70 ± 0.25 ± 0.14, and we have inverted.
[71] ADEVA 91E report the inverse quantity as 20.84 ± 0.29 (including statistical and systematic errors), and we have inverted.
[72] ALEXANDER 91F report the inverse quantity as 20.95 ± 0.22, and we have inverted.
[73] ADEVA 90I report $\Gamma(\text{hadrons})/\Gamma(\ell\ell)$ = 21.02 ± 0.62 and we invert.
[74] AKRAWY 90M report $\Gamma(\text{hadrons})/\Gamma(\ell\ell) = 21.72^{+0.71}_{-0.65}$, and we invert.
[75] DECAMP 90P quote the inverse quantity as 20.82 ± 0.37 and we have inverted.

$\Gamma(\ell^+\ell^-)/\Gamma_{\text{total}}$ $(\frac{1}{3}\Gamma_1+\frac{1}{3}\Gamma_2+\frac{1}{3}\Gamma_3)/\Gamma$

Our fit is an average of e^+e^-, $\mu^+\mu^-$, and $\tau^+\tau^-$, whereas the LEP numbers shown are the result of a fit requiring lepton universality.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.03337±0.00022 OUR FIT Error includes scale factor of 1.1.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.03347±0.00013	57k	[76] LEP 92	RVUE	E^{ee}_{cm}= 88–94 GeV
0.0338 ±0.0002 ±0.0001	10k	[77] ABREU 91F	DLPH	E^{ee}_{cm}= 88–94 GeV
0.0334 ±0.0003	10k	[78] ADEVA 91E	L3	E^{ee}_{cm}= 88–94 GeV
0.0333 ±0.0002	18k	[79] ALEXANDER 91F	OPAL	E^{ee}_{cm}= 88–94 GeV
0.0337 ±0.0004 ±0.0003	4512	[80] ADEVA 90J	L3	E^{ee}_{cm}= 88–94 GeV

[76] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.
[77] ABREU 91F report $\Gamma(\text{hadrons})/\Gamma(\text{leptons})$ = 20.70 ± 0.25 ± 0.14 and provided us with this branching ratio from the same data and analysis.
[78] ADEVA 91E error includes statistical and systematic errors.
[79] ALEXANDER 91F report $\Gamma(\text{hadrons})/\Gamma(\text{leptons})$ = 20.95 ± 0.22, and provided us with this branching ratio from the same data and analysis.
[80] ADEVA 90J report $\Gamma(\ell\ell)$ = 84.0 ± 0.9 ± 0.8; we divide by their Γ(total) = 2.494 ± 0.025 GeV.

$\Gamma(\nu\overline{\nu}$ (or other invisible modes)$)/\Gamma_{\text{total}}$ Γ_5/Γ

We report here only direct measurements of the branching ratio to invisible modes. The fit value is dominated by the difference between the total and the observed modes, and is therefore essentially independent of these values.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.202±0.004 OUR FIT				
0.206±0.023 OUR AVERAGE				
0.216±0.032±0.016	61	[81] ADEVA 92	L3	E^{ee}_{cm}= 88–94 GeV
0.199±0.028±0.012	73	[82] AKRAWY 91D	OPAL	E^{ee}_{cm}= 88–94 GeV

[81] ADEVA 92 report Γ(inv) = 540 ± 80 ± 40 MeV, and we use their Γ(total) = 2501 ± 17 ± 5 MeV to convert to a branching ratio.
[82] AKRAWY 91D report Γ(inv) = 0.50 ± 0.07 ± 0.03 GeV, and use their value of $\Gamma(Z)$ = 2.51 ± 0.02 GeV to convert to a branching ratio.

$\Gamma(\text{hadrons})/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.6980±0.0033 OUR FIT				
0.6980±0.0033 OUR AVERAGE				
0.696 ±0.006	165k	[83] DECAMP 92B	ALEP	E^{ee}_{cm}= 88–94 GeV
0.700 ±0.006 ±0.003	124k	[84] ABREU 91F	DLPH	E^{ee}_{cm}= 88–94 GeV
0.699 ±0.009	115k	[85] ADEVA 91E	L3	E^{ee}_{cm}= 88–94 GeV
0.698 ±0.006	166k	[86] ALEXANDER 91F	OPAL	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.6993±0.0031	570k	[87] LEP 92	RVUE	E^{ee}_{cm}= 88–94 GeV
0.693 ±0.030	11k	[88] ABREU 90	DLPH	E^{ee}_{cm}= 88–95 GeV
0.687 ±0.025	17k	[89,90] ADEVA 90D	L3	E^{ee}_{cm}= 88–94 GeV
0.701 ±0.016	89k	[91] ADEVA 90I	L3	E^{ee}_{cm}= 88–95 GeV
0.687 ±0.031 ±0.020	3701	[89] AKRAWY 90	OPAL	E^{ee}_{cm}= 89–93 GeV
0.725 ±0.017	26k	[92] AKRAWY 90E	OPAL	E^{ee}_{cm}= 88–95 GeV
0.689 ±0.030		[89] DECAMP 90B	ALEP	E^{ee}_{cm}= 90–92 GeV
0.710 ±0.015	17k	DECAMP 90D	ALEP	E^{ee}_{cm}= 88–95 GeV
0.691 ±0.012	56k	DECAMP 90P	ALEP	E^{ee}_{cm}= 88–95 GeV

[83] DECAMP 92B also report 0.702 ± 0.005 assuming lepton universality.
[84] ABREU 91F report Γ(hadrons) = 1.726 ± 0.019 GeV and provided us with this branching ratio from the same data and analysis. Lepton universality is not assumed.
[85] ADEVA 91E error includes statistical and systematic errors. They also report 0.697 ± 0.007 assuming lepton universality.
[86] ALEXANDER 91F assume lepton universality, but find negligible difference without lepton universality. They report Γ(hadrons) = 1.739 ± 0.017 GeV, and provided us with this branching ratio from the same data and analysis.
[87] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included. Assumes lepton universality.
[88] ABREU 90 result is from Γ(hadrons) = 1.741 ± 0.061 GeV.
[89] Obtained branching ratio using $\sigma(\text{hadrons}) = (12\pi/m^2(Z))\,\Gamma(e)\Gamma(h)/\Gamma^2(Z)$.
[90] ADEVA 90D result is from Γ(hadrons) = 1.744 ± 0.053 GeV.
[91] ADEVA 90I report Γ(hadrons) = 1.748 ± 0.035; we divide by their $\Gamma(Z)$ = 2.492 ± 0.025 to obtain branching ratio.
[92] AKRAWY 90E result is from Γ(hadrons) = 1.838 ± 0.046 GeV and assumes lepton universality. Both statistical and systematic errors are included.

$\Gamma((u\overline{u}+c\overline{c})/2)/\Gamma(\text{hadrons})$ Γ_7/Γ_6

VALUE	DOCUMENT ID	TECN	COMMENT
0.191±0.031±0.040	[93] ALEXANDER 91E	OPAL	E^{ee}_{cm}= 88–94 GeV

[93] ALEXANDER 91E result is from analysis of final state photons.

$\Gamma((d\overline{d}+s\overline{s}+b\overline{b})/3)/\Gamma(\text{hadrons})$ Γ_8/Γ_6

VALUE	DOCUMENT ID	TECN	COMMENT
0.206±0.021±0.028	[94] ALEXANDER 91E	OPAL	E^{ee}_{cm}= 88–94 GeV

[94] ALEXANDER 91E result is from analysis of final state photons.

$\Gamma(c\overline{c})/\Gamma(\text{hadrons})$ Γ_9/Γ_6

We assume that AKRAWY 91E and DECAMP 90L have a common systematic error of ±0.025. We also assume that ALEXANDER 91B and ABREU 90H separately have a common systematic error of ±0.025. Without these assumptions our average would be 0.180 ± 0.027.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.180±0.030 OUR EVALUATION				
0.223±0.032±0.059		[95] AKRAWY 91E	OPAL	E^{ee}_{cm}= 88–95 GeV
0.186±0.035±0.020	115	[96] ALEXANDER 91B	OPAL	E^{ee}_{cm}= 88–95 GeV
0.162±0.030±0.050	381	[97] ABREU 90H	DLPH	E^{ee}_{cm}= 91 GeV
0.148±0.044$^{+0.045}_{-0.038}$	1383	[98] DECAMP 90L	ALEP	E^{ee}_{cm}= 88–94 GeV

[95] AKRAWY 91E systematic error includes the uncertainty from semileptonic branching ratios (±0.025) plus other systematics (±0.053).
[96] ALEXANDER 91B include all errors due to their experiment in the first quoted error and all others in the second (±0.020).
[97] ABREU 90H use CLEO probability for $c\overline{c} \rightarrow D^*(2010)^{\pm}$ X with $D^*(2010)^{\pm} \rightarrow D^0\pi^{\pm}$. Systematic error includes ±0.026 due to uncertainties in branching ratios.
[98] DECAMP 90L find $B(c \rightarrow e)\Gamma(c\overline{c})/\Gamma(\text{hadrons}) = 0.0133 \pm 0.0040^{+0.0038}_{-0.0031}$. Assumes $B(c \rightarrow e)$ = 0.090 ± 0.013. Systematic error includes about ±0.025 due to uncertainties in branching ratios.

$\Gamma(b\overline{b})/\Gamma(\text{hadrons})$ Γ_{10}/Γ_6

We assume a common systematic error (due to semileptonic branching ratios) of ±0.016 for ADEVA 91C, AKRAWY 91E, DECAMP 90L, and KRAL 90. Our estimate of the final error may not be reliable, because these experiments use different values and errors for the semileptonic branching ratios. Without this assumption our average would be 0.217 ± 0.010.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.218±0.015 OUR EVALUATION				
0.222$^{+0.033}_{-0.031}$±0.017		[99] ABREU 92	DLPH	E^{ee}_{cm}= 88–94 GeV
0.221±0.004±0.013	3893	[100] ADEVA 91C	L3	E^{ee}_{cm}= 88–95 GeV
0.193±0.006±0.024	1494	[101] AKRAWY 91E	OPAL	E^{ee}_{cm}= 88–95 GeV
0.251±0.049±0.030	32	[102] JACOBSEN 91	MRK2	E^{ee}_{cm}= 91 GeV
0.215±0.017±0.024	1383	[103] DECAMP 90L	ALEP	E^{ee}_{cm}= 88–94 GeV
0.23 $^{+0.10}_{-0.08}$ $^{+0.05}_{-0.04}$	15	[104] KRAL 90	MRK2	E^{ee}_{cm}= 89–93 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.204±0.014±0.024	171	[105] ADEVA 90E	L3	E^{ee}_{cm}= 88–95 GeV

[99] ABREU 92 result is from an indirect technique. They measure the lifetime τ_B, but use a world average of τ_B independent of $\Gamma(b\overline{b})$ and compare to their $\Gamma(b\overline{b})$ dependent lifetime from a hadron sample.
[100] ADEVA 91C report $\Gamma(b\overline{b})$ = 385 ± 7 ± 11 ± 19 MeV; we use their Γ(hadrons) = 1742 ± 19 MeV to obtain the branching ratio. The systematic error includes the semileptonic branching ratio uncertainty (±0.011) plus other systematics (±0.006).
[101] For AKRAWY 91E, the systematic error includes the uncertainty from semileptonic branching ratios (±0.021) plus other systematics (±0.011).
[102] JACOBSEN 91 tagged $b\overline{b}$ events by requiring coincidence of ≥ 3 tracks with significant impact parameters using vertex detector. Systematic error includes lifetime and decay uncertainties (±0.014).
[103] DECAMP 90L find $B(b \rightarrow e)\Gamma(b\overline{b})/\Gamma(\text{hadrons})$ = 0.0219 ± 0.0017 ± 0.0010. They assume $B(b \rightarrow e)$ = 0.102 ± 0.007 ± 0.007. The quoted systematic error is dominated by that from the semileptonic branching ratio.
[104] KRAL 90 used isolated leptons and found $\Gamma(B\overline{B})/\Gamma(\text{total}) = 0.17^{+0.07}_{-0.06}{}^{+0.04}_{-0.03}$.
[105] ADEVA 90E used isolated muons and found $B(B \rightarrow \mu)\Gamma(b\overline{b})$ = 41.7 ± 2.9 ± 3.0 MeV. The systematic error of ±0.024 above includes 0.02 due to uncertainty in $B(B \rightarrow \mu)$ added in quadrature to ±0.014 systematic.

$\Gamma(\pi^0\gamma)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.1\times10^{-4}$	95	DECAMP 92	ALEP	E^{ee}_{cm}= 88–94 GeV
$<1.5\times10^{-4}$	95	ABREU 91E	DLPH	E^{ee}_{cm}= 88–94 GeV
$\mathbf{<1.4\times10^{-4}}$	95	AKRAWY 91F	OPAL	E^{ee}_{cm}= 88–94 GeV
$<2.9\times10^{-4}$	95	ADEVA 90K	L3	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.9\times10^{-4}$	95	AKRAWY 90F	OPAL	E^{ee}_{cm}= 88–95 GeV
$<4.9\times10^{-4}$	95	DECAMP 90J	ALEP	E^{ee}_{cm}= 88–95 GeV

$\Gamma(\eta\gamma)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<5.1\times10^{-5}}$	95	DECAMP 92	ALEP	E^{ee}_{cm}= 88–94 GeV
$<2.8\times10^{-4}$	95	ABREU 91E	DLPH	E^{ee}_{cm}= 88–94 GeV
$<2.0\times10^{-4}$	95	AKRAWY 91F	OPAL	E^{ee}_{cm}= 88–94 GeV
$<4.1\times10^{-4}$	95	ADEVA 90K	L3	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<5.8\times10^{-4}$	95	AKRAWY 90F	OPAL	E^{ee}_{cm}= 88–95 GeV
$<4.6\times10^{-4}$	95	DECAMP 90J	ALEP	E^{ee}_{cm}= 88–95 GeV

$\Gamma(\eta'(958)\gamma)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<4.2\times10^{-5}}$	95	DECAMP 92	ALEP	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.2\times10^{-4}$	95	DECAMP 90J	ALEP	E^{ee}_{cm}= 88–95 GeV

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_{14}/Γ

This decay would violate the Landau-Yang theorem.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<1.4\times10^{-4}}$	95	AKRAWY 91F	OPAL	E^{ee}_{cm}= 88–94 GeV
$<2.9\times10^{-4}$	95	ADEVA 90K	L3	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.7\times10^{-4}$	95	AKRAWY 90F	OPAL	E^{ee}_{cm}= 88–95 GeV

$\Gamma(\gamma\gamma\gamma)/\Gamma_{total}$ — Γ_{15}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.4\times10^{-4}$	95	ABREU 91E	DLPH	E^{ee}_{cm}= 88–94 GeV
$\mathbf{<6.6\times10^{-5}}$	95	AKRAWY 91F	OPAL	E^{ee}_{cm}= 88–94 GeV
$<1.2\times10^{-4}$	95	ADEVA 90K	L3	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.8\times10^{-4}$	95	AKRAWY 90F	OPAL	E^{ee}_{cm}= 88–95 GeV

$\Gamma(\pi^\pm W^\mp)/\Gamma_{total}$ — Γ_{16}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<7\times10^{-5}}$	95	DECAMP 92	ALEP	E^{ee}_{cm}= 88–94 GeV

$\Gamma(\rho^\pm W^\mp)/\Gamma_{total}$ — Γ_{17}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<8.3\times10^{-5}}$	95	DECAMP 92	ALEP	E^{ee}_{cm}= 88–94 GeV

$\Gamma(J/\psi(1S)\,X)/\Gamma_{total}$ — Γ_{18}/Γ

VALUE (units 10^{-3})	DOCUMENT ID	TECN	COMMENT
4.5±0.8±0.7	[106] ALEXANDER 91G	OPAL	E^{ee}_{cm}= 88–94 GeV

[106] ALEXANDER 91G systematic error includes 0.4×10^{-3} systematic plus 0.6×10^{-3} from error on $J/\psi(1S)\to\ell^+\ell^-$ branching fraction.

$\Gamma(D^*(2010)^\pm\,X)/\Gamma(\text{hadrons})$ — Γ_{19}/Γ_6

VALUE	EVTS	DOCUMENT ID	TECN
0.26±0.05	362	[107] DECAMP 91J	ALEP

[107] DECAMP 91J report $B(D^*(2010)^+\to D^0\pi^+)B(D^0\to K^-\pi^+)\ \Gamma(D^*(2010)^\pm X)/\Gamma(\text{hadrons}) = (5.11\pm0.34)\times10^{-3}$. They obtained above number assuming $B(D^0\to K^-\pi^+) = (3.62\pm0.34\pm0.44)\%$ and $B(D^*(2010)^+\to D^0\pi^+) = (55\pm4)\%$.

$\Gamma(\text{anomalous }\gamma + \text{hadrons})/\Gamma_{total}$ — Γ_{20}/Γ

Limits on additional sources of prompt photons beyond expectations for final-state bremsstrahlung.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<3.2\times10^{-3}}$	95	[108] AKRAWY 90J	OPAL	E^{ee}_{cm}= 88–95 GeV

[108] AKRAWY 90J report $\Gamma(\gamma\,X) <$ 8.2 MeV at 95%CL. They assume a three-body $\gamma q\bar{q}$ distribution and use $E(\gamma) > 10$ GeV.

$\Gamma(e^+e^-\gamma)/\Gamma_{total}$ — Γ_{21}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<5.2\times10^{-4}}$	95	[109] ACTON 91B	OPAL	E^{ee}_{cm}= 91.1 GeV

[109] ACTON 91B looked for isolated photons with $E>2\%$ of beam energy (>0.9 GeV).

$\Gamma(\mu^+\mu^-\gamma)/\Gamma_{total}$ — Γ_{22}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<5.6\times10^{-4}}$	95	[110] ACTON 91B	OPAL	E^{ee}_{cm}= 91.1 GeV

[110] ACTON 91B looked for isolated photons with $E>2\%$ of beam energy (>0.9 GeV).

$\Gamma(\tau^+\tau^-\gamma)/\Gamma_{total}$ — Γ_{23}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<7.3\times10^{-4}}$	95	[111] ACTON 91B	OPAL	E^{ee}_{cm}= 91.1 GeV

[111] ACTON 91B looked for isolated photons with $E>2\%$ of beam energy (>0.9 GeV).

$\Gamma(e^\pm\mu^\mp)/\Gamma(e^+e^-)$ — Γ_{24}/Γ_1

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.07	90	ALBAJAR 89	UA1	$E^{p\bar{p}}_{cm}$= 546,630 GeV

$\Gamma(e^\pm\mu^\mp)/\Gamma_{total}$ — Γ_{24}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.6\times10^{-5}$	95	DECAMP 92	ALEP	E^{ee}_{cm}= 88–94 GeV
$\mathbf{<2.4\times10^{-5}}$	95	ADEVA 91G	L3	E^{ee}_{cm}= 88–94 GeV
$<4.6\times10^{-5}$	95	AKRAWY 91B	OPAL	E^{ee}_{cm}= 88–94 GeV

$\Gamma(e^\pm\tau^\mp)/\Gamma_{total}$ — Γ_{25}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.2\times10^{-4}$	95	DECAMP 92	ALEP	E^{ee}_{cm}= 88–94 GeV
$\mathbf{<3.4\times10^{-5}}$	95	ADEVA 91G	L3	E^{ee}_{cm}= 88–94 GeV
$<7.2\times10^{-5}$	95	AKRAWY 91B	OPAL	E^{ee}_{cm}= 88–94 GeV

$\Gamma(\mu^\pm\tau^\mp)/\Gamma_{total}$ — Γ_{26}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.0\times10^{-4}$	95	DECAMP 92	ALEP	E^{ee}_{cm}= 88–94 GeV
$\mathbf{<4.8\times10^{-5}}$	95	ADEVA 91G	L3	E^{ee}_{cm}= 88–94 GeV
$<3.5\times10^{-4}$	95	AKRAWY 91B	OPAL	E^{ee}_{cm}= 88–94 GeV

CHARGE ASYMMETRY IN $e^+e^-\to\mu^+\mu^-$ (including radiative corrections)

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.8 ± 2.0 ±0.5		91.2	ABREU 91	DLPH
1.4 ± 2.2 ±0.5		91.2	ADEVA 91E	L3
0.9 ± 1.5		91.2	ALEXANDER 91F	OPAL
$-29.0\ ^{+5.0}_{-4.8}$ ±0.5	(−32.1)	56.9	[112] ABE 90I	VNS
18 ± 8	(+1)	91.28	ADEVA 90D	L3
− 9.9 ± 1.5 ±0.5	(−9.2)	35	HEGNER 90	JADE
0.05± 0.22	(0.026)	91.14	[113] ABRAMS 89D	MRK2
−43.4 ±17.0	(−24.9)	52.0	[114] BACALA 89	AMY
−11.0 ±16.5	(−29.4)	55.0	[114] BACALA 89	AMY
−30.0 ±12.4	(−31.2)	56.0	[114] BACALA 89	AMY
−46.2 ±14.9	(−33.0)	57.0	[114] BACALA 89	AMY
−29 ±13	(−25.9)	53.3	ADACHI 88C	TOPZ
+ 5.3 ± 5.0 ±0.5	(−1.2)	14.0	ADEVA 88	MRKJ
−10.4 ± 1.3 ±0.5	(−8.6)	34.8	ADEVA 88	MRKJ
−12.3 ± 5.3 ±0.5	(−10.7)	38.3	ADEVA 88	MRKJ
−15.6 ± 3.0 ±0.5	(−14.9)	43.8	ADEVA 88	MRKJ
− 1.0 ± 6.0	(−1.2)	13.9	BRAUNSCH... 88D	TASS
− 9.1 ± 2.3 ±0.5	(−8.6)	34.5	BRAUNSCH... 88D	TASS
$-10.6\ ^{+2.2}_{-2.3}$ ±0.5	(−8.9)	35.0	BRAUNSCH... 88D	TASS
$-17.6\ ^{+4.4}_{-4.3}$ ±0.5	(−15.2)	43.6	BRAUNSCH... 88D	TASS
− 4.8 ± 6.5 ±1.0	(−11.5)	39	BEHREND 87C	CELL
−18.8 ± 4.5 ±1.0	(−15.5)	44	BEHREND 87C	CELL
+ 2.7 ± 4.9	(−1.2)	13.9	BARTEL 86C	JADE
−11.1 ± 1.8 ±1.0	(−8.6)	34.4	BARTEL 86C	JADE
−17.3 ± 4.8 ±1.0	(−13.7)	41.5	BARTEL 86C	JADE
−22.8 ± 5.1 ±1.0	(−16.6)	44.8	BARTEL 86C	JADE
− 6.3 ± 0.8 ±0.2	(−6.3)	29	ASH 85	MAC
− 4.9 ± 1.5 ±0.5	(−5.9)	29	DERRICK 85	HRS
− 7.1 ± 1.7	(−5.7)	29	LEVI 83	MRK2
−16.1 ± 3.2	(−9.2	34.2	BRANDELIK 82C	TASS

[112] ABE 90I measurements in the range 50 ≤ $\sqrt{s}$ ≤ 60.8 GeV.

[113] ABRAMS 89D asymmetry includes both 9 $\mu^+\mu^-$ and 15 $\tau^+\tau^-$ events.

[114] BACALA 89 systematic error is about 5%.

CHARGE ASYMMETRY IN $e^+e^- \to \tau^+\tau^-$ (including radiative corrections)

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$7 \pm 3 \pm 1$		91.2	ADEVA 91E	L3
-0.9 ± 1.6		91.2	ALEXANDER 91F	OPAL
$-32.8^{+6.4}_{-6.2} \pm 1.5$	(−32.1)	56.9	[115] ABE 90I	VNS
$-8.1 \pm 2.0 \pm 0.6$	(−9.2)	35	HEGNER 90	JADE
-18.4 ± 19.2	(−24.9)	52.0	[116] BACALA 89	AMY
-17.7 ± 26.1	(−29.4)	55.0	[116] BACALA 89	AMY
-45.9 ± 16.6	(−31.2)	56.0	[116] BACALA 89	AMY
-49.5 ± 18.0	(−33.0)	57.0	[116] BACALA 89	AMY
-20 ± 14	(−25.9)	53.3	ADACHI 88C	TOPZ
$-10.6 \pm 3.1 \pm 1.5$	(−8.5)	34.7	ADEVA 88	MRKJ
$-8.5 \pm 6.6 \pm 1.5$	(−15.4)	43.8	ADEVA 88	MRKJ
$-6.0 \pm 2.5 \pm 1.0$	(8.8)	34.6	BARTEL 85F	JADE
$-11.8 \pm 4.6 \pm 1.0$	(14.8)	43.0	BARTEL 85F	JADE
$-5.5 \pm 1.2 \pm 0.5$	(−0.063)	29.0	FERNANDEZ 85	MAC
-4.2 ± 2.0	(0.057)	29	LEVI 83	MRK2
-10.3 ± 5.2	(−9.2)	34.2	BEHREND 82	CELL
-0.4 ± 6.6	(−9.1)	34.2	BRANDELIK 82C	TASS

[115] ABE 90I measurements in the range $50 \le \sqrt{s} \le 60.8$ GeV.
[116] BACALA 89 systematic error is about 5%.

CHARGE ASYMMETRY IN $e^+e^- \to c\bar{c}$

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$6.4 \pm 3.9 \pm 3.0$		91.2	DECAMP 91E	ALEP
$-12.9 \pm 7.8 \pm 5.5$	(−13.6)	35	BEHREND 90D	CELL
$7.7 \pm 13.4 \pm 5.0$	(−22.1)	43	BEHREND 90D	CELL
$-12.8 \pm 4.4 \pm 4.1$	(−13.6)	35	ELSEN 90	JADE
$-10.9 \pm 12.9 \pm 4.6$	(−23.2)	44	ELSEN 90	JADE
-14.9 ± 6.7	(−13.3)	35	OULD-SAADA 89	JADE

CHARGE ASYMMETRY IN $e^+e^- \to b\bar{b}$

Experimental and Standard Model values are somewhat event-selection dependent. Standard Model expectations contain some assumptions on $B - \overline{B}^0$ mixing.

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$9.7 \pm 5.7 \pm 1.4$	(9.)	91	AKRAWY 91E	OPAL
$12.6 \pm 2.8 \pm 1.2$		91.2	DECAMP 91E	ALEP
$-71 \pm 34 ^{+7}_{-8}$	(−58)	58.3	SHIMONAKA 91	TOPZ
$13.0^{+4.4}_{-4.2} \pm 2.0$	(+8.8)	91.16	ADEVA 90Q	L3
$-22.2 \pm 7.7 \pm 3.5$	(−26.0)	35	BEHREND 90D	CELL
$-49.1 \pm 16.0 \pm 5.0$	(−39.7)	43	BEHREND 90D	CELL
-28 ± 11	(−23)	35	BRAUNSCH... 90	TASS
$-16.6 \pm 7.7 \pm 4.8$	(−24.3)	35	ELSEN 90	JADE
$-33.6 \pm 22.2 \pm 5.2$	(−39.9)	44	ELSEN 90	JADE
$3.4 \pm 7.0 \pm 3.5$	(−16.0)	29.0	BAND 89	MAC
$-72 \pm 28 \pm 13$	(−56)	55.2	SAGAWA 89	AMY

CHARGE ASYMMETRY IN $e^+e^- \to q\bar{q}$

Summed over five lighter flavors.

Experimental and Standard Model values are somewhat event-selection dependent. Standard Model expectations contain some assumptions on $B - \overline{B}^0$ mixing.

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$9.1 \pm 1.4 \pm 1.6$	(9.0)	57.9	ADACHI 91	TOPZ
$-0.84 \pm 0.15 \pm 0.04$		91	DECAMP 91B	ALEP
$8.3 \pm 2.9 \pm 1.9$	(8.7)	56.6	STUART 90	AMY
$11.4 \pm 2.2 \pm 2.1$	(8.7)	57.6	ABE 89L	VNS
6.0 ± 1.3	(5.0)	34.8	GREENSHAW 89	JADE
8.2 ± 2.9	(8.5)	43.6	GREENSHAW 89	JADE

CHARGE ASYMMETRY IN $p\bar{p} \to Z \to e^+e^-$

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$5.2 \pm 5.9 \pm 0.4$		91	ABE 91E	CDF

REFERENCES FOR Z

ABREU 92 ZPHY C (to be pub.) +Adam, Adami, Adye+ (DELPHI Collab.)
CERN-PPE/91-131
ADEVA 92 PL B275 209 +Adriani, Aguilar-Benitez+ (L3 Collab.)
ALITTI 92B PL B (to be pub.) +Ambrosini, Ansari, Autiero, Bareyre+ (UA2 Collab.)
CERN-PPE/91-163
DECAMP 92 PRPL (to be pub.) +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
CERN-PPE/91-149
DECAMP 92B ZPHY C53 1 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
LEP 92 PL B (to be pub.) +ALEPH, DELPHI, L3, OPAL (LEP Collabs.)
CERN-EP/91-232
ABE 91E PRL 67 1502 +Amidei, Apollinari+ (CDF Collab.)
ABREU 91 PL B260 240 +Adam, Adami+ (DELPHI Collab.)
ABREU 91E PL B268 296 +Adam, Adami, Adye, Akesson+ (DELPHI Collab.)
ABREU 91F NP B367 511 +Adam, Adami, Adye, Akesson, Alekseev+(DELPHI Collab.)
ACTON 91B PL B273 338 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ADACHI 91 PL B255 613 +Anazawa, Doser, Enomoto+ (TOPAZ Collab.)
ADEVA 91C PL B261 177 +Adriani, Aguilar-Benitez+ (L3 Collab.)
ADEVA 91E ZPHY C51 179 +Adriani, Aguilar-Benitez, Akbari, Alcarez+ (L3 Collab.)
ADEVA 91G PL B271 453 +Adriani, Aguilar-Benitez+ (L3 Collab.)
AKRAWY 91B PL B254 293 +Alexander, Allison+ (OPAL Collab.)
AKRAWY 91D ZPHY C50 373 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
AKRAWY 91E PL B263 311 +Alexander, Allison+ (OPAL Collab.)
AKRAWY 91F PL B257 531 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ALEXANDER 91B PL B262 341 +Allison, Allport, Anderson, Arcelli+ (OPAL Collab.)
ALEXANDER 91E PL B264 219 +Allison, Allport+ (OPAL Collab.)
ALEXANDER 91F ZPHY C52 175 +Allison, Allport, Anderson, Arcelli+ (OPAL Collab.)
ALEXANDER 91G PL B266 485 +Allison, Allport+ (OPAL Collab.)
ALITTI 91C ZPHY C52 209 +Ambrosini, Ansari, Autiero+ (UA2 Collab.)
DECAMP 91B PL B259 377 +Deschizeaux, Goy+ (ALEPH Collab.)
DECAMP 91E PL B263 325 +Deschizeaux, Goy+ (ALEPH Collab.)
DECAMP 91J PL B266 218 +Deschizeaux, Goy, Lees+ (ALEPH Collab.)
JACOBSEN 91 PRL 67 3347 +Koetke, Adolphsen, Fujino+ (Mark II Collab.)
SHIMONAKA 91 PL B268 457 +Fujii, Miyamoto+ (TOPAZ Collab.)
AARNIO 90 PL B241 425 +Abreu, Adam, Adami+ (DELPHI Collab.)
ABE 90I ZPHY C48 13 +Amako, Arai, Asano, Chiba+ (VENUS Collab.)
ABREU 90 PL B241 435 +Adam, Adami+ (DELPHI Collab.)
ABREU 90H PL B252 140 +Adam, Adami, Adye+ (DELPHI Collab.)
ADACHI 90F PL B234 525 +Doser, Enomoto, Fujii+ (TOPAZ Collab.)
ADEVA 90 PL B236 109 +Adriani, Aguilar-Benitez, Akbari+ (L3 Collab.)
ADEVA 90C PL B237 136 +Adriani, Aguilar-Benitez, Akbari+ (L3 Collab.)
ADEVA 90D PL B238 122 +Adriani, Aguilar-Benitez, Akbari+ (L3 Collab.)
ADEVA 90E PL B241 416 +Adriani, Aguilar-Benitez, Akbari+ (L3 Collab.)
ADEVA 90G PL B247 473 +Adriani, Aguilar-Benitez+ (L3 Collab.)
ADEVA 90I PL B249 341 +Adriani, Aguilar-Benitez, Akbari, Alcarez+ (L3 Collab.)
ADEVA 90J PL B250 183 +Adriani, Aguilar-Benitez+ (L3 Collab.)
ADEVA 90K PL B250 199 +Adriani, Aguilar-Benitez, Akbari, Alcarez+ (L3 Collab.)
ADEVA 90Q PL B252 713 +Adriani, Aguilar-Benitez+ (L3 Collab.)
AKRAWY 90 PL B235 379 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
AKRAWY 90E PL B240 497 +Alexander, Allison, Allport+ (OPAL Collab.)
AKRAWY 90F PL B241 133 +Alexander, Allison, Allport+ (OPAL Collab.)
AKRAWY 90J PL B246 285 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
AKRAWY 90M PL B247 458 +Alexander, Allison+ (OPAL Collab.)
ALITTI 90B PL B241 150 +Ansari, Ansorge, Autiero+ (UA2 Collab.)
BEHREND 90D ZPHY C47 333 +Criegee, Field, Franke+ (CELLO Collab.)
BRAUNSCH... 90 ZPHY C48 433 Braunschweig, Gerhards, Kirschfink+ (TASSO Collab.)
DECAMP 90B PL B234 399 +Deschizeaux, Lees, Minard, Crespo+ (ALEPH Collab.)
DECAMP 90D PL B235 399 +Deschizeaux, Lees, Minard, Crespo+ (ALEPH Collab.)
DECAMP 90J PL B241 635 +Deschizeaux, Goy, Lees+ (ALEPH Collab.)
DECAMP 90L PL B244 551 +Deschizeaux, Goy+ (ALEPH Collab.)
DECAMP 90P ZPHY C48 365 +Deschizeaux, Goy, Lees+ (ALEPH Collab.)
ELSEN 90 ZPHY C46 349 +Allison, Ambrus, Barlow+ (JADE Collab.)
HEGNER 90 ZPHY C46 547 +Naroska, Schroth, Allison+ (JADE Collab.)
KRAL 90 PRL 64 1211 +Abrams, Adolphsen, Averill, Ballam+ (Mark II Collab.)
STUART 90 PRL 64 983 +Breedon, Kim, Ko, Lander, Maeshima+ (AMY Collab.)
ABE 89 PRL 62 613 +Amidei, Apollinari, Ascori, Atac+ (CDF Collab.)
ABE 89C PRL 63 720 +Amidei, Apollinari, Atac, Auchincloss+ (CDF Collab.)
ABE 89L PL B232 425 +Amako, Arai, Asano, Chiba+ (VENUS Collab.)
ABRAMS 89B PRL 63 2173 +Adolphsen, Averill, Ballam, Barish+ (Mark II Collab.)
ABRAMS 89D PRL 63 2780 +Adolphsen, Averill, Ballam, Barish+ (Mark II Collab.)
ADEVA 89 PL B231 509 +Adriani, Aguilar-Benitez, Akbari+ (L3 Collab.)
ALBAJAR 89 ZPHY C44 15 +Albrow, Allkofer, Arnison, Astbury+ (UA1 Collab.)
BACALA 89 PL B218 112 +Malchow, Sparks, Imlay, Kirk+ (AMY Collab.)
BAND 89 PL B218 369 +Camporesi, Chadwick, Delfino, Desangro+ (MAC Collab.)
DAGOSTINI 89 PL B229 160 D'Agostini, DeBoer, Grindhammer (ROMA, MPIM, SLAC)
GREENSHAW 89 ZPHY C42 1 +Warming, Allison, Ambrus, Barlow+ (JADE Collab.)
MORI 89 PL B218 499 +Nozaki, Blanis, Bodek, Budd+ (AMY Collab.)
OULD-SAADA 89 ZPHY C44 567 +Allison, Ambrus, Barlow, Bartel+ (JADE Collab.)
SAGAWA 89 PRL 63 2341 +Lim, Abe, Fujii, Higashi+ (AMY Collab.)
ADACHI 88C PL B208 319 +Aihara, Dijkstra, Enomoto, Fujii+ (TOPAZ Collab.)
ADEVA 88 PR D38 2665 +Anderhub, Ansari, Becker+ (Mark-J Collab.)
BRAUNSCH... 88D ZPHY C40 163 Braunschweig, Gerhards, Kirschfink+ (TASSO Collab.)
ANSARI 87 PL B186 440 +Bagnaia, Banner, Battiston+ (UA2 Collab.)
ANSARI 87C PL B194 158 +Bagnaia, Banner, Battiston+ (UA2 Collab.)
BEHREND 87C PL B191 209 +Buerger, Criegee, Dainton+ (CELLO Collab.)
BARTEL 86C ZPHY C30 371 +Becker, Cords, Felst, Haidt+ (JADE Collab.)
Also 85B ZPHY C26 507 Bartel, Becker, Bowdery, Cords+ (JADE Collab.)
Also 82 PL 108B 140 Bartel, Cords, Dittmann, Eichler+ (JADE Collab.)
ALTARELLI 85B ZPHY C27 617 +Ellis, Martinelli (CERN, FNAL, FRAS)
ASH 85 PRL 55 1831 +Band, Blume, Camporesi+ (MAC Collab.)
BARTEL 85F PL 161B 188 +Becker, Cords, Felst+ (JADE Collab.)
DERRICK 85 PR D31 2352 +Fernandez, Fries, Hyman+ (HRS Collab.)
FERNANDEZ 85 PRL 54 1620 +Ford, Qi, Read+ (MAC Collab.)
ARNISON 83C PL 126B 398 +Astbury, Aubert, Bacci+ (UA1 Collab.)
LEVI 83 PRL 51 1941 +Blocker, Strait+ (Mark II Collab.)
BEHREND 82 PL 114B 282 +Chen, Fenner, Field+ (CELLO Collab.)
BRANDELIK 82C PL 110B 173 +Braunschweig, Gather (TASSO Collab.)

g or gluon

$I(J^P) = 0(1^-)$

SU(3) color octet

Mass $m = 0$. Theoretical value. A mass as large as a few MeV may not be precluded.

Searches for Higgs Bosons — H^0 and $H^\pm$

NOTE ON THE HIGGS BOSON

(by I. Hinchliffe, LBL)

The Standard Model[1] contains one neutral scalar Higgs boson, which is a remnant of the mechanism that breaks the SU(2)× U(1) symmetry and generates the W and Z boson masses. The Higgs couples to quarks and leptons of mass m_f with a strength $gm_f/2M_W$. Its coupling to W and Z bosons is of strength g, where g is the coupling constant of the SU(2) gauge theory. Consequently its coupling to stable matter is very small, and its production and detection in experiments is very difficult. An exception is its production in the decay of the Z boson. Since large numbers of Z's can be produced and the coupling of the Z to the Higgs is unsuppressed, experiments at LEP are now able to rule out a significant range of Higgs masses.

If the Higgs mass is very large, the couplings of the Higgs to itself and to longitudinally polarized gauge bosons become large. Requiring that these couplings remain weak enough so that perturbation theory is applicable implies that $M_H \lesssim 1$ TeV.[2] While this is not an absolute bound, it is an indication of the mass scale at which one can no longer speak of an elementary Higgs boson. This fact is made more clear if one notes that the width of the Higgs boson is proportional to the cube of its mass and that a boson of mass 1 TeV has a width of 500 GeV.

It is believed that scalar field theories of the type used to describe Higgs self-interactions can only be effective theories valid over a limited range of energies if the Higgs self-coupling and hence Higgs mass is nonzero. A theory of this type that is valid at all energy scales must have zero coupling. The range of energies over which the interacting theory is valid is a function of the Higgs self-coupling and hence its mass. An upper bound on the Higgs mass can then be determined by requiring that the theory be valid (*i.e.*, have a nonzero value of the renormalized Higgs self-coupling) at all scales up to the Higgs mass.[3] Non-perturbative calculations using lattice[4] gauge theory that can be used to compute at arbitrary values of the Higgs mass indicate that $M_H < 640$ GeV.

If the Higgs mass were small, then the vacuum (ground) state with the correct value of M_W would cease to be the true ground state of the theory.[5] A theoretical constraint can then be obtained from the requirement that this is not the case, i.e., that the our universe is in the true minimum of the Higgs potential. The constraint can be parameterized approximately as[6]

$$M_H > 1.85\,(m_{\rm top} - 85\ {\rm GeV})\ .$$

This constraint may be too restrictive. Strictly speaking we can only require that the predicted lifetime of our universe, if it is not at the true minimum of the Higgs potential, be longer than its observed age. This constraint can be approximated by[8,9]

$$M_H > 5.9\,(m_{\rm top} - 170\ {\rm GeV})\ .$$

Experiments at LEP[10] are able to exclude a large range of Higgs masses. They search for the decay $Z \to HZ^*$. Here Z^* refers to a virtual Z boson that can appear in the detector as e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $\nu\overline{\nu}$ (i.e., missing energy) or hadrons. The experimental searches have considered both $H \to$ hadrons and $H \to \tau^+\tau^-$. The best limits are shown in the listings below.

Extensions of the standard model, such as those based on supersymmetry,[19] can have more complicated spectra of Higgs bosons. The simplest extension has two Higgs doublets whose neutral components have vacuum expectation values v_1 and v_2, both of which contribute to the W and Z masses. The physical particle spectrum contains one charged Higgs boson ($H^\pm$), two neutral scalars (H_1^0, H_2^0), and one pseudoscalar (P^0) if CP is conserved in the scalar sector.[20] In the simplest version of the supersymmetric model one of these neutral scalars has mass less than the Z boson. In models where all fermions of the same electric charge receive their masses from only one of the two doublets (v_2 gives mass to the charge 2/3 quarks, while v_1 gives mass to the charged leptons and the charge 1/3 quarks), there are, as in the standard model, no flavor-changing neutral currents at lowest order in perturbation theory. The H_i^0 and P^0 couplings to fermions depend on v_2/v_1 and are either enhanced or suppressed relative to the couplings in the standard model. Experiments at LEP are able to exclude ranges of masses for neutral Higgs particles in these models. These ranges depend on the values of v_2/v_1. See the listings below on H_1^0, Mass Limits in Supersymmetric Models.

Searches for charged Higgs bosons depend on the assumed branching fractions to $\nu\tau$, $c\overline{s}$, and $c\overline{b}$. See the listings for $H^\pm$ Mass Limit.

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H^0 (Higgs Boson) MASS LIMITS

These limits apply to the Higgs boson of the three-generation Standard Model with the minimal Higgs sector. Limits that depend on the $Ht\bar{t}$ coupling may also apply to a Higgs boson of an extended Higgs sector whose couplings to up-type quarks are comparable to or larger than those of the standard one-doublet model H^0 couplings.

For early Higgs search papers, see J. Ellis, M.K. Gaillard, D.V. Nanopoulos, Nuclear Physics **B106** 292 (1976).

For recent and comprehensive reviews, see Gunion, Haber, Kane, and Dawson, "The Higgs Hunter's Guide," (Addison-Wesley, Menlo Park, CA, 1990) and R.N. Cahn, Reports on Progress in Physics **52** 389 (1989). For a review of theoretical bounds on the Higgs mass, see M. Sher, Physics Reports (Physics Letters C) **179** 273 (1989).

Limits from Coupling to $Z/W^\pm$

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>48	**(CL = 95%) OUR LIMIT**				
>48	95	[1] DECAMP	92	ALEP	$Z \to H^0 Z^*$
>38	95	[2] ABREU	91C	DLPH	$Z \to H^0 Z^*$
>11.3	95	[3] ACTON	91	OPAL	$H^0 \to$ anything
>41.8	95	[4] ADEVA	91	L3	$Z \to H^0 Z^*$
none 3–44	95	[5] AKRAWY	91	OPAL	$Z \to H^0 Z^*$
none 0.21–14	95	[6] ABREU	90C	DLPH	$Z \to H^0 Z^*$
none 2–32	95	[7] ADEVA	90H	L3	$Z \to H^0 Z^*$
> 2	99	[8] ADEVA	90N	L3	$Z \to H^0 Z^*$
none 0.032–15	95	[9] DECAMP	90	ALEP	$Z \to H^0 Z^*$
> 0.057	95	[10] DECAMP	90M	ALEP	$Z \to H^0 ee,\ H^0 \mu\mu$
none 11–41.6	95	[11] DECAMP	90N	ALEP	$Z \to H^0 Z^*$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 0.21	99	[12] ABREU	91B	DLPH	$Z \to H^0 Z^*$
		[13] ADEVA	91D	L3	$Z \to H^0 \gamma$
none 3–25.3	95	[14] AKRAWY	91C	OPAL	$Z \to H^0 Z^*$
> 1.4	68	[15] ELLIS	91B	RVUE	Electroweak
		[16] HIOKI	91	RVUE	Electroweak
none 0.21–0.818	90	[17] ABE	90E	CDF	$p\bar{p} \to (W^\pm, Z) + H^0 + X$
none 0.846–0.987	90	[17] ABE	90E	CDF	$p\bar{p} \to (W^\pm, Z) + H^0 + X$
none 3.0–19.3	95	[18] AKRAWY	90C	OPAL	$Z \to H^0 Z^*$
> 0.21	95	[19] AKRAWY	90P	OPAL	$Z \to H^0 Z^*$
none 11–24	95	[20] DECAMP	90H	ALEP	$Z \to H^0 Z^*$
> 1.8	68	[21] ELLIS	90B	RVUE	Electroweak

[1] DECAMP 92 searched for most possible final states for $Z \to H^0 Z^*$.
[2] ABREU 91C searched for $Z \to H^0 + (ee,\ \mu\mu,\ \tau\tau,\ \nu\bar{\nu})$ with $H^0 \to q\bar{q}$. Only one candidate was found, in the channel ee + 2jets, with a dijet mass 35.4 ± 5 GeV/c^2, consistent with the expected background of 1.0 ± 0.2 events in the 3 channels e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, and of 2.8 ± 1.3 events in all 4 channels. This paper excludes 12–38 GeV. The range 0–12 GeV is eliminated by combining with the analyses of ABREU 90C and ABREU 91B.
[3] ACTON 91 searched for $e^+e^- \to Z^* H^0$ where $Z^* \to e^+e^-$, $\mu^+\mu^-$, or $\nu\bar{\nu}$ and $H^0 \to$ anything. Without assuming the minimal Standard Model mass-lifetime relationship, the limit is $m(H^0) > 9.5$ GeV.
[4] ADEVA 91 searched for $Z \to H^0 + (\mu\mu,\ ee,\ \nu\bar{\nu})$. This paper only excludes $15 < m(H^0) < 41.8$ GeV. The 0–15 GeV range is excluded by combining with the analyses of previous L3 papers.
[5] AKRAWY 91 searched for the channels $Z \to H^0 + (\nu\bar{\nu}, ee, \mu\mu, \tau\tau)$ with $H^0 \to q\bar{q}, \tau\tau$, and $Z \to H^0 q\bar{q}$ with $H^0 \to \tau\tau$.
[6] ABREU 90C searched for the channels $Z \to H^0 + (\nu\bar{\nu}, ee, \mu\mu)$ and $H^0 + q\bar{q}$ for $m(H) < 1$ GeV.
[7] ADEVA 90H searched for $Z \to H^0 + (\mu\mu, ee, \nu\bar{\nu})$.
[8] ADEVA 90N looked for $Z \to H^0 + (ee,\mu\mu)$ with missing H^0 and with $H^0 \to ee, \mu\mu, \pi^+\pi^-, K^+K^-$.
[9] DECAMP 90 limits based on 11,550 Z events. They searched for $Z \to H^0 + (\nu\bar{\nu},\ ee,\ \mu\mu,\ \tau\tau,\ q\bar{q})$. The decay $Z \to H^0 \nu\bar{\nu}$ provides the most powerful search means, but the quoted results sum all channels. Different analysis methods are used for $m(H^0) < 2m(\mu)$ where Higgs would be long-lived. The 99% confidence limits exclude $m(H^0) =$ 0.040–12 GeV.
[10] DECAMP 90M looked for $Z \to H^0 \ell\ell$, where H^0 decays outside the detector.
[11] DECAMP 90N searched for the channels $Z \to H^0 + (\nu\bar{\nu}, ee, \mu\mu, \tau\tau)$ with $H^0 \to$ (hadrons, $\tau\tau$).
[12] ABREU 91B searched for $Z \to H^0 + \ell\bar{\ell}$ with missing H^0 and $Z \to H^0 + (\nu\bar{\nu},\ \ell\bar{\ell},\ q\bar{q})$ with $H^0 \to ee$.
[13] ADEVA 91D obtain a limit $B(Z \to H^0\gamma) \cdot B(H^0 \to \text{hadrons}) < 4.7 \times 10^{-4}$ (95%CL) for $m(H^0) =$ 30–86 GeV. The limit is not sensitive enough to exclude a standard H^0.
[14] AKRAWY 91C searched the decay channels $Z \to H^0 + (\nu\bar{\nu},\ ee,\ \mu\mu)$ with $H^0 \to q\bar{q}$.
[15] ELLIS 91B result is from a fit to electroweak data from LEP and elsewhere. They also find $m(H)<160$ GeV at 68%CL and $0.5 < m(H) < 1500$ GeV at 90%CL with $m(t)$ unconstrained.
[16] HIOKI 91 use $m(Z)$, $\Gamma_{tot}(Z)$, and $m(W)$ to exclude a region in the $m(t)$–$m(H^0)$ plane. See their Fig. 1.
[17] ABE 90E looked for associated production of H^0 with $W^\pm$ or Z in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV. Searched for H^0 decays into $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^-. Most of the excluded region is also excluded at 95% CL.
[18] AKRAWY 90C based on 825 nb^{-1}. The decay $Z \to H^0\nu\bar{\nu}$ with $H^0 \to \tau\bar{\tau}$ or $q\bar{q}$ provides the most powerful search means, but the quoted results sum all channels.
[19] AKRAWY 90P looked for $Z \to H^0 + (ee,\mu\mu)$ (H^0 missing) and $Z \to H^0\nu\bar{\nu}$, $H^0 \to e^+e^-, \gamma\gamma$.
[20] DECAMP 90H limits based on 25,000 $Z \to$ hadron events.
[21] ELLIS 90B result is from a fit to various electroweak data. Also if $m(t) = 120$ GeV, ELLIS 90B find $m(H) < 600$ GeV at 68%CL.

Limits from Other Techniques

From Quarkonium Decay

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.086	90	[22] ANTREASYAN	90C	CBAL	$\Upsilon(1S) \to H^0\gamma$
none 0.29–0.57	90	[23] ALBRECHT	89	ARG	$\Upsilon(1S) \to H^0\gamma$ ($H^0 \to \pi^+\pi^-$)
none 0.21–5	90	[24] LEE-FRANZINI	88	CUSB	$\Upsilon(1S,3S) \to \gamma H^0$
		[25] DRUZHININ	87	ND	$\phi \to \gamma H^0$ ($H^0 \to \pi^0\pi^0$)

[22] ANTREASYAN 90C obtain $B(\Upsilon(1S) \to H^0\gamma) < 3.5 \times 10^{-5}$ at 90% CL for $m(H^0) < 2m(e)$ and similar limits for heavier Higgs masses. The listed limit assumes the QCD/relativistic reduction factor for the width of 0.5. The limit is reduced to 39 MeV if 0.25 is used instead.
[23] ALBRECHT 89 give a limit $B(\Upsilon(1S) \to H^0\gamma) \cdot B(H^0 \to \pi^+\pi^-) <$ 3–4.5 $\times 10^{-5}$ for $m(H^0) =$ 290–570 MeV, which is lower than the predition including first order QCD corrections and assuming $B(H^0 \to \pi^+\pi^-) > 45\%$.
[24] LEE-FRANZINI 88 presents updated results from the CUSB experiment (see FRANZINI 87 for more details). First order QCD correction included with $\alpha_S \sim 0.2$ ($\Lambda = 0.2$ GeV and $n(f) = 4$). The order α_S correction reduced the rate for $\Upsilon(1S) \to H^0\gamma$ by a factor of 2 (yielding these limits). The impact of order α_S^2 and of relativistic corrections are unknown. If they amounted to another factor of 2 suppression, the above limit would be essentially eliminated.
[25] DRUZHININ 87 sets limit $B(\phi \to \gamma H^0) \cdot B(H^0 \to \pi^0\pi^0) < 8 \times 10^{-5}$ at CL=90% for $m(H^0) =$ 0.6–1 GeV which is still far from the standard Higgs model prediction and does not exclude the existence of light Higgs bosons.

From B Decay

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 0.21–3.57		[26] DAWSON	90	RVUE	$B \to \mu^+\mu^-$ X; $B \to K\ (\mu^+\mu^-, \pi^+\pi^-, K^+K^-)$
none 0.21–1.0	90	[27] ALAM	89B	CLEO	$B \to H^0 K$, ($H^0 \to \mu^+\mu^-, \pi^+\pi^-$)
none 1.0–3.6	90	[27] ALAM	89B	CLEO	$B \to H^0$ X ($H^0 \to \mu^+\mu^-$)
none 3.6–4.6		[28] EILAM	89	RVUE	$B \to H^0$ X, ($H^0 \to \mu^+\mu^-$)
none 0.211–0.700		[29] RABY	89	RVUE	$B \to \mu^+\mu^-$ X m(top) >80 GeV
none 0.07–0.21	90	[30] SNYDER	89	MRK2	$B \to H^0$ X ($H^0 \to e^+e^-$)
none 0.00103–3.57		[29] CHIVUKULA	88	RVUE	$B \to H^0$ X, m(top) > 80 GeV
none 2–3.7		[29] GRINSTEIN	88	RVUE	$B \to H^0$ X, m(top) > 80 GeV

[26] Based on ALTHOFF 84G, ALAM 89B, and ALBRECHT 87D. Some processes considered require the assumption $B(B \to H^0 K)/B(B \to H^0\ X) > 0.01$. Other processes require theoretical assumptions regarding $B(H \to \pi^+\pi^-)$ when considering masses in the interval 0.9–1.2 GeV.
[27] ALAM 89B searched for inclusive and exclusive decays of B mesons into H^0 and can exclude the mass range $2m(\mu)$–$2m(\tau)$ with a wide margin provided $m(t) \gtrsim m(W)$, possibly except for masses near $\chi_0(3410)$, where the mixing effect can reduce $B(H^0 \to \mu^+\mu^-)$ significantly.
[28] EILAM 89 assume m(top) > 90 GeV and vary $|V_{ub}/V_{cb}|^2$ from 0 to 0.026.
[29] Limits assume m(top) > 80 GeV and $|V_{ts}V^*_{tb}/V_{cb}| \approx 1$. CHIVUKULA 88 excludes $m(H^0)$ between $2m(e)$ and $2m(\tau)$ from the limits on $B \to \mu^+\mu^- +$ X by taking the $B(H^0 \to \mu^+\mu^-)$ estimate of VOLOSHIN 86. GRINSTEIN 88 argues that this estimate of VOLOSHIN 86 is unreliable, and excludes $m(H^0)$ between 2 GeV and 3.7 GeV where perturbative QCD is used to estimate $B(H^0 \to \mu^+\mu^-)$.
[30] SNYDER 89 exclude the mass range 70–210 MeV with a wide margin provided that $m(t) \gtrsim m(W)$. A limit $B(B \to H^0\ X) \cdot B(H^0 \to e^+e^-) < 22\%$ (90% CL) is given for $m(H^0) = 50$ MeV.

From K Decay

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.026	90	[31] ATIYA	90	CNTR	$K^+ \to \pi^+ H^0$
		[32] ATIYA	90B	CNTR	$K^+ \to \pi^+ H^0$, $H^0 \to \gamma\gamma$
none 0.012–0.211	90	[33] BARR	90	CNTR	$K_L^0 \to \pi^0 H^0$ $(H^0 \to e^+ e^-)$
>0.32		[34] DAWSON	90	RVUE	K decays
>0.3		[35] LEUTWYLER	90	RVUE	$K^+ \to \pi^+ H^0$
none 0.22–0.32		[36] ATIYA	89	CNTR	$K^+ \to \pi^+ H^0$ $(H^0 \to \mu^+ \mu^-)$
>0.28		[37] CHENG	89	RVUE	$K^\pm \to \pi^\pm H$
>0.36		[38] CHIVUKULA	88	RVUE	$K \to \pi^+ H^0$
	90	[39] BAKER	87	CALO	$K^\pm \to \pi^\pm H^0$ $(H^0 \to e^+ e^-)$
none 0.05–0.211		[40] WILLEY	86	RVUE	$K^\pm \to \pi^\pm H^0$ $(H^0 \to e^+ e^-)$

[31] ATIYA 90 sets limits on $B(K^+ \to \pi^+ H^0)$ varying from $< 6.4 \times 10^{-9}$ for $m(H^0) \approx$ 0 MeV to $< 10^{-6}$ for $m(H^0) = 26$ MeV.

[32] ATIYA 90B give 90% CL limits on $B(K^+ \to \pi^+ H^0)\cdot B(H^0 \to \gamma\gamma)$ for $m(H^0) < 100$ MeV ranging from 10^{-4} to 10^{-7} depending on the mass.

[33] BARR 90 set $m(H^0)$-dependent limits on $B(K_L^0 \to \pi^0 H^0)$ in the region where $B(H^0 \to e^+ e^-) \approx 1$. The limit varies from $B(K_L^0 \to \pi^0 H^0) < 10^{-7}$ at $m(H^0) = 12$ MeV to $< 2 \times 10^{-8}$ for $50 \le m(H^0) \le 211$ MeV. BARR 90 allow for nonzero H^0 lifetime.

[34] Based on ASANO 81B, YAMAZAKI 84, BAKER 87, ATIYA 89, and BARR 90. DAWSON 90 used theoretical calculations and various assumptions such as $m(t)$ >80 GeV and Im $V_{td}^* V_{ts}$ >0.2 $\sin^5\theta_C$.

[35] LEUTWYLER 90 give a consistent analysis of the $K \to \pi H^0$ amplitude based on chiral theory and find that all contributions except the t-quark loop are unimportant numerically provided the t-quark mass is of order or bigger than 100 GeV. Hence, a light Higgs can probably be ruled out.

[36] ATIYA 89 give a limit $B(K^+ \to \pi^+ H^0)\cdot B(H^0 \to \mu^+ \mu^-) < 1.5 \times 10^{-7}$ (90% CL) for $m(H^0) = 220$–320 MeV, which is lower than the prediction unless there is an accidental cancellation in the CP-conserving part of the amplitude and the CP-violating part is unexpectedly small. See WILLEY 89 and CHENG 89.

[37] CHENG 89 concludes even if real part of $K^+ \to \pi^+ H$ amplitude is cancelled accidentally, the imaginary contribution alone rules out $m(H) < 2m(\pi)$.

[38] CHIVUKULA 88 uses chiral perturbation theory to estimate $K \to \pi^+ H^0$ amplitudes with a conservative sign assignment for the relative sign of the $\Delta I = 1/2$ term, and exclude $m(H^0)$ below 0.36 GeV barring cancellation among terms, by using the limits on $K \to \pi^+$ X with X = $\mu^+\mu^-$, e^+e^-, or missing particles. For a criticism see DAWSON 90.

[39] BAKER 87 sets limit $B(K^\pm \to \pi^\pm H^0)\cdot B(H^0 \to e^+ e^-) < 8 \times 10^{-7}$ at CL=90% for $m(H^0) < 100$ MeV if H^0 travels much less than 1.4 cm in the lab frame ($p(K^+)$ = 5.8 GeV). The expected lifetime of the standard H^0 is too long to be effectively detected by the experiment and their limit on the branching ratio is significantly weakened accordingly. In view of the uncertainty in the theoretical prediction for $B(K \to \pi H)$, no definite conclusion can be drawn from the result. See also DAWSON 90.

[40] WILLEY 86 re-examined the theoretical estimate of the decay $K^\pm \to \pi^\pm H^0$ rate via the one-loop sdH^0 coupling. The experimental bound $B(K \to \pi\mu\mu) < 2.4 \times 10^{-6}$ is not strong enough to rule out $2m(\mu) < m(H^0) < 2m(\pi^0)$. For a criticism see DAWSON 90.

From Coupling with Nucleons

Some of the experiments for a light Higgs utilize its coupling with nucleons. We parameterize the Higgs-nucleon coupling (which is dominantly isoscalar) as $g_{HNN} = \eta_{HNN}(\sqrt{2}G_F)^{1/2}\, m(N)$. The limits depend on the value of η_{HNN} used. Shifman *et al.* [Physics Letters **78B** 443 (1978)] obtained $\eta_{HNN} = 0.22$ assuming three heavy flavors. More recently, T.P. Cheng [Physical Review **D38** 2869 (1988)], H.-Y. Cheng [Physics Letters **B219** 347 (1989)], and Barbieri and Curci [Physics Letters **B219** 503 (1989)] took into account the strange-quark content of the proton as well as the heavy quark effects, and derived $\eta_{HNN} = 0.56$.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 0.001–0.08	95	BLUEMLEIN	91	BDMP	$pN \to H^0$ X, $(H^0 \to e^+ e^-, 2\gamma)$
>0.018		[41] GRIFOLS	89	RVUE	$\sigma_{tot}(n\text{Pb})$
none 0.03–0.20		[42] YEPES	89B	RVUE	$pN \to H^0$ X $(H^0 \to e^+ e^-)$
>0.010	68	[43] BELTRAMI	86	SPEC	Muonic atoms
none 0.003–0.012	95	[44] FREEDMAN	84	CNTR	He* $\to$ HeH^0 $(H^0 \to e^+ e^-)$
none 0.00103–0.00584		[45] MUKHOPAD...	84	RVUE	O* $\to$ OH^0 $(H^0 \to e^+ e^-)$
		[46] HOFFMAN	83	CNTR	$\pi p \to n H^0$ $(H^0 \to e^+ e^-)$
>0.006		[47] BARBIERI	75	RVUE	$nN \to nN$

[41] GRIFOLS 89 use the neutron-lead total cross-section measurement at kinetic energies of 50 eV – 50 keV by SCHMIEDMAYER 88 and argue that the agreement of the measured energy dependence with the prediction of a hard-core potential model is lost by light-Higgs exchange. The limit of 18 MeV is obtained for $\eta_{HNN} = 0.56$ and is reduced to 12 MeV for $\eta_{HNN} = 0.22$.

[42] YEPES 89B reanalyzed a Fermilab experiment (BECHIS 78), which looked for a long-lived neutral lepton and found none, and argues that their limit is many orders of magnitude lower than expected from low-mass Higgs bremsstrahlung production followed by the decay to e^+e^-.

[43] BELTRAMI 86 measured the wavelengths of the $3d_{5/2}$–$2p_{3/2}$ X-ray transitions in muonic ^{24}Mg and ^{28}Si and found the deviation from QED $\delta\lambda/\lambda = (-0.2 \pm 3.1) \times 10^{-6}$. The listed limit uses $\eta_{HNN} = 0.23$. The experiment excludes $m(H^0) \lesssim 1$ MeV by more than 3 s.d.

[44] FREEDMAN 84 is ANL experiment with dynamitron proton bombarding tritium to form He*. $\eta_{HNN} = 0.30$ is used to derive the limit. They also reanalyze KOHLER 74 He* data to find no mass region is excluded by that data. See also footnote for MUKHOPADHYAY 84 below.

[45] MUKHOPADHYAY 84 examine KOHLER 74 He* and C* data. Claim that no mass region can be excluded by 74 He* data since He* decay width to proton is large [B(He* $\to$ H^0He) = 3.4×10^{-11} is very small]. Above limit is from KOHLER 74 O* decay data.

[46] HOFFMAN 83 looked for e^+e^- peak from Higgs produced in $\pi^- p \to H^0 n$ at 300 MeV/c. Set CL = 90% limit $d\sigma/dt\, B(e^+e^-) < 3.5 \times 10^{-32}$ cm^2/GeV^2 for $140 < m(H^0) < 160$ MeV, which does not exclude H^0 with the standard one-doublet-model couplings.

[47] BARBIERI 75 studied Higgs boson exchange effect in neutron-lead scattering data of ALEKSANDROV 66 and found limit $(g^2_{H^0 nn}/4\pi)\,(m(H^0)/\text{MeV})^{-4} \lesssim 3.4 \times 10^{-11}$ for $m(H^0) \gtrsim 1$ MeV. This gives the listed limit for $\eta_{HNN} = 0.2$ and 10 MeV for $\eta_{HNN} = 0.56$. Lighter mass region $m(H^0) \lesssim 1$ MeV would be incompatible with the measured angular distribution.

From Other Techniques

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 0.0012–0.052	90	DAVIER	89	BDMP	$e^- Z \to e H^0 Z$ $(H^0 \to e^+ e^-)$
none 0.010–0.10	90	[48] EGLI	89	CNTR	$\pi^+ \to e^+ \nu H^0$ $(H^0 \to e^+ e^-)$
		[49] LINDNER	89	THEO	Vacuum stability
none 0.015–0.04	90	[50] YEPES	89	RVUE	$\pi^\pm \to e^\pm \nu H^0$ $(H^0 \to e^+ e^-)$
		[51] DZHELYADIN	81		$\eta' \to \eta H^0$ $(H^0 \to \mu^+ \mu^-)$
		[52] WITTEN	81	COSM	
		[52] GUTH	80	COSM	
		[52] SHER	80	COSM	

[48] EGLI 89 give a limit for $B(\pi^+ \to e^+ \nu H^0)\cdot B(H^0 \to e^+ e^-)$ ranging from 10^{-9} to 10^{-11} for the mass range 10–110 MeV. The theoretical prediction they use is too large by a factor of 162/49 (see DAWSON 89, DAWSON 90, and CHENG 89). The lower limit given above is reevaluated by us.

[49] LINDNER 89 require vacuum stability and numerically solve the renormalization equations to two-loop order. If m(top) = 100, 110, 120 GeV, then m(Higgs) > 20, 34, 50 GeV. However, it is possible that the vacuum is not stable but is very long-lived.

[50] YEPES 89 reanalyzed a BNL beam-dump experiment (JACQUES 80) which looked for electron pairs in 7 foot BC downstream from the dump and found none.

[51] DZHELYADIN 81 obtained $B(\eta' \to \eta\mu^+\mu^-) < 1.5 \times 10^{-5}$ (CL = 90%), and argued that it excludes H^0 with the standard one-doublet-model couplings in $\mu^+\mu^-$ channel for $m(H^0) = 0.25$–0.409 GeV. However, the number 0.409 is not well-determined due to theoretical uncertainties in $B(H^0 \to \mu^+\mu^-)$.

[52] Limits from cosmological considerations of SU(2) × U(1) symmetry-breaking phase transition occurring only after extreme supercooling, resulting in too high a ratio of entropy to baryon number. Limits apply to the standard one-doublet model H^0, with 'zero bare mass' whose physical mass is determined by the Coleman-Weinberg mechanism of dynamical symmetry breakdown. These limits depend on the mass of the top quark approximately according to $m(H^0) > 10.4[1 - 4m(t)^4/(2m_W^4 + m_Z^4)]^{1/2}$ GeV when $m(t)$ <80 GeV. So for $m(t) \approx 80$ GeV, there is no limit. If $m(t)$ > 80 GeV, then vacuum stability arguments may give bounds on $m(H)$, see LINDNER 89 above.

H^0 (Higgs Boson) MASS LIMITS in Extended Higgs Models

The parameter x denotes the Higgs coupling to charge $-1/3$ quarks and charged leptons relative to the value in the standard one-Higgs-doublet model.

In order to prevent flavor-changing neutral currents in models with more than one Higgs doublet, only one of the Higgs doublets can couple to quarks of charge 2/3. The same requirement applies independently to charge $-1/3$ quarks and to leptons. Higgs couplings can be enhanced or suppressed.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>3.57	95	[53] ACTON	91	OPAL	$Z \to H^0 Z^*$
		[54] DECAMP	91F	ALEP	$Z \to H^0 \ell^+ \ell^-$
		[55] DECAMP	91I	ALEP	Z decay
>0.21	95	[56] AKRAWY	90P	OPAL	$Z \to H^0 Z^*$
		[57] DAVIER	89	BDMP	$e^- Z \to e H^0 Z$ $(H^0 \to e^+ e^-)$
		[58] SNYDER	89	MRK2	$B \to H^0$ X $(H^0 \to e^+ e^-)$
none 0.6–6.2	90	[59] FRANZINI	87	CUSB	$\Upsilon(1S) \to \gamma H^0$, x=2
none 0.6–7.9	90	[59] FRANZINI	87	CUSB	$\Upsilon(1S) \to \gamma H^0$, x=4
none 3.7–5.6	90	[60] ALBRECHT	85J	ARG	$\Upsilon(1S) \to \gamma H^0$, x=2
none 3.7–8.2	90	[60] ALBRECHT	85J	ARG	$\Upsilon(1S) \to \gamma H^0$, x=4

[53] ACTON 91 limit is valid for any H^0 having $\Gamma(Z \to H^0 Z^*)$ more than 0.24 (0.56) times that for the standard Higgs boson for Higgs masses below $2m(\mu)$ $(2m(\tau))$.

[54] DECAMP 91F search for $Z \to H^0 \ell^+ \ell^-$ where H^0 escapes before decaying. Combining this with DECAMP 90M and DECAMP 90N, they obtain $B(Z \to H^0 \ell^+ \ell^-)/B(Z \to \ell^+\ell^-) < 2.5 \times 10^{-3}$ (95%CL) for $m(H^0) < 60$ GeV.

[55] See Figs. 1, 3, 4, 5 of DECAMP 91I for excluded regions for the masses and mixing angles in general two-doublet models.

[56] AKRAWY 90P limit is valid for any H^0 having $\Gamma(Z \to H^0 Z^*)$ more than 0.57 times that for the Standard Higgs boson.

[57] DAVIER 89 give excluded region in $m(H^0)$-x plane for $m(H^0)$ ranging from 1.2 MeV to 50 MeV.

[58] SNYDER 89 give limits on $B(B \to H^0 X) \cdot B(H^0 \to e^+e^-)$ for $100 < m(H^0) < 200$ MeV, $c\tau < 24$ mm.
[59] First order QCD correction included with $\alpha_s \approx 0.2$. Their figure 4 shows the limits vs. x.
[60] ALBRECHT 85J found no mono-energetic photons in both $\Upsilon(1S)$ and $\Upsilon(2S)$ radiative decays in the range 0.5 GeV $<E(\gamma)<$4.0 GeV with typically BR<0.01 for $\Upsilon(1S)$ and BR< 0.02 for $\Upsilon(2S)$ at 90% CL. These upper limits are 5–10 times the prediction of the standard Higgs-doublet model. The quoted 90% limit $B(\Upsilon(1S) \to H^0\gamma) < 1.5 \times 10^{-3}$ at $E(\gamma) = 1.07$ GeV contradicts previous Crystal Ball observation of $(4.7 \pm 1.1) \times 10^{-3}$; see their reference 3. Their figure 8a shows the upper limits of x^2 as a function of $E(\gamma)$ by assuming no QCD corrections. We used $m(H^0) = m(\Upsilon)\,(1-2E(\gamma)/m(\Upsilon))^{1/2}$.

H_1^0 (Higgs Boson) MASS LIMITS in Supersymmetric Models

The minimal supersymmetric model has two complex doublets of Higgs bosons. The resulting physical states are two scalars [H_1^0 and H_2^0, where we define $m(H_1^0) < m(H_2^0)$], a pseudoscalar (A^0), and a charged Higgs pair ($H^{\pm}$). There are two free parameters in the theory which can be chosen to be $m(A^0)$ and $\tan\beta = v_2/v_1$, the ratio of vacuum expectation values of the two Higgs doublets. Tree-level Higgs masses are constrained by the model to be $m(H_1^0) \le m(Z)$, $m(H_2^0) \ge m(Z)$, $m(A^0) \ge m(H_1^0)$, and $m(H^{\pm}) \ge m(W)$. However, as describe in the "Note on Supersymmetry," recent calculations of one-loop radiative corrections show that these relations may be violated. Many experimental analyses have not taken into account these corrections; footnotes indicate when these corrections are included.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>29	95	[61] ABREU	91C	DLPH	any $\tan\beta$
>41	95	[62] DECAMP	91I	ALEP	$\tan\beta > 1$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 0.21	95	[63] ABREU	91B	DLPH	any $\tan\beta$
>28	95	[64] ABREU	91B	DLPH	any $\tan\beta$
>34	95	[61] ABREU	91C	DLPH	$\tan\beta > 0.6$
none 3–38	95	[65] AKRAWY	91C	OPAL	$\tan\beta > 6$
none 3–22	95	[65] AKRAWY	91C	OPAL	$\tan\beta > 0.5$
		[66] BLUEMLEIN	91	BDMP	$pN \to H_1^0 X$, ($H_1^0 \to e^+e^-, 2\gamma$)
> 9	95	[67] ABREU	90E	DLPH	any $\tan\beta$
>13	95	[67] ABREU	90E	DLPH	$\tan\beta > 1$
>26	95	[68] ADEVA	90R	L3	$\tan\beta > 1$
none 0.05–3.1	95	[69] DECAMP	90E	ALEP	any $\tan\beta$
none 0.05–13	95	[69] DECAMP	90E	ALEP	$\tan\beta > 0.6$
none 0.006–20	95	[69] DECAMP	90E	ALEP	$\tan\beta > 2$
>37.1	95	[69] DECAMP	90E	ALEP	$\tan\beta > 6$
none 0.05–20	95	[70] DECAMP	90H	ALEP	$\tan\beta > 0.6$
none 0.006–21.4	95	[70] DECAMP	90H	ALEP	$\tan\beta > 2$
> 3.1	95	[71] DECAMP	90M	ALEP	any $\tan\beta$

[61] ABREU 91C searched for $Z \to H_1^0 Z^*$ and $Z \to H_1^0 A^0$ with H_1^0, $A^0 \to \tau\tau$ or jet-jet. Small mass values are excluded by ABREU 91B.
[62] DECAMP 91I searched for $Z \to H_1^0 Z^*$, and $Z \to H_1^0 A^0 \to$ 4jets or $\tau\tau jj$ or $3A^0$. Their limits take into account the one-loop radiative corrections to the Higgs potential with varied top and squark masses.
[63] ABREU 91B result is based on negative search for $Z \to H_1^0 f\bar{f}$ and the limit on invisible Z width $\Gamma(Z \to H_1^0 A^0) <$ 39 MeV (95%CL), assuming $m(A^0) < m(H_1^0)$.
[64] ABREU 91B result obtained by combining with analysis of ABREU 90I.
[65] AKRAWY 91C result from $Z \to H_1^0 A^0 \to$ 4jet or $\tau^+\tau^- jj$ or 4τ and $Z \to H_1^0 Z^*$ ($H_1^0 \to q\bar{q}$, $Z^* \to \nu\bar{\nu}$ or e^+e^- or $\mu^+\mu^-$). See paper for the excluded region for the case $\tan\beta < 1$. Although these limits do not take into account the one-loop radiative corrections, the authors have reported unpublished results including these corrections and showed that the excluded region becomes larger.
[66] BLUEMLEIN 91 excluded certain range of $\tan\beta$ for $m(H_1^0) <$ 120 MeV, $m(A^0) <$ 80 MeV.
[67] ABREU 90E searched for $Z \to H_1^0 A^0$ and $Z \to H_1^0 Z^*$. $m(H_1^0) <$ 210 MeV is not excluded by this analysis.
[68] ADEVA 90R result is from $Z \to H_1^0 A^0 \to$ 4jet or $\tau\tau jj$ or 4τ and $Z \to H_1^0 Z^*$. Some region of $m(H_1^0) <$ 4 GeV is not excluded by this analysis.
[69] DECAMP 90E look for $Z \to H_1^0 A^0$ as well as $Z \to H_1^0 \ell^+\ell^-$, $Z \to H_1^0 \nu\bar{\nu}$ with 18610 Z decays. Their search includes signatures in which H_1^0 and A^0 decay to $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, or $q\bar{q}$. See their figures of $m(H_1^0)$ vs. $\tan\beta$
[70] DECAMP 90H is similar to DECAMP 90E but with 25,000 Z decays.
[71] DECAMP 90M looked for $Z \to H^0 \ell\ell$, where H_1^0 decays outside the detector. This excludes a region in the ($m(H_1^0)$, $\tan\beta$) plane centered at $m(H_1^0) =$ 50 MeV, $\tan\beta =$ 0.5. This limit together with DECAMP 90E result excludes $m(H_1^0) <$ 3 GeV for any $\tan\beta$.

A^0 (Pseudoscalar Higgs Boson) MASS LIMITS in Supersymmetric Models

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
none 3–40.5	95	[72] AKRAWY	91C	OPAL	$\tan\beta > 1$, if 3 GeV $< m(H_1^0) < m(A^0)$
>20	95	[73] DECAMP	91I	ALEP	$\tan\beta > 1$
>12	95	[74] ABREU	90E	DLPH	$\tan\beta < 1$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>34	95	[75] ABREU	91C	DLPH	$\tan\beta > 3$
>34	95	[74] ABREU	90E	DLPH	$\tan\beta > 1$, $m(H_1^0) < m(A^0)$
>39	95	[76] ADEVA	90R	L3	$\tan\beta > 1$, $m(H_1^0) < m(A^0)$

[72] AKRAWY 91C result from $Z \to H_1^0 A^0 \to$ 4jet or $\tau^+\tau^- jj$ or 4τ. See paper for the excluded region for the case $\tan\beta < 1$.
[73] DECAMP 91I searched for $Z \to H_1^0 Z^*$, and $Z \to H_1^0 A^0 \to$ 4jets or $\tau\tau jj$ or $3A^0$. Their limits take into account the one-loop radiative corrections to the Higgs potential with varied top and squark masses. For $m(t) =$ 140 GeV and $m(\tilde{q}) =$ 1 TeV, the limit is $m(A^0) >$ 31 GeV.
[74] ABREU 90E searched $Z \to H_1^0 A^0$ and $Z \to H_1^0 Z^*$. $m(A^0) <$ 210 MeV is not excluded by this analysis.
[75] ABREU 91C searched for $Z \to H_1^0 Z^*$ and $Z \to H_1^0 A^0$ with H_1^0, $A^0 \to \tau\tau$ or jet-jet. Small mass values are excluded by ABREU 91B.
[76] ADEVA 90R result is from $Z \to H_1^0 A^0 \to$ 4jet or $\tau\tau jj$ or 4τ and $Z \to H_1^0 Z^*$. Some region of $m(A^0) <$ 5 GeV is not excluded by this analysis.

MASS LIMITS for Associated Higgs Production in e^+e^- Interactions

In multi-Higgs models, associated production of Higgs via virtual or real Z in e^+e^- annihilation, $e^+e^- \to H_1^0 H_2^0$, is possible if H_1^0 and H_2^0 have opposite CP eigenvalues. Limits are for the mass of the heavier Higgs H_2^0 in two-doublet models.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>45	95	[77] DECAMP	90H	ALEP	$m(H_1^0) <$ 20 GeV
>37.5	95	[77] DECAMP	90H	ALEP	$m(H_1^0) < m(H_2^0)$
none 5–45	95	[78] KOMAMIYA	90	MRK2	$m(H_1^0) <$ 0.5 GeV, $H_2^0 \to q\bar{q}$ or $\tau^+\tau^-$
> 8	90	[79] KOMAMIYA	89	MRK2	$H_1^0 \to \mu^+\mu^-$, $H_2^0 \to q\bar{q}, \tau^+\tau^-$
>28	95	[80] LOW	89	AMY	$m(H_1^0) \lesssim$ 20 MeV, $H_2^0 \to q\bar{q}$
none 2–9	90	[81] AKERLOF	85	HRS	$m(H_1^0) = 0$, $H_2^0 \to f\bar{f}$
none 4–10	90	[82] ASH	85C	MAC	$m(H_1^0) =$ 0.2 GeV, $H_2^0 \to \tau^+\tau^-, c\bar{c}$
none 1.3–24.7	95	[81] BARTEL	85L	JADE	$m(H_1^0) =$ 0.2 GeV, $H_2^0 \to f\bar{f}$ or $f\bar{f}H_1^0$
none 1.2–13.6	95	[81] BEHREND	85	CELL	$m(H_1^0) = 0$, $H_2^0 \to f\bar{f}$
none 1–11	90	[81] FELDMAN	85	MRK2	$m(H_1^0) = 0$, $H_2^0 \to f\bar{f}$
none 1–9	90	[81] FELDMAN	85	MRK2	$m(H_1^0) = m(H_2^0)$, $H_2^0 \to f\bar{f}$

[77] DECAMP 90H search for $Z \to H_1^0 e^+e^-$, $H_1^0 \mu^+\mu^-$, $H_1^0 \tau^+\tau^-$, $H_1 q\bar{q}$, low multiplicity final states, τ-τ-jet-jet final states and 4-jet final states.
[78] KOMAMIYA 90 limits valid for $\cos^2(\alpha-b) \approx 1$. They also search for the cases $H_1^0 \to \mu^+\mu^-$, $\tau^+\tau^-$, and $H_2^0 \to H_1^0 H_1^0$. See their Fig. 2 for limits for these cases.
[79] KOMAMIYA 89 assume $B(H_1^0 \to \mu^+\mu^-) =$ 100 %, $2m(\mu) < m(H_1^0) < m(\tau)$. The limit is for maximal mixing. A limit of $m(H_2^0) >$ 18 GeV for the case $H_2^0 \to H_1^0 H_1^0$ ($H_1^0 \to \mu^+\mu^-$) is also given. From PEP at $\sqrt{s} =$ 29 GeV.
[80] LOW 89 assume that H_1^0 escapes the detector. The limit is for maximal mixing. A reduced limit of 24 GeV is obtained for the case $H_2^0 \to H_1^0 f\bar{f}$. Limits for a Higgs-triplet model are also discussed. $E_{cm}^{ee} =$ 50–60.8 GeV.
[81] The limit assumes maximal mixing and that H_1^0 escapes the detector.
[82] ASH 85 assumes that H_1^0 escapes undetected. The bound applies up to a mixing suppression factor of 5.

$H^{\pm}$ (Charged Higgs or Techni-pion) MASS LIMITS

Most of the following limits assume $B(H^+ \to \tau^+\nu) + B(H^+ \to c\bar{s}) = 1$. DECAMP 90I, BEHREND 87, and BARTEL 86 assume $B(H^+ \to \tau^+\nu) + B(H^+ \to c\bar{s}) + B(H^+ \to c\bar{b}) = 1$. All limits from Z decays as well as ADACHI 90B assume that H^+ has weak isospin $T_3 = +1/2$. For a discussion of techni-particles, see EICHTEN 86.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>41.7	95	[83,84] DECAMP	92	ALEP	$B(\tau\nu)$= 0–1
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[85] ALBAJAR	91B	UA1	$t \to bH^+$, $H^+ \to \tau^+\nu$
none 8.0–20.2	95	[86] YUZUKI	91	VNS	$B(\ell\nu) =$ 0–1
>29	95	[83,87] ABREU	90B	DLPH	$B(\tau\nu) =$ 0–1
>19	95	[83,88] ADACHI	90B	TOPZ	$B(\tau\nu) =$ 0–1
>36.5	95	[83,89] ADEVA	90M	L3	$B(\tau\nu) =$ 0–1
>35	95	[83,90] AKRAWY	90K	OPAL	$B(\tau\nu) =$ 0–1
>35.4	95	[83,91] DECAMP	90I	ALEP	$B(\tau\nu) =$ 0–1

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
none 10–20	95	[92] SMITH	90B	AMY	$B(\tau\nu) > 0.7$
>19	95	[91] BEHREND	87	CELL	$B(\tau\nu) = 0–1$
>18	95	[93] BARTEL	86	JADE	$B(\tau\nu)$=0.1–1.0
>17	95	[93] ADEVA	85	MRKJ	$BR(\tau\,\nu)$=0.25–1.0

[83] Studied $H^+H^- \rightarrow (\tau\nu)+(\tau\nu)$, $H^+H^- \rightarrow (\tau\nu)$ + hadrons, $H^+H^- \rightarrow$ hadrons.

[84] DECAMP 92 limit improves to 45.3 for $B(\tau\nu)$=1.

[85] ALBAJAR 91B search for $W \rightarrow t\bar{b}$ and $t\bar{t}$ production in $p\bar{p}$ collisions with the decay chain $t \rightarrow H^+b$, $H^+ \rightarrow \tau^+\nu$, in single muon plus jets and dimuon channels. For $m(t)$ = 60 GeV, $m(H^+) < 47$ GeV is excluded at 95%CL if $\tan\beta > 2.3$. The search is restricted to small values of $m(t)$, and no limit on $m(H^+)$ is obtained if $m(t) > 61$ GeV. Note that existing limits on $m(t)$ are not valid if $t \rightarrow H^+b$.

[86] YUZUKI 91 assume photon exchange. The limit is valid for any decay mode $H^+ \rightarrow e\nu$, $\mu\nu$, $\tau\nu$, $q\bar{q}$ with five flavors. For $B(\ell\nu) = 1$, the limit improves to 25.0 GeV.

[87] ABREU 90B limit improves to 36 GeV for $B(\tau\nu) = 1$.

[88] ADACHI 90B limit improves to 22 GeV for $B(\tau\nu) = 0.6$.

[89] ADEVA 90M limit improves to 42.5 GeV for $B(\tau\nu) = 1$.

[90] AKRAWY 90K limit improves to 43 GeV for $B(\tau\nu) = 1$.

[91] If $B(H^+ \rightarrow \tau^+\nu)$ = 100%, the DECAMP 90I limit improves to 43 GeV.

[92] SMITH 90B limit applies for $v_2/v_1 > 2$ in a model in which H_2 couples to u-type quarks and charged leptons.

[93] Studied $H^+H^- \rightarrow (\tau\nu) + (\tau\nu)$, $H^+H^- \rightarrow (\tau\nu)$ + hadrons. Search for muon opposite hadronic shower.

MASS LIMITS for $H^{\pm\pm}$ (doubly-charged Higgs boson)

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 6.5–36.6	95	[94] SWARTZ	90	MRK2	$T_3(H^{++}) = +1$
none 7.3–34.3	95	[94] SWARTZ	90	MRK2	$T_3(H^{++}) = 0$

[94] SWARTZ 90 assume $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ (any flavor). The limits are valid for the Higgs-lepton coupling $g(H\ell\ell) \gtrsim 7.4 \times 10^{-7}/[m(H)/\mathrm{GeV}]^{1/2}$. The limits improve somewhat for ee and $\mu\mu$ decay modes.

REFERENCES FOR H^0 and $H^{\pm}$

DECAMP 92 PRPL (to be pub.) +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
CERN-PPE/91-149
ABREU 91B ZPHY C51 25 +Adam, Adami, Adye, Akesson+ (DELPHI Collab.)
ABREU 91C NP B (to be pub.) +Adam, Adami, Adye, Akesson+ (DELPHI Collab.)
CERN-PPE/91-132
ACTON 91 PL B268 122 +Alexander, Allison, Allport+ (OPAL Collab.)
ADEVA 91 PL B257 450 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ADEVA 91D PL B262 155 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
AKRAWY 91 PL B253 511 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
AKRAWY 91C ZPHY C49 1 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ALBAJAR 91B PL B257 459 +Allkofer, Ankoviak, Apsimon+ (UA1 Collab.)
BLUEMLEIN 91 ZPHY C51 341 +Brunner, Grabosch+ (BERL, BUDA, JINR, SERP)
DECAMP 91F PL B262 139 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
DECAMP 91I PL B265 475 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
ELLIS 91B PL B (to be pub.) +Fogli, Lisi (CERN, BARI)
BARI-TH.85/91
HIOKI 91 MPL A6 2129 (TOKU)
YUZUKI 91 PL B267 309 +Haba, Abe, Amako, Arai, Asano+ (VENUS Collab.)
ABE 90E PR D41 1717 +Amidei, Appollinari, Atac, Auchincloss+ (CDF Collab.)
ABREU 90B PL B241 449 +Adam, Adami, Adye, Alekseev+ (DELPHI Collab.)
ABREU 90C NP B342 1 +Adam, Adami, Adye, Alekseev+ (DELPHI Collab.)
ABREU 90E PL B245 276 +Adam, Adami, Adye, Alekseev+ (DELPHI Collab.)
ABREU 90I sub. HEP-90 Singapore +Adam, Adami, Adye, Alekseev+ (DELPHI Collab.)
CERN-PPE/90-163
ADACHI 90B PL B240 513 +Aihara, Doeser, Enomoto+ (TOPAZ Collab.)
ADEVA 90H PL B248 203 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ADEVA 90M PL B252 511 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ADEVA 90N PL B252 518 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ADEVA 90R PL B251 311 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
AKRAWY 90C PL B236 224 +Alexander, Allison, Allport+ (OPAL Collab.)
AKRAWY 90K PL B242 299 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
AKRAWY 90P PL B251 211 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ANTREASYAN 90C PL B251 204 +Bartels, Besset, Bieler, Bienlein+ (Crystal Ball Collab.)
ATIYA 90 PRL 64 21 +Chiang, Frank, Haggerty, Ito, Kycia+ (BNL-787 Collab.)
ATIYA 90B PRL 65 1188 +Chiang, Frank, Haggerty, Ito, Kycia+ (BNL-787 Collab.)
BARR 90 PL B235 356 +Clark+ (CERN, EDIN, MANZ, LALO, PISA, SIEG)
DAWSON 90 PR D41 2844 +Gunion, Haber (BNL, UCD, UCSC)
DECAMP 90 PL B236 233 +Deschizeaux, Lees, Minard, Crespo+ (ALEPH Collab.)
DECAMP 90E PL B237 291 +Deschizeaux, Lees, Minard+ (ALEPH Collab.)
DECAMP 90H PL B241 141 +Deschizeaux, Lees, Minard+ (ALEPH Collab.)
DECAMP 90I PL B241 623 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
DECAMP 90M PL B245 289 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
DECAMP 90N PL B246 306 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
ELLIS 90B PL B249 543 +Fogli (CERN)
KOMAMIYA 90 PRL 64 2881 +Abrams, Adolphsen, Averill, Ballam+ (Mark II Collab.)
LEUTWYLER 90 NP B343 369 +Shifman (BERN)
SMITH 90B PR D42 949 +McNeil, Breedon, Kim, Ko+ (AMY Collab.)
SWARTZ 90 PRL 64 2877 +Abrams, Adolphsen, Averill, Ballam+ (Mark II Collab.)
ALAM 89B PR D40 712 +Katayama, Kim, Li, Lou, Sun+ (CLEO Collab.)
Also 89C PR D40 3790 erratum Alam, Katayama, Kim, Li, Lou, Sun+ (CLEO Collab.)
ALBRECHT 89 ZPHY C42 349 +Boeckmann, Glaeser, Harder+ (ARGUS Collab.)
ATIYA 89 PRL 63 2177 +Chiang, Frank, Haggerty, Ito, Kycia+ (BNL-787 Collab.)
BARBIERI 89 PL B219 503 +Curci
CAHN 89 RPP 52 389
CHENG 89 PR D40 2980 +Yu (AST)
CHENG 89B PL B219 347
DAVIER 89 PL B229 150 +Nguyen Ngoc (LALO)
DAWSON 89 PL B222 143 (BNL)
EGLI 89 PL B222 533 +Engfer, Grab, Hermes, Kraus+ (SINDRUM Collab.)
EILAM 89 PL B231 184 +Nakada, Wyler (PSI, ZURI)
GRIFOLS 89 PRL 63 1346 +Masso, Peris (BARC)
KOMAMIYA 89 PR D40 721 +Fordham, Abrams, Adolphsen, Akerlof+ (Mark II Collab.)
LINDNER 89 PL B228 139 +Sher, Zaglauer (FNAL, WUSL)
LOW 89 PL B228 548 +Xu, Abashian, Gotow, Hu, Mattson+ (AMY Collab.)
RABY 89 PR D39 828 +West, Hoffman (LANL)
SHER 89 PRPL 179 273
SNYDER 89 PL B229 169 +Murray, Abrams, Adolphsen, Akerlof+ (Mark II Collab.)
WILLEY 89 PR D39 2784 (PITT)
YEPES 89 PL B227 182 (MCGI)
YEPES 89B PL B229 156 (MCGI)
CHENG 88 PR D38 2869
CHIVUKULA 88 PL B207 86 +Manohar (BOST, MIT)
Also 89 PL B217 568 (erratum) Chivukula, Manohar (BOST, MIT)
GRINSTEIN 88 PL B211 363 +Hall, Randall (LBL, UCB)
LEE-FRANZINI 88 Munich HEP Conf. p. 1432 (CUSB Collab.)
SCHMIEDM... 88 PRL 61 1065 Schmiedmayer, Rauch, Riehs (TUW)
Also 88B PRL 61 2509 erratum Schmiedmayer, Rauch, Riehs (TUW)
ALBRECHT 87D PL B199 451 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
BAKER 87 PRL 59 2832 +Gordon, Lazarus+ (BNL, SIN, WASH, YALE)
Also 88 PRL 60 472 erratum Baker, Gordon+ (BNL, SIN, WASH, YALE)
BEHREND 87 PL B193 376 +Buerger, Criegee, Dainton+ (CELLO Collab.)
DRUZHININ 87 ZPHY C37 1 +Dubrovin, Eidelman, Golubev+ (NOVO)
FRANZINI 87 PR D35 2883 +Son, Tuts, Youssef, Zhao+ (CUSB Collab.)
BARTEL 86 ZPHY C31 359 +Becker, Felst, Haidt+ (JADE Collab.)
BELTRAMI 86 NP A451 679 +Aas, Beer, Dechambrier, Goudsmit+ (ETH, FRIB)
EICHTEN 86 PR D34 1547 +Hinchliffe, Lane, Quigg+ (FNAL, LBL, OSU)
VOLOSHIN 86 SJNP 43 495 +Okun (ITEP)
Translated from YAF 43 779.
WILLEY 86 PL B173 480 (PITT)
ADEVA 85 PL 152B 439 +Becker, Becker-Szendy+ (Mark-J Collab.)
AKERLOF 85 PL 156B 271 +Bonvicini, Chapman, Errede+ (HRS Collab.)
ALBRECHT 85J ZPHY C29 167 +Binder, Harder+ (ARGUS Collab.)
ASH 85 PRL 55 1831 +Band, Blume, Camporesi+ (MAC Collab.)
ASH 85C PRL 54 2477 +Band, Blume, Camporesi+ (MAC Collab.)
BARTEL 85L PL 155B 288 +Becker, Cords, Felst, Hagiwara+ (JADE Collab.)
BEHREND 85 PL 161B 182 +Burger, Criegee, Fenner+ (CELLO Collab.)
FELDMAN 85 PRL 54 2289 +Abrams, Amidei, Baden+ (Mark II Collab.)
ALTHOFF 84G ZPHY C22 219 +Braunschweig, Kirschfink+ (TASSO Collab.)
FREEDMAN 84 PRL 52 240 +Napolitano, Camp, Kroupa (ANL, CHIC)
MUKHOPAD... 84 PR D29 565 Mukhopadhyay, Goudsmit+ (RPI, SIN, LISB)
YAMAZAKI 84 PRL 52 1089 +Ishikawa, Taniguchi, Yamanaka+ (TOKY, KEK)
HOFFMAN 83 PR D28 660 +Frank, Mischke, Moir, Schardt (LANL, ARZS)
ASANO 81B PL 107B 159 +Kikutani, Kurokawa, Miyachi+ (KEK, TOKY, OSAK)
DZHELYADIN 81 PL 105B 239 +Golovkin, Konstantinov, Kubarovski+ (SERP)
WITTEN 81 NP B177 477 (HARV)
GUTH 80 PRL 45 1131 +Weinberg (SLAC)
JACQUES 80 PR D21 1206 +Kalelkar, Miller, Plano+ (RUTG, STEV, COLU)
SHER 80 PR D22 2989 (UCSC)
Also 83 ANP 148 95 Flores, Sher (UCSC, UCI)
BECHIS 78 PRL 40 602 +Chang, Dombeck, Ellsworth, Glasser, Lau+ (UMD)
SHIFMAN 78 PL 78B 443 +
ELLIS 76 NP B106 292 +Gaillard, Nanopoulos (CERN)
BARBIERI 75 PL 57B 270 +Ericson (CERN)
KOHLER 74 PRL 33 1628 +Watson, Becker (LOCK)
ALEKSANDROV 66 JETPL 4 134 +Samosvat, Sereeter, Tsoi (JINR)
Translated from ZETF 4 196.

Searches for Heavy Bosons Other Than Higgs Bosons

We list here various limits on charged and neutral heavy vector bosons (other than W's and Z's), heavy scalar bosons (other than Higgs bosons), vector or scalar leptoquarks, and axigluons.

W_R (Right-Handed W Boson) MASS LIMITS

Assuming a light right-handed neutrino, except for BEALL 82, LANGACKER 89B, and COLANGELO 91. $g_R = g_L$ assumed. [Limits in the next section are also valid for W_R if $m(\nu_R) \ll m(W_R)$.] Some limits assume manifest left-right symmetry, *i.e.*, the equality of left- and right Cabibbo-Kobayashi-Maskawa matrices. For a comprehensive review, see LANGACKER 89B.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 406	90	[1] JODIDIO	86	ELEC	Any L-R mixing angle
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 240	90	[2] AQUINO	91	RVUE	Neutron decay
> 496	90	[2] AQUINO	91	RVUE	Neutron and muon decay
> 700		[3] COLANGELO	91	THEO	K^0_L–K^0_S mass difference
> 300	90	[4] LANGACKER	89B	RVUE	General
> 160	90	[5] BALKE	88	CNTR	$\mu \rightarrow e\nu\bar{\nu}$
> 482	90	[1] JODIDIO	86	ELEC	L-R mix angle =0
> 800		MOHAPATRA	86	RVUE	$SU(2)_L \times SU(2)_R \times U(1)$
> 400	95	[6] STOKER	85	ELEC	Any L-R mix ang.
> 475	95	[6] STOKER	85	ELEC	L-R mix ang <0.041
		[7] BERGSMA	83	CHRM	$\nu_\mu e \rightarrow \mu\nu_e$
> 380	90	[8] CARR	83	ELEC	μ^+ decay
>1600		[9] BEALL	82	THEO	K^0_L–K^0_S mass difference

[1] JODIDIO 86 is the same TRIUMF experiment as STOKER 85 (and CARR 83); however, it uses a different technique. The results given here are combined results of the two techniques. The technique here involves precise measurement of the end-point e^+ spectrum in the decay of the highly polarized μ^+. Alternative results can be obtained by fixing $m(W_R)$ and obtaining limits on the L-R mixing angle ζ: If $m(W_R) = \infty$, then $|\zeta| < 0.040$ whereas for unconstrained $m(W_R)$, $-0.056 < \zeta < 0.040$.

[2] AQUINO 91 limits obtained from neutron lifetime and asymmetries together with unitarity of the CKM matrix. Manifest left-right symmetry assumed. Corresponding range for the L-R mixing angle is $-0.0006 < \zeta < 0.0028$. Stronger of the two limits also includes muon decay results.

[3] COLANGELO 91 limit uses hadronic matrix elements evaluated by QCD sum rule and is less restrictive than BEALL 82 limit which uses vacuum saturation approximation. Manifest left-right symmetry assumed.

[4] LANGACKER 89B limit is for any ν_R mass (either Dirac or Majorana) and for a general class of right-handed quark mixing matrices.
[5] BALKE 88 limit is for $m(\nu_{eR}) = 0$ and $m(\nu_{\mu R}) \leq 50$ MeV. Limits come from precise measurements of the muon decay asymmetry as a function of the positron energy.
[6] STOKER 85 is same TRIUMF experiment as CARR 83. Here they measure the decay e^+ spectrum asymmetry above 46 MeV/c using a muon-spin-rotation technique. Assumed a light right-handed neutrino. Quoted limits are from combining with CARR 83.
[7] BERGSMA 83 set limit $m(W_2)/m(W_1) > 1.9$ at CL = 90%.
[8] CARR 83 is TRIUMF experiment with a highly polarized μ^+ beam. Looked for deviation from V−A at the high momentum end of the decay e^+ energy spectrum. Limit from previous world-average muon polarization parameter is $m(W_R) > 240$ GeV. Assumes a light right-handed neutrino.
[9] BEALL 82 limit is obtained assuming that W_R contribution to K^0_L–K^0_S mass difference is smaller than the standard one, neglecting the top quark contributions. Manifest left-right symmetry assumed.

MASS LIMITS for W' (A Heavy Charged Vector Boson Other Than W) in Hadron Collider Experiments

Couplings of W' to quarks and leptons are taken to be identical with those of W. The following limits are obtained from $p\overline{p} \rightarrow W'$ X with W' decaying to the mode indicated in the comments. Experiments other than ABE 91F assume no new decay channels (esp. $t\overline{b}$) are open.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>520	95	[10] ABE	91F	CDF	$W' \rightarrow e\nu, \mu\nu$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 101–158	90	[11] ALITTI	91	UA2	$W' \rightarrow q\overline{q}$
>220	90	[12] ALBAJAR	89	UA1	$W' \rightarrow e\nu$
>209	90	[13] ANSARI	87D	UA2	$W' \rightarrow e\nu$
>210	90	[14] ARNISON	86B	UA1	$W' \rightarrow e\nu$
>170	90	[15] ARNISON	83D	UA1	$W' \rightarrow e\nu$

[10] ABE 91F assume leptonic branching ratio of 1/12 for each lepton flavor. The limit from the $e\nu$ ($\mu\nu$) mode alone is 490 (435) GeV. These limits apply to W_R if $m(\nu_R) \lesssim 15$ GeV and ν_R does not decay in the detector. Cross section limit $\sigma \cdot$ B < (1–10) pb is given for $m(W') =$ 100–550 GeV; see Fig. 2.
[11] ALITTI 91 search is based on two-jet invariant mass spectrum, assuming B($W' \rightarrow q\overline{q}$) = 67.6%. Limit on $\sigma \cdot$B as a function of two-jet mass is given in Fig. 7.
[12] ALBAJAR 89 cross section limit at 630 GeV is $\sigma(W')$ B($e\nu$) < 4.1 pb (90% CL).
[13] See Fig. 5 of ANSARI 87D for the excluded region in the $m(W')$–$[(g_{W'q})^2$ B($W' \rightarrow e\overline{\nu}$)] plane. Note that the quantity $(g_{W'q})^2$ B($W' \rightarrow e\overline{\nu}$) is normalized to unity for the standard W couplings.
[14] ARNISON 86B find no excess at large p_T in 148 $W \rightarrow e\nu$ events. Set limit $\sigma \times$ B($e\nu$) <10 pb at CL = 90% at E_{cm} = 546 and 630 GeV.
[15] ARNISON 83D find among 47 $W \rightarrow e\nu$ candidates no event with excess p_T. Also set $\sigma \times$ B($e\nu$) <30 pb with CL = 90% at E_{cm} = 540 GeV.

MASS LIMITS for Z' (Heavy Neutral Vector Boson Other Than Z)

NOTE ON THE Z' SEARCHES

The mass bounds depend on the gauge group and the gauge coupling of a Z' boson. The limits listed below are not exhaustive but include only typical Z' bosons that appear frequently in the literature. The following notations are used for these Z' bosons.

Z_1: Z_1 is a clone of the Z and is introduced as a convenient way to gauge the limits rather than with a theoretical motivation. It is assumed to have exactly the same couplings as the Z but a different mass.

Left-right symmetric bosons: Z_{LR} is the extra neutral boson which appears in left-right symmetric models with the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ or $SU(2)_L \times U(1)_R \times U(1)_{B-L}$, where $U(1)_R$ is the third component of $SU(2)_R$ and the weak hypercharge $Y = T_{3R} + \frac{1}{2}(B-L)$. The Z_{LR} couples to $\alpha T_{3R} - (1/2\alpha)(B-L)$ with the coupling strength g' (the weak hypercharge gauge coupling). The parameter α is model dependent. For left-right symmetric coupling $g_L = g_R$, $\alpha = (1-2\sin^2\theta_W)^{1/2}/\sin\theta_W \approx 1.53$, which is used for the limits in the listing unless noted. Another typical case $\alpha = (2/3)^{1/2}$ is identical to Z_χ (discussed below) with the coupling $g_\chi = g'$.

E_6 bosons: Two new neutral gauge bosons appear in E_6 models. One is contained in the SO(10) subgroup and the other is not:

$$E_6 \longrightarrow SO(10) \times U(1)_\psi ,$$
$$SO(10) \longrightarrow SU(5) \times U(1)_\chi .$$

One Z' is assumed to be relatively light, which in general is a linear combination of the two:

$$Z_\beta = Z_\chi \cos\beta + Z_\psi \sin\beta .$$

The gauge quantum numbers of the ordinary quarks and leptons are shown in the table:

f	T_{3R}	Y	$B-L$	$\sqrt{24}Q_\chi$	$\sqrt{\frac{72}{5}}Q_\psi$	Q_η
ν_L, e^-_L	0	$-\frac{1}{2}$	-1	$+3$	$+1$	$+\frac{1}{6}$
ν_R	$+\frac{1}{2}$	0	-1	$+5$	-1	$+\frac{5}{6}$
e^-_R	$-\frac{1}{2}$	-1	-1	$+1$	-1	$+\frac{1}{3}$
u_L, d_L	0	$+\frac{1}{6}$	$+\frac{1}{3}$	-1	$+1$	$-\frac{1}{3}$
u_R	$+\frac{1}{2}$	$+\frac{2}{3}$	$+\frac{1}{3}$	$+1$	-1	$+\frac{1}{3}$
d_R	$-\frac{1}{2}$	$-\frac{1}{3}$	$+\frac{1}{3}$	-3	-1	$-\frac{1}{6}$

In particular, the χ charge is related to others by $\sqrt{24}Q_\chi = 4Y - 5(B-L)$. Also notice that the Z_ψ coupling is pure axial for all quarks and leptons.

Another typical case Z_η is defined as

$$Z_\eta = \sqrt{\tfrac{3}{8}}Z_\chi - \sqrt{\tfrac{5}{8}}Z_\psi ,$$

which appears in a superstring-motivated model.

A reference gauge coupling for these bosons is $g' = e/\cos\theta_W$, which is predicted if there is no intermediate symmetry breaking scale.

In general, these Z' models require the existence of a set of new fermions (belonging to the 27 representation of E_6) to cancel gauge anomalies, and possibly superpartners. An exception is Z_χ, for which only right-handed neutrinos are necessary. For the direct limits from hadron colliders, it is often assumed that these new fermions are heavy and are not produced in the decay of the Z'.

Limits for Z_1

Z_1 is assumed to have couplings with quarks and leptons which are identical to those of Z.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>412	95	ABE	92B	CDF	$p\overline{p} \rightarrow Z_1$ X, $Z_1 \rightarrow e^+e^-, \mu^+\mu^-$
>426	90	[16] ABE	90F	VNS	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>387	95	[17] ABE	91D	CDF	$p\overline{p} \rightarrow Z_1$ X, $Z_1 \rightarrow e^+e^-$
>307	90	[18] GEIREGAT	91	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
>208	90	[19] HAGIWARA	90	RVUE	e^+e^-
>173	90	[20] ALBAJAR	89	UA1	$p\overline{p} \rightarrow Z_1$ X, $Z_1 \rightarrow e^+e^-$
>180	90	[21] ANSARI	87D	UA2	$p\overline{p} \rightarrow Z_1$ X ($Z_1 \rightarrow e^+e^-$)
>160	90	[22] ARNISON	86B	UA1	$p\overline{p} \rightarrow Z_1$ X ($Z_1 \rightarrow e^+e^-$)

[16] ABE 90F use data for R, $R_{\ell\ell}$, and $A_{\ell\ell}$. They fix $m(W) = 80.49 \pm 0.43 \pm 0.24$ GeV and $m(Z) = 91.13 \pm 0.03$ GeV.
[17] ABE 91D give $\sigma(Z')\cdot B(e^+e^-) < 1.31$ pb (95%CL) for $m(Z') > 200$ GeV at $E_{cm} = 1.8$ TeV. Limits ranging from 2 to 30 pb are given for $m(Z') = 100$–200 GeV.
[18] GEIREGAT 91 limit is from comparison of g_V^e from $\nu_\mu e$ scattering with $\Gamma(Z \to ee)$ from LEP. Zero mixing assumed.
[19] HAGIWARA 90 perform a fit to e^+e^- data at PEP, PETRA, and TRISTAN including $\mu^+\mu^-$, $\tau^+\tau^-$, and hadron cross sections and asymmetries.
[20] ALBAJAR 89 cross section limit at 630 GeV is $\sigma(Z_1)$ B(ee) < 4.2 pb (90% CL).
[21] See Fig. 5 of ANSARI 87D for the excluded region in the $m(Z_1)$–$[(g_{Z_1 q})^2$ B$(Z_1 \to e^+e^-)]$ plane. Note that the quantity $(g_{Z_1 q})^2$B$(Z_1 \to e^+e^-)$ is normalized to unity for the standard Z couplings.
[22] ARNISON 86B find no excess e^+e^- pairs among 13 pairs from Z. Set limit $\sigma \times$ B(e^+e^-) <13 pb at CL = 90% at E_{cm} = 546 and 630 GeV.

Limits for Z_{LR}

Z_{LR} is the extra neutral boson in left-right symmetric models. $g_L = g_R$ is assumed unless noted. Values in parentheses assume stronger constraint on the Higgs sector, usually motivated by superstring models. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>310	95	[23] ABE 92B	CDF	$p\overline{p}$
>325	90	[24] AMALDI 87	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>230	95	[25] ABE 92B	CDF	$p\overline{p}$
(> 800)	90	[26] ALTARELLI 91B	RVUE	Z parameters
(> 795)	90	[27] DELAGUILA 91	RVUE	
		[28] DELAGUILA 91C	RVUE	
[> 500]		[29] GRIFOLS 90	ASTR	SN 1987A; light ν_R
(> 460)	90	[30] HE 90B	RVUE	
>189		[31] DELAGUILA 89	RVUE	$p\overline{p}$
>278	90	[32] DURKIN 86	RVUE	
>150	95	[33] ADEVA 85B	MRKJ	$e^+e^- \to \mu^+\mu^-$

[23] These limits assume that Z' decays to known fermions only.
[24] A wide range of neutral current data as of 1986 are used in the fit.
[25] These limits assume that Z' decays to all E_6 fermions and their superpartners.
[26] ALTARELLI 91B is based on Z mass, widths, and A_{FB}. The limits are for superstring motivated models with extra assumption on the Higgs sector. $m(t) > 90$ GeV and $m(H^0) < 1$ TeV assumed. For large $m(t)$, the bound improves drastically. Bounds for $Z - Z'$ mixing angle and Z mass shift without this model assumption are also given in the paper.
[27] DELAGUILA 91 bounds have extra assumption of superstring motivated Higgs sector. From νN neutral current data with $m(Z) = 91.10 \pm 0.04$ GeV, $m(t) > 77$ GeV, $m(H^0) < 1$ TeV assumed.
[28] See Fig. 2 of DELAGUILA 91C for the allowed region in $m(t)$–$m(Z_{LR})$ plane from electroweak data.
[29] GRIFOLS 90 limit holds for $m(\nu_R) \lesssim 1$ MeV. See also GRIFOLS 90D, RIZZO 91.
[30] HE 90B model assumes a specific Higgs sector. Neutral current data of COSTA 88 as well as $m(Z)$ is used. g_R is left free in the fit.
[31] DELAGUILA 89 limit is based on $\sigma(p\overline{p} \to Z')\cdot B(Z' \to e^+e^-) < 1.8$ pb at CERN $p\overline{p}$ collider.
[32] A wide range of neutral current data as of 1985 are used in the fit.
[33] ADEVA 85B measure asymmetry of μ-pair production, following formalism of RIZZO 81.

Limits for Z_χ

Z_χ is the extra neutral boson in SO(10) → SU(5) × U(1)$_\chi$. $g_\chi = e/\cos\theta_W$ is assumed unless otherwise stated. We list limits with the assumption $\rho = 1$ but with no further constraints on the Higgs sector. Values in parentheses assume stronger constraint on the Higgs sector motivated by superstring models. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>340	95	[34] ABE 92B	CDF	$p\overline{p}$
>320	90	[35] GONZALEZ-G..91	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>280	95	[36] ABE 92B	CDF	$p\overline{p}$
(> 500)	90	[37] ALTARELLI 91B	RVUE	Z parameters
(> 570)		[38] BUCHMUEL... 91	RVUE	Z parameters
(> 555)	90	[39] DELAGUILA 91	RVUE	
		[40] DELAGUILA 91C	RVUE	
[>1470]		[41] FARAGGI 91	COSM	Nucleosynthesis; light ν_R
>221		[42] MAHANTHAP..91	RVUE	Cs
>231	90	[43,44] ABE 90F	VNS	e^+e^-
>206	90	[44,45] ABE 90F	RVUE	e^+e^-, $\nu_\mu e$
>335		[46] BARGER 90B	RVUE	$p\overline{p}$
(> 650)	90	[47] GLASHOW 90	RVUE	
[> 1140]		[48] GONZALEZ-G..90D	COSM	Nucleosynthesis; light ν_R
[> 2100]		[49] GRIFOLS 90	ASTR	SN 1987A; light ν_R
none <150 or > 363	90	[50] HAGIWARA 90	RVUE	e^+e^-
>177		[51] DELAGUILA 89	RVUE	$p\overline{p}$
>280	95	[52] DORENBOS... 89	CHRM	$g_\chi = g_Z$
>352	90	[53] COSTA 88	RVUE	
>170	90	[54] ELLIS 88	RVUE	$p\overline{p}$
>273	90	[53] AMALDI 87	RVUE	
>266	90	[55] MARCIANO 87	RVUE	
>283	90	[56] DURKIN 86	RVUE	

[34] These limits assume that Z' decays to known fermions only.
[35] GONZALEZ-GARCIA 91 limit is based on low-energy neutral current data, Z mass and widths, $m(W)$ from ABE 90G. 100 < $m(t)$ < 200 GeV, $m(H^0) = 100$ GeV assumed. Dependence on $m(t)$ is shown in Fig. 7.
[36] These limits assume that Z' decays to all E_6 fermions and their superpartners.
[37] ALTARELLI 91B is based on Z mass, widths, and A_{FB}. The limits are for superstring motivated models with extra assumption on the Higgs sector. $m(t) > 90$ GeV and $m(H^0) < 1$ TeV assumed. For large $m(t)$, the bound improves drastically. Bounds for $Z - Z'$ mixing angle and Z mass shift without this model assumption are also given in the paper.
[38] BUCHMUELLER 91 limit is from LEP data. Specific assumption is made for the Higgs sector.
[39] DELAGUILA 91 bounds have extra assumption of superstring motivated Higgs sector. From νN neutral current data with $m(Z) = 91.10 \pm 0.04$ GeV, $m(t) > 77$ GeV, $m(H^0) < 1$ TeV assumed.
[40] See Fig. 2 of DELAGUILA 91C for the allowed region in $m(t)$–$m(Z_\chi)$ plane from electroweak data.
[41] FARAGGI 91 limit assumes the nucleosynthesis bound on the effective number of neutrinos $\Delta N_\nu < 0.5$ and is valid for $m(\nu_R) < 1$ MeV.
[42] MAHANTHAPPA 91 limit is from atomic parity violation in Cs with $m(W)$, $m(Z)$.
[43] ABE 90F use data for R, $R_{\ell\ell}$, and $A_{\ell\ell}$.
[44] ABE 90F fix $m(W) = 80.49 \pm 0.43 \pm 0.24$ GeV and $m(Z) = 91.13 \pm 0.03$ GeV.
[45] e^+e^- data for R, $R_{\ell\ell}$, $A_{\ell\ell}$, and $A_{c\overline{c}}$ below Z as well as $\nu_\mu e$ scattering data of GEIREGAT 89 is used in the fit.
[46] BARGER 90B limit is based on CDF limit $\sigma(p\overline{p} \to Z')\cdot B(Z' \to e^+e^-) < 1$ pb (Nodulman, EPS Conf. '89). Assumes no new threshold is open for Z' decay.
[47] GLASHOW 90 model assumes a specific Higgs sector. See GLASHOW 90B.
[48] These authors claim that the nucleosynthesis bound on the effective number of light neutrinos ($\delta N_\nu < 1$) constrains Z' masses if ν_R is light ($\lesssim 1$ MeV).
[49] GRIFOLS 90 limit holds for $m(\nu_R) \lesssim 1$ MeV. See also GRIFOLS 90D, RIZZO 91.
[50] HAGIWARA 90 perform a fit to e^+e^- data at PEP, PETRA, and TRISTAN including $\mu^+\mu^-$, $\tau^+\tau^-$, and hadron cross sections and asymmetries. The upper mass limit disappears at 2.7 s.d.
[51] DELAGUILA 89 limit is based on $\sigma(p\overline{p} \to Z')\cdot B(Z' \to e^+e^-) < 1.8$ pb at CERN $p\overline{p}$ collider.
[52] DORENBOSCH 89 obtain the limit $(g_\chi/g_Z)^2\cdot(m(Z)/m(Z_\chi))^2 < 0.11$ at 95% CL from the processes $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ and $\nu_\mu e \to \nu_\mu e$.
[53] A wide range of neutral current data as of 1986 are used in the fit.
[54] Z' mass limits from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider [based on ANSARI 87D and GEER Uppsala Conf. 87]. The limits apply when Z' decays only into light quarks and leptons.
[55] MARCIANO 87 limit from unitarity of Cabibbo-Kobayashi-Maskawa matrix.
[56] A wide range of neutral current data as of 1985 are used in the fit.

Limits for Z_ψ

Z_ψ is the extra neutral boson in E_6 → SO(10) × U(1)$_\psi$. $g_\psi = e/\cos\theta_W$ is assumed unless otherwise stated. We list limits with the assumption $\rho = 1$ but with no further constraints on the Higgs sector. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>320	95	[57] ABE 92B	CDF	$p\overline{p}$
>154	90	[58] AMALDI 87	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>180	95	[59] ABE 92B	CDF	$p\overline{p}$
>105	90	[60,61] ABE 90F	VNS	e^+e^-
>146	90	[61,62] ABE 90F	RVUE	e^+e^-, $\nu_\mu e$
>320		[63] BARGER 90B	RVUE	$p\overline{p}$
[> 160]		[64] GONZALEZ-G..90D	COSM	Nucleosynthesis; light ν_R
[> 2000]		[65] GRIFOLS 90D	ASTR	SN 1987A; light ν_R
>136	90	[66] HAGIWARA 90	RVUE	e^+e^-
>146	90	[67] DURKIN 86	RVUE	

[57] These limits assume that Z' decays to known fermions only.
[58] A wide range of neutral current data as of 1986 are used in the fit.
[59] These limits assume that Z' decays to all E_6 fermions and their superpartners.
[60] ABE 90F use data for R, $R_{\ell\ell}$, and $A_{\ell\ell}$.
[61] ABE 90F fix $m(W) = 80.49 \pm 0.43 \pm 0.24$ GeV and $m(Z) = 91.13 \pm 0.03$ GeV.
[62] e^+e^- data for R, $R_{\ell\ell}$, $A_{\ell\ell}$, and $A_{c\overline{c}}$ below Z as well as $\nu_\mu e$ scattering data of GEIREGAT 89 is used in the fit.
[63] BARGER 90B limit is based on CDF limit $\sigma(p\overline{p} \to Z')\cdot B(Z' \to e^+e^-) < 1$ pb (Nodulman, EPS Conf. '89). Assumes no new threshold is open for Z' decay.
[64] These authors claim that the nucleosynthesis bound on the effective number of light neutrinos ($\delta N_\nu < 1$) constrains Z' masses if ν_R is light ($\lesssim 1$ MeV).
[65] GRIFOLS 90D limit holds for $m(\nu_R) \lesssim 1$ MeV. See also RIZZO 91.
[66] HAGIWARA 90 perform a fit to e^+e^- data at PEP, PETRA, and TRISTAN including $\mu^+\mu^-$, $\tau^+\tau^-$, and hadron cross sections and asymmetries.
[67] A wide range of neutral current data as of 1985 are used in the fit.

Limits for Z_η

Z_η is the extra neutral boson in E_6 models, corresponding to $Q_\eta = \sqrt{3/8}\,Q_\chi - \sqrt{5/8}\,Q_\psi$. $g_\eta = e/\cos\theta_W$ is assumed unless otherwise stated. We list limits with the assumption $\rho = 1$ but with no further constraints on the Higgs sector. Values in parentheses assume stronger constraint on the Higgs sector motivated by superstring models. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>340	95	[68] ABE 92B	CDF	$p\overline{p}$
>125	90	[69,70] ABE 90F	VNS	e^+e^-

Gauge & Higgs Boson Full Listings

Heavy Bosons Other than Higgs Bosons

• • • We do not use the following data for averages, fits, limits, etc. • • •

>230	95	[71] ABE	92B	CDF	$p\overline{p}$
(> 300)	90	[72] ALTARELLI	91B	RVUE	Z parameters
		[73] DELAGUILA	91C	RVUE	
>120	90	[74] GONZALEZ-G..91		RVUE	
>115	90	[70,75] ABE	90F	RVUE	e^+e^-, $\nu_\mu e$
>340		[76] BARGER	90B	RVUE	$p\overline{p}$
[> 820]		[77] GONZALEZ-G..90D		COSM	Nucleosynthesis; light ν_R
[> 3300]		[78] GRIFOLS	90	ASTR	SN 1987A; light ν_R
>100	90	[79] HAGIWARA	90	RVUE	e^+e^-
[> 1040]		[77] LOPEZ	90	COSM	Nucleosynthesis; light ν_R
>173		[80] DELAGUILA	89	RVUE	$p\overline{p}$
>129	90	[81] COSTA	88	RVUE	
>156	90	[82] ELLIS	88	RVUE	
>167	90	[83] ELLIS	88	RVUE	$p\overline{p}$
>111	90	[81] AMALDI	87	RVUE	
>143	90	[84] BARGER	86B	RVUE	$p\overline{p}$
>130	90	[85] DURKIN	86	RVUE	
[> 760]		[77] ELLIS	86	COSM	Nucleosynthesis; light ν_R
[> 500]		[77] STEIGMAN	86	COSM	Nucleosynthesis; light ν_R

[68] These limits assume that Z' decays to known fermions only.

[69] ABE 90F use data for R, $R_{\ell\ell}$, and $A_{\ell\ell}$.

[70] ABE 90F fix $m(W) = 80.49 \pm 0.43 \pm 0.24$ GeV and $m(Z) = 91.13 \pm 0.03$ GeV.

[71] These limits assume that Z' decays to all E_6 fermions and their superpartners.

[72] ALTARELLI 91B is based on Z mass, widths, and A_{FB}. The limits are for superstring motivated models with extra assumption on the Higgs sector. $m(t) > 90$ GeV and $m(H^0) < 1$ TeV assumed. For large $m(t)$, the bound improves drastically. Bounds for $Z - Z'$ mixing angle and Z mass shift without this model assumption are also given in the paper.

[73] See Fig. 7(d) in DELAGUILA 91C for Z_η mass-mixing limit from electroweak data.

[74] GONZALEZ-GARCIA 91 limit is based on low-energy neutral current data, LEP Z mass and widths, $m(W)$ from ABE 90G. $100 < m(t) < 200$ GeV, $m(H^0) = 100$ GeV assumed. Dependence on $m(t)$ is shown in Fig. 8.

[75] e^+e^- data for R, $R_{\ell\ell}$, $A_{\ell\ell}$, and $A_{c\overline{c}}$ below Z as well as $\nu_\mu e$ scattering data of GEIREGAT 89 is used in the fit.

[76] BARGER 90B limit is based on CDF limit $\sigma(p\overline{p} \rightarrow Z')\cdot B(Z' \rightarrow e^+e^-) < 1$ pb (Nodulman, EPS Conf. '89). Assumes no new threshold is open for Z' decay.

[77] These authors claim that the nucleosynthesis bound on the effective number of light neutrinos ($\delta N_\nu < 1$) constrains Z' masses if ν_R is light ($\lesssim 1$ MeV).

[78] GRIFOLS 90 limit holds for $m(\nu_R) \lesssim 1$ MeV. See also GRIFOLS 90D, RIZZO 91.

[79] HAGIWARA 90 perform a fit to e^+e^- data at PEP, PETRA, and TRISTAN including $\mu^+\mu^-$, $\tau^+\tau^-$, and hadron cross sections and asymmetries.

[80] DELAGUILA 89 limit is based on $\sigma(p\overline{p} \rightarrow Z')\cdot B(Z' \rightarrow e^+e^-) < 1.8$ pb at CERN $p\overline{p}$ collider.

[81] A wide range of neutral current data as of 1986 are used in the fit.

[82] Z_η mass limits obtained by combining constraints from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider and the global analysis of neutral current data by COSTA 88. Least favorable spectrum of three (E_6 27) generations of particles and their superpartners are assumed.

[83] Z' mass limits from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider [based on ANSARI 87D and GEER Uppsala Conf. 87]. The limits apply when Z' decays only into light quarks and leptons.

[84] BARGER 86B limit is based on UA1/UA2 limit on $p\overline{p} \rightarrow Z'$, $Z' \rightarrow e^+e^-$ (Lepton Photon Symp., Kyoto, '85). Extra decay channels for Z' are assumed not be open.

[85] A wide range of neutral current data as of 1985 are used in the fit.

Limits for other Z'

$$Z_\beta = Z_\chi \cos\beta + Z_\psi \sin\beta$$

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>360		[86] ALTARELLI	91	RVUE	Z_β with $\tan\beta = \sqrt{3/5}$; Cs
		[87] DELAGUILA	91C	RVUE	
>190		[88] MAHANTHAP..91		RVUE	Z_β with $\tan\beta = \sqrt{3/5}$; Cs
		[89] GRIFOLS	90C	RVUE	
		[90] DELAGUILA	89	RVUE	$p\overline{p}$
>180	90	[91,92] COSTA	88	RVUE	Z_β with $\tan\beta = \sqrt{15}$
>158	90	[93] ELLIS	88	RVUE	Z_β ($\tan\beta = \sqrt{15}$), $p\overline{p}$

[86] ALTARELLI 91 limit is from atomic parity violation in Cs together with LEP, CDF data. $Z - Z'$ mixing is assumed to be zero to set the limit.

[87] Fig. 7(c) and (e) in DELAGUILA 91C give limits for $\tan\beta = -1/\sqrt{15}$ and $\tan\beta = \sqrt{15}$ from electroweak data.

[88] MAHANTHAPPA 91 limit is from atomic parity violation in Cs with $m(W)$, $m(Z)$. See Table III of MAHANTHAPPA 91 (corrected in erratum) for limits on various Z' models.

[89] GRIFOLS 90C obtains a limit for Z' mass as a function of mixing angle β (his $\theta = \beta - \pi/2$), which is derived from a LAMPF experiment on $\sigma(\nu_e e)$ (ALLEN 90). The result is shown in Fig. 1.

[90] See Table I of DELAGUILA 89 for limits on various Z' models.

[91] $g_\beta = e/\cos\theta_W$ and $\rho = 1$ assumed.

[92] A wide range of neutral current data as of 1986 are used in the fit.

[93] Z' mass limits from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider [based on ANSARI 87D and GEER Uppsala Conf. 87]. The limits apply when Z' decays only into light quarks and leptons.

MASS LIMITS for a Heavy Neutral Boson Coupling to e^+e^-

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 55–61		[94] ODAKA	89	VNS	$\Gamma(X^0 \rightarrow e^+e^-)$ $\cdot B(X^0 \rightarrow$ hadrons) $\gtrsim$ 0.2 MeV
>45	95	[95] DERRICK	86	HRS	$\Gamma(X^0 \rightarrow e^+e^-)$=6 MeV
>46.6	95	[96] ADEVA	85	MRKJ	$\Gamma(X^0 \rightarrow e^+e^-)$=10 keV
>48	95	[96] ADEVA	85	MRKJ	$\Gamma(X^0 \rightarrow e^+e^-)$=4 MeV
none 39.8–45.5		[97] ADEVA	84	MRKJ	$\Gamma(X^0 \rightarrow e^+e^-)$=10 keV
>47.8	95	[97] ADEVA	84	MRKJ	$\Gamma(X^0 \rightarrow e^+e^-)$=4 MeV
none 39.8–45.2		[97] BEHREND	84C	CELL	
>47	95	[97] BEHREND	84C	CELL	$\Gamma(X^0 \rightarrow e^+e^-)$=4 MeV

[94] ODAKA 89 looked for a narrow or wide scalar resonance in $e^+e^- \rightarrow$ hadrons at E_{cm} = 55.0–60.8 GeV.

[95] DERRICK 86 found no deviation from the Standard Model Bhabha scattering at E_{cm}= 29 GeV and set limits on the possible scalar boson e^+e^- coupling. See their figure 4 for excluded region in the $\Gamma(X^0 \rightarrow e^+e^-)$-$m(X^0)$ plane. Electronic chiral invariance requires a parity doublet of X^0, in which case the limit applies for $\Gamma(X^0 \rightarrow e^+e^-)$ = 3 MeV.

[96] ADEVA 85 first limit is from 2γ, $\mu^+\mu^-$, hadrons assuming X^0 is a scalar. Second limit is from e^+e^- channel. E_{cm} = 40–47 GeV. Supercedes ADEVA 84.

[97] ADEVA 84 and BEHREND 84C have E_{cm} = 39.8–45.5 GeV. MARK-J searched X^0 in $e^+e^- \rightarrow$ hadrons, 2γ, $\mu^+\mu^-$, e^+e^- and CELLO in the same channels plus τ pair. No narrow or broad X^0 is found in the energy range. They also searched for the effect of X^0 with $m(X) > E_{cm}$. The second limits are from Bhabha data and for spin-0 singlet. The same limits apply for $\Gamma(X^0 \rightarrow e^+e^-) = 2$ MeV if X^0 is a spin-0 doublet. The second limit of BEHREND 84C was read off from their figure 2. The original papers also list limits in other channels.

MASS LIMITS for Leptoquarks

The bound is for scalar leptoquarks unless noted.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
> 44 GeV	95		[98] DECAMP	92	ALEP	First or second generation
> 45 GeV	95		[98] DECAMP	92	ALEP	Third generation
> 43.2 GeV	95		[98] ADEVA	91B	L3	First generation
> 43.4 GeV	95		[98] ADEVA	91B	L3	Second generation
> 44.2 GeV	95		[98] ALEXANDER	91	OPAL	First or second generation
> 41.4 GeV	95		[98] ALEXANDER	91	OPAL	Third generation
• • • We do not use the following data for averages, fits, limits, etc. • • •						
none 8.9–22.6 GeV	95		[99] KIM	90	AMY	First generation
none 10.2–23.2 GeV	95		[99] KIM	90	AMY	Second generation
none 5–20.8 GeV	95		[100] BARTEL	87B	JADE	
none 7–20.5 GeV	95	2	[101] BEHREND	86B	CELL	
>350 TeV			[102] DESHPANDE	83	RVUE	Pati-Salam X-boson
> 1 TeV			[103] SHANKER	82	RVUE	PS leptoquark
>125 TeV			[103] SHANKER	82	RVUE	Vector-leptoquark

[98] Limits are for charge $-1/3$, isospin-0 scalar leptoquarks decaying to $\ell^- q$ or νq with any branching ratio. See paper for limits for other charge-isospin assignments of leptoquarks.

[99] KIM 90 assume pair production of charge 2/3 scalar-leptoquark via photon exchange. The decay of the first (second) generation leptoquark is assumed to be any mixture of de^+ and $u\overline{\nu}$ ($s\mu^+$ and $c\overline{\nu}$). See paper for limits for specific branching ratios.

[100] BARTEL 87B limit is valid when a pair of charge 2/3 spinless leptoquarks X is produced with point coupling, and when they decay under the constraint $B(X \rightarrow c\overline{\nu}_\mu) + B(X \rightarrow s\mu^+) = 1$.

[101] BEHREND 86B assumed that a charge 2/3 spinless leptoquark, χ, decays either into $s\mu^+$ or $c\overline{\nu}$: $B(\chi \rightarrow s\mu^+) + B(\chi \rightarrow c\overline{\nu}) = 1$.

[102] DESHPANDE 83 used upper limit on $K^0_L \rightarrow \mu e$ decay with renormalization-group equations to estimate coupling at the heavy boson mass. See also DIMOPOULOS 81.

[103] From $(\pi \rightarrow e\nu)/(\pi \rightarrow \mu\nu)$ ratio.

MASS LIMITS for g_A (axigluon)

Axigluons are massive color-octet gauge bosons in chiral color models and have axial-vector coupling to quarks with the same coupling strength as gluons.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>50	95	[104] CUYPERS	91	RVUE	$\sigma(e^+e^- \rightarrow$ hadrons)
none 120–210	95	[105] ABE	90H	CDF	$p\overline{p} \rightarrow g_A X$, $g_A \rightarrow$ 2jets
>29		[106] ROBINETT	89	THEO	Partial-wave unitarity
none 150–310	95	[107] ALBAJAR	88B	UA1	$p\overline{p} \rightarrow g_A X$, $g_A \rightarrow$ 2jets
>20		BERGSTROM	88	RVUE	$p\overline{p} \rightarrow \Upsilon X$ via $g_A g$
> 9		[108] CUYPERS	88	RVUE	Υ decay
>25		[109] DONCHESKI	88B	RVUE	Υ decay

[104] CUYPERS 91 compare α_s measured in Υ decay and that from R at PEP/PETRA energies.

[105] ABE 90H assumes $\Gamma(g_A) = N\alpha_s m(g_A)/6$ with $N = 5$ ($\Gamma(g_A) = 0.09 m(g_A)$). For N = 10, the excluded region is reduced to 120–150 GeV.

[106] ROBINETT 89 result demands partial-wave unitarity of $J = 0$ $t\overline{t} \rightarrow t\overline{t}$ scattering amplitude and derives a limit $m(g_A) > 0.5\, m(t)$. Assumes $m(t) > 56$ GeV.

[107] ALBAJAR 88B result is from the nonobservation of a peak in two-jet invariant mass distribution. $\Gamma(g_A) < 0.4\, m(g_A)$ assumed. See also BAGGER 88.

[108] CUYPERS 88 requires $\Gamma(\Upsilon \to g g_A) < \Gamma(\Upsilon \to ggg)$. A similar result is obtained by DONCHESKI 88.

[109] DONCHESKI 88B requires $\Gamma(\Upsilon \to g q\overline{q})/\Gamma(\Upsilon \to ggg) < 0.25$, where the former decay proceeds via axigluon exchange. A more conservative estimate of < 0.5 leads to $m(g_A) > 21$ GeV.

X^0 (Heavy Boson) Searches in Z Decays

Searches for radiative transition of Z to a lighter spin-0 state X^0 decaying to hadrons or a lepton pair. The limits are for the product of branching ratios.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.1 \times 10^{-4}$	95	[110] ACTON	91B	OPAL	$X^0 \to e^+e^-$
$<9 \times 10^{-5}$	95	[110] ACTON	91B	OPAL	$X^0 \to \mu^+\mu^-$
$<1.1 \times 10^{-4}$	95	[110] ACTON	91B	OPAL	$X^0 \to \tau^+\tau^-$
$<2.8 \times 10^{-4}$	95	[111] ADEVA	91D	L3	$X^0 \to e^+e^-$
$<2.3 \times 10^{-4}$	95	[111] ADEVA	91D	L3	$X^0 \to \mu^+\mu^-$
$<4.7 \times 10^{-4}$	95	[112] ADEVA	91D	L3	$X^0 \to$ hadrons
$<8 \times 10^{-4}$	95	[113] AKRAWY	90J	OPAL	$X^0 \to$ hadrons

[110] ACTON 91B limits are for $m(X^0) = 60$–85 GeV.

[111] ADEVA 91D limits are for $m(X^0) = 30$–89 GeV.

[112] ADEVA 91D limits are for $m(X^0) = 30$–86 GeV.

[113] AKRAWY 90J give $\Gamma(Z \to \gamma X^0)\cdot B(X^0 \to \text{hadrons}) < 1.9$ MeV (95%CL) for $m(X^0) = 32$–80 GeV. We divide by $\Gamma(Z) = 2.5$ GeV to get product of branching ratios. For nonresonant transitions, the limit is $B(Z \to \gamma q\overline{q}) < 8.2$ MeV assuming three-body phase space distribution.

Heavy Particle Production in Quarkonium Decays

Limits are for branching ratios to modes shown.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5.6 \times 10^{-5}$	90	[114] ANTREASYAN	90C	CBAL	$\Upsilon(1S) \to X^0\gamma$, $m(X^0) < 7.2$ GeV
		[115] ALBRECHT	89	ARG	

[114] ANTREASYAN 90C assume that X^0 does not decay in the detector.

[115] ALBRECHT 89 give limits for $B(\Upsilon(1S), \Upsilon(2S) \to X^0\gamma)\cdot B(X^0 \to \pi^+\pi^-, K^+K^-, p\overline{p})$ for $m(X^0) < 3.5$ GeV.

REFERENCES FOR Searches for Heavy Bosons Other Than Higgs Bosons

ABE 92B PRL (to be pub.) +Amidei, Apollianari, Atac, Auchincloss+ (CDF Collab.)
(to be published in March 9, 1992 issue)
DECAMP 92 PRPL (to be pub.) +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
CERN-PPE/91-149
ABE 91D PRL 67 2418 +Amidei, Apollinari, Atac, Auchincloss+ (CDF Collab.)
ABE 91F PRL 67 2609 +Amidei, Apollinari, Atac, Auchincloss+ (CDF Collab.)
ACTON 91B PL B273 338 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ADEVA 91B PL B261 169 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ADEVA 91D PL B262 155 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ALEXANDER 91 PL B263 123 +Allison, Allport, Anderson, Arcelli+ (OPAL Collab.)
ALITTI 91 ZPHY C49 17 +Ansari, Ansorge, Autiero, Bareyre+ (UA2 Collab.)
ALTARELLI 91 PL B261 146 +Casalbuoni, De Curtis+ (CERN, FIRZ, GEVA)
ALTARELLI 91B PL B263 459 +Casalbuoni, De Curtis+ (CERN, FIRZ, GEVA)
Also 90 PL B245 669 Altarelli, Casalbuoni, Feruglio, Gatto (CERN, LECE, GEVA)
AQUINO 91 PL B261 280 +Fernandez, Garcia (CINV, PUEB)
BUCHMUEL... 91 PL B267 395 Buchmueller, Greub, Minkowski (DESY, BERN)
COLANGELO 91 PL B253 154 +Nardulli (BARI)
CUYPERS 91 PL B259 173 +Falk, Frampton (DURH, HARV, UNCC)
DELAGUILA 91 PL B254 497 del Aguila, Moreno, Quiros (BARC, MADE, CERN)
DELAGUILA 91C NP B361 45 del Aguila, Moreno, Quiros (BARC, MADE)
FARAGGI 91 MPL A6 61 +Nanopoulos (TAMU)
GEIREGAT 91 PL B259 499 +Vilain, Wilquet, Binder, Burkard+ (CHARM II Collab.)
GONZALEZ-G... 91 PL B259 365 Gonzalez-Garcia, Valle (VALE)
Also 90C NP B345 312 Gonzalez-Garcia, Valle (VALE)
MAHANTHAP... 91 PR D43 3093 Mahanthappa, Mohapatra (COLO)
Also 91B PR D44 1616 (erratum) Mahanthappa, Mohapatra (COLO)
RIZZO 91 PR D44 202 (WISC, ISU)
ABE 90F PL B246 297 +Amako, Arai, Asano, Chiba+ (VENUS Collab.)
ABE 90G PRL 65 2243 +Amidei, Apollinari, Atac+ (CDF Collab.)
ABE 90H PR D41 1722 +Amidei, Apollinari, Ascoli, Atac+ (CDF Collab.)
AKRAWY 90J PL B246 285 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ALLEN 90 PRL 64 1330 +Chen, Doe+ (UCI, LASL, UMD)
ANTREASYAN 90C PL B251 204 +Bartels, Besset, Bieler, Bienlein+ (Crystal Ball Collab.)
BARGER 90B PR D42 152 +Hewett, Rizzo (WISC, ISU)
GLASHOW 90 PR D42 3224 +Sarid (HARV)
GLASHOW 90B PRL 64 725 +Sarid (HARV)
GONZALEZ-G... 90D PL B240 163 Gonzalez-Garcia, Valle (VALE)
GRIFOLS 90 NP B331 244 +Masso (BARC)
GRIFOLS 90C MPL A5 2657 (BARC)
GRIFOLS 90D PR D42 3293 +Masso, Rizzo (BARC, CERN, WISC, ISU)
HAGIWARA 90 PR D41 815 +Najima, Sakuda, Terunuma (KEK, DURH, YCC, HIRO)
HE 90B PL B240 441 +Joshi, Volkas (MELB)
Also 90C PL B244 580 (erratum) He, Joshi, Volkas (MELB)
KIM 90 PL B240 243 +Breedon, Ko, Lander, Maeshima, Malchow+ (AMY Collab.)
LOPEZ 90 PL B241 392 +Nanopoulos (TAMU)
ALBAJAR 89 ZPHY C44 15 +Albrow, Allkofer, Arnison, Astbury+ (UA1 Collab.)
ALBRECHT 89 ZPHY C42 349 +Boeckmann, Glaeser, Harder+ (ARGUS Collab.)
DELAGUILA 89 PR D40 2481 del Aguila, Moreno, Quiros (BARC, MADE)
Also 90B PR D41 134 del Aguila, Moreno, Quiros (BARC, MADE)
Also 90C PR D42 262 (erratum) del Aguila, Moreno, Quiros (BARC, MADE)
DORENBOS... 89 ZPHY C41 567 Dorenbosch, Udo, Allaby, Amaldi+ (CHARM Collab.)
GEIREGAT 89 PL B232 539 +Vilain, Wilquet, Bergsma, Binder+ (CHARM II Collab.)
LANGACKER 89B PR D40 1569 +Uma Sankar (PENN)
ODAKA 89 JPSJ 58 3037 +Kondo, Abe, Amako+ (VENUS Collab.)
ROBINETT 89 PR D39 834 (PSU)
ALBAJAR 88B PL B209 127 +Albrow, Allkofer, Astbury, Aubert+ (UA1 Collab.)
BAGGER 88 PR D37 1188 +Schmidt, King (HARV, BOST)
BALKE 88 PR D37 587 +Gidal, Jodidio+ (LBL, UCB, COLO, NWES, TRIU)
BERGSTROM 88 PL B212 386 (STOH)
COSTA 88 NP B297 244 +Ellis, Fogli, Nanopoulos+ (PADO, BARI, WISC, LBL)
CUYPERS 88 PRL 60 1237 +Frampton (UNCC)
DONCHESKI 88 PL B206 137 +Grotch, Robinett (PSU)
DONCHESKI 88B PR D38 412 +Grotch, Robinett (PSU)
ELLIS 88 PL B202 417 Ellis, Franzini, Zwirner (CERN, UCB, LBL)
AMALDI 87 PR D36 1385 +Bohm, Durkin, Langacker+ (CERN, AACH, OSU+)
ANSARI 87D PL B195 613 +Bagnaia, Banner+ (UA2 Collab.)
BARTEL 87B ZPHY C36 15 +Becker, Felst+ (JADE Collab.)
MARCIANO 87 PR D35 1672 +Sirlin (BNL, NYU)
ARNISON 86B EPL 1 327 +Albrow, Allkofer+ (UA1 Collab.)
BARGER 86B PRL 56 30 +Deshpande, Whisnant (WISC, OREG, FSU)
BEHREND 86B PL B178 452 +Buerger, Criegee, Fenner, Field+ (CELLO Collab.)
DERRICK 86 PL 166B 463 +Gan, Kooijman, Loos+ (HRS Collab.)
DURKIN 86 PL 166B 436 +Langacker (PENN)
ELLIS 86 PL 167B 457 +Enqvist, Nanopoulos, Sarkar (CERN, OXF)
JODIDIO 86 PR D34 1967 +Balke, Carr, Gidal, Shinsky+ (LBL, NWES, TRIU)
Also 88 PR D37 237 erratum Jodidio, Balke, Carr+ (LBL, NWES, TRIU)
MOHAPATRA 86 PR D34 909 (UMD)
STEIGMAN 86 PL B176 33 +Olive, Schramm, Turner (BART, MINN+)
ADEVA 85 PL 152B 439 +Becker, Becker-Szendy+ (Mark-J Collab.)
ADEVA 85B PRL 55 665 +Becker, Becker-Szendy+ (Mark-J Collab.)
STOKER 85 PRL 54 1887 +Balke, Carr, Gidal+ (LBL, NWES, TRIU)
ADEVA 84 PRL 53 134 +Barber, Becker, Berdugo+ (Mark-J Collab.)
BEHREND 84C PL 140B 130 +Burger, Criegee, Fenner+ (CELLO Collab.)
ARNISON 83D PL 129B 273 +Astbury, Aubert, Bacci+ (UA1 Collab.)
BERGSMA 83 PL 122B 465 +Dorenbosch, Jonker+ (CHARM Collab.)
CARR 83 PRL 51 627 +Gidal, Gobbi, Jodidio, Oram+ (LBL, NWES, TRIU)
DESHPANDE 83 PR D27 1193 +Johnson (OREG)
BEALL 82 PRL 48 848 +Bander, Soni (UCI, UCLA)
SHANKER 82 NP B204 375 (TRIU)
DIMOPOUL... 81 NP B182 77 Dimopoulos, Raby, Kane (STAN, MICH)
RIZZO 81 PR D24 704 +Senjanovic (BNL)

Searches for Axions (A^0) and Other Very Light Bosons

NOTE ON AXIONS

In this section we list limits for very light neutral (pseudo) scalar bosons that couple weakly to stable matter. Typical examples are pseudo-Goldstone bosons like axions (A^0),[1] familons,[2] and Majorons,[3] associated, respectively, with spontaneously broken Peccei-Quinn,[4] family, and lepton-number symmetries.

Peccei-Quinn symmetry gives a natural solution to the strong CP-violation problem. Axion mass and its coupling to stable particles are inversely proportional to the scale of the Peccei-Quinn symmetry breaking f_A. The original axion model[4,1] assumes $f_A = v$, where $v = (\sqrt{2}G_F)^{-1/2} = 247$ GeV is the scale of the electroweak symmetry breaking, and has two Higgs doublets as minimal ingredients. By requiring tree-level flavor conservation, the axion mass and its couplings are completely fixed in terms of one parameter, the ratio of the vacuum expectation values of two Higgs fields. The result of extensive experimental searches for such an axion have been negative.[5]

Observation of a narrow-peak structure in positron spectra from heavy ion collisions[6] suggested a particle of mass 1.8 MeV that decays into e^+e^-. Variants of the original axion model, which keep $f_A = v$, but drop the constraints of tree-level flavor conservation, were proposed.[7] Extensive searches for this particle, A^0(1.8 MeV), ended up with another negative result.[8]

One way to avoid these experimental constraints is to make A^0 sufficiently massive. One way to achieve this is to introduce a new strong interaction (QC′D) with $\Lambda_{\mathrm{QC'D}} \gg \Lambda_{\mathrm{QCD}}$, whose anomaly couples to the axion.[9] A^0 can receive significant mass from the QC′D sector if QC′D colored quarks are massive.

Another way to save the Peccei-Quinn idea is to discard the proposition $f_A = v$ and introduce a new scale. With $f_A \gg v$, the A^0 mass becomes smaller and its coupling weaker, thus one can easily avoid all the existing experimental limits; hence such models are called invisible axion models.[10,11] Various invisible axion models can be constructed by identifying f_A with other large mass scales such as the Planck mass, the GUT scale, the SUSY-breaking scale, and so on. It has been found, however, that invisible axions are not completely elusive. Cosmological considerations on the matter density of our universe suggest[12] $f_A < \mathcal{O}(10^{12})$ GeV as a possible upper bound on the scale. Lower bounds of $f_A > \mathcal{O}(10^7)$ GeV are obtained from astrophysics,[13] where axion emission from the center of stellar objects can speed up their evolutionary time scales. The recent observation of the supernova SN1987A improves the lower bound to $f_A > \mathcal{O}(10^{10})$ GeV. Various terrestrial experiments to detect 'invisible' axions by making use of their coupling to photons have been proposed,[14] and the first result of such experiments appeared recently.

There is also a Note on "invisible" axions later in this section.

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A^0 (Axion) MASS LIMITS from Astrophysics and Cosmology

These bounds depend on model-dependent assumptions (i.e. — on a combination of axion parameters).

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>0.2	BARROSO	82	ASTR	Standard Axion
>0.25	[1] RAFFELT	82	ASTR	Standard Axion
>0.2	[2] DICUS	78C	ASTR	Standard Axion
	MIKAELIAN	78	ASTR	Stellar emission
>0.3	[2] SATO	78	ASTR	Standard Axion
>0.2	VYSOTSKII	78	ASTR	Standard Axion

[1] Lower bound from 5.5 MeV γ-ray line from the sun.

[2] Lower bound from requiring the red giants' stellar evolution not be disrupted by axion emission.

A^0 (Axion) Searches in Stable Particle Decays

Limits are for branching ratios.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<1 \times 10^{-7}$	90		[3] ATIYA	90B	CNTR	$K^+ \to \pi^+ A^0$, $(A^0 \to \gamma\gamma)$
$<8 \times 10^{-7}$	90		[4] BAKER	87	CALO	$K^\pm \to \pi^\pm A^0$ $(A^0 \to e^+ e^-)$
$<1.3 \times 10^{-8}$	90		[5] KORENCHE...	87	SPEC	$\pi^+ \to e^+ \nu A^0$ $(A^0 \to e^+ e^-)$
$<1 \times 10^{-9}$	90	0	[6] EICHLER	86	SPEC	Stopped $\pi^+ \to e^+ \nu A^0$
$<2 \times 10^{-5}$	90		[7] YAMAZAKI	84	SPEC	For $160<m<260$ MeV
$<(1.5\text{–}4) \times 10^{-6}$	90		[7] YAMAZAKI	84	SPEC	K decay, $m(A^0) \ll$ 100 MeV
		0	[8] ASANO	82	CNTR	Stopped $K^+ \to \pi^+ A^0$
		0	[9] ASANO	81B	CNTR	Stopped $K^+ \to \pi^+ A^0$
			[10] ZHITNITSKII	79		Heavy axion

[3] ATIYA 90B limit is for $B(K^+ \to \pi^+ A^0) \cdot B(A^0 \to \gamma\gamma)$ and applies for $m(A^0) = 50$ MeV, $\tau(A^0) < 10^{-10}$ s. Limits are also provided for $0 < m(A^0) < 100$ MeV, $\tau(A^0) < 10^{-8}$ s.

[4] BAKER 87 limit assumes that the A^0 travels much less than 1.4 cm in the lab before decaying.

[5] KORENCHENKO 87 limit assumes $m(A^0) = 1.7$ MeV, $\tau(A^0) \lesssim 10^{-12}$ s, and $B(A^0 \to e^+ e^-) = 1$.

[6] EICHLER 86 looked for $\pi^+ \to e^+ \nu A^0$ followed by $A^0 \to e^+ e^-$. Limits on the branching fraction depend on the mass and and lifetime of A^0. The quoted limits are valid when $\tau(A^0) \gtrsim 3. \times 10^{-10}$s if the decays are kinematically allowed.

[7] YAMAZAKI 84 looked for a discrete line in $K^+ \to \pi^+ X$. Sensitive to wide mass range (5–300 MeV), independent of whether X decays promptly or not.

[8] ASANO 82 at KEK set limits for $B(K^+ \to \pi^+ A^0)$ for $m(A^0)$ <100 MeV as BR $< 4. \times 10^{-8}$ for $\tau(A^0 \to n\gamma\text{'s}) > 1. \times 10^{-9}$ s, BR $< 1.4 \times 10^{-6}$ for $\tau < 1. \times 10^{-9}$s.

[9] ASANO 81B is KEK experiment. Set $B(K^+ \to \pi^+ A^0) < 3.8 \times 10^{-8}$ at CL = 90%.

[10] ZHITNITSKII 79 argue that a heavy axion predicted by YANG 78 (3 $< m <$40 MeV) contradicts experimental muon anomalous magnetic moments.

A^0 (Axion) Searches in Quarkonium and Positronium Decays

Decay or transition of positronium and quarkonium. Limits are for branching ratio.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<1.1 \times 10^{-6}$	90		[11] ASAI	91	CNTR	o-Ps $\to A^0 \gamma$, $m(A^0) < 800$ keV
$<4.0 \times 10^{-5}$	90		ANTREASYAN	90C	CBAL	$\Upsilon(1S) \to A^0 \gamma$
			[12] ANTREASYAN	90C	RVUE	
$<3.8 \times 10^{-4}$	90		GNINENKO	90	CNTR	o-Ps $\to A^0 \gamma$, $m(A^0) <$ 30 keV
$<(1\text{–}5) \times 10^{-4}$	95		[13] TSUCHIAKI	90	CNTR	o-Ps $\to A^0 \gamma$, $m(A^0) =$ 300–900 keV
$<6.4 \times 10^{-5}$	90		[14] ORITO	89	CNTR	o-Ps $\to A^0 \gamma$, $m(A^0) < 30$ keV
$<5 \times 10^{-5}$	90		[15] DRUZHININ	87	ND	$\phi \to \gamma A^0$ $(A^0 \to e^+ e^-)$
$<2 \times 10^{-3}$	90		[16] DRUZHININ	87	ND	$\phi \to \gamma A^0$ $(A^0 \to \gamma\gamma)$
$<7 \times 10^{-6}$	90		[17] DRUZHININ	87	ND	$\phi \to \gamma A^0$ $(A^0 \to$ missing$)$
$<3.1 \times 10^{-4}$	90	0	[18] ALBRECHT	86D	ARG	$\Upsilon(1S) \to \gamma A^0$ $(A^0 \to e^+ e^-)$
$<4 \times 10^{-4}$	90	0	[18] ALBRECHT	86D	ARG	$\Upsilon(1S) \to \gamma A^0$ $(A^0 \to \mu^+ \mu^-$, $\pi^+ \pi^-$, $K^+ K^-)$

$<8 \times 10^{-4}$	90	1	[19] ALBRECHT	86D	ARG	$\Upsilon(1S) \rightarrow \gamma A^0$
$<1.3 \times 10^{-3}$	90	0	[20] ALBRECHT	86D	ARG	$\Upsilon(1S) \rightarrow \gamma A^0$ ($A^0 \rightarrow e^+e^-, \gamma\gamma$)
$<2. \times 10^{-3}$	90		[21] BOWCOCK	86	CLEO	$\Upsilon(2S) \rightarrow \Upsilon(1S) \rightarrow A^0$
$<5. \times 10^{-3}$	90		[22] MAGERAS	86	CUSB	$\Upsilon(1S) \rightarrow A^0\gamma$
			[23] AMALDI	85	CNTR	Ortho-positronium
$<3. \times 10^{-4}$	90		[24] ALAM	83	CLEO	$\Upsilon(1S) \rightarrow A^0\gamma$
			[25] CARBONI	83	CNTR	Ortho-positronium
$<9.1 \times 10^{-4}$	90		[26] NICZYPORUK	83	LENA	$\Upsilon(1S) \rightarrow A^0\gamma$
$<1.4 \times 10^{-5}$	90		[27] EDWARDS	82	CBAL	$J/\psi \rightarrow A^0\gamma$
$<3.5 \times 10^{-4}$	90		[28] SIVERTZ	82	CUSB	$\Upsilon(1S) \rightarrow A^0\gamma$
$<1.2 \times 10^{-4}$	90		[28] SIVERTZ	82	CUSB	$\Upsilon(3S) \rightarrow A^0\gamma$

[11] ASAI 91 limit translates to $g^2_{A^0 e^+e^-}/4\pi < 1.1 \times 10^{-11}$ (90%CL) for $m(A^0) < 800$ keV.

[12] The combined limit of ANTREASYAN 90C and EDWARDS 82 excludes standard axion with $m(A^0) < 2m(e)$ at 90% CL as long as $C_\Upsilon C_{J/\psi} > 0.09$, where C_V ($V = \Upsilon, J/\psi$) is the reduction factor for $\Gamma(V \rightarrow A^0\gamma)$ due to QCD and/or relativistic corrections. The same data excludes $0.02 < x < 260$ (90% CL) if $C_\Upsilon = C_{J/\psi} = 0.5$, and further combining with ALBRECHT 86D result excludes $5 \times 10^{-5} < x < 260$. x is the ratio of the vacuum expectation values of the two Higgs fields. These limits use conventional assumption $\Gamma(A^0 \rightarrow ee) \propto x^{-2}$. The alternative assumption $\Gamma(A^0 \rightarrow ee) \propto x^2$ gives a somewhat different excluded region $0.00075 < x < 44$.

[13] The TSUCHIAKI 90 limit is based on inclusive photon spectrum and is independent of A^0 decay modes.

[14] ORITO 89 limit translates to $g^2_{A^0 ee}/4\pi < 6.2 \times 10^{-10}$. Somewhat more sensitive limits are obtained for larger $m(A^0)$: $B < 7.6 \times 10^{-6}$ at 100 keV.

[15] The first DRUZHININ 87 limit is valid when $\tau(A^0)/m(A^0) < 3 \times 10^{-13}$ s/MeV and $m(A^0) < 20$ MeV.

[16] The second DRUZHININ 87 limit is valid when $\tau(A^0)/m(A^0) < 5 \times 10^{-13}$ s/MeV and $m(A^0) < 20$ MeV.

[17] The third DRUZHININ 87 limit is valid when $\tau(A^0)/m(A^0) > 7 \times 10^{-12}$ s/MeV and $m(A^0) < 200$ MeV.

[18] $\tau(A^0) < 1 \times 10^{-13}$s and $m(A^0) < 1.5$ GeV. Applies for $A^0 \rightarrow \gamma\gamma$ when $m(A^0) < 100$ MeV.

[19] $\tau(A^0) > 1 \times 10^{-7}$s.

[20] Independent of $\tau(A^0)$.

[21] BOWCOCK 86 looked for A^0 that decays into e^+e^- in the cascade decay $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ followed by $\Upsilon(1S) \rightarrow A^0\gamma$. The limit for BR($\Upsilon(1S) \rightarrow A^0\gamma$)BR($A^0 \rightarrow e^+e^-$) depends on $m(A^0)$ and $\tau(A^0)$. The quoted limit for $m(A^0)$=1.8 MeV is at $\tau(A^0) \sim 2. \times 10^{-12}$s, where the limit is the worst. The same limit $2. \times 10^{-3}$ applies for all lifetimes for masses $2m(e) < m(A^0) < 2m(\mu)$ when the results of this experiment are combined with the results of ALAM 83.

[22] MAGERAS 86 looked for $\Upsilon(1S) \rightarrow \gamma A^0$ ($A^0 \rightarrow e^+e^-$). The quoted branching fraction limit is for $m(A^0) = 1.7$ MeV, at $\tau(A^0) \sim 4. \times 10^{-13}$s where the limit is the worst.

[23] AMALDI 85 set limits B($A^0\gamma$) / B($\gamma\gamma\gamma$) $< (1\text{–}5) \times 10^{-6}$ for $m(A^0) = 900\text{–}100$ keV which are about 1/10 of the CARBONI 83 limits.

[24] ALAM 83 is at CESR. This limit combined with limit for B($J/\psi \rightarrow A^0\gamma$) (EDWARDS 82) excludes standard axion.

[25] CARBONI 83 looked for orthopositronium $\rightarrow A^0\gamma$. Set limit for A^0 electron coupling squared, $g(eeA^0)^2/(4\pi) < 6. \times 10^{-10}\text{–}7. \times 10^{-9}$ for $m(A^0)$ from 150–900 keV (CL = 99.7%). This is about 1/10 of the bound from g–2 experiments.

[26] NICZYPORUK 83 is DESY-DORIS experiment. This limit together with lower limit 9.2×10^{-4} of B($\Upsilon \rightarrow A^0\gamma$) derived from B($J/\psi(1S) \rightarrow A^0\gamma$) limit (EDWARDS 82) excludes standard axion.

[27] EDWARDS 82 looked for $J/\psi \rightarrow \gamma A^0$ decays by looking for events with a single γ [of energy $\sim$ 1/2 the $J/\psi(1S)$ mass], plus nothing else in the detector. The limit is inconsistent with the axion interpretation of the FAISSNER 81B result.

[28] SIVERTZ 82 is CESR experiment. Looked for $\Upsilon \rightarrow \gamma A^0$, A^0 undetected. Limit for 1S (3S) is valid for $m(A^0) < 7$ GeV (4 GeV).

A^0 (Axion) Production in Hadron Collisions

Limits are for $\sigma(A^0)$ / $\sigma(\pi^0)$.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
			[29] BLUEMLEIN	91	BDMP	$A^0 \rightarrow e^+e^-, 2\gamma$
			[30] FAISSNER	89	OSPK	Beam dump, $A^0 \rightarrow e^+e^-$
			[31] DEBOER	88	RVUE	$A^0 \rightarrow e^+e^-$
			[32] EL-NADI	88	EMUL	$A^0 \rightarrow e^+e^-$
			[33] FAISSNER	88	OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
			[34] BADIER	86	BDMP	$A^0 \rightarrow e^+e^-$
$<2. \times 10^{-11}$	90	0	[35] BERGSMA	85	CHRM	CERN beam dump
$<1. \times 10^{-13}$	90	0	[35] BERGSMA	85	CHRM	CERN beam dump
		24	[36] FAISSNER	83	OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
			[37] FAISSNER	83B	RVUE	LAMPF beam dump
			[38] FRANK	83B	RVUE	LAMPF beam dump
			[39] HOFFMAN	83	CNTR	$\pi p \rightarrow nA^0$ ($A^0 \rightarrow e^+e^-$)
			[40] FETSCHER	82	RVUE	See FAISSNER 81B
		12	[41] FAISSNER	81	OSPK	CERN PS ν wideband
		15	[42] FAISSNER	81B	OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
		8	[43] KIM	81	OSPK	26 GeV $pN \rightarrow A^0$ X
		0	[44] FAISSNER	80	OSPK	Beam dump, $A^0 \rightarrow e^+e^-$
$<1. \times 10^{-8}$	90		[45] JACQUES	80	HLBC	28 GeV protons
$<1. \times 10^{-14}$	90		[45] JACQUES	80	HLBC	Beam dump
			[46] SOUKAS	80	CALO	28 GeV p beam dump
			[47] BECHIS	79	CNTR	
$<1. \times 10^{-8}$	90		[48] COTEUS	79	OSPK	Beam dump
$<1. \times 10^{-3}$	95		[49] DISHAW	79	CALO	400 GeV pp
$<1. \times 10^{-8}$	90		ALIBRAN	78	HYBR	Beam dump
$<6. \times 10^{-9}$	95		ASRATYAN	78B	CALO	Beam dump
$<1.5 \times 10^{-8}$	90		[50] BELLOTTI	78	HLBC	Beam dump
$<5.4 \times 10^{-14}$	90		[50] BELLOTTI	78	HLBC	$m(A^0)$=1.5 MeV
$<4.1 \times 10^{-9}$	90		[50] BELLOTTI	78	HLBC	$m(A^0)$=1 MeV
$<1. \times 10^{-8}$	90		[51] BOSETTI	78B	HYBR	Beam dump
			[52] DONNELLY	78		
$<0.5 \times 10^{-8}$	90		HANSL	78D	WIRE	Beam dump
			[53] MICELMAC...	78		
			[54] VYSOTSKII	78		

[29] BLUEMLEIN 91 is a proton beam dump experiment at Serpukhov. No candidate event for $A^0 \rightarrow e^+e^-$, 2γ are found. Fig. 6 gives the excluded region in $m(A^0)$-x plane ($x = \tan\beta = v_2/v_1$). Standard axion is excluded for $0.2 < m(A^0) < 3.2$ MeV for most $x > 1$, 0.2–11 MeV for most $x < 1$.

[30] FAISSNER 89 searched for $A^0 \rightarrow e^+e^-$ in a proton beam dump experiment at SIN. No excess of events was observed over the background. A standard axion with mass $2m(e)$–20 MeV is excluded. Lower limit on f_{A^0} of $\sim 10^4$ GeV is given for $m(A^0) = 2m(e)$–20 MeV.

[31] DEBOER 88 reanalyze EL-NADI 88 data and claim evidence for three distinct states with mass $\sim$ 1.1, $\sim$ 2.1, and $\sim$ 9 MeV, lifetimes 10^{-16}–10^{-15} s decaying to e^+e^- and note the similarity of the data with those of a cosmic-ray experiment by Bristol group (B.M. Anand, Proc. of the Royal Society of London **A22** 183 (1953)). For a criticism see PERKINS 89, who suggests that the events are compatible with π^0 Dalitz decay. DEBOER 89B is a reply which contests the criticism.

[32] EL-NADI 88 claim the existence of a neutral particle decaying into e^+e^- with mass 1.60 ± 0.59 MeV, lifetime $(0.15 \pm 0.01) \times 10^{-14}$ s, which is produced in heavy ion interactions with emulsion nuclei at $\sim$ 4 GeV/c/nucleon.

[33] FAISSNER 88 is a proton beam dump experiment at SIN. They found no candidate event for $A^0 \rightarrow \gamma\gamma$. A standard axion decaying to 2γ is excluded except for a region $x \sim 1$. Lower limit on f_{A^0} of 10^2–10^3 GeV is given for $m(A^0) = 0.1$–1 MeV.

[34] BADIER 86 did not find long-lived A^0 in 300 GeV π^- Beam Dump Experiment that decays into e^+e^- in the mass range $m(A^0) = (20\text{–}200)$ MeV, which excludes the A^0 decay constant $f(A^0)$ in the interval (60–600) GeV. See their figure 6 for excluded region on $f(A^0)$-$m(A^0)$ plane.

[35] BERGSMA 85 look for $A^0 \rightarrow 2\gamma$, e^+e^-, $\mu^+\mu^-$. First limit above is for $m(A^0) = 1$ MeV; second is for 200 MeV. See their figure 4 for excluded region on $f_{A^0}-m(A^0)$ plane, where f_{A^0} is A^0 decay constant. For Peccei-Quinn PECCEI 77 A^0, $m(A^0) <$180 keV and $\tau >$0.037 s. (CL = 90%). For the axion of FAISSNER 81B at 250 keV, BERGSMA 85 expect 15 events but observe zero.

[36] FAISSNER 83 observed 19 1-γ and 12 2-γ events where a background of 4.8 and 2.3 respectively is expected. A small-angle peak is observed even if iron wall is set in front of the decay region.

[37] FAISSNER 83B extrapolate SIN γ signal to LAMPF ν experimental condition. Resulting 370 γ's are not at variance with LAMPF upper limit of 450 γ's. Derived from LAMPF limit that $[d\sigma(A^0)/d\omega$ at $90°]m(A^0)/\tau(A^0) < 14 \times 10^{-35}$ cm^2 sr^{-1} MeV ms^{-1}. See comment on FRANK 83B.

[38] FRANK 83B stress the importance of LAMPF data bins with negative net signal. By statistical analysis say that LAMPF and SIN-A0 are at variance when extrapolation by phase-space model is done. They find LAMPF upper limit is 248 not 450 γ's. See comment on FAISSNER 83B.

[39] HOFFMAN 83 set CL = 90% limit $d\sigma/dt$ B(e^+e^-) $<3.5 \times 10^{-32}$ cm^2/GeV^2 for 140 $< m(A^0) <$160 MeV. Limit assumes $\tau(A^0) < 10^{-9}$ s.

[40] FETSCHER 82 reanalyzes SIN beam-dump data of FAISSNER 81. Claims no evidence for axion since 2-γ peak rate remarkably decreases if iron wall is set in front of the decay region.

[41] FAISSNER 81 see excess μe events. Suggest axion interactions.

[42] FAISSNER 81B is SIN 590 MeV proton beam dump. Observed 14.5 ± 5.0 events of 2γ decay of long-lived neutral penetrating particle with $m(2\gamma) \lesssim 1$ MeV. Axion interpretation with η-A^0 mixing gives $m(A^0) = 250 \pm 25$ keV, $\tau_{(2\gamma)} = (7.3 \pm 3.7) \times 10^{-3}$ s from above rate. See critical remarks below in comments of FETSCHER 82, FAISSNER 83, FAISSNER 83B, FRANK 83B, and BERGSMA 85. Also see in the next subsection ALEKSEEV 82, CAVAIGNAC 83, and ANANEV 85.

[43] KIM 81 analyzed 8 candidates for $A^0 \rightarrow 2\gamma$ obtained by Aachen-Padova experiment at CERN with 26 GeV protons on Be. Estimated axion mass is about 300 keV and lifetime is $(0.86 \sim 5.6) \times 10^{-3}$ s depending on models. Faissner (private communication), says axion production underestimated and mass overestimated. Correct value around 200 keV.

[44] FAISSNER 80 is SIN beam dump experiment with 590 MeV protons looking for $A^0 \rightarrow e^+e^-$ decay. Assuming $A^0/\pi^0 = 5.5 \times 10^{-7}$, obtained decay rate limit 20/(A^0 mass) MeV/s (CL = 90%), which is about 10^{-7} below theory and interpreted as upper limit to $m(A^0) < 2m(e^-)$.

[45] JACQUES 80 is a BNL beam dump experiment. First limit above comes from nonobservation of excess neutral-current-type events [σ(production)σ(interactaction) $< 7. \times 10^{-68}$ cm^4, CL = 90%]. Second limit is from nonobservation of axion decays into 2γ's or e^+e^-, and for axion mass a few MeV.

[46] SOUKAS 80 at BNL observed no excess of neutral-current-type events in beam dump.

[47] BECHIS 79 looked for the axion production in low energy electron Bremsstrahlung and the subsequent decay into either 2γ or e^+e^-. No signal found. CL = 90% limits for model parameter(s) are given.

[48] COTEUS 79 is a beam dump experiment at BNL.

[49] DISHAW 79 is a calorimetric experiment and looks for low energy tail of energy distributions due to energy lost to weakly interacting particles.

[50] BELLOTTI 78 first value comes from search for $A^0 \to e^+e^-$. Second value comes from search for $A^0 \to 2\gamma$, assuming mass $<2m(e^-)$. For any mass satisfying this, limit is above value × (mass^{-4}). Third value uses data of PL 60B 401 and quotes σ(production)σ(interaction) $< 10^{-67}$ cm^4.

[51] BOSETTI 78B quotes σ(production)σ(interaction) $<2. \times 10^{-67}$ cm^4.

[52] DONNELLY 78 examines data from reactor neutrino experiments of REINES 76 and GURR 74 as well as SLAC beam dump experiment. Evidence is negative.

[53] MICELMACHER 78 finds no evidence of axion existence in reactor experiments of REINES 76 and GURR 74. (See reference under DONNELLY 78 below).

[54] VYSOTSKII 78 derived lower limit for the axion mass 25 keV from luminosity of the sun and 200 keV from red supergiants.

A^0 (Axion) Searches in Reactor Experiments

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[55] KETOV	86	SPEC	Reactor, $A^0 \to \gamma\gamma$
	[56] KOCH	86	SPEC	Reactor; $A^0 \to \gamma\gamma$
	[57] DATAR	82	CNTR	Light water reactor
	[58] VUILLEUMIER	81	CNTR	Reactor, $A^0 \to 2\gamma$

[55] KETOV 86 searched for A^0 at the Rovno nuclear power plant. They found an upper limit on the A^0 production probability of 0.8 $[100\text{ keV}/m(A^0)]^6 \times 10^{-6}$ per fission. In the standard axion model, this corresponds to $m(A^0) >150$ keV. Not valid for $m(A^0) \gtrsim 1$ MeV.

[56] KOCH 86 searched for $A^0 \to \gamma\gamma$ at nuclear power reactor Biblis A. They found an upper limit on the A^0 production rate of $\omega(A^0)/\omega(\gamma(M1)) < 1.5 \times 10^{-10}$ (CL=95%). Standard axion with $m(A^0) = 250$ keV gives 10^{-5} for the ratio. Not valid for $m(A^0) >1022$ keV.

[57] DATAR 82 looked for $A^0 \to 2\gamma$ in neutron capture ($np \to dA^0$) at Tarapur 500 MW reactor. Sensitive to sum of $I = 0$ and $I = 1$ amplitudes. With ZEHNDER 81 $[(I = 0) - (I = 1)]$ result, assert nonexistence of standard A^0.

[58] VUILLEUMIER 81 is at Grenoble reactor. Set limit $m(A^0) <280$ keV.

A^0 (Axion) and Other Light Boson (X^0) Searches in Nuclear Transitions

Limits are for branching ratio.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$< 1.5 \times 10^{-9}$	95		[59] ASANUMA	90	CNTR	^{241}Am decay
$<(0.4\text{–}10) \times 10^{-3}$	95		[60] DEBOER	90	CNTR	$^8\text{Be}^* \to {}^8\text{Be}A^0$, $A^0 \to e^+e^-$
$<(0.2\text{–}1) \times 10^{-3}$	90		[61] BINI	89	CNTR	$^{16}\text{O}^* \to {}^{16}\text{O}X^0$, $X^0 \to e^+e^-$
			[62] AVIGNONE	88	CNTR	$\text{Cu}^* \to \text{Cu}A^0$ ($A^0 \to 2\gamma$, $A^0 e \to \gamma e$, $A^0 Z \to \gamma Z$)
$< 1.5 \times 10^{-4}$	90		[63] DATAR	88	CNTR	$^{12}\text{C}^* \to {}^{12}\text{C}A^0$, $A^0 \to e^+e^-$
$< 5 \times 10^{-3}$	90		[64] DEBOER	88C	CNTR	$^{16}\text{O}^* \to {}^{16}\text{O}X^0$, $X^0 \to e^+e^-$
$< 3.4 \times 10^{-5}$	95		[65] DOEHNER	88	SPEC	$^2\text{H}^*$, $A^0 \to e^+e^-$
$< 4 \times 10^{-4}$	95		[66] SAVAGE	88	CNTR	Nuclear decay (isovector)
$< 3 \times 10^{-3}$	95		[66] SAVAGE	88	CNTR	Nuclear decay (isoscalar)
< 0.106	90		[67] HALLIN	86	SPEC	^{6}Li isovector decay
<10.8	90		[67] HALLIN	86	SPEC	^{10}B isoscalar decays
< 2.2	90		[67] HALLIN	86	SPEC	^{14}N isoscalar decays
$< 4 \times 10^{-4}$	90	0	[68] SAVAGE	86B	CNTR	$^{14}\text{N}^*$
			[69] ANANEV	85	CNTR	Li*, deut* $A^0 \to 2\gamma$
			[70] CAVAIGNAC	83	CNTR	^{97}Nb*, deut* transition $A^0 \to 2\gamma$
			[71] ALEKSEEV	82B	CNTR	Li*, deut* transition $A^0 \to 2\gamma$
			[72] LEHMANN	82	CNTR	$\text{Cu}^* \to \text{Cu}A^0$ ($A^0 \to 2\gamma$)
		0	[73] ZEHNDER	82	CNTR	Li*, Nb* decay, n-capt.
		0	[74] ZEHNDER	81	CNTR	$\text{Ba}^* \to \text{Ba}A^0$ ($A^0 \to 2\gamma$)
			[75] CALAPRICE	79		Carbon

[59] The ASANUMA 90 limit is for the branching fraction of X^0 emission per ^{241}Amα decay and valid for $\tau(X^0) < 3 \times 10^{-11}$ s.

[60] The DEBOER 90 limit is for the branching ratio $^8\text{Be}^*$ (18.15 MeV, 1^+) $\to {}^8\text{Be}A^0$, $A^0 \to e^+e^-$ for the mass range $m(A^0) = 4$–15 MeV.

[61] The BINI 89 limit is for the branching fraction of $^{16}\text{O}^*$ (6.05 MeV, 0^+) $\to {}^{16}\text{O}X^0$, $X^0 \to e^+e^-$ for $m(X) = 1.5$–3.1 MeV. $\tau(X^0) \lesssim 10^{-11}$ s is assumed. The spin-parity of X is restricted to 0^+ or 1^-.

[62] AVIGNONE 88 looked for the 1115 keV transition $\text{C}^* \to \text{Cu}A^0$, either from $A^0 \to 2\gamma$ in-flight decay or from the secondary A^0 interactions by Compton and by Primakoff processes. Limits for axion parameters are obtained for $m(A^0) < 1.1$ MeV.

[63] DATAR 88 rule out light pseudoscalar particle emission through its decay $A^0 \to e^+e^-$ in the mass range 1.02–2.5 MeV and lifetime range 10^{-13}–10^{-8} s. The above limit is for $\tau = 5 \times 10^{-13}$ s and $m = 1.7$ MeV; see the paper for the τ-m dependence of the limit.

[64] The limit is for the branching fraction of $^{16}\text{O}^*$ (6.05 MeV, 0^+) $\to {}^{16}\text{O}X^0$, $X^0 \to e^+e^-$ against internal pair conversion for $m(X^0) = 1.7$ MeV and $\tau(X^0) < 10^{-11}$ s. Similar limits are obtained for $m(X^0) = 1.3$–3.2 MeV. The spin parity of X^0 must be either 0^+ or 1^-. The limit at 1.7 MeV is translated into a limit for the X^0-nucleon coupling constant: $g^2_{X^0 NN}/4\pi < 2.3 \times 10^{-9}$.

[65] The DOEHNER 88 limit is for $m(A^0) = 1.7$ MeV, $\tau(A^0) < 10^{-10}$ s. Limits less than 10^{-4} are obtained for $m(A^0) = 1.2$–2.2 MeV.

[66] SAVAGE 88 looked for A^0 that decays into e^+e^- in the decay of the 9.17 MeV $J^P = 2^+$ state in ^{14}N, 17.64 MeV state $J^P = 1^+$ in ^{8}Be, and the 18.15 MeV state $J^P = 1^+$ in ^{8}Be. This experiment constrains the isovector coupling of A^0 to hadrons, if $m(A^0) = (1.1 \to 2.2)$ MeV and the isoscalar coupling of A^0 to hadrons, if $m(A^0) = (1.1 \to 2.6)$ MeV. Both limits are valid only if $\tau(A^0) \lesssim 1 \times 10^{-11}$ s.

[67] Limits are for $\Gamma(A^0(1.8\text{ MeV}))/\Gamma(\pi M1)$; i.e., for 1.8 MeV axion emission normalized to the rate for internal emission of e^+e^- pairs. Valid for $\tau(A^0) < 2 \times 10^{-11}$s. ^{6}Li isovector decay data strongly disfavor PECCEI 86 model I, whereas the ^{10}B and ^{14}N isoscalar decay data strongly reject PECCEI 86 model II and III.

[68] SAVAGE 86B looked for A^0 that decays into e^+e^- in the decay of the 9.17 MeV $J^P = 2^+$ state in ^{14}N. Limit on the branching fraction is valid if $\tau(A^0) \lesssim 1. \times 10^{-11}$s for $m(A^0) = (1.1$–$1.7)$ MeV. This experiment constrains the iso-vector coupling of A^0 to hadrons.

[69] ANANEV 85 with IBR-2 pulsed reactor exclude standard A^0 at CL = 95% masses below 470 keV (Li* decay) and below $2m(e)$ for deuteron* decay.

[70] CAVAIGNAC 83 at Bugey reactor exclude axion at any $m(^{97}\text{Nb*decay})$ and axion with $m(A^0)$ between 275 and 288 keV (deuteron* decay).

[71] ALEKSEEV 82 with IBR-2 pulsed reactor exclude standard A^0 at CL = 95% mass-ranges $m(A^0)$ <400 keV (Li* decay) and 330 keV $<m(A^0)<$2.2 MeV. (deuteron* decay).

[72] LEHMANN 82 obtained $A^0 \to 2\gamma$ rate $<6.2 \times 10^{-5}$/s (CL = 95%) excluding $m(A^0)$ between 100 and 1000 keV.

[73] ZEHNDER 82 used Goesgen 2.8GW light-water reactor to check A^0 production. No 2γ peak in Li*, Nb* decay (both single p transition) nor in n capture (combined with previous Ba* negative result) rules out standard A^0. Set limit $m(A^0) <60$ keV for any A^0.

[74] ZEHNDER 81 looked for $\text{Ba}^* \to A^0\text{Ba}$ transition with $A^0 \to 2\gamma$. Obtained 2γ coincidence rate $<2.2 \times 10^{-5}$/s (CL = 95%) excluding $m(A^0) >160$ keV (or 200 keV depending on Higgs mixing). However, see BARROSO 81.

[75] CALAPRICE 79 saw no axion emission from excited states of carbon. Sensitive to axion mass between 1 and 15 MeV.

A^0 (Axion) Limits from Its Electron Coupling

Limits are for $\tau(A^0 \to e^+e^-)$.

VALUE (s)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 4×10^{-16}–4.5×10^{-12}	90	[76] BROSS	91	BDMP	$eN \to eA^0N$ ($A^0 \to ee$)
		[77] GUO	90	BDMP	$eN \to eA^0N$ ($A^0 \to ee$)
		[78] BJORKEN	88	CALO	$A \to e^+e^-$ or 2γ
		[79] BLINOV	88	MD1	$ee \to eeA^0$ ($A^0 \to ee$)
none 1×10^{-14}–1×10^{-10}	90	[80] RIORDAN	87	BDMP	$eN \to eA^0N$ ($A^0 \to ee$)
none 1×10^{-14}–1×10^{-11}	90	[81] BROWN	86	BDMP	$eN \to eA^0N$ ($A^0 \to ee$)
none 6×10^{-14}–9×10^{-11}	95	[82] DAVIER	86	BDMP	$eN \to eA^0N$ ($A^0 \to ee$)
none 3×10^{-13}–1×10^{-7}	90	[83] KONAKA	86	BDMP	$eN \to eA^0N$ ($A^0 \to ee$)

[76] The listed BROSS 91 limit is for $m(A^0) = 1.14$ MeV. B($A^0 \to e^+e^-$) = 1 assumed. Excluded domain in the $\tau(A^0)$–$m(A^0)$ plane extends up to $m(A^0) \approx 7$ MeV (see Fig. 5). Combining with electron $g-2$ constraint, axions coupling only to e^+e^- ruled out for $m(A^0) < 4.8$ MeV (90%CL).

[77] GUO 90 use the same apparatus as BROWN 86 and improve the previous limit in the shorter lifetime region. Combined with $g-2$ constraint, axions coupling only to e^+e^- are ruled out for $m(A^0) < 2.7$ MeV (90% CL).

[78] BJORKEN 88 reports limits on axion parameters (f_A, m_A, τ_A) for $m(A^0) < 200$ MeV from electron beam-dump experiment with production via Primakoff photoproduction, bremsstrahlung from electrons, and resonant annihilation of positrons on atomic electrons.

[79] BLINOV 88 assume zero spin, $m = 1.8$ MeV and lifetime $< 5 \times 10^{-12}$ s and find $\Gamma(A^0 \to \gamma\gamma)$B($A^0 \to e^+e^-$) < 2 eV (CL=90%).

[80] Assumes $A^0\gamma\gamma$ coupling is small and hence Primakoff production is small. Their figure 2 shows limits on axions for $m(A^0) < 15$ MeV.

[81] Uses electrons in hadronic showers from an incident 800 GeV proton beam. Limits for $m(A^0) < 15$ MeV are shown in their figure 3.

[82] $m(A^0) = 1.8$ MeV assumed. The excluded domain in the $\tau(A^0)$–$m(A^0)$ plane extends up to $m(A^0) \approx 14$ MeV, see their figure 4.

[83] The limits are obtained from their figure 3. Also given is the limit on the $A^0\gamma\gamma$–$A^0e^+e^-$ coupling plane by assuming Primakoff production.

Search for A^0 (Axion) Resonance in Bhabha Scattering

The limit is for $[\Gamma(A^0 \to e^+e^-)]^2/\Gamma_{tot}$ (= Γ_{tot} if only the decay channel to e^+e^- is present).

VALUE (10^{-3} eV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.013	95	TSERTOS	91	CNTR	$m(A^0) = 1.832$ MeV
< 5	97	BAUER	90	CNTR	$m(A^0) = 1.832$ MeV

none 0.09–1.5	95	[84] JUDGE	90	CNTR	$m(A^0)$ = 1.832 MeV, elastic
< 1.9	97	[85] TSERTOS	89	CNTR	$m(A^0)$ = 1.82 MeV
<(10–40)	97	[85] TSERTOS	89	CNTR	$m(A^0)$ = 1.51–1.65 MeV
<(1–2.5)	97	[85] TSERTOS	89	CNTR	$m(A^0)$ = 1.80–1.86 MeV
< 31	95	LORENZ	88	CNTR	$m(A^0)$ = 1.646 MeV
< 94	95	LORENZ	88	CNTR	$m(A^0)$ = 1.726 MeV
< 23	95	LORENZ	88	CNTR	$m(A^0)$ = 1.782 MeV
< 19	95	LORENZ	88	CNTR	$m(A^0)$ = 1.837 MeV
< 3.8	97	[86] TSERTOS	88	CNTR	$m(A^0)$ = 1.832 MeV
		[87] VANKLINKEN	88	CNTR	
		[88] MAIER	87	CNTR	
<2500	90	MILLS	87	CNTR	$m(A^0)$ = 1.8 MeV
		[89] VONWIMMER...	87	CNTR	

[84] JUDGE 90 excludes an elastic pseudoscalar e^+e^- resonance for 4.5×10^{-13} s $< \tau(A^0) < 7.5\times10^{-12}$ s (95% CL) at $m(A^0)$ = 1.832 MeV. Comparable limits can be set for $m(A^0)$ = 1.776–1.856 MeV.

[85] See also TSERTOS 88B in references.

[86] The upper limit listed in TSERTOS 88 is too large by a factor of 4. See TSERTOS 88B, footnote 3.

[87] VANKLINKEN 88 looked for relatively long-lived resonance ($\tau = 10^{-10}$–10^{-12} s). The sensitivity is not sufficient to exclude such a narrow resonance.

[88] MAIER 87 obtained limits $R\Gamma \lesssim$ 60 eV (100 eV) at $m(A^0) \sim$ 1.64 MeV (1.83 MeV) for energy resolution $\Delta E_{cm} \sim$ 3 keV, where R is the resonance cross section normalized to that of Bhabha scattering, and $\Gamma = \Gamma^2_{ee}/\Gamma_{tot}$. For a discussion implying that $\Delta E_{cm} \sim$ 10 keV, see TSERTOS 89.

[89] VONWIMMERSPERG 87 measured Bhabha scattering for E_{cm} = 1.37–1.86 MeV and found a possible peak at 1.73 with $\int \sigma dE_{cm} = 14.5 \pm 6.8$ keV·b. For a comment and a reply, see VANKLINKEN 88B and VONWIMMERSPERG 88. Also see CONNELL 88.

Search for A^0 (Axion) Resonance in $e^+e^- \to \gamma\gamma$

The limit is for $\Gamma(A^0 \to e^+e^-)\cdot\Gamma(A^0 \to \gamma\gamma)/\Gamma_{tot}$

VALUE (10^{-3} eV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 6.6	95	[90] TRZASKA	91	CNTR	$m(A^0)$ = 1.8 MeV
		[91] FOX	89	CNTR	
< 0.11	95	[92] MINOWA	89	CNTR	$m(A^0)$ = 1.062 MeV
<33	97	CONNELL	88	CNTR	$m(A^0)$ = 1.580 MeV
<42	97	CONNELL	88	CNTR	$m(A^0)$ = 1.642 MeV
<73	97	CONNELL	88	CNTR	$m(A^0)$ = 1.782 MeV
<79	97	CONNELL	88	CNTR	$m(A^0)$ = 1.832 MeV

[90] TRZASKA 91 also give limits in the range $(6.6–30)\times10^{-3}$ eV (95%CL) for $m(A^0)$ = 1.6–2.0 MeV.

[91] FOX 89 measured positron annihilation with an electron in the source material into two photons and found no signal at 1.062 MeV ($< 9\times10^{-5}$ of two-photon annihilation at rest).

[92] Similar limits are obtained for $m(A^0)$ = 1.045–1.085 MeV.

Searches for Goldstone Bosons (X^0)

(Including Horizontal Bosons and Majorons.) Limits are for branching ratios.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
			[93] BOBRAKOV	91		Electron quasi-magnetic interaction
$<3.3\times10^{-2}$	95		[94] ALBRECHT	90E	ARG	$\tau \to \mu X^0$. Familon
$<1.8\times10^{-2}$	95		[94] ALBRECHT	90E	ARG	$\tau \to e X^0$. Familon
$<6.4\times10^{-9}$	90		[95] ATIYA	90	CNTR	$K^+ \to \pi^+ X^0$. Familon
$<1.1\times10^{-9}$	90		[96] BOLTON	88	CBOX	$\mu^+ \to e^+\gamma X^0$. Familon
			[97] CHANDA	88	ASTR	Sun, Majoron
			[98] CHOI	88	ASTR	Majoron, SN 1987A
$<5\times10^{-6}$	90		[99] PICCIOTTO	88	CNTR	$\pi \to e\nu X^0$, Majoron
$<1.3\times10^{-9}$	90		[100] GOLDMAN	87	CNTR	$\mu \to e\gamma X^0$. Familon
$<3\times10^{-4}$	90		[101] BRYMAN	86B	RVUE	$\mu \to e X^0$. Familon
$<1.\times10^{-10}$	90	0	[102] EICHLER	86	SPEC	$\mu^+ \to e^+ X^0$. Familon
$<2.6\times10^{-6}$	90		[103] JODIDIO	86	SPEC	$\mu^+ \to e^+ X^0$. Familon
			[104] BALTRUSAIT...	85	MRK3	$\tau \to \ell X^0$. Familon
			[105] DICUS	83	COSM	ν (hvy) $\to \nu$ (light) X^0

[93] BOBRAKOV 91 searched for anomalous magnetic interactions between polarized electrons expected from the exchange of a massless pseudoscalar boson (arion). A limit $x_e^2 < 2\times10^{-4}$ (95%CL) is found for the effective anomalous magneton parametrized as $x_e(G_F/8\pi\sqrt{2})^{1/2}$.

[94] ALBRECHT 90E limits are for $B(\tau \to \ell X^0)/B(\tau \to \ell\nu\overline{\nu})$. Valid for $m(X^0) < 100$ MeV. The limits rise to 7.1% (for μ), 5.0% (for e) for $m(X^0)$ = 500 MeV.

[95] ATIYA 90 limit is for $m(X^0) = 0$. The limit $B < 1\times10^{-8}$ holds for $m(X^0) < 95$ MeV. For the reduction of the limit due to finite lifetime of X^0, see their Fig. 3.

[96] BOLTON 88 limit corresponds to $F > 3.1\times10^9$ GeV, which does not depend on the chirality property of the coupling.

[97] CHANDA 88 find $v_T < 10$ MeV for the weak-triplet Higgs vev. in Gelmini-Roncadelli model, and $v_S > 5.8\times10^6$ GeV in the singlet Majoron model.

[98] CHOI 88 used the observed neutrino flux from the supernova SN 1987A to exclude the neutrino Majoron Yukawa coupling h in the range $2\times10^{-5} < h < 3\times10^{-4}$ for the interaction $L_{int} = \frac{1}{2}ih\overline{\psi}^c_\nu\gamma_5\psi_\nu\phi_X$. For several families of neutrinos, the limit applies for $(\Sigma h_i^4)^{1/4}$.

[99] PICCIOTTO 88 limit applies when $m(X^0) < 55$ MeV and $\tau(X^0) > 2$ns, and it decreases to 4×10^{-7} at $m(X^0)$ = 125 MeV, beyond which no limit is obtained.

[100] GOLDMAN 87 limit corresponds to $F > 2.9\times10^9$ GeV for the family symmetry breaking scale from the Lagrangian $L_{int} = (1/F)\overline{\psi}_\mu\gamma^\mu\,(a+b\gamma_5)\,\psi_e\partial_\mu\phi_{X^0}$ with $a^2+b^2 = 1$. This is not as sensitive as the limit $F > 9.9\times10^9$ GeV derived from the search for $\mu^+ \to e^+X^0$ by JODIDIO 86, but does not depend on the chirality property of the coupling.

[101] Limits are for $\Gamma(\mu \to eX^0)/\Gamma(\mu \to e\nu\overline{\nu})$. Valid when $m(X^0)$ = 0–93.4, 98.1–103.5 MeV.

[102] EICHLER 86 looked for $\mu^+ \to e^+X^0$ followed by $X^0 \to e^+e^-$. Limits on the branching fraction depend on the mass and lifetime of X^0. The quoted limits are valid when $\tau(X^0) \lesssim 3.\times10^{-10}$ s if the decays are kinematically allowed.

[103] JODIDIO 86 corresponds to $F > 9.9\times10^9$ GeV for the family symmetry breaking scale with the parity-conserving effective Lagrangian $L_{int} = (1/F)\,\overline{\psi}_\mu\gamma^\mu\psi_e\partial^\mu\phi_{X^0}$.

[104] BALTRUSAITIS 85 search for light Goldstone boson(X^0) of broken U(1). CL = 95% limits are $B(\tau \to \mu^+X^0)/B(\tau \to \mu^+\nu\nu) <0.125$ and $B(\tau \to e^+X^0)/B(\tau \to e^+\nu\nu) <0.04$. Inferred limit for the symmetry breaking scale is $m >$3000 TeV.

[105] The primordial heavy neutrino must decay into ν and familon, f_A, early so that the red-shifted decay products are below critical density, see their table. In addition, $K \to \pi f_A$ and $\mu \to e\, f_A$ are unseen. Combining these excludes m(heavy ν) between 5×10^{-5} and 5×10^{-4} MeV (μ decay) and m(heavy ν) between 5×10^{-5} and 0.1 MeV (K-decay).

Majoron Searches in Neutrinoless Double β Decay

Limits are for the half-life of neutrinoless $\beta\beta$ decay with a Majoron emission. Previous indications for neutrinoless double beta decay with majoron emission have been superceded. No experiment currently claims any such evidence. For a review, see DOI 88.

VALUE (years)	CL%	DOCUMENT ID		TECN	COMMENT
> 1.4 × 10^{21}	90	CALDWELL	87	CNTR	^{76}Ge
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 1.9 × 10^{20}	68	BARABASH	89	CNTR	^{136}Xe
> 1.0 × 10^{21}	90	FISHER	89	CNTR	^{76}Ge
> 3.3 × 10^{20}	90	ALSTON-...	88	CNTR	^{100}Mo
(6 ±1) × 10^{20}		AVIGNONE	87	CNTR	^{76}Ge
> 4.4 × 10^{20}	90	ELLIOTT	87	SPEC	^{82}Se
> 1.2 × 10^{21}	90	FISHER	87	CNTR	^{76}Ge
		[106] VERGADOS	82	CNTR	

[106] VERGADOS 82 sets limit $g_H < 4\times10^{-3}$ for (dimensionless) lepton-number violating coupling, g_H, of scalar boson (Majoron) to neutrinos, from analysis of data on double β decay of ^{48}Ca.

INVISIBLE A^0 (AXION) MASS LIMITS FROM ASTROPHYSICS AND COSMOLOGY

Limits on $m(A^0)$ are obtained from the axion coupling to electrons, nucleons, or photons. Quoted limits are often expressed in terms of the axion decay constant f_A which can be defined in terms of the mass or axion-electron coupling by $m(A^0) = 3.5\times10^{10}g_{Ae}\cos^{-2}\beta\,\text{eV} = 7.2\times10^7(\text{GeV}/f_A)(N/6)\,\text{eV}$ [using the conventions detailed in Srednicki[1]; for other conventions take $f_A \to 2f_A$ (Bardeen[2]) or $f_A \to 4f_A$ (Kaplan[3])] where N is the number of quarks with Peccei-Quinn charge (usually the number of quark flavors) and $\cos^2\beta = v_1^2/(v_1^2+v_2^2)$ is determined by the vacuum expectation values of the two Higgs doublets coupling to up and down quarks (and charged leptons). For the coupling to photons $m(A^0) = 6.9\times10^9$ $(g_{A\gamma}/\text{GeV}^{-1})\,\text{eV}$ and for the coupling to nucleons $m(A^0) = 7.7\times10^7 g_{AN}/c_{AN}\,\text{eV}$ where c_{AN} depends on the details of the coupling of axions to nucleons. These couplings are defined by

$$\mathcal{L}_{int} = -\frac{1}{4}g_{A\gamma}\,\phi_A\,F_{\mu\nu}\,\widetilde{F}^{\mu\nu} = g_{A\gamma}\,\phi_A\,\mathbf{E}\cdot\mathbf{B}\ ,$$

$$\mathcal{L}_{int} = ig_{Ae}\,\phi_A\,\overline{\psi}_e\,\gamma_5\psi_e\ , \qquad \text{and}$$

$$\mathcal{L}_{int} = ig_{AN}\,\phi_A\,\overline{\psi}_N\,\gamma_5\,\psi_N\ .$$

The factors in these equations are model dependent, in particular $g_{Ae} = 0$ in the KSVZ[4] models. In the comment for each limit below, D indicates that the limit is specific to DFSZ[5] axions, K to KSVZ axions (The limits quoted assume $N = 6$ and $v_1 = v_2$.)

References

1. M. Srednicki, Nucl. Phys. **B260**, 689 (1985).
2. W. Bardeen and H. Tye, Phys. Lett. **74B**, 229 (1978).
3. D. Kaplan, Nucl. Phys. **B260**, 215 (1985).
4. J.E. Kim, Phys. Rev. Lett. **43**, 103 (1979); M.A. Shifman, A.I. Vainstein, and V.I. Zakharov, Nucl. Phys. **B166**, 493 (1980).
5. A.R. Zhitnitsky, Sov. Jour. Nucl. Phys. **31**, 260 (1980); and M. Dine, W. Fischler, and M. Srednicki, Phys. Lett. **104B**, 199 (1981).

Invisible A^0 (Axion) MASS LIMITS from Astrophysics and Cosmology

$v_1 = v_2$ is usually assumed (v_i = vacuum expectation values). For a review of these limits, see RAFFELT 90C and TURNER 90.

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
none 3–8	[107] BERSHADY	91	ASTR	D,K, intergalactic light
	[108] RAFFELT	91B	ASTR	D,K, SN 1987A
$< 1 \times 10^{-3}$	[109] RESSELL	91	ASTR	K, intergalactic light
none 10^{-3}–3	BURROWS	90	ASTR	D,K, SN 1987A
	[110] ENGEL	90	ASTR	D,K, SN 1987A
< 0.02	[111] RAFFELT	90D	ASTR	D, red giant
$< 1 \times 10^{-3}$	[112] BURROWS	89	ASTR	D,K, SN 1987A
$<(1.4\text{–}10) \times 10^{-3}$	[113] ERICSON	89	ASTR	D,K, SN 1987A
$< 3.6 \times 10^{-4}$	[114] MAYLE	89	ASTR	D,K, SN 1987A
<12	CHANDA	88	ASTR	D, Sun
$< 1 \times 10^{-3}$	RAFFELT	88	ASTR	D,K, SN 1987A
	[115] RAFFELT	88B	ASTR	red giant
< 0.07	FRIEMAN	87	ASTR	D, red giant
< 0.7	[116] RAFFELT	87	ASTR	K, red giant
< 2–5	TURNER	87	COSM	K, thermal production
< 0.01	[117] DEARBORN	86	ASTR	D, red giant
< 0.06	RAFFELT	86	ASTR	D, red giant
< 0.7	[118] RAFFELT	86	ASTR	K, red giant
< 0.03	RAFFELT	86B	ASTR	D, white dwarf
< 1	[119] KAPLAN	85	ASTR	K, red giant
< 0.003–0.02	IWAMOTO	84	ASTR	D, K, neutron star
$> 1 \times 10^{-5}$	ABBOTT	83	COSM	D,K, mass density of the universe
$> 1 \times 10^{-5}$	DINE	83	COSM	D,K, mass density of the universe
< 0.04	ELLIS	83B	ASTR	D, red giant
$> 1 \times 10^{-5}$	PRESKILL	83	COSM	D,K, mass density of the universe
< 0.1	BARROSO	82	ASTR	D, red giant
< 1	[120] FUKUGITA	82	ASTR	D, stellar cooling
< 0.07	FUKUGITA	82B	ASTR	D, red giant

[107] BERSHADY 91 searched for a line at wave length from 3100–8300 Å expected from 2γ decays of relic thermal axions in intergalactic light of three rich clusters of galaxies.
[108] RAFFELT 91B argue that previous SN 1987A bounds must be relaxed due to corrections to nucleon bremsstrahlung processes.
[109] RESSELL 91 uses absence of any intracluster line emission to set limit.
[110] ENGEL 90 rule out $10^{-10} \lesssim g_{AN} \lesssim 10^{-3}$, which for a hadronic axion with EMC motivated axion-nucleon couplings corresponds to 2.5×10^{-3} eV $\lesssim m(A^0) \lesssim 2.5 \times 10^4$ eV. The constraint is loose in the middle of the range, i.e. for $g_{AN} \sim 10^{-6}$.
[111] RAFFELT 90D is a re-analysis of DEARBORN 86.
[112] The region $m(A^0) \gtrsim 2$ eV is also allowed.
[113] ERICSON 89 considered various nuclear corrections to axion emission in a supernova core, and found a reduction of the previous limit (MAYLE 88) by a large factor.
[114] MAYLE 89 limit based on naive quark model couplings of axion to nucleons. Limit based on couplings motivated by EMC measurements is 2–4 times weaker. The limit from axion-electron coupling is weak: see HATSUDA 88B.
[115] RAFFELT 88B derives a limit for the energy generation rate by exotic processes in helium-burning stars $\epsilon < 100$ erg g^{-1} s^{-1}, which gives a firmer basis for the axion limits based on red giant cooling.
[116] RAFFELT 87 also gives a limit $g_{A\gamma} < 1 \times 10^{-10}$ GeV^{-1}.
[117] DEARBORN 86 also gives a limit $g_{A\gamma} < 1.4 \times 10^{-11}$ GeV^{-1}.
[118] RAFFELT 86 gives a limit $g_{A\gamma} < 1.1 \times 10^{-10}$ GeV^{-1} from red giants and $< 2.4 \times 10^{-9}$ GeV^{-1} from the sun.
[119] KAPLAN 85 says $m(A^0) < 23$ eV is allowed for a special choice of model parameters.
[120] FUKUGITA 82 gives a limit $g_{A\gamma} < 2.3 \times 10^{-10}$ GeV^{-1}.

Search for Relic Invisible Axions

Limits are for $[G_{A\gamma\gamma}/m(A^0)]^2 \rho_A$ where $G_{A\gamma\gamma}$ denotes the axion two-photon coupling, $L_{int} = \frac{G_{A\gamma\gamma}}{4} \phi_A F_{\mu\nu} \tilde{F}^{\mu\nu} = G_{A\gamma\gamma} \phi_A \mathbf{E} \cdot \mathbf{B}$, and ρ_A is the axion energy density near the earth.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2 \times 10^{-41}$		[121] HAGMANN	90	CNTR	$m(A^0) = (5.4\text{–}5.9) 10^{-6}$ eV
$<1.3 \times 10^{-42}$	95	[122] WUENSCH	89	CNTR	$m(A^0) = (4.5\text{–}10.2) 10^{-6}$ eV
$<2 \times 10^{-41}$	95	[122] WUENSCH	89	CNTR	$m(A^0) = (11.3\text{–}16.3) 10^{-6}$ eV

[121] HAGMANN 90 experiment is based on the proposal of SIKIVIE 83.
[122] WUENSCH 89 looks for condensed axions near the earth that could be converted to photons in the presence of an intense electromagetic field via the Primakoff effect, following the proposal of SIKIVIE 83. The theoretical prediction with $[G_{A\gamma\gamma}/m(A^0)]^2 = 2 \times 10^{-14}$ MeV^{-4} (the three generation DFSZ model) and $\rho_A = 300$ MeV/cm^3 that makes up galactic halos gives $(G_{A\gamma\gamma}/m(A^0))^2 \rho_A = 4 \times 10^{-44}$. Note that our definition of $G_{A\gamma\gamma}$ is $(1/4\pi)$ smaller than that of WUENSCH 89.

Search for Invisible Axions by Laser

Limits are for the axion-two-photon coupling $G_{A\gamma\gamma}$ defined by $L = G_{A\gamma\gamma} \phi_A \mathbf{E} \cdot \mathbf{B}$.

VALUE	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$<2.5 \times 10^{-6}$	[123] SEMERTZIDIS	90	$m(A^0) < 7 \times 10^{-4}$ eV

[123] SEMERTZIDIS 90 experiment is based on the proposal of MAIANI 86. The limit is obtained by taking the noise amplitude as the upper limit. Limits extend to $m(A^0) = 4 \times 10^{-3}$ where $G_{A\gamma\gamma} < 1 \times 10^{-4}$ GeV^{-1}.

REFERENCES FOR Searches for Axions (A^0) and Other Very Light Bosons

ASAI	91	PRL 66 2440	+Orito, Yoshimura, Haga	(TOKY)
BERSHADY	91	PRL 66 1398	+Ressell, Turner	(CHIC, FNAL, EFI)
BLUEMLEIN	91	ZPHY C51 341	+Brunner, Grabosch+	(BERL, BUDA, JINR, SERP)
BOBRAKOV	91	JETPL 53 294	+Borisov, Lasakov, Serebrov, Tal'daev, Trofimova	(PINP)
		Translated from ZETFP 53 283.		
BROSS	91	PRL 67 2942	+Crisler, Pordes, Volk, Errede, Wrbanek	(FNAL, ILL)
RAFFELT	91B	PRL 67 2605	+Seckel	(MPIM, BRTD)
RESSELL	91	PR D44 3001		(CHIC, FNAL)
TRZASKA	91	PL B269 54	+Dejbakhsh, Dutta, Li, Cormier	(TAMU)
TSERTOS	91	PL B266 259	+Kienle, Judge, Schreckenbach	(ILLG, GSI)
ALBRECHT	90E	PL B246 278	+Ehrlichmann, Harder, Krueger+	(ARGUS Collab.)
ANTREASYAN	90C	PL B251 204	+Bartels, Besset, Bieler, Bienlein+	(Crystal Ball Collab.)
ASANUMA	90	PL B237 588	+Minowa, Tsukamoto, Orito, Tsunoda	(TOKY)
ATIYA	90	PRL 64 21	+Chiang, Frank, Haggerty, Ito, Kycia+	(BNL-787 Collab.)
ATIYA	90B	PRL 65 1188	+Chiang, Frank, Haggerty, Ito, Kycia+	(BNL-787 Collab.)
BAUER	90	NIM B50 300	+Briggmann, Carstanjen, Connell, et al	(STUT, PSI, GSI)
BURROWS	90	PR D42 3297	+Ressell, Turner	(ARIZ, CHIC, FNAL)
DEBOER	90	JP G16 L1	de Boer, Lehmann, Steyaert	(LVLN)
ENGEL	90	PRL 65 960	+Seckel, Hayes	(BRTD, LANL)
GNINENKO	90	PL B237 287	+Klubakov, Poblaguev, Postoev	(INRM)
GUO	90	PR D41 2924	+Kaplan, Alde+	(NIU, LANL, FNAL, CASE, TEXA)
HAGMANN	90	PR D42 1297	+Sikivie, Sullivan, Tanner	(FLOR)
JUDGE	90	PRL 65 972	+Krusche, Schreckenbach, Tsertos, Kienle	(ILLG, GSI)
RAFFELT	90C	PRPL 198 1		(MPIM)
RAFFELT	90D	PR D41 1324		(MPIM)
SEMERTZIDIS	90	PRL 64 2988	+Cameron, Cantatore+	(ROCH, BNL, FNAL, TRST)
TSUCHIAKI	90	PL B236 81	+Orito, Yoshida, Minowa	(TOKY)
TURNER	90	PRPL 197 67		(FNAL)
BARABASH	89	PL B223 273	+Kuzminov, Lobashev, Novikov+	(ITEP, INRM)
BINI	89	PL B221 99	+Fazzini, Giannatiempo, Poggi, Sona+	(FIRZ, CERN, AARH)
BURROWS	89	PR D39 1020	+Turner, Brinkmann	(ARIZ, CHIC, FNAL, BOCH)
Also	88	PRL 60 1797	Turner	(FNAL, EFI)
DEBOER	89B	PRL 62 2639	de Boer, van Dantzig	(ANIK)
ERICSON	89	PL B219 507	+Mathiot	(CERN, IPN)
FAISSNER	89	ZPHY C44 557	+Heinrigs, Preussger, Reitz, Samm+	(AACH, BERL, PSI)
FISHER	89	PL B218 257	+Boehm, Bovet, Egger+	(CIT, NEUC, PSI)
FOX	89	PR C39 288	+Kemper, Cottle, Zingarelli	(FSU)
MAYLE	89	PL B219 515	+Wilson, Ellis+	(LLL, CERN, MINN, FNAL, CHIC, OSU)
Also	88	PL B203 188	Mayle, Wilson+	(LLL, CERN, MINN, FNAL, CHIC, OSU)
MINOWA	89	PRL 62 1091	+Orito, Tlsuchiaki, Tlsukamoto	(TOKY)
ORITO	89	PRL 63 597	+Yoshimura, Haga, Minowa, Tsuchiaki	(TOKY)
PERKINS	89	PRL 62 2638		(OXF)
TSERTOS	89	PR D40 1397	+Kozhuharov, Armbruster, Kienle+	(GSI, ILLG)
WUENSCH	89	PR D40 3153	+De Panfilis-Wuensch, Semertzidis+	(ROCH, BNL, FNAL)
Also	87	PRL 59 839	De Panfilis, Melissinos, Moskowitz+	(ROCH, BNL, FNAL)
ALSTON-...	88	PRL 60 1928	Alston-Garnjost, Dougherty+	(LBL, MTHO, UNM)
AVIGNONE	88	PR D37 618	+Baktash, Barker, Calaprice+	(PRIN, USCR, ORNL, WASH)
BJORKEN	88	PR D38 3375	+Ecklund, Nelson, Abashian+	(FNAL, SLAC, VPI)
BLINOV	88	SJNP 47 563	+Bondar, Bukin, Vorobyev, Groshev+	(NOVO)
		Translated from YAF 47 889.		
BOLTON	88	PR D38 2077	+Cooper, Frank, Hallin+	(LANL, STAN, CHIC, TEMP)
Also	86	PRL 56 2461	Bolton, Bowman, Cooper+	(LANL, STAN, CHIC, TEMP)
Also	86	PRL 57 3241	Grosnick, Wright, Bolton+	(CHIC, LANL, STAN, TEMP)
CHANDA	88	PR D37 2714	+Nieves, Pal	(UMD, UPR, MASA)
CHOI	88	PR D37 3225	+Kim, Kim, Lam	(JHU)
CONNELL	88	PRL 60 2242	+Fearick, Hoernle, Sideras-Haddad, Sellschop	(WITW)
DATAR	88	PR C37 250	+Fortier, Gales, Hourani+	(IPN)
DEBOER	88	PRL 61 1274	de Boer, van Dantzig	(ANIK)
Also	89	PRL 62 2644 erratum	de Boer, van Dantzig	(ANIK)
Also	89	PRL 62 2638	Perkins	(OXF)
Also	89B	PRL 62 2639	de Boer, van Dantzig	(ANIK)
DEBOER	88C	JP G14 L131	de Boer, Deutsch, Lehmann, Prieels, Steyaert	(LVLN)
DOEHNER	88	PR D38 2722	+Last, Arnold, Freedman, Dubbers	(HEID, ANL, ILLG)
DOI	88	PR D37 2575	+Kotani, Takasugi	(OSAK)
EL-NADI	88	PRL 61 1271	+Badawy	(CAIR)
FAISSNER	88	ZPHY C37 231	+Heinrigs, Preussger, Reitz, Samm+	(AACH, BERL, SIN)
HATSUDA	88B	PL B203 469	+Yoshimura	(KEK)
LORENZ	88	PL B214 10	+Mageras, Stiegler, Huszar	(MPIM, PSI)
MAYLE	88	PL B203 188	+Wilson+	(LLL, CERN, MINN, FNAL, CHIC, OSU)
PICCIOTTO	88	PR D37 1131	+Ahmad, Britton, Bryman, Clifford+	(TRIU, CNRC)
RAFFELT	88	PRL 60 1793	+Seckel	(UCB, LLL, UCSC)
RAFFELT	88B	PR D37 549	+Dearborn	(UCB, LLL)

SAVAGE 88 PR D37 1134 +Filippone, Mitchell (CIT)
TSERTOS 88 PL B207 273 +Kozhuharov, Armbruster, Kienle+ (GSI, ILLG)
TSERTOS 88B ZPHY A331 103 +Kozhuharov, Armbruster, Kienle+ (GSI, ILLG)
VANKLINKEN 88 PL B205 223 van Klinken, Meiring, de Boer, Schaafsma+ (GRON, GSI)
VANKLINKEN 88B PRL 60 2442 van Klinken (GRON)
VONWIMMER... 88 PRL 60 2443 von Wimmersperg (BNL)
AVIGNONE 87 AIP Conf. 1987 +Brodzinski, Miley, Reeves (SCUC, PNL)
AIP Conf. Proc. Salt Lake City, UT
BAKER 87 PRL 59 2832 +Gordon, Lazarus+ (BNL, SIN, WASH, YALE)
Also 88 PRL 60 472 erratum Baker, Gordon+ (BNL, SIN, WASH, YALE)
CALDWELL 87 PRL 59 419 +Eisberg, Grumm, Witherell+ (UCSB, LBL)
DRUZHININ 87 ZPHY C37 1 +Dubrovin, Eidelman, Golubev+ (NOVO)
ELLIOTT 87 PRL 59 1649 +Hahn, Moe (UCI)
FISHER 87 PL B192 460 +Boehm, Bovet, Egger+ (CIT, NEUC, SIN)
FRIEMAN 87 PR D36 2201 +Dimopoulos, Turner (SLAC, STAN, FNAL, EFI)
GOLDMAN 87 PR D36 1543 +Hallin, Hoffman+ (LANL, CHIC, STAN, TEMP)
KORENCHE... 87 SJNP 46 192 Korenchenko, Kostin, Mzhaviya+ (JINR)
Translated from YAF 46 313.
MAIER 87 ZPHY A326 527 +Bauer, Briggmann, Carstanjen+ (STUT, GSI)
MILLS 87 PR D36 707 +Levy (BELL)
RAFFELT 87 PR D36 2211 +Dearborn (LLL, UCB)
RIORDAN 87 PRL 59 755 +Krasny, Lang, Barbaro, Bodek+ (ROCH, CIT+)
TURNER 87 PRL 59 2489 (FNAL, EFI)
VONWIMMER... 87 PRL 59 266 von Wimmersperg, Connell, Hoernle, Sideras-Haddad (WITW)
ALBRECHT 86D PL B179 403 +Binder, Boeckmann+ (ARGUS Collab.)
BADIER 86 ZPHY C31 21 +Bemporad, Boucrot, Callot+ (NA3 Collab.)
BOWCOCK 86 PRL 56 2676 +Giles, Hassard, Kinoshita+ (CLEO Collab.)
BROWN 86 PRL 57 2101 + (FNAL, WASH, KYOT, KEK, COLU, STON, SACL)
BRYMAN 86B PRL 57 2787 +Clifford (TRIU)
DAVIER 86 PL B180 295 +Jeanjean, Nguyen Ngoc (LALO)
DEARBORN 86 PRL 56 26 +Schramm, Steigman (LLL, CHIC, FNAL, BART)
EICHLER 86 PL B175 101 +Felawka, Kraus, Niebuhr+ (SINDRUM Collab.)
HALLIN 86 PRL 57 2105 +Calparice, Dunford, McDonald (PRIN)
JODIDIO 86 PR D34 1967 +Balke, Carr, Gidal, Shinsky+ (LBL, NWES, TRIU)
Also 88 PR D37 237 erratum Jodidio, Balke, Carr+ (LBL, NWES, TRIU)
KETOV 86 JETPL 44 146 +Klimov, Nikolaev, Mikaelyan+ (KIAE)
Translated from ZETFP 44 114.
KOCH 86 NC 96A 182 +Schult (JULI)
KONAKA 86 PRL 57 659 +Imai, Kobayashi, Masaike, Miyake+ (KYOT, KEK)
MAGERAS 86 PRL 56 2672 +Franzini, Tuts, Youssef+ (MPIM, COLU, STON)
MAIANI 86 PL B175 359 +Petronzio, Zavattini (CERN)
PECCEI 86 PL B172 435 +Wu, Yanagida (DESY)
RAFFELT 86 PR D33 897 (MPIM)
RAFFELT 86B PL 166B 402 (MPIM)
SAVAGE 86B PRL 57 178 +McKeown, Filippone, Mitchell (CIT)
AMALDI 85 PL 153B 444 +Carboni, Jonson, Thun (CERN)
ANANEV 85 SJNP 41 585 +Kalinina, Lushchikov, Olshevskii+ (JINR)
Translated from YAF 41 912.
BALTRUSAIT... 85 PRL 55 1842 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BERGSMA 85 PL 157B 458 +Dorenbosch, Allaby, Amaldi+ (CHARM Collab.)
KAPLAN 85 NP B260 215 (HARV)
IWAMOTO 84 PRL 53 1198 (UCSB, WUSL)
YAMAZAKI 84 PRL 52 1089 +Ishikawa, Taniguchi, Yamanaka+ (TOKY, KEK)
ABBOTT 83 PL 120B 133 +Sikivie (BRAN, FLOR)
ALAM 83 PR D27 1665 + (VAND, CORN, ITHA, HARV, OHIO, ROCH+)
CARBONI 83 PL 123B 349 +Dahme (CERN, MUNI)
CAVAIGNAC 83 PL 121B 193 +Hoummada, Koang, Ost+ (ISNG, LAPP)
DICUS 83 PR D28 1778 +Teplitz (TEXA, UMD)
DINE 83 PL 120B 137 +Fischler (IAS, PENN)
ELLIS 83B NP B223 252 +Olive (CERN)
FAISSNER 83 PR D28 1198 +Heinrigs, Preussger, Samm (AACH)
FAISSNER 83B PR D28 1787 +Frenzel, Heinrigs, Preussger+ (AACH)
FRANK 83B PR D28 1790 + (LANL, YALE, LBL, MIT, SACL, SIN, CNRC, BERN)
HOFFMAN 83 PR D28 660 +Frank, Mischke, Moir, Schardt (LANL, ARZS)
NICZYPORUK 83 ZPHY C17 197 +Jakubowski, Zeludziewicz+ (LENA Collab.)
PRESKILL 83 PL 120B 127 +Wise, Wilczek (HARV, UCSB)
SIKIVIE 83 PRL 51 1415 (FLOR)
Also 84 PRL 52 695 (erratum) Sikivie (FLOR)
ALEKSEEV 82 JETP 55 591 +Kartamyshev, Makarin+ (KIAE)
Translated from ZETF 82 1007.
ALEKSEEV 82B JETPL 36 116 +Kalinina, Kruglov, Kulikov+ (MOSU, JINR)
Translated from ZETFP 36 94.
ASANO 82 PL 113B 195 +Kikutani, Kurokawa, Miyachi+ (KEK, TOKY, OSAK)
BARROSO 82 PL 116B 247 +Branco (LISB)
DATAR 82 PL 114B 63 +Baba, Betigeri, Singh (BHAB)
EDWARDS 82 PRL 48 903 +Partridge, Peck, Porter+ (Crystal Ball Collab.)
FETSCHER 82 JP G8 L147 (ETH)
FUKUGITA 82 PRL 48 1522 +Watamura, Yoshimura (KEK)
FUKUGITA 82B PR D26 1840 +Watamura, Yoshimura (KEK)
LEHMANN 82 PL 115B 270 +Lesquoy, Muller, Zylberajch (SACL)
RAFFELT 82 PL 119B 323 +Stodolsky (MPIM)
SIVERTZ 82 PR D26 717 +Lee-Franzini, Horstkotte+ (CUSB Collab.)
VERGADOS 82 PL 109B 96 (CERN)
ZEHNDER 82 PL 110B 419 +Gabathuler, Vuilleumier (ETH, SIN, CIT)
ASANO 81B PL 107B 159 +Kikutani, Kurokawa, Miyachi+ (KEK, TOKY, OSAK)
BARROSO 81 PL 106B 91 +Mukhopadhyay (SIN)
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ZEHNDER 81 PL 104B 494 (ETH)
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JACQUES 80 PR D21 1206 +Kalelkar, Miller, Plano+ (RUTG, STEV, COLU)
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BECHIS 79 PRL 42 1511 +Dombeck+ (UMD, COLU, AFRR)
CALAPRICE 79 PR D20 2708 +Dunford, Kouzes, Miller+ (PRIN)
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LEPTONS

QUARKS

Notes in the Lepton Listings

LEPTONS

NOTE ON NEUTRINOS

(by R.E. Shrock, State Univ. of New York, Stony Brook)

In addition to the ν_e, ν_μ, and ν_τ sections, the *Review of Particle Properties* includes sections on "Searches for Massive Neutrinos and Lepton Mixing," "Number of Light Neutrino Types," "Heavy Lepton Searches," and "Constraints from Cosmology and Astrophysics." For some early work on effects of neutrino oscillations and mixing, see Refs. 1–2.

As an aid to understanding the limits on neutrino masses and lepton mixing, we recall that, in contrast to other particles in this Review, the neutrinos ν_e, ν_μ, and ν_τ are defined as weak eigenstates (the weak $I_3 = 1/2$ components of the $SU(2)_L$ lepton doublets) which couple with unit strength to e, μ, and τ, respectively. These neutrino weak eigenstates are not, in general, states of definite mass. In the standard SU(2) × U(1) electroweak theory with its usual fermion assignments (*i.e.* no neutrino singlets) and no $I = 1$, $Y = 2$ Higgs field, the neutrinos are massless and hence degenerate, so that it is possible to define the weak eigenstates to be simultaneous mass eigenstates. However, in the general case of possibly massive (nondegenerate) neutrinos, the weak eigenstates have no well-defined masses, but instead are linear combinations of mass eigenstates. Let us denote the charged leptons as the set $\{\ell_a\}$, $a = 1,\ldots,n$, where $n \geq 3$, with $\ell_1 = e$, $\ell_2 = \mu$, and $\ell_3 = \tau$. From the LEP measurement of the Z width (see section on "Number of Light Neutrinos"), one knows that there are only three neutrinos which couple to the Z in the usual way and have masses $m_\nu < m_Z/2$; of course, this measurement does not preclude the existence of neutrinos with masses $m_\nu > m_Z/2$ or the existence of SU(2) × U(1)-singlet neutral leptons. The latter are often called "right-handed neutrino singlets," although, since they are singlets, it is a convention whether one writes them as $(N_j)_R$ or $(N'_j)_L = (N^c_j)_L$. The left-handed components of the weak eigenstates of the neutrinos, $(\nu_{\ell_a})_L$ can be expressed in terms of mass eigenstates by the transformation

$$(\nu_{\ell_a})_L = \sum_j U_{aj}(\nu_j)_L \qquad (1)$$

where the $\{\nu_j\}$ denote these mass eigenstates and consist of n members together with possible additional SU(2) × U(1) singlet neutral leptons, often called "sterile" neutrinos. The ordering of the mass eigenbasis can be defined so that U is as nearly diagonal as possible, *i.e.* (with no sum on j) $|U_{jj}| \geq |U_{jk}|$, $k \neq j$. Of course, this does not imply that $m_{\nu_j} > m_{\nu_k}$ for $j > k$.

Thus, as was noted in Ref. 3, decays such as $^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \overline{\nu}_e$ and $\pi^+ \to \mu^+ + \nu_\mu$, which have been used to set the best bounds on the respective neutrino masses, really consist of sums of the separate decay modes $^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \overline{\nu}_j$ and $\pi^+ \to \mu^+ + \nu_k$, where the ν_j and ν_k are mass eigenstates, and the indices j and k range over all of the values allowed by phase space in these respective decays. The coupling strengths for the j'th mode in ^{3}H β decay and the k'th mode in $\pi^+_{\mu 2}$ decay are given, respectively, by $|U_{1j}|^2$ and $|U_{2k}|^2$. In general, these modes are incoherent, although in the limit in which the ν_j all become degenerate they would become coherent. There are, in addition certain kinematic factors depending on the m_{ν_j} which enter in determining the branching ratio for a given decay mode. Assuming that the off-diagonal elements of the lepton mixing matrix U are small relative to the diagonal elements, the dominantly coupled decays are the ones with coupling strength $|U_{aj}|^2$, $a = j$, *i.e.*, $^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \overline{\nu}_1$ and $\pi^+ \to \mu^+ + \nu_2$.

Hence, it follows that the old neutrino mass limits quoted in the literature for "m_{ν_e}," "m_{ν_μ}," and "m_{ν_τ}" should really be interpreted as limits on the corresponding mass eigenstates.[3,4] For example, a bound on "m_{ν_e}" from a study of tritium β decay really constitutes a weighted limit on each of the mass eigenstates ν_j in the weak eigenstate ν_e which are kinematically allowed in tritium decay and which are coupled with strength $|U_{1j}|^2$ sufficiently large to make a significant contribution to the observed spectrum. It is thus certainly a limit on ν_1, since this is, by the definition, of the order of the mass eigenbasis, the dominantly coupled neutrino. If lepton mixing is hierarchical, as quark mixing is known to be, *i.e.*, if $|U_{jj}|^2 \gg |U_{jk}|^2$, $j \neq k$, then ν_1 is the only mass eigenstate significantly constrained by a bound on "m_{ν_e}." Furthermore, strictly speaking, a neutrino mass limit cannot be stated in isolation; it always contains some implicit dependence on the relevant lepton mixing angles. Fortunately, this dependence is relatively unimportant for the dominantly coupled decay modes, *i.e.*, $e\overline{\nu}_1$, $\mu\overline{\nu}_2$, and $\tau\overline{\nu}_3$ and hence the mass limits on "m_{ν_e}," "m_{ν_μ}," and "m_{ν_τ}" can be reinterpreted as being limits on m_{ν_j}, $j = 1$, 2, and 3, respectively.

There are two general types of (Lorentz-invariant) neutrino mass terms: Dirac masses of the form $m_D\overline{\nu}_L\chi_R + h.c.$, and Majorana masses of the form $m_L\overline{\nu}_L\nu^c_R + h.c. = m_L\nu^T_L C\nu^T_L + h.c.$ and $m_R\overline{\chi}^c_L N_R + h.c. = m_R\chi^T_R C N_R + h.c.$, where $C\gamma^T_\mu C^{-1} = -\gamma_\mu$. Dirac mass terms conserve total lepton number $L_{\rm tot}$, while Majorana mass terms violate $L_{\rm tot}$. In the standard electroweak theory, extended to include massive neutrinos, (i) a Dirac mass term transforms as a weak $I = 1/2$ operator, and is coupled to the $I = 1/2$ Higgs to make an SU(2) × U(1) singlet operator; (ii) a Majorana mass term involving the $I = 1/2$ left-handed neutrinos transforms as $I = 1$ and must be coupled to an operator with $I = 1$ (and $Y = 2$) to make a gauge-invariant singlet; (iii) a Majorana-mass term involving the SU(2) × U(1) singlet neutral leptons, conventionally considered to be right-handed, is a singlet; it could be present as a bare mass term or couple to some other singlet operator. In general, in the Standard Model if there are 3 left-handed $I = 1/2$ lepton doublets and k neutral lepton singlets, then, in a compact notation, we consider ν_L to be the n-component vector of left-handed $I = 1/2$ neutrinos and χ_R to be the k-dimensional vector of singlets, taken to be right-handed. The general neutrino mass term in the Lagrangian is then given by

$$-\mathcal{L}_m = \frac{1}{2}(\overline{\nu}_L, \overline{\chi}_L^c)\begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu_R^c \\ \chi_R \end{pmatrix} + h.c. \quad (2)$$

where M_L and M_R are 3×3 and $k \times k$ Majorana mass matrices and M_D is a $3 \times k$ Dirac mass matrix. The Majorana mass matrices satisfy $M_L = M_L^T$, $M_R = M_R^T$. The diagonalization of this matrix yields $3 + k$ mass eigenstates, which are, in general, of Majorana type. Dirac neutrinos can be constructed from two Majorana neutrino mass eigenstates whose masses are equal in magnitude.[5] For this reason, Dirac neutrino masses may be considered to be a special (degenerate) case of Majorana neutrino masses, and the latter may be regarded as the generic case. From the similarity transformation which diagonalizes the neutrino mass matrix, together with the similarity transformation which diagonalizes the charged lepton mass matrix (where, of course, only Dirac masses are allowed by electric charge conservation), one constructs the lepton mixing matrix U. In general, since U is not the identity, neutrino masses naturally give rise to lepton family number violation.

In addition to mass and lifetime limits, this Review includes limits on various other possible properties, including electric charge, the *CPT*-violating difference $m_{\nu_1} - m_{\overline{\nu}_1}$, and a magnetic dipole moment. These are of interest because a massless purely chiral Dirac neutrino cannot have a magnetic (or electric) dipole moment. In the standard electroweak theory, extended to allow for Dirac neutrino masses, the neutrino magnetic dipole moment is nonzero and given,[6] to leading order, as

$$\mu_{\nu_j} = \frac{3eG_F m_{\nu_j}}{8\pi^2\sqrt{2}} = 3.2 \times 10^{-19}(m_{\nu_j}/1\text{ eV})\mu_B \quad (3)$$

where G_F is the Fermi constant and $\mu_B = e/(2m_e)$ is the Bohr magneton. The neutrino electric dipole moment violates both time reversal invariance and parity; although it is nonzero in general, it is quite small (see, *e.g.* Ref. 7). The operator products which define the magnetic and electric dipole moments, *viz.*, $\overline{\nu}\sigma_{\alpha\beta}\nu F^{\alpha\beta}$ and $\overline{\nu}\sigma_{\alpha\beta}\gamma_5\nu F^{\alpha\beta}$, respectively (where $F^{\alpha\beta}$ is the electromagnetic field strength tensor) vanish identically if ν is a Majorana neutrino because of the Majorana property that $\nu^c = \pm\nu$. Thus, a Majorana neutrino has identically zero magnetic and electric dipole moments.

Only the diagonal magnetic and electric dipole moments are static properties of a given neutrino mass eigenstate. Transition magnetic and electric dipole moments exist in general for both Dirac and Majorana neutrinos but are not static properties and hence are not considered here. Occasionally, one also finds references to the "neutrino charge radius" in the literature. This is defined via the Taylor series expansion of the generalized vector Dirac form factor multiplying γ_μ in the electromagnetic current matrix element: $F_1^V(q^2) = F_1^V(0) + q^2 dF_1^V/dq^2|_{q^2=0} + \mathcal{O}[(q^2)^2]$, where q denotes the 4-momentum of the photon [see, *e.g.* Ref. 7 Eq. (2.20)]. The electric charge is $Q = F^V(0) = 0$ for a neutrino, and the charge radius is given by $\langle r^2 \rangle = (1/6)dF_1^V/dq^2|_{q^2=0}$. However, since this is multiplied by q^2 in the Taylor series expansion, it never occurs for a real photon, where $q^2 = 0$, and hence is not an S-matrix element, *i.e.*, not a physical quantity. In a gauge theory, this is manifested in the fact that the charge radius is gauge-dependent.

If one considers the possibility of nonzero masses for neutrinos, then for consistency one must also consider the leptonic mixing which would in general occur concomitantly. Accordingly, this *Review* devotes a section to correlated bounds on neutrino masses and lepton mixing angles. These can be divided into two types. First, there are those due to decays involving neutrinos in the final state, which must be recognized to have the possible multimode structure pointed out above. In the two most sensitive cases suggested as tests for neutrino masses and mixing, one obtains a limit on m_{ν_j} and $|U_{aj}|^2$ individually for each j. The peak-search test proposed in Ref. 3 was applied to existing data in that paper and a subsequent one;[4] it was applied in new experiments on 2-body leptonic decays of K^+ and π^+ by several groups at SIN (PSI), KEK, and TRIUMF. The results are catalogued in corresponding subsections on limits on $|U_{1j}|^2$ and $|U_{2j}|^2$. The kink-search test was also applied by a number of groups and the experimental situation has been a matter of controversy for several years (see below).

Second, there are limits due to processes involving the propagation and subsequent interaction of neutrinos. The latter are often called neutrino oscillation limits, although this term is strictly correct only if the differences in neutrino masses are sufficiently small relative to their momenta that the propagation is effectively coherent in a quantum mechanical sense; otherwise, the individual ν_j from a given decay such as $\pi_{\mu 2}$ or $K_{\mu 2}$ propagate in a measurably incoherent manner, and there is no oscillation. Experimentalists usually present their results in terms of a simplifying model in which mixing is assumed to occur only between two neutrino species. The relevant transformation equation becomes

$$\begin{pmatrix} \nu_{\ell_a} \\ \nu_{\ell_b} \end{pmatrix}_L = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}_L \quad (4)$$

where again $\nu_{\ell_1} = \nu_e$, etc. Let the distance between the source of the neutrinos and their point of interaction be denoted x, and their energy as E. Assume furthermore that the m_{ν_i} are such that the coherence assumption is valid. Then the probability of an initial ν_{ℓ_a}, having propagated for a distance $t = x$ (with $1 - v/c \ll 1$) being equal to ν_{ℓ_b} is given by

$$|\langle \nu_{\ell_b}|\nu_{\ell_a}(t)\rangle|^2 = \sin^2 2\theta \sin^2\Big(\frac{\Delta m^2 x}{4E}\Big) \quad (5a)$$

where

$$\Delta m^2 = m_{\nu_i}^2 - m_{\nu_j}^2\ . \quad (5b)$$

Thus, neutrino oscillation experiments cannot measure individual neutrino masses, but only differences of masses squared, and indeed these are generally weighted in a more complicated way by lepton mixing matrix coefficients for the general case where there is mixing among more than just two species. Experimental results are presented as allowed regions on a plot, the axes of which are $|\Delta m^2|$ and $\sin^2 2\theta$. These are often summarized in terms of the upper limit on Δm^2 (the absolute value is usually suppressed in the notation) for maximal mixing, $\sin^2 2\theta = 1$, and the upper limit on $\sin^2 2\theta$ for "large" Δm^2, *i.e.*, sufficiently large $|\Delta m^2|$ that the detector averages over many cycles of oscillation (or there ceases to be any coherence). We refer the reader to the original papers for the two-dimensional plots expressing the actual limits; because of lack of space, in this Review we shall generally limit ourselves to listing the above types of limits.

Neutrinoless double β decay experiments test for total lepton number violation such as would result for Majorana neutrino masses. This process takes place when a nucleus with Z protons and $A = Z + N$ nucleons decays according to $(Z, A) \to (Z + 2, A) + e^- + e^-$, violating total lepton number by 2 units. In the case of neutrinos with masses which are sufficiently light, an upper limit on neutrinoless double β decay yields a correlated upper limit on the quantity

$$\overline{m} = \Big| \sum_j U_{1j}^2 m_{\nu_j} \Big| \; .$$

Note that cancellations may occur in the sum, since in general U_{1j} is complex. Experiments also cite limits on η, a parameter related to the chirality of the effective leptonic currents involved. For early reviews of neutrinoless double β decay, see Refs. 8 and 9; Ref. 10 is a more current review.

The Fall 1991 experimental situation is somewhat unsettled.

Direct searches for nonzero neutrino masses have not yielded any uncontested positive signal. As of 1987 Boris *et al.*[11] (ITEP) still observed a nonzero ν_e mass 17 eV $< m_{\nu_1} <$ 40 eV, as in earlier ITEP reports. (More precisely, this and other measurements are of the primary mass eigenstate ν_1 contained in this weak eigenstate.) Fritschi *et al.*[12] appeared to disagree with this result obtaining the upper bound $m_{\nu_1} <$ 18 eV (95% CL). A critique by Boris *et al.* is given in Ref. 13; see also the criticism of Boris *et al.* by Bergkvist.[14,15] A number of other tritium decay experiments have since been performed. None has obtained positive evidence for $m_{\nu_1} \neq 0$, and the more recent have achieved a sensitivity which allows them to refute the ITEP claim: Robertson *et al.*[16] report $m_{\nu_1} <$ 9.3 eV, and Kawakami *et al.*[17] obtain $m_{\nu_1} <$ 13 eV.

The experiments which report upper limits actually measure $m^2_{\nu_1}$. It is assumed that the measurement errors are Gaussian, and there is no constraint that $m^2_{\nu_1} > 0$. When this requirement is imposed to a given measurement or to the weighted sum of such measurements by the method discussed in Section III of this *Review*, an upper limit at a given confidence limit can be obtained. For the three measurements given in the above paragraph, the formal combined upper limit is 7.3 eV at the 90% CL. However, we caution the reader in using this number since the Robertson *et al.*[16] result, which dominates the combined limit, has a negative central value for $m^2_{\nu_1}$ and implies only a 3% probability that $m^2_{\nu_1}$ is positive. Kawakami *et al.*[17] also report a central value of $m^2_{\nu_1}$ which is negative, although by a smaller amount, relative to the errors. The authors of these papers are, of course, aware of this problem; see, *e.g.*, the discussion at the end of Robertson *et al.*

There are no such claims of nonzero values of m_{ν_μ} or m_{ν_τ} (more exactly, m_{ν_2} and m_{ν_3}, respectively) from direct kinematic searches. These are performed using $\pi^+ \to \mu^+ \nu_\mu$ decay and several different τ decays.

Many experiments have also been performed to search for correlated evidence of neutrino masses and lepton mixing. Despite an early positive claim in 1980 for evidence of neutrino oscillations based on a reactor (anti)neutrino experiment by Reines *et al.*,[18] a large number of subsequent searches for neutrino oscillations at accelerators and reactors have been performed and none has yielded uncontested evidence for such oscillations. Concerning the positive claim by Cavaignac *et al.*,[19] Zacek *et al.*[20] stated that "Our experiment excludes this area (the oscillation parameter region allowed by the Bugey data[19]) almost completely, thus disproving the indications of neutrino oscillations of Cavaignac *et al.* with a high degree of confidence." Further, the positive claim for neutrino oscillations by Bernardi *et al.*[21] has essentially been retracted by the group.[22]

There is one controversy which has continued unresolved for six years and which has generated much recent research activity. In 1985 Simpson reported observing a kink in the ^{3}H β decay spectrum, indicating the emission of a heavy neutrino with mass m_{ν_j} = 17 keV and coupling coefficient $|U_{1j}|^2 = 0.03 \pm 0.01$.[23] (The spectral excess at low electron kinetic energy on which this claim was based had actually been observed much earlier by Conway and Johnston,[24] but at that time it was not interpreted as due to the emission of an admixed massive neutrino.) Seven experiments were soon performed to check this finding, and all of them disagreed with it: five on ^{35}S β decay,[25–29] one on the photon spectrum in ^{55}Fe electron capture with inner bremsstrahlung (IBEC),[30] one on ^{73}Ni β decay,[31] and one on ^{125}I β decay.[32] The results of these and other experiments for which written reports have been made available are summarized in Fig. 1.

Another ^{63}Ni experiment by Wark and Boehm, reported at a neutrino conference, again disagreed with Simpson's result.[33] In a 1989 paper[34] Hime and Simpson reported new ^{3}H decay data and corrected the analysis in the 1985 Simpson experiment[23] to include screening effects as suggested by Lindhard and Hansen,[35] and the resultant value the coupling coefficient was reduced to $0.005 < |U_{1j}|^2 < 0.018$. This value thus supercedes the value of $|U_{1j}|^2 = 0.03 \pm 0.01$ originally reported. In papers in 1986[36] and 1989,[37] Simpson and Hime made criticisms of all of the experiments which disagreed with with the original experiment.[23] In particular, Simpson's own reanalysis of the Ohi *et al.* data[29] led him to claim that these data do in fact show evidence for the emission of a 17 keV neutrino, contrary to the claim of Ohi *et al.*

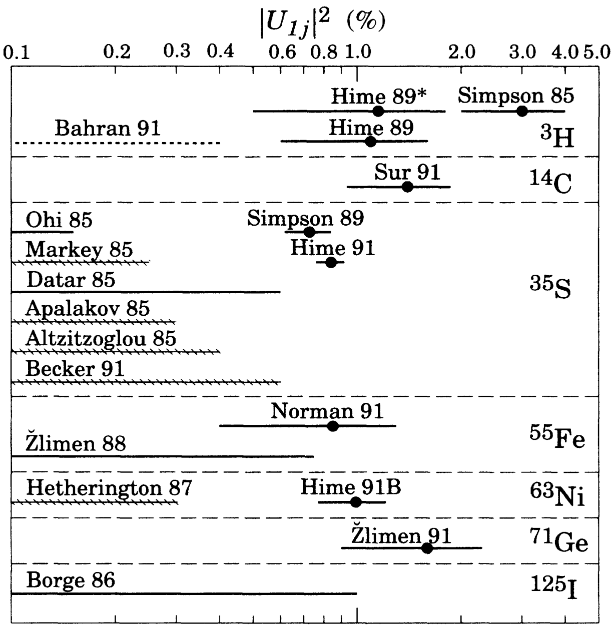

Fig. 1. Coupling coefficient $|U_{1j}|^2$ measurements (points with error bars) and limits (bars on left) obtained in experiments on the emission of 17 keV (anti)neutrino in nuclear β decay. Most results are given in the listings, but Bahran 91, Becker 91, and Norman 90 are from reports and conference proceedings. Confidence limits vary with experiment; consult the listings. Solid lines indicate experiments using solid state detectors, cross-hatched lines indicate those using magnetic spectrometers, and the dotted line (Bahran 91) indicates a proportional wire chamber experiment. Hime 89 consists of new measurements of ^{3}H decay and a reanalysis of Simpson 85; the latter is indicated by the asterisk. The reference shorthand given in the figure is given explicitly in the references,[23,25–32,38,40–44] and agrees with those given in the Listings.

Positive results have recently been reported in papers by Sur *et al.* (^{14}C),[38] by Hime and Jelly[39] (^{35}S), Žlimen *et al.*[40] (IBEC in ^{71}Ge), in conference proceedings by Norman *et al.*[41] (same group as Sur *et al.*, but IBEC in ^{55}Fe), and in a preprint by Hime and Jelley[42] (^{63}Ni). Other preprints and reports find no evidence for any massive neutrino and claim to exclude the Hime-Simpson values of 17 keV and $|U_{1j}|^2 \sim 0.01$ at better than the 99% CL.[43,44] Further results were presented at a topical workshop at Lawrence Berkeley Laboratory in December 1991; unfortunately, the workshop did not have proceedings. It is hoped that a consensus may be reached in the near future on this very important issue.

Solar neutrino experiments give indirect evidence for massive neutrinos and lepton mixing. The pioneering experiment is the ^{37}Cl radiochemical solar neutrino experiment of R. Davis and his group has been running (with one gap) since before 1970.[45,46] It has recently been joined by the Kamiokande experiment in Japan,[47,48,49] which consists of a large water Čerenkov detector, and the Soviet-American Gallium Experiment (SAGE) at Baksan, USSR.[50] The Davis experiment has consistently found a deficiency in the measured flux of (high-energy, mainly from the ^{8}B reaction) neutrinos from the sun. The measured flux is about three times smaller than the flux predicted by theoretical calculations.[51,52,53] The deficiency in the solar neutrino flux has been confirmed by the Kamiokande II experiment,[47,48] which again is sensitive to relatively high-energy neutrinos. (The ratio of observed to expected flux seen by the Kamiokande group is somewhat higher than that observed by Davis, but is still significantly below unity.) SAGE is sensitive to the low-energy neutrinos from the main fusion reaction in the sun, the *pp* chain. The collaboration has set an upper limit of 79 SNU's (90% CL) on the solar neutrino flux, to be compared with the predicted flux of about 130 SNU's. An important feature of this result is that while researchers believe that the flux of high-energy neutrinos due to the ^{8}B chain can be calculated with reasonable reliability, this flux constitutes only a tiny fraction of the total neutrino output of the sun and is quite sensitive to various parameters characterizing the sun, such as the central temperature. In contrast, the flux of the *pp* neutrinos constitutes the dominant part of the solar neutrino flux, is essentially determined by the known solar luminosity, and is considered to be reliably calculable. One explanation of the results of these three experiments is that neutrino oscillations take place during the transit from the production point in the sun to the interaction point in the earth. These oscillations may involve mixing with either ν_μ and ν_τ or "sterile" neutrino components. An appealing scenario is that of resonant neutrino oscillations, the Mikheyev-Smirnov-Wolfenstein (MSW) effect.[54] Details of this mechanism can be found in the reviews cited at the end of this note and in the references in the original papers. In contrast to the direct mass searches, the peak and kink searches, and searches for neutrino oscillations and double β decay, however, conclusions drawn from solar neutrino experiments about the properties of neutrinos are indirect and always depend on the correctness of our understanding of solar astrophysics.

For some recent reviews on neutrino physics, see Refs. 55–58; these contain further references to the original literature.

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Some other sources of information on neutrinos include *Neutrino-90 Conference*, the *1991 Rencontre de Moriond Workshop*, the *International Conferences on High Energy Physics* (even years), and the *Lepton-Photon Conferences* (odd years). Special conferences on neutrino physics have also been held from time to time, such as the conference at Osaka (eds. T. Kotani and colleagues) in 1986.

ν_e

$J = \frac{1}{2}$

Not in general a mass eigenstate. See note on neutrino properties above.

These limits apply to ν_1, the primary mass eigenstate in ν_e. They would also apply to any other ν_j which mixes strongly in ν_e and has sufficiently small mass that it can occur in the respective decay. The neutrino mass may be of a Dirac or Majorana type; the former conserves total lepton number while the latter violates it. Either would violate lepton family number, since nothing forces the neutrino mass eigenstates to coincide with the neutrino interaction eigenstates. For limits on a Majorana ν_e mass, see the section on "Searches for Massive Neutrinos and Lepton Mixing," part (C), entitled "Searches for Neutrinoless Double-β Decay."

From the analysis of neutrino events from SN 1987A it is possible to get model-dependent upper bounds on neutrino masses. Since these depend significantly on astrophysical assumptions, since they are model-dependent, and since different papers disagree strongly as to the values of the bounds, we do not list them here. For thorough statistical studies, see Sperlgel[1] and Abbott[2] and references therein.

Our mass limit for ν_e is taken from the average in the ν_e "Mass Squared" section immediately below this section.

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ν_e MASS

Most of the data from which these limits are derived are from β^- decay experiments in which a $\overline{\nu}_e$ is produced, so that that really apply to $m(\overline{\nu}_1)$. Assuming *CPT* invariance, a limit on $m(\overline{\nu}_1)$ is the same as a limit on $m(\nu_1)$. Results from studies of electron capture transitions, given below "$\nu_1 - \overline{\nu}_1$ MASS DIFFERENCE", give limits on $m(\nu_1)$ itself.

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
OUR LIMIT		[1] PDG 92		See the note below.
<13	95	[2] KAWAKAMI 91	CNTR	
< 9.3	95	[3] ROBERTSON 91	CNTR	^{3}Hβ decay
<18	95	[4] FRITSCHI 86	CNTR	$\overline{\nu}_e$, ^{3}H
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<14	95	AVIGNONE 90	ASTR	Supernova SN 1987A
<23		LOREDO 89	ASTR	SN 1987A
		ABBOTT 88	ASTR	Supernova SN 1987A
<29	95	[5] KAWAKAMI 88	CNTR	Repl. by KAWAKAMI 91
		[6] SPERGEL 88	ASTR	Supernova SN 1987A
17 to 40		[7] BORIS 87	CNTR	$\overline{\nu}_e$, ^{3}H
<27	95	[8] WILKERSON 87	CNTR	$\overline{\nu}_e$, ^{3}H

[1] PDG 92 formal upper limit, as obtained from the m^2 average in the next section, is 7.3 eV at the 90%CL. Caution is urged in interpreting this result, however, because the m^2 average is dominated by the ROBERTSON 91 result, which is nearly 2σ negative.

[2] KAWAKAMI 91 experiment uses tritium-labeled arachidic acid. This result may be obtained from the $m^2(\nu_1)$ limit by combining the errors in quadrature and using the method described in the Probability, Statistics, and Monte Carlo section in Chapter III of this Review. This was also done in ROBERTSON 91, although the authors report a different procedure.

[3] ROBERTSON 91 experiment uses gaseous molecular tritium. The result is in strong disagreement with the earlier claims by the ITEP group [LUBIMOV 80, BORIS 87 (+ BORIS 88 erratum)] that $m(\nu_1)$ lies between 17 and 40 eV. However, the probability of a positive m^2 is only 3% if statistical and systematic error are combined in quadrature.

[4] FRITSCHI 86 multiply their statistical error by 1.645 (for 95% CL), add this linearly to their unmultiplied systematic error (204 eV^2) and do NOT add in the m^2 value (-11 eV^2) to obtain their 95% CL limit (m<18 eV). To adjust for our quadratic addition of errors, and our multiplication of both the statistical and systematic errors by the factor 1.645, we set the systematic error to 178 eV^2.

[5] KAWAKAMI 88 multiply their statistical error by the appropriate factor for 95% CL when $m^2 > 0$ is required (1.74), add this linearly to their unmultiplied systematic error (173 eV^2) and add the m^2 value (223 eV^2) to obtain their 95% CL limit (m<29 eV). To adjust for our quadratic addition of errors and our multiplication of both the statistical and systematic errors by the factor 1.645 we set the systematic error to 269 eV^2 to yield the same limit.

[6] SPERGEL 88 rule out masses greater than 16 eV.

[7] See also comment in BORIS 87B and erratum in BORIS 88.

[8] WILKERSON 87 multiply both statistical and systematic errors by 1.645 (for 95% CL), add them in quadrature and add the (negative) m^2 value (-57 eV^2) to obtain their 95% CL limit (m<27 eV).

ν_e MASS SQUARED

The tritium experiments which yield the best limits for $m(\nu_e)$ actually measure mass squared. Any effort to combine their results to obtain an improved limit, therefore requires use of the mass squared results shown here. Note that we exclude the results of BORIS 87 because of controversy over the possible existence of large unreported systematic errors, see BERGKVIST 85B, BERGKVIST 86, SIMPSON 84, and REDONDO 89. For a review see ROBERTSON 88.

VALUE (eV^2)	CL%	DOCUMENT ID	TECN	COMMENT
−107± 60 OUR AVERAGE				
− 65± 85± 65	95	[9] KAWAKAMI 91	CNTR	$\overline{\nu}_e$, tritium
−147± 68± 41	95	[10] ROBERTSON 91	CNTR	$\overline{\nu}_e$, tritium
− 11± 63±178		[11] FRITSCHI 86	CNTR	$\overline{\nu}_e$, tritium
• • • We do not use the following data for averages, fits, limits, etc. • • •				
223±244±269		[12] KAWAKAMI 88	CNTR	Repl. by KAWAKAMI 91
− 57±453±118		[13] WILKERSON 87	CNTR	Repl. by ROBERTSON 91

[9] KAWAKAMI 91 experiment uses tritium-labeled arachidic acid.

[10] ROBERTSON 91 experiment uses gaseous molecular tritium. The result is in strong disagreement with the earlier claims by the ITEP group [LUBIMOV 80, BORIS 87 (+ BORIS 88 erratum)] that $m(\nu_1)$ lies between 17 and 40 eV. However, the probability of a positive m^2 is only 3% if statistical and systematic error are combined in quadrature.

[11] FRITSCHI 86 multiply their statistical error by 1.645 (for 95% CL), add this linearly to their unmultiplied systematic error (204 eV^2) and do NOT add in the m^2 value (-11 eV^2) to obtain their 95% CL limit (m<18 eV). To adjust for our quadratic addition of errors, and our multiplication of both the statistical and systematic errors by the factor 1.645, we set the systematic error to 178 eV^2.

[12] KAWAKAMI 88 multiply their statistical error by the appropriate factor for 95% CL when $m^2 > 0$ is required (1.74), add this linearly to their unmultiplied systematic error (173 eV^2) and add the m^2 value (223 eV^2) to obtain their 95% CL limit (m<29 eV). To adjust for our quadratic addition of errors and our multiplication of both the statistical and systematic errors by the factor 1.645 we set the systematic error to 269 eV^2 to yield the same limit.

[13] WILKERSON 87 multiply both statistical and systematic errors by 1.645 (for 95% CL), add them in quadrature and add the (negative) m^2 value (-57 eV^2) to obtain their 95% CL limit (m<27 eV).

$\nu_1 - \overline{\nu}_1$ MASS DIFFERENCE

These are measurement of $m(\nu_1)$ (in contrast to $m(\overline{\nu}_1)$, given above). The masses can be different for a Dirac neutrino in the absense of *CPT* invariance. The test is not very strong.

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
< 225	95	SPRINGER 87	CNTR	ν, ^{163}Ho
< 550	68	YASUMI 86	CNTR	ν, ^{163}Ho
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1250		[14] YASUMI 83	CNTR	ν, ^{163}Ho
<1300		ANDERSEN 82	CNTR	ν, ^{163}Ho
< 4.5×10^5	90	CLARK 74	ASPK	K_{e3} decay
<4100	67	BECK 68	CNTR	ν, ^{22}Na

[14] Assumes upper limit on *Q*-value reported by ANDERSEN 82. Replaced by YASUMI 86.

ν_1 CHARGE

VALUE (units: electron charge)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$<2 \times 10^{-15}$	[15] BARBIELLINI 87	ASTR	Supernova SN 1987A
$<1 \times 10^{-13}$	BERNSTEIN 63	ASTR	Solar energy losses

[15] Precise limit depends on assumptions about the intergalactic or galactic magnetic fields and about the direct distance and time through the field.

ν_1 MEAN LIFE

VALUE (s)	CL%	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
>278	90	[16] LOSECCO 87B	IMB

[16] LOSECCO 87B assumes observed rate of 2.1 SNU (solar neutrino units) comes from sun while 7.0 ± 3.0 is theory.

ν_1 (MEAN LIFE) / MASS

See also the Listings in the Neutrino Bounds from Astrophysics and Cosmology section.

VALUE (s/eV)	CL%	DOCUMENT ID	TECN	COMMENT
>300	90	[17] REINES 74	CNTR	$\overline{\nu}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> 6.4	90	[18] KRAKAUER 91	CNTR	$\overline{\nu}$ at LAMPF
> 6.3×10^{15}		[19,20] CHUPP 89	ASTR	$m(\nu)$< 20 eV
		[21] COWSIK 89	ASTR	
> 1.7×10^{15}		[20] KOLB 89	ASTR	$m(\nu)$< 20 eV
		[22] RAFFELT 89	RVUE	$\overline{\nu}$ (Dirac, Majorana)
		[23] RAFFELT 89B	ASTR	
		[24] BOUCHEZ 88	CNTR	$\overline{\nu}$ (Dirac, Majorana)
		[25] FRIEMAN 88	ASTR	
> 8.3×10^{14}		[25] VONFEILIT... 88	ASTR	
> 22	68	[26] OBERAUER 87		$\overline{\nu}_R$ (Dirac)
> 38	68	[26] OBERAUER 87		$\overline{\nu}$ (Majorana)
> 59	68	[26] OBERAUER 87		$\overline{\nu}_L$ (Dirac)
> 30	68	KETOV 86	CNTR	$\overline{\nu}$ (Dirac)
> 20	68	KETOV 86	CNTR	$\overline{\nu}$ (Majorana)
> 7×10^9		[27] RAFFELT 85	ASTR	
		[28] HENRY 81	ASTR	$m(\nu)$= 16–20 eV
		[29] KIMBLE 81	ASTR	$m(\nu)$= 10–100 eV
> 2×10^{21}		[30] STECKER 80	ASTR	$m(\nu)$= 10–100 eV

[17] REINES 74 looked for ν_e of nonzero mass decaying to a neutral of lesser mass + γ. Used liquid scintillator detector near fission reactor. Finds lab lifetime 6. × 10^7 s or more. Above value of (mean life)/mass assumes average effective neutrino energy of 0.2 MeV. To obtain the limit 6. × 10^7 s REINES 74 assumed that the full $\overline{\nu}_e$ reactor flux could be responsible for yielding decays with photon energies in the interval 0.1 MeV – 0.5 MeV. This represents some overestimate so their lower limit is an over-estimate of the lab lifetime (P. Vogel, private communication, 1984).

[18] KRAKAUER 91 quotes the limit $\tau/m(\nu_1) > (0.3a^2 + 9.8a + 15.9)$ s/eV, where a is a parameter describing the asymmetry in the neutrino decay defined as $dN_\gamma/d\cos\theta = (1/2)(1 + a\cos\theta)$ $a = 0$ for a Majorana neutrino, but can vary from -1 to 1 for a Dirac neutrino. The bound given by the authors is the most conservative (which applies for $a = -1$).

[19] CHUPP 89 should be multiplied by a branching ratio (about 1) and a detection efficiency (about 1/4), and pertains to radiative decay of any neutrino to a lighter or sterile neutrino.

[20] Nonobservation of γ's in coincidence with ν's from SN 1987A.

[21] COWSIK 89 use observations of supernova SN 1987A to set the limit for the lifetime of a neutrino with $1 < m < 50$ MeV decaying through $\nu_H \to \nu_1 ee$ to be $\tau > 4 \times 10^{15}$ exp($-m$/5 MeV) s.

[22] RAFFELT 89 uses KYULDJIEV 84 to obtain $\tau m^3 > 3 \times 10^{18}$ s eV^3 (based on $\overline{\nu}_e e^-$ cross sections). The bound is not valid if electric and magnetic transition moments are equal for Dirac neutrinos.

[23] RAFFELT 89B analyze stellar evolution and exclude the region $3 \times 10^{12} < \tau m^3 < 3 \times 10^{21}$ s eV^3.

[24] BOUCHEZ 88 reports limits in the nearly degenerate mass case.

[25] Model-dependent theoretical analysis of SN 1987A neutrinos.

[26] OBERAUER 87 bounds are from comparison of observed and expected rate of reactor neutrinos.
[27] RAFFELT 85 limit is from solar x- and γ-ray fluxes.
[28] HENRY 81 uses UV flux from clusters of galaxies to find $\tau > 1.1 \times 10^{25}$ s for radiative decay.
[29] KIMBLE 81 uses extreme UV flux limits to find $\tau > 10^{22}$–10^{23} s.
[30] STECKER 80 limit based on UV background; result given is $\tau > 4 \times 10^{22}$ s at $m(\nu) =$ 20 eV.

ν_1 MAGNETIC MOMENT

Must vanish for Majorana neutrino or purely chiral massless Dirac neutrino. The value of the magnetic moment for the standard SU(2) × U(1) electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = (3.20 \times 10^{-19}) m_\nu \mu_B$ where m_ν is in eV and $\mu_B = e\hbar/2m_e$ is the Bohr magneton. Given the upper bound $m(\nu_1) < 7.3$ eV, it follows that for the extended standard electroweak theory, $\mu(\nu_1) < 2.3 \times 10^{-18}\ \mu_B$. Current experiments are not yet challenging this limit. There is considerable controversy over the validity of many of the claimed upper limits on the magnetic moment from the astrophysical data. For example, VOLOSHIN 90 states that "in connection with the astrophysical limits on μ_ν, ... there is by now a general consensus that contrary to the initial claims (BARBIERI 88, LATTIMER 88, GOLDMAN 88, NOTZOLD 88), essentially no better than quoted limits (from previous constraints) can be derived from detection of the neutrino flux from the supernova SN1987A." See VOLOSHIN 88 and VOLOSHIN 88C.

VALUE (μ_B)	CL%	DOCUMENT ID		TECN	COMMENT
<1.08 × 10^{-9}	90	KRAKAUER	90	CNTR	LAMPF $\nu_e e \to \nu_e e$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[31] FIORENTINI	91	ASTR	
$<2 \times 10^{-12}$	95	[32] RAFFELT	90	ASTR	Red giant luminosity
$<1 \times 10^{-11}$		[33] RAFFELT	89B	ASTR	Cooling helium stars
$<(2\text{–}8) \times 10^{-12}$		[33,34,35] BARBIERI	88	ASTR	Supernova SN 1987A
		[36] FUKUGITA	88	COSM	Primordial magn. fields
$<1 \times 10^{-12}$		[34,35,37] GOLDMAN	88	ASTR	Supernova SN 1987A
$<5 \times 10^{-13}$		[33,35] LATTIMER	88	ASTR	Supernova SN 1987A
$\leq 1.5 \times 10^{-12}$		[33,35] NOETZOLD	88	ASTR	Supernova SN 1987A
$\leq 3 \times 10^{-11}$		[33] RAFFELT	88B	ASTR	He burning stars
$<1.1 \times 10^{-11}$		[33] FUKUGITA	87	ASTR	Cooling helium stars
$<4 \times 10^{-11}$		LYNN	81	ASTR	
$<8.5 \times 10^{-11}$		BEG	78	ASTR	Stellar plasmons
$<6 \times 10^{-11}$		[38] SUTHERLAND	76	ASTR	Red giants + degen. dwarfs
$<1 \times 10^{-10}$		BERNSTEIN	63	ASTR	Cooling white dwarfs
$<1.4 \times 10^{-9}$		COWAN	57	CNTR	Reactor $\bar{\nu}_e$

[31] FIORENTINI 91 is a study of the statistical significance of possible correlation of solar neutrino flux with sunspot cycle. Data do not imply any evidence for a nonzero neutrino magnetic moment, although they are consistent with a moment of order $1 \times 10^{-10}/\mu_B$.
[32] RAFFELT 90 limit applies for a diagonal magnetic moment of a Dirac neutrino, or for a transition magnetic moment of a Majorana neutrino. In the latter case, the same analysis gives $< 1.4 \times 10^{-12}$. Limit at 95%CL obtained from δM_C.
[33] Significant dependence on details of stellar models.
[34] A limit of 10^{-13} is obtained with even more model-dependence.
[35] These papers have assumed that the right-handed neutrino is inert; see BARBIERI 88B.
[36] FUKUGITA 88 find magnetic dipole moments of any two neutrino species are bounded by $\mu < 10^{-16}\ [10^{-9}\ G/B_0]$ where B_0 is the present-day intergalactic field strength.
[37] Some dependence on details of stellar models.
[38] We obtain above limit from SUTHERLAND 76 using their limit $f < 1/3$.

NONSTANDARD CONTRIBUTIONS TO NEUTRINO SCATTERING

We report limits on the so-called neutrino charge radius squared in this section. This quantity is not an observable, physical quantity and this is reflected in the fact that it is gauge dependent. It is not necessarily positive. A more general interpretation of the experimental results is that they are limits on certain nonstandard contributions to neutrino scattering.

VALUE (10^{-32} cm^2)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.1 ± 2.3	ALLEN	91	CNTR	$\nu_e e$ elas scat
-1.1 ± 1.0	[39] AHRENS	90	CNTR	$\nu_\mu e$ elas scat
-0.3 ± 1.5	[40] DORENBOS...	89	CHRM	$\nu_\mu e$ elas scat
	[41] GRIFOLS	89B	ASTR	SN 1987A

[39] AHRENS 90 result is obtained from reanalysis in ALLEN 91, followed by our reduction to obtain 1 σ errors.
[40] DORENBOSCH 89 result is obtained from reanalysis in ALLEN 91, followed by our reduction to obtain 1σ errors.
[41] GRIFOLS 89B sets a limit of $\langle r^2 \rangle < 0.2 \times 10^{-32}$ cm^2 for right-handed neutrinos.

ν_e REFERENCES

PDG	92	PR D45, Part 2	Hikasa, Barnett, Stone+	(KEK, LBL, BOST+)
ALLEN	91	PR D43 R1	+Chen, Doe, Hausammann	(UCI, LANL, UMD)
FIORENTINI	91	PL B253 181	+Mezzorani	(CAGL, INFN)
KAWAKAMI	91	PL B256 105	+Kato, Ohshima+	(TOKY, TOHO, TINT, KOBE, KEK)
KRAKAUER	91	PR D44 R6	+Talaga, Allen, Chen+	(LAMPF E225 Collab.)
ROBERTSON	91	PRL 67 957	+Bowles, Stephenson, Wark, Wilkerson, Knapp	(LASL, LLL)
AHRENS	90	PR D41 3297	+	(BNL, BROW, HIRO, KEK, OSAK, PENN, STON)
AVIGNONE	90	PR D41 682	+Collar	(SCUC)
KRAKAUER	90	PL B252 177	+Talaga, Allen, Chen+	(LAMPF E225 Collab.)
RAFFELT	90	PRL 64 2856		(MPIM)
VOLOSHIN	90	NP B (Proc. Suppl) 19 433		(ITEP)
Neutrino 90 Conference				
CHUPP	89	PRL 62 505	+Vestrand, Reppin	(UNH, MPIM)
COWSIK	89	PL B218 91	+Schramm, Hoflich	(WUSL, TATA, CHIC, MPIM)
DORENBOS...	89	ZPHY C41 567	Dorenbosch, Udo, Allaby, Amaldi+	(CHARM Collab.)
GRIFOLS	89B	PR D40 3819		(BARC)
KOLB	89	PRL 62 509	+Turner	(CHIC, FNAL)
LOREDO	89	ANYAS 571 601	+Lamb	(CHIC)
RAFFELT	89	PR D39 2066		(PRIN, UCB)
RAFFELT	89B	APJ 336 61	+Dearborn, Silk	(UCB, LLL)
REDONDO	89	PR C40 368	+Robertson	(LANL)
ABBOTT	88	NP B299 734	+De Rujula, Walker	(BRAN, CERN, BOST)
BARBIERI	88	PRL 61 27	+Mohapatra	(PISA, UMD)
BARBIERI	88B	PL B213 69	+Mohapatra, Yanagida	(PISA, UMD, MICH)
BORIS	88	PRL 61 245 erratum	+Golutvin, Laptin+	(ITEP, ASCI)
BOUCHEZ	88	PL B207 217	+Pichard, Soirat, Spiro, Declais	(SACL, MARS)
FRIEMAN	88	PL B200 115	+Haber, Freese	(SLAC, UCSC, UCSB)
FUKUGITA	88	PRL 60 879	+Notzold, Raffelt, Silk	(KYOT, MPIM, UCB)
GOLDMAN	88	PRL 60 1789	+Aharanov, Alexander, Nussinov	(TELA)
KAWAKAMI	88	JPSJ 57 2873	+Kato, Naito, Nisimura+	(INUS, TOKY, TINT, KEK)
LATTIMER	88	PRL 61 23	+Cooperstein	(STON, BNL)
Also	88B	PRL 61 2633 erratum	Lattimer, Cooperstein	(STON, BNL)
NOETZOLD	88	PR D38 1658		(MPIM)
NOTZOLD	88	PR D38 1658		(MPIM)
RAFFELT	88B	PR D37 549	+Dearborn	(UCB, LLL)
ROBERTSON	88	ARNPS 38 185	+Knapp	(LANL, LLL)
SPERGEL	88	PL B200 366	+Bahcall	(IAS)
VOLOSHIN	88	PL B209 360		(ITEP)
Also	88B	JETPL 47 501	Voloshin	(ITEP)
		Translated from ZETFP 47 421.		
VOLOSHIN	88C	JETPL 68 690		(ITEP)
VONFEILIT...	88	PL B200 580	Von Feilitzsch, Oberauer	(MUNT)
BARBIELLINI	87	Nature 329 21	+Cocconi	(CERN)
BORIS	87	PRL 58 2019	+Golutvin, Laptin+	(ITEP, ASCI)
Also	88	PRL 61 245 erratum	Boris, Golutvin, Laptin+	(ITEP, ASCI)
BORIS	87B	JETPL 45 333	+Golutvin, Laptin+	(ITEP)
		Translated from ZETFP 45 267.		
FUKUGITA	87	PR D36 3817	+Yazaki	(KYOT, TOKY)
LOSECCO	87B	PR D35 2073	+Bionta, Blewitt, Bratton+	(IMB Collab.)
OBERAUER	87	PL B198 113	+von Feilitzsch, Mossbauer	(MUNT)
SPRINGER	87	PR A35 679	+Bennet, Baisden+	(LLNL)
WILKERSON	87	PRL 58 2023	+Bowles, Browne+	(LANL, PRIN, UCSD)
BERGKVIST	86	Moriond Conf., Vol. M48, 465		(STOH)
FRITSCHI	86	PL B173 485	+Holzschuh, Kundig+	(ZURI, SIN)
KETOV	86	JETPL 44 146	+Klimov, Nikolaev, Mikaelyan+	(KIAE)
		Translated from ZETFP 44 114.		
YASUMI	86	PL B181 169	+Ando+	(KEK, OSAK, TOHO, TSUK, KYOT, INUS+)
BERGKVIST	85B	PL 159B 408		(STOH)
RAFFELT	85	PR D31 3002		(MPIM)
KYULDJIEV	84	NP B243 387		(SOFI)
SIMPSON	84	PR D30 1110		(GUEL)
YASUMI	83	PL 122B 461	+Rajasekaran+	(KEK, OSAK, TINT, TOHO, TSUK)
ANDERSEN	82	PL 113B 72	+Beyer, Charpak, Derujula+	(AARH, CERN, RISO)
HENRY	81	PRL 47 618	+Feldman	(JHU)
KIMBLE	81	PRL 46 80	+Bowyer, Jakobsen	(UCB)
LYNN	81	PR D23 2151		(COLU)
FUJIKAWA	80	PRL 45 963	+Shrock	(STON)
LUBIMOV	80	PL 94B 266	+Novikov, Nozik, Tretyakov, Kosik	(ITEP)
Also	80	SJNP 32 154	Kozik, Lubimov, Novikov+	(ITEP)
		Translated from YAF 32 301.		
Also	81	JETP 54 616	Lubimov, Novikov, Nozik+	(ITEP)
		Translated from ZETF 81 1158.		
STECKER	80	PRL 45 1460		(NASA)
BEG	78	PR D17 1395	+Marciano, Ruderman	(ROCK, COLU)
SUTHERLAND	76	PR D13 2700	+Ng, Flowers+	(PENN, COLU, NYU)
CLARK	74	PR D9 533	+Elioff, Frisch, Johnson, Kerth, Shen+	(LBL)
REINES	74	PRL 32 180	+Sobel, Gurr	(UCI)
Also	78	Private Comm.	Barnes	(PURD)
BECK	68	ZPHY 216 229	+Daniel	(MPIH)
BERNSTEIN	63	PR 132 1227	+Ruderman, Feinberg	(NYU, COLU)
COWAN	57	PR 107 528	+Reines	(LANL)

ν_μ

$J = \frac{1}{2}$

Not in general a mass eigenstate. See note on neutrinos in the ν_e section above.

ν_μ MASS

Applies to ν_2, the primary mass eigenstate in ν_μ. Would also apply to any other ν_j which mixes strongly in ν_μ and has sufficiently small mass that it can occur in the respective decays. (This would be nontrivial only for $j \geq 3$, given the ν_e mass limit above.)

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
<0.27	90	[1] ABELA	84	SPEC	$m^2 = -0.097 \pm 0.072$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.3		[2] FULLER	91	COSM	Nucleosynthesis
<0.42		[2] LAM	91	COSM	Nucleosynthesis
< 0.005–0.027		NATALE	91	ASTR	SN 1987A
<0.014		[3] GANDHI	90	ASTR	SN 1987A
<0.014		[3,4] GRIFOLS	90B	ASTR	SN 1987A
<0.03		[3] GAEMERS	89		SN 1987A
<0.50	90	ANDERHUB	82	SPEC	$m^2 = -0.14 \pm 0.20$
<0.52	90	[5] LU	80	CNTR	$m^2 = 0.102 \pm 0.119$
<0.65	90	CLARK	74	ASPK	$K_{\mu 3}$ decay

[1] ABELA 84 used the PDG 84 value for $\pi^{\pm}$ mass, in conjunction with μ momentum measurement in $\pi \rightarrow \mu\nu_\mu$ decay to obtain $m < 0.25$ and $m^2 = -0.16 \pm 0.08$. The values shown here for mass and m^2 are corrected values obtained by JECKELMAN 86 from the ABELA 84 data using the more accurate $\pi^{\pm}$ mass of JECKELMAN 86.
[2] Assumes neutrino lifetime >1 s.
[3] There would be an increased cooling rate if Dirac neutrino mass is included. Limit is on $\sqrt{m^2(\nu_\mu)+m^2(\nu_\tau)}$, and error becomes very large if ν_τ is nonrelativistic, which occurs near the lab limit of 35 MeV.
[4] GRIFOLS 90B estimated error is a factor of 3.
[5] LU 80 combines DAUM 79 $\pi^+ \rightarrow \mu^+\nu_\mu$ measurement with new LU 80 π^- mass and replaces DAUM 79. LU 80 is not independent of ABELA 84.

$\nu_2 - \overline{\nu}_2$ MASS DIFFERENCE

Test of *CPT* for a Dirac neutrino. (Not a very strong test.)

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.45	90	CLARK	74	ASPK	$K_{\mu 3}$ decay

ν_2 (MEAN LIFE) / MASS

These limits often apply to ν_τ (ν_3) also.

VALUE (s/eV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
>15.4	90		[6] KRAKAUER	91	CNTR	ν_μ and $\overline{\nu}_\mu$ at LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$> 6.3 \times 10^{15}$			[7,8] CHUPP	89	ASTR	$m(\nu)$< 20 eV
$> 1.7 \times 10^{15}$			[8] KOLB	89	ASTR	$m(\nu)$< 20 eV
			[9,10] HATSUDA	88	ASTR	
$> 3.3 \times 10^{14}$			[11,12] VONFEILIT...	88	ASTR	
> 0.11	90	0	[13] FRANK	81	CNTR	$\nu\overline{\nu}$ LAMPF
			[14] HENRY	81	ASTR	$m(\nu)$= 16–20 eV
			[15] KIMBLE	81	ASTR	$m(\nu)$= 10–100 eV
			[16] REPHAELI	81	ASTR	$m(\nu)$= 30–150 eV
			[17] DERUJULA	80	ASTR	$m(\nu)$= 10–100 eV
$> 2 \times 10^{21}$			[18] STECKER	80	ASTR	$m(\nu)$= 10–100 eV
$> 1.0 \times 10^{-2}$	90	0	[13] BLIETSCHAU	78	HLBC	ν_μ, CERN GGM
$> 1.7 \times 10^{-2}$	90	0	[13] BLIETSCHAU	78	HLBC	$\overline{\nu}_\mu$, CERN GGM
$> 2.2 \times 10^{-3}$	90	0	[13] BARNES	77	DBC	ν, ANL 12-ft
$> 3. \times 10^{-3}$	90	0	[13] BELLOTTI	76	HLBC	ν, CERN GGM
$> 1.3 \times 10^{-2}$	90	1	[13] BELLOTTI	76	HLBC	$\overline{\nu}$, CERN GGM

[6] KRAKAUER 91 quotes the limit $\tau/m(\nu_1) > (0.75a^2 + 21.65a + 26.3)$ s/eV, where a is a parameter describing the asymmetry in the neutrino decay defined as $dN_\gamma/d\cos\theta = (1/2)(1 + a\cos\theta)$ The parameter $a = 0$ for a Majorana neutrino, but can vary from -1 to 1 for a Dirac neutrino. The bound given by the authors is the most conservative (which applies for $a = -1$).
[7] CHUPP 89 should be multiplied by a branching ratio (about 1) and a detection efficiency (about 1/4), and pertains to radiative decay of any neutrino to a lighter or sterile neutrino.
[8] Nonobservation of γ's in coincidence with ν's from SN 1987A. Additional limits are given for higher-mass ranges.
[9] Model-dependent theoretical analysis.
[10] HATSUDA 88 argues that previous bounds on radiative decays of neutrinos produced in supernovae explosions may not be valid (because $\nu_H \rightarrow \gamma\nu$ might be dominated by processes such as $\nu_H e \rightarrow \nu e$ if e number density is high enough), and that, in fact, a neutrino mean life/mass of 0.2–0.6 s/eV may be consistent with the data.
[11] Model-dependent theoretical analysis of SN 1987A neutrinos.
[12] Limit applies to ν_τ also.
[13] These experiments look for $\nu_\mu \rightarrow \nu_e\gamma$ or $\overline{\nu}_\mu \rightarrow \overline{\nu}_e\gamma$.
[14] HENRY 81 uses UV flux from clusters of galaxies to find $\tau > 1.1 \times 10^{25}$ s for radiative decay.
[15] KIMBLE 81 uses extreme UV flux limits to find $\tau > 10^{22}$–10^{23} s.
[16] REPHAELI 81 consider ν decay γ effect on neutral H in early universe; based on M31 HI concludes $\tau > 10^{24}$ s.
[17] DERUJULA 80 finds $\tau > 3 \times 10^{23}$ s based on CDM neutrino decay contribution to UV background.
[18] STECKER 80 limit based on UV background; result given is $\tau > 4 \times 10^{22}$ s at $m(\nu)$ = 20 eV.

$|(v - c) / c|$ ($v \equiv \nu_2$ VELOCITY)

Expected to be zero for massless neutrino.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •							
<0.4	95	9800	KALBFLEISCH	79	SPEC		
<2.0	99	77	ALSPECTOR	76	SPEC	0	>5 GeV ν
<4.0	99	26	ALSPECTOR	76	SPEC	0	<5 GeV ν

ν_2 MAGNETIC MOMENT

Must vanish for Majorana neutrino or purely chiral massless Dirac neutrino. The value of the magnetic moment for the standard SU(2) × U(1) electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = (3.2 \times 10^{-19}) m_\nu \mu_B$ where m_ν is in eV and $\mu_B = e\hbar/2m_e$ is the Bohr magneton. Given the upper bound $m(\nu_2)$ < 0.27 MeV, it follows that for the extended standard electroweak theory, $\mu(\nu_2) < 0.86 \times 10^{-13}\ \mu_B$.

VALUE (μ_B)	CL%	DOCUMENT ID		TECN	COMMENT
$<8.5 \times 10^{-10}$	90	AHRENS	90	CNTR	$\nu_\mu e \rightarrow \nu_\mu e$
$\mathbf{<7.4 \times 10^{-10}}$	90	KRAKAUER	90	CNTR	(ν_μ, $\overline{\nu}_\mu$) e elast.
$<9.5 \times 10^{-10}$	90	ABE	87B	CNTR	$\nu_\mu e \rightarrow \nu_\mu e$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1 \times 10^{-8}$	95	[19] DORENBOS...	91	CHRM	$\nu_\mu e \rightarrow \nu_\mu e$
$<2 \times 10^{-12}$	95	[20] RAFFELT	90	ASTR	Red giant luminosity
$<1 \times 10^{-11}$		[21] RAFFELT	89B	ASTR	Cooling helium stars
$<1.1 \times 10^{-11}$		[21,22] FUKUGITA	87	ASTR	Cooling helium stars
$<6 \times 10^{-14}$		[23] NUSSINOV	87	ASTR	Cosmic EM backgrounds
$<4 \times 10^{-11}$		LYNN	81	ASTR	
$<8.5 \times 10^{-11}$		[22] BEG	78	ASTR	Stellar plasmons
$<8.1 \times 10^{-9}$		[24] KIM	74	RVUE	$\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
$<1 \times 10^{-10}$		[25] BERNSTEIN	63	ASTR	Cooling white dwarfs

[19] DORENBOSCH 91 corrects an incorrect statement in DORENBOSCH 89 that the ν_2 magnetic moment is $< 1 \times 10^{-9}$ at the 95%CL. DORENBOSCH 89 measures both $\nu_\mu e$ and $\overline{\nu}_\mu e$ elastic scattering and assume $\mu(\nu_\mu) = \mu(\overline{\nu}_\mu)$.
[20] RAFFELT 90 limit applies for a diagonal magnetic moment of a Dirac neutrino, or for a transition magnetic moment of a Majorana neutrino. In the latter case, the same analysis gives $< 1.4 \times 10^{-12}$. Limit at 95%CL obtained from δM_c.
[21] Significant dependence on details of stellar properties.
[22] If $m(\nu_2) < 10$ keV.
[23] For $m(\nu_2)$ = 8–200 eV. NUSSINOV 87 examines transition magnetic moments for $\nu_\mu \rightarrow \nu_e$ and obtain $< 3 \times 10^{-15}$ for $m(\nu_2) > 16$ eV and $< 6 \times 10^{-14}$ for $m(\nu_2) > 4$ eV.
[24] KIM 74 is a theoretical analysis of $\overline{\nu}_\mu$ reaction data.
[25] If $m(\nu_2) < 1$ keV.

ν_μ REFERENCES

DORENBOS...	91	ZPHY C51 142	Dorenbosch, Udo, Allaby, Amaldi+	(CHARM Collab.)
FULLER	91	PR D43 3136	+Malaney	(UCSD)
KRAKAUER	91	PR D44 R6	+Talaga, Allen, Chen+	(LAMPF E225 Collab.)
LAM	91	PR D44 3345	+Ng	(AST)
NATALE	91	PL B258 227		(CAMP)
AHRENS	90	PR D41 3297	+	(BNL, BROW, HIRO, KEK, OSAK, PENN, STON)
GANDHI	90	PL B246 149	+Burrows	(ARIZ)
GRIFOLS	90B	PL B242 77	+Masso	(BARC, CERN)
KRAKAUER	90	PL B252 177	+Talaga, Allen, Chen+	(LAMPF E225 Collab.)
RAFFELT	90	PRL 64 2856		(MPIM)
CHUPP	89	PRL 62 505	+Vestrand, Reppin	(UNH, MPIM)
DORENBOS...	89	ZPHY C41 567	Dorenbosch, Udo, Allaby, Amaldi+	(CHARM Collab.)
GAEMERS	89	PR D40 309	+Gandhi, Lattimer	(AIKH, STON)
KOLB	89	PRL 62 509	+Turner	(CHIC, FNAL)
RAFFELT	89B	APJ 336 61	+Dearborn, Silk	(UCB, LLL)
HATSUDA	88	PL B203 462	+Lim, Yoshimura	(KEK)
VONFEILIT...	88	PL B200 580	Von Feilitzsch, Oberauer	(MUNT)
ABE	87B	PRL 58 636	+	(BNL, BROW, HIRO, KEK, OSAK, PENN, STON)
FUKUGITA	87	PR D36 3817	+Yazaki	(KYOT, TOKY)
NUSSINOV	87	PR D36 2278	+Rephaeli	(TELA)
JECKELMAN	86	PRL 56 1444	+Nakada, Beer+	(ETH, FRIB)
ABELA	84	PL 146B 431	+Daum, Eaton, Frosch, Jost, Kettle+	(SIN)
PDG	84	RMP 56 No. 2 Pt. II	Wohl, Cahn, Rittenberg+	(LBL, CIT, CERN)
ANDERHUB	82	PL 114B 76	+Boecklin, Hofer, Kottmann+	(ETH, SIN)
FRANK	81	PR D24 2001	+Burman+	(LASL, YALE, MIT, SACL, SIN+)
HENRY	81	PRL 47 618	+Feldman	(JHU)
KIMBLE	81	PRL 46 80	+Bowyer, Jakobsen	(UCB)
LYNN	81	PR D23 2151		(COLU)
REPHAELI	81	PL 106B 73	+Szalay	(UCSB, CHIC)
DERUJULA	80	PRL 45 942	+Glashow	(MIT, HARV)
FUJIKAWA	80	PRL 45 963	+Shrock	(STON)
LU	80	PRL 45 1066	+Delker, Dugan, Wu, Caffrey+	(YALE, COLU, JHU)
STECKER	80	PRL 45 1460		(NASA)
DAUM	79	PR D20 2692	+Eaton, Frosch, Hirschmann+	(SIN)
Also	76	PL 60B 380	Daum, Dubal, Eaton, Frosch+	(SIN, ETH)
Also	78	PL 74B 126	Daum, Eaton, Frosch, Hirschmann+	(SIN)
KALBFLEISCH	79	PRL 43 1361	+Baggett, Fowler+	(FNAL, PURD, BELL)
BEG	78	PR D17 1395	+Marciano, Ruderman	(ROCK, COLU)
BLIETSCHAU	78	NP B133 205	+Deden, Hasert, Krenz+	(Gargamelle Collab.)
BARNES	77	PRL 38 1049	+Carmony, Dauwe, Fernandez+	(PURD, ANL)
ALSPECTOR	76	PRL 36 837	+	(BNL, PURD, CIT, FNAL, ROCK)
BELLOTTI	76	LNC 17 553	+Cavalli, Fiorini, Rollier	(MILA)
CLARK	74	PR D9 533	+Elioff, Frisch, Johnson, Kerth, Shen+	(LBL)
KIM	74	PR D9 3050	+Mather, Okubo	(ROCH)
BERNSTEIN	63	PR 132 1227	+Ruderman, Feinberg	(NYU, COLU)

ν_τ

$J = \frac{1}{2}$

Existence indirectly established from τ decay data combined with ν reaction data. See for example FELDMAN 81. KIRKBY 79 rule out $J = 3/2$ using $\tau \to \pi\nu_\tau$ branching ratio.

Not in general a mass eigenstate. See note on neutrinos in the ν_e section above.

ν_τ MASS

Applies to ν_3, the primary mass eigenstate in ν_τ. Would also apply to any other ν_j which mixes strongly in ν_τ and has sufficiently small mass that it can occur in the respective decays. (This would be nontrivial only for a hypothetical $j \geq 4$, given the ν_e and ν_μ mass limits above.)

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 35	95	12	[1] ALBRECHT	88B	ARG	E^{ee}_{cm}= 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 0.3			[2] FULLER	91	COSM	Nucleosynthesis
none 0.5–25			[3] KOLB	91	COSM	Nucleosynthesis
< 0.42			[2] LAM	91	COSM	Nucleosynthesis
< 0.005–0.027			NATALE	91	ASTR	SN 1987A
< 0.014			[4] GANDHI	90	ASTR	SN 1987A
< 0.014 or > 34			[4,5] GRIFOLS	90B	ASTR	SN 1987A
< 0.03			[4] GAEMERS	89		SN 1987A
< 76	95	13	[6] ABACHI	87	HRS	E^{ee}_{cm}= 29 GeV
< 85	95		[7] CSORNA	87B	CLEO	E^{ee}_{cm}= 10–11 GeV
< 84	95	10	[8] ABACHI	86	HRS	Repl. by ABACHI 87
< 70	95	102	[9] ALBRECHT	85I	ARG	E^{ee}_{cm}= 10 GeV
<125	95	3	[10] BURCHAT	85	MRK2	E^{ee}_{cm}= 29 GeV
<143	95	22	[11] MATTEUZZI	85	MRK2	E^{ee}_{cm}= 29 GeV
<157	95	4	[12] MILLS	85	DLCO	E^{ee}_{cm}= 29 GeV
<250	95		[13] BLOCKER	82D	MRK2	E^{ee}_{cm}= 5.2 GeV
<250	95	594	[14,15] BACINO	79B	DLCO	E^{ee}_{cm}= 3.5–7.4 GeV

[1] ALBRECHT 88 bound comes from analysis of $\tau \to 5\pi^\pm\nu_\tau$ decay mode.
[2] Assumes neutrino lifetime >1 s.
[3] KOLB 91 exclusion region is for Dirac neutrino with lifetime >1 s; other limits are given.
[4] There would be an increased cooling rate if Dirac neutrino mass is included. Limit is on $\sqrt{m^2(\nu_\mu)+m^2(\nu_\tau)}$, and error becomes very large if ν_τ is nonrelativistic, which occurs near the lab limit of 35 MeV.
[5] GRIFOLS 90B estimated error is a factor of 3.
[6] Bound comes from analysis of $\tau \to 5\pi^\pm(\pi^0)\nu_\tau$ decay mode in 13 decay events.
[7] CSORNA 87B also quote result as 31 ± 25 ± 20 MeV. Bound comes from analysis of $\tau \to 3\pi^\pm(\pi^0)\nu_\tau$ decay mode.
[8] Bound comes from analysis of $\tau \to 5\pi^\pm\pi^0\nu_\tau$ decay mode (5 events) and to a lesser extent from $\tau \to 5\pi^\pm\nu_\tau$ mode (5 events).
[9] Bound comes from analysis of $\tau \to 3\pi^\pm\nu_\tau$ decay mode.
[10] Bound comes from analysis of $\tau \to 5\pi^\pm(\pi^0)\nu_\tau$ decay.
[11] Bound comes from analysis of $\tau \to 3\pi^\pm\pi^0\nu_\tau$ decay mode.
[12] Bound comes from analysis of $\tau \to K^\pm K^\mp\pi^\pm\nu_\tau$ decay mode.
[13] Bound comes from analysis of $\tau \to \pi\nu_\tau$ decay mode.
[14] Bound comes from analysis of leptonic decay spectrum.
[15] BACINO 79B experiment rules out V+A decay, disfavors pure V or A, and is in good agreement with V−A.

ν_3 (MEAN LIFE) / MASS

These limits often apply to ν_μ (ν_2) also.

VALUE (s/eV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[16] GRANEK	91	COSM	Decaying L^0
	[17] WALKER	90	ASTR	$m(\nu)$= 0.03 –~ 2 MeV
$>6.3 \times 10^{15}$	[18,19] CHUPP	89	ASTR	$m(\nu)$< 20 eV
$>1.7 \times 10^{15}$	[19] KOLB	89	ASTR	$m(\nu)$< 20 eV
	[20] TERASAWA	88	COSM	$m(\mu)$= 30–70 MeV
	[21] KAWASAKI	86	COSM	$m(\nu)$>10 MeV
	[22] LINDLEY	85	COSM	$m(\nu)$> 10 MeV
	[23] BINETRUY	84	COSM	$m(\nu)$~ 1 MeV
	[24] SARKAR	84	COSM	$m(\nu)$= 10–100 MeV
	[25] HENRY	81	ASTR	$m(\nu)$= 16–20 eV
	[26] KIMBLE	81	ASTR	$m(\nu)$= 10–100 eV
	[27] REPHAELI	81	ASTR	$m(\nu)$= 30–150 eV
	[28] DERUJULA	80	COSM	$m(\nu)$= 10–100 eV
$>2 \times 10^{21}$	[29] STECKER	80	ASTR	$m(\nu)$= 10–100 eV
	[30] DICUS	78	COSM	$m(\nu)$= 0.5–30 MeV
$<3 \times 10^{-11}$	[31] FALK	78	ASTR	$m(\nu)$<10 MeV
	[32] COWSIK	77	ASTR	

[16] GRANEK 91 considers heavy neutrino decays to $\gamma\nu_L$ and $3\nu_L$, where $m(\nu_L)$<100 keV. Lifetime is calculated as a function of heavy neutrino mass, branching ratio into $\gamma\nu_L$, and $m(\nu_L)$.
[17] WALKER 90 uses SN 1987A γ flux limits after 289 days to find $m(\tau) > 1.1 \times 10^{15}$ eV s.
[18] CHUPP 89 should be multiplied by a branching ratio (about 1) and a detection efficiency (about 1/4), and pertains to radiative decay of any neutrino to a lighter or sterile neutrino.
[19] Nonobservation of γ's in coincidence with ν's from SN 1987A. Additional limits are given for higher-mass ranges.
[20] TERASAWA 88 finds only $10^2 < \tau < 10^4$ allowed for 30–70 MeV ν's from primordal nucleosynthesis.
[21] KAWASAKI 86 concludes that light elements in primordal nucleosynthesis would be destroyed by radiative decay of neutrinos with 10 MeV<$m(\nu)$<1 GeV unless $\tau \lesssim 10^4$ s.
[22] LINDLEY 85 considers destruction of cosmologically-produced light elements, and finds $\tau < 2 \times 10^3$ s for 10 MeV <$m(\nu)$<100 MeV. See also LINDLEY 79.
[23] BINETRUY 84 finds $\tau < 10^8$ s for neutrinos in a radiation-dominated universe.
[24] SARKAR 84 finds τ < 20 s at $m(\nu)$=10 MeV, with higher limits for other $m(\nu)$, and claims that all masses between 1 MeV and 50 MeV are ruled out.
[25] HENRY 81 uses UV flux from clusters of galaxies to find $\tau > 1.1 \times 10^{25}$ s for radiative decay.
[26] KIMBLE 81 uses extreme UV flux limits to find $\tau > 10^{22}$–10^{23} s.
[27] REPHAELI 81 consider ν decay γ effect on neutral H in early universe; based on M31 HI concludes $\tau > 10^{24}$ s.
[28] DERUJULA 80 finds $\tau > 3 \times 10^{23}$ s based on CDM neutrino decay contribution to UV background.
[29] STECKER 80 limit based on UV background; result given is $\tau > 4 \times 10^{22}$ s at $m(\nu)$ = 20 eV.
[30] DICUS 78 considers effect of ν decay photons on light-element production, and finds lifetime must be less than "hours." See also DICUS 77.
[31] FALK 78 finds lifetime constraints based on supernova energetics.
[32] COWSIK 77 considers varity of scenarios. For neutrinos produced in the big bang, present limits on optical photon flux require $\tau > 10^{23}$ s for $m(\nu)$~ 1 eV. See also COWSIK 79 and GOLDMAN 79.

ν_3 MAGNETIC MOMENT

Must vanish for Majorana neutrino or purely chiral massless Dirac neutrino. The value of the magnetic moment for the standard SU(2) × U(1) electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = (3.20 \times 10^{-19}) m_\nu \mu_B$ where m_ν is in eV and $\mu_B = e\hbar/2m_e$ is the Bohr magneton. Given the upper bound $m(\nu_3)$ < 35 MeV, it follows that for the extended standard electroweak theory, $\mu(\nu_3) < 1.1 \times 10^{-11}$ μ_B.

VALUE (μ_B)	CL%	DOCUMENT ID		TECN	COMMENT
$<4. \times 10^{-6}$	90	[33] GROTCH	88	RVUE	$e^+e^- \to \nu\bar{\nu}\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5.6 \times 10^{-6}$	90	DESHPANDE	91	RVUE	$e^+e^- \to \nu\bar{\nu}\gamma$
$<2 \times 10^{-12}$	95	[34] RAFFELT	90	ASTR	Red giant luminosity
$<1 \times 10^{-11}$		[35] RAFFELT	89B	ASTR	Cooling helium stars
$<1.1 \times 10^{-11}$		[35,36] FUKUGITA	87	ASTR	Cooling helium stars
$<6 \times 10^{-14}$		[37] NUSSINOV	87	ASTR	Cosmic EM backgrounds
$<8.5 \times 10^{-11}$		[36] BEG	78	ASTR	Stellar plasmons

[33] GROTCH 88 combined data from MAC, ASP, CELLO, and Mark J.
[34] RAFFELT 90 limit valid if $m(\nu_3)$ < 5 keV. It applies for a diagonal magnetic moment of a Dirac neutrino, or for a transition magnetic moment of a Majorana neutrino. In the latter case, the same analysis gives $< 1.4 \times 10^{-12}$. Limit at 95%CL obtained from δM_c.
[35] Significant dependence on details of stellar properties.
[36] If $m(\nu_3)$ < 10 keV.
[37] For $m(\nu_3)$ = 8–200 eV. NUSSINOV 87 examines transition magnetic moments for $\nu_\tau \to \nu_e$ and obtain $< 3 \times 10^{-15}$ for $m(\nu_3)$ < 16 eV and $< 6 \times 10^{-14}$ for $m(\nu_3)$ > 4 eV.

LIMIT ON ν_τ PRODUCTION IN BEAM DUMP EXPERIMENT

VALUE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[38] DORENBOS...	88	CHRM
	[39] BOFILL	87	CNTR
	[40] TALEBZADEH	87	BEBC
	[41] USHIDA	86C	EMUL
	[42] ASRATYAN	81	HLBC
	[43] FRITZE	80	BEBC

[38] DORENBOSCH 88 is CERN SPS beam dump experiment with the CHARM detector. $\nu_\tau + \bar{\nu}_\tau$ flux is <21% of the total prompt flux at 90% CL.
[39] BOFILL 87 is a Fermilab narrow-band ν beam with a fine-grained neutrino detector.
[40] TALEBZADEH 87 is a CERN SPS beam dump experiment with the BEBC detector. Mixing probability $P(\nu_e \to \nu_\tau)$ <18% at 90% CL.
[41] USHIDA 86C is a Fermilab wide-band ν beam with a hybrid emulsion spectrometer. Mixing probabilities $P(\nu_e \to \nu_\tau)$ <7.3% and $P(\nu_\mu \to \nu_\tau)$ <0.2% at 90% CL.
[42] ASRATYAN 81 is a Fermilab wide-band $\bar{\nu}$ beam with a 15 foot bubble chamber. Mixing probability $P(\bar{\nu}_\mu \to \bar{\nu}_\tau)$ <2.2% at 90% CL.
[43] FRITZE 80 is CERN SPS experiment with BEBC. Neutral-current/charged-current ratio corresponds to R = (prompt-ν_τ-induced events)/(all prompt-ν events) <0.1. Mixing probability $P(\nu_e \to \nu_\tau)$ <0.35 at CL = 90%.

ν_τ REFERENCES

DESHPANDE	91	PR D43 943	+Sarma	(OREG, TATA)
FULLER	91	PR D43 3136	+Malaney	(UCSD)
GRANEK	91	IJMP A6 2387	+McKellar	(MELB)
KOLB	91	PRL 67 533	+Turner, Chakravorty, Schramm	(FNAL, CHIC)
LAM	91	PR D44 3345	+Ng	(AST)
NATALE	91	PL B258 227		(CAMP)
GANDHI	90	PL B246 149	+Burrows	(ARIZ)
GRIFOLS	90B	PL B242 77	+Masso	(BARC, CERN)
RAFFELT	90	PRL 64 2856		(MPIM)
WALKER	90	PR D41 689		(HARV)
CHUPP	89	PRL 62 505	+Vestrand, Reppin	(UNH, MPIM)
GAEMERS	89	PR D40 309	+Gandhi, Lattimer	(AIKH, STON)
KOLB	89	PRL 62 509	+Turner	(CHIC, FNAL)
RAFFELT	89B	APJ 336 61	+Dearborn, Silk	(UCB, LLL)
ALBRECHT	88	PL B207 349	+Binder, Boeckmann+	(ARGUS Collab.)
ALBRECHT	88B	PL B202 149	+Binder, Boeckmann+	(ARGUS Collab.)
DORENBOS...	88	ZPHY C40 497	Dorenbosch, Allaby, Amaldi, Barbiellini+	(CHARM Collab.)
GROTCH	88	ZPHY C39 553	+Robinett	(PSU)
TERASAWA	88	NP B302 697	+Kawasaki, Sato	(TOKY)
ABACHI	87	PR D35 2880	+Baringer, Bylsma, DeBonte+	(HRS Collab.)
BOFILL	87	PR D36 3309	+Busza, Eldridge+	(MIT, FNAL, MSU)
CSORNA	87B	PR D35 2747	+Mestayer, Panvini, Word+	(CLEO Collab.)
FUKUGITA	87	PR D36 3817	+Yazaki	(KYOT, TOKY)
NUSSINOV	87	PR D36 2278	+Rephaeli	(TELA)
TALEBZADEH	87	NP B291 503	+Guy, Venus+	(BEBC WA66 Collab.)
ABACHI	86	PRL 56 1039	+Akerlof, Baringer, Beltrami+	(HRS Collab.)
KAWASAKI	86	PL B178 71	+Terasawa, Sato	(TOKY)
USHIDA	86C	PRL 57 2897	+Kondo, Tasaka, Park, Song+	(FNAL-E531 Collab.)
ALBRECHT	85I	PL 163B 404	+Binder, Drescher, Schubert+	(ARGUS Collab.)
BURCHAT	85	PRL 54 2489	+Schmidke, Yelton, Abrams+	(Mark II Collab.)
LINDLEY	85	APJ 294 1		(FNAL)
MATTEUZZI	85	PR D32 800	+Barklow+	(Mark II Collab.)
MILLS	85	PRL 54 624	+Pal, Atwood, Baillon+	(DELCO Collab.)
BINETRUY	84	PL 134B 174	+Girardi, Salati	(LAPP)
SARKAR	84	PL 148B 347	+Cooper	(OXF, CERN)
BLOCKER	82D	PL 109B 119	+Dorfan, Abrams, Alam+	(Mark II Collab.)
ASRATYAN	81	PL 105B 301	+Efremenko, Fedotov+	(ITEP, FNAL, SERP, MICH)
FELDMAN	81	SLAC-PUB-2839		(SLAC, STAN)
Santa Cruz APS.				
HENRY	81	PRL 47 618	+Feldman	(JHU)
KIMBLE	81	PRL 46 80	+Bowyer, Jakobsen	(UCB)
REPHAELI	81	PL 106B 73	+Szalay	(UCSB, CHIC)
DERUJULA	80	PRL 45 942	+Glashow	(MIT, HARV)
FRITZE	80	PL 96B 427		(AACH, BONN, CERN, LOIC, OXF, SACL)
FUJIKAWA	80	PRL 45 963	+Shrock	(STON)
STECKER	80	PRL 45 1460		(NASA)
BACINO	79B	PRL 42 749	+Ferguson, Nodulman, Slater+	(DELCO Collab.)
COWSIK	79	PR D19 2219		(TATA)
GOLDMAN	79	PR D19 2215	+Stephenson	(LASL)
KIRKBY	79	SLAC-PUB-2419		(SLAC) J
Batavia Lepton Photon Conference.				
LINDLEY	79	MNRAS 188 15P		(SUSS)
BEG	78	PR D17 1395	+Marciano, Ruderman	(ROCK, COLU)
DICUS	78	PR D17 1529	+Kolb, Teplitz, Wagoner	(TEXA, VPI, STAN)
FALK	78	PL 79B 511	+Schramm	(CHIC)
COWSIK	77	PRL 39 784		(MPIM, TATA)
DICUS	77	PRL 39 168	+Kolb, Teplitz	(TEXA, VPI)

e

$J = \frac{1}{2}$

e MASS

The mass is known much more precisely in u (atomic mass units) than in MeV (see the footnote). The conversion from u to MeV, 1 u = 931.49432 ± 0.00028 MeV, involves the relatively poorly known electronic charge.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0.51099906±0.00000015	[1] COHEN	87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.5110034 ±0.0000014	COHEN	73	RVUE	1973 CODATA value

[1] The mass is known much more precisely in u: $m = (5.48579903 \pm 0.00000013) \times 10^{-4}$ u.

[m(e^+) − m(e^-)] / AVERAGE m

A test of *CPT*.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4 \times 10^{-8}$	90	CHU	84	CNTR	Positronium spectroscopy

e MEAN LIFE / BRANCHING FRACTION

A test of charge conservation. See the Note that follow this section. We use the best "disappearance" limit for the Summary Tables. The best limit for the specific channel $e^- \to \nu\gamma$ is much better.

VALUE (yr)	CL%	DOCUMENT ID		TECN	COMMENT
$>1.9 \times 10^{23}$	68	REUSSER	91	CNTR	Ge K-shell disappearance
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>1.5 \times 10^{25}$	68	AVIGNONE	86	CNTR	$e^- \to \nu\gamma$
$>1 \times 10^{39}$		[2] ORITO	85	ASTR	Astrophysical argument
$>3 \times 10^{23}$	68	BELLOTTI	83B	CNTR	$e^- \to \nu\gamma$
$>2 \times 10^{22}$	68	BELLOTTI	83B	CNTR	Ge K-shell disappearance
$>3.5 \times 10^{23}$	68	KOVALCHUK	79	CNTR	$e^- \to \nu\gamma$
$>2 \times 10^{22}$	68	[3] KOVALCHUK	79	CNTR	Disappearance
$>5.3 \times 10^{21}$		[3] STEINBERG	75	CNTR	Disappearance
$>2 \times 10^{21}$		[3,4] MOE	65	CNTR	Disappearance
$>4 \times 10^{22}$		MOE	65	CNTR	$e^- \to \nu\gamma$

[2] Assuming that electromagnetic forces extend out to large enough distances and that the age of our galaxy is 10^{10} years.

[3] These limits are for all modes in which decay particles escape from the detector without depositing energy.

[4] The MOE 65 limit is re-estimated by STEINBERG 75 to be 10^{20} years.

NOTE ON TESTING CHARGE CONSERVATION AND THE PAULI EXCLUSION PRINCIPLE

by L.B. Okun (ITEP, Moscow)

This Note is condensed and edited from a review which appeared in Comm. Nucl. Part. Phys. **19**, 99 (1989), copyright © Gordon and Breach Science Publishers Inc. The Russian language original is L.B. Okun, Uspekhi Fiz Nauk **158**, 293 (1989).

Electric charge conservation and the exclusion principle are among the most fundamental principles in modern physics. The two are interconnected because violations of the principles are often searched for in the same experiment. They are also singled out by the inability of theorists to construct a self-consistent phenomenological framework for a quantitative measure of the accuracy with which the principles have been tested.

I. Experiments already done

Exclusive experiments with electrons. More than 30 years ago, Feinberg and Goldhaber[1] carried out an experiment with an NaI detector aimed at testing the stability of the electron. They looked for characteristic x rays expected when a vacancy in the atomic shell of iodine is filled (see Fig. 1) and deduced a lower limit for the electron lifetime of about 10^{18} yr. In 1965 Moe and Reines[2] raised this limit to 10^{20} yr; and by searching for monochromatic γ rays with energy $m_e/2$, they deduced a lower limit for the lifetime of the process $e \to \nu\gamma$ of 4×10^{22} yr.

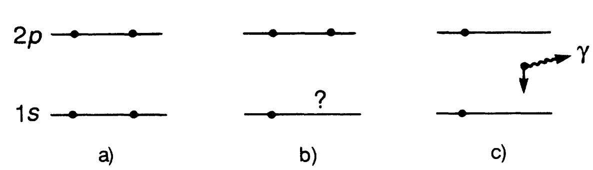

Fig. 1. (a) Filled $1s$ and $2p$ shells of iodine. (b) Electron mysteriously disappears from $1s$ shell, violating charge conservation. (c) Electron from p shell jumps to $1s$ shell, emitting a characteristic x ray.

In 1974 Reines and Sobel[3] used the result of the search by Moe and Reines[2] for characteristic iodine x rays to place a limit on the possible violation of the Pauli principle. This time they considered a transition not to a vacancy, but to a filled atomic shell (Fig. 1, but *without* the disappearance of a $1s$ electron).

A similar search for x rays in 1975 by Steinberg *et al.*[4] with a germanium detector gave $\tau_e > 5 \times 10^{21}$ yr. In 1979 Kovalchuk, Pomansky, and Smolnikov[5] raised the limit to 2×10^{22} yr (again with NaI), and in 1983 Bellotti *et al.*[6] obtained the same result with germanium.

In 1986 Avignone *et al.*[7] repeated the 1965 search by Moe and Reines for $e \to \nu\gamma$ decay, this time with a germanium detector, and concluded that $\tau(e \to \nu\gamma) > 1.5 \times 10^{25}$ yr.

An exclusive experiment with nucleons. The above experiments tested electrons. The same considerations have also been applied to nucleons. In 1979 Logan and Ljubičič[8] tested the Pauli principle by searching for γ rays with energies of the order of 20 MeV. Such γ rays would signal the transition of a nucleon in the ^{12}C nucleus from the $2p$ shell to a filled $1s$ shell. They obtained a lower limit of 2×10^{20} yr for the characteristic time of a $^{12}\text{C} \to {}^{12}\widetilde{\text{C}}\gamma$ transition for the creation of a "non-Paulian" nucleus $^{12}\widetilde{\text{C}}$ with five nucleons in the $1s$ shell.

Inclusive experiments with nucleons. Inclusive experiments differ from exclusive ones by not choosing a specific mechanism through which the phenomenon under investigation is realized. For electric charge, it is as if charge Q_1 enters a "black box" and charge Q_2 leaves it.

The first inclusive experiment was done in 1979 by Norman and Seamster,[9] who established that $\tau(^{87}\text{Rb} \to {}^{87}\text{Sr}) > 1.9 \times 10^{18}$ yr. In 1980 Barabanov *et al.*[10] established another such limit, $\tau(^{71}\text{Ga} \to {}^{71}\text{Ge}) > 2.3 \times 10^{23}$ yr, a byproduct of developing a radiochemical technique for the gallium-germanium detector of low-energy solar neutrinos at the Baksan Neutrino Observatory.

Global limit for charge nonconservation. A global approach to possible charge nonconservation was advanced in 1976 by Pomansky,[11] who concluded that the imbalance of electric current in the atmosphere of the Earth due to the decay of electrons or, more generally, due to charge nonconservation in the atoms of the Earth cannot be larger than 200 A. Taking into account that the Earth contains 2×10^{51} electrons, he obtained $\tau_e > 5 \times 10^{22}$ yr.

A review of experimental tests of the Pauli exclusion principle and of charge nonconservation was given in 1980 by Reines and Sobel.[12]

II. Theoretical papers on charge nonconservation

In 1978, Zeldovich, Voloshin, and Okun[13,14] considered a number of problems that arise when one tries to construct a self-consistent phenomenological description of nonconservation of electric charge. Some of the main conclusions of these papers are summarized below.

Impossibility of spontaneous breaking of charge conservation. Zeldovich *et al.*[13,14] showed that electric charge nonconservation, unlike spontaneous breaking of electroweak symmetry, cannot be realized spontaneously because the photon, unlike the Z^0, is extremely light or (even worse) massless. As is well known, the Higgs mechanism of spontaneous breaking of a U(1) gauge symmetry calls for the existence of a charged scalar field. After the breaking, the imaginary part of this field becomes the third (longitudinal) component of the now-massive vector boson, while the real part becomes a Higgs boson.

The characteristic mass parameter of the charged scalar field determines the mass of the Higgs field and of the gauge boson. In electroweak theory, this mass parameter is very large (on the order of the W and Z masses). But for charge nonconservation, it has to be extremely small, on the order of the photon mass.

As photons are practically massless, the charged scalar boson must also be practically massless. Emission and absorption of such almost-massless charged bosons would drastically change the whole of electrodynamics, so their existence in our world is definitely ruled out.

On the other hand, the nonspontaneous, explicit breaking of charge conservation would lead to catastrophic bremsstrahlung of longitudinal photons.

Catastrophic bremsstrahlung in the case of explicit charge nonconservation. If charge (and current) is conserved, the amplitude for emission of a longitudinal photon is negligibly small, being proportional to em_γ/ω, where e is the electric charge, m_γ is the mass of the photon, and ω is its energy (we use units in which $\hbar = c = 1$).

If charge is not conserved, the situation is opposite: the amplitude for emission of a longitudinal photon is proportional to $e\omega/m_\gamma$ and therefore is extremely large. As a result, the probability for emission of two longitudinal photons is larger than for one, for three is larger than for two, and so on.

For example, if electrons can decay into three neutrinos, with an extremely small coupling constant g (see Fig. 2a), the neutrinos would be accompanied by an immense number of longitudinal photons (Fig. 2b). The energy m_e released in the decay is carried away by the photons, not by the neutrinos, and the energy of each of the photons is extremely small.

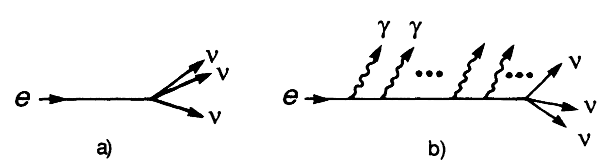

Fig. 2. (a) Hypothetical decay $e \to \nu\nu\nu$, violating charge conservation. (b) Catastrophic bremsstrahlung accompanying $e \to \nu\nu\nu$ decay.

The same applies to the decay $e \to \nu\gamma$, which becomes $e \to \nu + N_\gamma\gamma$, and one can show that

$$N_\gamma \approx 3\Big(\frac{\alpha}{4\pi}\frac{m_e^2}{m_\gamma^2}\Big)^{1/3} \approx 10^{14} \text{ to } 10^{21} \ .$$

Here the smaller number (10^{14}) corresponds to an upper limit on m_γ derived from the measurement of the magnetic field of Jupiter, while the larger number corresponds to a less certain limit $1/m_\gamma \gtrsim 10^{22}$ cm derived from the observed dimensions of galactic magnetic fields.

The probability of the electron decay is proportional to

$$\Gamma_e \sim m_e g^2 e^{N_\gamma} .$$

Thus, all the energy released in this decay is carried away by infra-infra...infrared photons, that is, by a practically static field. There is no γ ray with energy $m_e/2$ and no characteristic x rays when an electron disappears in an atom (the size of an atom is negligible compared with the characteristic wavelength of the longitudinal photons, so the atom may be considered to be point-like), and the almost static field of longitudinal photons is practically unobservable.

Thus one must conclude that all the exclusive experiments discussed above would have been unable to discover electron decay or charge-nonconserving nuclear transformations even if such phenomena do occur in nature. Only the limits obtained from the inclusive, nonspectroscopic searches and the global limit remain valid.

"Self-healing" by radiative corrections. The discussion may have created an impression that explicit breaking of charge conservation is a reasonable basis for a self-consistent theory of the phenomenon. But this is deceiving. The large probability of emitting real longitudinal photons is accompanied by a large probability of emission and absorption of virtual longitudinal photons by the same particle. Thus, radiative corrections are expected to be so huge that the term "corrections" is really inappropriate. It turns out[13,14] that these "corrections" suppress the charge-nonconserving amplitude by an exponentially small factor and in this way "heal" the theory.

Recent theoretical papers. The last few years have witnessed a revival of interest in the problem of charge nonconservation. The possibility of constructing a renormalizable theory with an explicitly nonconserved electromagnetic current was discussed in 1986 by Nakazato *et al.*[15] In 1987, Huang[16] attempted to spontaneously break charge conservation in the framework of broken SU(5) symmetry, Nussinov[17] considered the influence of an external potential on electron decay, and Mohapatra[18] proposed a model in which charge nonconservation is caused by electron-positron vacuum oscillations and conjectured that such a theory is only logarithmically divergent. In 1988, Suzuki[19] discussed minicharged particles. All except the last of these papers were reviewed and critically analyzed by Tsypin,[20] whose main conclusion is that the verdict of Refs. 13 and 14 is not refuted.

III. Theoretical papers on Pauli principle violation

A nonconformist approach to the Pauli principle can be traced to remarks by P.A.M. Dirac, W. Pauli, and E. Fermi. By carefully reading the books by Dirac[21] and Pauli,[22] one can conclude that in the framework of quantum mechanics with a Hamiltonian that is permutationally invariant, transitions to a filled shell are forbidden independent of the validity of the Pauli principle, because such transitions would change the permutational symmetry of a wave function of a given set of particles.

In 1934, E. Fermi discussed in one of his popular science articles the possibility that electrons are a "little bit" nonidentical.[23] He concluded that a tiny nonidentity would drastically change the properties of atoms during the billions of years of their existence.

Attempts to violate (on paper) the Pauli principle have failed as a consequence of rather general theorems based on fundamental properties of field theory. Relevant (and complementary) lists of references may be found in Refs. 24 and 25. By some accident, these lists do not contain a very important paper by Luders and Zumino.[26] There is an excellent explanation of how the Pauli principle makes QED self-consistent in the last published lecture of Feynman.[27]

IV. Proposals for future experiments

A number of new experimental searches of violation of the Pauli principle have been suggested during the last few years.[24,28–33] Among the objects to be investigated are stable non-Paulian molecules, atoms, atomic nuclei, and hadrons. Let us consider some of them.

The ground state $^3S_1$ of orthohelium can be searched for either by electron spin resonance[24,30,31] or by Zeeman splitting of an atomic beam.[32]

An atom of sodium with three electrons in the K shell will lack an active valence electron and will chemically resemble neon, but the optical spectrum of this false neon will differ from that of real neon. After separation and enrichment, the false neon could be searched for with tunable lasers by well-developed techniques, such as those of resonance excitation, photo-ionization,[24,31,33] or neutron activation.[33]

There is also a proposal to search for x rays or Auger electrons from a piece of matter when exposing it to "new" electrons via a strong electric current.[29,30]

If the exclusion principle is violated at the quark level,[27] unusual baryons belonging to an S-wave 70-plet of SU(6) should exist (among them an octet with $J^P = 3/2^+$ and a decuplet with $J^P = 1/2^+$), and some of them should be stable.

There is a Russian saying, "New is well-forgotten old." Some of the experiments suggested recently are similar to experiments done many years ago, when physicists (at least some of them) were not absolutely sure that β particles were identical to ordinary electrons, or that there were no other particles of the same mass and charge as ordinary electrons. For instance, in 1948 Goldhaber and Scharff-Goldhaber[34] stopped β rays from ^{14}C in lead and looked for K-shell x rays. They set a 3% upper limit on the existence of such x rays and therefore concluded that β particles are identical with electrons. (Earlier studies on the identity of β particles and electrons are reviewed by Crane.[35])

In 1968 Fishbach, Kirsten, and Shaeffer[36] searched for a "false ^{9}He" they called ^{9}Be′—a Be atom with two ordinary electrons and two false electrons e', all of them in the K shell. They established that the abundance in the atmosphere of such false ^{9}He is less than 10^{-6} of that of normal ^{4}He.

At present, we do not doubt that there is only one particle with the mass and charge of the electron. A second electron would be abundantly produced by colliders; it would destroy the excellent agreement of QED with a great number of experiments. So these old searches may be considered to be searches for the violation of the exclusion principle.

Turning now from the Pauli principle to charge conservation, we stress the great potential of gallium-germanium detectors at Baksan (60 tons of Ga) and Gran Sasso (30 tons of Ga). These detectors will be able to raise the lower limit for the Ga-Ge spontaneous transformation time from 10^{23} yr to 10^{26}–10^{27} yr.

In spite of the fact that at present we have no theoretically self-consistent framework for a description of violation of charge conservation or the exclusion principle, experimentalists should not stop testing these most fundamental concepts of modern physics. In fundamental physics, if something can be tested, it should be tested.

V. Postscript (1989)

After completing this note, I learned about three other papers that discuss or describe experimental tests for the violation of the Pauli Principle.

V. Novikov and A. Pomansky[37] suggest a search for non-Paulian isotopes with atomic charge $Z+1$ whose chemical analogs with atomic charge Z have a very low abundance; for instance, to look for non-Paulian carbon, which chemically appears like boron. As the abundance of normal boron is six orders of magnitude smaller than that of carbon, this would give an enhancement factor of the order of 10^6 in the search for "false boron." Especially promising are mass-spectroscopic searches for false "^{12}B" (the non-Paulian ^{12}C), since ordinary ^{12}B does not occur in nature. Other promising pairs of elements are fluorine-neon and chlorine-argon. The search for false "F" and "Cl" using accelerator mass spectrometry is discussed by V. Novikov, A. Pomansky, and E. Nolte.[38] The technique of accelerator mass spectrometry is rather advanced; see, for instance, Refs. 39 and 40, which give results of searches for some rare isotopes at the level of sensitivity $10^{-14} - 10^{-16}$. With this technique, lower limits for the lifetimes of Pauli-forbidden transitions in the ballpark of 10^{31} years could be achieved.

An attempt to introduce a large number of "fresh" electrons into a copper sample and to observe x rays was undertaken recently by E. Ramberg and G. Snow.[41] In principle this experiment is similar to that of M. Goldhaber and G. Scharff-Goldhaber.[34] However, this time the "fresh" electrons were supplied not by a radioactive β source but by a strong electric current.

VI. Post-postscript (1991)

The absence of a consistent phenomenological interpretation seems to stimulate rather than prevent further searches for exclusive manifestations of electric charge nonconservation and Pauli principle violation.

There are some new limits from the NaI detector ELEGANTS V of the Osaka group[42]: for K-transition x rays, $T_{1/2} > 1.5 \times 10^{23}$ yr; for γ rays from $e \to \nu\gamma, T_{1/2} > 2.8 \times 10^{24}$ yr; for charge-nonconserving radiative K-capture, $^{127}\mathrm{I} + e \to {}^{127}\mathrm{I} + \nu\gamma, T_{1/2} > 1.0 \times 10^{23}$ yr.

Kekez *et al.*[43] derived from data from the Liquid Scintillator Detector under Mont Blanc for $\beta^{\pm}$ decay of ^{12}C into non-Paulian nuclei $^{12}\widetilde{\mathrm{N}}$ and $^{12}\widetilde{\mathrm{B}}$ the limit $\beta^2/2 < 6.5 \times 10^{-34}$, where the parameter β is that introduced by Ignatiev and Kuzmin.[28]

An accelerator mass-spectroscopic search by Novikov *et al.*[44] for non-Paulian atoms of neon and argon with three electrons in the 1s shell gives upper limits on their concentrations:

$$^{20}\widetilde{\mathrm{Ne}}/\mathrm{Ne} < 2 \times 10^{-21},$$

$$^{36}\widetilde{\mathrm{Ar}}/^{36}\mathrm{Ar} < 4 \times 10^{-17}\ .$$

For a new theoretical attempt involving particles with small violations of Fermi or Bose statistics, see Greenberg.[45]

J. Gillaspy of the National Institute of Standards and Technology has created a database[46] on various theoretical and experimental topics concerning violations of the Pauli exclusion principle.

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1. G. Feinberg and M. Goldhaber, *Proc. Natl. Acad. Sci.* (US)B45, 1301 (1959).
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e MAGNETIC MOMENT ANOMALY

$\mu_e/\mu_B - 1 = (g-2)/2$

For the most accurate theoretical calculation, see KINOSHITA 81. The COHEN 87 value assumes the $g/2$ values for e^+ and e^- are equal, as required by *CPT*.

Some older results have been omitted.

VALUE (units 10^{-6})	DOCUMENT ID		TECN	CHG	COMMENT
1159.652193 ±0.000010	COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1159.6521884±0.0000043	VANDYCK	87	MRS	−	Single electron
1159.6521879±0.0000043	VANDYCK	87	MRS	+	Single positron
1159.652200 ±0.000040	VANDYCK	86	MRS	−	Single electron
1159.652222 ±0.000050	SCHWINBERG	81	MRS	+	Single positron

$g(e^+)/g(e^-) - 1$, e^+e^- COMPARISON

A test of *CPT*.

VALUE (units 10^{-12})	CL%	DOCUMENT ID		TECN	COMMENT
− 0.5± 2.1		[5] VANDYCK	87	MRS	Penning trap
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 12	95	[6] VASSERMAN	87	CNTR	Assumes $m(e^+) = m(e^-)$
22 ±64		SCHWINBERG	81	MRS	Penning trap

[5] VANDYCK 87 measured $(g_-/g_+)-1$ and we converted it.
[6] VASSERMAN 87 measured $(g_+ - g_-)/(g-2)$. We multiplied by $(g-2)/g = 1.2 \times 10^{-3}$.

e ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance.

VALUE (10^{-26} e-cm)	CL%	DOCUMENT ID		TECN	COMMENT
− 0.27± 0.83		[7] ABDULLAH	90	MRS	^{205}Tl beams
• • • We do not use the following data for averages, fits, limits, etc. • • •					
− 14 ± 24		CHO	89	NMR	Tl F molecules
− 1.5 ± 5.5 ±1.5		MURTHY	89		Cesium, no *B* field
− 50 ±110		LAMOREAUX	87	NMR	^{199}Hg
190 ±340	90	SANDARS	75	MRS	Thallium
70 ±220	90	PLAYER	70	MRS	Xenon
< 300	90	WEISSKOPF	68	MRS	Cesium

[7] ABDULLAH 90 uses the relativistic enhancement of a valence electron's electric dipole moment in a high-Z atom.

e REFERENCES

REUSSER	91	PL B255 143	+Treichel, Boehm+	(NEUC, CIT, PSI)
ABDULLAH	90	PRL 65 2347	+Carlberg, Commins, Gould, Ross	(LBL, UCB)
CHO	89	PRL 63 2559	+Sangster, Hinds	(YALE)
MURTHY	89	PRL 63 965	+Krause, Li, Hunter	(AMHT)
COHEN	87	RMP 59 1121	+Taylor	(RISC, NBS)
LAMOREAUX	87	PRL 59 2275	+Jacobs, Heckel, Raab, Fortson	(WASH)
VANDYCK	87	PRL 59 26	Van Dyck, Schwinberg, Dehmelt	(WASH)
VASSERMAN	87	PL B198 302	+Vorobyov, Gluskin+	(NOVO)
Also	87B	PL B187 172	Vasserman, Vorobyov, Gluskin+	(NOVO)
AVIGNONE	86	PR D34 97	+Brodzinski, Hensley, Miley, Reeves+	(PNL, SCUC)
VANDYCK	86	PR D34 722	Van Dyck, Schwinberg, Dehmelt	(WASH)
ORITO	85	PRL 54 2457	+Yoshimura	(TOKY, KEK)
CHU	84	PRL 52 1689	+Mills, Hall	(BELL, NBS, COLO)
BELLOTTI	83B	PL 124B 435	+Corti, Fiorini, Liguori, Pullia+	(MILA)
KINOSHITA	81	PRL 47 1573	+Lindquist	(CORN)
SCHWINBERG	81	PRL 47 1679	+Van Dyck, Dehmelt	(WASH)
KOVALCHUK	79	JETPL 29 145	+Pomansky, Smolnikov	(INRM)
		Translated from ZETFP 29 163.		
SANDARS	75	PR A11 473	+Sternheimer	(OXF, BNL)
STEINBERG	75	PR D12 2582	+Kwiatkowski, Maenhaut+	(UMD)
COHEN	73	JPCRD 2 663	+Taylor	(RISC, NBS)
PLAYER	70	JP B3 1620	+Sandars	(OXF)
WEISSKOPF	68	PRL 21 1645	+Carrico, Gould, Lipworth+	(BRAN)
MOE	65	PR 140B 992	+Reines	(CASE)

μ

$J = \frac{1}{2}$

μ MASS

The mass is known more precisely in u (atomic mass units) than in MeV (see the footnote). The conversion from u to MeV, 1 u = 931.49432 ± 0.00028 MeV, involves the relatively poorly known electronic charge.

Where $m(\mu)/m(e)$ was measured, we used the 1986 CODATA value for $m(e) = 0.51099906 \pm 0.00000015$ MeV.

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
105.658389±0.000034	[1] COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
105.65841 ±0.00033	[2] BELTRAMI	86	SPEC	−	Muonic atoms
105.658432±0.000064	[3] KLEMPT	82	CNTR	+	Incl. in MARIAM 82
105.658386±0.000044	[4] MARIAM	82	CNTR	+	
105.65856 ±0.00015	[5] CASPERSON	77	CNTR	+	
105.65836 ±0.00026	[6] CROWE	72	CNTR		
105.65865 ±0.00044	[7] CRANE	71	CNTR		

[1] The mass is known more precisely in u: $m = 0.113428913 \pm 0.000000017$ u. COHEN 87 makes use of the other entries below.
[2] BELTRAMI 86 gives $m(\mu)/m(e) = 206.76830(64)$.
[3] KLEMPT 82 gives $m(\mu)/m(e) = 206.76835(11)$.
[4] MARIAM 82 gives $m(\mu)/m(e) = 206.768259(62)$.
[5] CASPERSON 77 gives $m(\mu)/m(e) = 206.76859(29)$.
[6] CROWE 72 gives $m(\mu)/m(e) = 206.7682(5)$.
[7] CRANE 71 gives $m(\mu)/m(e) = 206.76878(85)$.

μ MEAN LIFE

Measurements with an error $> 0.001 \times 10^{-6}$ s have been omitted.

VALUE (10^{-6} s)	DOCUMENT ID		TECN	CHG
2.19703 ±0.00004 OUR AVERAGE				
2.197078±0.000073	BARDIN	84	CNTR	+
2.197025±0.000155	BARDIN	84	CNTR	−
2.19695 ±0.00006	GIOVANETTI	84	CNTR	+
2.19711 ±0.00008	BALANDIN	74	CNTR	+
2.1973 ±0.0003	DUCLOS	73	CNTR	+

μ^+/μ^- MEAN LIFE RATIO

A test of *CPT*.

VALUE	DOCUMENT ID		TECN	COMMENT
1.000024±0.000078	BARDIN	84	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.0008 ±0.0010	BAILEY	79	CNTR	Storage ring
1.000 ±0.001	MEYER	63	CNTR	Mean life μ^+/μ^-

μ MAGNETIC MOMENT ANOMALY

$\mu_\mu/(e\hbar/2m_\mu)-1 = (g_\mu-2)/2$

For reviews of theory and experiments, see HUGHES 85, KINOSHITA 84, COMBLEY 81, FARLEY 79, and CALMET 77.

VALUE (units 10^{-6})	DOCUMENT ID		TECN	CHG	COMMENT
1165.9230±0.0084	COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1165.910 ±0.011	[8] BAILEY	79	CNTR	+	Storage ring
1165.937 ±0.012	[8] BAILEY	79	CNTR	−	Storage ring
1165.923 ±0.0085	[8] BAILEY	79	CNTR	±	Storage ring
1165.922 ±0.009	[8] BAILEY	77	CNTR	±	Storage ring
1166.16 ±0.31	BAILEY	68	CNTR	±	Storage rings
1162.0 ±5.0	CHARPAK	62	CNTR	+	

[8] BAILEY 79 is final result. Includes BAILEY 77 data. We use μ/p magnetic moment ratio = 3.1833452 and recalculate the BAILEY 79 values. Third BAILEY 79 result is first two combined.

μ^+-TO-μ^- g-FACTOR RATIO MINUS ONE, $(g_+/g_-)-1$

A test of *CPT*.

VALUE (units 10^{-8})	DOCUMENT ID	
−2.6±1.6	BAILEY	79

μ ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance.

VALUE (10^{-19} e-cm)	DOCUMENT ID		TECN	CHG	COMMENT
3.7±3.4	[9] BAILEY	78	CNTR	±	Storage ring
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.6±4.5	BAILEY	78	CNTR	+	Storage rings
0.8±4.3	BAILEY	78	CNTR	−	Storage rings

[9] This is the combination of the two BAILEY 78 results given below.

μ/p MAGNETIC MOMENT RATIO

This ratio is used to obtain a precise value of the muon mass. Measurements with an error > 0.00001 have been omitted.

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
3.18334547±0.00000047	[10] COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.1833441 ±0.0000017	KLEMPT	82	CNTR	+	Precession strob
3.1833461 ±0.0000011	MARIAM	82	CNTR	+	HFS splitting
3.1833448 ±0.0000029	CAMANI	78	CNTR	+	See KLEMPT 82
3.1833403 ±0.0000044	CASPERSON	77	CNTR	+	HFS splitting
3.1833402 ±0.0000072	COHEN	73	RVUE		1973 CODATA value
3.1833467 ±0.0000082	CROWE	72	CNTR	+	Precession phase

[10] COHEN 87 (1986 CODATA) value was fitted using their own selection of the following data. Because their value is from a multiparameter fit, correlations with other quantities may be important and one cannot arrive at this result by any average of these data alone.

μ^- DECAY MODES

μ^+ modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)		Confidence level
Γ_1	$e^-\overline{\nu}_e\nu_\mu$		~ 100 %		
Γ_2	$e^-\overline{\nu}_e\nu_\mu\gamma$	[a]	(1.4 ±0.4) %		
Γ_3	$e^-\overline{\nu}_e\nu_\mu e^+e^-$	[b]	(3.4 ±0.4) $\times 10^{-5}$		
	Lepton Family number (*LF*) violating modes				
Γ_4	$e^-\nu_e\overline{\nu}_\mu$	*LF*	< 1.8	%	90%
Γ_5	$e^-\gamma$	*LF*	< 4.9	$\times 10^{-11}$	90%
Γ_6	$e^-e^+e^-$	*LF*	< 1.0	$\times 10^{-12}$	90%
Γ_7	$e^-2\gamma$	*LF*	< 7.2	$\times 10^{-11}$	90%

[a] This only includes events with the γ energy > 10 MeV. Since the $e^-\overline{\nu}_e\nu_\mu$ and $e^-\overline{\nu}_e\nu_\mu\gamma$ modes cannot be clearly separated, we regard the latter mode as a subset of the former.

[b] See the Listings below for the energy limits used in this measurement.

μ^- BRANCHING RATIOS

$\Gamma(e^-\overline{\nu}_e\nu_\mu\gamma)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.014 ±0.004		CRITTENDEN	61	CNTR	γ KE > 10 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
	862	BOGART	67	CNTR	γ KE > 14.5 MeV
0.0033±0.0013		CRITTENDEN	61	CNTR	γ KE > 20 MeV
	27	ASHKIN	59	CNTR	

$\Gamma(e^-\overline{\nu}_e\nu_\mu e^+e^-)/\Gamma_{total}$ — Γ_3/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
3.4±0.2±0.3	7443	[11] BERTL	85	SPEC	+	SINDRUM
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2.2±1.5	7	[12] CRITTENDEN	61	HLBC	+	$E(e^+e^-)$>10 MeV
2	1	[13] GUREVICH	60	EMUL	+	
1.5±1.0	3	[14] LEE	59	HBC	+	

[11] BERTL 85 has transverse momentum cut p_T > 17 MeV/c. Systematic error was increased by us.

[12] CRITTENDEN 61 count only those decays where total energy of either (e^+, e^-) combination is >10 MeV.

[13] GUREVICH 60 interpret their event as either virtual or real photon conversion. e^+ and e^- energies not measured.

[14] In the three LEE 59 events, the sum of energies E(e^+) + E(e^-) + E(e^+) was 51 MeV, 55 MeV, and 33 MeV.

$\Gamma(e^-\nu_e\overline{\nu}_\mu)/\Gamma_{total}$ — Γ_4/Γ

Forbidden by the additive conservation law for lepton family number. A multiplicative law predicts this branching ratio to be 1/2. For a review see NEMETHY 81.

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 0.018	90	KRAKAUER	91B	CALO	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 0.05	90	[15] BERGSMA	83	CALO		$\overline{\nu}_\mu e \to \mu^-\overline{\nu}_e$
< 0.09	90	JONKER	80	CALO		See BERGSMA 83
−0.001±0.061		WILLIS	80	CNTR	+	
0.13 ±0.15		BLIETSCHAU	78	HLBC	±	Avg. of 4 values
< 0.25	90	EICHTEN	73	HLBC	+	

[15] BERGSMA 83 gives a limit on the inverse muon decay cross-section ratio $\sigma(\overline{\nu}_\mu e^- \to \mu^-\overline{\nu}_e)/\sigma(\nu_\mu e^- \to \mu^-\nu_e)$, which is essentially equivalent to $\Gamma(e^-\nu_e\overline{\nu}_\mu)/\Gamma_{total}$ for small values like that quoted.

$\Gamma(e^-\gamma)/\Gamma_{total}$ — Γ_5/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-11})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 4.9	90	BOLTON	88	CBOX	+	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<100	90	AZUELOS	83	CNTR	+	TRIUMF
< 17	90	KINNISON	82	SPEC	+	LAMPF
<100	90	SCHAAF	80	ELEC	+	SIN

$\Gamma(e^-e^+e^-)/\Gamma_{total}$ — Γ_6/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-12})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 1.0	90	[16] BELLGARDT	88	SPEC	+	SINDRUM
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 36	90	BARANOV	91	SPEC	+	ARES
< 35	90	BOLTON	88	CBOX	+	LAMPF
< 2.4	90	[16] BERTL	85	SPEC	+	SINDRUM
<160	90	[16] BERTL	84	SPEC	+	SINDRUM
<130	90	[16] BOLTON	84	CNTR		LAMPF

[16] These experiments assume a constant matrix element.

$\Gamma(e^-2\gamma)/\Gamma_{total}$ — Γ_7/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-11})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 7.2	90	BOLTON	88	CBOX	+	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 840	90	[17] AZUELOS	83	CNTR	+	TRIUMF
<5000	90	[18] BOWMAN	78	CNTR		DEPOMMIER 77 data

[17] AZUELOS 83 uses the phase space distribution of BOWMAN 78.
[18] BOWMAN 78 assumes an interaction Lagrangian local on the scale of the inverse μ mass.

LIMIT ON $\mu^- \rightarrow e^-$ CONVERSION

Forbidden by lepton family number conservation.

$\sigma(\mu^- {}^{32}S \rightarrow e^- {}^{32}S)$ / $\sigma(\mu^- {}^{32}S \rightarrow \nu_\mu {}^{32}P^*)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<7 × 10^{-11}	90	BADERT...	80	STRC	SIN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4 × 10^{-10}	90	BADERT...	77	STRC	SIN

$\sigma(\mu^-$ Cu $\rightarrow e^-$ Cu) / $\sigma(\mu^-$ Cu $\rightarrow$ capture)

VALUE	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.6 × 10^{-8}	90	BRYMAN	72	SPEC

$\sigma(\mu^-$ Ti $\rightarrow e^-$ Ti) / $\sigma(\mu^-$ Ti $\rightarrow$ capture)

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.6 × 10^{-12}	90	AHMAD	88	TPC	TRIUMF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.6 × 10^{-11}	90	BRYMAN	85	TPC	TRIUMF

$\sigma(\mu^-$ Pb $\rightarrow e^-$ Pb) / $\sigma(\mu^-$ Pb $\rightarrow$ capture)

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.9 × 10^{-10}	90	AHMAD	88	TPC	TRIUMF

LIMIT ON $\mu^- \rightarrow e^+$ CONVERSION

Forbidden by total lepton number conservation.

$\sigma(\mu^- {}^{32}S \rightarrow e^+ {}^{32}Si^*)$ / $\sigma(\mu^- {}^{32}S \rightarrow \nu_\mu {}^{32}P^*)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<9 × 10^{-10}	90	BADERT...	80	STRC	SIN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.5 × 10^{-9}	90	BADERT...	78	STRC	SIN

$\sigma(\mu^- {}^{127}I \rightarrow e^+ {}^{127}Sb^*)$ / $\sigma(\mu^- {}^{127}I \rightarrow$ anything)

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3 × 10^{-10}	90	[19] ABELA	80	CNTR	Radiochemical tech.

[19] ABELA 80 is upper limit for $\mu^- e^+$ conversion leading to particle-stable states of ^{127}Sb. Limit for total conversion rate is higher by a factor less than 4 (G. Backenstoss, private communication).

$\sigma(\mu^-$ Cu $\rightarrow e^+$ Co) / $\sigma(\mu^-$ Cu $\rightarrow \nu_\mu$ Ni)

VALUE	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<2.6 × 10^{-8}	90	BRYMAN	72	SPEC
<2.2 × 10^{-7}	90	CONFORTO	62	OSPK

$\sigma(\mu^-$ Ti $\rightarrow e^+$ Ca) / $\sigma(\mu^-$ Ti $\rightarrow$ capture)

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.7 × 10^{-10}	90	[20] AHMAD	88	TPC	TRIUMF

[20] Assuming a giant-resonance-excitation model.

LIMIT ON MUONIUM → ANTIMUONIUM CONVERSION

Forbidden by lepton family number conservation.

$R_g = G_C / G_F$

The effective Lagrangian for the $\mu^+ e^- \rightarrow \mu^- e^+$ conversion is assumed to be

$$\mathcal{L} = 2^{-1/2}\, G_C\, [\overline{\psi}_\mu \gamma_\lambda (1-\gamma_5)\psi_e]\,[\overline{\psi}_\mu \gamma_\lambda (1-\gamma_5)\psi_e] + \text{h.c.}$$

The experimental result is then an upper limit on G_C/G_F, where $G_F = 1.166 \times 10^{-5}$ GeV^{-2} is the Fermi coupling constant.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
< 0.16	90	MATTHIAS	91	SPEC	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.29	90	HUBER	90B	CNTR	TRIUMF
< 0.88	90	HUBER	88	CNTR	See HUBER 90B
< 7.5	90	NI	87	CNTR	LAMPF
<20	95	BEER	86	CNTR	TRIUMF
<42	95	MARSHALL	82	CNTR	

NOTE ON MUON DECAY PARAMETERS

(by W. Fetscher and H.-J. Gerber, ETH Zürich)

In the decay $\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$, if m_e is neglected, the energy and angular distribution of the electron in the rest frame of a polarized muon ($\mu^\mp$) is given by the Michel spectrum,

$$d\Gamma \propto \left\{3(1-x) + \frac{2\rho}{3}(4x-3) \mp \xi \cos\theta \left[1 - x + \frac{2\delta}{3}(4x-3)\right]\right\} \times x^2 dx\, d(\cos\theta)\ . \quad (1)$$

Here θ is the angle between the electron momentum and the muon spin, and $x \equiv 2E_e/m_\mu$. The parameters ρ, ξ, and $\xi\delta$ are defined below. For pure $V-A$ coupling, $\rho = \xi\delta = \frac{3}{4}$, $\xi = 1$, and the differential decay rate is

$$d\Gamma = \frac{G^2 m_\mu^5}{192\pi^3}\left\{3 - 2x \pm \cos\theta(1-2x)\right\} x^2 dx\; d(\cos\theta)\ , \quad (2)$$

where the coefficient of the curly bracket is the total decay rate.

When m_e is not neglected and the electron polarization is considered within the framework of the most general local, derivative-free, leptonic four-fermion interaction, there are additional parameters: ρ and η for the energy spectrum, ξ and δ for the angular distribution, and ζ', ζ'', α, β, α', and β' for the polarization of the electron. In the notation of Fetscher *et al.*,[1] the matrix element is

$$\frac{4G_o}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T \\ \epsilon,\mu=R,L \\ (n,m)}} g^\gamma_{\epsilon\mu} < \overline{e}_\epsilon \,|\, \Gamma^\gamma \,|\, (\nu_e)_n > < (\overline{\nu}_\mu)_m \,|\, \Gamma_\gamma \,|\, \mu_\mu >\ , \quad (3)$$

with n and m determined by γ, ϵ, and μ. ($\gamma = S,V,T$; and ϵ, μ, m, $n = R, L$ refer to $e^-, \mu^-, \nu_\mu, \overline{\nu}_e$, respectively).

The 10 complex amplitudes $g^\gamma_{\epsilon\mu}$ constitute 19 free parameters to be determined by experiment. As shown by Langacker and London,[2] explicit lepton-number nonconservation still leads to a matrix element equivalent to the one above. The Standard Model has $g^V_{LL} = 1$ and all others equal to zero.

The sign conventions and definitions of the covariants of Scheck[3] are used.

Assuming massless neutrinos, Kinoshita and Sirlin[4] define ten real constants, a, b, c, a', b', c', α, β, α', and β', which serve as a model-independent summary of all possible measurements on the decay electron from polarized and unpolarized muons. The values of these constants have been determined (see the Listings below). The relations to the decay parameters are

$$\rho - \frac{3}{4} = \frac{3}{4}(-a + 2c)/A\ ,$$

$$\eta = (\alpha - 2\beta)/A\ ,$$

$$\delta - \frac{3}{4} = \frac{9}{4} \cdot \frac{(a' - 2c')/A}{1 - [a + 3a' + 4(b + b') + 6c - 14c']/A}\ ,$$

$$1 - \xi\frac{\delta}{\rho} = 4\frac{[(b + b') + 2(c - c')]/A}{1 - (a - 2c)/A}\ ,$$

$$1-\xi' = [(a+a') + 4(b+b)' + 6(c+c')]/A \ ,$$

$$1-\xi'' = (-2a+20c)/A \ ,$$

where

$$A = a + 4b + 6c \ .$$

Also

$$a = 16\,(|g^V_{RL}|^2 + |g^V_{LR}|^2) + |g^S_{RL} + 6\,g^T_{RL}|^2 + |g^S_{LR} + 6\,g^T_{LR}|^2 \ ,$$

$$a' = 16\,(|g^V_{RL}|^2 - |g^V_{LR}|^2) + |g^S_{RL} + 6\,g^T_{RL}|^2 - |g^S_{LR} + 6\,g^T_{LR}|^2 \ ,$$

$$\alpha = 8\,\mathrm{Re}\,\{g^V_{RL}(g^S_{LR} + 6\,g^T_{LR})^* + g^V_{LR}(g^S_{RL} + 6\,g^T_{RL})^*\} \ ,$$

$$\alpha' = 8\,\mathrm{Im}\,\{-g^V_{RL}(g^S_{LR} + 6\,g^T_{LR})^* + g^V_{LR}(g^S_{RL} + 6\,g^T_{RL})^*\} \ ,$$

$$b = 4\,(|g^V_{RR}|^2 + |g^V_{LL}|^2) + |g^S_{RR}|^2 + |g^S_{LL}|^2 \ ,$$

$$b' = 4\,(|g^V_{RR}|^2 - |g^V_{LL}|^2) + |g^S_{RR}|^2 - |g^S_{LL}|^2 \ ,$$

$$\beta = -4\,\mathrm{Re}\{g^V_{RR}\,(g^S_{LL})^* + g^V_{LL}\,(g^S_{RR})^*\} \ ,$$

$$\beta' = 4\,\mathrm{Im}\{g^V_{RR}\,(g^S_{LL})^* - g^V_{LL}\,(g^S_{RR})^*\} \ ,$$

$$\mathrm{c} = \frac{1}{2}\{|g^S_{RL} - 2\,g^T_{RL}|^2 + |g^S_{LR} - 2\,g^T_{LR}|^2\} \ ,$$

$$\mathrm{c}' = \frac{1}{2}\{|g^S_{RL} - 2\,g^T_{RL}|^2 - |g^S_{LR} - 2\,g^T_{LR}|^2\} \ .$$

In order to determine all the amplitudes $g^\gamma_{\epsilon\mu}$ in Eq. (3) uniquely from experiments, Fetscher *et al.*[1] introduce the four probabilities $Q_{\epsilon\mu}\,(\epsilon,\mu = R,L)$, for the decay of a μ-handed muon into an ϵ-handed electron and show that there exist upper bounds for Q_{RR}, Q_{LR}, and Q_{RL}, and a lower bound for Q_{LL}. These probabilities are expressed as

$$Q_{\epsilon\mu} = \frac{1}{4}|g^S_{\epsilon\mu}|^2 + |g^V_{\epsilon\mu}|^2 + 3(1-\delta_{\epsilon\mu})|g^T_{\epsilon\mu}|^2 \ , \qquad (4)$$

where $\delta_{\epsilon\mu} = 1$ for $\epsilon = \mu$, and $\delta_{\epsilon\mu} = 0$ for $\epsilon \neq \mu$. They take the values

$$Q_{RR} = 2(b+b')/A$$

$$Q_{RL} = [(a+a') + 6(c+c')]/2A,$$

$$Q_{LR} = [(a-a') + 6(c-c')]/2A,$$

$$Q_{LL} = 2(b-b')/A \ ,$$

with $A = 16$.

Since these upper bounds are found to be small, and since the helicity of the ν_μ in pion decay is known from experiments[6,7] to be -1 to very high precision,[8] the cross section S of *inverse* muon decay, normalized to the $V-A$ value, yields[1]

$$\left|g^S_{LL}\right|^2 \leq 4(1-S) \qquad (5)$$

and

$$\left|g^V_{LL}\right|^2 = S \ . \qquad (6)$$

Thus the Standard Model assumption of a pure $V-A$ leptonic charged weak interaction for e and μ is confirmed (within errors) by experiments at energies far below $m_W c^2$: Eq. (6) yields a lower limit for $V-A$, and Eqs. (4) and (5) give upper limits for the other four-fermion interactions. The existence of such upper limits may also be seen from $Q_{RR} + Q_{RL} = (1-\xi')/2$ and $Q_{RR} + Q_{LR} = \frac{1}{2}(1 + \xi/3 - 16\xi\delta/9)$. Table 1 gives the current experimental limits for the $g^\gamma_{\epsilon\mu}$'s.

Limits on the "charge retention" coordinates, as used in the older literature (*e.g.*, Ref. 11), are given by Burkard *et al.*[12]

Table 1. Ninety-percent confidence level experimental limits for the coupling constants $g^\gamma_{\epsilon\mu}$. The limits on $|g^S_{LL}|$ and $|g^V_{LL}|$ are from Ref. 9. The other limits are from Ref. 10.

$\lvert g^S_{RR}\rvert < 0.066$	$\lvert g^V_{RR}\rvert < 0.033$	
$\lvert g^S_{LR}\rvert < 0.125$	$\lvert g^V_{LR}\rvert < 0.060$	$\lvert g^T_{LR}\rvert < 0.036$
$\lvert g^S_{RL}\rvert < 0.424$	$\lvert g^V_{RL}\rvert < 0.110$	$\lvert g^T_{RL}\rvert < 0.122$
$\lvert g^S_{LL}\rvert < 0.55$	$\lvert g^V_{LL}\rvert > 0.96$	

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1. W. Fetscher, H.-J. Gerber, and K.F. Johnson, Phys. Lett. **B173**, 102 (1986).
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3. F. Scheck, in *Leptons, Hadrons, and Nuclei* (North Holland, Amsterdam, 1983).
4. T. Kinoshita and A. Sirlin, Phys. Rev. **108**, 844 (1957).
5. K. Mursula and F. Scheck, Nucl. Phys. **B253**, 189 (1985).
6. A. Jodidio *et al.*, Phys. Rev. **D34**, 1967 (1986); and Phys. Rev. **D37**, 237 (1988).
7. L.Ph. Roesch *et al.*, Helv. Phys. Acta **55**, 74 (1982).
8. W. Fetscher, Phys. Lett. **140B**, 117 (1984).
9. S.R. Mishra *et al.*, Phys. Lett. **B252**, 170 (1990), and S.R. Mishra, private communication. See also D. Geiregat *et al.*, Phys. Lett. **B247**, 131 (1990).
10. B. Balke *et al.*, Phys. Rev. **D37**, 587 (1988).
11. S.E. Derenzo, Phys. Rev. **181**, 1854 (1969).
12. H. Burkard *et al.*, Phys. Lett. **160B**, 343 (1985).

μ DECAY PARAMETERS

ρ PARAMETER

(V−A) theory predicts $\rho = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.7518±0.0026		DERENZO	69	RVUE		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.762 ±0.008	170k	[21] FRYBERGER	68	ASPK	+	25–53 MeV e^+
0.760 ±0.009	280k	[21] SHERWOOD	67	ASPK	+	25–53 MeV e^+
0.7503±0.0026	800k	[21] PEOPLES	66	ASPK	+	20–53 MeV e^+

[21] η constrained = 0. These values incorporated into a two parameter fit to ρ and η by DERENZO 69.

η PARAMETER

(V−A) theory predicts $\eta = 0$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
−0.007±0.013 OUR AVERAGE						
−0.007±0.013	5.3M	[22] BURKARD	85B	FIT	+	9–53 MeV e^+
−0.12 ±0.21	6346	DERENZO	69	HBC	+	1.6–6.8 MeV e^+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−0.012±0.015±0.003	5.3M	[23] BURKARD	85B	CNTR	+	9–53 MeV e^+
0.011±0.081±0.026	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+
−0.7 ±0.5	170k	[24] FRYBERGER	68	ASPK	+	25–53 MeV e^+
−0.7 ±0.6	280k	[24] SHERWOOD	67	ASPK	+	25–53 MeV e^+
0.05 ±0.5	800k	[24] PEOPLES	66	ASPK	+	20–53 MeV e^+
−2.0 ±0.9	9213	[25] PLANO	60	HBC	+	Whole spectrum

[22] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.
[23] $\alpha = \alpha' = 0$ assumed.
[24] ρ constrained = 0.75.
[25] Two parameter fit to ρ and η; PLANO 60 discounts value for η.

δ PARAMETER

(V−A) theory predicts $\delta = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.7486±0.0026±0.0028		[26] BALKE	88	SPEC	+	Surface μ^+'s
• • • We do not use the following data for averages, fits, limits, etc. • • •						
		[27] VOSSLER	69			
0.752 ±0.009	490k	FRYBERGER	68	ASPK	+	25–53 MeV e^+
0.782 ±0.031		KRUGER	61			
0.78 ±0.05	8354	PLANO	60	HBC	+	Whole spectrum

[26] BALKE 88 uses $\rho = 0.752 \pm 0.003$.
[27] VOSSLER 69 has measured the asymmetry below 10 MeV. See comments about radiative corrections in VOSSLER 69.

(ξ PARAMETER) × (μ LONGITUDINAL POLARIZATION)

(V−A) theory predicts $\xi = 1$, longitudinal polarization = 1.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.0027±0.0079±0.0030		BELTRAMI	87	CNTR		SIN, π decay in flight
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.975 ±0.015		AKHMANOV	68	EMUL		140 kG
0.975 ±0.030	66k	GUREVICH	64	EMUL		Repl. by AKHMANOV 68
0.903 ±0.027		[28] ALI-ZADE	61	EMUL	+	27 kG
0.93 ±0.06	8354	PLANO	60	HBC	+	8.8 kG
0.97 ±0.05	9k	BARDON	59	CNTR		Bromoform target

[28] Depolarization by medium not known sufficiently well.

ξ × (μ LONGITUDINAL POLARIZATION) × δ / ρ

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
>0.99677	90	[29] JODIDIO	86	SPEC	+	TRIUMF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.9966	90	[30] STOKER	85	SPEC	+	μ-spin rotation
>0.9959	90	CARR	83	SPEC	+	11 kG

[29] JODIDIO 86 includes data from CARR 83 and STOKER 85. The above value is the result given in the erratum: JODIDIO 88.
[30] STOKER 85 find ($\xi P_\mu \delta/\rho$) >0.9955 and >0.9966, where first limit is from new μ spin-rotation data and second is from combination with CARR 83 data. $(\delta/\rho) = 1.0$ in V−A theory.

ξ' = LONGITUDINAL POLARIZATION OF e^+

(V−A) theory predicts the longitudinal polarization = ±1 for $e^\pm$, respectively. We have flipped the sign for e^- so our programs can average.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.00 ±0.04 OUR AVERAGE						
0.998±0.045	1M	BURKARD	85	CNTR	+	Bhabha + annihil
0.89 ±0.28	29k	SCHWARTZ	67	OSPK	−	Moller scattering
0.94 ±0.38		BLOOM	64	CNTR	+	Brems. transmiss.
1.04 ±0.18		DUCLOS	64	CNTR	+	Bhabha scattering
1.05 ±0.30		BUHLER	63	CNTR	+	Annihilation

ξ'' PARAMETER

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.65±0.36	326k	[31] BURKARD	85	CNTR	+	Bhabha + annihil

[31] BURKARD 85 measure $(\xi''\text{-}\xi\xi')/\xi$ and ξ' and set $\xi = 1$.

TRANSVERSE e^+ POLARIZATION IN PLANE OF μ SPIN, e^+ MOMENTUM

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.016±0.021±0.01	5.3M	BURKARD	85B	CNTR	+	Annihil 9–53 MeV

TRANSVERSE e^+ POLARIZATION NORMAL TO PLANE OF μ SPIN, e^+ MOMENTUM

Zero if T invariance holds.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.007±0.022±0.007	5.3M	BURKARD	85B	CNTR	+	Annihil 9–53 MeV

α/A

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.4± 4.3		[32] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
15 ±50 ±14	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+

[32] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

α'/A

Zero if T invariance holds.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
− 0.2± 4.3		[33] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−47 ±50 ±14	5.3M	[34] BURKARD	85B	CNTR	+	9–53 MeV e^+

[33] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.
[34] BURKARD 85B measure e^+ polarizations P_{T_1} and P_{T_2} versus e^+ energy.

β/A

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
3.9± 6.2		[35] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2 ±17 ±6	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+

[35] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

β'/A

Zero if T invariance holds.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.5± 6.3		[36] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
17 ±17 ±6	5.3M	[37] BURKARD	85B	CNTR	+	9–53 MeV e^+

[36] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.
[37] BURKARD 85B measure e^+ polarizations P_{T_1} and P_{T_2} versus e^+ energy.

a/A

This comes from an alternative parameterization to that used in the Summary Table (see Note on Muon Decay Parameters above).

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<15.9	90	[38] BURKARD	85B	FIT

[38] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

a'/A

This comes from an alternative parameterization to that used in the Summary Table (see Note on Muon Decay Parameters above).

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
5.3±4.1	[39] BURKARD	85B	FIT

[39] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

$(b'+b)/A$

This comes from an alternative parameterization to that used in the Summary Table (see Note on Muon Decay Parameters above).

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.04	90	[40] BURKARD	85B	FIT

[40] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

c/A

This comes from an alternative parameterization to that used in the Summary Table (see Note on Muon Decay Parameters above).

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<6.4	90	[41] BURKARD	85B	FIT

[41] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

c'/A

This comes from an alternative parameterization to that used in the Summary Table (see Note on Muon Decay Parameters above).

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3.5±2.0	[42] BURKARD	85B	FIT

[42] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

$\overline{\eta}$ PARAMETER

(V−A) theory predicts $\overline{\eta} = 0$. $\overline{\eta}$ affects spectrum of radiative muon decay.

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.02 ±0.08 OUR AVERAGE					
−0.014±0.090	EICHENBER...	84	ELEC	+	ρ free
+0.09 ±0.14	BOGART	67	CNTR	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.035±0.098	EICHENBER...	84	ELEC	+	ρ=0.75 assumed

μ REFERENCES

BARANOV 91 SJNP 53 802 +Vanko, Glazov, Evtukhovich+ (JINR)
Translated from YAF 53 1302.
KRAKAUER 91B PL B263 534 +Talaga, Allen, Chen, Doe+ (UMD, UCI, LANL)
MATTHIAS 91 PRL 66 2716 +Ahn+ (YALE, HEID, WILL, GSI, PSI, BNL)
Also 91B PRL 67 932 erratum Matthias, Ahn+ (YALE, HEID, WILL, GSI, PSI, BNL)
HUBER 90B PR D41 2709 + (WYOM, VICT, ARIZ, ROCH, TRIU, SFRA, BRCO)
AHMAD 88 PR D38 2102 +Azuelos+ (TRIU, VICT, VPI, BRCO, MONT, CNRC)
Also 87 PRL 59 970 Ahmad+ (TRIU, VPI, VICT, BRCO, MONT, CNRC)
BALKE 88 PR D37 587 +Gidal, Jodidio+ (LBL, UCB, COLO, NWES, TRIU)
BELLGARDT 88 NP B299 1 +Otter, Eichler+ (SINDRUM Collab.)
BOLTON 88 PR D38 2077 +Cooper, Frank, Hallin+ (LANL, STAN, CHIC, TEMP)
Also 86 PRL 56 2461 Bolton, Bowman, Cooper+ (LANL, STAN, CHIC, TEMP)
Also 86 PRL 57 3241 Grosnick, Wright, Bolton+ (CHIC, LANL, STAN, TEMP)
HUBER 88 PRL 61 2189 +Beer+ (WYOM, VICT, ARIZ, ROCH, TRIU, BRCO)
JODIDIO 88 PR D37 237 erratum +Balke, Carr+ (LBL, NWES, TRIU)
BELTRAMI 87 PL B194 326 +Burkard, Von Dincklage+ (ETH, SIN, MANZ)
COHEN 87 RMP 59 1121 +Taylor (RISC, NBS)
NI 87 PRL 59 2716 +Arnold, Chmely+ (YALE, LANL, WILL, MISS, HEID)
BEER 86 PRL 57 671 +Marshall, Mason+ (VICT, TRIU, WYOM)
BELTRAMI 86 NP A451 679 +Aas, Beer, Dechambrier, Goudsmit+ (ETH, FRIB)
JODIDIO 86 PR D34 1967 +Balke, Carr, Gidal, Shinsky+ (LBL, NWES, TRIU)
Also 88 PR D37 237 erratum Jodidio, Balke, Carr+ (LBL, NWES, TRIU)
BERTL 85 NP B260 1 +Egli, Eichler+ (SINDRUM Collab.)
BRYMAN 85 PRL 55 465 + (TRIU, CNRC, BRCO, LANL, CHIC, CARL+)
BURKARD 85 PL 150B 242 +Corriveau, Egger+ (ETH, SIN, MANZ)
BURKARD 85B PL 160B 343 +Corriveau, Egger+ (ETH, SIN, MANZ)
Also 81B PR D24 2004 Corriveau, Egger, Fetscher+ (ETH, SIN, MANZ)
Also 83B PL 129B 260 Corriveau, Egger, Fetscher+ (ETH, SIN, MANZ)
HUGHES 85 CNPP 14 341 +Kinoshita (YALE, CORN)
STOKER 85 PRL 54 1887 +Balke, Carr, Gidal+ (LBL, NWES, TRIU)
BARDIN 84 PL 137B 135 +Duclos, Magnon+ (SACL, CERN, BGNA, FIRZ)
BERTL 84 PL 140B 299 +Eichler, Felawka+ (SINDRUM Collab.)
BOLTON 84 PRL 53 1415 +Bowman, Carlini+ (LANL, CHIC, STAN, TEMP)
EICHENBER... 84 NP A412 523 Eichenberger, Engfer, VanderSchaff (ZURI)
GIOVANETTI 84 PR D29 343 +Dey, Eckhause, Hart+ (WILL)
KINOSHITA 84 PRL 52 717 +Nizic, Okamoto (CORN)
AZUELOS 83 PRL 51 164 +Depommier, Leroy, Martin+ (MONT, TRIU, BRCO)
Also 77 PRL 39 1113 Depommier+ (MONT, BRCO, TRIU, VICT, MELB)
BERGSMA 83 PL 122B 465 +Dorenbosch, Jonker+ (CHARM Collab.)
CARR 83 PRL 51 627 +Gidal, Gobbi, Jodidio, Oram+ (LBL, NWES, TRIU)
KINNISON 82 PR D25 2846 +Anderson, Matis, Wright+ (EFI, STAN, LANL)
Also 79 PRL 42 556 Bowman, Cooper, Hamm+ (LASL, EFI, STAN)
KLEMPT 82 PR D25 652 +Schulze, Wolf, Camani, Gygax+ (MANZ, ETH)
MARIAM 82 PRL 49 993 +Beer, Bolton, Egan, Gardner+ (YALE, HEID, BERN)
MARSHALL 82 PR D25 1174 +Warren, Oram, Kiefl (BRCO)
COMBLEY 81 PRPL 68 93 +Farley, Picasso (SHEF, RMCS, CERN)
NEMETHY 81 CNPP 10 147 +Hughes (LBL, YALE)
ABELA 80 PL 95B 318 +Backenstoss, Simons, Wuest+ (BASL, KARL)
BADERT... 80 LNC 28 401 Badertscher, Borer, Czapek, Flueckiger+ (BERN)
Also 82 NP A377 406 Badertscher, Borer, Czapek, Flueckiger+ (BERN)
JONKER 80 PL 93B 203 +Panman, Udo, Allaby+ (CHARM Collab.)
SCHAAF 80 NP A340 249 +Engfer, Povel, Dey+ (ZURI, ETH, SIN)
Also 77 PL 72B 183 Povel, Dey, Walter, Pfeiffer+ (ZURI, ETH, SIN)
WILLIS 80 PRL 44 522 +Hughes+ (YALE, LBL, LASL, SACL, SIN, CNRC+)
Also 80B PRL 45 1370 Willis+ (YALE, LBL, LASL, SACL, SIN, CNRC+)
BAILEY 79 NP B150 1 (CERN, DARE, MANZ)
FARLEY 79 ARNPS 29 243 +Picasso (RMCS, CERN)
BADERT... 78 PL 79B 371 Badertscher, Borer, Czapek, Flueckiger+ (BERN)
BAILEY 78 JP G4 345 (DARE, BERN, SHEF, MANZ, RMCS, CERN, BIRM)
Also 79 NP B150 1 Bailey (CERN, DARE, MANZ)
BLIETSCHAU 78 NP B133 205 +Deden, Hasert, Krenz+ (Gargamelle Collab.)
BOWMAN 78 PRL 41 442 +Cheng, Li, Matis (LASL, IAS, CMU, EFI)
CAMANI 78 PL 77B 326 +Gygax, Klempt, Schenck, Schulze+ (ETH, MANZ)
BADERT... 77 PRL 39 1385 Badertscher, Borer, Czapek, Flueckiger+ (BERN)
BAILEY 77 PL 67B 225 + (CERN Muon Storage Ring Collab.)
Also 77C PL 68B 191 Bailey+ (CERN, DARE, BERN, SHEF, MANZ+)
Also 75 PL 55B 420 Bailey+ (CERN Muon Storage Ring Collab., BIRM)
CALMET 77 RMP 49 21 +Narison, Perrottet+ (MARS)
CASPERSON 77 PRL 38 956 +Crane+ (BERN, HEID, LASL, WYOM, YALE)
DEPOMMIER 77 PRL 39 1113 + (MONT, BRCO, TRIU, VICT, MELB)
BALANDIN 74 JETP 40 811 +Grebenyuk, Zinov, Konin, Ponomarev (JINR)
Translated from ZETF 67 1631.
COHEN 73 JPCRD 2 663 +Taylor (RISC, NBS)
DUCLOS 73 PL 47B 491 +Magnon, Picard (SACL)
EICHTEN 73 PL 46B 281 +Deden, Hasert, Krenz+ (Gargamelle Collab.)
BRYMAN 72 PRL 28 1469 +Blecher, Gotow, Powers (VPI)
CROWE 72 PR D5 2145 +Hague, Rothberg, Schenck+ (LBL, WASH)
CRANE 71 PRL 27 474 +Casperson, Crane, Egan, Hughes+ (YALE)
DERENZO 69 PR 181 1854 (EFI)
VOSSLER 69 NC 63A 423 (EFI)
AKHMANOV 68 SJNP 6 230 +Gurevich, Dobretsov, Makarina+ (KIAE)
Translated from YAF 6 316.
BAILEY 68 PL 28B 287 +Bartl, VonBochmann, Brown, Farley+ (CERN)
Also 72 NC 9A 369 Bailey, Bartl, VonBochmann, Brown+ (CERN)
FRYBERGER 68 PR 166 1379 (EFI)
BOGART 67 PR 156 1405 +Dicapua, Nemethy, Strelzoff (COLU)
SCHWARTZ 67 PR 162 1306 (EFI)
SHERWOOD 67 PR 156 1475 (EFI)
PEOPLES 66 Nevis 147 unpub. (COLU)
BLOOM 64 PL 8 87 +Dick, Feuvrais, Henry, Macq, Spighel (CERN)
DUCLOS 64 PL 9 62 +Heintze, DeRujula, Soergel (CERN)
GUREVICH 64 PL 11 185 +Makarina+ (KIAE)
BUHLER 63 PL 7 368 +Cabibbo, Fidecaro, Massam, Muller+ (CERN)
MEYER 63 PR 132 2693 +Anderson, Bleser, Lederman+ (COLU)
CHARPAK 62 PL 1 16 +Farley, Garwin+ (CERN)
CONFORTO 62 NC 26 261 +Conversi, Dilella+ (INFN, ROMA, CERN)
ALI-ZADE 61 JETP 13 313 +Gurevich, Nikolski
Translated from ZETF 40 452.
CRITTENDEN 61 PR 121 1823 +Walker, Ballam (WISC, MSU)
KRUGER 61 UCRL 9322 unpub. (LRL)
GUREVICH 60 JETP 10 225 +Nikolski, Surkova (ITEP)
Translated from ZETF 37 318.
PLANO 60 PR 119 1400 (COLU)
ASHKIN 59 NC 14 1266 +Fazzini, Fidecaro, Lipman, Merrison+ (CERN)
BARDON 59 PRL 2 56 +Berley, Lederman (COLU)
LEE 59 PRL 3 55 +Samios (COLU)

OTHER RELATED PAPERS

DEPOMMIER 80 NP A335 97 (MONT)
BASILE 78B NC 45A 281 +Cara-Romeo, Cifarelli, Contin+ (CERN, BGNA)
KINOSHITA 78 Tokyo Conf. 571 (CORN)
SCHECK 78 PRPL 44C 187 (MANZ)
COMBLEY 74 PRPL 14 1 +Picasso (CERN)
LAUTRUP 72 PRPL 3 193 +Peterman, DeRafael (CERN, BURE)
RICH 72 RMP 44 250 +Wesley (MICH)

τ

$J = \frac{1}{2}$

τ discovery paper was PERL 75. $e^+e^- \rightarrow \tau^+\tau^-$ cross-section threshold behavior and magnitude are consistent with pointlike spin-1/2 Dirac particle. BRANDELIK 78 ruled out pointlike spin-0 or spin-1 particle. FELDMAN 78 ruled out $J = 3/2$. KIRKBY 79 also ruled out J=integer, $J = 3/2$.

NOTE ON THE τ DECAY PROBLEM

(by K.G. Hayes, Hillsdale College)

A problem with contributions to the τ one-prong topological branching ratio was first noticed in 1984:[1,2] If world averages were considered, and if theoretical predictions were used to limit certain poorly-measured modes (such as $\tau^- \rightarrow \text{hadron}^- 2\pi^0\nu_\tau$ and $\tau^- \rightarrow \text{hadron}^- \geq 3\pi^0\nu_\tau$), then the the measured inclusive one-prong topological branching ratio was significantly larger than the sum of the exclusive one-prong decay modes. This persistent problem might be due to errors in measurements of some of the exclusive one-prong modes or the one-prong topological branching ratio itself, errors in the estimates of the experimental errors, errors in the theoretical predictions used to limit the poorly-measured modes, or perhaps the existence of one-prong modes that had not been included in the sum over exclusive modes. In the past no single experiment had sufficient statistical precision to resolve the issue, so it was also possible that the averaging procedure underestimated the error on the average due to common systematic errors between experiments.

There have been recent improvements in the situation. The LEP experiments can select $Z \rightarrow \tau^+\tau^-$ events with excellent efficiency (typically 70%) and low backgrounds (typically a few percent). Their measurements of the topological branching ratios are consistent with each other and with the previous world average [our 1990 average value for $B_1 \equiv B(\tau^- \rightarrow$ 1-prong ≥ 0 neutrals $\nu) = 86.13 \pm 0.33\%$; the ALEPH[3] and L3[4] measurements of B_1 are $85.45^{+0.69}_{-0.73} \pm 0.65\%$ and $85.6 \pm 0.6 \pm 0.3\%$ respectively]. Although early low-energy measurements of B_1 were in error, it is very unlikely that the current world average for B_1 is incorrect by more than about 0.5%.

In addition to selecting τ events with high efficiency and purity, the LEP experiments also have excellent electron and muon identification capabilities. Their measurements of $B_e \equiv B(\tau^- \rightarrow e^-\overline{\nu}_e\nu_\tau)$ and $B_\mu \equiv B(\tau^- \rightarrow \mu^-\overline{\nu}_\mu\nu_\tau)$ (see the Full Listings) are consistent with the previous world average values, and contribute about 50% of the weight to the current world averages. It is very unlikely that errors in the current averages for B_e or B_μ contribute significantly to the one-prong problem.

The ALEPH and CELLO collaborations[3,5] have each measured a complete set of τ branching ratios and find no one-prong problem in their data. The ALEPH results for many τ branching ratios are the most precise currently available. The ALEPH analysis is also notable in that their branching ratios are normalized to the number of τ events produced as determined from the measured number of $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ events. The sum of their topological branching ratios is $99.9 \pm 0.70 \pm 0.51 \pm 0.52\%$ where the errors are statistical, systematic, and normalization uncertainty, respectively.

Table 1. Branching fractions of the τ (%)

Decay Mode	World Average	Sum of ALEPH and CELLO Weights (%)	Avg. of ALEPH and CELLO	Avg. Excluding ALEPH and CELLO
B_1	85.94 ± 0.23	27	85.02 ± 0.44	86.28 ± 0.27
B_3	14.06 ± 0.20	33	14.67 ± 0.35	13.76 ± 0.25
$e^- \overline{\nu}_e \nu_\tau$	17.85 ± 0.29	31	18.19 ± 0.52	17.69 ± 0.35
$\mu^- \overline{\nu}_\mu \nu_\tau$	17.45 ± 0.27	33	17.45 ± 0.47	17.45 ± 0.33
$\text{hadron}^- \nu_\tau$	12.47 ± 0.35	53	13.09 ± 0.49	11.78 ± 0.51
$\text{hadron}^- \pi^0 \nu_\tau$	23.4 ± 0.6	48	24.3 ± 0.9	22.6 ± 0.9
$\text{hadron}^- 2\pi^0 \nu_\tau$	9.0 ± 0.6	48	10.4 ± 0.9	7.6 ± 0.9
$\text{hadron}^- \geq 3\pi^0 \nu_\tau$	1.8 ± 0.6	96	1.8 ± 0.6	1.1 ± 0.2 (see text)
$2\,\text{hadron}^- \text{hadron}^+ \nu_\tau$	8.0 ± 0.3	38	9.4 ± 0.5	7.2 ± 0.4
$2\,\text{hadron}^- \text{hadron}^+ \geq 1\,\text{neutral}\ \nu_\tau$	5.2 ± 0.4	45	5.3 ± 0.5	5.1 ± 0.5
B_5 (see text)	0.11 ± 0.03		0.11 ± 0.03	0.11 ± 0.03
$\sum$ all	95.3 ± 1.3		100.1 ± 1.8	90.6 ± 1.6
$\sum$ 1-prong	82.0 ± 1.2		85.3 ± 1.6	78.2 ± 1.4
$\sum$ 3-prong	13.2 ± 0.5		14.7 ± 0.7	12.3 ± 0.6
$100 - \sum$ all	4.7 ± 1.3		-0.1 ± 1.8	9.4 ± 1.6
$B_1 - \sum$ 1-prong	3.9 ± 1.2		-0.2 ± 1.7	8.1 ± 1.5
$B_3 - \sum$ 3-prong	0.9 ± 0.5		0.0 ± 0.8	1.5 ± 0.7

Table 2. Difference between ALEPH and CELLO average and world average excluding ALEPH and CELLO

Decay Mode	(%)
B_1	-1.3 ± 0.5
B_3	0.9 ± 0.4
$e^- \overline{\nu}_e \nu_\tau$	0.5 ± 0.6
$\mu^- \overline{\nu}_\mu \nu_\tau$	0.0 ± 0.6
$\text{hadron}^- \pi^0 \nu_\tau$	1.3 ± 0.7
$\text{hadron}^- \pi^0 \nu_\tau$	1.7 ± 1.3
$\text{hadron}^- 2\pi^0 \nu_\tau$	2.9 ± 1.3
$\text{hadron}^- \geq 3\pi^0 \nu_\tau$	0.7 ± 0.6
$2\,\text{hadron}^- \text{hadron}^+ \nu_\tau$	2.3 ± 0.7
$2\,\text{hadron}^- \text{hadron}^+ \geq 1\,\text{neutral}\ \nu_\tau$	0.2 ± 0.7

This allows them to set a limit on totally undetected τ decay modes of $< 2.1\%$ at the 95% confidence level. Together, the CELLO and ALEPH results contribute a significant fraction of the total weight to the world average of many τ branching ratios relevant to the one-prong problem, and this has reduced the size and significance of the one-prong discrepancy in the current world averages.

The current status of the τ decay mode problem is summarized in Tables 1 and 2. Table 1 gives the world average values for all experiments, the sum of the ALEPH and CELLO weights in world averages, the average of only the ALEPH and CELLO results, and the average excluding the ALEPH and CELLO results. Table 2 gives the difference between the average of ALEPH and CELLO results and the other experiments.

The decay modes selected to form a complete set are those which are closest to what is actually detected in most experiments: electrons, muons, charged hadrons, and photons which are reconstructed into neutral pions. For example, the branching ratio $B(\text{hadron}^- \nu_\tau)$ contains contributions from $\tau^- \to \pi^- \nu_\tau$, $\tau^- \to K^- \nu_\tau$, and $\tau^- \to \pi^- K_L \nu_\tau$. The values listed are averages and are not the results of a constrained fit. The averages are slightly different from the values in the Full Listings since some experimental measurements contributing to these averages are listed under different modes, and no scale factors have been used to inflate the errors. The recent CELLO and ALEPH measurements contribute 96% of the weight for $B(\text{hadron}^- \geq 3\pi^0 \nu_\tau)$, so for the average excluding the ALEPH and CELLO result, we use the theoretical prediction[2] that $B(\pi^- 3\pi^0 \nu_\tau)/B(e^- \overline{\nu}_e \nu_\tau) = 0.055 \pm 0.005$, and assume $B(K^- \geq 3\pi^0 \nu_\tau) = 0.001 \pm 0.001$ and that $B(\pi^- \geq 4\pi^0 \nu_\tau)$ is negligible. In the Full Listings, the definitions of $B(\text{hadron}^- 2\pi^0 \nu_\tau)$ and $B(2\,\text{hadron}^- \text{hadron}^+ \nu_\tau)$ exclude the contribution from $\tau^- \to K^*(892)^- \nu_\tau$ decays, but they are included here. The current world average for $B(\text{5-prong}) = 0.11 \pm 0.03\%$ is used for all three sets of averages.

Conclusions: Although the one-prong discrepancy remains in the world averages excluding the ALEPH and CELLO results, no problem is apparent in the ALEPH and CELLO averages. The most significant differences between the ALEPH and CELLO results and the other measurements occur in the values for $B(2\,\text{hadron}^- \text{hadron}^+ \nu_\tau)$ and $B(\text{hadron}^- 2\pi^0 \nu_\tau)$. It is clear (see the Full Listings) that significant discrepancies exist between some individual measurements in these modes. It is interesting to note that unlike the case for other large modes, no firm theoretical predictions for the branching ratio of these two modes exist [although isospin constraints[2] require $B(\pi^- 2\pi^0 \nu_\tau) \leq B(2\pi^- \pi^+ \nu_\tau)$]. Smaller differences exist in the values for B_1, $B(\text{hadron}^- \nu_\tau)$, and $B(\text{hadron}^- \pi^0 \nu_\tau)$. Although the statistical significance of the differences is not large for most modes, in all cases the differences have appropriate signs so that the sum is a problem. Further precise experimental measurements are needed to clarify the situation.

References

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3. D. Decamp *et al.*, (ALEPH Collab.), CERN-PPE/91-186, submitted to Z. Phys. **C**.
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τ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
$1784.1^{+2.7}_{-3.6}$ OUR AVERAGE					
1787 ±10		BLOCKER	80	MRK2	E^{ee}_{cm}= 3.5–6.7 GeV
$1783\ ^{+3}_{-4}$	692	[1] BACINO	78B	DLCO	E^{ee}_{cm}= 3.1–7.4 GeV
$1787\ ^{+10}_{-18}$	299	[2] BARTEL	78	SPEC	E^{ee}_{cm}= 3.6–4.4 GeV
1807 ±20		BRANDELIK	78	DASP	E^{ee}_{cm}= 3.1–5.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1803 ±16	1138	BLOCKER	82D	MRK2	Incl. in BLOCKER 80

[1] BACINO 78B value comes from $e^\pm X^\mp$ threshold. Published mass 1782 MeV increased by 1 MeV using the high precision $\psi(2S)$ mass measurement of ZHOLENTZ 80 to eliminate the absolute SPEAR energy calibration uncertainty.

[2] BARTEL 78 fits energy dependence of cross section for $e^\pm$ and $\mu^\pm$ events. Mass value not dependent on whether V−A or V+A decay assumed.

τ MEAN LIFE

VALUE (10^{-12} s)	EVTS	DOCUMENT ID		TECN	COMMENT
0.305±0.006 OUR AVERAGE					
0.314±0.023±0.009		ABREU	91D	DLPH	E^{ee}_{cm}= 88–94 GeV
0.308±0.013		ACTON	91C	OPAL	E^{ee}_{cm}= 88–94 GeV
0.309±0.023±0.030	2817	ADEVA	91F	L3	E^{ee}_{cm}= 88.3–94.3 GeV
0.301±0.029	3780	KLEINWORT	89	JADE	E^{ee}_{cm}= 35–46 GeV
0.288±0.016±0.017	807	AMIDEI	88	MRK2	E^{ee}_{cm}= 29 GeV
0.306±0.020±0.014	695	BRAUNSCH...	88C	TASS	E^{ee}_{cm}= 36 GeV
0.299±0.015±0.010	1311	ABACHI	87C	HRS	E^{ee}_{cm}= 29 GeV
0.295±0.014±0.011	5696	ALBRECHT	87P	ARG	E^{ee}_{cm}= 9.3–10.6 GeV
0.309±0.017±0.007	3788	BAND	87B	MAC	E^{ee}_{cm}= 29 GeV
0.325±0.014±0.018	8470	BEBEK	87C	CLEO	E^{ee}_{cm}= 10.5 GeV
0.315±0.036±0.040	10k	FERNANDEZ	85	MAC	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.318^{+0.081}_{-0.094}$	50	ALTHOFF	84D	TASS	Repl. by BRAUNSCHWEIG 88C
0.320±0.054	156	JAROS	83	MRK2	Repl. by AMIDEI 88

τ MAGNETIC MOMENT ANOMALY

$\mu_\tau/(e\hbar/2m_\tau)-1 = (g_\tau-2)/2$

For a theoretical calculation [$(g_\tau-2)/2 = 11773(3) \times 10^{-7}$], see SAMUEL 91B.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.12	90	GRIFOLS	91	RVUE	$Z \to \tau\tau\gamma$ at LEP

τ ELECTRIC DIPOLE MOMENT

VALUE (e-cm)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<7 \times 10^{-16}$	90	GRIFOLS	91	RVUE	$Z \to \tau\tau\gamma$ at LEP
$<1.6 \times 10^{-16}$	90	DELAGUILA	90	RVUE	$e^+e^- \to \tau^+\tau^-$ E^{ee}_{cm}= 35 GeV

τ^- DECAY MODES

τ^+ modes are charge conjugates of the modes below. "$h^\pm$" stands for $\pi^\pm$ or $K^\pm$. "ℓ" stands for e or μ. "Neutral" means neutral hadron whose decay products include γ's and/or π^0's.

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	particle$^-$ $\geq$ 0 neutrals ν_τ ("1-prong")	(85.82±0.25) %	S=1.3
Γ_2	$\mu^-\overline{\nu}_\mu\nu_\tau$	(17.58±0.27) %	S=1.1
Γ_3	$\mu^-\overline{\nu}_\mu\nu_\tau\gamma$ (E_γ > 37 MeV)	(2.3 ±1.1) × 10^{-3}	
Γ_4	$e^-\overline{\nu}_e\nu_\tau$	(17.93±0.26) %	S=1.1
Γ_5	h^- $\geq$ 0 neutrals ν_τ	(50.3 ±0.4) %	S=1.2
Γ_6	$h^-\nu_\tau$	(12.7 ±0.4) %	S=1.1
Γ_7	$\pi^-\nu_\tau$	(11.6 ±0.4) %	S=1.2
Γ_8	K^- $\geq$ 0 neutrals ν_τ	(1.68±0.24) %	
Γ_9	$K^-\nu_\tau$	(6.7 ±2.3) × 10^{-3}	S=1.3
Γ_{10}	K^- $\geq$ 1 neutrals ν_τ	($1.2\ ^{+0.5}_{-0.6}$) %	
Γ_{11}	h^- $\geq$ 1 neutrals ν_τ	(37.6 ±0.5) %	S=1.2
Γ_{12}	$h^-\pi^0\nu_\tau$	(24.4 ±0.6) %	S=1.1
Γ_{13}	$\pi^-\pi^0\nu_\tau$	(24.0 ±0.6) %	S=1.1
Γ_{14}	$\pi^-\pi^0$ non-$\rho(770)$ ν_τ		
Γ_{15}	h^- $\geq$ $2\pi^0\nu_\tau$	(13.2 ±0.7) %	S=1.3
Γ_{16}	$h^-2\pi^0\nu_\tau$	(10.3 ±0.9) %	S=1.7
Γ_{17}	h^- $\geq$ $3\pi^0\nu_\tau$	(2.7 ±0.9) %	S=1.9
Γ_{18}	$h^-3\pi^0\nu_\tau$		
Γ_{19}	$2h^-h^+$ $\geq$ 0 neutrals ν_τ ("3-prong")	(14.06±0.25) %	S=1.3
Γ_{20}	$h^-h^-h^+\nu_\tau$	(8.4 ±0.4) %	S=1.4
Γ_{21}	$\pi^-\pi^-\pi^+\nu_\tau$	(5.6 ±0.7) %	
Γ_{22}	$\pi^-\rho^0\nu_\tau$	(5.4 ±1.7) %	
Γ_{23}	$a_1(1260)^-\nu_\tau$		
Γ_{24}	$\pi^-\pi^-\pi^+$ non-$\rho(770)^0\nu_\tau$	< 1.4 %	CL=95%
Γ_{25}	$h^-h^-h^+$ $\geq$ 1 neutrals ν_τ	(5.3 ±0.4) %	S=1.3
Γ_{26}	$\pi^-\pi^-\pi^+\pi^0\nu_\tau$		
Γ_{27}	$(a_1(1260)\pi)^-$ ν_τ		
Γ_{28}	$(\rho\pi)^0$ $\pi^-\nu_\tau$		
Γ_{29}	$\rho^0\pi^0\pi^-\nu_\tau$		
Γ_{30}	$\rho^+\pi^-\pi^-\nu_\tau$		
Γ_{31}	$\rho^-\pi^+\pi^-\nu_\tau$		
Γ_{32}	$\omega\pi^-$ $\geq$ 0 neutrals ν_τ	(1.6 ±0.4) %	
Γ_{33}	$\omega\pi^-\nu_\tau$	(1.6 ±0.5) %	
Γ_{34}	$K^-h^+h^-$ $\geq$ 0 neutrals ν_τ	< 6 × 10^{-3}	CL=90%
Γ_{35}	$K^-\pi^+\pi^-$ $\geq$ 0 neutrals ν_τ	($2.2\ ^{+1.6}_{-1.3}$) × 10^{-3}	
Γ_{36}	$K^-K^+\pi^-\nu_\tau$	($2.2\ ^{+1.7}_{-1.1}$) × 10^{-3}	
Γ_{37}	$3h^-2h^+$ $\geq$ 0 neutrals ν_τ ("5-prong")	(1.11±0.24) × 10^{-3}	
Γ_{38}	$3h^-2h^+\nu_\tau$	(5.6 ±1.6) × 10^{-4}	
Γ_{39}	$3h^-2h^+\pi^0\nu_\tau$	(5.1 ±2.2) × 10^{-4}	
Γ_{40}	$4h^-3h^+$ $\geq$ 0 neutrals ν_τ ("7-prong")	< 1.9 × 10^{-4}	CL=90%
Γ_{41}	K^0h^- $\geq$ 0 neutrals ν_τ	(1.30±0.30) %	
Γ_{42}	$K^*(892)^-$ $\geq$ 0 neutrals ν_τ	(1.43±0.17) %	
Γ_{43}	K^-K^0 $\geq$ 0 neutrals ν_τ	< 8 × 10^{-3}	CL=90%
Γ_{44}	$K^*(892)^0K^-$ $\geq$ 0 neutrals ν_τ	(3.2 ±1.4) × 10^{-3}	
Γ_{45}	$\overline{K}^*(892)^0\pi^-$ $\geq$ 0 neutrals ν_τ	(3.8 ±1.7) × 10^{-3}	
Γ_{46}	$a_0(980)^-$ $\geq$ 0 neutrals ν_τ		
Γ_{47}	$K^*(892)^-\nu_\tau$	(1.42±0.18) %	
Γ_{48}	$K_2^*(1430)^-\nu_\tau$	< 3 × 10^{-3}	CL=95%
Γ_{49}	$K^0K^-\nu_\tau$	< 2.6 × 10^{-3}	CL=95%
Γ_{50}	K^0K^- $\geq$ 1 neutrals ν_τ	< 2.6 × 10^{-3}	CL=95%
Γ_{51}	$K^0h^+h^-h^-$ $\geq$ 0 neutrals ν_τ	< 1.7 × 10^{-3}	CL=95%
Γ_{52}	$\eta\pi^-$ $\geq$ 0 neutrals ν_τ	< 1.3 %	CL=95%
Γ_{53}	$\eta\pi^-\nu_\tau$	< 9 × 10^{-3}	CL=95%
Γ_{54}	$\eta\pi^-\pi^0\nu_\tau$	< 1.1 %	CL=95%
Γ_{55}	$\eta\pi^-\pi^0\pi^0\nu_\tau$	< 1.2 %	CL=95%
	The following are sometimes subreactions of 3-prong inclusive η searches		
Γ_{56}	$\eta\pi^+\pi^-\pi^-$ $\geq$ 0 neutrals ν_τ	< 3 × 10^{-3}	CL=90%
Γ_{57}	$\eta\eta\pi^-$ $\geq$ 0 neutrals ν_τ	< 5 × 10^{-3}	CL=90%
Γ_{58}	$\eta\eta\pi^-\nu_\tau$	< 8.3 × 10^{-3}	CL=95%
Γ_{59}	$\eta\eta\pi^-\pi^0\nu_\tau$	< 9 × 10^{-3}	CL=95%

Lepton number (L) or Lepton Family number (LF) violating modes (In the modes below, ℓ means a sum over e and μ modes)

Γ_{60}	e^- charged particles + μ^- charged particles	LF	<4	%	CL=90%
Γ_{61}	μ^- charged particles	LF			
Γ_{62}	e^- charged particles	LF			
Γ_{63}	$\mu^-\gamma$	LF	<5.5	$\times 10^{-4}$	CL=90%
Γ_{64}	$e^-\gamma$	LF	<2.0	$\times 10^{-4}$	CL=90%
Γ_{65}	$\mu^-\pi^0$	LF	<8.2	$\times 10^{-4}$	CL=90%
Γ_{66}	$e^-\pi^0$	LF	<1.4	$\times 10^{-4}$	CL=90%
Γ_{67}	μ^-K^0	LF	<1.0	$\times 10^{-3}$	CL=90%
Γ_{68}	e^-K^0	LF	<1.3	$\times 10^{-3}$	CL=90%
Γ_{69}	$\mu^-\rho^0$	LF	<3.8	$\times 10^{-5}$	CL=90%
Γ_{70}	$e^-\rho^0$	LF	<3.9	$\times 10^{-5}$	CL=90%
Γ_{71}	$e^-K^*(892)^0$	LF	<5.4	$\times 10^{-5}$	CL=90%
Γ_{72}	$\mu^-K^*(892)^0$	LF	<5.9	$\times 10^{-5}$	CL=90%
Γ_{73}	$e^-\eta$	LF	<2.4	$\times 10^{-4}$	CL=90%
Γ_{74}	$\ell^-\ell^-\ell^+$	LF	<3.4	$\times 10^{-5}$	CL=90%
Γ_{75}	$e^-e^+e^-$	LF	<2.7	$\times 10^{-5}$	CL=90%
Γ_{76}	$(e\mu\mu)^-$	LF	<2.7	$\times 10^{-5}$	CL=90%
Γ_{77}	$e^-\mu^+\mu^-$	LF	<2.7	$\times 10^{-5}$	CL=90%
Γ_{78}	$e^+\mu^-\mu^-$	LF	<1.6	$\times 10^{-5}$	CL=90%
Γ_{79}	$(\mu ee)^-$	LF	<2.7	$\times 10^{-5}$	CL=90%
Γ_{80}	$\mu^-e^+e^-$	LF	<2.7	$\times 10^{-5}$	CL=90%
Γ_{81}	$\mu^+e^-e^-$	LF	<1.6	$\times 10^{-5}$	CL=90%
Γ_{82}	$\mu^-\mu^+\mu^-$	LF	<1.7	$\times 10^{-5}$	CL=90%
Γ_{83}	$\ell^\pm\pi^\mp\pi^-$	L,LF	<6.3	$\times 10^{-5}$	CL=90%
Γ_{84}	$e^\mp\pi^\pm\pi^-$	L,LF	<6.0	$\times 10^{-5}$	CL=90%
Γ_{85}	$e^-\pi^+\pi^-$	LF	<4.2	$\times 10^{-5}$	CL=90%
Γ_{86}	$e^+\pi^-\pi^-$	L,LF	<1.7	$\times 10^{-5}$	CL=90%
Γ_{87}	$\mu^\mp\pi^\pm\pi^-$	L,LF	<3.9	$\times 10^{-5}$	CL=90%
Γ_{88}	$\mu^-\pi^+\pi^-$	LF	<3.9	$\times 10^{-5}$	CL=90%
Γ_{89}	$\mu^+\pi^-\pi^-$	L,LF	<3.9	$\times 10^{-5}$	CL=90%
Γ_{90}	$\ell^\pm\pi^\mp K^-$	L,LF	<1.2	$\times 10^{-4}$	CL=90%
Γ_{91}	$(e\pi K)^-$, all charged	L,LF	<7.7	$\times 10^{-5}$	CL=90%
Γ_{92}	$e^-\pi^\pm K^\mp$	LF	<5.8	$\times 10^{-5}$	CL=90%
Γ_{93}	$e^-\pi^+K^-$	LF	<4.2	$\times 10^{-5}$	CL=90%
Γ_{94}	$e^-\pi^-K^+$	LF	<5.8	$\times 10^{-5}$	CL=90%
Γ_{95}	$e^+\pi^-K^-$	L,LF	<4.9	$\times 10^{-5}$	CL=90%
Γ_{96}	$(\mu\pi K)^-$, all charged	L,LF	<7.7	$\times 10^{-5}$	CL=90%
Γ_{97}	$\mu^-\pi^\pm K^\mp$	LF	<7.7	$\times 10^{-5}$	CL=90%
Γ_{98}	$\mu^-\pi^+K^-$	LF	<7.7	$\times 10^{-5}$	CL=90%
Γ_{99}	$\mu^-\pi^-K^+$	LF	<7.7	$\times 10^{-5}$	CL=90%
Γ_{100}	$\mu^+\pi^-K^-$	L,LF	<4.0	$\times 10^{-5}$	CL=90%
Γ_{101}	e^- light spinless boson	LF	<3.2	$\times 10^{-3}$	CL=95%
Γ_{102}	μ^- light spinless boson	LF	<6	$\times 10^{-3}$	CL=95%

CONSTRAINED FIT INFORMATION

An overall fit to 23 branching ratios uses 101 measurements and one constraint to determine 11 parameters. The overall fit has a $\chi^2 = 91.8$ for 91 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_4	−4									
x_7	−5	−5								
x_9	0	0	−53							
x_{13}	−11	−11	−11	0						
x_{16}	−8	−8	−9	0	−21					
x_{17}	−10	−10	−12	0	−26	−72				
x_{20}	−2	−1	−1	0	−2	−2	−3			
x_{25}	−2	−1	−1	0	−2	−2	−2	−84		
x_{37}	−1	0	−1	0	−1	−1	−1	0	0	
x_{47}	−1	0	−14	0	−8	−2	−2	−5	−4	0
	x_2	x_4	x_7	x_9	x_{13}	x_{16}	x_{17}	x_{20}	x_{25}	x_{37}

τ^- BRANCHING RATIOS

$\Gamma(\text{particle}^- \geq 0 \text{ neutrals } \nu_\tau \text{ ("1-prong")})/\Gamma_{total}$

$\Gamma_1/\Gamma = (\Gamma_2+\Gamma_4+\Gamma_7+\Gamma_9+\Gamma_{13}+\Gamma_{16}+\Gamma_{17}+0.771\Gamma_{47})/\Gamma$

Charged particle can be e, μ, or hadron. Since 5-prong branching fraction is very small this branching fraction is not independent of 3-prong value ($\Gamma(2h^- h^+ \geq 0$ neutrals ν_τ ("3-prong"))/Γ_{total}).

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
85.82±0.25 OUR FIT	Error includes scale factor of 1.3.			
85.6 ±0.6 OUR AVERAGE				
$85.45^{+0.69}_{-0.73}\pm0.65$		DECAMP	92C ALEP	E^{ee}_{cm}= 88–95 GeV
85.6 ±0.6 ±0.3	3300	[3] ADEVA	91F L3	E^{ee}_{cm}= 88.3–94.3 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
86.4 ±0.3 ±0.3		ABACHI	89B HRS	E^{ee}_{cm}= 29 GeV
84.9 ±0.4 ±0.3		BEHREND	89B CELL	E^{ee}_{cm}= 14–47 GeV
84.7 ±0.8 ±0.6		[4] AIHARA	87B TPC	E^{ee}_{cm}= 29 GeV
87.1 ±1.0 ±0.7		[5] BURCHAT	87 MRK2	E^{ee}_{cm}= 29 GeV
87.9 ±0.5 ±1.2		RUCKSTUHL	86 DLCO	E^{ee}_{cm}= 29 GeV
87.2 ±0.5 ±0.8		SCHMIDKE	86 MRK2	E^{ee}_{cm}= 29 GeV
86.9 ±0.2 ±0.3	4098	AKERLOF	85B HRS	Repl. by ABACHI 89B
$84.7\pm1.1\ ^{+1.6}_{-1.3}$	169	[6] ALTHOFF	85 TASS	E^{ee}_{cm}= 34.5 GeV
86.1 ±0.5 ±0.9		BARTEL	85F JADE	E^{ee}_{cm}= 34.6 GeV
87.8 ±1.3 ±3.9		[7] BERGER	85 PLUT	E^{ee}_{cm}= 34.6 GeV
86.7 ±0.3 ±0.6		FERNANDEZ	85 MAC	E^{ee}_{cm}= 29 GeV
85.2 ±0.9 ±1.5	660	AIHARA	84C TPC	Repl. by AIHARA 87B
85.2 ±2.6 ±1.3	178	BEHREND	84 CELL	Repl. by BEHREND 89B
85.1 ±2.8 ±1.3	182	BEHREND	84 CELL	Repl. by BEHREND 89B
84.0 ±2.0	672	BEHREND	82 CELL	Repl. by BEHREND 89B
86 ±2 ±1	764	BLOCKER	82C MRK2	Repl. by SCHMIDKE 86

[3] Not independent of ADEVA 91F $\Gamma(2h^- h^+ \geq 0$ neutrals ν_τ ("3-prong"))/Γ_{total} value.
[4] Not independent of AIHARA 87B $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{total}$, $\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{total}$, and $\Gamma(h^- \geq 0$ neutrals $\nu_\tau)/\Gamma_{total}$ values.
[5] Not independent of SCHMIDKE 86 value (also not independent of BURCHAT 87 value for $\Gamma(2h^- h^+ \geq 0$ neutrals ν_τ ("3-prong"))/Γ_{total}.
[6] Not independent of ALTHOFF 85 $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{total}$, $\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{total}$, $\Gamma(h^- \geq 0$ neutrals $\nu_\tau)/\Gamma_{total}$, and $\Gamma(2h^- h^+ \geq 0$ neutrals ν_τ ("3-prong"))/Γ_{total} values.
[7] Not independent of (1-prong + $0\pi^0$) and (1-prong + $\geq 1\pi^0$) values.

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{total}$ — Γ_2/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
17.58±0.27 OUR FIT	Error includes scale factor of 1.1.			
17.33±0.29 OUR AVERAGE				
17.35±0.41±0.37		DECAMP	92C ALEP	E^{ee}_{cm}= 88–95 GeV
17.5 ±0.8 ±0.5	624	ADEVA	91F L3	E^{ee}_{cm}= 88.3–94.3 GeV
16.8 ±0.5 ±0.4	903	ALEXANDER	91D OPAL	E^{ee}_{cm}= 88.3–94.3 GeV
17.7 ±0.8 ±0.4	568	BEHREND	90 CELL	E^{ee}_{cm}= 35 GeV
17.4 ±1.0	2197	ADEVA	88 MRKJ	E^{ee}_{cm}= 14–16 GeV
17.7 ±1.2 ±0.7		AIHARA	87B TPC	E^{ee}_{cm}= 29 GeV
18.3 ±0.9 ±0.8		BURCHAT	87 MRK2	E^{ee}_{cm}= 29 GeV
$12.9\pm1.7\ ^{+0.7}_{-0.5}$		ALTHOFF	85 TASS	E^{ee}_{cm}= 34.5 GeV
18.0 ±1.0 ±0.6		[8] BALTRUSAIT...85	MRK3	E^{ee}_{cm}= 3.77 GeV
19.4 ±1.6 ±1.7	153	BERGER	85 PLUT	E^{ee}_{cm}= 34.6 GeV
17.6 ±2.6 ±2.1	47	BEHREND	83C CELL	E^{ee}_{cm}= 34 GeV
17.8 ±2.0 ±1.8		BERGER	81B PLUT	E^{ee}_{cm}= 9–32 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
17.8 ±0.7 ±0.5		[9] AIHARA	87B TPC	E^{ee}_{cm}= 29 GeV
17.4 ±0.6 ±0.8	1201	ADEVA	86B MRKJ	Repl. by ADEVA 88
18.8 ±0.8 ±0.7	558	[10] BARTEL	86D JADE	E^{ee}_{cm}= 34.6 GeV
17.7 ±0.7		[11] BARTEL	86D JADE	E^{ee}_{cm}= 34.6 GeV
18.3 ±0.9 ±0.5	473	[12] ASH	85B MAC	E^{ee}_{cm}= 29 GeV
17.3 ±0.5		[13] ASH	85B MAC	E^{ee}_{cm}= 29 GeV

[8] Error correlated with BALTRUSAITIS 85 $e\nu\overline{\nu}$ value.
[9] Combined result of AIHARA 87B $e\nu\overline{\nu}$ and $\mu\nu\overline{\nu}$ measurements assuming $B(\mu\nu\overline{\nu})/B(e\nu\overline{\nu}) = 0.973$.
[10] BARTEL 86D assume B("1 prong") = 0.866 ± 0.003.
[11] This is a combined result of BARTEL 86D $e\nu\overline{\nu}$ and $\mu\nu\overline{\nu}$ measurements assuming $B(\mu\nu\overline{\nu})/B(e\nu\overline{\nu}) = 0.973$.
[12] ASH 85B assume B("1 prong") = 0.867.
[13] This is a combined result of ASH 85B $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{total}$, $\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{total}$, and $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma^2_{total}$ measurements assuming $B(\mu\overline{\nu}\nu)/B(e\overline{\nu}\nu) = 0.97$.

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma(\text{particle}^- \geq 0 \text{ neutrals } \nu_\tau \text{ ("1-prong")})$

$\Gamma_2/\Gamma_1 = \Gamma_2/(\Gamma_2+\Gamma_4+\Gamma_7+\Gamma_9+\Gamma_{13}+\Gamma_{16}+\Gamma_{17}+0.771\Gamma_{47})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.2049±0.0031 OUR FIT	Error includes scale factor of 1.1.			
0.214 ±0.008 OUR AVERAGE				
0.217 ±0.009 ±0.008		BARTEL	86D JADE	E^{ee}_{cm}= 34.6 GeV
0.211 ±0.010 ±0.006	390	ASH	85B MAC	E^{ee}_{cm}= 29 GeV

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau\gamma)/\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)$ — Γ_3/Γ_2

$E_\gamma > 37$ MeV.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.013±0.006	10	[14] WU	90	MRK2	E^{ee}_{cm}= 29 GeV

[14] Requirements on detected γs correspond to a τ rest frame energy cutoff $E_\gamma > 37$ MeV.

$\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{total}$ — Γ_4/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
17.93±0.26 OUR FIT Error includes scale factor of 1.1.					
17.94±0.27 OUR AVERAGE					
19.2 ±0.4 ±0.6	2960	AMMAR	92	CLEO	E^{ee}_{cm}= 10.5–10.9 GeV
18.09±0.45±0.45		DECAMP	92C	ALEP	E^{ee}_{cm}= 88–95 GeV
17.7 ±0.7 ±0.6	686	ADEVA	91F	L3	E^{ee}_{cm}= 88.3–94.3 GeV
17.4 ±0.5 ±0.4	964	ALEXANDER	91D	OPAL	E^{ee}_{cm}= 88.3–94.3 GeV
17.0 ±0.5 ±0.6	1.7k	ABACHI	90	HRS	E^{ee}_{cm}= 29 GeV
18.4 ±0.8 ±0.4	644	BEHREND	90	CELL	E^{ee}_{cm}= 35 GeV
16.3 ±0.3 ±3.2		JANSSEN	89	CBAL	E^{ee}_{cm}=9.4–10.6 GeV
18.4 ±1.2 ±1.0		AIHARA	87B	TPC	E^{ee}_{cm}= 29 GeV
19.1 ±0.8 ±1.1		BURCHAT	87	MRK2	E^{ee}_{cm}= 29 GeV
20.4 ±3.0 $^{+1.4}_{-0.9}$		ALTHOFF	85	TASS	E^{ee}_{cm}= 34.5 GeV
18.2 ±0.7 ±0.5		[15] BALTRUSAIT...	85	MRK3	E^{ee}_{cm}= 3.77 GeV
13.0 ±1.9 ±2.9		BERGER	85	PLUT	E^{ee}_{cm}= 34.6 GeV
18.3 ±2.4 ±1.9	60	BEHREND	83C	CELL	E^{ee}_{cm}= 34 GeV
16.0 ±1.3	459	[16] BACINO	78B	DLCO	E^{ee}_{cm}= 3.1–7.4 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
18.3 ±0.7 ±0.5		[17] AIHARA	87B	TPC	E^{ee}_{cm}= 29 GeV
17.0 ±0.7 ±0.9	515	[18] BARTEL	86D	JADE	E^{ee}_{cm}= 34.6 GeV
18.2 ±0.8		[19] BARTEL	86D	JADE	E^{ee}_{cm}= 34.6 GeV
18.0 ±0.9 ±0.6	390	[20] ASH	85B	MAC	E^{ee}_{cm}= 29 GeV
17.8 ±0.5		[21] ASH	85B	MAC	E^{ee}_{cm}= 29 GeV

[15] Error correlated with BALTRUSAITIS 85 $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{total}$.

[16] BACINO 78B value comes from fit to events with $e^\pm$ and one other nonelectron charged prong.

[17] Combined result of AIHARA 87B $e\nu\overline{\nu}$ and $\mu\nu\overline{\nu}$ measurements assuming $B(\mu\nu\overline{\nu})/B(e\nu\overline{\nu}) = 0.973$.

[18] BARTEL 86D assume B("1 prong") = 0.866 ± 0.003.

[19] Combined result of BARTEL 86D $e\nu\overline{\nu}$ and $\mu\nu\overline{\nu}$ measurements assuming $B(\mu\nu\overline{\nu})/B(e\nu\overline{\nu}) = 0.973$.

[20] ASH 85B assume B("1 prong") = 0.867.

[21] This is a combined result of ASH 85B $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{total}$, $\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{total}$, and $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma^2_{total}$ measurements assuming $B(\mu\overline{\nu}\nu)/B(e\overline{\nu}\nu) = 0.97$.

$\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma(\text{particle}^- \geq 0 \text{ neutrals } \nu_\tau \text{ ("1-prong")})$

$\Gamma_4/\Gamma_1=\Gamma_4/(\Gamma_2+\Gamma_4+\Gamma_7+\Gamma_9+\Gamma_{13}+\Gamma_{16}+\Gamma_{17}+0.771\Gamma_{47})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.2089±0.0031 OUR FIT Error includes scale factor of 1.1.					
0.202 ±0.009 OUR AVERAGE					
0.196 ±0.008 ±0.010		BARTEL	86D	JADE	E^{ee}_{cm}= 34.6 GeV
0.208 ±0.010 ±0.007	390	ASH	85B	MAC	E^{ee}_{cm}= 29 GeV

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma^2_{total}$ — $\Gamma_2\Gamma_4/\Gamma^2$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0315±0.0006 OUR FIT Error includes scale factor of 1.1.					
0.0293±0.0022 OUR AVERAGE					
0.0288±0.0017±0.0019		ASH	85B	MAC	E^{ee}_{cm}= 29 GeV
0.030 ±0.005	257	BLOCKER	82D	MRK2	E^{ee}_{cm}= 3.5–6.7 GeV
0.034 ±0.008 ±0.005	20	[22] BACINO	79C	DLCO	E^{ee}_{cm}= 3.6–7.4 GeV

[22] BACINO 79C quotes $B(\mu) = 0.21 \pm 0.05 \pm 0.03$ assuming $B(e) = 0.16$. We multiply by 0.16 to get above value.

$\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)$ — Γ_4/Γ_2

Predicted to be 1 for sequential lepton, 2 for para-electron, and 1/2 for para-muon. Para-electron also ruled out by HEILE 78.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.020±0.022 OUR FIT Error includes scale factor of 1.1.					
0.86 ±0.17 OUR AVERAGE					
0.75 ±0.23	154	[23] BLOCKER	82D	MRK2	E^{ee}_{cm}= 3.5–6.7 GeV
1.09 ±0.38	18	[24] BRANDELIK	78	DASP	E^{ee}_{cm}= 3.1–5.2 GeV
0.92 ±0.37	21	BURMESTER	77C	PLUT	Assumes V−A decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.91 ±0.06 ±0.05		[25] BARTEL	86D	JADE	E^{ee}_{cm}= 34.6 GeV
0.98 ±0.07 ±0.04	390	[26] ASH	85B	MAC	E^{ee}_{cm}= 29 GeV

[23] BLOCKER 82D gives the inverse of this ratio as 1.33 ± 0.18 ± 0.36.

[24] BRANDELIK 78 quotes the inverse of this ratio as 0.92 ± 0.32.

[25] BARTEL 86D gives the inverse of this ratio as 1.10 ± 0.07 ± 0.06. Not independent of BARTEL 86D $e\nu\overline{\nu}$ and $\mu\nu\overline{\nu}$ values.

[26] Not independent of ASH 85B $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{total}$ and $\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{total}$ values.

$\Gamma(h^-\nu_\tau)/\Gamma(\text{particle}^- \geq 0 \text{ neutrals } \nu_\tau \text{ ("1-prong")})$

$\Gamma_6/\Gamma_1=(\Gamma_7+\Gamma_9+\frac{1}{3}\Gamma_{47})/(\Gamma_2+\Gamma_4+\Gamma_7+\Gamma_9+\Gamma_{13}+\Gamma_{16}+\Gamma_{17}+0.771\Gamma_{47})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.148±0.004 OUR FIT Error includes scale factor of 1.1.					
0.135±0.009 OUR AVERAGE					
0.131±0.006±0.009	798	[27] FORD	87	MAC	E^{ee}_{cm}= 29 GeV
0.143±0.007±0.013	328	[28] BARTEL	86D	JADE	E^{ee}_{cm}= 34.6 GeV

[27] FORD 87 result divided by 0.865, their assumed value for B("1 prong").

[28] BARTEL 86D result divided by 0.866, their assumed value for B("1 prong").

$\Gamma(\pi^-\nu_\tau)/\Gamma_{total}$ — Γ_7/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
11.6±0.4 OUR FIT Error includes scale factor of 1.2.					
11.7±0.4±1.8	1138	BLOCKER	82D	MRK2	E^{ee}_{cm}= 3.5–6.7 GeV

$\Gamma(\pi^-\nu_\tau)\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma^2_{total}$ — $\Gamma_4\Gamma_7/\Gamma^2$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0207±0.0008 OUR FIT Error includes scale factor of 1.2.					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.013 ±0.005 ±0.002	10	[29] BACINO	79C	DLCO	E^{ee}_{cm}= 3.6–7.4 GeV
0.015 ±0.005 ±0.005	23	[30] ALEXANDER	78B	PLUT	E^{ee}_{cm}= 3.6–5 GeV

[29] BACINO 79C quote $B(\pi) = 0.080 \pm 0.032 \pm 0.013$ assuming $B(e) = 0.16$. We multiply by 0.16 to get above value.

[30] ALEXANDER 78B quote $B(\pi) = 0.090 \pm 0.029 \pm 0.029$ using $B(e) = 0.167 \pm 0.010$. We multiply by 0.167 to get above value.

$\Gamma(h^-\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ — $\Gamma_6/\Gamma_4=(\Gamma_7+\Gamma_9+\frac{1}{3}\Gamma_{47})/\Gamma_4$

VALUE	DOCUMENT ID		TECN	COMMENT
0.708±0.023 OUR FIT Error includes scale factor of 1.1.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.647±0.039±0.061	[31] BARTEL	86D	JADE	E^{ee}_{cm}= 34.6 GeV

[31] Combined result of BARTEL 86D $e\nu\overline{\nu}$, $\mu\nu\overline{\nu}$, and $\pi^-\nu$ assuming $B(\mu\nu\overline{\nu})/B(e\nu\overline{\nu}) = 0.973$.

$\Gamma(K^-\nu_\tau)/\Gamma_{total}$ — Γ_9/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.67±0.23 OUR FIT Error includes scale factor of 1.3.					
0.67±0.23 OUR AVERAGE Error includes scale factor of 1.3.					
0.59±0.18	16	MILLS	84	DLCO	E^{ee}_{cm}= 29 GeV
1.3 ±0.5	15	BLOCKER	82B	MRK2	E^{ee}_{cm}= 3.9–6.7 GeV

$\Gamma(h^-\nu_\tau)/\Gamma_{total}$ — $\Gamma_6/\Gamma=(\Gamma_7+\Gamma_9+\frac{1}{3}\Gamma_{47})/\Gamma$

Inclusion of the $\frac{1}{3}B(\tau^- \to K^*(892)^-\nu_\tau)$ corrects, at <0.26% level, for undetected K^0_L's, which are predominately from $K^*(892)^-$ decay.

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
12.7 ±0.4 OUR FIT Error includes scale factor of 1.1.					
12.7 ±0.4 OUR AVERAGE					
13.32±0.44±0.33		[32] DECAMP	92C	ALEP	E^{ee}_{cm}= 88–95 GeV
12.1 ±0.7 ±0.5	309	ALEXANDER	91D	OPAL	E^{ee}_{cm}= 88.3–94.3 GeV
12.3 ±0.9 ±0.5	1338	BEHREND	90	CELL	E^{ee}_{cm}= 35 GeV
11.1 ±1.1 ±1.4		[33] BURCHAT	87	MRK2	E^{ee}_{cm}= 29 GeV
13.0 ±2.0 ±4.0		BERGER	85	PLUT	E^{ee}_{cm}= 34.6 GeV
11.2 ±1.7 ±1.2	34	[34] BEHREND	83C	CELL	E^{ee}_{cm}= 34 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
11.3 ±0.5 ±0.8	798	[35] FORD	87	MAC	E^{ee}_{cm}= 29 GeV
12.3 ±0.6 ±1.1	328	[36] BARTEL	86D	JADE	E^{ee}_{cm}= 34.6 GeV

[32] DECAMP 92C consider $\tau^- \to h^-(K^0_S \to \pi^+\pi^-)\nu$ to be a 1-prong mode, which affects their 1-prong topological branching ratio relative to other experiments.

[33] BURCHAT 87 with 1.1% added to remove their correction for K^- and $K^*(892)^-$ backgrounds.

[34] BEHREND 83C quote $B(\pi^-\nu_\tau) = 9.9 \pm 1.7 \pm 1.3$ after subtracting 1.3 ± 0.5 to correct for $B(K^-\nu_\tau)$.

[35] FORD 87 result with 0.67% added to remove their K^- correction and adjusted for 1992 B("1 prong").

[36] BARTEL 86D result with 0.59% added to remove their K^- correction and adjusted for 1992 B("1 prong").

$\Gamma(K^- \geq 1 \text{ neutrals } \nu_\tau)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.2±0.5$^{+0.2}_{-0.4}$	9	AIHARA	87B	TPC	E^{ee}_{cm}= 29 GeV

$\Gamma(K^- \geq 0 \text{ neutrals } \nu_\tau)/\Gamma_{total}$ — $\Gamma_8/\Gamma=(\Gamma_9+\Gamma_{10})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.68±0.24 OUR AVERAGE					
1.6 ±0.4 ±0.2	35	AIHARA	87B	TPC	E^{ee}_{cm}= 29 GeV
1.71±0.29	53	MILLS	84	DLCO	E^{ee}_{cm}= 29 GeV

$\Gamma(h^-\pi^0\nu_\tau)/\Gamma_{\text{total}}$ — $\Gamma_{12}/\Gamma=(\Gamma_{13}+\frac{1}{3}\Gamma_{47})/\Gamma$

Inclusion of the $\frac{1}{3}B(\tau^- \to K^*(892)^-\nu_\tau)$ corrects, at <0.26% level, for undetected K^0_L's, which are predominately from $K^*(892)^-$ decay.

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
24.4 ±0.6 OUR FIT Error includes scale factor of 1.1.				
23.8 ±0.8 OUR AVERAGE				
25.02±0.64±0.88	1849	DECAMP 92C	ALEP	E^{ee}_{cm}= 88–95 GeV
22.0 ±0.8 ±1.9	800	ANTREASYAN 91	CBAL	E^{ee}_{cm}= 9.4–10.6 GeV
22.6 ±1.5 ±0.7	1101	BEHREND 90	CELL	E^{ee}_{cm}= 35 GeV
23.1 ±1.9 ±1.6		BEHREND 84	CELL	E^{ee}_{cm}= 14,22 GeV

$\Gamma(\pi^-\pi^0\nu_\tau)/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
24.0±0.6 OUR FIT Error includes scale factor of 1.1.				
22.2±1.0 OUR AVERAGE				
21.5±0.4±1.9	4400	[37] ALBRECHT 88L	ARG	E^{ee}_{cm}= 10 GeV
23.0±1.3±1.7	582	ADLER 87B	MRK3	E^{ee}_{cm}= 3.77 GeV
22.3±0.6±1.4	629	YELTON 86	MRK2	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
25.8±1.7±2.5		[38] BURCHAT 87	MRK2	E^{ee}_{cm}= 29 GeV

[37] The authors divide by $(\Gamma_2+\Gamma_4+\Gamma_7+\Gamma_9)/\Gamma = 0.467$ to obtain this result.
[38] BURCHAT 87 value is not independent of YELTON 86 value. Nonresonant decays included.

$\Gamma(\pi^-\pi^0\text{ non-}\rho(770)\,\nu_\tau)/\Gamma_{\text{total}}$ — Γ_{14}/Γ

VALUE (%)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.3±0.1±0.3	[39] BEHREND 84	CELL	E^{ee}_{cm}= 14,22 GeV

[39] BEHREND 84 assume a flat nonresonant mass distribution down to the $\rho(770)$ mass, using events with mass above 1300 to set the level.

$\Gamma(h^- \geq 2\pi^0\nu_\tau)/\Gamma_{\text{total}}$ — $\Gamma_{15}/\Gamma=(\Gamma_{16}+\Gamma_{17}+0.105\Gamma_{47})/\Gamma$

Experimental situation is confused. The data below are not added into the overall fit at this time. Acceptances for individual modes contributing to this category vary greatly. For modes $(\tau^- \to \pi^- X\,\nu_\tau)$, AIHARA 86E (TPC) quote $B(2\pi^0\pi^-\nu_\tau) + 1.6B(3\pi^0\pi^-\nu_\tau) + 1.1B(\pi^0\eta\pi^-\nu_\tau) = 0.139 \pm 0.020 \pm 0.019$ and GAN 87 (Mark II) quote $B(2\pi^0\pi^-\nu_\tau) + 0.95B(3\pi^0\pi^-\nu_\tau) + 0.43B(\pi^0\eta\pi^-\nu_\tau) = 0.090 \pm 0.010 \pm 0.012$.

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
13.2±0.7 OUR FIT Error includes scale factor of 1.3.				
13.7±1.1 OUR AVERAGE				
14.0±1.2±0.6	938	BEHREND 90	CELL	E^{ee}_{cm}= 35 GeV
12.0±1.4±2.5		[40] BURCHAT 87	MRK2	E^{ee}_{cm}= 29 GeV
$13.9\pm2.0^{+1.9}_{-2.2}$		AIHARA 86E	TPC	E^{ee}_{cm}= 29 GeV

[40] Error correlated with BURCHAT 87 $\Gamma(\rho^-\nu e)/\Gamma$(total) value.

$\Gamma(h^- \geq 1\text{ neutrals }\nu_\tau)/\Gamma_{\text{total}}$ — $\Gamma_{11}/\Gamma=(\Gamma_{13}+\Gamma_{16}+\Gamma_{17}+0.438\Gamma_{47})/\Gamma$

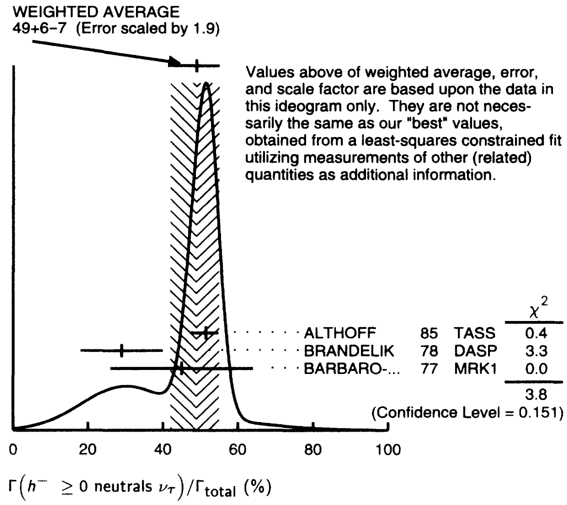
VALUE (%)	DOCUMENT ID	TECN	COMMENT
37.6±0.5 OUR FIT Error includes scale factor of 1.2.			
39.1±1.6 OUR AVERAGE Error includes scale factor of 1.1.			
38.4±1.2±1.0	[41] BURCHAT 87	MRK2	E^{ee}_{cm}= 29 GeV
42.7±2.0±2.9	BERGER 85	PLUT	E^{ee}_{cm}= 34.6 GeV

[41] BURCHAT 87 quote for $B(\pi^\pm \geq 1\text{ neutral }\nu_\tau) = 0.378 \pm 0.012 \pm 0.010$. We add 0.006 to account for contribution from $(K^{*-}\nu_\tau)$ which they fixed at BR = 0.013.

$\Gamma(h^- \geq 0\text{ neutrals }\nu_\tau)/\Gamma_{\text{total}}$ — $\Gamma_5/\Gamma=(\Gamma_7+\Gamma_9+\Gamma_{13}+\Gamma_{16}+\Gamma_{17}+0.771\Gamma_{47})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
50.3± 0.4 OUR FIT Error includes scale factor of 1.2.				
$49\ ^{+6}_{-7}$ OUR AVERAGE Error includes scale factor of 1.9. See the ideogram below.				
$51.5\pm\ 2.9^{+1.6}_{-2.6}$		ALTHOFF 85	TASS	E^{ee}_{cm}= 34.5 GeV
29 ±11		BRANDELIK 78	DASP	Assumes V−A decay
45 ±19	19	BARBARO-... 77	MRK1	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
48.6± 1.2±0.9		[42] AIHARA 87B	TPC	E^{ee}_{cm}= 29 GeV
22 ±14		[43] BRANDELIK 80	TASS	E^{ee}_{cm}= 30 GeV

[42] Not independent of AIHARA 87B $e\nu\overline{\nu}$, $\mu\nu\overline{\nu}$, and $\pi^+2\pi^-(\geq 0\pi^0)\nu$ values.
[43] Not independent of BRANDELIK 80 $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{\text{total}}$, $\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{\text{total}}$, and Γ(particle$^-$ ≥ 0 neutrals ν_τ ("1-prong"))$/\Gamma_{\text{total}}$ values.

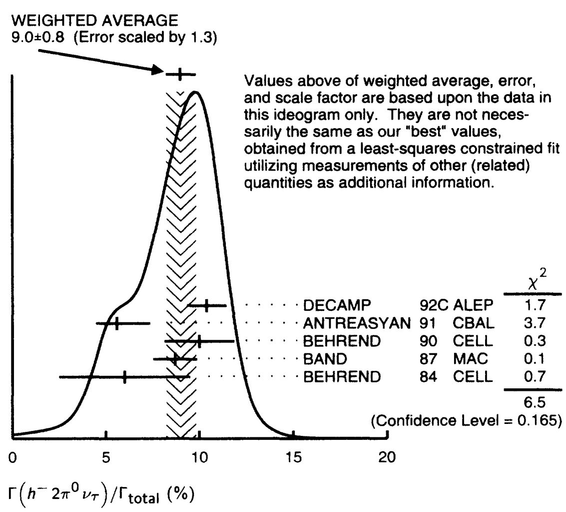


$\Gamma(h^-2\pi^0\nu_\tau)/\Gamma_{\text{total}}$ — Γ_{16}/Γ

Entries are corrected for $K^*(892)^-\nu_\tau$ contributions.

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
10.3 ±0.9 OUR FIT Error includes scale factor of 1.7.				
9.0 ±0.8 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.				
10.38±0.66±0.82	809	[44] DECAMP 92C	ALEP	E^{ee}_{cm}= 88–95 GeV
$5.6\ \pm0.5\ ^{+1.7}_{-1.0}$	133	[45] ANTREASYAN 91	CBAL	E^{ee}_{cm}= 9.4–10.6 GeV
10.0 ±1.5 ±1.1	333	[46] BEHREND 90	CELL	E^{ee}_{cm}= 35 GeV
8.7 ±0.4 ±1.1	815	[47] BAND 87	MAC	E^{ee}_{cm}= 29 GeV
6.0 ±3.0 ±1.8		BEHREND 84	CELL	E^{ee}_{cm}= 14,22 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
6.2 ±0.6 ±1.2		[48] GAN 87	MRK2	E^{ee}_{cm}= 29 GeV

[44] We subtract 0.0015 to account for $\tau^- \to K^*(892)^-\nu_\tau$ contribution.
[45] ANTREASYAN 91 subtract 0.001 to account for the $\tau^- \to K^*(892)^-\nu_\tau$ contribution.
[46] BEHREND 90 subtract 0.002 to account for the $\tau^- \to K^*(892)^-\nu_\tau$ contribution.
[47] BAND 87 assume $B(\pi^-3\pi^0\nu_\tau) = 0.01$ and $B(\pi^-\pi^0\eta\nu_\tau) = 0.005$.
[48] GAN 87 analysis use photon multiplicity distribution. See comments for $\Gamma(h^- \geq 2\pi^0\nu_\tau)/\Gamma_{\text{total}}$.



$\Gamma(h^- \geq 3\pi^0\nu_\tau)/\Gamma_{\text{total}}$ — Γ_{17}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
2.7 ±0.9 OUR FIT Error includes scale factor of 1.9.				
1.8 ±0.5 OUR AVERAGE				
1.53±0.40±0.46	186	DECAMP 92C	ALEP	E^{ee}_{cm}= 88–95 GeV
3.2 ±1.0 ±1.0		[49] BEHREND 90	CELL	E^{ee}_{cm}= 35 GeV
3.0 ±2.2 ±1.5		BEHREND 84	CELL	E^{ee}_{cm}= 14,22 GeV

[49] Not independent of BEHREND 90 $\Gamma(\text{hadron}^- \geq 2\pi^0\nu_\tau)/\Gamma_{\text{total}}$ and $\Gamma(\pi^-2\pi^0\nu_\tau)/\Gamma_{\text{total}}$ values.

$\Gamma(h^- 3\pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{18}/Γ

VALUE (%)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.0^{+1.4}_{-0.1}{}^{+1.1}_{-0.1}$	[50] GAN	87	MRK2	E^{ee}_{cm}= 29 GeV

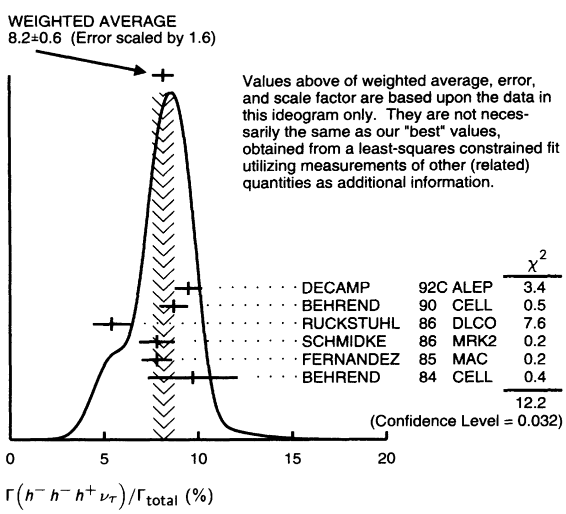
[50] Highly correlated with GAN 87 $\Gamma(\eta\pi^-\pi^0\nu_\tau)/\Gamma_{total}$ value. Authors quote $B(\pi^\pm 3\pi^0\nu_\tau) + 0.67B(\pi^\pm\eta\pi^0\nu_\tau) = 0.047 \pm 0.010 \pm 0.011$.

$\Gamma(h^- h^- h^+ \nu_\tau)/\Gamma_{total}$ — Γ_{20}/Γ

Some inconsistency exists for this mode since experiments differ in how they treat $B(\tau^- \to h^-(K^0_S \to \pi^+\pi^-)\nu_\tau)$ decays.

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
8.4 ±0.4 OUR FIT Error includes scale factor of 1.4.					
8.2 ±0.6 OUR AVERAGE Error includes scale factor of 1.6. See the ideogram below.					
9.49±0.36±0.63		DECAMP	92C	ALEP	E^{ee}_{cm}= 88–95 GeV
8.7 ±0.7 ±0.3	694	[51] BEHREND	90	CELL	E^{ee}_{cm}= 35 GeV
5.4 ±1.0		RUCKSTUHL	86	DLCO	E^{ee}_{cm}= 29 GeV
7.8 ±0.5 ±0.8	890	SCHMIDKE	86	MRK2	E^{ee}_{cm}= 29 GeV
7.8 ±0.8	1255	[52] FERNANDEZ	85	MAC	E^{ee}_{cm}= 29 GeV
9.7 ±2.0 ±1.3		BEHREND	84	CELL	E^{ee}_{cm}= 14,22 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
7.0 ±0.3 ±0.7	1566	[53] BAND	87	MAC	E^{ee}_{cm}= 29 GeV
6.7 ±0.8 ±0.9		[54] BURCHAT	87	MRK2	E^{ee}_{cm}= 29 GeV

[51] BEHREND 90 subtract 0.3% to account for the $\tau^- \to K^*(892)^-\nu_\tau$ contribution to measured events.
[52] FERNANDEZ 85 result listed with 0.3% subtracted to correct for $\tau^- \to K^*(892)^-$ contribution.
[53] BAND 87 subtract for charged kaon modes; not independent of FERNANDEZ 85 value.
[54] BURCHAT 87 value is not independent of SCHMIDKE 86 value.



$\Gamma(\pi^-\pi^-\pi^+\nu_\tau)/\Gamma_{total}$ — Γ_{21}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
5.6±0.7	593	[55] ALBRECHT	86B	ARG	E^{ee}_{cm}= 10 GeV

[55] ALBRECHT 86B does not include kaon modes. Statistical and systematic errors are added in quadrature by authors.

$\Gamma(\pi^-\rho^0\nu_\tau)/\Gamma_{total}$ — Γ_{22}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
5.4±1.7	27	WAGNER	80	PLUT	E^{ee}_{cm}= 4–5 GeV

$\Gamma(a_1(1260)^-\nu_\tau)/\Gamma_{total}$ — Γ_{23}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
10.8±3.4	27	[56] WAGNER	80	PLUT	E^{ee}_{cm}= 4–5 GeV

[56] Not independent of WAGNER 80 $\Gamma(\pi^-\rho^0\nu_\tau)/\Gamma_{total}$ value. Assumes that all $(\nu\rho^0\pi^\pm)$ events are $(\nu a_1^\pm)$ and $B(\ell^\pm\nu\overline{\nu}) = 0.173 \pm 0.013$.

$\Gamma(\pi^-\pi^-\pi^+ \text{ non-}\rho(770)^0\nu_\tau)/\Gamma_{total}$ — Γ_{24}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<1.4	95	WAGNER	80	PLUT	E^{ee}_{cm}= 4–5 GeV

$\Gamma(h^- h^- h^+ \ge 1 \text{ neutrals } \nu_\tau)/\Gamma_{total}$ — Γ_{25}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
5.3 ±0.4 OUR FIT Error includes scale factor of 1.3.					
4.8 ±0.6 OUR AVERAGE					
4.95±0.29±0.65	570	DECAMP	92C	ALEP	E^{ee}_{cm}= 88–95 GeV
4.2 ±0.5 ±0.9	203	[57] ALBRECHT	87L	ARG	E^{ee}_{cm}= 10 GeV
6.2 ±2.3 ±1.7		BEHREND	84	CELL	E^{ee}_{cm}= 14,22 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5.6 ±0.7 ±0.3	352	[58] BEHREND	90	CELL	E^{ee}_{cm}= 35 GeV
6.1 ±0.8 ±0.9		[59] BURCHAT	87	MRK2	E^{ee}_{cm}= 29 GeV
6.4 ±1.2		[60] RUCKSTUHL	86	DLCO	E^{ee}_{cm}= 29 GeV
4.7 ±0.5 ±0.8	530	[61] SCHMIDKE	86	MRK2	E^{ee}_{cm}= 29 GeV
5.2 ±0.8		FERNANDEZ	85	MAC	E^{ee}_{cm}= 29 GeV

[57] ALBRECHT 87L measure the product of branching ratios $B(3\pi^\pm\pi^0\nu_\tau)$ $B((e\overline{\nu}$ or $\mu\overline{\nu}$ or π or K or ρ) $\nu_\tau) = 0.029$ and use the PDG 86 values for the second branching ratio which sum to 0.69 ± 0.03 to get the quoted value.
[58] BEHREND 90 measurement includes possible events with $>1\pi^0$.
[59] BURCHAT 87 value is not independent of SCHMIDKE 86 value.
[60] Contributions from kaons and from $>1\pi^0$ are subtracted. Not independent of (3-prong $+ 0\pi^0$) and (3-prong $+ \ge 0\pi^0$) values.
[61] Not independent of SCHMIDKE 86 $\pi^+2\pi^-\nu$ and $\pi^+2\pi^-(\ge 0\pi^0)\nu$ values.

$\Gamma(h^- h^- h^+ \nu_\tau)/[\Gamma(h^- h^- h^+ \nu_\tau) + \Gamma(h^- h^- h^+ \ge 1 \text{ neutrals } \nu_\tau)]$ — $\Gamma_{20}/(\Gamma_{20}+\Gamma_{25})$

Not independent of values for $\Gamma(h^- h^- h^+\nu_\tau)/\Gamma_{total}$ and $\Gamma(2h^- h^+ \ge 0$ neutrals ν_τ ("3-prong"))$/\Gamma_{total}$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.611±0.031 OUR FIT Error includes scale factor of 1.4.					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.37\ ^{+0.35}_{-0.20}$	103	ALTHOFF	85	TASS	E^{ee}_{cm}= 34.5 GeV
0.61 ±0.03 ±0.05		FERNANDEZ	85	MAC	E^{ee}_{cm}= 29 GeV

$\Gamma(2h^- h^+ \ge 0 \text{ neutrals } \nu_\tau \text{ ("3-prong")})/\Gamma_{total}$ — $\Gamma_{19}/\Gamma = (\Gamma_{20}+\Gamma_{25}+0.229\Gamma_{47})/\Gamma$

Some inconsistency exists for this mode since experiments differ in how they treat $B(\tau^- \to h^-(K^0_S \to \pi^+\pi^-))$ decays.

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
14.06± 0.25 OUR FIT Error includes scale factor of 1.3.					
14.02± 0.25 OUR AVERAGE Error includes scale factor of 1.2.					
$14.35^{+\ 0.40}_{-\ 0.45}\pm0.24$		DECAMP	92C	ALEP	E^{ee}_{cm}= 88–95 GeV
14.4 ± 0.6 ±0.3		ADEVA	91F	L3	E^{ee}_{cm}= 88.3–94.3 GeV
13.5 ± 0.3 ±0.3		ABACHI	89B	HRS	E^{ee}_{cm}= 29 GeV
15.0 ± 0.4 ±0.3		BEHREND	89B	CELL	E^{ee}_{cm}= 14–47 GeV
15.1 ± 0.8 ±0.6		AIHARA	87B	TPC	E^{ee}_{cm}= 29 GeV
12.1 ± 0.5 ±1.2		RUCKSTUHL	86	DLCO	E^{ee}_{cm}= 29 GeV
12.8 ± 0.5 ±0.8	1420	SCHMIDKE	86	MRK2	E^{ee}_{cm}= 29 GeV
$15.3 \pm 1.1\ ^{+1.3}_{-1.6}$	367	ALTHOFF	85	TASS	E^{ee}_{cm}= 34.5 GeV
13.6 ± 0.5 ±0.8		BARTEL	85F	JADE	E^{ee}_{cm}= 34.6 GeV
13.3 ± 0.3 ±0.6		FERNANDEZ	85	MAC	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
12.8 ± 1.0 ±0.7		[62] BURCHAT	87	MRK2	E^{ee}_{cm}= 29 GeV
13.0 ± 0.2 ±0.3	4098	AKERLOF	85B	HRS	Repl. by ABACHI 89B
12.2 ± 1.3 ±3.9		[63] BERGER	85	PLUT	E^{ee}_{cm}= 34.6 GeV
14.8 ± 0.9 ±1.5	660	AIHARA	84C	TPC	Repl. by AIHARA 87B
14.8 ± 2.0 ±1.3	178	BEHREND	84	CELL	Repl. by BEHREND 89B
14.5 ± 2.2 ±1.3	182	BEHREND	84	CELL	Repl. by BEHREND 89B
15.0 ± 2.0	186	BEHREND	82	CELL	Repl. by BEHREND 89B
14 ± 2	152	BLOCKER	82C	MRK2	Repl. by SCHMIDKE 86
24 ± 6	35	BRANDELIK	80	TASS	E^{ee}_{cm}= 30 GeV
32 ± 5	692	[64] BACINO	78B	DLCO	E^{ee}_{cm}= 3.1–7.4 GeV
35 ±11		[64] BRANDELIK	78	DASP	Assumes V−A decay
18 ± 6.5	33	[64] JAROS	78	MRK1	E^{ee}_{cm}> 6 GeV

[62] BURCHAT 87 value is not independent of SCHMIDKE 86 value.
[63] Not independent of BERGER 85 $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{total}$, $\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{total}$, $\Gamma(h^- \ge 1$ neutrals $\nu_\tau)/\Gamma_{total}$, and $\Gamma(h^-\nu_\tau)/\Gamma_{total}$, and therefore not used in the fit.
[64] Low energy experiments are not in average or fit because the systematic errors in background subtraction are judged to be large.

$\Gamma((a_1(1260)\pi)^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$ — Γ_{27}/Γ_{26}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.44	95	[65] ALBRECHT	91D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

[65] ALBRECHT 91D not independent of their $\Gamma(\omega\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$, $\Gamma(\rho^0\pi^0\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$, $\Gamma(\rho^+\pi^-\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$, and $\Gamma(\rho^-\pi^+\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$ values.

$\Gamma(\rho^0\pi^0\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$ — Γ_{29}/Γ_{26}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.30±0.04±0.02	393	ALBRECHT	91D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

$\Gamma(\rho^+\pi^-\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$ — Γ_{30}/Γ_{26}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.10±0.03±0.04	142	ALBRECHT	91D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

$\Gamma(\rho^-\pi^+\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$ — Γ_{31}/Γ_{26}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.26±0.05±0.01	370	ALBRECHT	91D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

$[\Gamma(\rho^+\pi^-\pi^-\nu_\tau)+\Gamma(\rho^-\pi^+\pi^-\nu_\tau)]/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$ — $(\Gamma_{30}+\Gamma_{31})/\Gamma_{26}$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.33±0.06±0.01	475	[66] ALBRECHT	91D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

[66] ALBRECHT 91D not independent of their $\Gamma(\rho^+\pi^-\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$ and $\Gamma(\rho^-\pi^+\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$ values.

$\Gamma((\rho\pi)^0\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$ — $\Gamma_{28}/\Gamma_{26}=(\Gamma_{29}+\Gamma_{30}+\Gamma_{31})/\Gamma_{26}$

VALUE	DOCUMENT ID		TECN	COMMENT
0.64±0.07±0.03	[67] ALBRECHT	91D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

[67] ALBRECHT 91D not independent of their $\Gamma(\rho^+\pi^-\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$, $\Gamma(\rho^-\pi^+\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$, and $\Gamma(\rho^0\pi^0\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$ values.

$[\Gamma(\rho^0\pi^0\pi^-\nu_\tau)+\Gamma(\rho^+\pi^-\pi^-\nu_\tau)+\Gamma(\rho^-\pi^+\pi^-\nu_\tau)+\Gamma(\omega\pi^-\nu_\tau)]/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$ — $(\Gamma_{29}+\Gamma_{30}+\Gamma_{31}+\Gamma_{33})/\Gamma_{26}$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
>0.81	95	[68] ALBRECHT	91D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

[68] ALBRECHT 91D not independent of their $\Gamma(\omega\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$, $\Gamma(\rho^0\pi^0\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$, $\Gamma(\rho^+\pi^-\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$, and $\Gamma(\rho^-\pi^+\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$ values.

$\Gamma(\omega\pi^- \geq 0\text{ neutrals }\nu_\tau)/\Gamma_{total}$ — Γ_{32}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.65±0.3±0.2	1513	ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV

$\Gamma(\omega\pi^-\nu_\tau)/\Gamma_{total}$ — Γ_{33}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.60±0.27±0.41	139	BARINGER	87	CLEO	E^{ee}_{cm}= 10.5 GeV

$\Gamma(\omega\pi^-\nu_\tau)/\Gamma(\pi^-\pi^-\pi^+\pi^0\nu_\tau)$ — Γ_{33}/Γ_{26}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.33±0.04±0.02	458	ALBRECHT	91D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

$\Gamma(K^-h^+h^- \geq 0\text{ neutrals }\nu_\tau)/\Gamma_{total}$ — Γ_{34}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.6	90	AIHARA	84C	TPC	E^{ee}_{cm}= 29 GeV

$\Gamma(K^-\pi^+\pi^- \geq 0\text{ neutrals }\nu_\tau)/\Gamma_{total}$ — Γ_{35}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
$0.22^{+0.16}_{-0.13}$	9	[69] MILLS	85	DLCO	E^{ee}_{cm}= 29 GeV

[69] Error correlated with MILLS 85 ($KK\pi\nu$) value. Excludes 23% systematic error.

$\Gamma(K^-K^+\pi^-\nu_\tau)/\Gamma_{total}$ — Γ_{36}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
$0.22^{+0.17}_{-0.11}$	9	[70] MILLS	85	DLCO	E^{ee}_{cm}= 29 GeV

[70] Error correlated with MILLS 85 ($K\pi\pi^0\nu$) value. Excludes 23% systematic error.

$\Gamma(3h^-2h^+ \geq 0\text{ neutrals }\nu_\tau\text{ ("5-prong")})/\Gamma_{total}$ — Γ_{37}/Γ

VALUE (%)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.111±0.024 OUR FIT						
0.110±0.024 OUR AVERAGE						
$0.10\ ^{+0.05}_{-0.04}\ \pm0.03$			DECAMP	92C	ALEP	E^{ee}_{cm}= 88–95 GeV
0.16 ±0.13 ±0.04			BEHREND	89B	CELL	E^{ee}_{cm}= 14–47 GeV
0.102±0.029		13	BYLSMA	87	HRS	E^{ee}_{cm}= 29 GeV
0.3 ±0.1 ±0.2			BARTEL	85F	JADE	E^{ee}_{cm}= 34.6 GeV
0.16 ±0.08 ±0.04		4	BURCHAT	85	MRK2	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.34	95		ADEVA	91F	L3	E^{ee}_{cm}= 88.3–94.3 GeV
<0.7	95	0	ALTHOFF	85	TASS	E^{ee}_{cm}= 34.5 GeV
0.13 ±0.04		10	BELTRAMI	85	HRS	Repl. by BYLSMA 87
<0.17	95	2	FERNANDEZ	85	MAC	E^{ee}_{cm}= 29 GeV
<0.3	90	4	AIHARA	84C	TPC	E^{ee}_{cm}= 29 GeV
<0.9	95	1	BEHREND	84	CELL	E^{ee}_{cm}= 14,22 GeV
1.0 ±0.4		10	BEHREND	82	CELL	Repl. by BEHREND 89B
<0.5	95	2	BLOCKER	82C	MRK2	E^{ee}_{cm}= 29 GeV
<6.0	95		BRANDELIK	80	TASS	E^{ee}_{cm}= 30 GeV

$[\Gamma(h^-h^-h^+ \geq 1\text{ neutrals }\nu_\tau)+\Gamma(3h^-2h^+ \geq 0\text{ neutrals }\nu_\tau)]/\Gamma_{total}$ — $(\Gamma_{25}+\Gamma_{37})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
5.4 ±0.5 OUR AVERAGE					
5.05±0.29±0.65	570	DECAMP	92C	ALEP	E^{ee}_{cm}= 88–95 GeV
5.8 ±0.7 ±0.2	352	[71] BEHREND	90	CELL	E^{ee}_{cm}= 35 GeV

[71] BEHREND 90 not independent of their $\Gamma(h^-h^-h^+ \geq 1\text{ neutrals }\nu_\tau)/\Gamma_{total}$ measurement.

$\Gamma(3h^-2h^+\nu_\tau)/\Gamma_{total}$ — Γ_{38}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.056±0.016 OUR AVERAGE					
0.064±0.023±0.01	12	ALBRECHT	88B	ARG	E^{ee}_{cm}= 10 GeV
0.051±0.020	7	BYLSMA	87	HRS	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.067±0.030	5	[72] BELTRAMI	85	HRS	Repl. by BYLSMA 87

[72] The error quoted is statistical only.

$\Gamma(3h^-2h^+\pi^0\nu_\tau)/\Gamma_{total}$ — Γ_{39}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.051±0.022	6	BYLSMA	87	HRS	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.067±0.030	5	[73] BELTRAMI	85	HRS	Repl. by BYLSMA 87

[73] The error quoted is statistical only.

$\Gamma(4h^-3h^+ \geq 0\text{ neutrals }\nu_\tau\text{ ("7-prong")})/\Gamma_{total}$ — Γ_{40}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.019	90	BYLSMA	87	HRS	E^{ee}_{cm}= 29 GeV

$\Gamma(K^0h^- \geq 0\text{ neutrals }\nu_\tau)/\Gamma_{total}$ — Γ_{41}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.3 ±0.3	44	TSCHIRHART	88	HRS	E^{ee}_{cm}= 29 GeV

$\Gamma(K^*(892)^- \geq 0\text{ neutrals }\nu_\tau)/\Gamma_{total}$ — Γ_{42}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.43±0.17 OUR AVERAGE					
1.43±0.11±0.13	475	[74] GOLDBERG	90	CLEO	E^{ee}_{cm}= 9.4–10.9 GeV
1.4 ±0.9 ±0.3	5	AIHARA	87B	TPC	E^{ee}_{cm}= 29 GeV

[74] GOLDBERG 90 estimates that 10% of observed $K^*(892)$ are accompanied by a π^0.

$\Gamma(K^-K^0 \geq 0\text{ neutrals }\nu_\tau)/\Gamma_{total}$ — Γ_{43}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.8	90	GOLDBERG	90	CLEO	E^{ee}_{cm}= 9.4–10.9 GeV

$\Gamma(K^*(892)^0K^- \geq 0\text{ neutrals }\nu_\tau)/\Gamma_{total}$ — Γ_{44}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.32±0.08±0.12	119	GOLDBERG	90	CLEO	E^{ee}_{cm}= 9.4–10.9 GeV

$\Gamma(\overline{K}^*(892)^0\pi^- \geq 0\text{ neutrals }\nu_\tau)/\Gamma_{total}$ — Γ_{45}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.38±0.11±0.13	105	GOLDBERG	90	CLEO	E^{ee}_{cm}= 9.4–10.9 GeV

$[\Gamma(a_0(980)^- \geq 0\text{ neutrals }\nu_\tau)\times B(a_0(980)\to K^0K^-)]/\Gamma_{total}$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.8 x 10^{-4}	90	GOLDBERG	90	CLEO	E^{ee}_{cm}= 9.4–10.9 GeV

$\Gamma(K^*(892)^-\nu_\tau)/\Gamma_{total}$ — Γ_{47}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.42±0.18 OUR FIT					
$1.39^{+0.18}_{-0.20}$ OUR AVERAGE					
$1.23\pm0.21^{+0.11}_{-0.21}$	54	[75] ALBRECHT	88L	ARG	E^{ee}_{cm}= 10 GeV
1.9 ±0.3 ±0.4	44	[76] TSCHIRHART	88	HRS	E^{ee}_{cm}= 29 GeV
1.5 ±0.4 ±0.4	15	[77] AIHARA	87C	TPC	E^{ee}_{cm}= 29 GeV
1.3 ±0.3 ±0.3	31	YELTON	86	MRK2	E^{ee}_{cm}= 29 GeV
1.7 ±0.7	11	DORFAN	81	MRK2	E^{ee}_{cm}= 4.2–6.7 GeV

[75] The authors divide by Γ_1/Γ = 0.865 to obtain this result.
[76] Not independent of TSCHIRHART 88 $\Gamma(\tau^-\to K^0h^- \geq 0\text{ neutrals }\nu_\tau)/\Gamma(\text{total})$.
[77] Decay π^- identified in this experiment, is assumed in the others.

$\Gamma(K_2^*(1430)^-\nu_\tau)/\Gamma_{total}$ — Γ_{48}/Γ

VALUE (%)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.3	95		TSCHIRHART	88	HRS	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.9	95	0	DORFAN	81	MRK2	E^{ee}_{cm}= 4.2–6.7 GeV

$\Gamma(K^0K^-\nu_\tau)/\Gamma_{total}$ — Γ_{49}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.26	95	AIHARA	87C	TPC	E^{ee}_{cm}= 29 GeV

$\Gamma(K^0 K^- \geq 1 \text{ neutrals } \nu_\tau)/\Gamma_{\text{total}}$ — Γ_{50}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.26	95	AIHARA	87C	TPC	E^{ee}_{cm}= 29 GeV

$\Gamma(K^0 h^+ h^- h^- \geq 0 \text{ neutrals } \nu_\tau)/\Gamma_{\text{total}}$ — Γ_{51}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.17	95	TSCHIRHART	88	HRS	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.27	90	BELTRAMI	85	HRS	E^{ee}_{cm}= 29 GeV

$\Gamma(\eta\pi^- \geq 0 \text{ neutrals } \nu_\tau)/\Gamma_{\text{total}}$ — Γ_{52}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<1.3	95	ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.1	90	ABACHI	87B	HRS	E^{ee}_{cm}= 29 GeV
<2.1	95	BARINGER	87	CLEO	E^{ee}_{cm}= 10.5 GeV

$\Gamma(\eta\pi^- \nu_\tau)/\Gamma_{\text{total}}$ — Γ_{53}/Γ

VALUE (%)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.9	95		ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.4	90		BEHREND	88	CELL	E^{ee}_{cm}= 14–46.8 GeV
<1.8	95		BARINGER	87	CLEO	E^{ee}_{cm}= 10.5 GeV
<2.5	90	0	COFFMAN	87	MRK3	E^{ee}_{cm}= 3.77 GeV
5.1±1.0±1.2		65	DERRICK	87	HRS	E^{ee}_{cm}= 29 GeV
<1.0	95		GAN	87B	MRK2	E^{ee}_{cm}= 29 GeV

$\Gamma(\eta\pi^-\pi^0 \nu_\tau)/\Gamma_{\text{total}}$ — Γ_{54}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<1.1	95	ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.1	95	BARINGER	87	CLEO	E^{ee}_{cm}= 10.5 GeV
$4.2^{+0.7}_{-1.2}\pm1.6$		[78] GAN	87	MRK2	E^{ee}_{cm}= 29 GeV

[78] Highly correlated with GAN 87 $\Gamma(\pi^- 3\pi^0 \nu_\tau)/\Gamma$(total) value.

$\Gamma(\eta\pi^-\pi^0\pi^0 \nu_\tau)/\Gamma_{\text{total}}$ — Γ_{55}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<1.2	95	ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV

$\Gamma(\eta\pi^+\pi^-\pi^- \geq 0 \text{ neutrals } \nu_\tau)/\Gamma_{\text{total}}$ — Γ_{56}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.3	90	ABACHI	87B	HRS	E^{ee}_{cm}= 29 GeV

$\Gamma(\eta\eta\pi^- \geq 0 \text{ neutrals } \nu_\tau)/\Gamma_{\text{total}}$ — Γ_{57}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.5	90	ABACHI	87B	HRS	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.5	95	BARINGER	87	CLEO	E^{ee}_{cm}= 10.5 GeV

$\Gamma(\eta\eta\pi^- \nu_\tau)/\Gamma_{\text{total}}$ — Γ_{58}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.83	95	ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV

$\Gamma(\eta\eta\pi^-\pi^0 \nu_\tau)/\Gamma_{\text{total}}$ — Γ_{59}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.9	95	ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV

$[\Gamma(\mu^- \text{ charged particles}) + \Gamma(e^- \text{ charged particles})]/\Gamma_{\text{total}}$ — $\Gamma_{60}/\Gamma=(\Gamma_{61}+\Gamma_{62})/\Gamma$

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.04	90	[79] BURMESTER	77C	PLUT	E^{ee}_{cm}= 4–5 GeV

[79] Assumes same μ, e momentum spectrum as (μe + nothing detected).

$\Gamma(\mu^-\gamma)/\Gamma_{\text{total}}$ — Γ_{63}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<5.5 × 10^{-4}	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(e^-\gamma)/\Gamma_{\text{total}}$ — Γ_{64}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.0 × 10^{-4}	90	KEH	88	CBAL	E^{ee}_{cm}= 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<6.4 × 10^{-4}	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(\mu^-\pi^0)/\Gamma_{\text{total}}$ — Γ_{65}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<8.2 × 10^{-4}	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(e^-\pi^0)/\Gamma_{\text{total}}$ — Γ_{66}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.4 × 10^{-4}	90	KEH	88	CBAL	E^{ee}_{cm}= 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.1 × 10^{-3}	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(\mu^- K^0)/\Gamma_{\text{total}}$ — Γ_{67}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.0 × 10^{-3}	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(e^- K^0)/\Gamma_{\text{total}}$ — Γ_{68}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.3 × 10^{-3}	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(\mu^-\rho^0)/\Gamma_{\text{total}}$ — Γ_{69}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.8 × 10^{-5}	90	ALBRECHT	87M	ARG	E^{ee}_{cm}= 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.4 × 10^{-4}	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(e^-\rho^0)/\Gamma_{\text{total}}$ — Γ_{70}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.9 × 10^{-5}	90	ALBRECHT	87M	ARG	E^{ee}_{cm}= 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.7 × 10^{-4}	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(e^- K^*(892)^0)/\Gamma_{\text{total}}$ — Γ_{71}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<5.4 × 10^{-5}	90	ALBRECHT	87M	ARG	E^{ee}_{cm}= 10 GeV

$\Gamma(\mu^- K^*(892)^0)/\Gamma_{\text{total}}$ — Γ_{72}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<5.9 × 10^{-5}	90	ALBRECHT	87M	ARG	E^{ee}_{cm}= 10 GeV

$\Gamma(e^-\eta)/\Gamma_{\text{total}}$ — Γ_{73}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.4 × 10^{-4}	90	KEH	88	CBAL	E^{ee}_{cm}= 10 GeV

$\Gamma(\ell^-\ell^-\ell^+)/\Gamma_{\text{total}}$ — $\Gamma_{74}/\Gamma=(\Gamma_{75}+\Gamma_{77}+\Gamma_{78}+\Gamma_{80}+\Gamma_{81}+\Gamma_{82})/\Gamma$

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.4 × 10^{-5}	90	[80] BOWCOCK	90	CLEO	E^{ee}_{cm}= 10.4–10.9
<3.8 × 10^{-5}	90	ALBRECHT	87M	ARG	E^{ee}_{cm}= 10 GeV

[80] Inclusion of a potentially model-dependent cut on decay track opening angles reduces BOWCOCK 90 limit to 2.6 × 10^{-5}.

$\Gamma(e^- e^+ e^-)/\Gamma_{\text{total}}$ — Γ_{75}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.7 × 10^{-5}	90	BOWCOCK	90	CLEO	E^{ee}_{cm}= 10.4–10.9
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.8 × 10^{-5}	90	ALBRECHT	87M	ARG	E^{ee}_{cm}= 10 GeV
<4.0 × 10^{-4}	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma((e\mu\mu)^-)/\Gamma_{\text{total}}$ — $\Gamma_{76}/\Gamma=(\Gamma_{77}+\Gamma_{78})/\Gamma$

Test of lepton number and lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.7 × 10^{-5}	90	BOWCOCK	90	CLEO	E^{ee}_{cm}= 10.4–10.9

$\Gamma(e^-\mu^+\mu^-)/\Gamma_{\text{total}}$ — Γ_{77}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.7 × 10^{-5}	90	BOWCOCK	90	CLEO	E^{ee}_{cm}= 10.4–10.9
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.3 × 10^{-5}	90	ALBRECHT	87M	ARG	E^{ee}_{cm}= 10 GeV
<3.3 × 10^{-4}	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(e^+\mu^-\mu^-)/\Gamma_{total}$ — Γ_{78}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.6 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.8 \times 10^{-5}$	90	ALBRECHT 87M	ARG	E_{cm}^{ee}= 10 GeV

$\Gamma((\mu ee)^-)/\Gamma_{total}$ — $\Gamma_{79}/\Gamma=(\Gamma_{80}+\Gamma_{81})/\Gamma$

Test of lepton number and lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.7 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9

$\Gamma(\mu^- e^+ e^-)/\Gamma_{total}$ — Γ_{80}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.7 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.3 \times 10^{-5}$	90	ALBRECHT 87M	ARG	E_{cm}^{ee}= 10 GeV
$<4.4 \times 10^{-4}$	90	HAYES 82	MRK2	E_{cm}^{ee}= 3.8–6.8 GeV

$\Gamma(\mu^+ e^- e^-)/\Gamma_{total}$ — Γ_{81}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.6 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.8 \times 10^{-5}$	90	ALBRECHT 87M	ARG	E_{cm}^{ee}= 10 GeV

$\Gamma(\mu^-\mu^+\mu^-)/\Gamma_{total}$ — Γ_{82}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$< 1.7 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$< 2.9 \times 10^{-5}$	90	ALBRECHT 87M	ARG	E_{cm}^{ee}= 10 GeV
$<49 \times 10^{-5}$	90	HAYES 82	MRK2	E_{cm}^{ee}= 3.8–6.8 GeV

$\Gamma(e^\mp\pi^\pm\pi^-)/\Gamma_{total}$ — $\Gamma_{84}/\Gamma=(\Gamma_{85}+\Gamma_{86})/\Gamma$

Test of lepton number and lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<6.0 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9

$\Gamma(e^-\pi^+\pi^-)/\Gamma_{total}$ — Γ_{85}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.2 \times 10^{-5}$	90	ALBRECHT 87M	ARG	E_{cm}^{ee}= 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<6.0 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9

$\Gamma(e^+\pi^-\pi^-)/\Gamma_{total}$ — Γ_{86}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.7 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<6.3 \times 10^{-5}$	90	ALBRECHT 87M	ARG	E_{cm}^{ee}= 10 GeV

$\Gamma(\mu^\mp\pi^\pm\pi^-)/\Gamma_{total}$ — $\Gamma_{87}/\Gamma=(\Gamma_{88}+\Gamma_{89})/\Gamma$

Test of lepton number and lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.9 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9

$\Gamma(\mu^-\pi^+\pi^-)/\Gamma_{total}$ — Γ_{88}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.9 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<4.0 \times 10^{-5}$	90	ALBRECHT 87M	ARG	E_{cm}^{ee}= 10 GeV

$\Gamma(\mu^+\pi^-\pi^-)/\Gamma_{total}$ — Γ_{89}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.9 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<6.3 \times 10^{-5}$	90	ALBRECHT 87M	ARG	E_{cm}^{ee}= 10 GeV

$\Gamma(\ell^\pm\pi^\mp\pi^-)/\Gamma_{total}$ — $\Gamma_{83}/\Gamma=(\Gamma_{85}+\Gamma_{86}+\Gamma_{88}+\Gamma_{89})/\Gamma$

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<6.3 \times 10^{-5}$	90	ALBRECHT 87M	ARG	E_{cm}^{ee}= 10 GeV

$\Gamma((e\pi K)^-$, all charged$)/\Gamma_{total}$ — $\Gamma_{91}/\Gamma=(\Gamma_{93}+\Gamma_{94}+\Gamma_{95})/\Gamma$

Test of lepton number and lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<7.7 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9

$\Gamma(e^-\pi^\pm K^\mp)/\Gamma_{total}$ — $\Gamma_{92}/\Gamma=(\Gamma_{93}+\Gamma_{94})/\Gamma$

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.8 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9

$\Gamma(e^-\pi^+K^-)/\Gamma_{total}$ — Γ_{93}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.2 \times 10^{-5}$	90	ALBRECHT 87M	ARG	E_{cm}^{ee}= 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<5.8 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9

$\Gamma(e^-\pi^-K^+)/\Gamma_{total}$ — Γ_{94}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.8 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9

$\Gamma(e^+\pi^-K^-)/\Gamma_{total}$ — Γ_{95}/Γ

Test of lepton number and lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$< 4.9 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<12 \times 10^{-5}$	90	ALBRECHT 87M	ARG	E_{cm}^{ee}= 10 GeV

$\Gamma((\mu\pi K)^-$, all charged$)/\Gamma_{total}$ — $\Gamma_{96}/\Gamma=(\Gamma_{98}+\Gamma_{99}+\Gamma_{100})/\Gamma$

Test of lepton number and lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<7.7 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9

$\Gamma(\mu^-\pi^\pm K^\mp)/\Gamma_{total}$ — $\Gamma_{97}/\Gamma=(\Gamma_{98}+\Gamma_{99})/\Gamma$

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<7.7 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9

$\Gamma(\mu^-\pi^+K^-)/\Gamma_{total}$ — Γ_{98}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$< 7.7 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<12 \times 10^{-5}$	90	ALBRECHT 87M	ARG	E_{cm}^{ee}= 10 GeV

$\Gamma(\mu^-\pi^-K^+)/\Gamma_{total}$ — Γ_{99}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<7.7 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9

$\Gamma(\ell^\pm\pi^\mp K^-)/\Gamma_{total}$ — $\Gamma_{90}/\Gamma=(\Gamma_{93}+\Gamma_{94}+\Gamma_{98}+\Gamma_{99})/\Gamma$

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.2 \times 10^{-4}$	90	ALBRECHT 87M	ARG	E_{cm}^{ee}= 10 GeV

$\Gamma(\mu^+\pi^-K^-)/\Gamma_{total}$ — Γ_{100}/Γ

Test of lepton number and lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$< 4.0 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E_{cm}^{ee}= 10.4–10.9
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<12 \times 10^{-5}$	90	ALBRECHT 87M	ARG	E_{cm}^{ee}= 10 GeV

$\Gamma(e^-$ light spinless boson$)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ — Γ_{101}/Γ_4

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.018	95	[81] ALBRECHT 90E	ARG	E_{cm}^{ee}= 9.4–10.6 GeV
<0.040	95	[82] BALTRUSAIT...85	MRK3	E_{cm}^{ee}= 3.77 GeV

[81] ALBRECHT 90E limit holds for mass < 100 MeV, and rises to 0.050 for mass = 500 MeV.

[82] BALTRUSAITIS 85 limit holds for mass < 100 MeV.

$\Gamma(\mu^-$ light spinless boson$)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ — Γ_{102}/Γ_4

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.033	95	[83] ALBRECHT 90E	ARG	E_{cm}^{ee}= 9.4–10.6 GeV
<0.125	95	[84] BALTRUSAIT...85	MRK3	E_{cm}^{ee}= 3.77 GeV

[83] ALBRECHT 90E limit holds for mass < 100 MeV, and rises to 0.071 for mass = 500 MeV.

[84] BALTRUSAITIS 85 limit holds for mass < 100 MeV.

τ DECAY PARAMETERS

ρ (MICHEL) PARAMETER

(V−A) theory predicts ρ = 0.75.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.727±0.033 OUR AVERAGE					
0.742±0.035±0.020	8000	ALBRECHT	90E	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
0.64 ±0.06 ±0.07	2753	JANSSEN	89	CBAL	E^{ee}_{cm}=9.4–10.6 GeV
0.79 ±0.10 ±0.10	3732	FORD	87B	MAC	E^{ee}_{cm}= 29 GeV
0.71 ±0.09 ±0.03	1426	BEHRENDS	85	CLEO	e^+e^- near $\Upsilon(4S)$
0.72 ±0.15	594	BACINO	79B	DLCO	E^{ee}_{cm}= 3.5–7.4 GeV

AXIAL VECTOR COUPLING CONSTANT PRODUCT $2g_A g_V/(g_A^2+g_V^2)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{1.14 \pm 0.34^{+0.34}_{-0.17}}$	3.9k	ALBRECHT	90I	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

AXIAL VECTOR COUPLING CONSTANT RATIO g_V/g_A

VALUE	DOCUMENT ID		TECN	COMMENT
0.01±0.04	[85] ALEXANDER	91D	OPAL	E^{ee}_{cm}= 88.3–94.3 GeV

[85] ALEXANDER 91D measures the τ polarization at the Z using the momentum spectra in $\tau^- \to e^- \overline{\nu}_e \nu_\tau$, $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$, and $\tau^- \to$ hadron$^-$ ν_τ decays.

CHARGED COUPLING CONSTANT RELATIVE TO μ (G_τ/G_μ)

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.94^{+0.12}_{-0.09} \pm 0.09}$	ALTHOFF	84D	TASS	E^{ee}_{cm}= 43 GeV

τ REFERENCES

AMMAR 92 PR D (to be pub.) +Baringer, Coppage+ (CLEO Collab.)
DECAMP 92C ZPHY (to be pub.) +Deschizeaux, Goy, Lees+ (ALEPH Collab.)
CERN-PPE-91-186
ABREU 91D PL B267 422 +Adam, Adami, Adye+ (DELPHI Collab.)
ACTON 91C PL B273 355 +Alexander, Allison, Allport+ (OPAL Collab.)
ADEVA 91F PL B265 451 +Adriani, Aguilar-Benitez, Akbari+ (L3 Collab.)
ALBRECHT 91D PL B260 259 +Ehrlichmann, Hamacher, Krueger+ (ARGUS Collab.)
ALEXANDER 91D PL B266 201 +Allison, Allport, Anderson+ (OPAL Collab.)
ANTREASYAN 91 PL B259 216 +Bartels, Besset, Bieler+ (Crystal Ball Collab.)
GRIFOLS 91 PL B255 611 +Mendez (BARC)
SAMUEL 91B PRL 67 668 +Li, Mendel (OKSU, WONT)
ABACHI 90 PR D41 1414 +Derrick, Kooijman, Musgrave+ (HRS Collab.)
ALBRECHT 90E PL B246 278 +Ehrlichmann, Harder, Krueger+ (ARGUS Collab.)
ALBRECHT 90I PL B250 164 +Ehrlichmann, Harder, Krueger+ (ARGUS Collab.)
BEHREND 90 ZPHY C46 537 +Criegee, Field, Franke+ (CELLO Collab.)
BOWCOCK 90 PR D41 805 +Kinoshita, Pipkin, Procario+ (CLEO Collab.)
DELAGUILA 90 PL B252 116 +Sher (BARC, WILL)
GOLDBERG 90 PL B251 223 +Haupt, Horwitz, Jain+ (CLEO Collab.)
WU 90 PR D41 2339 +Hayes, Perl, Barklow+ (Mark II Collab.)
ABACHI 89B PR D40 902 +Derrick, Kooijman, Musgrave+ (HRS Collab.)
BEHREND 89B PL B222 163 +Criegee, Dainton, Field+ (CELLO Collab.)
JANSSEN 89 PL B228 273 +Antreasyan, Bartels, Besset+ (Crystal Ball Collab.)
KLEINWORT 89 ZPHY C42 7 +Allison, Ambrus, Barlow+ (JADE Collab.)
ADEVA 88 PR D38 2665 +Anderhub, Ansari, Becker+ (Mark-J Collab.)
ALBRECHT 88B PL B202 149 +Binder, Boeckmann+ (ARGUS Collab.)
ALBRECHT 88L ZPHY C41 1 +Boeckmann, Glaeser, Harder+ (ARGUS Collab.)
ALBRECHT 88M ZPHY C41 405 +Boeckmann, Glaeser, Harder+ (ARGUS Collab.)
AMIDEI 88 PR D37 1750 +Trilling, Abrams, Baden+ (Mark II Collab.)
BEHREND 88 PL B200 226 +Criegee, Dainton, Field+ (CELLO Collab.)
BRAUNSCH... 88C ZPHY C39 331 Braunschweig, Kirschfink, Martyn+ (TASSO Collab.)
KEH 88 PL B212 123 +Antreasyan, Bartels, Besset+ (Crystal Ball Collab.)
TSCHIRHART 88 PL B205 407 +Abachi, Akerlof, Baringer+ (HRS Collab.)
ABACHI 87B PL B197 291 +Baringer, Bylsma, De Bonte+ (HRS Collab.)
ABACHI 87C PRL 59 2519 +Akerlof, Baringer, Blockus+ (HRS Collab.)
ADLER 87B PRL 59 1527 +Becker, Blaylock, Bolton+ (Mark III Collab.)
AIHARA 87B PR D35 1553 +Alston-Garnjost, Avery+ (TPC Collab.)
AIHARA 87C PRL 59 751 +Alston-Garnjost, Avery+ (TPC Collab.)
ALBRECHT 87L PL B185 223 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
ALBRECHT 87M PL B185 228 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
ALBRECHT 87P PL B199 580 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
BAND 87 PL B198 297 +Camporesi, Chadwick, Delfino+ (MAC Collab.)
BAND 87B PRL 59 415 +Bosman, Camporesi, Chadwick+ (MAC Collab.)
BARINGER 87 PRL 59 1993 +McIlwain, Miller, Shibata+ (CLEO Collab.)
BEBEK 87C PR D36 690 +Berkelman, Blucher, Cassel+ (CLEO Collab.)
BURCHAT 87 PR D35 27 +Feldman, Barklow, Boyarski+ (Mark II Collab.)
BYLSMA 87 PR D35 2269 +Abachi, Baringer, DeBonte+ (HRS Collab.)
COFFMAN 87 PR D36 2185 +Dubois, Eigen, Hauser+ (Mark III Collab.)
DERRICK 87 PL B189 260 +Kooijman, Loos, Musgrave+ (HRS Collab.)
FORD 87 PR D35 408 +Qi, Read, Smith+ (MAC Collab.)
FORD 87B PR D36 1971 +Qi, Read, Smith+ (MAC Collab.)
GAN 87 PRL 59 411 +Abrams, Amidei, Baden+ (Mark II Collab.)
GAN 87B PL B197 561 +Abrams, Amidei, Baden+ (Mark II Collab.)
ADEVA 86B PL B179 177 +Ansari, Becker, Becker-Szendy+ (Mark-J Collab.)
AIHARA 86E PRL 57 1836 +Alston-Garnjost, Avery+ (TPC Collab.)
ALBRECHT 86B ZPHY C33 7 +Donker, Gabriel, Edwards+ (ARGUS Collab.)
BARTEL 86D PL B182 216 +Becker, Felst, Haidt, Knies+ (JADE Collab.)
PDG 86 PL 170B Aguilar-Benitez, Porter+ (CERN, CIT+)
RUCKSTUHL 86 PRL 56 2132 +Stroynowski, Atwood, Barish+ (DELCO Collab.)
SCHMIDKE 86 PRL 57 527 +Abrams, Matteuzzi, Amidei+ (Mark II Collab.)
YELTON 86 PRL 56 812 +Dorfan, Abrams, Amidei+ (Mark II Collab.)
AKERLOF 85B PRL 55 570 +Baranko, Baringer, Beltrami+ (HRS Collab.)
ALTHOFF 85 ZPHY C26 521 +Braunschweig, Kirschfink+ (TASSO Collab.)
ASH 85B PRL 55 2118 +Band, Blume, Camporesi+ (MAC Collab.)
BALTRUSAIT... 85 PRL 55 1842 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BARTEL 85F PL 161B 188 +Becker, Cords, Felst+ (JADE Collab.)
BEHRENDS 85 PR D32 2468 +Gentile, Guida, Guida, Morrow+ (CLEO Collab.)
BELTRAMI 85 PRL 54 1775 +Bylsma, DeBonte, Gan+ (HRS Collab.)
BERGER 85 ZPHY C28 1 +Genzel, Lackas, Pielorz+ (PLUTO Collab.)
BURCHAT 85 PRL 54 2489 +Schmidke, Yelton, Abrams+ (Mark II Collab.)
FERNANDEZ 85 PRL 54 1620 +Ford, Qi, Read+ (MAC Collab.)
MILLS 85 PRL 54 624 +Pal, Atwood, Baillon+ (DELCO Collab.)
AIHARA 84C PR D30 2436 +Alston-Garnjost, Badtke, Bakken+ (TPC Collab.)
ALTHOFF 84D PL 141B 264 +Braunschweig, Kirschfink+ (TASSO Collab.)
BEHREND 84 ZPHY C23 103 +Fenner, Schachter, Schroder+ (CELLO Collab.)
MILLS 84 PRL 52 1944 +Ruckstuhl, Atwood, Baillon+ (DELCO Collab.)
BEHREND 83C PL 127B 270 +Chen, Fenner, Gumpel+ (CELLO Collab.)
JAROS 83 PRL 51 955 +Amidei, Trilling, Abrams+ (Mark II Collab.)
BEHREND 82 PL 114B 282 +Chen, Fenner, Field+ (CELLO Collab.)
BLOCKER 82B PRL 48 1586 +Abrams, Alam, Blondel+ (Mark II Collab.)
BLOCKER 82C PRL 49 1369 +Levi, Abrams, Amidei+ (Mark II Collab.)
BLOCKER 82D PL 109B 119 +Dorfan, Abrams, Alam+ (Mark II Collab.) J
HAYES 82 PR D25 2869 +Perl, Alam, Boyarski+ (Mark II Collab.)
BERGER 81B PL 99B 489 +Genzel, Grigull, Lackas+ (PLUTO Collab.)
DORFAN 81 PRL 46 215 +Blocker, Abrams, Alam+ (Mark II Collab.)
BLOCKER 80 LBL-10801 Thesis (LBL)
BRANDELIK 80 PL 92B 199 +Braunschweig, Gather+ (TASSO Collab.)
WAGNER 80 ZPHY C3 193 +Alexander, Criegee, Dehne+ (PLUTO Collab.)
ZHOLENTZ 80 PL 96B 214 +Kurdadze, Lelchuk, Mishnev+ (NOVO)
Also 81 SJNP 34 814 Zholentz, Kurdadze, Lelchuk+ (NOVO)
Translated from YAF 34 1471.
BACINO 79B PRL 42 749 +Ferguson, Nodulman, Slater+ (DELCO Collab.)
BACINO 79C PRL 42 6 +Ferguson, Nodulman, Slater+ (DELCO Collab.)
KIRKBY 79 SLAC-PUB-2419 (SLAC) J
Batavia Lepton Photon Conference.
ALEXANDER 78B PL 78B 162 +Criegee, Dehne, Derikum+ (PLUTO Collab.)
BACINO 78B PRL 41 13 +Ferguson, Nodulman, Slater+ (DELCO Collab.) J
Also 78 Tokyo Conf. 249 Kirz (STON)
Also 80 PL 96B 214 Zholentz, Kurdadze, Lelchuk, Mishnev+ (NOVO)
BARTEL 78 PL 77B 331 +Dittmann, Duinker, Olsson, Oneill+ (DESY, HEID)
BRANDELIK 78 PL 73B 109 +Braunschweig, Martyn, Sander+ (DASP Collab.) J
FELDMAN 78 Tokyo Conf. 777 (SLAC) J
HEILE 78 NP B138 189 +Perl, Abrams, Alam, Boyarski+ (SLAC, LBL)
JAROS 78 PRL 40 1120 +Abrams, Alam+ (SLAC, LBL, NWES, HAWA)
BARBARO-... 77 PRL 39 1058 Barbaro-Galtieri, Kwan+ (LBL, NWES, SLAC, HAWA)
BURMESTER 77C PL 68B 301 +Criegee, Dehne, Derikum+ (PLUTO Collab.)
PERL 75 PRL 35 1489 +Abrams, Boyarski, Breidenbach+ (LBL, SLAC)

OTHER RELATED PAPERS

PERL 91 RPP (to be pub.) (SLAC)
SLAC-PUB-5614
PICH 90 MPL A5 1995 (VALE)
BARISH 88 PRPL 157 1 +Stroynowski (CIT)
GAN 88 IJMP A3 531 +Perl (SLAC)
HAYES 88 PR D38 3351 +Perl (SLAC)
PERL 80 ARNPS 30 299 (SLAC)
ALLES-... 79 LNC 25 404 Alles-Borelli (BGNA) J
FLUGGE 79 ZPHY C1 121 (DESY)
AZIMOV 78 SPU 21 225 +Frankfurt, Khoze (PINP)
PERL 78 SLAC-PUB-2219 (SLAC)
Karlsruhe Summer Institute.
FLUGGE 77 Boston Conf. (DESY)
Also issued as DESY 77/35.
PERL 77B Hamburg Symp. (SLAC)
Also issued as SLAC-PUB-2022.

Number of Light Neutrino Types

The neutrinos referred to in this section are those of the Standard SU(2) × U(1) Electroweak Model possibly extended to allow nonzero neutrino masses. Light neutrinos are those with $m(\nu) \ll m(Z^0)$. The limits are on the number of neutrino families or species.

NOTE ON THE NUMBER OF LIGHT NEUTRINO TYPES FROM COLLIDER EXPERIMENTS

(by Dean Karlen, Carleton University)

The most precise measurements of the number of light neutrino types, N_ν, come from studies of Z production in e^+e^- collisions. At the time of this report, a total of 650,000 visible Z decays have been used in the analyses published by the four LEP experiments, ALEPH,[1] DELPHI,[2] L3,[3] and OPAL.[4] The invisible partial width, $\Gamma_{\rm inv}$, is determined from these data by subtracting the measured visible partial widths, corresponding to Z decays into quarks and charged leptons, from the total Z width. The invisible width is assumed to be due to N_ν light neutrino species each contributing the neutrino partial width Γ_ν as given by the Standard Model. The Standard Model value for Γ_ν, however, is uncertain by about 1% due to the unknown top quark mass. In order to reduce this uncertainty, the Standard Model value for the ratio of the neutrino to charged leptonic partial widths, $(\Gamma_\nu/\Gamma_\ell)_{\rm SM} = 1.993 \pm 0.004$, is used instead to determine the number of light neutrino types:

$$N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\rm SM}$$

The combined LEP result is $N_\nu = 3.00 \pm 0.05 \pm 0.006$,[5] where the first error is the combined statistical and systematic uncertainty and the second is the uncertainty from allowing the top quark mass to vary between 90 and 200 GeV.

In the past, when only small samples of Z decays had been recorded by the LEP experiments and by the Mark II at SLC, the uncertainty in N_ν was reduced by using Standard Model fits to the measured hadronic cross sections at several center-of-mass energies near the Z resonance. With the present data samples, this approach leads to only a slight improvement in the experimental uncertainty.[2,4] Since this method is much more dependent on the Standard Model and the top quark mass, the approach described above is favored.

Before the advent of the SLC and LEP, limits on the number of neutrino generations were placed by experiments at lower-energy e^+e^- colliders by measuring the cross section of the process $e^+e^- \to \nu\bar{\nu}\gamma$. The ASP, CELLO, MAC, MARK J, and VENUS experiments observed a total of 3.9 events above background,[6] leading to a 95% CL limit of $N_\nu < 4.8$. This process has since been measured at LEP by the OPAL experiment,[7] where 73 events were observed with an expected background of 8, yielding $N_\nu = 3.0 \pm 0.4 \pm 0.2$.

Experiments at $p\bar{p}$ colliders also placed limits on N_ν by determining the total Z width from the observed ratio of $W^\pm \to \ell^\pm\nu$ to $Z \to \ell^+\ell^-$ events.[8] This involved a calculation that assumed Standard Model values for the total W width and the ratio of W and Z leptonic partial widths, and used an estimate of the ratio of Z to W production cross sections. Now that the Z width is very precisely known from the LEP experiments, the approach is now one of those used to determine the W width.

References

1. D. Decamp *et al.*, Z. Phys. **C53**, 1 (1992).
2. P. Abreu *et al.*, Nucl. Phys. **B367**, 511 (1992).
3. B. Adeva *et al.*, Z. Phys. **C51**, 179 (1991).
4. G. Alexander *et al.*, Z. Phys. **C52**, 175 (1991).
5. The LEP Collaborations: ALEPH, DELPHI, L3, and OPAL, CERN-PPE/91-232, submitted to Phys. Lett. **B**.
6. C. Hearty *et al.*, Phys. Rev. **D39**, 3207 (1989); H.J Behrend *et al.*, Phys. Lett. **B215**, 186 (1988); W.T. Ford *et al.*, Phys. Rev. **D33**, 3472 (1986); H. Wu, Ph.D. Thesis, Univ. Hamburg (1986); K. Abe *et al.*, Phys. Lett. **B232**, 431 (1989).
7. M.Z. Akwary *et al.*, Z. Phys. **C50**, 373 (1991).
8. R. Ansari *et al.*, Phys. Lett. **B186**, 440 (1987); C. Albajar *et al.*, Phys. Lett. **B198**, 271 (1987).

Number from e^+e^- Colliders

Number of ν Types Including ν_e, ν_μ, ν_τ

VALUE	DOCUMENT ID		TECN	COMMENT
2.99±0.04 OUR AVERAGE				
3.24±0.46±0.22	[1] ADEVA	92	L3	E^{ee}_{cm}= 91 GeV at LEP
2.97±0.07	[2] DECAMP	92B	ALEP	E^{ee}_{cm}= 91 GeV at LEP
2.93±0.04±0.07	[2] ABREU	91F	DLPH	E^{ee}_{cm}= 91 GeV at LEP
3.05±0.10	[2] ADEVA	91E	L3	E^{ee}_{cm}= 91 GeV at LEP
3.0 ±0.4 ±0.2	[1] AKRAWY	91D	OPAL	E^{ee}_{cm} = 91 GeV at LEP
3.05±0.09±0.005	[2,3] ALEXANDER	91F	OPAL	E^{ee}_{cm}= 91 GeV at LEP
2.8 ±0.6	[4] ABRAMS	89B	MRK2	E^{ee}_{cm}= 91 GeV at SLC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.00±0.05	[5] LEP	92	RVUE	E^{ee}_{cm}= 91 GeV at LEP
3.12±0.24±0.25	AARNIO	90	DLPH	E^{ee}_{cm}= 91 GeV at LEP
2.97±0.26	[4] ABREU	90	DLPH	E^{ee}_{cm}= 91 GeV at LEP
3.23±0.29	[6] ADEVA	90D	L3	E^{ee}_{cm}= 91 GeV at LEP
3.01±0.11	ADEVA	90I	L3	E^{ee}_{cm}= 91 GeV at LEP
3.3 ±0.7	[6] AKRAWY	90	OPAL	E^{ee}_{cm}= 91 GeV at LEP
$2.73\pm0.26^{+0.02}_{-0.04}$	[6,7] AKRAWY	90E	OPAL	E^{ee}_{cm}= 91 GeV at LEP
$3.09\pm0.19^{+0.06}_{-0.12}$	[4,7] AKRAWY	90E	OPAL	E^{ee}_{cm}= 91 GeV at LEP
3.35±0.41	[6] DECAMP	90B	ALEP	E^{ee}_{cm}= 91 GeV at LEP
3.01±0.15±0.05	[4,7] DECAMP	90D	ALEP	E^{ee}_{cm}= 91 GeV at LEP
2.91±0.13	DECAMP	90P	ALEP	E^{ee}_{cm}= 91 GeV at LEP
2.4 ±0.4 ±0.5	[4] AARNIO	89	DLPH	E^{ee}_{cm}= 91 GeV at LEP

[1] Result is from a direct measurement of the invisible Z width via photon counting.
[2] Simultaneous fits to all measured cross section data.
[3] Second error is from uncertainty in top and Higgs mass.
[4] These papers assume standard model couplings.
[5] Simultaneous fits to all measured cross section data from all four LEP experiments.
[6] These papers measure leptonic widths and are more model independent. However, they divide the measured invisible width by the standard model width for neutrinos. They are less precise, as discussed in the minireview.
[7] The second error is due to theoretical uncertainties.

Limits from Astrophysics and Cosmology

Number of Light ν Types Including ν_e, ν_μ, ν_τ

("light" means < about 1 MeV). See also OLIVE 81. For a review of limits based on Nucleosynthesis, Supernovae, and also on terrestial experiments, see DENEGRI 90.

VALUE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
< 3.3	WALKER	91	COSM
< 3.4	OLIVE	90	COSM
< 5.2	ELLIS	86	COSM
< 4	STEIGMAN	86	COSM
< 4	YANG	84	COSM
< 4	YANG	79	COSM
< 7	STEIGMAN	77	COSM
	PEEBLES	71	COSM
<16	[8] SHVARTSMAN	69	COSM
	HOYLE	64	COSM

[8] SHVARTSMAN 69 limit inferred from his equations.

Number Coupling with Less Than Full Weak Strength

VALUE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<20	[9] OLIVE	81C	COSM
<20	[9] STEIGMAN	79	COSM

[9] Limit varies with strength of coupling. See also WALKER 91.

REFERENCES FOR Limits on Number of Light Neutrino Types

ADEVA	92	PL B275 209	+Adriani, Aguilar-Benitez+	(L3 Collab.)
DECAMP	92B	ZPHY C53 1	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
LEP	92	PL B276 247	+ALEPH, DELPHI, L3, OPAL	(LEP Collabs.)
ABREU	91F	NP B367 511	+Adam, Adami, Adye, Akesson, Alekseev+	(DELPHI Collab.)
ADEVA	91E	ZPHY C51 179	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
AKRAWY	91D	ZPHY C50 373	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ALEXANDER	91F	ZPHY C52 175	+Allison, Allport, Anderson, Arcelli+	(OPAL Collab.)
WALKER	91	APJ 376 51	+Steigman, Schramm+	(HSCA, OSU, CHIC, MINN)
AARNIO	90	PL B241 425	+Abreu, Adam, Adami+	(DELPHI Collab.)
ABREU	90	PL B241 435	+Adam, Adami+	(DELPHI Collab.)
ADEVA	90D	PL B238 122	+Adriani, Aguilar-Benitez, Akbari+	(L3 Collab.)
ADEVA	90I	PL B249 341	+Adriani, Aguilar-Benitez, Akbari, Alcarez+	(L3 Collab.)
AKRAWY	90	PL B235 379	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
AKRAWY	90E	PL B240 497	+Alexander, Allison, Allport+	(OPAL Collab.)
DECAMP	90B	PL B234 399	+Deschizeaux, Lees, Minard, Crespo+	(ALEPH Collab.)
DECAMP	90D	PL B235 399	+Deschizeaux, Lees, Minard, Crespo+	(ALEPH Collab.)
DECAMP	90P	ZPHY C48 365	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
DENEGRI	90	RMP 62 1	+Sadoulet, Spiro	(CERN, UCB, SACL)
OLIVE	90	PL B236 454	+Schramm, Steigman, Walker	(MINN, CHIC, OSU, HARV)
AARNIO	89	PL B231 539	+Abreu, Adam, Adrianos, Adye+	(DELPHI Collab.)
ABRAMS	89B	PRL 63 2173	+Adolphsen, Averill, Ballam, Barish+	(Mark II Collab.)
ELLIS	86	PL 167B 457	+Enqvist, Nanopoulos, Sarkar	(CERN, OXF)
STEIGMAN	86	PL B176 33	+Olive, Schramm, Turner	(BART, MINN+)
YANG	84	APJ 281 493	+Turner, Steigman, Schramm, Olive	(CHIC, BART)
OLIVE	81	APJ 246 557	+Schramm, Steigman, Turner, Yang+	(CHIC, BART)
OLIVE	81C	NP B180 497	+Schramm, Steigman	(EFI, BART)
STEIGMAN	79	PRL 43 239	+Olive, Schramm	(BART, EFI)
YANG	79	APJ 227 697	+Schramm, Steigman, Rood	(CHIC, YALE, VIRG)
STEIGMAN	77	PL 66B 202	+Schramm, Gunn	(YALE, CHIC, CIT)
PEEBLES	71	Physical Cosmology Princeton Univ. Press (1971)		(PRIN)
SHVARTSMAN	69	JETPL 9 184 Translated from ZETFP 9 315.		(MOSU)
HOYLE	64	Nature 203 1108	+Tayler	(CAMB)

Heavy Lepton Searches

NOTE ON HEAVY LEPTON SEARCHES

Data on the $\tau^{\pm}$ are listed in a separate section, following the e and μ listings. Data on excited leptons (e^*, μ^*, τ^*) appear in the section "Searches for Quark and Lepton Compositeness." Searches for fractionally charged heavy leptons are included in the section on "Free Quark Searches."

The following section contains information on searches for heavy leptons of other types.

Several types of heavy leptons (that is, non-strongly-interacting fermions other than e and μ) have been proposed. In the Full Listings, following a historical practice specific to this area, we distinguish four types.[1] Each has a corresponding antiparticle with opposite charge and lepton number. For convenience we omit writing the antiparticles in the following descriptions. The four types are:

Sequential leptons (L^-, ν_L). Such a pair has often been assumed to have its own separately strictly conserved lepton number $n_L = +1$. Such a conservation law means that the radiative decays

$$\left.\begin{array}{l} L^- \to e^-\gamma \\ L^- \to \mu^-\gamma \\ L^- \to \tau^-\gamma \end{array}\right\} \text{ are forbidden .}$$

while the weak decays (assuming m_{L^-} sufficiently large)

$$\left.\begin{array}{l} L^- \to \nu_L e^- \overline{\nu}_e \\ L^- \to \nu_L \mu^- \overline{\nu}_\mu \\ L^- \to \nu_L \tau^- \overline{\nu}_\mu \\ L^- \to \nu_L \textit{ hadrons} \end{array}\right\} \text{ are allowed .}$$

There could be an increasing mass sequence of such pairs. It is frequently assumed that the neutrinos are massless (a natural concomitant of the L number conservation law).

Decay rates are assumed to be calculable from conventional weak interaction theory. For example, for an L^- mass between 1 GeV and 3 GeV, the branching fraction to each of the two leptonic modes above should be roughly 10% to 20%. For an L^- mass above 1 GeV, the mean life should be $\lesssim 10^{-12}$ second.

Paraleptons (e_P^+, e_P^0), (μ_P^+, μ_P^0), (τ_P^+, τ_P^0). The lepton number of (e_P^+, e_P^0) is the same as that of (ν_e, e^-), and similarly for the other paraleptons. Radiative decays are again forbidden, and decays similar to those allowed for L^- are allowed here, *e.g.*,

$$\mu_P^+ \to \nu_\mu e^+ \nu_e$$
$$\mu_P^+ \to \nu_\mu \mu^+ \nu_\mu$$
$$\mu_P^+ \to \nu_\mu \textit{ hadrons.}$$

However, the lightest member is not stable as is the case for sequential leptons, so that bizarre decay schemes such as

$$e_P^+ \to e_P^0 \mu^+ \nu_\mu$$
$$\hookrightarrow e^- e^+ \nu_e$$

(assuming $m_{e_P^0} < m_{e_P^+}$) are allowed. Occasional searches have been made for doubly-charged paraleptons.

Before the discovery of the Z^0 boson, heavy leptons of this type were proposed in unified gauge theories of weak and electromagnetic interactions to cancel unphysical high-energy behavior in such processes as $e^+e^- \to W^+W^-$.[2] The theoretical motivation disappeared with the discovery of neutral currents and confirmation of the standard electroweak theory. However, from a purely phenomenological viewpoint, it is still of interest to search for paraleptons.

Ortholeptons $(e_O^-, \mu_O^-, \tau_O^-)$. These are defined as having the same lepton numbers as the correponding regular leptons. The quantum numbers of an ortholepton are thus essentially equivalent to those of an excited lepton. Historically, the emphasis in the excited leptons has been on the radiative decay mode, and the connection with compositeness, whereas the ortholepton denotation has been a more general category. Reflecting this, we list limits on excited leptons in the section on compositeness. Ortholeptons may or may not have associated neutral leptons. Both radiative decays and regular weak decays similar to those of sequential leptons can occur.

Long-lived penetrating particles. Heavy leptons could have long mean lives under certain circumstances. For example, if $m_{\nu_L} > m_{L^-}$, then L^-, the sequential lepton, would only be able to decay via lepton mixing and could have a relatively long lifetime.

Perl's review[3] gives further details.

References

1. M.L. Perl and P. Rapidis, SLAC-PUB-1496 (October 1974).
2. J.D. Bjorken and C.H. Llewellyn Smith, Phys. Rev. **D7**, 887 (1973).
3. M. Perl, SLAC-PUB-2752 (1981).

Limits apply only to heavy lepton types specified. See review above for description of types. $L, e_P, \mu_P, \tau_P, e_O, \mu_O$, and τ_O denote sequential lepton, para-electron, para-muon, para-tau, ortho-electron, ortho-muon, and ortho-tau, respectively. As noted, limits for excited leptons (e^*, μ^*, τ^*) are included in the section on "Searches for Quark and Lepton Compositeness."

Charged Heavy Lepton MASS LIMITS

Sequential Charged Heavy Lepton ($L^{\pm}$) MASS LIMITS

These experiments assumed that a fourth generation $L^{\pm}$ decayed to a fourth generation ν_L (or L^0) where ν_L was stable. New data show that stable ν_L have $m(\nu_L) > 42.7$ GeV so that the above assumption is not valid for any mass limit ≤ 42.7 GeV. One can instead assume that $L^{\pm}$ decays via mixing to ν_e, ν_μ and/or ν_τ, and in that context the limits below are meaningful.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>42.8	95	ADEVA	90S	L3	Dirac
>44.3	95	AKRAWY	90G	OPAL	
>42.7	95	DECAMP	90F	ALEP	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 12.6–29.6	95	KIM	91B	AMY	Massless ν assumed

none 0.5–10	95	[1] RILES	90	MRK2	For $(m(L^-)-m(L^0))$ > 0.25–0.4 GeV
> 8		[2] STOKER	89	MRK2	For $(m(L^+)-m(L^0))$= 0.4 GeV
>12		[2] STOKER	89	MRK2	For $m(L^0)$=0.9 GeV
>27.6	95	[3] ABE	88	VNS	
>25.5	95	[4] ADACHI	88B	TOPZ	
none 1.5–22.0	95	BEHREND	88C	CELL	
>25.0	95	[5] IGARASHI	88	AMY	
>27.6	95	[6] KIM	88	AMY	
>41	90	[7] ALBAJAR	87B	UA1	
>25.0	95	YOSHIDA	87B	VNS	
>22.5	95	[8] ADEVA	85	MRKJ	
>18.		[9] ADEVA	83B	MRKJ	
>18.0	95	[10] BARTEL	83	JADE	
>14.	95	ADEVA	82	MRKJ	
none 4–14.5	95	[11] BERGER	81B	PLUT	
>15.5	95	[12] BRANDELIK	81	TASS	
>13.		[13] AZIMOV	80		
>16.	95	[14] BARBER	80B	CNTR	
> 0.490		[15] ROTHE	69	RVUE	

[1] RILES 90 limits were the result of a special analysis of the data in the case where the mass difference $m(L^-)-m(L^0)$ was allowed to be quite small, where L^0 denotes the neutrino into which the sequential charged lepton decays. With a slightly reduced $m(L^{\pm})$ range, the mass difference extends to about 4 GeV.

[2] STOKER 89 (Mark II at PEP) gives bounds on charged heavy lepton (L^+) mass for the generalized case in which the corresponding neutral heavy lepton (L^0) in the SU(2) doublet is not of negligible mass.

[3] ABE 88 search for L^+ and $L^- \rightarrow$ hadrons looking for acoplanar jets. The bound is valid for $m(\nu) < 10$ GeV.

[4] ADACHI 88B search for hadronic decays giving acoplanar events with large missing energy. E_{cm}^{ee} = 52 GeV.

[5] IGARASHI 88 search for multi-hadron events with isolated leptons. E_{cm}^{ee} = 50–52 GeV.

[6] KIM 88 search for $L^{\pm} \rightarrow$ hadrons with $L^{\mp} \rightarrow$ isolated lepton X and for $L^{\pm}$ and $L^{\mp} \rightarrow$ hadrons. E_{cm}^{ee} = 56 GeV.

[7] Assumes associated neutrino is approximately massless.

[8] ADEVA 85 analyze one-isolated-muon data and sensitive to τ <10 nanosec. Assume B(lepton) = 0.30. E_{cm} = 40–47 GeV.

[9] ADEVA 83B looked for muon opposite against a hadron jet.

[10] BARTEL 83 limit is from PETRA e^+e^- experiment with average E_{cm} = 34.2 GeV.

[11] BERGER 81B is DESY DORIS and PETRA experiment. Looking for $e^+e^- \rightarrow L^+L^-$.

[12] BRANDELIK 81 is DESY-PETRA experiment. Looking for $e^+e^- \rightarrow L^+L^-$.

[13] AZIMOV 80 estimated probabilities for $M+N$ type events in $e^+e^- \rightarrow L^+L^-$ deducing semi-hadronic decay multiplicities of L from e^+e^- annihilation data at E_{cm} = $(2/3)m(L)$. Obtained above limit comparing these with e^+e^- data (BRANDELIK 80).

[14] BARBER 80B looked for $e^+e^- \rightarrow L^+L^-$, $L \rightarrow \nu_L^+$ X with MARK-J at DESY-PETRA.

[15] ROTHE 69 examines previous data on μ pair production and π and K decays.

Stable Charged Heavy Lepton ($L^{\pm}$) MASS LIMITS

VALUE (GeV)	CL%	DOCUMENT ID		TECN
>42.8 (CL = 95%) OUR LIMIT				
>28.2	95	[16] ADACHI	90C	TOPZ
none 18.5–42.8	95	AKRAWY	90O	OPAL
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>26.5	95	DECAMP	90F	ALEP
none $m(\mu)$–36.3	95	SODERSTROM	90	MRK2

[16] ADACHI 90C put lower limits on the mass of stable charged particles with electric charge Q satisying $2/3 < Q/e < 4/3$ and with spin 0 or 1/2. We list here the special case for a stable charged heavy lepton.

Charged Ortho-Electron ($e_O^{\pm}$) MASS LIMITS

See also the section "MASS LIMITS for Excited e" in the section on "Searches for Quark and Lepton Compositeness."

VALUE (GeV)	EVTS	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 0.25–2.3		[17] BACCI	77B	SPEC	±
>0.6	0	[18] BACCI	73	ELEC	±
>2.2	0	[18] BACCI	73	ELEC	±
none 0.263–1.32		[19] LICHTENSTEIN	70	SPEC	−
none 0.1–1.3		[20] BOLEY	68	SPEC	−
none 0.3–0.7		[21] BUDNITZ	66	SPEC	−
>1.0	0	[22] BEHREND	65	SPEC	−
none 0.12–0.57		[23] BETOURNE	65	SPEC	−

[17] BACCI 77B is same type as BACCI 73. Lower mass limit corresponds to λ^2 limit of 4×10^{-5}, upper value is for λ^2 limit of 1.5×10^{-3}.

[18] BACCI 73 is Frascati e^+e^- experiment. Looks for $e_O \rightarrow e\gamma$. Mass limit depends on coupling constant λ for this decay. First value above is for $\lambda^2 > 9 \times 10^{-5}$, second is for $\lambda^2 > 10^{-3}$.

[19] LICHTENSTEIN 70 is Cornell experiment measuring e Bremsstrahlung. Mass limit depends on coupling constant. First value above is for λ^2 >0.17, second is for λ^2 >0.42.

[20] BOLEY 68 is CEA experiment. Looks for $ep \rightarrow e_O p$. Mass of 0.1 corresponds to coupling constant $\lambda^2 > 3 \times 10^{-4}$, mass limit of 1.3 to λ^2 >0.01.

[21] BUDNITZ 66 is CEA experiment. Looks for $ep \rightarrow e_O p$.

[22] BEHREND 65 is DESY experiment. Looks for $ep \rightarrow e_O p$, $e_O \rightarrow e\gamma$. This mass limit corresponds to a limit on λ^2 of 6.25×10^{-4}.

[23] BETOURNE 65 is Orsay experiment. Looks for $ep \rightarrow e_O p$. Mass of 0.12 corresponds to coupling constant λ^2 >0.0016, mass of 0.57 to λ^2 >0.22.

Charged Ortho-Muon ($\mu_O^{\pm}$) MASS LIMITS

See also the section "MASS LIMITS for Excited μ" in the section on "Searches for Quark and Lepton Compositeness."

VALUE (GeV)	CL%	EVTS	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>10.3	98		[24] ASRATYAN	78		−
> 7.5		0	[25] CNOPS	78	HLBC	−
> 1.8	90		[26] ASRATYAN	74	HLBC	±
none 0–2.0			[27] GITTLESON	74	SPEC	
none 0.2–0.6			[28] LIBERMAN	69	OSPK	−

[24] ASRATYAN 78 analyzes dependence of (neutral current/charged current) on energy of associated hadrons. Uses data of HOLDER 77 — ν_μ interactions at CERN-SPS.

[25] CNOPS 78 is FNAL experiment looking for ν_μNe $\rightarrow L^{\pm}$, followed by $L^{\pm} \rightarrow e^{\pm}\nu\nu$.

[26] ASRATYAN 74 uses EICHTEN 73 data on ν nucleon $\rightarrow e^-$ hadrons and $\overline{\nu}$ nucleon $\rightarrow e^+$ hadrons to set limits on orthomuon production.

[27] GITTLESON 74 is $\mu p \rightarrow p\,\mu_O$ search. Coupling constant λ^2 is <0.01 for mass up to 0.7 GeV, limit on λ^2 rises to <0.1 for mass of 2.0 GeV.

[28] LIBERMAN 69 is a BNL experiment measuring muon Bremsstrahlung.

Charged Para-Muon ($\mu_P^{\pm}$) MASS LIMITS

VALUE (GeV)	CL%	EVTS	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 9.0		0	[29] CNOPS	78	HLBC	+
>10.0			[30] ERRIQUEZ	78	BEBC	+
>12.	90		[31] HOLDER	78	CNTR	+
> 8.4	90		[32] BARISH	74	SPEC	+
> 2.0	90	0	[33] BARISH	73B	ASPK	+
> 2.4	90	0	[34] EICHTEN	73	HLBC	+

[29] CNOPS 78 is FNAL experiment looking for ν_μNe $\rightarrow L^{\pm}$, followed by $L^{\pm} \rightarrow e^{\pm}\nu\nu$.

[30] ERRIQUEZ 78 is CERN SPS experiment. Looks for ν_μ nucleon $\rightarrow \mu^- e^+$ X. Finds cross section for producing heavy lepton $\rightarrow e^+ < 0.7 \times 10^{-3} \times$ CC cross section

[31] HOLDER 78 is a CERN ν experiment looking for ν_μ nucleon $\rightarrow \mu^+$ anything. Assumes $\mu_P^+ \rightarrow \mu^+ 2\nu_\mu$ with BR = 0.2.

[32] BARISH 74 is FNAL 50,135 GeV ν experiment. Looks for (ν nucleon $\rightarrow \mu_P^+$ X). Assumes ($\mu_P^+ \rightarrow \mu^+\nu_\mu\nu_\mu$) with BR = 0.3.

[33] BARISH 73B is FNAL 50,145 GeV ν experiment. Looks for (ν nucleon $\rightarrow \mu_P^+$ X). Assumes ($\mu_P^+ \rightarrow \mu^+\nu_\mu\nu_\mu$) with BR = 0.3.

[34] EICHTEN 73 is CERN 1–10 GeV ν experiment. Looks for μ_P^+ produced in ν nucleon $\rightarrow \mu_P^+$ hadrons assuming 15% decay to $e^+\nu_\mu\nu_e$.

Charged Long-Lived Heavy Lepton MASS LIMITS

VALUE (GeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.1	0	[35] ANSORGE	73B	HBC	−	Long-lived
none 0.55–4.5		[36] BUSHNIN	73	CNTR	−	Long-lived
none 0.2–0.92		[37] BARNA	68	CNTR	−	Long-lived
none 0.97–1.03		[37] BARNA	68	CNTR	−	Long-lived

[35] ANSORGE 73B looks for electron pair production and electron-like Bremsstrahlung.

[36] BUSHNIN 73 is SERPUKOV 70 GeV p experiment. Masses assume mean life above 7×10^{-10} and 3×10^{-8} respectively. Calculated from cross section (see "Charged Quasi-Stable Lepton Production Differential Cross Section" below) and 30 GeV muon pair production data.

[37] BARNA 68 is SLAC photoproduction experiment.

Doubly-Charged Heavy Lepton MASS LIMITS

VALUE (GeV)	CL%	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 1–9 GeV	90	[38] CLARK	81	SPEC	++

[38] CLARK 81 is FNAL experiment with 209 GeV muons. Bounds apply to μ_P which couples with full weak strength to muon. See also section on "Doubly-Charged Lepton Produciton Cross Section."

Stable Neutral Heavy Lepton MASS LIMITS

Note that LEP results in combination with REUSSER 91 exclude a fourth stable neutrino with m< 2400 GeV.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>45.0	95	ABREU	92B	DLPH	Dirac
>39.5	95	ABREU	92B	DLPH	Majorana
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>44.1	95	ALEXANDER	91F	OPAL	Dirac
>37.2	95	ALEXANDER	91F	OPAL	Majorana
none 3–100	90	SATO	91	KAM2	Kamiokande II
>42.8	95	[39] ADEVA	90S	L3	Dirac
>34.8	95	[39] ADEVA	90S	L3	Majorana
>42.7	95	DECAMP	90F	ALEP	Dirac

[39] ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies $|U_{1j}|^2 + |U_{2j}|^2 + |U_{3j}|^2 > 6.2 \times 10^{-8}$ at $m(L^0)$ = 20 GeV and $> 5.1 \times 10^{-10}$ for $m(L^0)$ = 40 GeV.

Neutral Heavy Lepton MASS LIMITS

Limits apply only to heavy lepton type given in comment at right of data Listings. See review above for description of types. L, e_P, μ_P, e_O, μ_O stand for sequential lepton, para-electron, para-muon, ortho-electron, ortho-muon respectively. For a review, see GAN 88.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>46.4	95	[40] ADEVA	90S	L3	Dirac
>45.1	95	[40] ADEVA	90S	L3	Majorana
>46.5	95	[41] AKRAWY	90L	OPAL	Coupling to e or μ
>45.7	95	[41] AKRAWY	90L	OPAL	Coupling to τ
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>44.5	95	[42] ABREU	92B	DLPH	Dirac
>39.0	95	[42] ABREU	92B	DLPH	Majorana
>41	95	[43,44] BURCHAT	90	MRK2	Dirac, $\lvert U_{\ell j}\rvert^2 > 10^{-10}$
>19.6	95	[43,44] BURCHAT	90	MRK2	Dirac, all $\lvert U_{\ell j}\rvert^2$
none 25–45.7	95	[43,45] DECAMP	90F	ALEP	Dirac $\lvert U_{\ell j}\rvert^2 > 10^{-13}$
none 8.2–26.5	95	[46] SHAW	89	AMY	Dirac L^0, $\lvert U_{ej}\rvert^2 > 10^{-6}$
none 8.3–22.4	95	[46] SHAW	89	AMY	Majorana L^0, $\lvert U_{ej}\rvert^2 > 10^{-6}$
none 8.1–24.9	95	[46] SHAW	89	AMY	Majorana L^0, $\lvert U_{\mu j}\rvert^2 > 10^{-6}$
none 1.8–6.7	90	[47] AKERLOF	88	HRS	$\lvert U_{ej}\rvert^2=1$
none 1.8–6.4	90	[47] AKERLOF	88	HRS	$\lvert U_{\mu j}\rvert^2=1$
none 2.5–6.3	80	[47] AKERLOF	88	HRS	$\lvert U_{\tau j}\rvert^2=1$
none 0.6–34.6	95	[48] BEHREND	88C	CELL	$L^0=e^0_P$, $V-A$ coupling $\lvert U_{ej}\rvert^2=1$
none 0.4–37.4	95	[48] BEHREND	88C	CELL	$L^0=e^0_P$, $V+A$ coupling $\lvert U_{ej}\rvert^2=1$
none 0.25–14	90	[49] MISHRA	87	CNTR	$\lvert U_{\mu j}\rvert^2=1.$
none 0.25–10	90	[49] MISHRA	87	CNTR	$\lvert U_{\mu j}\rvert^2=0.1$
none 0.25–7.7	90	[49] MISHRA	87	CNTR	$\lvert U_{\mu j}\rvert^2=0.03$
none 1.–2.	90	[50] WENDT	87	MRK2	$\lvert U_{e \text{ or } \mu j}\rvert^2=0.1$
none 2.2–4.	90	[50] WENDT	87	MRK2	$\lvert U_{e \text{ or } \mu j}\rvert^2=0.001$
none 2.3–3.	90	[50] WENDT	87	MRK2	$\lvert U_{\tau j}\rvert^2=0.1$
none 3.2–4.8	90	[50] WENDT	87	MRK2	$\lvert U_{\tau j}\rvert^2=0.001$
none 0.3–0.9	90	[51] BADIER	86	CNTR	$\lvert U_{ej}\rvert^2=0.8$
none 0.33–2.0	90	[51] BADIER	86	CNTR	$\lvert U_{ej}\rvert^2=0.03$
none 0.6–0.7	90	[51] BADIER	86	CNTR	$\lvert U_{\mu j}\rvert^2=0.8$
none 0.6–2.0	90	[51] BADIER	86	CNTR	$\lvert U_{\mu j}\rvert^2=0.01$–$0.001$
>24.5	95	[52] BARTEL	83	JADE	e^0_P or e^0_O, $V+A$
>22.5	95	[52] BARTEL	83	JADE	e^0_P or e^0_O, $V-A$
none 1–9	90	[53] CLARK	81	SPEC	μ^0_P
> 1.2		MEYER	77	MRK1	Neutral

[40] ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies $\lvert U_{1j}\rvert^2 + \lvert U_{2j}\rvert^2 + \lvert U_{3j}\rvert^2 > 6.2 \times 10^{-8}$ at $m(L^0) = 20$ GeV and $> 5.1 \times 10^{-10}$ for $m(L^0) = 40$ GeV.

[41] AKRAWY 90L limits valid if coupling strength is greater than a mass-dependent value, e.g., 4.9×10^{-7} at $m(L^0) = 20$ GeV, 3.5×10^{-8} at 30 GeV, 4×10^{-9} at 40 GeV.

[42] ABREU 92B limit is for mixing matrix element ≈ 1 for coupling to e or μ. Reduced somewhat for coupling to τ, increased somewhat for smaller mixing matrix element. Replaces ABREU 91F.

[43] Limits apply for $\ell = e$, μ, or τ and for $V-A$ decays of Dirac neutrinos.

[44] BURCHAT 90 searched for Z decay to unstable L^0 pairs at SLC. It includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[45] For $25 < m(L^0) < 42.7$ GeV, DECAMP 90F exclude an L^0 for all values of $\lvert U_{\ell j}\rvert^2$.

[46] SHAW 89 also excludes the mass region from 8.0 to 27.2 GeV for Dirac L^0 and from 8.1 to 23.6 GeV for Majorana L^0 with equal full-strength couplings to e and μ. SHAW 89 also gives correlated bounds on lepton mixing.

[47] AKERLOF 88 is PEP e^+e^- experiment at $E_{cm} = 29$ GeV. The L^0 is assumed to decay via $V-A$ to e or μ or τ plus a virtual W.

[48] The first bound of BEHREND 88C applies for a general L^0. The second and third have their assumptions indicated.

[49] MISHRA 87 is Fermilab neutrino experiment looking for either dimuon or double vertex events (hence long-lived).

[50] WENDT 87 is MARK-II search at PEP for heavy ν with decay length 1–20 cm (hence long-lived).

[51] BADIER 86 is a search for a long-lived penetrating sequential lepton produced in π^- – nucleon collisions with lifetimes in the range from $5. \times 10^{-7}$–$5. \times 10^{-11}$ s and decaying into at least two charged particles. U_{ej} and U_{mj} are mixing angles to ν_e and ν_μ. See also the BADIER 86 entry in the section "Searches for Massive Neutrinos and Lepton Mixing".

[52] BARTEL 83 is PETRA e^+e^- experiment with average $W_{cm} = 34.2$ GeV. First (second) limit is for V+A(V−A) type $W^- e_P e$ coupling.

[53] CLARK 81 is FNAL experiment with 209 GeV muons. Bounds apply to para-muon which couples with full weak strength to muon. See also section on "Neutral Heavy Lepton Production Cross Section (μ Nucleon)" below.

Astrophysical Limits on Neutrino MASS for $m(\nu) > 1$ MeV

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 10–2400	90	[54] REUSSER	91	CNTR	HPGe search
none 3–100	90	SATO	91	KAM2	Kamiokande II
		[55] ENQVIST	89	COSM	
none 12–1400		[56] CALDWELL	88	COSM	Dirac ν
none 4–16	90	[56,57] OLIVE	88	COSM	Dirac ν
none 4–35	90	OLIVE	88	COSM	Majorana ν
>4.2 to 4.7		SREDNICKI	88	COSM	Dirac ν
>5.3 to 7.4		SREDNICKI	88	COSM	Majorana ν
none 20–1000	95	[56] AHLEN	87	COSM	Dirac ν
>4.1		GRIEST	87	COSM	Dirac ν

[54] REUSSER 91 uses existing $\beta\beta$ detector (see FISHER 89) to search for CDM Dirac neutrinos.

[55] ENQVIST 89 argue that there is no cosmological upper bound on heavy neutrinos.

[56] These results assume that neutrinos make up dark matter in the galactic halo.

[57] Limits based on annihilations in the sun and are due to an absence of high energy neutrinos detected in underground experiments.

Doubly-Charged Lepton Production Cross Section (μN Scattering)

VALUE (cm^2)	EVTS	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<6. \times 10^{-38}$	0	[58] CLARK	81	SPEC	++

[58] CLARK 81 is FNAL experiment with 209 GeV muon. Looked for μ^+ nucleon $\rightarrow \overline{\mu}^0_P$ X, $\overline{\mu}^0_P \rightarrow \mu^+\mu^-\overline{\nu}_\mu$ and $\mu^+ n \rightarrow \mu^{++}_P$ X, $\mu^{++}_P \rightarrow 2\mu^+\nu_\mu$. Above limits are for $\sigma \times$ BR taken from their mass-dependence plot figure 2.

Neutral Heavy Lepton Production Cross Section (μN)

VALUE (cm^2)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<4. \times 10^{-38}$	0	[59] CLARK	81	SPEC	0	μ^0_P
$<1.22 \times 10^{-34}$		[60] LEBRITTON	80	SPEC	0	$M^0 \rightarrow \mu^+\mu^-\nu$

[59] CLARK 81 is FNAL experiment with 209 GeV muon. Looked for μ^+ nucleon $\rightarrow \overline{\mu}^0_P$ X, $\overline{\mu}^0_P \rightarrow \mu^+\mu^-\overline{\nu}_\mu$ and $\mu^+ n \rightarrow \mu^{++}_P$ X, $\mu^{++}_P \rightarrow 2\mu^+\nu_\mu$. Above limits are for $\sigma \times$ BR taken from their mass-dependence plot figure 2.

[60] LEBRITTON 80 is BNL experiment with 10.5 GeV muons. Trimuons are consistent with QED trident and diffractively produced ρ decay.

Neutral Heavy Lepton Production Cross Section

$\sigma \times$ B($\tau \rightarrow$ new neutral lepton) $\times$ B(neutral lepton $\rightarrow e\pi$ or $\mu\pi$)

VALUE (10^{-5} nb)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<450	90	[61] MEYER	77	MRK1	For $m(L)$=0.5 GeV
<250	90	[61] MEYER	77	MRK1	For $m(L)$=1.5 GeV

[61] MEYER 77 experiment looks for narrow neutral resonance in $e^-\pi$ and $\mu^-\pi$ channels. See "Heavy Lepton MASS LIMITS" section above.

$\sigma(L\overline{L}) \times [B(L \rightarrow e\nu X) + B(\overline{L} \rightarrow e\nu X)]$

VALUE (10^{-5} nb)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 8	90	[62] ERREDE	84	HRS	For $m(L)$=1 GeV
<18	90	[62] ERREDE	84	HRS	For $m(L)$=2 GeV
<20	90	[62] ERREDE	84	HRS	For $m(L)$=3 GeV
<11	90	[62] ERREDE	84	HRS	For $m(L)$=4 or 5 GeV
<13	90	[62] ERREDE	84	HRS	For $m(L)$=6 GeV
<17	90	[62] ERREDE	84	HRS	For $m(L)$=7 GeV

[62] Assuming X = μ. If X = meson, limits are 20% higher. ERREDE 84 say these limits are comparable to those expected from naive theory. e^+e^-, $E_{cm} = 29$ GeV. See also GRONAU 84, RIZZO 84.

$\sigma(L_1 + L_2) \times$ B($L_1 \rightarrow$ only light neutrinos)

VALUE (10^{-5} nb)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 4.7	90	[63] AKERLOF	85	HRS	For $m(L)$=2 GeV
<18.	90	[63] AKERLOF	85	HRS	For $m(L)$=10 GeV

[63] AKERLOF 85 observe no monojets above background. They use standard couplings to Z to find $\sigma(L_1 + L_2) = 0.36$ pb. Above data then imply B($L_1 \rightarrow$ light neutrinos) <13–50% for $m(L)$ = 2–10 GeV.

$\sigma(L\overline{L}) \times BR_1 \times BR_2 / \sigma$(standard via virtual Z)

where BR_1 and BR_2 are branching ratios leading to events with two or four charged particles, and σ(standard) $= 0.35(\beta(3+\beta^2)/4)$ pb with β = velocity/c of L.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 0.1–0.2	90	0	[64] PERL	85	MRK2	For $m(L)$<1 GeV

[64] PERL 85 examine a variety of models and processes. They search up to $m(L)$ = 14 GeV but are most sensitive for $m(L)$ <1 GeV. They require lepton lifetime $< m(L) 10^{-11}$ s [$m(L)$ in GeV] which limits their ability to constrain the mixing of a 4th conventional generation.

REFERENCES FOR Heavy Lepton Searches

ABREU 92B PL B274 230 +Adams, Adami, Adye+ (DELPHI Collab.)
ABREU 91F NP B367 511 +Adam, Adami, Adye, Akesson, Alekseev+ (DELPHI Collab.)
ALEXANDER 91F ZPHY C52 175 +Allison, Allport, Anderson, Arcelli+ (OPAL Collab.)
KIM 91B IJMP A6 2583 +Smith, Breedon, Ko+ (AMY Collab.)
REUSSER 91 PL B255 143 +Treichel, Boehm+ (NEUC, CIT, PSI)
SATO 91 PR D44 2220 +Hirata, Kajita, Kifune, Kihara+ (Kamioka Collab.)
ADACHI 90C PL B244 352 +Aihara, Doser, Enomoto+ (TOPAZ Collab.)
ADEVA 90S PL B251 321 +Adriani, Aguilar-Benitez, Akbari+ (L3 Collab.)
AKRAWY 90G PL B240 250 +Alexander, Allison, Allport+ (OPAL Collab.)
AKRAWY 90L PL B247 448 +Alexander, Allison, Allport+ (OPAL Collab.)
AKRAWY 90O PL B252 290 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
BURCHAT 90 PR D41 3542 +King, Abrams, Adolphsen+ (Mark II Collab.)
DECAMP 90F PL B236 511 +Deschizeaux, Lees, Minard+ (ALEPH Collab.)
JUNG 90 PRL 64 1091 +Van Kooten, Abrams, Adolphsen+ (Mark II Collab.)
RILES 90 PR D42 1 +Perl, Barklow+ (Mark II Collab.)
SODERSTROM 90 PRL 64 2980 +McKenna, Abrams, Adolphsen, Averill+ (Mark II Collab.)
ABRAMS 89C PRL 63 2447 +Adolphsen, Averill, Ballam+ (Mark II Collab.)
ENQVIST 89 NP B317 647 +Kainulainen, Maalampi (HELS)
FISHER 89 PL B218 257 +Boehm, Bovet, Egger+ (CIT, NEUC, PSI)
SHAW 89 PRL 63 1342 +Blanis, Bodek, Budd+ (AMY Collab.)
STOKER 89 PR D39 1811 +Perl, Abrams+ (Mark II Collab.)
ABE 88 PRL 61 915 +Amako, Arai, Asano, Chiba (VENUS Collab.)
ADACHI 88B PR D37 1339 +Aihara, Dijkstra, Enomoto+ (TOPAZ Collab.)
AKERLOF 88 PR D37 577 +Chapman, Errede, Ken+ (HRS Collab.)
BEHREND 88C ZPHY C41 7 +Buerger, Criegee, Dainton+ (CELLO Collab.)
CALDWELL 88 PRL 61 510 +Eisberg, Grumm, Witherell+ (UCSB, UCB, LBL)
GAN 88 IJMP A3 531 +Perl (SLAC)
IGARASHI 88 PRL 60 2359 +Myung, Chiba, Hanaoka+ (AMY Collab.)
KIM 88 PRL 61 911 +Son, Bacala, Imlay+ (AMY Collab.)
OLIVE 88 PL B205 553 +Srednicki (MINN, UCSB)
SREDNICKI 88 NP B310 693 +Watkins, Olive (MINN, UCSB)
AHLEN 87 PL B195 603 +Avignone, Brodzinski+ (BOST, SCUC, HARV, CHIC)
ALBAJAR 87B PL B185 241 +Albrow, Allkofer, Arnison+ (UA1 Collab.)
GRIEST 87 NP B283 681 +Seckel (UCSC, CERN)
Also 88 NP B296 1034 erratum Griest, Seckel (UCSC, CERN)
MISHRA 87 PRL 59 1397 +Auchincloss+ (COLU, CIT, FNAL, CHIC, ROCH)
WENDT 87 PRL 58 1810 +Abrams, Amidei, Baden+ (Mark II Collab.)
YOSHIDA 87B PRL 59 2915 +Chiba, Endo+ (VENUS Collab.)
BADIER 86 ZPHY C31 21 +Bemporad, Boucrot, Callot+ (NA3 Collab.)
ADEVA 85 PL 152B 439 +Becker, Becker-Szendy+ (Mark-J Collab.)
Also 84C PRPL 109 131 Adeva, Barber, Becker+ (Mark-J Collab.)
AKERLOF 85 PL 156B 271 +Bonvicini, Chapman, Errede+ (HRS Collab.)
PERL 85 PR D32 2859 +Barklow, Boyarski+ (Mark II Collab.)
ERREDE 84 PL 149B 519 +Akerlof, Chapman, Harnew+ (HRS Collab.)
GRONAU 84 PR D29 2539 +Leung, Rosner (SYRA, FNAL, CHIC)
RIZZO 84 PL 136B 251 (ISU)
ADEVA 83B PRL 51 443 +Barber, Becker, Berdugo+ (Mark-J Collab.)
BARTEL 83 PL 123B 353 +Cords, Dietrich, Eichler+ (JADE Collab.)
ADEVA 82 PRL 48 967 +Barber, Becker, Berdugo+ (Mark-J Collab.)
BERGER 81B PL 99B 489 +Genzel, Grigull, Lackas+ (PLUTO Collab.)
BRANDELIK 81 PL 99B 163 +Braunschweig, Gather+ (TASSO Collab.)
CLARK 81 PRL 46 299 +Johnson, Kerth, Loken+ (UCB, LBL, FNAL, PRIN)
Also 82 PR D25 2762 Smith, Clark, Johnson, Kerth+ (LBL, FNAL, PRIN)
AZIMOV 80 JETPL 32 664 +Khoze (PINP)
Translated from ZETFP 32 677.
BARBER 80B PRL 45 1904 +Becker, Bei, Berghoff+ (Mark-J Collab.)
BRANDELIK 80 PL 92B 199 +Braunschweig, Gather+ (TASSO Collab.)
LEBRITTON 80 PL 89B 271 +McCal, Melissinos+ (ROCH, BNL, NSF)
ASRATYAN 78 PL 76B 237 +Kubantsev (ITEP)
CNOPS 78 PRL 40 144 +Connolly, Kahn, Kirk+ (BNL, COLU)
ERRIQUEZ 78 PL 77B 227 (BARI, BIRM, BRUX, EPOL, RHEL, SACL, LOUC)
HOLDER 78 PL 74B 277 +Knobloch, May+ (CDHS Collab.)
BACCI 77B PL 71B 227 +Dezorzi, Penso, Stella+ (ROMA, FRAS)
HOLDER 77 PL 70B 393 +Knobloch, May+ (CDHS Collab.)
MEYER 77 PL 70B 469 +Nguyen, Abrams+ (SLAC, LBL, NWES, HAWA)
ASRATYAN 74 PL 49B 488 +Gershtein, Kaftanov, Kubantsev, Lapin+ (SERP)
BARISH 74 PRL 32 1387 +Bartlett, Buchholz, Merritt+ (CIT, FNAL)
GITTLESON 74 PR D10 1379 +Kirk+ (HARV, ROCH, COLU, FNAL)
ANSORGE 73B PR D7 26 +Baker, Krzesinski, Neale, Rushbrooke+ (CAVE)
BACCI 73 PL 44B 530 +Parisi, Penso, Salvini, Stella+ (ROMA, FRAS)
BARISH 73B PRL 31 410 +Bartlett, Buchholz, Humphrey+ (CIT, FNAL)
BUSHNIN 73 NP B58 476 +Dunaitzev, Golovkin, Kubarovsky+ (SERP)
Also 72 PL 42B 136 Golovkin, Grachev, Shodyrev+ (SERP)
EICHTEN 73 PL 46B 281 +Deden, Hasert, Krenz+ (Gargamelle Collab.)
LICHTENSTEIN 70 PR D1 825 +Ash, Berkelman, Hartill+ (CORN)
LIBERMAN 69 PRL 22 663 +Hoffman, Engels+ (HARV, CASE, MCGI, SLAC)
ROTHE 69 NP B10 241 +Wolsky (PENN)
BARNA 68 PR 173 1391 +Cox, Martin, Perl, Tan, Toner, Zipf+ (SLAC, STAN)
BOLEY 68 PR 167 1275 +Elias, Friedman, Hartmann, Kendall+ (MIT, CEA)
BUDNITZ 66 PR 141 1313 +Dunning, Goitein, Ramsey, Walker+ (HARV)
BEHREND 65 PRL 15 900 +Brasse, Engler, Ganssauge+ (DESY, KARL)
BETOURNE 65 PL 17 70 +Ngoc, Perez-y-Jorba+ (ORSA)

OTHER RELATED PAPERS

PERL 81 SLAC-PUB-2752 (SLAC)
Physics in Collision Conference.

Searches for Massive Neutrinos and Lepton Mixing

Searches for the effects of nonzero neutrino masses and lepton mixing are listed here. Direct searches for masses of dominantly coupled neutrinos are listed in the appropriate section on ν_e, ν_μ, or ν_τ. The results in the present section are correlated upper bounds on mixing matrix coefficients U_{aj} versus neutrino mass. These results are divided into four main sections:

1. bounds from particle and nuclear decays
2. bounds from neutrino reactions, including reactor and accelerator neutrino oscillation experiments, and solar neutrino measurements
3. searches for neutrinoless double-β decay
4. searches for mixing of $(\mu^- e^+)$ and $(\mu^+ e^-)$

Discussion of the ν_e mass limit, the "17 keV neutrino," and solar neutrino observations are given in the "Note of Neutrinos" by R.E. Shrock in the ν_e section near the beginning of these data listings. Several reviews are also listed there.

(A) Bounds from Particle and Nuclear Decays

Limits on $|U_{1j}|^2$ as Function of $m(\nu_j)$

Application of Kink and Peak Search Test to Existing Data

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1 \times 10^{-4}$	68	[1] SHROCK	81	THEO	$m(\nu_j)$=10 MeV
$<5 \times 10^{-6}$	68	[1] SHROCK	81	THEO	$m(\nu_j)$=60 MeV
<1	95	[2] SIMPSON	81B		$m(\nu_j)$=0.1 keV
$<4 \times 10^{-3}$	95	[2] SIMPSON	81B		$m(\nu_j)$=10 keV
<0.1	68	[3] SHROCK	80	THEO	$m(\nu_j)$=0.1–3 MeV
$<1 \times 10^{-5}$	68	[4] SHROCK	80	THEO	$m(\nu_j)$=80 MeV
$<3 \times 10^{-6}$	68	[4] SHROCK	80	THEO	$m(\nu_j)$=160 MeV

[1] Analysis of $(\pi^+ \to e^+\nu_e)/(\pi^+ \to \mu^+\nu_\mu)$ and $(K^+ \to e^+\nu_e)/(K^+ \to \mu^+\nu_\mu)$ decay ratios.
[2] Application of kink search test to tritium β decay Kurie plot.
[3] Application of test to search for kinks in β decay Kurie plots.
[4] Analysis of $(K^+ \to e^+\nu_e)$ spectrum.

New Experiments to Apply Peak and Kink Search Tests

Limits on $|U_{1j}|^2$ as function of $m(\nu_j)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5 \times 10^{-6}$	90	DELEENER-...	91		$m(\nu_j)$ = 20 MeV
$<5 \times 10^{-7}$	90	DELEENER-...	91		$m(\nu_j)$ = 40 MeV
$<3 \times 10^{-7}$	90	DELEENER-...	91		$m(\nu_j)$ = 60 MeV
$<1 \times 10^{-6}$	90	DELEENER-...	91		$m(\nu_j)$ = 80 MeV
$<1 \times 10^{-6}$	90	DELEENER-...	91		$m(\nu_j)$ = 100 MeV
$<5 \times 10^{-7}$	90	AZUELOS	86	CNTR	$m(\nu_j)$=60 MeV
$<2 \times 10^{-7}$	90	AZUELOS	86	CNTR	$m(\nu_j)$=80 MeV
$<3 \times 10^{-7}$	90	AZUELOS	86	CNTR	$m(\nu_j)$=100 MeV
$<1 \times 10^{-6}$	90	AZUELOS	86	CNTR	$m(\nu_j)$=120 MeV
$<2 \times 10^{-7}$	90	AZUELOS	86	CNTR	$m(\nu_j)$=130 MeV
$<8 \times 10^{-6}$		DELEENER-...	86	CNTR	$m(\nu_j)$=20 MeV
$<4 \times 10^{-7}$		DELEENER-...	86	CNTR	$m(\nu_j)$=60 MeV
$<2 \times 10^{-6}$		DELEENER-...	86	CNTR	$m(\nu_j)$=100 MeV
$<7 \times 10^{-6}$		DELEENER-...	86	CNTR	$m(\nu_j)$=120 MeV
$<1 \times 10^{-4}$	90	[5] BRYMAN	83B	CNTR	$m(\nu_j)$=5 MeV
$<1.5 \times 10^{-6}$	90	BRYMAN	83B	CNTR	$m(\nu_j)$=53 MeV
$<1 \times 10^{-5}$	90	BRYMAN	83B	CNTR	$m(\nu_j)$=70 MeV
$<1 \times 10^{-4}$	90	BRYMAN	83B	CNTR	$m(\nu_j)$=130 MeV

[5] BRYMAN 83B obtain upper limits from both direct peak search and analysis of $B(\pi \to e\nu)/B(\pi \to \mu\nu)$. Latter limits are not listed, except for this entry (i.e. — we list the most stringent limits for given mass).

Searches for Decays of Massive ν

Limits on $|U_{1j}|^2$ as function of $m(\nu_j)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<6.2 \times 10^{-8}$	95	ADEVA	90S	L3	$m(\nu_j) = 20$ GeV
$<5.1 \times 10^{-10}$	95	ADEVA	90S	L3	$m(\nu_j) = 40$ GeV
all values ruled out	95	[6] BURCHAT	90	MRK2	$m(\nu_j) < 19.6$ GeV
$<1 \times 10^{-10}$	95	[6] BURCHAT	90	MRK2	$m(\nu_j) = 22$ GeV
$<1 \times 10^{-11}$	95	[6] BURCHAT	90	MRK2	$m(\nu_j) = 41$ GeV
all values ruled out	95	DECAMP	90F	ALEP	$m(\nu_j)$= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP	90F	ALEP	$m(\nu_j)$= 42.7–45.7 GeV
$<5 \times 10^{-3}$	90	AKERLOF	88	HRS	$m(\nu_j)$=1.8 GeV
$<2 \times 10^{-5}$	90	AKERLOF	88	HRS	$m(\nu_j)$=4 GeV
$<3 \times 10^{-6}$	90	AKERLOF	88	HRS	$m(\nu_j)$=6 GeV
$<1.2 \times 10^{-7}$	90	BERNARDI	88	CNTR	$m(\mu_j)$=100 MeV
$<1 \times 10^{-8}$	90	BERNARDI	88	CNTR	$m(\mu_j)$=200 MeV
$<2.4 \times 10^{-9}$	90	BERNARDI	88	CNTR	$m(\mu_j)$=300 MeV
$<2.1 \times 10^{-9}$	90	BERNARDI	88	CNTR	$m(\mu_j)$=400 MeV
$<2 \times 10^{-2}$	68	[7] OBERAUER	87		$m(\nu_j)$=1.5 MeV
$<8 \times 10^{-4}$	68	[7] OBERAUER	87		$m(\nu_j)$=4.0 MeV
$<8 \times 10^{-3}$	90	BADIER	86	CNTR	$m(\nu_j)$=400 MeV
$<8 \times 10^{-5}$	90	BADIER	86	CNTR	$m(\nu_j)$=1.7 GeV
$<8 \times 10^{-8}$	90	BERNARDI	86	CNTR	$m(\nu_j)$=100 MeV
$<4 \times 10^{-8}$	90	BERNARDI	86	CNTR	$m(\nu_j)$=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI	86	CNTR	$m(\nu_j)$=400 MeV
$<3 \times 10^{-5}$	90	DORENBOS...	86	CNTR	$m(\nu_j)$=150 MeV
$<1 \times 10^{-6}$	90	DORENBOS...	86	CNTR	$m(\nu_j)$=500 MeV
$<1 \times 10^{-7}$	90	DORENBOS...	86	CNTR	$m(\nu_j)$=1.6 GeV
$<7 \times 10^{-7}$	90	[8] COOPER-...	85	HLBC	$m(\nu_j)$=0.4 GeV
$<8 \times 10^{-8}$	90	[8] COOPER-...	85	HLBC	$m(\nu_j)$=1.5 GeV
$<1 \times 10^{-2}$	90	[9] BERGSMA	83B	CNTR	$m(\nu_j)$=10 MeV
$<1 \times 10^{-5}$	90	[9] BERGSMA	83B	CNTR	$m(\nu_j)$=110 MeV
$<6 \times 10^{-7}$	90	[9] BERGSMA	83B	CNTR	$m(\nu_j)$=410 MeV
$<1 \times 10^{-5}$	90	GRONAU	83		$m(\nu_j)$=160 MeV
$<1 \times 10^{-6}$	90	GRONAU	83		$m(\nu_j)$=480 MeV

[6] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[7] OBERAUER 87 bounds from search for $\nu \rightarrow \nu' ee$ decay mode using reactor (anti)neutrinos.

[8] COOPER-SARKAR 85 also give limits based on model-dependent assumptions for ν_τ flux. We do not list these. Note that for this bound to be nontrivial, j is not equal to 3, i.e. ν_j cannot be the dominant mass eigenstate in ν_τ since $m(\nu_3)$ <70 MeV (ALBRECHT 85I). Also, of course, j is not equal to 1 or 2, so a fourth generation would be required for this bound to be nontrivial.

[9] BERGSMA 83B also quote limits on $|U_{13}|^2$ where the index 3 refers to the mass eigenstate dominantly coupled to the τ. Those limits were based on assumptions about the D_s mass and $D_s \rightarrow \tau\nu_\tau$ branching ratio which are no longer valid. See COOPER-SARKAR 85.

Kink Search in Nuclear β Decay

VALUE (units 10^{-3})	CL%	$m(\nu_j)$ (keV)	ISOTOPE	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
8.4 ± 0.6±0.5		17.0 ± 0.4	^{35}S	Si(Li) det	HIME	91
9.9 ± 1.2±1.8		16.75 ± 0.35 ± 0.15	^{63}Ni	Solid state det	HIME	91B
14.0 ± 4.5±1.4		17 ± 2	^{14}C	^{14}C in HPGe	[10] SUR	91
16 ± 7		$17.2^{+1.9}_{-1.1}$	^{71}Ge	γ in Ge	[11] ZLIMEN	91
		17		THEO	[12] DRUKAREV	89
6 to 16		16.9 ± 0.4	^{3}H	In HPGe	HIME	89
5 to 18		17.1 ± 0.2	^{3}H	In Si(Li)	[13] HIME	89
7.3 ± 0.9±0.6		16.9 ± 0.4	^{35}S	Si(Li)	[14] SIMPSON	89
< 7.4	99.7	16.4–17.4	^{55}Fe	IBEC; γ det	[15] ZLIMEN	88
< 3	90	17	^{63}Ni	Mag spect	[16] HETHERING...	87
< 10	90	17	^{125}I	IBEC; γ det	[17] BORGE	86
10 to 20		17		RVUE	[18] SIMPSON	86
< 4	99	17	^{35}S	Mag spect	ALTZITZOG...	85
< 7.5	99	5–50	^{35}S	Mag spect	ALTZITZOG...	85
< 8	90	80	^{35}S	Mag spect	[19] APALIKOV	85
< 1.5	90	60	^{35}S	Mag spect	APALIKOV	85
< 8	90	30	^{35}S	Mag spect	APALIKOV	85
< 3	90	17	^{35}S	Mag spect	APALIKOV	85
< 45	90	4	^{35}S	Mag spect	APALIKOV	85
< 6	90	17	^{35}S	Si(Li)	DATAR	85
< 10	90	5–30	^{35}S	Si(Li)	DATAR	85
< 3.0	90	5–50		Mag spect	MARKEY	85
< 2.5	90	17		Mag spect	MARKEY	85
< 0.62	90	48	^{35}S	Si(Li)	OHI	85
< 0.90	90	30	^{35}S	Si(Li)	OHI	85
< 1.30	90	20	^{35}S	Si(Li)	OHI	85
< 1.50	90	17	^{35}S	Si(Li)	OHI	85
< 3.30	90	10	^{35}S	Si(Li)	OHI	85
30 ± 10		17.1 ± 0.2	^{3}H	In Si(Li)	[20] SIMPSON	85
< 25	90	30	^{64}Cu	Mag spect	[21] SCHRECK...	83
< 4	90	140	^{64}Cu	Mag spect	[21] SCHRECK...	83
< 8	90	440	^{64}Cu	Mag spect	[21] SCHRECK...	83
<100	90	0.1–3000		THEO	[22] SHROCK	80
			^{3}H	Prop. cntr	[23] CONWAY	59

[10] SUR 91 reports an LBL experiment using a solid state Ge crystal grown with ^{14}C inside. In a conference report (NORMAN 91), the authors also report indications for the emission of a 17 keV neutrino in the ^{55}Fe inner bremsstrahlung transition: $m(\nu_j) = 21 \pm 2$ keV with $|U_{1j}|^2 = 0.0085 \pm 0.0045$.

[11] ZLIMEN 91 used a HPGe detector to observe the inner bremsstrahlung electron capture transition of ^{71}Ge in an external source. Reported errors on both parameters are given as 95%CL limits, which in the case of normal distributions corresponds to 1.96σ.

[12] DRUKAREV 89 claims that taking into account screening effects can explain Simpson's claims without invoking a massive neutrino or other unconventional physics. A similar criticism concerning screening corrections had been made by LINDHARD 86.

[13] HIME 89 corrects the analysis of the data of SIMPSON 85 for screening effects as suggested by LINDHARD 86, giving a smaller range for $|U_{1j}|^2$, as cited above. This value should therefore replace that given in SIMPSON 85, which has been retracted.

[14] SIMPSON 89 and HIME 89 report kinks due to the emission of a massive neutrino in ^{35}S and ^{3}Hβ decays, respectively.

[15] ZLIMEN 88 report an experiment on ^{55}Fe, observing internal bremsstrahlung in electron capture (IBEC). For a contemporary review of IBEC, see LOGAN 89.

[16] HETHERINGTON 87 reports no evidence for any massive neutrino signal for $m(\nu_j)$ in the range from 4 to 40 keV, and, in particular, set the upper limit cited above on $|U_{1j}|^2$ for a hypothetical 17 keV neutrino.

[17] BORGE 86 results originally presented as evidence against the SIMPSON 85 claim of a 17 keV antineutrino emitted with $|U_{1j}|^2 = 0.03$ in ^{3}H decay.

[18] SIMPSON 86 is a reanalysis of the OHI 85 data and claims that these data show evidence of heavy neutrino emission with $m(\nu_j) = 17$ keV and $|U_{1j}|^2$ = from 0.01 to 0.02, consistent with the earlier reported observation by SIMPSON 85. This conclusion strongly disagrees with the conclusion reached by OHI 85 from their analysis of their own data. SIMPSON 86 also states that "a similar threshold effect (due to supposed heavy neutrino emission) is seen in several of the other published ^{35}S experiments as well."

[19] This limit was taken from the figure 3 of APALIKOV 85; the text gives a more restrictive limit of 1.7×10^{-3} at CL = 90%.

[20] SIMPSON 85. See footnotes on SIMPSON 89 and SIMPSON 86, as well as comments by HAXTON 85, KALBFLEISCH 85, EMAN 86, LINDHARD 86, DRUKAREV 86, and further discussion by SIMPSON 89 and HIME 89.

[21] SCHRECKENBACH 83 is a combined measurement of the β^+ and β^- spectrum.

[22] SHROCK 80 was a retroactive analysis of data on several superallowed β decays to search for kinks in the Kurie plot.

[23] CONWAY 59 first reported a spectral excess of about 1% at electron kinetic energy of 1 keV in ^{3}Hβ decay, but did not interpret it as the emission of a massive neutrino. Indeed, no searches for masses admixed neutrinos were performed prior to 1980; cf. SHROCK 80. This spectral excess was again observed in SIMPSON 85, apparently without knowledge of the CONWAY 59 finding. Spectral excesses in this kinetic energy region were also reported in HAMILTON 58 and JOHNSON 58, and in other references cited therein.

Limits on $|U_{2j}|^2$ as Function of $m(\nu_j)$

Application of Peak Search Test to Existing Data

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<6 \times 10^{-6}$	95	[24] ASANO	81		$m(\nu_j)$=240 MeV
$<5 \times 10^{-7}$	95	[24] ASANO	81		$m(\nu_j)$=280 MeV
$<6 \times 10^{-6}$	95	[24] ASANO	81		$m(\nu_j)$=300 MeV
$<3 \times 10^{-2}$	95	[25] SHROCK	81	THEO	$m(\nu_j)$=7 MeV
$<1 \times 10^{-2}$	95	[25] SHROCK	81	THEO	$m(\nu_j)$=13 MeV
$<1 \times 10^{-4}$	68	[25] SHROCK	81	THEO	$m(\nu_j)$=13 MeV
$<3 \times 10^{-5}$	68	[25] SHROCK	81	THEO	$m(\nu_j)$=33 MeV
$<6 \times 10^{-3}$	68	[26] SHROCK	81	THEO	$m(\nu_j)$=80 MeV
$<5 \times 10^{-3}$	68	[26] SHROCK	81	THEO	$m(\nu_j)$=120 MeV
$<5 \times 10^{-2}$	95	[25] SHROCK	80	THEO	$m(\nu_j)$=4–6 MeV

[24] Analysis of experiment on $K^+ \rightarrow \mu^+ \nu_\mu \nu_X \overline{\nu}_X$ decay.

[25] Analysis of magnetic spectrometer experiment, bubble chamber experiment, and emulsion experiment on $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay.

[26] Analysis of magnetic spectrometer experiment on $K \rightarrow \mu, \nu_\mu$ decay.

Application of Peak Search Test to New Experiments

Limits on $|U_{2j}|^2$ as function of $m(\nu_j)$

VALUE	CL%	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2 \times 10^{-2}$	90	DAUM	87	$m(\nu_j)$=1 MeV
$<1 \times 10^{-3}$	90	DAUM	87	$m(\nu_j)$=2 MeV
$<6 \times 10^{-5}$	90	DAUM	87	3 MeV < $m(\nu_j)$ < 19.5 MeV
$<3 \times 10^{-2}$	90	[27] MINEHART	84	$m(\nu_j)$=2 MeV
$<1 \times 10^{-3}$	90	[27] MINEHART	84	$m(\nu_j)$=4 MeV
$<3 \times 10^{-4}$	90	[27] MINEHART	84	$m(\nu_j)$=10 MeV
$<5 \times 10^{-6}$	90	[28] HAYANO	82	$m(\nu_j)$=330 MeV
$<1 \times 10^{-4}$	90	[28] HAYANO	82	$m(\nu_j)$=70 MeV
$<9 \times 10^{-7}$	90	[28] HAYANO	82	$m(\nu_j)$=250 MeV
$<1 \times 10^{-1}$	90	[27] ABELA	81	$m(\nu_j)$=4 MeV
$<7 \times 10^{-5}$	90	[27] ABELA	81	$m(\nu_j)$=10.5 MeV
$<2 \times 10^{-4}$	90	[27] ABELA	81	$m(\nu_j)$=11.5 MeV
$<2 \times 10^{-5}$	90	[27] ABELA	81	$m(\nu_j)$=16–30 MeV
$<2 \times 10^{-5}$	95	[28] ASANO	81	$m(\nu_j)$=170 MeV
$<3 \times 10^{-6}$	95	[28] ASANO	81	$m(\nu_j)$=210 MeV
$<3 \times 10^{-6}$	95	[28] ASANO	81	$m(\nu_j)$=230 MeV
$<1 \times 10^{-2}$	95	[27] CALAPRICE	81	$m(\nu_j)$=7 MeV
$<3 \times 10^{-3}$	95	[27] CALAPRICE	81	$m(\nu_j)$=33 MeV

[27] $\pi^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.
[28] $K^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.

Peak Search in Muon Capture

Limits on $|U_{2j}|^2$ as function of $m(\nu_j)$

VALUE	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$<1 \times 10^{-1}$	DEUTSCH	83	$m(\nu_j)$=45 MeV
$<7 \times 10^{-3}$	DEUTSCH	83	$m(\nu_j)$=70 MeV
$<1 \times 10^{-1}$	DEUTSCH	83	$m(\nu_j)$=85 MeV

Searches for Decays of Massive ν

Limits on $|U_{2j}|^2$ as function of $m(\nu_j)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<6.2 \times 10^{-8}$	95	ADEVA	90S	L3	$m(\nu_j)$ = 20 GeV
$<5.1 \times 10^{-10}$	95	ADEVA	90S	L3	$m(\nu_j)$ = 40 GeV
all values ruled out	95	[29] BURCHAT	90	MRK2	$m(\nu_j)$ < 19.6 GeV
$<1 \times 10^{-10}$	95	[29] BURCHAT	90	MRK2	$m(\nu_j)$ = 22 GeV
$<1 \times 10^{-11}$	95	[29] BURCHAT	90	MRK2	$m(\nu_j)$ = 41 GeV
all values ruled out	95	DECAMP	90F	ALEP	$m(\nu_j)$= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP	90F	ALEP	$m(\nu_j)$= 42.7–45.7 GeV
$<5 \times 10^{-4}$	90	[30] KOPEIKIN	90	CNTR	$m(\nu_j)$ = 5.2 MeV
$<5 \times 10^{-3}$	90	AKERLOF	88	HRS	$m(\nu_j)$=1.8 GeV
$<2 \times 10^{-5}$	90	AKERLOF	88	HRS	$m(\nu_j)$=4 GeV
$<3 \times 10^{-6}$	90	AKERLOF	88	HRS	$m(\nu_j)$=6 GeV
$<1 \times 10^{-7}$	90	BERNARDI	88	CNTR	$m(\mu_j)$=200 MeV
$<3 \times 10^{-9}$	90	BERNARDI	88	CNTR	$m(\mu_j)$=300 MeV
$<4 \times 10^{-4}$	90	[31] MISHRA	87	CNTR	$m(\nu_j)$=1.5 GeV
$<4 \times 10^{-3}$	90	[31] MISHRA	87	CNTR	$m(\nu_j)$=2.5 GeV
$<0.9 \times 10^{-2}$	90	[31] MISHRA	87	CNTR	$m(\nu_j)$=5 GeV
<0.1	90	[31] MISHRA	87	CNTR	$m(\nu_j)$=10 GeV
$<8 \times 10^{-4}$	90	BADIER	86	CNTR	$m(\nu_j)$=600 MeV
$<1.2 \times 10^{-5}$	90	BADIER	86	CNTR	$m(\nu_j)$=1.7 GeV
$<3 \times 10^{-8}$	90	BERNARDI	86	CNTR	$m(\nu_j)$=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI	86	CNTR	$m(\nu_j)$=350 MeV
$<1 \times 10^{-6}$	90	DORENBOS...	86	CNTR	$m(\nu_j)$=500 MeV
$<1 \times 10^{-7}$	90	DORENBOS...	86	CNTR	$m(\nu_j)$=1600 MeV
$<0.8 \times 10^{-5}$	90	[32] COOPER-...	85	HLBC	$m(\nu_j)$=0.4 GeV
$<1.0 \times 10^{-7}$	90	[32] COOPER-...	85	HLBC	$m(\nu_j)$=1.5 GeV

[29] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.
[30] KOPEIKIN 90 find no $m(\nu_j)$ in the interval 1–6.3 MeV at 90%CL for maximal mixing.
[31] See also limits on $|U_{3j}|$ from WENDT 87.
[32] COOPER-SARKAR 85 also give limits based on model-dependent assumptions for ν_τ flux. We do not list these. Note that for this bound to be nontrivial, j is not equal to 3, i.e. ν_j cannot be the dominant mass eigenstate in ν_τ since $m(\nu_3)$ <70 MeV (ALBRECHT 85I). Also, of course, j is not equal to 1 or 2, so a fourth generation would be required for this bound to be nontrivial.

Limits on $|U_{3j}|^2$ as a Function of $m(\nu_j)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<6.2 \times 10^{-8}$	95	ADEVA	90S	L3	$m(\nu_j)$ = 20 GeV
$<5.1 \times 10^{-10}$	95	ADEVA	90S	L3	$m(\nu_j)$ = 40 GeV
all values ruled out	95	[33] BURCHAT	90	MRK2	$m(\nu_j)$ < 19.6 GeV
$<1 \times 10^{-10}$	95	[33] BURCHAT	90	MRK2	$m(\nu_j)$ = 22 GeV
$<1 \times 10^{-11}$	95	[33] BURCHAT	90	MRK2	$m(\nu_j)$ = 41 GeV
all values ruled out	95	DECAMP	90F	ALEP	$m(\nu_j)$= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP	90F	ALEP	$m(\nu_j)$= 42.7–45.7 GeV
$<5 \times 10^{-2}$	80	AKERLOF	88	HRS	$m(\nu_j)$=2.5 GeV
$<9 \times 10^{-5}$	80	AKERLOF	88	HRS	$m(\nu_j)$=4.5 GeV

[33] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

Limits on $|U_{aj}|^2$

Where a = 1, 2 from ρ parameter in μ decay.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1 \times 10^{-2}$	68	SHROCK	81B	THEO	$m(\nu_j)$=10 MeV
$<2 \times 10^{-3}$	68	SHROCK	81B	THEO	$m(\nu_j)$=40 MeV
$<4 \times 10^{-2}$	68	SHROCK	81B	THEO	$m(\nu_j)$=70 MeV

Limits on $|U_{1j} \times U_{2j}|$ as Function of $m(\nu_j)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<9 \times 10^{-5}$	90	BERNARDI	86	CNTR	$m(\nu_j)$=25 MeV
$<3.6 \times 10^{-7}$	90	BERNARDI	86	CNTR	$m(\nu_j)$=100 MeV
$<3 \times 10^{-8}$	90	BERNARDI	86	CNTR	$m(\nu_j)$=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI	86	CNTR	$m(\nu_j)$=350 MeV
$<1 \times 10^{-2}$	90	BERGSMA	83B	CNTR	$m(\nu_j)$=10 MeV
$<1 \times 10^{-5}$	90	BERGSMA	83B	CNTR	$m(\nu_j)$=140 MeV
$<7 \times 10^{-7}$	90	BERGSMA	83B	CNTR	$m(\nu_j)$=370 MeV

(B) Bounds from ν Reactions

Solar ν Experiments

Theoretical calculations of the expected solar rate are shown for comparison with experiment.

The unit of solar neutrino flux used in describing the results of radiochemical experiments (as well as the Sudbury $\nu_e D \rightarrow e^- pp$ experiment) is the solar neutrino unit, or SNU, defined as 1×10^{-36} captures s^{-1} (target atom)$^{-1}$. Results from the Kamiokande II $\nu_e e$ scattering experiment[1] are reported relative to expectation from the standard solar model (SSM). Both this experiment and Davis's ^{37}Cl capture experiment[2,3] are primarily sensitive to neutrinos from the decay of ^{8}B decay in the solar core. There are several versions of the SSM calculations which give different ^{8}B solar neutrino flux values;[4,5] Davis and the Kamiokande II group quote the measured solar neutrino flux relative to model calculations of Bahcall and Ulrich.[4] The Soviet-American Gallium Experiment (SAGE) is sensitive to the lower-energy neutrinos from the main pp reaction. Results from all experiments, including preliminary results from SAGE, indicate a serious solar neutrino deficit. Bethe[6] discusses various possible theoretical explanations. For reviews, see papers by Davis[3] and Kuo.[7]

References

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4. J.N. Bahcall and R.K. Ulrich, Rev. Mod. Phys. **60**, 297 (1988).
5. S. Turck-Cieèze *et al.*, Astrophys. J. **335**, 415 (1988).
6. H.A. Bethe, Phys. Rev. Lett. **63**, 837 (1989).
7. T.K. Kuo and J. Pantaleone, Rev. Mod. Phys. **61**, 937 (1989).

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
2.3 ± 0.3 SNU		[34] ABAZOV	91	HOME	^{37}Cl radiochemical
< 79 SNU	90	[35] ABAZOV	91B	SAGE	^{71}Ga → ^{71}Ge
(0.46 ± 0.05 ± 0.06) × SSM		[36] HIRATA	90	KAM2	Water Cerenkov
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[37] GARCIA	91	CNTR	Nuclear physics
		[38] HIRATA	91	KAM2	
		[39] FILIPPONE	90	THY	
		[40] HIRATA	90B	KAM2	
7.9 ± 2.6 SNU		[41] BAHCALL	88	THEO	^{37}Cl prediction; total theor. range
132^{+20}_{-17}		[41] BAHCALL	88	THEO	^{71}Ga prediction; total theor. range
5.8 ± 1.3 SNU		TURCK-CHI...	88	THEO	^{37}Cl prediction
125 ± 5 SNU		TURCK-CHI...	88	THEO	^{71}Ga prediction
5.8 ± 2.2 SNU		BAHCALL	84	THEO	^{37}CL prediction
2.1 ± 0.3 SNU		[42] DAVIS	84	HOME	^{37}Cl radiochemical
5.6 SNU		FILIPPONE	83	THEO	^{37}Cl prediction
7.0 ± 3.0 SNU		FILIPPONE	82	THEO	^{37}Cl prediction
6.9 ± 1.0 SNU		FOWLER	82	THEO	^{37}Cl prediction
7.3 SNU		BAHCALL	80	THEO	^{37}CL prediction

See also the reviews by BAHCALL 89 and DAVIS 89.

[34] ABAZOV 91 concerns the SAGE experiment reported under ABAZOV 91B, but incidently updates the DAVIS 84 results. After a gap the experiment was continued, and the above result is the average for 1970–1988. The experiment uses the reaction ^{37}Cl (ν_e,e) ^{37}Ar to detect the solar neutrinos. This reaction has a neutrino threshold energy of 0.814 MeV and hence is sensitive to the high-energy component of the neutrino flux, coming mainly from the ^{8}B reaction, with a maximum energy of 14 MeV.

[35] ABAZOV 91B uses a 30 ton gallium detector to search for the reaction ^{71}Ga (ν_e, e) ^{71}Ge. Limit is obtained from capture rate of $20^{+15}_{-20} \pm 32$ SNU obtained in first 6 months of operation. Since this reaction has a threshold neutrino energy of 0.236 MeV, it is sensitive to the low-energy neutrinos from the main pp chain (whose maximum energy is 0.420 MeV). The upper limit quoted is to be compared with the theoretical expectation of about 130 SNU; see BAHCALL 89B and references therein.

[36] HIRATA 90 data consists of 1040 days with threshold $E_e > 9.3$ MeV (first 450 days) or $E_e > 7.5$ MeV. "The total data sample is also analyzed for short-term variations; within the statistical error, no significant variation is observed." The flux is scaled by the value relative to the standard solar model (SSM) prediction. A theoretical flux of $(5.8 \pm 2.1) \times 10^6$ cm^{-2} s^{-1} is cited, with the central value corresponding to 7.9 SNU for ^{37}Cl experiment.

[37] GARCIA 91 reports a new study of ^{37}Caβ decays, with the result that the BAHCALL 88 SSM prediction for ^{37}Cl should be increased from 7.9 to 8.1 SNU.

[38] HIRATA 91 reports a search for day-night and semi-annual variations in the solar neutrino flux observed in the Kamiokande II Detector. The sample is the same 1040 day counting period used for HIRATA 90 and HIRATA 90B. "Within statistical error, no such short-time variations were observed." This result was used to constrain neutrino oscillation parameters, in the framework of oscillations between two mass eigenstates. "A region defined by $\sin^2 2\theta > 0.02$ and 2×10^{-6} eV^2 < $\Delta(m^2)$ < 1×10^{-5} eV^2 is excluded at the 90% CL without any assumptions on the absolute value of the expected solar neutrino flux."

[39] FILIPPONE 90 is a statistical analysis of solar neutrino data to test hypotheses of time dependence. The authors state "we have shown that in our unbiased analysis, the hypothesis of a time-independent ^{37}Cl neutrino capture rate is marginally rejected, having only 2% probability. However, it is disturbing that we are not able to find a simple hypothesis of time variation that would describe the data well. A capture rate anticorrelated with sunspot number, although more probable than the constant rate hypothesis, has a probablity of only 6%. One possible explanation of these results is simply the poor statistics of the ^{37}Cl experiment."

[40] HIRATA 90B gives an analysis of the implications of these data for allowed values of $\Delta(m^2)$ and $\sin^2 2\theta$ describing neutrino mixing between two mass eigenstates, in the model of resonant (MSW) neutrino oscillations. The possibility of regeneration as the neutrinos pass through the earth is neglected. Two limits are given, the first from the measured event rate alone, and the second from the combination of the measured event rate and the recoil electron energy spectrum. The latter "disfavor the region of adiabatic solutions $\Delta(m^2) \sim 1.3 \times 10^{-4}$ eV^2 and $7.2 \times 10^{-4} < \sin^2 2\theta < 6.3 \times 10^{-3}$ at 90%CL." The allowed regions in $\sin^2 2\theta$ vs. $\Delta(m^2)$ are given graphically; see Figs. 2(a) and 2(b) in the paper.

[41] BAHCALL 88 "total theoretical range is calculated by evaluating the 3σ uncertainties for all measured input parameters and using the full spread in calculated values for input quantitites that cannot be measured; the uncertainties from different quantities are combined quadratically." (Quotation from BAHCALL 89, p. 301.)

[42] DAVIS 84 is the average from the ^{37}Cl experiment at Homestake (HOME) mine from 1970–1983.

Deep Underground Detector Experiments

R= (Measured Flux of ν_μ) / (Expected Flux of ν_μ)

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[43] CASPER	91	IMB	
	[44] AGLIETTA	89		NUSEX
0.59±0.07	[45] HIRATA	88		Kamiokande II
0.95±0.22	[46] BOLIEV	81		Baksan
0.62±0.17	CROUCH	78		Case Western/UCI

[43] CASPER 91 correlates showering/nonshowering signature of single-ring events with parent atmospheric-neutrino flavor. They find nonshowering (≈ ν_μ induced) fraction is 0.41 ± 0.03 ± 0.02, as compared with expected 0.51 ± 0.05 (syst).

[44] AGLIETTA 89 finds no evidence for any anomaly in the neutrino flux. They define ρ = (measured number of ν_e's)/(measured number of ν_μ's). They report ρ(measured)=ρ(expected) = $0.96^{+0.32}_{-0.28}$.

[45] HIRATA 88 error is statistical.

[46] From this data BOLIEV 81 obtain the limit $\Delta(m^2) \leq 6 \times 10^{-3}$ eV^2 for maximal mixing, $\nu_\mu \not\to \nu_\mu$ type oscillation.

$\sin^2(2\theta)$ for Given $\Delta(m^2)$ ($\nu_e \leftrightarrow \nu_\mu$)

For a review see BAHCALL 89.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.47	90	[47] BERGER	90B	FREJ	$\Delta(m^2)$> 1 eV^2
<0.14	90	LOSECCO	87	IMB	$\Delta(m^2)$= 0.00011 eV^2

[47] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antineutrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_e \leftrightarrow \nu_\mu$)

VALUE (10^{-5} eV^2)	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<150	90	[48] BERGER	90B	FREJ

[48] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antineutrino oscillations.

$\sin^2(2\theta)$ for Given $\Delta(m^2)$ ($\nu_\mu \leftrightarrow \nu_\tau$)

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.6	90	[49] BERGER	90B	FREJ	$\Delta(m^2)$> 1 eV^2

[49] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antineutrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_\mu \leftrightarrow \nu_\tau$)

VALUE (10^{-5} eV^2)	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<350	90	[50] BERGER	90B	FREJ

[50] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antineutrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_\mu \to \nu_s$)

ν_S means ν_τ or any sterile (noninteracting) ν.

VALUE (10^{-5} eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3000 (or <550)	90	[51] OYAMA	89		Kamiokande II
< 4.2 or >54.	90	BIONTA	88	IMB	Flux has ν_μ, $\overline{\nu}_\mu$, ν_e, and $\overline{\nu}_e$

[51] OYAMA 89 gives a range of limits, depending on assumptions in their analysis. They argue that the region $\Delta(m^2) = (100\text{–}1000) \times 10^{-5}$ eV^2 is not ruled out by any data for large mixing.

Reactor $\overline{\nu}$ Experiments

Events (Observed/Expected) from Reactor $\overline{\nu}_e$ Experiments

VALUE	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.05 ±0.02 ±0.05	VUILLEUMIER	82	$\overline{\nu}_e p \to e^+ n$
0.955±0.035±0.110	[52] KWON	81	$\overline{\nu}_e p \to e^+ n$
0.89 ±0.15	[52] BOEHM	80	$\overline{\nu}_e p \to e^+ n$
0.38 ±0.21	[53,54] REINES	80	
0.40 ±0.22	[53,54] REINES	80	

[52] KWON 81 represents an analysis of a larger set of data from the same experiment as BOEHM 80.

[53] REINES 80 involves comparison of neutral- and charged-current reactions $\overline{\nu}_e d \to np\overline{\nu}_e$ and $\overline{\nu}_e d \to nne^+$ respectively. Combined analysis of reactor $\overline{\nu}_e$ experiments was performed by SILVERMAN 81.

[54] The two REINES 80 values correspond to the calculated $\overline{\nu}_e$ fluxes of AVIGNONE 80 and DAVIS 79 respectively.

---- $\overline{\nu}_e \not\to \overline{\nu}_e$ ----

$\Delta(m^2)$ for $\sin^2(2\theta)$=1

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.0083	90	VIDYAKIN	90		$\overline{\nu}_e p \to e^+ n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.04	90	[55] AFONIN	88	CNTR	$\overline{\nu}_e p \to e^+ n$
<0.05	68	[56] AFONIN	87		$\overline{\nu}_e p \to e^+ n$
<0.014	68	[57] VIDYAKIN	87		$\overline{\nu}_e p \to e^+ n$
<0.05	68	[56] AFONIN	86		$\overline{\nu}_e p \to e^+ n$
<0.019	90	[58] ZACEK	86		$\overline{\nu}_e p \to e^+ n$
<0.07	90	AFONIN	85		$\overline{\nu}_e p \to e^+ n$
<0.02	90	[59] ZACEK	85		$\overline{\nu}_e p \to e^+ n$
<0.016	90	[60] GABATHULER	84		$\overline{\nu}_e p \to e^+ n$
<0.1	90	AFONIN	83		$\overline{\nu}_e p \to e^+ n$
<0.13		BELENKII	83		$\overline{\nu}_e p \to e^+ n$

[55] Several different methods of data analysis are used in AFONIN 88. We quote the most stringent limits.
[56] AFONIN 86 and AFONIN 87 also give limits on $\sin^2(2\theta)$ for intermediate values of $\Delta(m^2)$.
[57] VIDYAKIN 87 bound is for L = 32.8 and 92.3 m distance from two reactors.
[58] This bound is from data for L=37.9 m, 45.9 m, and 64.7 m distance from Gosgen reactor.
[59] See the comment for ZACEK 85 in the section on $\sin^2(2\theta)$ below.
[60] This bound comes from a combination of the VUILLEUMIER 82 data at distance 37.9m from Gosgen reactor and new data at 45.9m.

$\Delta(m^2)$ for Given $\sin^2(2\theta)$

VALUE (eV^2)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.2±0.1	[61] CAVAIGNAC	84	$\overline{\nu}_e p \to e^+ n$

[61] $\sin^2(2\theta) = 0.25 \pm 0.1$. These are from best fit to data; see CAVAIGNAC 84 for plot of allowed regions in these variables. These data from Bugey reactor.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$ $\overline{\nu}_e \not\to \overline{\nu}_e$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.14	68	[62] VIDYAKIN	87		$\overline{\nu}_e p \to e^+ n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.2	90	[63] AFONIN	88	CNTR	$\overline{\nu}_e p \to e^+ n$
<0.21	68	AFONIN	87		$\overline{\nu}_e p \to e^+ n$
<0.21	90	[64] ZACEK	86		$\overline{\nu}_e p \to e^+ n$
<0.34	90	AFONIN	85		$\overline{\nu}_e p \to e^+ n$
<0.19	90	[65] ZACEK	85		$\overline{\nu}_e p \to e^+ n$
<0.16	90	[66] GABATHULER	84		$\overline{\nu}_e p \to e^+ n$
<0.4		[67] BELENKII	83		$\overline{\nu}_e p \to e^+ n$

[62] VIDYAKIN 87 bound is for L = 32.8 and 92.3 m distance from two reactors.
[63] Several different methods of data analysis are used in AFONIN 88. We quote the most stringent limits. Different upper limits on $\sin^2 2\theta$ apply at intermediate values of $\Delta(m^2)$.
[64] This bound is from data for L=37.9 m, 45.9 m, and 64.7 m distance from Gosgen reactor.
[65] ZACEK 85 (Gosgen reactor) gives two sets of bounds depending on what assumptions are used in the data analysis. The bounds in figure 3(a) of ZACEK 85 are progressively poorer for large $\Delta(m^2)$ whereas those of figure 3(b) approach a constant. We list the latter. Both sets of bounds use combination of data from 37.9, 45.9, and 64.7m distance from reactor. ZACEK 85 states "Our experiment excludes this area (the oscillation parameter region allowed by the Bugey data, CAVAIGNAC 84) almost completely, thus disproving the indications of neutrino oscillations of CAVAIGNAC 84 with a high degree of confidence."
[66] This bound comes from a combination of the VUILLEUMIER 82 data at distance 37.9m from Gosgen reactor and new data at 45.9m.
[67] This bound holds for $\Delta(m^2)$ >4 eV^2.

Accelerator Experiments

These experiments set bounds on $\Delta(m^2)$ *vs.* $\sin^2 2\theta$, where $\Delta(m^2)$ is magnitude of $[m^2(\nu_i) - m^2(\nu_j)]$ and θ is the mixing angle for the simplifying assumption of mixing between two neutrino families only. For a recent set of bounds assuming three neutrino families, see Blumer and Kleinknecht.[1]

Each experimental result is a plot giving allowed and excluded regions as functions of $\Delta(m^2)$ and $\sin^2 2\theta$. We quote two representative limits from each plot: (a) $\Delta(m^2)$ for $\sin^2 2\theta = 1$, and (b) $\sin^2 2\theta$ for *large* $\Delta(m^2)$, *ie.* sufficiently *large* $\Delta(m^2)$ that the detector would measure only an effect averaged over many oscillations. Experiments are of two general types: (a) searches for $\nu_a \to \nu_b$ $(b \neq a)$, *ie.* the appearance of ℓ_b from charged-current reaction of a ν_a beam, and (b) searches for the "disappearance" of part of the initital ν_a beam by comparing the number of observed ℓ_a events with the number expected from flux calculations. These experiments do not try to observe the anomalous ℓ_b's. We label such experiments as $\nu_a \not\to \nu_a$.

Reference

1. H. Blumer and K. Kleinknecht, Phys. Lett. **161B**, 407 (1985).

---- $\nu_\mu \to \nu_e$ ----

$\Delta(m^2)$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.09	90	ANGELINI	86	BEBC	$\sin^2(2\theta)$=1
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[68] ASTIER	90		
		[69] ASTIER	89	CNTR	
<0.1	90	BLUMENFELD	89	CNTR	$\sin^2 2\theta$=1
<1.3	90	AMMOSOV	88	HLBC	SKAT
<0.19	90	BERGSMA	88	CHRM	$\sin^2 2\theta$=1
		[70] LOVERRE	88	RVUE	
<2.4	90	[71] AHRENS	87	CNTR	$\sin^2(2\theta)$=1
<1.8	90	BOFILL	87	CNTR	$\sin^2(2\theta)$=1
5 to 10		[72] BERNARDI	86B	CNTR	$\sin^2(2\theta)$=0.02–0.04
<2.2	90	[73] BRUCKER	86	HLBC	$\sin^2(2\theta)$=1
<0.43	90	[71] AHRENS	85	CNTR	$\sin^2(2\theta)$=1
<3.2	90	[71] AHRENS	85	CNTR	$\sin^2(2\theta)$=0.02
<2.1	90	[71] AHRENS	85	CNTR	$\sin^2(2\theta)$=0.04
<0.20	90	BERGSMA	84	CHRM	$\sin^2(2\theta)$=1
<1.7	90	ARMENISE	81	GGM	$\sin^2(2\theta)$=1
<0.6	90	[73] BAKER	81	HLBC	$\sin^2(2\theta)$=1
<1.7	90	ERRIQUEZ	81	BEBC	$\sin^2(2\theta)$=1
<1.2	95	BLIETSCHAU	78	GGM	$\sin^2(2\theta)$=1
<1.2	95	BELLOTTI	76	GGM	$\sin^2(2\theta)$=1

[68] ASTIER 90 again finds an excess of electrons, as was reported in earlier papers by this collaboration. However, the authors concede that systematic effects weaken the statistical arguments and the consequent claim (in the earlier papers) of neutrino oscillations. An interpretation of these results in terms of neutrino oscillations seems to be already excluded by the BNL E734 (AHRENS 85) and the Los Alamos E645 (DURKIN 88) experiments.
[69] ASTIER 89 is a counter neutrino oscillation experiment at BNL AGS. ASTIER 89 reports a a positive effect with ν_e(observed)/ν_e(expected) = 2.2 ± 0.6 and $\overline{\nu}_e$(observed)/$\overline{\nu}_e$(expected) = 1.6 ± 0.9.
[70] LOVERRE 88 reports a less stringent, indirect limit based on theoretical analysis of neutral to charged current ratios.
[71] Liquid-scintillator calorimeter at BNL AGS.
[72] This is a typical fit to the data, assuming mixing between two species. As the authors state, this result is in conflict with earlier upper bounds on this type of neutrino oscillations.
[73] 15ft bubble chamber at FNAL.

$\sin^2(2\theta)$

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
< 3.4	90	[74] AHRENS	85	CNTR	Large $\Delta(m^2)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[75] ASTIER	89	CNTR	
< 16	90	BLUMENFELD	89	CNTR	Large $\Delta(m^2)$
< 2.5	90	AMMOSOV	88	HLBC	Large $\Delta(m^2)$
< 8	90	BERGSMA	88	CHRM	$\Delta(m^2) \geq 30$ eV^2
		[76] LOVERRE	88	RVUE	
< 10	90	[74] AHRENS	87	CNTR	Large $\Delta(m^2)$
< 15	90	BOFILL	87	CNTR	Large $\Delta(m^2)$
< 13	90	ANGELINI	86	BEBC	$\Delta(m^2)$=2.2 eV^2
20 to 40		BERNARDI	86B	CNTR	$\Delta(m^2)$=5–10
< 11	90	[77] BRUCKER	86	HLBC	Large $\Delta(m^2)$
< 9	90	[74] AHRENS	85	CNTR	$\Delta(m^2)$=5
< 3	90	[74] AHRENS	85	CNTR	$\Delta(m^2)$=10
<240	90	BERGSMA	84	CHRM	Large $\Delta(m^2)$
< 10	90	ARMENISE	81	GGM	Large $\Delta(m^2)$
< 6	90	[77] BAKER	81	HLBC	Large $\Delta(m^2)$
< 10	90	ERRIQUEZ	81	BEBC	Large $\Delta(m^2)$
< 4	95	BLIETSCHAU	78	GGM	Large $\Delta(m^2)$
< 10	95	BELLOTTI	76	GGM	Large $\Delta(m^2)$

[74] Liquid-scintillator calorimeter at BNL AGS.
[75] ASTIER 89 is a counter neutrino oscillation experiment at BNL AGS. ASTIER 89 reports a a positive effect with ν_e(observed)/ν_e(expected) = 2.2 ± 0.6 and $\overline{\nu}_e$(observed)/$\overline{\nu}_e$(expected) = 1.6 ± 0.9.
[76] LOVERRE 88 reports a less stringent, indirect limit based on theoretical analysis of neutral to charged current ratios.
[77] 15ft bubble chamber at FNAL.

---- $\overline{\nu}_\mu \to \overline{\nu}_e$ ----

$\Delta(m^2)$ for $\sin^2(2\theta)$=1

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.11	90	[78] DURKIN	88	CNTR	LAMPF

• • • We do not use the following data for averages, fits, limits, etc. • • •

<3.1	90	BOFILL	87	CNTR	FNAL
<2.4	90	TAYLOR	83	HLBC	15-ft FNAL
<0.91	90	[78] NEMETHY	81B	CNTR	LAMPF
<1	95	BLIETSCHAU	78	HLBC	GGM CERN PS

[78] In reaction $\overline{\nu}_e p \rightarrow e^+ n$.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.004	95	BLIETSCHAU	78	HLBC	GGM CERN PS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.014	90	[79] DURKIN	88	CNTR	LAMPF
<0.04	90	BOFILL	87	CNTR	FNAL
<0.013	90	TAYLOR	83	HLBC	15-ft FNAL
<0.2	90	[79] NEMETHY	81B	CNTR	LAMPF

[79] In reaction $\overline{\nu}_e p \rightarrow e^+ n$.

---- $\nu_\mu \rightarrow \nu_\tau$ ----

$\Delta(m^2)$ for $\sin^2(2\theta)=1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
< 0.9	90	USHIDA	86C	EMUL	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 4.5	90	BATUSOV	90B	EMUL	FNAL
<10.2	90	BOFILL	87	CNTR	FNAL
< 6.3	90	BRUCKER	86	HLBC	15-ft FNAL
< 4.6	90	ARMENISE	81	HLBC	GGM CERN SPS
< 3	90	BAKER	81	HLBC	15-ft FNAL
< 6	90	ERRIQUEZ	81	HLBC	BEBC CERN SPS
< 3	90	USHIDA	81	EMUL	FNAL

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.004	90	USHIDA	86C	EMUL	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.06	90	BATUSOV	90B	EMUL	FNAL
<0.34	90	BOFILL	87	CNTR	FNAL
<0.088	90	BRUCKER	86	HLBC	15-ft FNAL
<0.11	90	BALLAGH	84	HLBC	15-ft FNAL
<0.017	90	ARMENISE	81	HLBC	GGM CERN SPS
<0.06	90	BAKER	81	HLBC	15-ft FNAL
<0.05	90	ERRIQUEZ	81	HLBC	BEBC CERN SPS
<0.013	90	USHIDA	81	EMUL	FNAL

---- $\overline{\nu}_\mu \rightarrow \overline{\nu}_\tau$ ----

$\Delta(m^2)$ for $\sin^2(2\theta)=1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<2.2	90	ASRATYAN	81	HLBC	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<6.5	90	BOFILL	87	CNTR	FNAL
<7.4	90	TAYLOR	83	HLBC	15-ft FNAL

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.4 × 10^{-2}	90	ASRATYAN	81	HLBC	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.15	90	BOFILL	87	CNTR	FNAL
<8.8 × 10^{-2}	90	TAYLOR	83	HLBC	15-ft FNAL

---- $\nu_\mu \not\rightarrow \nu_\mu$ ----

$\Delta(m^2)$ for $\sin^2(2\theta)=1$

These experiments also allow sufficiently large $\Delta(m^2)$.

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.23 OR >100	90	DYDAK	84	CNTR	
<13 OR >1500	90	STOCKDALE	84	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.29 OR >22	90	BERGSMA	88	CHRM	
<7	90	BELIKOV	85	CNTR	Serpukhov
<8.0 OR >1250	90	STOCKDALE	85	CNTR	
<0.29 OR >22	90	BERGSMA	84	CHRM	
<8.0	90	BELIKOV	83	CNTR	

$\sin^2(2\theta)$ as Function of $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[80] STOCKDALE	85	CNTR	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.17	90	[81] BERGSMA	88	CHRM	
<0.07	90	[82] BELIKOV	85	CNTR	Serpukhov
<0.27	90	[81] BERGSMA	84	CHRM	CERN PS
<0.1	90	[83] DYDAK	84	CNTR	CERN PS
<0.02	90	[84] STOCKDALE	84	CNTR	FNAL
<0.1	90	[85] BELIKOV	83	CNTR	Serpukhov

[80] This bound applies for $\Delta(m^2) = 100$ eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $8 < \Delta(m^2) < 1250$ eV^2.

[81] This bound applies for $\Delta(m^2) = 0.7$–9. eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $0.28 < \Delta(m^2) < 22$ eV^2.

[82] This bound applies for a wide range of $\Delta(m^2) > 7$ eV^2. For some values of $\Delta(m^2)$, the value is less stringent; the least restrictive, nontrivial bound occurs approximately at $\Delta(m^2) = 300$ eV^2 where $\sin^2(2\theta) < 0.13$ at CL = 90%.

[83] This bound applies for $\Delta(m^2) = 1.$–10. eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $0.23 < \Delta(m^2) < 90$ eV^2.

[84] This bound applies for $\Delta(m^2) = 110$ eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $13 < \Delta(m^2) < 1500$ eV^2.

[85] Bound holds for $\Delta(m^2) = 20$–1000 eV^2.

---- $\nu_e \not\rightarrow \nu_e$ ----

$\Delta(m^2)$ for $\sin^2(2\theta)=1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
< 8	90	BAKER	81	HLBC	15-ft FNAL
<2.3 OR >8	90	NEMETHY	81B	CNTR	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<14.9	90	BRUCKER	86	HLBC	15-ft FNAL
<56	90	DEDEN	81	HLBC	BEBC CERN SPS
<10	90	ERRIQUEZ	81	HLBC	BEBC CERN SPS

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<7 × 10^{-2}	90	ERRIQUEZ	81	HLBC	BEBC CERN SPS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.54	90	BRUCKER	86	HLBC	15-ft FNAL
<0.6	90	BAKER	81	HLBC	15-ft FNAL
<0.3	90	DEDEN	81	HLBC	BEBC CERN SPS

---- $\overline{\nu}_e \rightarrow \overline{\nu}_\tau$ ----

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.7	90	[86] FRITZE	80	HYBR	BEBC CERN SPS

[86] Authors give $P(\nu_e \rightarrow \nu_\tau) < 0.35$, equivalent to above limit.

---- $\overline{\nu}_\mu \not\rightarrow \overline{\nu}_\mu$ ----

$\Delta(m^2)$ for $\sin^2(2\theta)=1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN
<7 OR >1200	90	STOCKDALE	85	CNTR

$\sin^2(2\theta)$ as Function of $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[87] STOCKDALE	85	CNTR	FNAL

[87] This bound applies for $\Delta(m^2)$ between 190 and 320 or = 530 eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $7 < \Delta(m^2) < 1200$ eV^2.

---- $\nu_e \rightarrow \nu_\tau$ ----

$\Delta(m^2)$ for $\sin^2(2\theta)=1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
< 9	90	USHIDA	86C	EMUL	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<44	90	TALEBZADEH	87	HLBC	BEBC

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.12	90	USHIDA	86C	EMUL	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.36	90	TALEBZADEH	87	HLBC	BEBC

---- $\nu_\mu \rightarrow (\overline{\nu}_e)_L$ ----

This is a limit on lepton family-number violation and total lepton-number violation. $(\overline{\nu}_e)_L$ denotes a hypothetical left-handed $\overline{\nu}_e$. The bound is quoted in terms of $\Delta(m^2)$, $\sin(2\theta)$, and α, where α denotes the fractional admixture of (V+A) charged current.

$\alpha\Delta(m^2)$ for $\sin^2(2\theta)=1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<7 × 10^{-1}	90	[88] COOPER	82	HLBC

[88] Existing bounds on V+A currents require α small — see COOPER 82.

$\alpha^2 \sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1 \times 10^{-3}$	90	[89] COOPER	82	HLBC

[89] Existing bounds on V+A currents require α small — see COOPER 82.

— — — — $\nu_e \rightarrow (\overline{\nu}_e)_L$ — — — —

See note above for $\nu_\mu \rightarrow (\overline{\nu}_e)_L$ limit

$\alpha \Delta(m^2)$ for $\sin^2(2\theta)$=1

VALUE (eV^2)	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<7	90	[90] COOPER	82	HLBC

[90] Existing bounds on V+A currents require α small — see COOPER 82.

$\alpha^2 \sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<5 \times 10^{-2}$	90	[91] COOPER	82	HLBC

[91] Existing bounds on V+A currents require α small — see COOPER 82.

(C) Searches for Neutrinoless Double β Decay

$\langle m(\nu) \rangle$, The Effective Weighted Sum of Neutrino MASSES Contributing to Neutrinoless Double β Decay

$\langle m(\nu) \rangle = |\Sigma\ U^2_{1j} m(\nu_j)|$, where the sum goes from 1 to n and where n = number of neutrino generations, and ν_j is a Majorana neutrino. Note that U^2_{1j}, not $|U_{1j}|^2$, occurs in the sum. the possibility of cancellations has been stressed

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 11–30	95	[92] BELLOTTI	91	CNTR	^{136}Xe + Theory
< 3.3–5.0		[93] WONG	91	TPC	^{136}Xe + Theory
		[94] YOU	91	CNTR	^{48}Ca
< 1.4–8	68	[95] VASENKO	90	CNTR	^{76}Ge + Theory
<4.3–28		[96] BELLOTTI	89	CNTR	THY ^{136}Xe
<12	68	[97] DANEVICH	89	CNTR	THY ^{76}Ge
<3.4–23		[98] FISHER	89	CNTR	THY ^{76}Ge
< 1.8		[99] CALDWELL	87	CNTR	THY ^{76}Ge
< 2.7	68	BELLOTTI	86	CNTR	THY ^{76}Ge
< 2.6	68	[100] CALDWELL	86	CNTR	THY ^{76}Ge
< 6	68	[101] CALDWELL	85	CNTR	THY ^{76}Ge
<20	68	[102] HUBERT	85	CNTR	^{76}Ge
< 3.8	68	[103] BELLOTTI	84	CNTR	THY ^{76}Ge
<22		FORSTER	84	CNTR	THY ^{76}Ge
<10	90	AVIGNONE	83	CNTR	THY ^{76}Ge
<22	68	[104] BELLOTTI	83	CNTR	THY ^{76}Ge
< 8.3	68	[104] BELLOTTI	83	CNTR	THY ^{76}Ge
< 5.6	95	KIRSTEN	83	SPEC	THY ^{128}Te/^{130}Te

[92] BELLOTTI 91 range of limits comes from range of theoretical calculations considered. Analysis uses difference between natural and enriched ^{136}Xe runs to obtain the $\beta\beta 0\nu$ limits, leading to "less stringent, but safer limits."

[93] WONG 91 uses the quasiparticle random phase approximation of ENGEL 88 to extract the above limit for the case of a transition caused by a Majorana neutrino mass.

[94] YOU 91 gives model-dependent limits on effective Majorana neutrino masses and lepton-number violating right-handed currents.

[95] VASENKO 90 range comes from the range of nuclear matrix elements which were used.

[96] BELLOTTI 89 gives model-dependent upper bounds on Majorana neutrino masses and on the admixture of right-handed lepton-number-violating currents.

[97] DANEVICH 89 uses calculations of GROTZ 86.

[98] FISHER 89 model-dependent bounds are for Majorana neutrino masses.

[99] CALDWELL 87 derives upper limits on effective neutrino masses are dependent on input for nuclear matrix elements; the authors also list two other limits for different input assumptions: 1.3 eV and 0.7 eV. Used calculations of DOI 83.

[100] CALDWELL 86 gives several limits depending on which calculation of nuclear matrix elements is used; we quote the most conservative, i.e., least stringent. Other limits are 1.0 eV and 1.9 eV. Authors note that the overall uncertainty due to the serious disagreement between nuclear calculations and both lab and geochemical measurements for regular 2-neutrino double β decay is also present in these limits.

[101] CALDWELL 85 uses results of HAXTON 81, HAXTON 82. Authors state that limit could be "two or three times larger."

[102] HUBERT 85 limit is obtained from analysis of data using theoretical calculations by HAXTON 81, HAXTON 82.

[103] See Table 1 of BELLOTTI 84 for their assessment of previous bounds.

[104] BELLOTTI 83 limits are obtained from analysis of data using theoretical calculations by DOI 83 and ROSEN 81.

Half-life Measurements and Limits for Double β Decay

Neutrino mass limits reported in the above table are derived from the lifetime measurements listed below. In all cases of double beta decay, $(Z,A) \rightarrow (Z+2,A) + 2\beta^- + (0 \text{ or } 2)\overline{\nu}_e$.

$t_{1/2}$(10^{21} yr)	CL%	ISOTOPE		TRANSITION	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 21	84	^{136}Xe	0ν	$0^+ \rightarrow 0^+$	Prop cntr	[105,106] BELLOTTI	91
> 18	84	^{136}Xe	0ν	$0^+ \rightarrow 0^+$	Prop cntr	[106,107] BELLOTTI	91
> 5	84	^{136}Xe	0ν	$0^+ \rightarrow 2^+$	Prop cntr	[106] BELLOTTI	91
> 0.16	84	^{136}Xe	2ν		Prop cntr	BELLOTTI	91
> 4.7	68	^{100}Mo	0ν		ELEGANTS V	EJIRI	91
$0.0115^{+0.0030}_{-0.0020}$		^{100}Mo	2ν		ELEGANTS V	[108] EJIRI	91
					Mass spect	[109] HYKAWY	91
2.0 ±0.6		^{238}U	$0\nu+2\nu$		Geochem	[110] TURKEVICH	91
> 250	90	^{136}Xe	0ν	$0^+ \rightarrow 0^+$	TPC	WONG	91
> 9.5	76	^{48}Ca	0ν		CaF_2 scint.	YOU	91
> 0.14	68	^{100}Mo	$0\nu+2\nu$	$0^+ \rightarrow 2^+$	γ in HPGe	BARABASH	90
> 0.042	68	^{100}Mo	$0\nu+2\nu$	$0^+ \rightarrow 0^+$	γ in HPGe	BARABASH	90
> 0.17	68	^{116}Cd	$0\nu+2\nu$	$0^+ \rightarrow 2^+$	γ in HPGe	BARABASH	90
0.9 ±0.1		^{76}Ge	2ν		Enriched Ge(Li)	VASENKO	90
>1300	68	^{76}Ge	0ν		Enriched Ge(Li)	VASENKO	90
> 10	68	^{76}Ge	0ν		Enriched Ge(Li)	[108] VASENKO	90
> 4.0	68	^{100}Mo	0ν	$0^+ \rightarrow 0^+$	Si(Li)	ALSTON-...	89
> 0.40	68	^{100}Mo	0ν	$0^+ \rightarrow 2^+$	Si(Li)	ALSTON-...	89
> 3.3	68	^{136}Xe	0ν	$0^+ \rightarrow 0^+$	Prop chamber	[105] BARABASH	89
> 2.9	68	^{136}Xe	0ν	$0^+ \rightarrow 0^+$	Prop chamber	[107] BARABASH	89
> 1.5	68	^{136}Xe	2ν	$0^+ \rightarrow 2^+$	Prop chamber	BARABASH	89
> 0.084	68	^{136}Xe	2ν	$0^+ \rightarrow 0^+$	Prop chamber	BARABASH	89
> 14	68	^{136}Xe	0ν	$0^+ \rightarrow 0^+$	Prop chamber	[105] BELLOTTI	89
> 12	68	^{136}Xe	0ν	$0^+ \rightarrow 0^+$	Prop chamber	[107] BELLOTTI	89
> 1.3	68	^{116}Cd	0ν		$^{116}CdWO_4$ scint	DANEVICH	89
> 270	68	^{76}Ge	0ν	$0^+ \rightarrow 2^+$	HPGe	FISHER	89
> 100	68	^{76}Ge	0ν	$0^+ \rightarrow 0^+$	HPGe	FISHER	89
> 60	68	^{76}Ge	0ν	$0^+ \rightarrow 2^+$	HPGe	[111] MORALES	88
> 500	68	^{76}Ge	0ν	$0^+ \rightarrow 0^+$	HPGe	CALDWELL	87
> 1.4	68	^{76}Ge	0ν	$0^+ \rightarrow 0^+$	HPGe	[112] CALDWELL	87
$0.11^{+0.08}_{-0.03}$		^{82}Se	2ν	$0^+ \rightarrow 0^+$	TPC	ELLIOTT	87B
> 120	68	^{76}Ge	0ν	$0^+ \rightarrow 0^+$	Coaxial Ge(Li)	BELLOTTI	86
> 12	68	^{76}Ge	0ν	$0^+ \rightarrow 2^+$	Coaxial Ge(Li)	BELLOTTI	86
> 250	68	^{76}Ge	0ν	$0^+ \rightarrow 0^+$	Ge	CALDWELL	86
> 50	68	^{76}Ge	0ν	$0^+ \rightarrow 2^+$	Ge	CALDWELL	86
> 7.0	68	^{82}Se	0ν	$0^+ \rightarrow 0^+$	TPC	ELLIOTT	86
> 0.10	68	^{82}Se	2ν	$0^+ \rightarrow 0^+$	TPC	[113] ELLIOTT	86
> 50	68	^{76}Ge	0ν		Coaxial Ge	CALDWELL	85
> 2.3	68	^{76}Ge	0ν		Ge(Li)	[114] HUBERT	85
> 120	68	^{76}Ge	0ν	$0^+ \rightarrow 0^+$	Ge(li)	BELLOTTI	84
> 17	68	^{76}Ge	0ν		Ge	FORSTER	84
> 17	90	^{76}Ge	0ν		Intrinsic Ge	AVIGNONE	83
> 20	68	^{76}Ge	0ν	$0^+ \rightarrow 0^+$	Coaxial Ge(Li)	BELLOTTI	83
2.60 ±0.28		^{128}Te	$0\nu+2\nu$		Geochem	[115] KIRSTEN	83
> 800		^{130}Te	$0\nu+2\nu$		Geochem	[115] KIRSTEN	83

[105] Limit for neutrino-mass induced decay.

[106] BELLOTTI 91 uses difference between natural and enriched ^{136}Xe runs to obtain $\beta\beta 0\nu$ limits, leading to "less stringent, but safer limits."

[107] Limit for lepton-number violating right-handed current-induced decay.

[108] VASENKO 90 limit for 0ν double β decay with majoron emission.

[109] HYKAWY 91 gives new mass spectrometer determination of the ^{76}Ge–^{76}Se mass difference, which for given input for the nuclear matrix elements gives information on limits on Majorana masses. Application to recent ^{76}Ge decay experiments produces no new evidence for $\beta\beta$ (0ν) decay.

[110] TURKEVICH 91 observes activity in old U sample. The authors compare their results with theoretical calculations. They state "Using the phase-space factors of Boehm and Vogel (BOEHM 87) leads to matrix element values for the ^{238}U transition in the same range as deduced for ^{130}Te and ^{76}Ge. On the other hand, the latest theoretical estimates (STAUDT 90) give an upper limit that is 10 times lower. This large discrepancy implies either a defect in the calculations or the presence of a faster path than the standard two-neutrino mode in this case." See BOEHM 87 and STAUDT 90.

[111] MORALES 88 notes a 2.5 sigma coincidence rate between electrons with energy 1483.7 ± 0.5 keV in the Ge detector and photons with energy 558 ± 15 keV in the NaI detector. They state "We conclude, therefore, that there exists a true coincidence effect... No explanation for such a peak has been found in our analysis of the background although the effect of a statistical fluctuation cannot be rejected as an interpretation of the effect... In spite of its low statistical significance, all these features might hypothetically be attributed to a neutrinoless double beta decay... one would get a half-life of $t_{1/2}(0^+ \rightarrow 2^+) = (1.1 \pm 0.5) \times 10^{22}$ yr."

[112] CALDWELL 87 limit for majoran emission.

[113] ELLIOTT 86 limit agrees with the geochemical limit and strongly disagrees with nuclear theory calculations, casting doubt on their application to derive limits on Majorana neutrino masses and η parameters from limits on neutrinoless double β decay.

[114] HUBERT 85 gives lifetime limits on neutrinoless double β decay of ^{76}Ge to excited states of ^{76}Se.

[115] KIRSTEN 83 reports "2σ" error.

Limits on Lepton-Number Violating (V+A) Current Admixture

η is defined as the fractional admixture of (V+A) charged current, relative to (V−A) in electron-type lepton sector.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<9 \times 10^{-6}$	68	[116] BELLOTTI 89	CNTR	THY ^{76}Ge
$<6 \times 10^{-5}$	68	[117] BELLOTTI 87	CNTR	^{128}Te,^{130}Te (+Theory)
$<6 \times 10^{-6}$	68	[118] CALDWELL 86	CNTR	THY ^{76}Ge
$<1.4 \times 10^{-5}$	68	[119] CALDWELL 85	CNTR	THY ^{76}Ge
$<0.9 \times 10^{-5}$	68	[119] CALDWELL 85	CNTR	THY ^{76}Ge
$<0.8 \times 10^{-5}$	68	[119] BELLOTTI 84	CNTR	THY ^{76}Ge
$<0.6 \times 10^{-5}$	68	[119] BELLOTTI 84	CNTR	THY ^{76}Ge
$<2.4 \times 10^{-5}$		AVIGNONE 83	CNTR	THY ^{76}Ge
$<4 \times 10^{-5}$	68	[120] BELLOTTI 83	CNTR	THY1 ^{76}Ge
$<1.5 \times 10^{-5}$	68	[120] BELLOTTI 83	CNTR	THY2 ^{76}Ge
$<2.4 \times 10^{-5}$	95	KIRSTEN 83	SPEC	THY ^{128}Te/^{130}Te

[116] See footnote on BELLOTTI 89 in section on Limits on $\langle m(\nu)\rangle$ above. BELLOTTI 89 gives two model-dependent limits, $\eta_{RR} < 9 \times 10^{-6}$ and $\eta_{LR} < 8 \times 10^{-8}$, both at the 68% CL. See also BARABASH 89.

[117] BELLOTTI 87 gives two limits, depending on the type of chirality mixing. These happen to be the same. BELLOTTI 87 limit is stated to be independent of neutrino mass.

[118] See previous comment for CALDWELL 86 in data block above. Other limits given by CALDWELL 86 for η (left-right) are 5.5×10^{-7} and 4.5×10^{-8}; as we did for the limit on a Majorana mass, we take the most conservative, i.e., least stringent of these model-dependent bounds.

[119] Two bounds given, depending on types of chirality mixing. See references.

[120] Limits are obtained from analysis of data using theoretical calculations by DOI 83 (= thy1) and ROSEN 81 (= thy2).

REFERENCES FOR Searches for Massive Neutrinos and Lepton Mixing

ABAZOV 91 Neutrino 90 +Abdurashitov+ (SAGE Collab.)
Proc. of the 14th Int. Conf. on Neutrino Phys. and Astrophysics
ABAZOV 91B PRL 67 3332 +Anosov, Faizov+ (SAGE Collab.)
BELLOTTI 91 PL B266 193 +Cremonesi, Fiorini, Gervasio+ (MILA, INFN)
CASPER 91 PRL 66 2561 +Becker-Szendy, Bratton, Cady+ (IMB Collab.)
DELEENER-... 91 PR D43 3611 De Leener-Rosier, Deutsch+ (LVLN, ZURI, LAUS)
EJIRI 91 PL B258 17 +Fushimi, Kamada, Kinoshita+ (OSAK)
GARCIA 91 PRL 67 3654 +Adelberger, Magnus, Swanson+ (WASH, CERN, LBL)
HIME 91 PL B257 441 +Jelley (OXF)
HIME 91B OUNP-91-21 +Jelley (OXF)
HIRATA 91 PRL 66 9 +Inoue, Kajita, Kihara+ (Kamiokande II Collab.)
HYKAWY 91 PRL 67 1708 +Nxumalo, Unger, Lander+ (MANI)
NORMAN 91 JP G17 S291 +Sur, Lesko+ (LBL)
SUR 91 PRL 66 2444 +Norman, Lesko+ (LBL)
TURKEVICH 91 PRL 67 3211 +Economou, Cowan (CHIC, LANL)
WONG 91 PRL 67 1218 +Boehm, Fisher, Gabathuler+ (CIT, PSI, NEUC)
YOU 91 PL B265 53 +Zhu, Lu+ (BHEP, CAST+)
ZLIMEN 91 PRL 67 560 +Ljubicic, Kaucic, Logan (ZAGR, OTTA)
ADEVA 90S PL B251 321 +Adriani, Aguilar-Benitez, Akbari+ (L3 Collab.)
ASTIER 90 NP B335 517 +Bernardi+ (BOST, BNL, CERN, LPNP)
BARABASH 90 PL B249 186 +Kopylov, Cherehovsky (ITEP, INRM)
BATUSOV 90B ZPHY C48 209 +Bunyatov, Kuznetsov, Poxharova+ (JINR, ITEP, SERP)
BERGER 90B PL B245 305 +Froehlich, Moench, Nisius+ (FREJUS Collab.)
BURCHAT 90 PR D41 3542 +King, Abrams, Adolphsen+ (Mark II Collab.)
DECAMP 90F PL B236 511 +Deschizeaux, Lees, Minard+ (ALEPH Collab.)
FILIPPONE 90 PL B246 546 +Vogel (CIT)
HIRATA 90 PRL 65 1297 +Inoue, Kajita+ (Kamiokande II Collab.)
HIRATA 90B PRL 65 1301 +Inoue, Kajita+ (Kamiokande II Collab.)
JUNG 90 PRL 64 1091 +Van Kooten, Abrams, Adolphsen+ (Mark II Collab.)
KOPEIKIN 90 JETPL 51 86 +Mikazlyan, Fayans (KIAE)
Translated from ZETFP 51 75.
STAUDT 90 EPL 13 31 +Muto, Klapdor-Kleingrothaus (MPIH)
VASENKO 90 MPL A5 1299 +Kirpichnikov, Kuznetsov, Starostin (ITEP, YERE)
VIDYAKIN 90 JETP 71 424 +Vyrodov, Gurevich, Koslov+ (KIAE)
Translated from ZETF 98 764.
ABRAMS 89C PRL 63 2447 +Adolphsen, Averill, Ballam+ (Mark II Collab.)
AGLIETTA 89 EPL 8 611 +Battistoni, Bellotti+ (FREJUS Collab.)
ALSTON-... 89 PRL 63 1671 Alston-Garnjost, Dougherty+ (LBL, MTHO, UNM, INEL)
ASTIER 89 PL B220 646 +Bernardi, Carugno, Chauveau+(LPNP, BOST, CERN, BNL)
BAHCALL 89 Neutrino Astrophysics, Cambridge Univ. Press (IAS)
BAHCALL 89B PR D40 931 +Haxton (IAS, WASH)
BARABASH 89 PL B223 273 +Kuzminov, Lobashev, Novikov+ (ITEP, INRM)
BELLOTTI 89 PL B221 209 +Cremonesi, Fiorini, Gervasio+ (MILA)
BLUMENFELD 89 PRL 62 2237 +Chi, Chichura, Chien+ (COLU, ILL, JHU)
DANEVICH 89 JETPL 49 476 +Zdesenko, Nikolaiko, Tretyak (INRU)
Translated from ZETFP 49 417.
DAVIS 89 ARNPS 39 467 +Mann, Wolfenstein (BNL, PENN, CMU)
DRUKAREV 89 SJNP 50 184 +Strikman (PINP)
Translated from YAF 50 294.
FISHER 89 PL B218 257 +Boehm, Bovet, Egger+ (CIT, NEUC, PSI)
HIME 89 PR D39 1837 +Simpson (GUEL)
LOGAN 89 NIM A280 167 (OTTA)
OYAMA 89 PR D39 1481 +Hirata, Kajita, Kifune+ (Kamiokande II Collab.)
SIMPSON 89 PR D39 1825 +Hime (GUEL)
AFONIN 88 JETP 67 213 +Ketov, Kopeikin, Mikaelyan+ (KIAE)
Translated from ZETF 94 1.
AKERLOF 88 PR D37 577 +Chapman, Errede, Ken+ (HRS Collab.)
AMMOSOV 88 ZPHY C40 487 +Belikov+ (SKAT Collab.)
BAHCALL 88 RMP 60 297 +Ulrich (IAS, UCLA)
BERGSMA 88 ZPHY C40 171 +Dorenbosch, Nieuwenhuis+ (CHARM Collab.)
BERNARDI 88 PL B203 332 +Carugno, Chauveau+ (LPNP, CERN, INFN, ATEN)
BIONTA 88 PR D38 768 +Blewitt, Bratton, Casper+ (IMB Collab.)
DURKIN 88 PRL 61 1811 +Harper, Ling+ (OSU, ANL, CIT, LBL, LSU, LANL)
ENGEL 88 PR C37 731 +Vogel, Zimbene
HIRATA 88 PL B205 416 +Kajita, Koshiba+ (Kamiokande II Collab.)
LOVERRE 88 PL B206 711 (INFN)
MORALES 88 NC 100A 525 +Morales, Nunez-Lagos, Puimedon+ (ZARA)
TURCK-CHI... 88 APJ 335 415 Turck-Chieze, Cahen, Casse, Doom (SACL, CAPI, BRUX)
ZLIMEN 88 PS 38 539 +Kaucic, Ljubicic, Logan (ZAGR, CARL)
AFONIN 87 JETPL 45 257 +Bogatov, Vershinskii+ (KIAE)
Translated from ZETFP 45 201.
AHRENS 87 PR D36 702 + (BNL, BROW, UCI, HIRO, KEK, OSAK, PENN, STON)
BELLOTTI 87 EPL 3 889 +Cattadori, Cremonesi, Fiorini+ (MILA)
BOEHM 87 Massive Neutrinos +Vogel (CIT)
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BOFILL 87 PR D36 3309 +Busza, Eldridge+ (MIT, FNAL, MSU)
CALDWELL 87 PRL 59 419 +Eisberg, Grumm, Witherell+ (UCSB, LBL)
DAUM 87 PR D36 2624 +Kettle, Jost+ (SIN, VIRG)
ELLIOTT 87B PRL 59 2020 +Hahn, Moe (UCI)
HETHERING... 87 PR C36 1504 Hetherington, Graham+ (CRNL)
LOSECCO 87 PL B184 305 +Bionta, Blewitt, Bratton+ (IMB Collab.)
MISHRA 87 PRL 59 1397 +Auchincloss+ (COLU, CIT, FNAL, CHIC, ROCH)
OBERAUER 87 PL B198 113 +von Feilitzsch, Mossbauer (MUNT)
TALEBZADEH 87 NP B291 503 +Guy, Venus+ (BEBC WA66 Collab.)
VIDYAKIN 87 JETP 66 243 +Vyrodov, Gurevich, Kozlov+ (KIAE)
Translated from ZETF 93 424.
WENDT 87 PRL 58 1810 +Abrams, Amidei, Baden+ (Mark II Collab.)
AFONIN 86 JETPL 44 142 +Bogatov, Borovoi, Vershinskii+ (KIAE)
Translated from ZETFP 44 111.
ANGELINI 86 PL B179 307 +Apostolakis, Baldini+ (PISA, ATHU, PADO, WISC)
AZUELOS 86 PRL 56 2241 +Britton, Bryman+ (TRIU, CNRC)
BADIER 86 ZPHY C31 21 +Bemporad, Boucrot, Callot+ (NA3 Collab.)
BELLOTTI 86 NC 95A 1 +Cremonesi, Fiorini, Liguori+ (MILA)
BERNARDI 86 PL 166B 479 +Carugno+ (LPNP, INFN, CDEF, ATEN, CERN)
BERNARDI 86B PL B181 173 +Carugno+ (LPNP, INFN, CDEF, ATEN, CERN)
BORGE 86 PS 34 591 +DeRujula, Hansen, Jonson+ (CERN, AARH, CUT)
BRUCKER 86 PR D34 2183 +Jacques, Kalelkar, Koller+ (RUTG, BNL, COLU)
CALDWELL 86 PR D33 2737 +Eisberg, Grumm, Hale, Witherell+ (UCSB, LBL)
DELEENER-... 86 PL B177 228 DeLeener-Rosier, Deutsch+ (LVLN, ZURI, LAUS)
DORENBOS... 86 PL 166B 473 Dorenbosch, Allaby, Amaldi+ (CHARM Collab.)
DRUKAREV 86 JETP 64 686 +Strikman (PINP)
Translated from ZETF 91 1160.
ELLIOTT 86 PRL 56 2582 +Hahn, Moe (UCI)
EMAN 86 PR C33 2128 +Tadic (ZAGR)
GROTZ 86 NC C9 535 +Klapdor (MPIH)
LINDHARD 86 PRL 57 965 +Hansen (AARH)
SIMPSON 86 PL B174 113 (GUEL)
USHIDA 86C PRL 57 2897 +Kondo, Tasaka, Park, Song+ (FNAL-E531 Collab.)
ZACEK 86 PR D34 2621 +Feilitzsch+ (CIT-SIN-TUM Collab.)
AFONIN 85 JETPL 41 435 +Borovoi, Dobrynin+ (KIAE)
Translated from ZETFP 41 355.
Also 85B JETPL 42 285 Afonin, Bogatov, Borovoi, Dobrynin+ (KIAE)
Translated from ZETFP 42 230.
AHRENS 85 PR D31 2732 +Aronson+ (BNL, BROW, KEK, OSAK, PENN+)
ALBRECHT 85I PL 163B 404 +Binder, Drescher, Schubert+ (ARGUS Collab.)
ALTZITZOG... 85 PRL 55 799 Altzitzoglou, Calaprice, Dewey+ (PRIN)
APALIKOV 85 JETPL 42 289 +Boris, Golutvin, Laptin, Lubimov+ (ITEP)
Translated from ZETFP 42 233.
BELIKOV 85 SJNP 41 589 +Volkov, Kochetkov, Mukhin+ (SERP)
Translated from YAF 41 919.
CALDWELL 85 PRL 54 281 +Eisberg, Grumm, Hale, Witherell+ (UCSB, LBL)
COOPER-... 85 PL 160B 207 Cooper-Sarkar+ (CERN, LOIC, OXF, SACL+)
DATAR 85 Nature 318 547 +Baba, Bhattacherjee, Bhuinya, Roy (BHAB, TATA)
HAXTON 85 PRL 55 807 (WASH, LASL)
HUBERT 85 NC 85A 19 +Leccia, Dassie, Mennrath+ (BCEN, ZARA)
KALBFLEISCH 85 PRL 55 2225 +Milton (OKLA)
MARKEY 85 PR C32 2215 +Boehm (CIT)
OHI 85 PL 160B 322 +Nakajima, Tamura+ (TOKY, INUS, KEK)
SIMPSON 85 PRL 54 1891 (GUEL)
STOCKDALE 85 ZPHY C27 53 +Bodek+ (ROCH, CHIC, COLU, FNAL)
ZACEK 85 PL 164B 193 +Zacek, Boehm+ (MUNI, CIT, SIN)
BAHCALL 84 A.I.P. 126 60 (IAS)
Proc., Solar Neutrinos and Neutrino Astronomy (Homestake 1984)
BALLAGH 84 PR D30 2271 +Bingham+ (UCB, LBL, FNAL, HAWA, WASH, WISC)
BELLOTTI 84 PL 146B 450 +Cremonesi, Fiorini, Liguori, Pullia+ (MILA)
BERGSMA 84 PL 142B 103 +Dorenbosch, Allaby, Abt+ (CHARM Collab.)
CAVAIGNAC 84 PL 148B 387 +Hoummada, Koang+ (ISNG, LAPP)
DAVIS 84 A.I.P. 123 1037 +Cleveland, Rowley (BNL)
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Also 84B Icoman 1983 Davis, Cherry, Davidson, Lande, Lee, Marshall+
Also 84 A.I.P. 126 1 Rowley, Cleveland, Davis (BNL)
DYDAK 84 PL 134B 281 +Feldman+ (CERN, DORT, HEID, SACL, WARS)
FORSTER 84 PL 138B 301 +Kwon, Markey, Boehm, Henrikson (CIT)
GABATHULER 84 PL 138B 449 +Boehm+ (CIT, SIN, MUNI)
MINEHART 84 PRL 52 804 +Ziock, Marshall, Stephens, Daum+ (VIRG, SIN)
STOCKDALE 84 PRL 52 1384 +Bodek+ (ROCH, CHIC, COLU, FNAL)
AFONIN 83 JETPL 38 436 +Bogatov, Borovoi, Vershinskii+ (KIAE)
Translated from ZETFP 38 361.
AVIGNONE 83 PRL 50 721 +Brodzinski, Brown, Evans, Hensley+ (SCUC, PNL)
BELENKII 83 JETPL 38 493 +Dobrynin, Zemlyakov, Mikaelyan+ (KIAE)
Translated from ZETFP 38 406.
BELIKOV 83 JETPL 38 661 +Volkov, Kochetkov, Mukhin, Sviridov+ (SERP)
Translated from ZETFP 38 547.
BELLOTTI 83 PL 121B 72 +Fiorini, Ligurori, Pullia, Sarracino+ (MILA)
BERGSMA 83B PL 128B 361 +Dorenbosch+ (CHARM Collab.)
BRYMAN 83B PRL 50 1546 +Dubois, Numao, Olaniya, Olin+ (TRIU, CNRC)
Also 83 PRL 50 7 Bryman, Dubois, Numao, Olaniya+ (TRIU, CNRC)
DEUTSCH 83 PR D27 1644 +Lebrun, Prieels (LVLN)
DOI 83 PTP 69 602 +Kotani, Nishiura, Takasugi (OSAK, KYOT)
FILIPPONE 83 PRL 50 412 +Elwyn, Davids+ (ANL, CHIC, VALP)
GRONAU 83 PR D28 2762 (HAIF)
KIRSTEN 83 PRL 50 474 +Richter, Jessberger (MPIH)
Also 83B ZPHY 16 189 Kirsten, Richter, Jessberger (MPIH)
SCHRECK... 83 PL 129B 265 Schreckenbach, Colvin+ (ISNG, ILLG)
TAYLOR 83 PR D28 2705 +Cence, Harris, Jones+ (HAWA, LBL, FNAL)
COOPER 82 PL 112B 97 +Guy, Michette, Tyndel, Venus (RL)
FILIPPONE 82 APJ 253 393 +Schramm (ANL, EFI)
FOWLER 82 A.I.P. 96 80 (CIT)
HAXTON 82 PR D25 2360 +Stephenson, Strottman (LANL, PURD)
HAYANO 82 PRL 49 1305 +Taniguchi, Yamanaka+ (TOKY, KEK, TSUK)
VUILLEUMIER 82 PL 114B 298 +Boehm, Egger+ (CIT, SIN, MUNI)
ABELA 81 PL 105B 263 +Daum, Eaton, Frosch, Jost, Kettle, Steiner (SIN)
ARMENISE 81 PL 100B 182 +Fogli-Muciaccia+ (BARI, CERN, MILA, LALO)
ASANO 81 PL 104B 84 +Hayano, Kikutani, Kurokawa+ (KEK, TOKY, OSAK)
Also 81 PR D24 1232 Shrock (STON)
ASRATYAN 81 PL 105B 301 +Efremenko, Fedotov+ (ITEP, FNAL, SERP, MICH)
BAKER 81 PRL 47 1576 +Connolly, Kahn, Kirk, Murtagh+ (BNL, COLU)
Also 78 PRL 40 144 Cnops, Connolly, Kahn, Kirk+ (BNL, COLU)
BOLIEV 81 SJNP 34 787 +Butkevich, Zakidyshev, Makoev+ (INRM)
Translated from YAF 34 1418.
CALAPRICE 81 PL 106B 175 +Schreiber, Schneider+ (PRIN, IND)
DEDEN 81 PL 98B 310 +Grassler, Boeckmann, Mermikides+ (BEBC Collab.)
ERRIQUEZ 81 PL 102B 73 +Natali+ (BARI, BIRM, LIBH, EPOL, RHEL, SACL+)
HAXTON 81 PRL 47 153 +Stephenson, Strottman (PURD, LASL)
KWON 81 PR D24 1097 +Boehm, Hahn, Henrikson+ (CIT, ISNG, MUNI)
NEMETHY 81B PR D23 262 + (YALE, LBL, LASL, MIT, SACL, SIN, CNRC, BERN)
ROSEN 81 Nu Conf. Hawaii (PURD)
Also 78 RMP 50 11 Bryman, Picciotto (TRIU, VICT)
SHROCK 81 PR D24 1232 (STON)
SHROCK 81B PR D24 1275 (STON)
SILVERMAN 81 PRL 46 467 +Soni (UCI, UCLA)
SIMPSON 81B PR D24 2971 (GUEL)
USHIDA 81 PRL 47 1694 + (AICH, FNAL, KOBE, SEOU, MCGI, NAGO, OSU+)
AVIGNONE 80 PR C22 594 +Greenwood (SCUC)
BAHCALL 80 PRL 45 945 +Lubow, Huebner+ (IAS, LASL, YALE, LLL, UCLA)
Also 76 Science 191 264 Bahcall, Davis (IAS, BNL)
BOEHM 80 PL 97B 310 +Cavaignac, Feilitzsch+ (ILLG, CIT, ISNG, MUNI)
FRITZE 80 PL 96B 427 (AACH, BONN, CERN, LOIC, OXF, SACL)

REINES	80	PRL 45 1307	+Sobel, Pasierb	(UCI)
Also	59	PR 113 273	Reines, Cowan	(LASL)
Also	66	PR 142 852	Nezrick, Reines	(CASE)
Also	76	PRL 37 315	Reines, Gurr, Sobel	(UCI)
SHROCK	80	PL 96B 159		(STON)
DAVIS	79	PR C19 2259	+Vogel, Mann, Schenter	(CIT)
BLIETSCHAU	78	NP B133 205	+Deden, Hasert, Krenz+	(Gargamelle Collab.)
CROUCH	78	PR D18 2239	+Landecker, Lathrop, Reines+	(CASE, UCI, WITW)
BELLOTTI	76	LNC 17 553	+Cavalli, Fiorini, Rollier	(MILA)
CONWAY	59	PR 116 1544	+Johnston	(PURD)
HAMILTON	58	PR 112 2010	+Langer, Smith	(IND)
JOHNSON	58	PR 112 2004	+Johnson, Langer	(IND)

Neutrino Bounds from Astrophysics and Cosmology

OMITTED FROM SUMMARY TABLE

The limits on the number of light neutrino types now appears in a separate section (following the τ-lepton section).

See the note on neutrinos by R.E. Shrock in the ν_e section near the beginning of these Listings. For information on neutrinos derived from more conventional (terrestrial) experiments, see the ν_e, ν_μ, ν_τ, and heavy-ν sections above.

NOTE ON CONSTRAINTS ON PARTICLES FROM SN 1987A

(by J. Ellis, CERN and D.N. Schramm, Univ. of Chicago)

According to the standard theory of Type II supernovae,[1] the core of a star with $M \gtrsim 8\ M_\odot$ collapses when its nuclear fuel is exhausted. The collapse releases the neutron star's binding energy of (2 to 4)$\times10^{53}$ ergs,[2] ejecting the outer regions of the star and leaving behind a remnant neutron star of mass 1.4 $M_\odot$ to 2 $M_\odot$. Only about 1% of the binding energy is emitted as kinetic energy or electromagnetic radiation; the rest is carried off by neutrinos,[3] with at most 1% radiated as gravitational waves.[4] The essential features of this standard theory agree with observations of SN 1987A, and the agreement can be used to constrain the properties of neutrinos and other conjectured light particles, as well as the equation of state of dense hadronic matter.

SN 1987A has been identified[5] with a blue giant star Sanduleak-69 202 with $M \sim 20 \pm 5\ M_\odot$, which was a 12^{th} magnitude star that had lost its red giant envelope. Its visual magnitude rose in a few hours to almost 4 and after 90 days to 3, the luminosity decayed quasi-exponentially with a lifetime $\sim$ 100 d, consistent with radioactive ^{56}Co decay. This and γ-ray line observations from the Solar Maximum satellite[6] argued that the ejecta included $\sim 0.075\ M_\odot$ of ^{56}Ni which decay to ^{56}Co and then to ^{56}Fe.[7] The synthesis of significant amounts of other heavy elements is consistent with the observations. While, in principle, x rays emitted from the shell could be due to neutrino decays,[8] we adopt the conventional view that they were emitted by relativistic electrons. The most important constraints on neutrinos and other light particles come from the observations of a neutrino burst associated with stellar collapse. The most significant of these observations were those by the IMB[9] and Kamiokande[10] experiments, which were coincident within the timing uncertainties (see also Ref. 11*). Because $\sigma(\overline{\nu}_e\, p \to n\, e^+)$ is much larger than other neutrino cross sections at low energies, it is believed that most of the events observed were due to $\overline{\nu}_e$ interactions. Taken together, the IMB and Kamiokande events suggest an integrated $\overline{\nu}_e$ luminosity of (3 to 9)$\times10^{52}$ $(D/50\ \text{kpc})^2$ ergs, where $D = 50\pm5$ kpc is the distance to SN 1987A. The distributions of neutrino energies were compatible with a thermal spectrum of temperature $T \sim$ (4 to 5) MeV, and the neutrino pulses lasted $\sim$ 10 s as expected in conventional models[1] of stellar collapse, according to which the central core reaches densities sufficiently high that neutrinos are trapped and diffuse out on this timescale.

Constraints on neutrinos: Since the IMB and Kamiokande neutrino pulses did not last much longer than expected, an upper limit on $m_{\overline{\nu}_e}$ can be derived. When deriving a limit, care must be taken to include the neutrino measurement errors and the likelihood that one or two events were due to background, as discussed in Ref. 13, resulting in the conservative upper limit

$$m_{\overline{\nu}_e} \lesssim 25\ \text{eV} \quad (90\%\ \text{CL})\ . \tag{1}$$

The absence of any indication of neutrino pulse-lengthening can also be used to give an upper bound on the electric charge of the $\overline{\nu}_e$, as discussed in Ref. 14:

$$|Q_{\overline{\nu}_e}| \lesssim 10^{-17}\ e\ . \tag{2}$$

There is a simple lower bound on the $\overline{\nu}_e$ lifetime from the persistence of the pulse out to 50 kpc:

$$\gamma\ \tau_{\overline{\nu}_e} \gtrsim 10^5\ \text{yr}\ . \tag{3}$$

Stronger limits can be set on individual decay modes; for example, the absence of accompanying γ rays implies (see Ref. 15):

$$\tau_{\overline{\nu}_e}/m_{\overline{\nu}_e} > \text{B}_\gamma 10^{15}\ \text{s/eV}\ . \tag{4}$$

where B_γ is the branching ratio into radiation.

The integrated luminosities for different ν and $\overline{\nu}$ species are expected to be similar. The neutron star binding energy can be calculated assuming various equations of state for neutron star matter as (2 to 4)$\times10^{53}$ ergs. Then, assuming equipartition of energy between ν and $\overline{\nu}$ species, and using the neutron star binding energy to bound the total energy carried by the emitted neutrinos, the above estimate of the $\overline{\nu}_e$ luminosity can be used[16] to estimate the number of neutrino species:

$$\begin{aligned} N_\nu &= 2.5^{+4.1}_{-0.8}\ , \\ &< 8 \quad (90\%\ \text{CL})\ . \end{aligned} \tag{5}$$

The consistency of the integrated $\overline{\nu}_e$ luminosity with $N_\nu = 3$ constrains the difference between the probabilities of $\overline{\nu}_e \to \overline{\nu}_X$, or ν_X and $\overline{\nu}_X$, or $\nu_X \to \overline{\nu}_e$ oscillations. In particular, an upper bound can be given on the magnetic moments μ_ν of neutrinos. Induced magnetic transitions to sterile right-handed neutrinos would allow more rapid loss of the available binding energy. Also, such neutrinos that had escaped from the inner core could be converted back to detectable 30–100 MeV neutrinos by the intergalactic magnetic field. The absence of such detections or rapid cooling gives the limit[17]

$$|\mu_\nu| \lesssim 10^{-12}\ \mu_B\ . \tag{6}$$

This bound applies only to Dirac neutrinos (static or transition moments) but not to Majorana transition moments.[18]

It is possible to constrain possible spin-flip processes that would cause an initially left-handed neutrino to metamorphose into a sterile right-handed Dirac state, using the fact that their emission from the core of the neutron star would have shortened the neutrino pulse and diminished its energy. Analytic calculations based on the absence of such an effect give an upper bound on the Dirac mass[19]

$$m_{\nu_D} < 10 \text{ keV} , \quad (7)$$

which is likely to be improved by detailed numerical calculations.

Constraints on other light particles: The consistency of the observed neutrino pulse with expectations places upper limits on energy emission via photinos, axions, majorons, and any other particles whose masses are less than a few MeV. Light photinos can be excluded unless the squark masses are[20]

$$m_{\tilde{q}} \lesssim 60 \text{ GeV} \quad \text{or} \quad \gtrsim 10 \text{ TeV} . \quad (8)$$

The lower range is excluded by accelerator experiments, and the upper range is deemed theoretically implausible. Analogous bounds on light Higgsinos are also given in Ref. 20. Like sterile neutrinos, axions emitted from the core of the embryonic neutron star would have shortened the neutrino pulse and diminished its energy. The absence of such effects gives a lower bound[20] on the axion decay constant f_a of

$$f_a \gtrsim 3 \times 10^{10} \text{ GeV} . \quad (9)$$

The precise value of this bound depends on the axion-nucleon couplings and on the behavior of dense hadronic matter: for more discussion, see Ref. 21. Analogous bounds on majorons and other light spin-zero bosons can be found in Ref. 22.

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* The claim[12] of an earlier neutrino pulse in the Mont Blanc experiment has less statistical significance and is difficult to reconcile with the absence of coincident observations in the Kamiokande detectors. Therefore we will not include it in our discussions.

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ν MASS

The limits on low mass ($m_\nu \lesssim$ 1 MeV) neutrinos apply to m_{tot} given by

$$m_{\text{tot}} = \sum_\nu (g_\nu/2) m_\nu ,$$

where g_ν is the number of spin degrees of freedom for ν plus $\overline{\nu}$: $g_\nu = 4$ for neutrinos with Dirac masses; $g_\nu = 2$ for Majorana neutrinos. The limits on high mass ($m_\nu > 1$ MeV) neutrinos apply separately to each neutrino type.

Limit on Total ν MASS, m(tot)

(Defined in the above note), of effectively stable neutrinos (i.e., those with mean lives greater than or equal to the age of the universe). These papers assumed Dirac neutrinos. When necessary, we have generalized the results reported so they apply to m(tot). For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85.

VALUE (eV)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<180	SZALAY	74	COSM
<132	COWSIK	72	COSM
<280	MARX	72	COSM
<400	GERSHTEIN	66	COSM

Astrophysical and Cosmological Limits on ν MASSES

If neutrinos are present as dark matter in galactic halos, limits on neutrino masses have been computed based on neutrino degeneracy and Fermi statistics. The results depend strongly on assumptions. See the references.

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	SPERGEL	88B	COSM	
	KAWASAKI	86	COSM	
	KAWASAKI	86B	COSM	
	TAKAHARA	86	COSM	supernovae
	MADSEN	85	COSM	Some anisotropy
	MADSEN	84	COSM	Assume isotropy
	SARKAR	84	COSM	Decaying neutrinos
	FREESE	83	COSM	Degenerate ν
	LIN	83	COSM	
	PRIMACK	83	COSM	
	BOND	81	COSM	Adiabatic
	DAVIS	81	COSM	Adiabatic+decaying ν's
	SCHRAMM	81	COSM	Isothermal
	TREMAINE	79	COSM	Isothermal

Limits on MASSES of Light Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<100–200	[1] OLIVE	82	COSM	Dirac ν
<200–2000	[1] OLIVE	82	COSM	Majorana ν

[1] Depending on interaction strength g_R where $g_R < G_F$.

Limits on MASSES of Heavy Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> 10	[2] OLIVE	82	COSM	g_R/G_F <0.1
>100	[2] OLIVE	82	COSM	g_R/G_F <0.01

[2] These results apply to heavy Majorana neutrinos and are summarized by the equation: $m(\nu) > 1.2$ GeV (G_F/g_R).

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SPERGEL	88B	PR D38 2014	+Weinberg, Gott	(PRIN)
KAWASAKI	86	PL B178 71	+Terasawa, Sato	(TOKY)
KAWASAKI	86B	PL 169B 280	+Sato	(TOKY)
TAKAHARA	86	PL B174 373	+Sato	(TOKY)
COWSIK	85	PL 151B 62		(TATA)
MADSEN	85	PRL 54 2720	+Epstein	(AARH, LANL)
FREESE	84	NP B233 167	+Schramm	(CHIC, FNAL)
MADSEN	84	APJ 282 11	+Epstein	(AARH, LANL)
SARKAR	84	PL 148B 347	+Cooper	(OXF, CERN)
SCHRAMM	84	PL 141B 337	+Steigman	(FNAL, BART)
FREESE	83	PR D27 1689	+Kolb, Turner	(CHIC, LANL)
LIN	83	APJ 266 L21	+Faber	(UCSC)
PRIMACK	83	Phil. 4th Workshop on Grand Unification		(UCSC)
Also	82	Nature 299 37	Blumenthal, Pagels, Primack	(UCSC, ROCK)
OLIVE	82	PR D25 213	+Turner	(CHIC, UCSB)
BERNSTEIN	81	PL 101B 39	+Feinberg	(STEV, COLU)
BOND	81	Nu Conf. Hawaii	+Szalay	(UCB, CHIC)
DAVIS	81	APJ 250 423	+Lecar, Pryor, Witten	(HARV, PRIN)
SCHRAMM	81	APJ 243 1	+Steigman	(CHIC, BART)
TREMAINE	79	PRL 42 407	+Gunn	(CIT, CAMB, CAIW)
VYSOTSKY	77	JETPL 26 188 Translated from ZETFP 26 200.	+Dolgov, Zeldovich	(ITEP)
SZALAY	76	AA 49 437	+Marx	(EOTV)
SZALAY	74	APAH 35 8	+Marx	(EOTV)
COWSIK	72	PRL 29 669	+McClelland	(UCB)
MARX	72	Nu Conf. Budapest	+Szalay	(EOTV)
GERSHTEIN	66	JETPL 4 120 Translated from ZETFP 4 189.	+Zeldovich	(KIAM)

QUARKS

This year we are introducing Quark Listings. The quark masses shown are not based on a set of papers. Since the subject of their masses is controversial, the purpose of these Listings is to provoke discussion. We ask that our readers send us comments and references (particularly on quark mass definitions and values). The masses that enter a QCD Lagrangian are "running" masses and depend on scale and renormalization scheme. These can be different from the heavy quark masses obtained in potential models. For this edition we have attempted to give a conservative range of masses. In the next edition we will provide a more extensive treatment.

d

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 5 to 15 MeV   Charge = $-\frac{1}{3}$ e $I_z = -\frac{1}{2}$

m_d/m_s = 0.04 to 0.06

The *d*-, *u*-, and *s*-quark masses are estimates of so-called "current-quark masses," with ratios m_u/m_d and m_d/m_s extracted from pion and kaon masses using chiral symmetry. The estimates of *d* and *u* masses are not without controversy and remain under active investigation. Within the literature there are even suggestions that the *u* quark could be essentially massless. The *s*-quark mass is estimated from SU(3) splitting in hadron masses.

u

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 2 to 8 MeV   Charge = $\frac{2}{3}$ e $I_z = +\frac{1}{2}$

m_u/m_d = 0.25 to 0.70

See the comment for the *d* quark above.

s

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 100 to 300 MeV   Charge = $-\frac{1}{3}$ e Strangeness = −1

See the comment for the *d* quark above.

c

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 1.3 to 1.7 GeV   Charge = $\frac{2}{3}$ e Charm = +1

The *c*-quark mass is estimated from charmonium and *D* masses. It corresponds to the potential model mass and not to the "running" mass.

b

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 4.7 to 5.3 GeV   Charge = $-\frac{1}{3}$ e Bottom = −1

The *b*-quark mass is estimated from bottomonium and *B* masses. It corresponds to the potential model mass and not to the "running" mass.

t

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m > 91 GeV   Charge = $\frac{2}{3}$ e Top = +1

(not discovered)

The *t*-quark mass shown assumes that the *t* quark would decay with 100% branching ratio as $t \to bW^+$ rather than to other modes such as $t \to bH^+$. Without this assumption the mass limit is $m > 55$ GeV. Standard Model analyses of precision experiments on the electroweak interactions suggest a mass between 110 and 190 GeV with $m < 200$ GeV at 95% CL (see the section on Top Hadrons).

(continued on the next page)

• Indicates the particle is in the Meson Summary Table—see Section II.

CHARMED STRANGE MESONS ($C = S = \pm1$)

BOTTOM MESONS ($B = \pm1$)

HEAVY QUARK SEARCHES

$c\overline{c}$ MESONS

$b\overline{b}$ MESONS

NON-$q\overline{q}$ CANDIDATES

Notes in the Meson Listings

• Indicates the particle is in the Meson Summary Table—see Section II.

LIGHT UNFLAVORED MESONS
$(S = C = B = 0)$

For $I = 1$ (π, b, ρ, a): $u\bar{d}$, $(u\bar{u}-d\bar{d})/\sqrt{2}$, $d\bar{u}$;
for $I = 0$ $(\eta, \eta', h, h', \omega, \phi, f, f')$: $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

NOTE ON DECAY CONSTANTS OF PSEUDOSCALAR MESONS

Charged mesons

The decay constant f_P for pseudoscalar meson P is defined by

$$\langle 0|A_\mu(0)|P(\mathbf{q})\rangle = i f_P\, q_\mu \ ,$$

where A_μ is the axial-vector part of the charged weak current after a Cabibbo-Kobayashi-Maskawa mixing-matrix element $V_{qq'}$ has been removed. The state vector is normalized by $\langle P(\mathbf{q})|P(\mathbf{q}')\rangle = (2\pi)^3 2E_q\,\delta(\mathbf{q}-\mathbf{q}')$, and its phase is chosen to make f_P real and positive. Note, however, that in many theoretical papers our $f_P/\sqrt{2}$ is denoted by f_P and called the pseudoscalar decay constant.

In determining f_P experimentally, radiative corrections must in principle be taken into account. Since the photon-loop correction introduces an infrared divergence that is canceled by soft-photon emission, we can determine f_P only from the combined rate for $P^\pm \to \ell^\pm\nu$ and $P^\pm \to \ell^\pm\nu\gamma$. This rate is given by

$$\Gamma\,[P \to \ell\nu(+\ell\nu\gamma)] =$$
$$\frac{G_F^2|V_{qq'}{}^2|}{8\pi} f_P^2\, m_\ell^2\, m_P \left(1 - \frac{m_\ell^2}{m_P^2}\right)^2 \left[1 + \frac{\alpha}{2\pi}(B + B_{\rm SD})\right] \ .$$

The term of order α contains an inner bremsstrahlung part B, which does not depend on the structure of the meson,[1–3] and a structure-dependent part $B_{\rm SD}$.[4,5] The former is given by

$$B = 4\left[\left(\frac{x^2+1}{x^2-1}\right)\ln x - 1\right]\left[\ln(x^2-1) - 2\ln x - \frac{3}{4}\right]$$
$$+ 4\left(\frac{x^2+1}{x^2-1}\right) L\left(1 - \frac{1}{x^2}\right) - \ln x - \frac{3}{4}$$
$$+ \frac{(10x^2-7)}{(x^2-1)^2}\ln x + \frac{(15x^2-21)}{4(x^2-1)} \ ,$$

where

$$L(z) = \int_0^z \ln(1-t)\frac{dt}{t} \ , \text{ and } x = m_P/m_\ell \ .$$

The values of B are -1.35 for $\pi^+ \to \mu^+\nu$, -6.44 for $K^+ \to \mu^+\nu$, and -12.0 for $D^+ \to \mu^+\nu$. There is a theoretical ambiguity concerning the structure-dependent part $B_{\rm SD}$. One way to avoid this uncertainty is to include all of $B_{\rm SD}$ as part of f_P. Then the numerical values are unambiguous, but theoretically unsatisfactory. To remove $B_{\rm SD}$ from f_P, we shall use[5]

$$B_{\rm SD} = 3\ln(m_Z/m_P) + \ln(m_Z/m_\rho) - 6\ln(m_\rho/m_\ell) + O(1) \ ,$$

where m_Z and m_ρ are the masses of the Z boson and the ρ meson. The values of $B_{\rm SD}$ are 12.3 for $\pi^+ \to \mu^+\nu$, 8.5 for $\pi^+ \to \mu^+\nu$, and 4.5 for $D^+ \to \mu^+\nu$, all with an uncertainty of order unity. The short-distance effects dominate in this $B_{\rm SD}$.

Using the experimental values of $V_{qq'}$ given in Eqs. (5), (7), and (8) of the "Cabibbo-Kobayashi-Maskawa Mixing Matrix" section and our current best values of branching ratios, lifetimes, and masses, and absorbing the $B_{\rm SD}$ term into f_P, we obtain:

$$f_{\pi^+} = (131.73 \pm 0.15)\text{ MeV} \ ,$$
$$f_{K^+} = (160.6 \pm 1.3)\text{ MeV} \ ,$$
$$f_{D^+} < 310\text{ MeV}\ \ (\text{CL} = 90\%) \ .$$

Making the $B_{\rm SD}$ correction, we obtain instead:

$$f_{\pi^+} = (130.8 \pm 0.3)\text{ MeV} \ ,$$
$$f_{K^+} = (159.8 \pm 1.4)\text{ MeV} \ .$$

The errors here are larger on account of the $O(1)$ estimated uncertainty in $B_{\rm SD}$. Note that the second value of f_{π^+} lies several standard deviations from the first value.

Light neutral mesons

The decay constants for the light neutral pseudoscalar mesons π^0, η, and η' are defined by

$$\langle 0|A_\mu(0)|P^0(\mathbf{q})\rangle = \mathrm{i}(f_P/\sqrt{2})q_\mu \ ,$$

where A_μ is a neutral axial vector current of octet or singlet. Values of $f_{\rm P}$ can be obtained from the two-photon decay $P^0 \to \gamma\gamma$, since in the $m_P = 0$ limit the decay matrix element is determined by the Adler-Bell-Jackiw anomaly.[6,7] However, large uncertainties enter values of f_P through extrapolation to the physical mass and, in the case of η and η', through the mixing angle, too.

The CELLO Collaboration has obtained the values[8]

$$f_{\pi^0} = 119 \pm 4\text{ MeV}$$
$$f_\eta = 133 \pm 10\text{ MeV}$$
$$f_{\eta'} = 126 \pm 7\text{ MeV} \ ,$$

while the TPC/2γ Collaboration has obtained[9]

$$f_\eta = 129 \pm 8\text{ MeV}$$
$$f_{\eta'} = 110 \pm 7\text{ MeV} \ .$$

(We have multipled the published values by $\sqrt{2}$ to be in accord with our definition of f_P.)

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$\pi^{\pm}$

$I^G(J^P) = 1^-(0^-)$

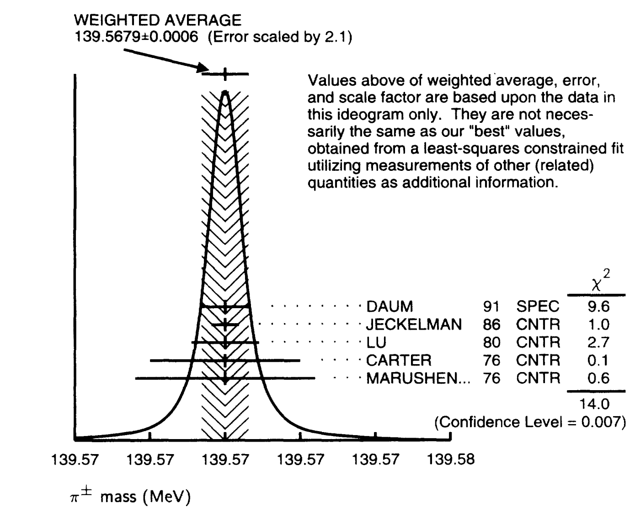
We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** (1988).

$\pi^{\pm}$ MASS

The fit uses the $\pi^{\pm}$ and π^0 mass and mass difference measurements. Measurements with an error > 0.005 MeV have been omitted from this Listing.

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
139.5679 ±0.0007 OUR FIT Error includes scale factor of 2.2.					
139.5679 ±0.0006 OUR AVERAGE Error includes scale factor of 2.1. See the ideogram below.					
139.56996±0.00067	[1] DAUM	91	SPEC	+	$\pi^+ \to \mu^+ \nu$
139.56752±0.00037	[2] JECKELMAN	86	CNTR	−	Mesonic atoms
139.5664 ±0.0009	[3] LU	80	CNTR	−	Mesonic atoms
139.5686 ±0.0020	CARTER	76	CNTR	−	Mesonic atoms
139.5660 ±0.0024	[3,4] MARUSHEN...	76	CNTR	−	Mesonic atoms
• • • We do not use the following data for averages, fits, limits, etc. • • •					
139.5704 ±0.0011	[1] ABELA	84	SPEC	+	See DAUM 91

[1] The DAUM 91 value includes the ABELA 84 result. The value assumes that $m(\nu_\mu) = 0$ and uses our $m(\mu) = 105.658389 \pm 0.000034$ MeV.
[2] JECKELMAN 86 gives $m(\pi)/m(e) = 273.12677(71)$. We use $m(e) = 0.51099906(15)$ MeV from COHEN 87.
[3] Value scaled with a new wavelength-energy conversion factor $V\lambda = 1.23984244(37) \times 10^{-6}$ eV m from COHEN 87.
[4] This MARUSHENKO 76 value used at the authors' request to use the accepted set of calibration γ energies. Error increased from 0.0017 MeV to include QED calculation error of 0.0017 MeV (12 ppm).



$\pi^+ - \mu^+$ MASS DIFFERENCE

Measurements with an error > 0.05 MeV have been omitted from this Listing.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
33.91157±0.00067		[5] DAUM	91	SPEC	+	$\pi^+ \to \mu^+ \nu$
33.9111 ±0.0011		ABELA	84	SPEC		See DAUM 91
33.925 ±0.025		BOOTH	70	CNTR	+	Magnetic spect.
33.881 ±0.035	145	HYMAN	67	HEBC	+	K^- He

[5] The DAUM 91 value assumes that $m(\nu_\mu) = 0$ and uses our $m(\mu) = 105.658389 \pm 0.000034$ MeV.

$[m(\pi^+) - m(\pi^-)]$ / AVERAGE m

A test of *CPT* invariance.

VALUE (units 10^{-4})	DOCUMENT ID		TECN
2±5	AYRES	71	CNTR

$\pi^{\pm}$ MEAN LIFE

Measurements with an error > 0.02×10^{-8} s have been omitted.

VALUE (10^{-8} s)	DOCUMENT ID		TECN	CHG
2.6030±0.0024 OUR AVERAGE				
2.609 ±0.008	DUNAITSEV	73	CNTR	+
2.602 ±0.004	AYRES	71	CNTR	±
2.604 ±0.005	NORDBERG	67	CNTR	+
2.602 ±0.004	ECKHAUSE	65	CNTR	+
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.640 ±0.008	[6] KINSEY	66	CNTR	+

[6] Systematic errors in the calibration of this experiment are discussed by NORDBERG 67.

$[\tau(\pi^+) - \tau(\pi^-)]$ / AVERAGE τ

A test of *CPT* invariance.

VALUE (units 10^{-4})	DOCUMENT ID		TECN
5.5± 7.1	AYRES	71	CNTR
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−14 ±29	PETRUKHIN	68	CNTR
40 ±70	BARDON	66	CNTR
23 ±40	[7] LOBKOWICZ	66	CNTR

[7] This is the most conservative value given by LOBKOWICZ 66.

π^+ DECAY MODES

π^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\mu^+ \nu_\mu$		(99.98782±0.00014) %	
Γ_2	$\mu^+ \nu_\mu \gamma$	[a]	(1.24 ±0.25) × 10^{-4}	
Γ_3	$e^+ \nu_e$		(1.218 ±0.014) × 10^{-4}	
Γ_4	$e^+ \nu_e \gamma$	[a]	(1.61 ±0.23) × 10^{-7}	
Γ_5	$e^+ \nu_e \pi^0$		(1.025 ±0.034) × 10^{-8}	
Γ_6	$e^+ \nu_e e^+ e^-$		(3.2 ±0.5) × 10^{-9}	
Γ_7	$e^+ \nu_e \nu \overline{\nu}$		< 5 × 10^{-6}	90%
	Lepton number (*L*) or Lepton Family number (*LF*) violating modes			
Γ_8	$\mu^+ \overline{\nu}_e$	*L*	< 1.5 × 10^{-3}	90%
Γ_9	$\mu^+ \nu_e$	*LF*	< 8.0 × 10^{-3}	90%
Γ_{10}	$\mu^- e^+ e^+ \nu$	*LF*	< 7.7 × 10^{-6}	90%

[a] See the Listings below for the energy range used in this measurement; low-energy γ's are not included. Measurements of $\Gamma(e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ always include decays with γ's, and measurements of $\Gamma(e^+\nu_e\gamma)$ and $\Gamma(\mu^+\nu_\mu\gamma)$ never include low-energy γ's. Therefore, since no clean separation is possible, we consider the modes with γ's to be subreactions of the modes without them, and let $[\Gamma(e^+\nu_e) + \Gamma(\mu^+\nu_\mu)]/\Gamma_{total} = 100\%$.

π^+ BRANCHING RATIOS

$\Gamma(e^+\nu_e)/\Gamma_{total}$ — Γ_3/Γ

See note [a] in the list of π^+ decay modes just above, and also the next block of data.

VALUE (units 10^{-4})	DOCUMENT ID
1.218±0.014 OUR EVALUATION	

$[\Gamma(e^+\nu_e) + \Gamma(e^+\nu_e\gamma)]/[\Gamma(\mu^+\nu_\mu) + \Gamma(\mu^+\nu_\mu\gamma)]$ — $(\Gamma_3+\Gamma_4)/(\Gamma_1+\Gamma_2)$

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN
1.218±0.014	32k	BRYMAN	86	CNTR
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.273±0.028	11k	[8] DICAPUA	64	CNTR
1.21 ±0.07		ANDERSON	60	CNTR

[8] DICAPUA 64 updated using current mean life.

$\Gamma(\mu^+\nu_\mu\gamma)/\Gamma_{total}$ — Γ_2/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.24±0.25	26	CASTAGNOLI	58	EMUL	$KE_\mu < 3.38$ MeV

$\Gamma(e^+\nu_e\gamma)/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-8})	EVTS	DOCUMENT ID		TECN	COMMENT
16.1±2.3		[9] BOLOTOV	90B	SPEC	17 GeV $\pi^- \to e^- \overline{\nu}_e \gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5.6±0.7	226	[10] STETZ	78	SPEC	$P_e > 56$ MeV/c
3.0	143	DEPOMMIER	63B	CNTR	$(KE)_{e^+\gamma} > 48$ MeV

[9] BOLOTOV 90B is for $E_\gamma > 21$ MeV, $E_e > 70 - 0.8\, E_\gamma$.
[10] STETZ 78 is for an $e^-\gamma$ opening angle > 132°. Obtains 3.7 when using same cutoffs as DEPOMMIER 63B.

$\Gamma(e^+\nu_e\pi^0)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-8})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.025±0.034 OUR AVERAGE						
1.026±0.039	1224	[11] MCFARLANE	85	CNTR	+	Decay in flight
1.00 $^{+0.08}_{-0.10}$	332	DEPOMMIER	68	CNTR	+	
1.07 ±0.21	38	[12] BACASTOW	65	OSPK	+	
1.10 ±0.26		[12] BERTRAM	65	OSPK	+	
1.1 ±0.2	43	[12] DUNAITSEV	65	CNTR	+	
0.97 ±0.20	36	[12] BARTLETT	64	OSPK	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.15 ±0.22	52	[12] DEPOMMIER	63	CNTR	+	See DEPOMMIER 68

[11] Combines a measured rate (0.394 ± 0.015)/s with 1982 PDG mean life.
[12] DEPOMMIER 68 says the result of DEPOMMIER 63 is at least 10% too large because of a systematic error in the π^0 detection efficiency, and that this may be true of all the previous measurements (also V. Soergel, private communication, 1972).

$\Gamma(e^+\nu_e e^+e^-)/\Gamma(\mu^+\nu_\mu)$ — Γ_6/Γ_1

VALUE (units 10^{-9})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
3.2±0.5±0.2		98	EGLI	89	SPEC		Uses R_{PCAC} = 0.068 ± 0.004
• • • We do not use the following data for averages, fits, limits, etc. • • •							
< 4.8	90		KORENCHE...	76B	SPEC	+	
<34	90		KORENCHE...	71	OSPK	+	

$\Gamma(e^+\nu_e\nu\overline{\nu})/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN
<5	90	PICCIOTTO	88	SPEC

$\Gamma(\mu^+\overline{\nu}_e)/\Gamma_{total}$ — Γ_8/Γ

Forbidden by total lepton number conservation.

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<1.5	90	COOPER	82	HLBC	Wideband ν beam

$\Gamma(\mu^+\nu_e)/\Gamma_{total}$ — Γ_9/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<8.0	90	COOPER	82	HLBC	Wideband ν beam

$\Gamma(\mu^-e^+e^+\nu)/\Gamma_{total}$ — Γ_{10}/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	CHG
<7.7	90	KORENCHE...	87	SPEC	+

π^+ — POLARIZATION OF EMITTED μ^+

$\pi^+ \to \mu^+\nu$

Tests the Lorentz structure of leptonic charged weak interactions.

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<(−0.9959)	90	[13] FETSCHER	84	RVUE	+	
−0.99±0.16		[14] ABELA	83	SPEC	−	μ X-rays

[13] FETSCHER 84 uses only the measurement of CARR 83.
[14] Sign of measurement reversed in ABELA 83 to compare with μ^+ measurements.

NOTE ON $\pi^{\pm} \to \ell^{\pm}\nu\gamma$ AND $K^{\pm} \to \ell^{\pm}\nu\gamma$ FORM FACTORS

(by H.S. Pruys, Zürich University)

In the radiative decay $P^{\pm} \to \ell^{\pm}\nu\gamma$, where P stands for π or K, ℓ for e or μ, and γ for a real or virtual photon (e^+e^- pair), both the vector and the axial-vector weak hadronic currents contribute to the decay amplitude. The vector current only gives a structure-dependent term (SD_V), but the axial-vector current gives two contributions, one for inner bremsstrahlung (IB) from the lepton and meson, and one for structure-dependent radiation (SD_A) from virtual hadronic states. The IB amplitudes are determined by the meson decay constants f_π and f_K.[1] The SD_V and SD_A amplitudes are parameterized by the vector form factor F_V and the axial-vector form factors F_A and R,[1–4]

$$M(\mathrm{SD}_V) = \frac{-eG_F V_{qq'}}{\sqrt{2}\, m_P}\epsilon^\mu \ell^\nu F_V \epsilon_{\mu\nu\sigma\tau} k^\sigma q^\tau ,$$

$$M(\mathrm{SD}_A) = \frac{-ie\, G_F V_{qq'}}{\sqrt{2}\, m_P}\epsilon^\mu \ell^\nu \{F_A [(s-t)g_{\mu\nu} - q_\mu k_\nu] + Rtg_{\mu\nu}\} .$$

Here $V_{qq'}$ is the Cabibbo-Kobayashi-Maskawa mixing-matrix element; ϵ^μ is the polarization vector of the real photon or the e^+e^- current, $\epsilon^\mu = (e/t)\overline{u}(p_-)\gamma^\mu v(p_+)$; ℓ^ν is the lepton-neutrino current, $\ell^\nu = \overline{u}(p_\nu)\gamma^\nu(1-\gamma_5)v(p_\ell)$; q and k are the meson and photon four-momenta; and $s = q\cdot k$ and $t = k^2$. The s and t dependence of the form factors is neglected, which is a good approximation for pions,[2] but not for kaons.[4] For pions, the vector form factor F_V^π is related via CVC to the π^0 lifetime, $|F_V^\pi| = (1/\alpha)\sqrt{2\Gamma_{\pi^0}/\pi m_{\pi^0}}$.[1] PCAC relates R to the electromagnetic radius of the meson,[2,4] $R^P = \frac{1}{3} m_P f_P \langle r_P^2\rangle$. The calculation of the other form factors, F_A^π, F_V^K, and F_A^K, is model dependent.[1,4]

For the decay $P^{\pm} \to \ell^{\pm}\nu\gamma$ with a real photon, the partial decay rate can be given analytically,[1,5]

$$\frac{d^2\Gamma_{P\to\ell\nu\gamma}}{dxdy} = \frac{d^2\Gamma_{\mathrm{IB}}}{dxdy} + \frac{d^2\Gamma_{\mathrm{SD}}}{dxdy} + \frac{d^2\Gamma_{\mathrm{INT}}}{dxdy} ,$$

$$\frac{d^2\Gamma_{\mathrm{SD}}}{dxdy} = \frac{\alpha}{8\pi}\Gamma_{P\to\ell\nu}\frac{1}{r(1-r)^2}\left(\frac{m_P}{f_P}\right)^2 \times \left[(F_V+F_A)^2\,\mathrm{SD}^+ + (F_V-F_A)^2\,\mathrm{SD}^-\right] ,$$

where

$$\mathrm{SD}^+ = (x+y-1-r)\left[(x+y-1)(1-x)-r\right] ,$$

$$\mathrm{SD}^- = (1-y+r)\left[(1-x)(1-y)+r\right] .$$

Here $x = 2E_\gamma/m_P$, $y = 2E_\ell/m_P$, and $r = (m_\ell/m_P)^2$. $\Gamma_{\mathrm{IB}}, \Gamma_{\mathrm{SD}}$, and Γ_{INT} are the contributions from inner brems-strahlung, structure-dependent radiation, and their interference.

In $\pi^{\pm} \to e^{\pm}\nu\gamma$ and $K^{\pm} \to e^{\pm}\nu\gamma$ decays, the interference terms are small, and thus only the absolute values $|F_A + F_V|$ and $|F_A - F_V|$ can be obtained. In $K^{\pm} \to \mu^{\pm}\nu\gamma$ decay, the interference term is important and thus the signs of F_V and F_A can be obtained. In $\pi^{\pm} \to \mu^{\pm}\nu\gamma$ decay, bremsstrahlung completely dominates. In $\pi^{\pm} \to e^{\pm}\nu e^+e^-$ and $K^{\pm} \to \ell^{\pm}\nu e^+e^-$ decays, all three form factors, F_V, F_A, and R, can be determined.

We list the $\pi^{\pm}$ form factors F_V, F_A, and R below. In the $K^{\pm}$ branching ratio section of the Full Listings, we list the sum $F_A + F_V$ and the difference $F_A - F_V$ of the axial-vector and vector form factors.

References

1. D.A. Bryman *et al.*, Phys. Reports **88**, 151 (1982). See also the "Note on Pseudoscalar-Meson Decay Constants," above.
2. A. Kersch and F. Scheck, Nucl. Phys. **B263**, 475 (1986).
3. W.T. Chu *et al.*, Phys. Rev. **166**, 1577 (1968).
4. D.Yu. Bardin and E.A. Ivanov, Sov. Jour. Nucl. Phys. **7**, 286 (1976).
5. S.G. Brown and S.A. Bludman, Phys. Rev. **136**, B1160 (1964).

$\pi^{\pm}$ FORM FACTORS

F_V, VECTOR FORM FACTOR

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.017±0.008 OUR AVERAGE					
0.014±0.009		[15] BOLOTOV	90B	SPEC	17 GeV $\pi^- \rightarrow e^- \overline{\nu}_e \gamma$
$0.023^{+0.015}_{-0.013}$	98	EGLI	89	SPEC	$\pi^+ \rightarrow e^+ \nu_e e^+ e^-$

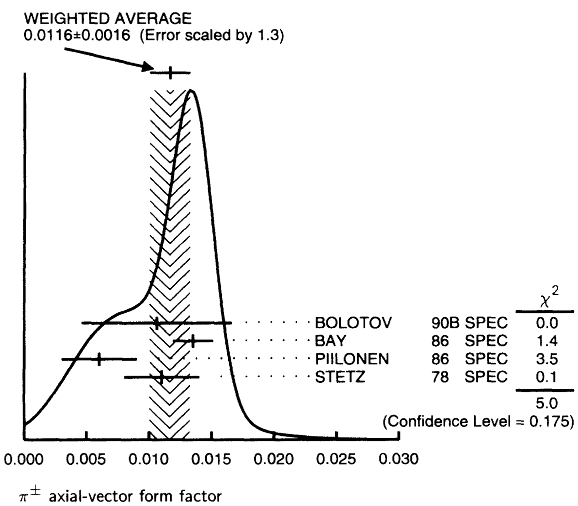
[15] BOLOTOV 90B only determines the absolute value.

F_A, AXIAL-VECTOR FORM FACTOR

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0116±0.0016 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.				
0.0106±0.0060		[16] BOLOTOV	90B	SPEC	17 GeV $\pi^- \rightarrow e^- \overline{\nu}_e \gamma$
0.0135±0.0016		[16] BAY	86	SPEC	$\pi^+ \rightarrow e^+ \nu \gamma$
0.006 ±0.003		[16] PIILONEN	86	SPEC	$\pi^+ \rightarrow e^+ \nu \gamma$
0.011 ±0.003		[16,17] STETZ	78	SPEC	$\pi^+ \rightarrow e^+ \nu \gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.021^{+0.011}_{-0.013}$	98	EGLI	89	SPEC	$\pi^+ \rightarrow e^+ \nu_e e^+ e^-$

[16] Using the vector form factor from CVC prediction $F_V = 0.0259 \pm 0.0005$. Only the absolute value of F_A is determined.

[17] The result of STETZ 78 has a two-fold ambiguity. We take the solution compatible with later determinations.



R, SECOND AXIAL-VECTOR FORM FACTOR

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.059^{+0.009}_{-0.008}}$	98	EGLI	89	SPEC	$\pi^+ \rightarrow e^+ \nu_e e^+ e^-$

REFERENCES FOR $\pi^{\pm}$

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1988 edition Physics Letters **B204** (1988).

DAUM 91 PL B265 425 +Frosch, Herter, Janousch, Kettle (PSI)
BOLOTOV 90B PL B243 308 +Gninenko, Djilkibaev, Isakov+ (INRM)
EGLI 89 PL B222 533 +Engfer, Grab, Hermes, Kraus+ (SINDRUM Collab.)
Also 86 PL B175 97 Egli, Engfer, Grab, Hermes+ (AACH, ETH, SIN, ZURI)
PDG 88 PL B204 Yost, Barnett+ (LBL+)
PICCIOTTO 88 PR D37 1131 +Ahmad, Britton, Bryman, Clifford+ (TRIU, CNRC)
COHEN 87 RMP 59 1121 +Taylor (RISC, NBS)
KORENCHE... 87 SJNP 46 192 Korenchenko, Kostin, Mzhaviya+ (JINR)
Translated from YAF 46 313.
BAY 86 PL B174 445 +Ruegger, Gabioud, Joseph, Loude+ (LAUS, ZURI)
BRYMAN 86 PR D33 1211 +Dubois, Macdonald, Numao+ (TRIU, CNRC)
Also 83 PRL 50 7 Bryman, Dubois, Numao, Olaniya+ (TRIU, CNRC)
JECKELMAN 86 PRL 56 1444 +Nakada, Beer+ (ETH, FRIB)
PIILONEN 86 PRL 57 1402 +Bolton, Cooper, Frank+ (LANL, TEMP, CHIC)
MCFARLANE 85 PR D32 547 +Auerbach, Gaille+ (TEMP, LANL)
ABELA 84 PL 146B 431 +Daum, Eaton, Frosch, Jost, Kettle+ (SIN)
Also 78 PL 74B 126 Daum, Eaton, Frosch, Hirschmann+ (SIN)
Also 79 PR D20 2692 Daum, Eaton, Frosch, Hirschmann+ (SIN)
FETSCHER 84 PL 140B 117 (ETH)
ABELA 83 NP A395 413 +Backenstoss, Kunold, Simons+ (BASL, KARL)
CARR 83 PRL 51 627 +Gidal, Gobbi, Jodidio, Oram+ (LBL, NWES, TRIU)
COOPER 82 PL 112B 97 +Guy, Michette, Tyndel, Venus (RL)
LU 80 PRL 45 1066 +Delker, Dugan, Wu, Caffrey+ (YALE, COLU, JHU)
STETZ 78 NP B138 285 +Carroll, Ortendahl, Perez-Mendez+ (LBL, UCLA)
CARTER 76 PRL 37 1380 +Dixit, Sundaresan+ (CARL, CNRC, CHIC, CIT)
KORENCHE... 76B JETP 44 35 Korenchenko, Kostin, Micelmacher+ (JINR)
Translated from ZETF 71 69.
MARUSHEN... 76 JETPL 23 72 Marushenko, Mezentsev, Petrunin+ (PINP)
Translated from ZETFP 23 80.
Also 76 Private Comm. Shafer (FNAL)
Also 78 Private Comm. Smirnov (PINP)
DUNAITSEV 73 SJNP 16 292 +Prokoshkin, Razuvaev+ (SERP)
Translated from YAF 16 524.
AYRES 71 PR D3 1051 +Cormack, Greenberg, Kenney+ (LRL, UCSB)
Also 67 PR 157 1288 Ayres, Caldwell, Greenberg, Kenney, Kurz+ (LRL)
Also 68 PRL 21 261 Ayres, Cormack, Greenberg+ (LRL, UCSB)
Also 69 UCRL 18369 Thesis Ayres (LRL)
Also 69 PRL 23 1267 Greenberg, Ayres, Cormack+ (LRL, UCSB)
KORENCHE... 71 SJNP 13 189 Korenchenko, Kostin, Micelmacher+ (JINR)
Translated from YAF 13 339.
BOOTH 70 PL 32B 723 +Johnson, Williams, Wormald (LIVP)
DEPOMMIER 68 NP B4 189 +Duclos, Heintze, Kleinknecht+ (CERN)
PETRUKHIN 68 JINR P1 3862 +Rykalin, Khazins, Cisek (JINR)
HYMAN 67 PL 25B 376 +Loken, Pewitt, McKenzie+ (ANL, CMU, NWES)
NORDBERG 67 PL 24B 594 +Lobkowicz, Burman (ROCH)
BARDON 66 PRL 16 775 +Dore, Dorfan, Krieger+ (COLU)
KINSEY 66 PR 144 1132 +Lobkowicz, Nordberg (ROCH)
LOBKOWICZ 66 PRL 17 548 +Melissinos, Nagashima+ (ROCH, BNL)
BACASTOW 65 PR 139B 407 +Ghesquiere, Wiegand, Larsen (LRL, SLAC)
BERTRAM 65 PR 139B 617 +Meyer, Carrigan+ (MICH, CMU)
DUNAITSEV 65 JETP 20 58 +Petrukhin, Prokoshkin+ (JINR)
Translated from ZETF 47 84.
ECKHAUSE 65 PL 19 348 +Harris, Shuler+ (WILL)
BARTLETT 64 PR 136B 1452 +Devons, Meyer, Rosen (COLU)
DICAPUA 64 PR 133B 1333 +Garland, Pondrom, Strelzoff (COLU)
Also 86 Private Comm. Pondrom (WISC)
DEPOMMIER 63 PL 5 61 +Heintze, Rubbia, Soergel (CERN)
DEPOMMIER 63B PL 7 285 +Heintze, Rubbia, Soergel (CERN)
ANDERSON 60 PR 119 2050 +Fujii, Miller+ (EFI)
CASTAGNOLI 58 PR 112 1779 +Muchnik (ROMA)

π^0

$I^G(J^{PC}) = 1^-(0^{-+})$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** (1988).

π^0 MASS

The fit uses the $\pi^{\pm}$ and π^0 mass and mass difference measurements.

VALUE (MeV)	DOCUMENT ID
134.9743±0.0008 OUR FIT	Error includes scale factor of 1.5.

$\pi^{\pm} - \pi^0$ MASS DIFFERENCE

The fit uses the $\pi^{\pm}$ and π^0 mass and mass difference measurements. Measurements with an error > 0.01 MeV have been omitted from this Listing.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4.5936 ±0.0005 OUR FIT				
4.5936 ±0.0005 OUR AVERAGE				
4.59364±0.00048	CRAWFORD	91	CNTR	$\pi^- p \rightarrow \pi^0 n$, n TOF
4.5930 ±0.0013	CRAWFORD	86	CNTR	$\pi^- p \rightarrow \pi^0 n$, n TOF
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.59366±0.00048	CRAWFORD	88B	CNTR	See CRAWFORD 91
4.6034 ±0.0052	VASILEVSKY	66	CNTR	
4.6056 ±0.0055	CZIRR	63	CNTR	

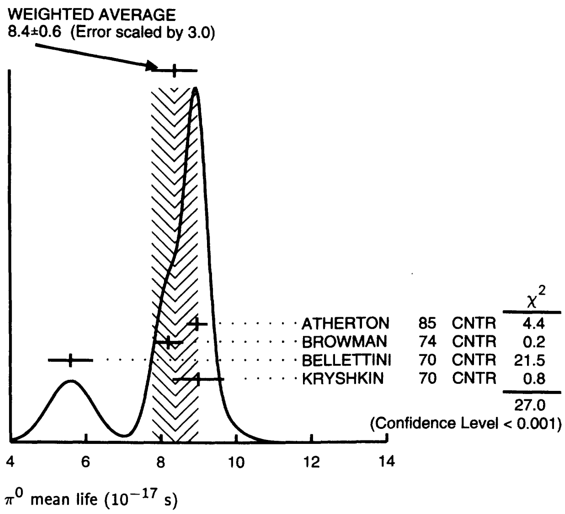
π^0 MEAN LIFE

Measurements with an error $> 1 \times 10^{-17}$ s have been omitted.

VALUE (10^{-17} s)	EVTS	DOCUMENT ID		TECN	COMMENT
8.4 ±0.6 OUR AVERAGE	Error includes scale factor of 3.0. See the ideogram below.				
8.97±0.22±0.17		ATHERTON	85	CNTR	
8.2 ±0.4		[1] BROWMAN	74	CNTR	Primakoff effect
5.6 ±0.6		BELLETTINI	70	CNTR	Primakoff effect
9 ±0.68		KRYSHKIN	70	CNTR	Primakoff effect
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.4 ±0.5 ±0.5	1182	[2] WILLIAMS	88	CBAL	$e^+e^- \rightarrow e^+e^-\pi^0$

[1] BROWMAN 74 gives a π^0 width $\Gamma = 8.02 \pm 0.42$ eV. The mean life is $\hbar/\Gamma$.

[2] WILLIAMS 88 gives $\Gamma(\gamma\gamma) = 7.7 \pm 0.5 \pm 0.5$ eV. We give here $\tau = \hbar/\Gamma$(total).



π^0 DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	2γ		(98.798 ± 0.032) %	S=1.1
Γ_2	$e^+e^-\gamma$		$(\ 1.198\pm0.032)$ %	S=1.1
Γ_3	γ positronium		$(\ 1.82\ \pm0.29\ )\times10^{-9}$	
Γ_4	$e^+e^+e^-e^-$		$(\ 3.14\ \pm0.30\ )\times10^{-5}$	
Γ_5	e^+e^-		$<\ 1.3\ \ \times10^{-7}$	CL=90%
Γ_6	4γ		$<\ 2\ \ \times10^{-8}$	CL=90%
Γ_7	$\nu\overline{\nu}$		[a] $<\ 8.3\ \ \times10^{-7}$	CL=90%
Γ_8	$\nu_e\overline{\nu}_e$		$<\ 1.7\ \ \times10^{-6}$	CL=90%
Γ_9	$\nu_\mu\overline{\nu}_\mu$		$<\ 3.1\ \ \times10^{-6}$	CL=90%
Γ_{10}	$\nu_\tau\overline{\nu}_\tau$		$<\ 2.1\ \ \times10^{-6}$	CL=90%
	Charge conjugation (C) or Lepton Family number (LF) violating modes			
Γ_{11}	3γ	C	$<\ 3.1\ \ \times10^{-8}$	CL=90%
Γ_{12}	μ^+e^-	LF	$<\ 1.6\ \ \times10^{-8}$	CL=90%
Γ_{13}	$\mu^+e^-\ +\ e^-\mu^+$	LF		

[a] Astrophysical and cosmological arguments give limits of order 10^{-13}; see the Full Listings.

CONSTRAINED FIT INFORMATION

An overall fit to 2 branching ratios uses 4 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 1.9 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i\delta x_j\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−100	
x_4	−1	0
	x_1	x_2

π^0 BRANCHING RATIOS

$\Gamma(e^+e^-\gamma)/\Gamma(2\gamma)$ — Γ_2/Γ_1

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.213±0.033 OUR FIT Error includes scale factor of 1.1.					
1.213±0.030 OUR AVERAGE					
1.25 ±0.04		SCHARDT	81	SPEC	$\pi^-p\to n\pi^0$
1.166±0.047	3071	[3] SAMIOS	61	HBC	$\pi^-p\to n\pi^0$
1.17 ±0.15	27	BUDAGOV	60	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.196		JOSEPH	60	THEO	QED calculation

[3] SAMIOS 61 value uses a Panofsky ratio = 1.62.

$\Gamma(\gamma\text{ positronium})/\Gamma(2\gamma)$ — Γ_3/Γ_1

VALUE (units 10^{-9})	EVTS	DOCUMENT ID		TECN	COMMENT
1.84±0.29	277	AFANASYEV	90	CNTR	pC 70 GeV

$\Gamma(e^+e^+e^-e^-)/\Gamma(2\gamma)$ — Γ_4/Γ_1

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	COMMENT
3.18±0.30 OUR FIT					
3.18±0.30	146	[4] SAMIOS	62B	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.28		MIYAZAKI	73	THEO	QED calculation

[4] SAMIOS 62B value uses a Panofsky ratio = 1.62.

$\Gamma(e^+e^-)/\Gamma(2\gamma)$ — Γ_5/Γ_1

VALUE (units 10^{-7})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.3	90		NIEBUHR	89	SPEC	$\pi^-p\to\pi^0n$ at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<5.3	90		ZEPHAT	87	SPEC	$\pi^-p\to\pi^0n$ 0.3 GeV/c
1.7 ±0.6 ±0.3		59	FRANK	83	SPEC	$\pi^-p\to n\pi^0$
1.8 ±0.6		58	MISCHKE	82	SPEC	See FRANK 83
$2.23^{+2.40}_{-1.10}$	90	8	FISCHER	78B	SPRK	$K^+\to\pi^+\pi^0$

$\Gamma(4\gamma)/\Gamma_{\rm total}$ — Γ_6/Γ

VALUE (units 10^{-8})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 2	90		MCDONOUGH	88	CBOX	π^-p at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<160	90		BOLOTOV	86C	CALO	
<440	90	0	AUERBACH	80	CNTR	

$\Gamma(\nu\overline{\nu})/\Gamma_{\rm total}$ — Γ_7/Γ

The astrophysical and cosmological limits are many orders of magnitude lower, but we use the best laboratory limit for the Summary Tables.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 0.83	90		[5] ATIYA	91	CNTR	$K^+\to\pi^+\nu\nu'$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<\ 2.9\times10^{-7}$			[6] LAM	91		Cosmological limit
$<\ 3.2\times10^{-7}$			[7] NATALE	91		SN 1987A
< 6.5	90		DORENBOS...	88	CHRM	Beam dump, prompt ν
<24	90	0	[5] HERCZEG	81	RVUE	$K^+\to\pi^+\nu\nu'$

[5] This limit applies to all possible $\nu\nu'$ states as well as to other massless, weakly interacting states.

[6] LAM 91 considers the production of right-handed neutrinos produced from the cosmic thermal background at the temperature of about the pion mass through the reaction $\gamma\gamma\to\pi^0\to\nu\overline{\nu}$.

[7] NATALE 91 considers the excess energy-loss rate from SN 1987A if the process $\gamma\gamma\to\pi^0\to\nu\overline{\nu}$ occurs, permitted if the neutrinos have a right-handed component as pointed out in LAM 91 (and confirmed by Natale), there is a factor 4 error in the NATALE 91 published result (0.8×10^{-7}).

$\Gamma(\nu_e\overline{\nu}_e)/\Gamma_{\rm total}$ — Γ_8/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	COMMENT
<1.7	90	DORENBOS...	88	CHRM	Beam dump, prompt ν
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.1	90	[8] HOFFMAN	88	RVUE	Beam dump, prompt ν

[8] HOFFMAN 88 analyzes data from a 400-GeV BEBC beam-dump experiment.

$\Gamma(\nu_\mu\overline{\nu}_\mu)/\Gamma_{\rm total}$ — Γ_9/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	COMMENT
<3.1	90	[9] HOFFMAN	88	RVUE	Beam dump, prompt ν
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<7.8	90	DORENBOS...	88	CHRM	Beam dump, prompt ν

[9] HOFFMAN 88 analyzes data from a 400-GeV BEBC beam-dump experiment.

$\Gamma(\nu_\tau\overline{\nu}_\tau)/\Gamma_{\rm total}$ — Γ_{10}/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	COMMENT
<2.1	90	[10] HOFFMAN	88	RVUE	Beam dump, prompt ν
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.1	90	DORENBOS...	88	CHRM	Beam dump, prompt ν

[10] HOFFMAN 88 analyzes data from a 400-GeV BEBC beam-dump experiment.

$\Gamma(3\gamma)/\Gamma_{\rm total}$ — Γ_{11}/Γ

Forbidden by C invariance.

VALUE (units 10^{-8})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 3.1	90		MCDONOUGH	88	CBOX	π^-p at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 38	90	0	HIGHLAND	80	CNTR	
<150	90	0	AUERBACH	78	CNTR	
<490	90	0	[11] DUCLOS	65	CNTR	
<490	90		[11] KUTIN	65	CNTR	

[11] These experiments give $B(3\gamma/2\gamma) < 5.0\times10^{-6}$.

$\Gamma(\mu^+ e^-)/\Gamma_{total}$ — Γ_{12}/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-8})	CL%	DOCUMENT ID		TECN	COMMENT
<1.6	90	LEE	90	SPEC	$K^+ \to \pi^+ \mu^+ e^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<7.8	90	CAMPAGNARI	88	SPEC	See LEE 90

$[\Gamma(\mu^+ e^-) + \Gamma(e^- \mu^+)]/\Gamma_{total}$ — Γ_{13}/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-8})	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<14		HERCZEG	84	RVUE	$K^+ \to \pi^+ \mu e$
$< 2 \times 10^{-7}$		HERCZEG	84	THEO	$\mu^- \to e^-$ conversion
< 7	90	BRYMAN	82	RVUE	$K^+ \to \pi^+ \mu e$

π^0 ELECTROMAGNETIC FORM FACTOR

The amplitude for the process $\pi^0 \to e^+ e^- \gamma$ contains a form factor $F(x)$ at the $\pi^0 \gamma\gamma$ vertex, where $x = [m(e^+ e^-)/m(\pi^0)]^2$. The parameter a in the linear expansion $F(x) = 1 + ax$ is listed below.

LINEAR COEFFICIENT OF π^0 ELECTROMAGNETIC FORM FACTOR

VALUE			EVTS	DOCUMENT ID		TECN	COMMENT
+0.0326±0.0026			127	[12] BEHREND	91	CELL	$e^+ e^- \to e^+ e^- \pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •							
−0.11	±0.03	±0.08	32k	FONVIEILLE	89	SPEC	Radiation corr.
0.12	$^{+0.05}_{-0.04}$			[13] TUPPER	83	THEO	FISCHER 78 data
+0.10	±0.03		30k	[14] FISCHER	78	SPEC	Radiation corr.
+0.01	±0.11		2200	DEVONS	69	OSPK	No radiation corr.
−0.15	±0.10			KOBRAK	61	HBC	No radiation corr.
−0.24	±0.16		3071	SAMIOS	61	HBC	No radiation corr.

[12] BEHREND 91 estimates that the systematic error is of the same order of magnitude as the statistical error given here.
[13] TUPPER 83 is a theoretical analysis of FISCHER 78 including 2-photon exchange in the corrections.
[14] The FISCHER 78 error is statistical only. The result without radiation corrections is +0.05 ± 0.03.

REFERENCES FOR π^0

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1988 edition Physics Letters **B204** (1988).

ATIYA	91	PRL 66 2189	+Chiang, Frank, Haggerty+	(BNL, LANL, PRIN, TRIU)
BEHREND	91	ZPHY C49 401	+Criegee, Field, Franke+	(CELLO Collab.)
CRAWFORD	91	PR D43 46	+Daum, Frosch, Jost, Kettle+	(PSI, VIRG)
LAM	91	PR D44 3345	+Ng	(AST)
NATALE	91	PL B258 227		(CAMP)
AFANASYEV	90	PL B236 116	+Chvyrov, Karpukhin+	(JINR, MOSU, SERP)
Also	90B	SJNP 51 664	Afanasyev, Gorchakov, Karpukhin, Komarov+	(JINR)
		Translated from YAF 51 1040.		
LEE	90	PRL 64 165	+Alliegro, Campagnari+	(BNL, FNAL, PSI, WASH, YALE)
FONVIEILLE	89	PL B233 65	+Bensayah, Berthot, Bertin+	(PASC, CBER, SACL)
NIEBUHR	89	PR D40 2796	+Eichler, Felawka, Kozlowski+	(SINDRUM Collab.)
CAMPAGNARI	88	PRL 61 2062	+Alliegro, Chaloupka+	(BNL, FNAL, PSI, WASH, YALE)
CRAWFORD	88B	PL B213 391	+Daum, Frosch, Jost, Kettle, Marshall+	(PSI, VIRG)
DORENBOS...	88	ZPHY C40 497	Dorenbosch, Allaby, Amaldi, Barbiellini+	(CHARM Collab.)
HOFFMAN	88	PL B208 149		(LANL)
MCDONOUGH	88	PR D38 2121	+Highland, McFarlane, Bolton+	(TEMP, LANL, CHIC)
PDG	88	PL B204	Yost, Barnett+	(LBL+)
WILLIAMS	88	PR D38 1365	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
ZEPHAT	87	JP G13 1375	+Playfer, van Doesburg, Bressani+	(OMICRON Collab.)
BOLOTOV	86C	JETPL 43 520	+Gninenko, Dzhilkibaev, Isakov	(INRM)
		Translated from ZETFP 43 405.		
CRAWFORD	86	PRL 56 1043	+Daum, Frosch, Jost, Kettle+	(SIN, VIRG)
ATHERTON	85	PL 158B 81	+Bovet, Coet+	(CERN, ISU, LUND, LPTP, EFI)
HERCZEG	84	PR D29 1954	+Hoffman	(LANL)
FRANK	83	PR D28 423	+Hoffman, Mischke, Moir+	(LANL, ARZS)
TUPPER	83	PR D28 2905	+Grose, Samuel	(OKSU)
BRYMAN	82	PR D26 2538		(TRIU)
MISCHKE	82	PRL 48 1153	+Frank, Hoffman, Moir, Sarracino+	(LANL, ARZS)
HERCZEG	81	PL 100B 347	+Hoffman	(LANL)
SCHARDT	81	PR D23 639	+Frank, Hoffmann, Mischke, Moir+	(ARZS, LANL)
AUERBACH	80	PL 90B 317	+Haik, Highland, McFarlane, Macek+	(TEMP, LASL)
HIGHLAND	80	PRL 44 628	+Auerbach, Haik, McFarlane, Macek+	(TEMP, LASL)
AUERBACH	78	PRL 41 275	+Highland, Johnson+	(TEMP, LASL)
FISCHER	78	PL 73B 359	+Extermann, Guisan, Mermod+	(GEVA, SACL)
FISCHER	78B	PL 73B 364	+Extermann, Guisan, Mermod+	(GEVA, SACL)
BROWMAN	74	PRL 33 1400	+Dewire, Gittelman, Hanson+	(CORN, BING)
MIYAZAKI	73	PR D8 2051	+Takasugi	(TOKY)
BELLETTINI	70	NC 66A 243	+Bemporad, Lubelsmey+	(PISA, BONN)
KRYSHKIN	70	JETP 30 1037	+Sterligov, Usov	(TMSK)
		Translated from ZETF 57 1917.		
DEVONS	69	PR 184 1356	+Nemethy, Nissim-Sabat, Capua+	(COLU, ROMA)
VASILEVSKY	66	PL 23 281	+Vishnyakov, Dunaitsev+	(JINR)
DUCLOS	65	PL 19 253	+Freytag, Heintze+	(CERN, HEID)
KUTIN	65	JETPL 2 243	+Petrukhin, Prokoshkin	(JINR)
		Translated from unknown journal.		
CZIRR	63	PR 130 341		(LRL)
SAMIOS	62B	PR 126 1844	+Plano, Prodell+	(COLU, BNL)
KOBRAK	61	NC 20 1115		(EFI)
SAMIOS	61	PR 121 275		(COLU, BNL)
BUDAGOV	60	JETP 11 755	+Viktor, Dzhelepov, Ermolov+	(JINR)
		Translated from ZETF 38 1047.		
JOSEPH	60	NC 16 997		(EFI)

η

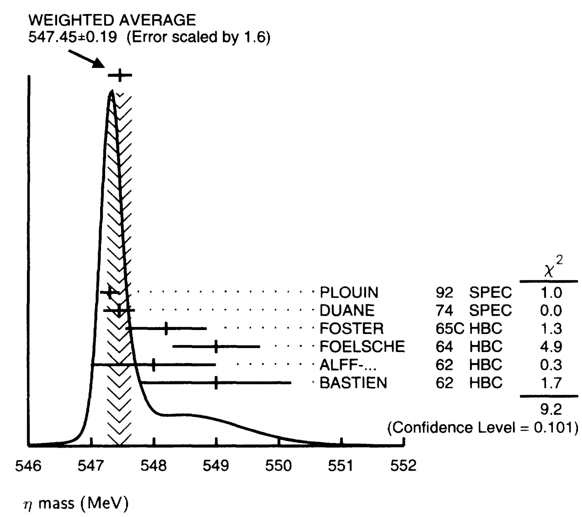
$I^G(J^{PC}) = 0^+(0^{-+})$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** (1988).

η MASS

Measurements with an error $\geq$ 2 MeV are omitted from the average.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
547.45±0.19 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.				
547.30±0.15		PLOUIN	92	SPEC	$dp \to \eta\, ^3$He
547.45±0.25		DUANE	74	SPEC	$\pi^- p \to n$ neutrals
548.2 ±0.65		FOSTER	65C	HBC	
549.0 ±0.7	148	FOELSCHE	64	HBC	
548.0 ±1.0	91	ALFF-...	62	HBC	
549.0 ±1.2	53	BASTIEN	62	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
555.0 ±2.0	250	JAMES	66	HBC	
552.0 ±3.0	325	KRAEMER	64	DBC	
549.3 ±2.9		DELCOURT	63	CNTR	
546.0 ±4.0	35	PICKUP	62	HBC	



η WIDTH

This is the partial decay rate $\Gamma(\eta \to \gamma\gamma)$ divided by the fitted branching fraction for that mode. See the Note on the Decay Rate $\Gamma(\eta \to \gamma\gamma)$, below.

VALUE (keV)	DOCUMENT ID
1.19±0.11 OUR FIT	Error includes scale factor of 1.8.

η DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	neutral modes		(70.8 ±0.8) %	S=1.2
Γ_2	2γ	[a]	(38.9 ±0.5) %	S=1.2
Γ_3	$3\pi^0$		(31.9 ±0.4) %	S=1.2
Γ_4	$\pi^0 2\gamma$		(7.1 ±1.4) $\times 10^{-4}$	
Γ_5	charged modes		(29.2 ±0.8) %	S=1.2
Γ_6	$\pi^+ \pi^- \pi^0$		(23.6 ±0.6) %	S=1.2
Γ_7	$\pi^+ \pi^- \gamma$		(4.88±0.15) %	S=1.2
Γ_8	$e^+ e^- \gamma$		(5.0 ±1.2) $\times 10^{-3}$	
Γ_9	$\mu^+ \mu^- \gamma$		(3.1 ±0.4) $\times 10^{-4}$	
Γ_{10}	$e^+ e^-$		< 3 $\times 10^{-4}$	CL=90%
Γ_{11}	$\mu^+ \mu^-$		(6.5 ±2.1) $\times 10^{-6}$	
Γ_{12}	$\pi^+ \pi^- e^+ e^-$		(1.3 $^{+1.3}_{-0.8}$) $\times 10^{-3}$	
Γ_{13}	$\pi^+ \pi^- 2\gamma$		< 2.1 $\times 10^{-3}$	
Γ_{14}	$\pi^+ \pi^- \pi^0 \gamma$		< 6 $\times 10^{-4}$	CL=90%
Γ_{15}	$\pi^0 \mu^+ \mu^- \gamma$		< 3 $\times 10^{-6}$	CL=90%

Charge conjugation (*C*), Parity (*P*), or Charge conjugation × Parity (*CP*) violating modes

Γ_{16}	3γ	C	< 5	$\times 10^{-4}$	
Γ_{17}	$\pi^+\pi^-$	P,CP	< 1.5	$\times 10^{-3}$	
Γ_{18}	$\pi^0 e^+ e^-$	C	< 4	$\times 10^{-5}$	CL=90%
Γ_{19}	$\pi^0 \mu^+ \mu^-$	C	< 5	$\times 10^{-6}$	CL=90%

[a] See the Note on the Decay Rate $\Gamma(\eta \to \gamma\gamma)$, below.

CONSTRAINED FIT INFORMATION

An overall fit to a partial width and 14 branching ratios uses 39 measurements and one constraint to determine 9 parameters. The overall fit has a $\chi^2 = 30.8$ for 31 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_3	57							
x_4	3	3						
x_6	−88	−84	−5					
x_7	−77	−74	−5	81				
x_8	−11	−10	−1	−3	−4			
x_9	0	0	0	0	0	0		
x_{12}	−3	−3	0	−13	−10	−2	0	
Γ	−13	−8	0	12	10	1	0	0
	x_2	x_3	x_4	x_6	x_7	x_8	x_9	x_{12}

	Mode	Rate (keV)	Scale factor
Γ_2	2γ	[a] 0.46 ± 0.04	1.8
Γ_3	$3\pi^0$	0.381 ± 0.035	1.8
Γ_4	$\pi^0 2\gamma$	$(8.5 \pm 1.9) \times 10^{-4}$	1.1
Γ_6	$\pi^+\pi^-\pi^0$	0.283 ± 0.028	1.7
Γ_7	$\pi^+\pi^-\gamma$	0.058 ± 0.006	1.7
Γ_8	$e^+e^-\gamma$	0.0059 ± 0.0015	1.1
Γ_9	$\mu^+\mu^-\gamma$	$(3.7 \pm 0.6) \times 10^{-4}$	1.1
Γ_{12}	$\pi^+\pi^-e^+e^-$	$0.0016^{+0.0015}_{-0.0010}$	

NOTE ON THE DECAY WIDTH $\Gamma(\eta \to \gamma\gamma)$

(by N.A. Roe, Lawrence Berkeley Laboratory)

In the measurements of $\Gamma(\eta \to \gamma\gamma)$ listed below, the results from two-photon production disagree with those from Primakoff production. Since the 1990 edition, one new two-photon measurement has been reported by MD-1; it is consistent with previous two-photon results, though the errors are somewhat larger. The weighted average of the two-photon measurements is 0.510 ± 0.026 keV, to be compared with the Primakoff-production measurement of BROWMAN 74B, 0.324 ± 0.046 keV.

In the two-photon measurements, η's are produced in the QED process $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\eta$. The calculation of the rate is believed to be well understood. The uncertainty due to the virtual photon form factor is small; WILLIAMS 88 quotes an uncertainty of 0.2% from this source. Backgrounds to the η signal from beam-gas interactions and other two-photon interactions with missing particles are also small.

In the Primakoff experiments, η's are produced by the interaction of a real photon with a virtual photon in the Coulomb field of the nucleus. There is coherent background from strong production of η's in the nuclear hadronic field, and interference between the strong and Primakoff production amplitudes. The angular dependences of the Primakoff signal and the background are different, allowing $\Gamma(\eta \to \gamma\gamma)$ to be extracted from a fit to the angular distribution. In the best fit to their data, BEMPORAD 67 found the coherent hadronic background to be consistent with zero. BROWMAN 74B had a wider range of photon energies, a higher maximum energy, better angular resolution, and higher statistics. They found a significant contribution from the hadronic background, especially at lower energies. BROWMAN 74B also reanalyzed the data of BEMPORAD 67 and found that it was compatible with their fit, including background terms. This suggests that the background was underestimated by BEMPORAD 67, and we consider their result to be superseded by that of BROWMAN 74B.

There remains the disagreement between the two-photon results and the result of BROWMAN 74B. The errors assigned by BROWMAN 74B include a 5.3% statistical error, a 12.2% systematic error for uncertainty in the accepted photon spectrum, and a 2.5% systematic error for uncertainty in the nuclear parameters used in the calculation of the Primakoff and nuclear form factors. The Primakoff form factor F_C is a function of the momentum transfer q and the production angle θ. As $q^2 \to 0$, the uncertainty in F_C due to the q^2 dependence vanishes. The minimum q^2 in this experiment ranged from -680 MeV^2 at the lowest energy to -174 MeV^2 at the highest. In this range, the result is sensitive to details in the calculation of F_C, but it is difficult to estimate the systematic error of this dependence. Another possible source of systematic error is in the phase of the interference term, ϕ. This was a free parameter in the fit, but was not well determined by the data because the interference contribution peaks in the same angular region as the Primakoff signal and so cannot be unambiguously separated by an angular fit. A reanalysis of the data would be necessary to determine whether any of these factors was overlooked in the determination of the systematic error.

Using the same apparatus, Browman *et al.*[1] measured $\Gamma(\pi^0 \to \gamma\gamma)$ to be 7.92 ± 0.42 eV, in good agreement with our world average of 7.7 ± 0.6 eV. (Our average includes the measurement of Browman *et al.*, but is dominated by a decay-length measurement by Atherton *et al.*[2] The error on the average involves a scale factor S=3.0 due to one outlying measurement.) However, the uncertainty due to F_C is reduced at lower momentum transfers, and q^2 was on the order of 100 times smaller in the π^0 measurement. The signal-to-background ratio is also larger, making the fit less sensitive to nuclear production.

A possible source of common systematic error in the two-photon experiments is the calculation of the two-photon luminosity function. However, WILLIAMS 88 measured the two-photon width of the π^0 as well as of the η, and their result, $7.7 \pm 0.5 \pm 0.5$ eV, is consistent with the world average quoted above.

To summarize, the two-photon measurements seem more reliable than the best Primakoff-production measurement. However, we include the latter in our average as there is no compelling reason to exclude it. The result, $\Gamma(\eta \to \gamma\gamma) = 0.46 \pm 0.04$ keV, is about one standard deviation from the average using only the two-photon measurements, 0.510 ± 0.026 keV, and the error is larger, due to the scale factor.

References

1. A. Browman *et al.*, Phys. Rev. Lett. **33**, 1400 (1974).
2. H.W. Atherton *et al.*, Phys. Lett. **158B**, 81 (1985).

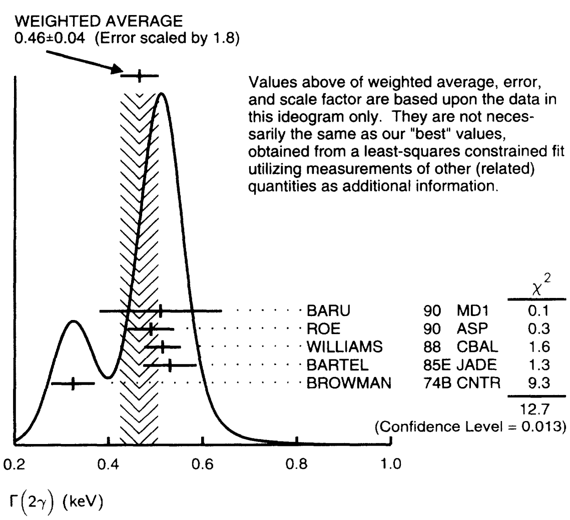
η DECAY RATES

$\Gamma(2\gamma)$ — Γ_2

See the above Note on the Decay Rate $\Gamma(\eta \to \gamma\gamma)$.

VALUE (keV)	EVTS	DOCUMENT ID	TECN	COMMENT
0.46 ±0.04 OUR FIT Error includes scale factor of 1.8.				
0.46 ±0.04 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.				
0.51 ±0.12 ±0.05	36	BARU 90	MD1	$e^+e^- \to e^+e^-\eta$
0.490±0.010±0.048	2287	ROE 90	ASP	$e^+e^- \to e^+e^-\eta$
0.514±0.017±0.035	1295	WILLIAMS 88	CBAL	$e^+e^- \to e^+e^-\eta$
0.53 ±0.04 ±0.04		BARTEL 85E	JADE	$e^+e^- \to e^+e^-\eta$
0.324±0.046		BROWMAN 74B	CNTR	Primakoff effect
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.64 ±0.14 ±0.13		AIHARA 86	TPC	$e^+e^- \to e^+e^-\eta$
0.56 ±0.16	56	WEINSTEIN 83	CBAL	$e^+e^- \to e^+e^-\eta$
1.00 ±0.22		[1] BEMPORAD 67	CNTR	Primakoff effect

[1] BEMPORAD 67 gives $\Gamma(2\gamma) = 1.21 \pm 0.26$ keV assuming $\Gamma(2\gamma)/\Gamma(\text{total}) = 0.314$. Bemporad private communication gives $\Gamma(2\gamma)^2/\Gamma(\text{total}) = 0.380 \pm 0.083$. We evaluate this using $\Gamma(2\gamma)/\Gamma(\text{total}) = 0.38 \pm 0.01$. Not included in average because the uncertainty resulting from the separation of the coulomb and nuclear amplitudes has apparently been underestimated.



η BRANCHING RATIOS

$\Gamma(\text{neutral modes})/\Gamma_{\text{total}}$ — $(\Gamma_2+\Gamma_3+\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.708±0.008 OUR FIT Error includes scale factor of 1.2.				
0.705±0.008	16k	BASILE 71D	CNTR	MM spectrometer
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.79 ±0.08		BUNIATOV 67	OSPK	

$\Gamma(2\gamma)/\Gamma(\text{neutral modes})$ — $\Gamma_2/(\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.5491±0.0028 OUR FIT				
0.549 ±0.004 OUR AVERAGE				
0.549 ±0.004		ALDE 84	GAM2	
0.535 ±0.018		BUTTRAM 70	OSPK	
0.59 ±0.033		BUNIATOV 67	OSPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.52 ±0.09	88	ABROSIMOV 80	HLBC	
0.60 ±0.14	113	KENDALL 74	OSPK	
0.57 ±0.09		STRUGALSKI 71	HLBC	
0.579 ±0.052		FELDMAN 67	OSPK	
0.416 ±0.044		DIGIUGNO 66	CNTR	Error doubled
0.44 ±0.07		GRUNHAUS 66	OSPK	
0.39 ±0.06		[2] JONES 66	CNTR	

[2] This result from combining cross sections from two different experiments.

$\Gamma(3\pi^0)/\Gamma(\text{neutral modes})$ — $\Gamma_3/(\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.4499±0.0028 OUR FIT				
0.450 ±0.004 OUR AVERAGE				
0.450 ±0.004		ALDE 84	GAM2	
0.439 ±0.024		BUTTRAM 70	OSPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.44 ±0.08	75	ABROSIMOV 80	HLBC	
0.32 ±0.09		STRUGALSKI 71	HLBC	
0.41 ±0.033		BUNIATOV 67	OSPK	Not indep. of $\Gamma(2\gamma)/\Gamma(\text{neutral modes})$
0.177 ±0.035		FELDMAN 67	OSPK	
0.209 ±0.054		DIGIUGNO 66	CNTR	Error doubled
0.29 ±0.10		GRUNHAUS 66	OSPK	

$\Gamma(3\pi^0)/\Gamma(2\gamma)$ — Γ_3/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
0.819±0.009 OUR FIT			
0.84 ±0.06 OUR AVERAGE			
0.91 ±0.14	COX 70B	HBC	
0.75 ±0.09	DEVONS 70	OSPK	
0.88 ±0.16	BALTAY 67D	DBC	
1.1 ±0.2	CENCE 67	OSPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.25 ±0.39	BACCI 63	CNTR	Inverse BR reported

$\Gamma(\pi^0 2\gamma)/\Gamma(\text{neutral modes})$ — $\Gamma_4/(\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID	TECN
0.00100±0.00020 OUR FIT		
0.0010 ±0.0002	ALDE 84	GAM2

$\Gamma(\pi^0 2\gamma)/\Gamma_{\text{total}}$ — Γ_4/Γ

These results are summarized in the review by LANDSBERG 85.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
7.1±1.4 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
7.1±1.7			[3] ALDE 84	GAM2	$\pi^- p \to \eta n$
9.5±2.3		70	BINON 82	GAM2	See ALDE 84
<30	90	0	DAVYDOV 81	GAM2	$\pi^- p \to \eta n$

[3] Not independent of the ALDE 84 result $\Gamma(\pi^0 2\gamma)/\Gamma(\text{neutral modes})$.

$\Gamma(\text{neutral modes})/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^+\pi^-\gamma) + \Gamma(e^+e^-\gamma)]$ — $(\Gamma_2+\Gamma_3+\Gamma_4)/(\Gamma_6+\Gamma_7+\Gamma_8)$

VALUE	EVTS	DOCUMENT ID	TECN
2.44±0.09 OUR FIT Error includes scale factor of 1.2.			
2.64±0.23		BALTAY 67B	DBC
• • • We do not use the following data for averages, fits, limits, etc. • • •			
4.5 ±1.0	280	[4] JAMES 66	HBC
3.20±1.26	53	[4] BASTIEN 62	HBC
2.5 ±1.0	10	[4] PICKUP 62	HBC

[4] These experiments not used in the averages as they do not separate clearly $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^+\pi^-\gamma$ from each other. The reported values thus probably contain some unknown fraction of $\eta \to \pi^+\pi^-\gamma$.

$\Gamma(2\gamma)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^+\pi^-\gamma) + \Gamma(e^+e^-\gamma)]$ — $\Gamma_2/(\Gamma_6+\Gamma_7+\Gamma_8)$

VALUE	EVTS	DOCUMENT ID	TECN
1.34±0.05 OUR FIT Error includes scale factor of 1.2.			
1.1 ±0.4 OUR AVERAGE			
1.51±0.93	75	KENDALL 74	OSPK
0.99±0.48		CRAWFORD 63	HBC

$\Gamma(\text{neutral modes})/\Gamma(\pi^+\pi^-\pi^0)$ — $(\Gamma_2+\Gamma_3+\Gamma_4)/\Gamma_6$

VALUE	EVTS	DOCUMENT ID	TECN
2.99±0.11 OUR FIT Error includes scale factor of 1.2.			
3.26±0.30 OUR AVERAGE			
2.54±1.89	74	KENDALL 74	OSPK
3.4 ±1.1	29	AGUILAR-... 72B	HBC
2.83±0.80	70	[5] BLOODWO... 72B	HBC
3.6 ±0.6	244	FLATTE 67B	HBC
2.89±0.56		ALFF-... 66	HBC
3.6 ±0.8	50	KRAEMER 64	DBC
3.8 ±1.1		PAULI 64	DBC

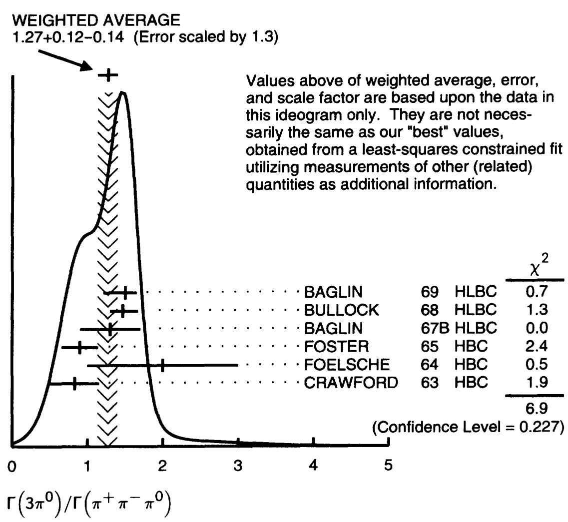
[5] Error increased from published value 0.5 by Bloodworth (private communication).

$\Gamma(2\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_2/Γ_6

VALUE	EVTS	DOCUMENT ID		TECN
1.64±0.06 OUR FIT Error includes scale factor of 1.2.				
1.69±0.21 OUR AVERAGE				
1.72±0.25	401	BAGLIN	69	HLBC
1.61±0.39		FOSTER	65	HBC

$\Gamma(3\pi^0)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_3/Γ_6

VALUE	EVTS	DOCUMENT ID		TECN
1.35±0.05 OUR FIT Error includes scale factor of 1.2.				
$1.27^{+0.12}_{-0.14}$ OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.				
$1.50^{+0.15}_{-0.29}$	199	BAGLIN	69	HLBC
$1.47^{+0.20}_{-0.17}$		BULLOCK	68	HLBC
1.3 ±0.4		BAGLIN	67B	HLBC
0.90±0.24		FOSTER	65	HBC
2.0 ±1.0		FOELSCHE	64	HBC
0.83±0.32		CRAWFORD	63	HBC



$\Gamma(\pi^+\pi^-\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_7/Γ_6

VALUE	EVTS	DOCUMENT ID		TECN
0.207±0.004 OUR FIT Error includes scale factor of 1.1.				
0.207±0.004 OUR AVERAGE Error includes scale factor of 1.1.				
0.209±0.004	18k	THALER	73	ASPK
0.201±0.006	7250	GORMLEY	70	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.28 ±0.04		BALTAY	67B	DBC
0.25 ±0.035		LITCHFIELD	67	DBC
0.30 ±0.06		CRAWFORD	66	HBC
0.196±0.041		FOSTER	65C	HBC

$\Gamma(e^+e^-\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_8/Γ_6

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
2.1±0.5 OUR FIT					
2.1±0.5	80	JANE	75B	OSPK	See the erratum

$\Gamma(\mu^+\mu^-\gamma)/\Gamma_{total}$ Γ_9/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
3.1±0.4 OUR FIT					
3.1±0.4	600	DZHELYADIN	80	SPEC	$\pi^- p \to \eta n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.5±0.75	100	BUSHNIN	78	SPEC	See DZHELYADIN 80

$\Gamma(e^+e^-)/\Gamma_{total}$ Γ_{10}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<3	90	DAVIES	74	RVUE	Uses ESTEN 67

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ Γ_{11}/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.65±0.21		27	DZHELYADIN	80B	SPEC	$\pi^- p \to \eta n$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2	95	0	WEHMANN	68	OSPK	

$\Gamma(\mu^+\mu^-)/\Gamma(2\gamma)$ Γ_{11}/Γ_2

VALUE (units 10^{-5})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
5.9±2.2	HYAMS	69	OSPK

$\Gamma(\pi^+\pi^-e^+e^-)/\Gamma(\pi^+\pi^-\gamma)$ Γ_{12}/Γ_7

VALUE	EVTS	DOCUMENT ID		TECN
$0.027^{+0.026}_{-0.017}$ OUR FIT				
0.026±0.026	1	GROSSMAN	66	HBC

$\Gamma(\pi^+\pi^-e^+e^-)/\Gamma_{total}$ Γ_{12}/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN
$0.13^{+0.13}_{-0.08}$ OUR FIT			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.7	RITTENBERG	65	HBC

$\Gamma(\pi^+\pi^-2\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_{13}/Γ_6

VALUE	CL%	DOCUMENT ID		TECN
<0.009		PRICE	67	HBC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.016	95	BALTAY	67B	DBC

$\Gamma(\pi^+\pi^-\pi^0\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_{14}/Γ_6

VALUE (units 10^{-2})	CL%	EVTS	DOCUMENT ID		TECN
<0.24	90	0	THALER	73	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.7	90		ARNOLD	68	HLBC
<1.6	95		BALTAY	67B	DBC
<7.0			FLATTE	67	HBC
<0.9			PRICE	67	HBC

$\Gamma(\pi^0\mu^+\mu^-\gamma)/\Gamma_{total}$ Γ_{15}/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	COMMENT
<3	90	DZHELYADIN	81	SPEC	$\pi^- p \to \eta n$

$\Gamma(3\gamma)/\Gamma(\text{neutral modes})$ $\Gamma_{16}/(\Gamma_2+\Gamma_3+\Gamma_4)$

Forbidden by C invariance.

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN
<7	95	ALDE	84	GAM2

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ Γ_{17}/Γ

Violates P and CP invariance.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN
<0.15	0	THALER	73	ASPK

$\Gamma(\pi^0e^+e^-)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_{18}/Γ_6

A single photon process forbidden by C parity.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN
< 1.9	90		JANE	75	OSPK
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 42	90		BAGLIN	67	HLBC
< 16	90	0	BILLING	67	HLBC
< 77		0	FOSTER	65B	HBC
<110			PRICE	65	HBC

$\Gamma(\pi^0e^+e^-)/\Gamma_{total}$ Γ_{18}/Γ

A single photon process forbidden by C parity.

VALUE (units 10^{-2})	CL%	EVTS	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.016	90	0	MARTYNOV	76	HLBC
<0.084	90		BAZIN	68	DBC
<0.7			RITTENBERG	65	HBC

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{total}$ Γ_{19}/Γ

A single photon process forbidden by C parity.

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<0.05	90	DZHELYADIN	81	SPEC	$\pi^- p \to \eta n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<5		WEHMANN	68	OSPK	

NOTE ON η DECAY PARAMETERS

C violation in η decays

A number of experiments have looked for charge asymmetries in $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^+\pi^-\gamma$ decays. Any difference between the π^+ and π^- spectra in either decay would indicate C violation in electromagnetic interactions. In sections that follow this Note, we list measurements of the following parameters:

(a) The left-right asymmetry

$$A = (N^+ - N^-)/(N^+ + N^-)\,,$$

where N^+ is the number of events in which the π^+ energy in the η rest frame is greater than the π^- energy, etc.

(b) For the decay $\eta \to \pi^+\pi^-\pi^0$, the sextant asymmetry

$$A_s = \frac{N_1 + N_3 + N_5 - N_2 - N_4 - N_6}{N_1 + N_2 + N_3 + N_4 + N_5 + N_6} ,$$

where the N_i are the numbers of events in sextants of the Dalitz plot; see, for example, Layter *et al.*[1] A_s is sensitive to an I=0 C-violating final state.

(c) For the decay $\eta \to \pi^+\pi^-\pi^0$, the quadrant asymmetry

$$A_q = \frac{N_1 + N_3 - N_2 - N_4}{N_1 + N_2 + N_3 + N_4} ,$$

where the N_i are numbers of events in quadrants of the Dalitz plot. A_q is sensitive to an I=2 C-violating final state.

(d) For the decay $\eta \to \pi^+\pi^-\gamma$, evidence for a D-wave contribution to the C-violating amplitude. The upper limit for this contribution is measured by the parameter β, defined by

$$dN/d\,|\cos\theta\,| \propto \sin^2\theta\,(1 + \beta\cos^2\theta) ,$$

where θ is the angle between the π^+ and the γ in the dipion center of mass. A term proportional to $\cos^2\theta$ could also come from P- and F-wave interference.

Dalitz plot for $\eta \to \pi^+\pi^-\pi^0$

The Dalitz plot for $\eta \to \pi^+\pi^-\pi^0$ decay may be fit to the distribution

$$|\,M(x,y)|^2 \propto (1 + ay + by^2 + cx + dx^2 + exy) .$$

Here

$$x = \sqrt{3}\,(T_+ - T_-)/Q ,$$

$$y = (3T_0/Q) - 1 ,$$

where T_+ ,T_- , and T_0 are the kinetic energies of the π^+, π^-, and π^0 in the η rest frame, and $Q = T_+ + T_0 + T_-$. The coefficient of the term linear in x is sensitive to C violation due to an I=0 or I=2 final state. In a section below, we list papers that measured a, b, c, and d, but do not tabulate values of these parameters because the assumptions made by different authors are not compatible and do not allow comparison of the numerical values.

Dalitz plot for $\eta \to \pi^0\pi^0\pi^0$

The Dalitz plot for the decay $\eta \to \pi^0\pi^0\pi^0$ may be fit to

$$|\,M\,|^2 \propto 1 + 2\alpha z ,$$

where

$$z = \frac{2}{3}\sum_{i=1}^{3}\left(\frac{3E_i - m_\eta}{m_\eta - 3m_{\pi^0}}\right)^2 = \frac{\rho^2}{\rho^2_{\rm max}} .$$

Here E_i is the energy of the $i^{\rm th}$ pion in the η rest frame, and ρ is the distance from the center of the Dalitz plot. We list measurements of the parameter α in a section below.

Reference

1. J.G. Layter *et al.*, Phys. Rev. Lett. **29**, 316 (1972).

η *C*-NONCONSERVING DECAY PARAMETERS

$\pi^+\pi^-\pi^0$ LEFT-RIGHT ASYMMETRY PARAMETER

Measurements with an error > 1.0×10^{-2} have been omitted.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN
0.09±0.17 OUR AVERAGE				
0.28±0.26	165k	JANE	74	OSPK
−0.05±0.22	220k	LAYTER	72	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.5 ±0.5	37k	[6] GORMLEY	68C	ASPK

[6] The GORMLEY 68C asymmetry is probably due to unmeasured (**E** × **B**) spark chamber effects. New experiments with (**E** × **B**) controls don't observe an asymmetry.

$\pi^+\pi^-\pi^0$ SEXTANT ASYMMETRY PARAMETER

Measurements with an error > 2.0×10^{-2} have been omitted.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN
0.18±0.16 OUR AVERAGE				
0.20±0.25	165k	JANE	74	OSPK
0.10±0.22	220k	LAYTER	72	ASPK
0.5 ±0.5	37k	GORMLEY	68C	WIRE

$\pi^+\pi^-\pi^0$ QUADRANT ASYMMETRY PARAMETER

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN
−0.17±0.17 OUR AVERAGE				
−0.30±0.25	165k	JANE	74	OSPK
−0.07±0.22	220k	LAYTER	72	ASPK

$\pi^+\pi^-\gamma$ LEFT-RIGHT ASYMMETRY PARAMETER

Measurements with an error > 2.0×10^{-2} have been omitted.

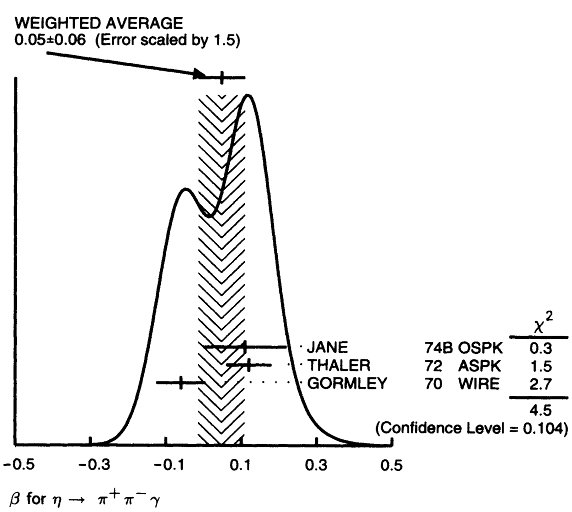
VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN
0.9 ±0.4 OUR AVERAGE				
1.2 ±0.6	35k	JANE	74B	OSPK
0.5 ±0.6	36k	THALER	72	ASPK
1.22±1.56	7257	GORMLEY	70	ASPK

$\pi^+\pi^-\gamma$ PARAMETER β

Sensitive to a *D*-wave contribution: $dN/d\cos\theta = \sin^2\theta\ (1 + \beta\ \cos^2\theta)$

VALUE	EVTS	DOCUMENT ID		TECN
0.05 ±0.06 OUR AVERAGE Error includes scale factor of 1.5. See the ideogram below.				
0.11 ±0.11	35k	JANE	74B	OSPK
0.12 ±0.06		[7] THALER	72	ASPK
−0.060±0.065	7250	GORMLEY	70	WIRE

[7] The authors don't believe this indicates *D*-wave because the dependence of β on the γ energy is inconsistent with theoretical prediction. A $\cos^2\theta$ dependence may also come from *P*- and *F*-wave interference.



ENERGY DEPENDENCE OF $\eta \to \pi^+\pi^-\pi^0$ DALITZ PLOT

See the Note on η Decay Parameters above. The following experiments fit to one or more of the coefficients a, b, c, d, or e for $|\text{matrix element}|^2 = 1 + ay + by^2 + cx + dx^2 + exy$.

VALUE	EVTS	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	81k	LAYTER	73	ASPK
	220k	LAYTER	72	ASPK
	1138	CARPENTER	70	HBC
	349	DANBURG	70	DBC
	7250	GORMLEY	70	WIRE
	526	BAGLIN	69	HLBC
	7170	CNOPS	68	OSPK
	37k	GORMLEY	68C	WIRE
	1300	CLPWY	66	HBC
	705	LARRIBE	66	HBC

α PARAMETER FOR $\eta \rightarrow 3\pi^0$

See the Note on η Decay Parameters above. The value here is of α in $|\text{matrix element}|^2 = 1 + 2\alpha z$.

VALUE	EVTS	DOCUMENT ID		TECN
−0.022±0.023	50k	ALDE	84	GAM2
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.32 ±0.37	192	BAGLIN	70	HLBC

REFERENCES FOR η

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1988 edition Physics Letters **B204** (1988).

PLOUIN 92 PL B (accepted) + (SATR, EPOL, IPN, SACL, GWU, UCLA, BGUN, LOUC)
BARU 90 ZPHY C48 581 +Blinov, Blinov+ (MD-1 Collab.)
ROE 90 PR D41 17 +Bartha, Burke, Garbincius+ (ASP Collab.)
PDG 88 PL B204 Yost, Barnett+ (LBL+)
WILLIAMS 88 PR D38 1365 +Antreasyan, Bartels, Besset+ (Crystal Ball Collab.)
AIHARA 86 PR D33 844 +Alston-Garnjost+ (TPC-2γ Collab.)
BARTEL 85E PL 160B 421 +Becker, Cords, Felst+ (JADE Collab.)
LANDSBERG 85 PRPL 128 310 (SERP)
ALDE 84 ZPHY C25 225 +Binon, Bricman, Donskov+ (SERP, BELG, LAPP)
Also 84B SJNP 40 918 Alde, Binon, Bricman+ (SERP, BELG, LAPP)
Translated from YAF 40 1447.
WEINSTEIN 83 PR D28 2896 +Antreasyan, Gu, Kollman+ (Crystal Ball Collab.)
BINON 82 SJNP 36 391 +Bricman, Gouanere+ (SERP, BELG, LAPP, CERN)
Translated from YAF 36 670.
Also 82B NC 71A 497 Binon, Bricman+ (SERP, BELG, LAPP, CERN)
DAVYDOV 81 LNC 32 45 +Donskov, Inyakin+ (SERP, BELG, LAPP, CERN)
Also 81B SJNP 33 825 Davydov, Binon+ (SERP, BELG, LAPP, CERN)
Translated from YAF 33 1534.
DZHELYADIN 81 PL 105B 239 +Golovkin, Konstantinov, Kubarovski+ (SERP)
Also 81C SJNP 33 822 Dzhelyadin, Viktorov, Golovkin+ (SERP)
Translated from YAF 33 1529.
ABROSIMOV 80 SJNP 31 195 +Ilina, Niszcz, Okhrimenko+ (JINR)
Translated from YAF 31 371.
DZHELYADIN 80 PL 94B 548 +Viktorov, Golovkin+ (SERP)
Also 80C SJNP 32 516 Dzhelyadin, Golovkin, Kachanov+ (SERP)
Translated from YAF 32 998.
DZHELYADIN 80B PL 97B 471 +Viktorov, Golovkin+ (SERP)
Also 80D SJNP 32 518 Dzhelyadin, Golovkin, Kachanov+ (SERP)
Translated from YAF 32 1002.
BUSHNIN 78 PL 79B 147 +Dzhelyadin, Golovkin, Gritsuk+ (SERP)
Also 78B SJNP 28 775 Bushnin, Golovkin, Gritsuk, Dzhelyadin+ (SERP)
Translated from YAF 28 1507.
MARTYNOV 76 SJNP 23 48 +Saltykov, Tarasov, Uzhinskii (JINR)
Translated from YAF 23 93.
JANE 75 PL 59B 99 +Grannis, Jones, Lipman, Owen+ (RHEL, LOWC)
JANE 75B PL 59B 103 +Grannis, Jones, Lipman, Owen+ (RHEL, LOWC)
Also 78B PL 73B 503 Jane
Erratum in private communication.
BROWMAN 74B PRL 32 1067 +Dewire, Gittelman, Hanson, Loh+ (CORN, BING)
DAVIES 74 NC 24A 324 +Guy, Zia (BIRM, RHEL, SHMP)
DUANE 74 PRL 32 425 +Binnie, Camilleri, Carr+ (LOIC, SHMP)
JANE 74 PL 48B 260 +Jones, Lipman, Owen+ (RHEL, LOWC, SUSS)
JANE 74B PL 48B 265 +Jones, Lipman, Owen+ (RHEL, LOWC, SUSS)
KENDALL 74 NC 21A 387 +Lanou, Massimo, Shapiro+ (BROW, BARI, MIT)
LAYTER 73 PR D7 2565 +Appel, Kotlewski, Lee, Stein, Thaler (COLU)
THALER 73 PR D7 2569 +Appel, Kotlewski, Layter, Lee, Stein (COLU)
AGUILAR-... 72B PR D6 29 Aguilar-Benitez, Chung, Eisner, Samios (BNL)
BLOODWO... 72B NP B39 525 Bloodworth, Jackson, Prentice, Yoon (TNTO)
LAYTER 72 PRL 29 316 +Appel, Kotlewski, Lee, Stein, Thaler (COLU)
THALER 72 PRL 29 313 +Appel, Kotlewski, Layter, Lee, Stein (COLU)
BASILE 71D NC 3A 796 +Bollini, Dalpiaz, Frabetti+ (CERN, BGNA, STRB)
STRUGALSKI 71 NP B27 429 +Chuvilo, Gemesy, Ivanovskaya+ (JINR)
BAGLIN 70 NP B22 66 +Bezaguet, Degrange+ (EPOL, MADR, STRB)
BUTTRAM 70 PRL 25 1358 +Kreisler, Mischke (PRIN)
CARPENTER 70 PR D1 1303 +Binkley, Chapman, Cox, Dagan+ (DUKE)
COX 70B PRL 24 534 +Fortney, Golson (DUKE)
DANBURG 70 PR D2 2564 +Abolins, Dahl, Davies, Hoch, Kirz+ (LRL)
DEVONS 70 PR D1 1936 +Grunhaus, Kozlowski, Nemethy+ (COLU, SYRA)
GORMLEY 70 PR D2 501 +Hyman, Lee, Nash, Peoples+ (COLU, BNL)
Also 70B Nevis 181 Thesis Gormley (COLU)
BAGLIN 69 PL 29B 445 +Bezaguet+ (EPOL, UCB, MADR, STRB)
Also 70 NP B22 66 Baglin, Bezaguet, Degrange+ (EPOL, MADR, STRB)
HYAMS 69 PL 29B 128 +Koch, Potter, VonLindern+ (CERN, MPIM)
ARNOLD 68 PL 27B 466 +Paty, Baglin, Bingham+ (STRB, MADR, EPOL, UCB)
BAZIN 68 PRL 20 895 +Goshaw, Zacher+ (PRIN, QUKI)
BULLOCK 68 PL 27B 402 +Esten, Fleming, Govan, Henderson+ (LOUC)
CNOPS 68 PRL 21 1609 +Hough, Cohn+ (BNL, ORNL, UCND, TENN, PENN)
GORMLEY 68C PRL 21 402 +Hyman, Lee, Nash, Peoples+ (COLU, BNL)
WEHMANN 68 PRL 20 748 +Engels+ (HARV, CASE, SLAC, CORN, MCGI)
BAGLIN 67 PL 24B 637 +Bezaguet, Degrange+ (EPOL, UCB)
BAGLIN 67B BAPS 12 567 +Bezaguet, Degrange+ (EPOL, UCB)
BALTAY 67B PRL 19 1498 +Franzini, Kim, Newman+ (COLU, STON)
BALTAY 67D PRL 19 1495 +Franzini, Kim, Newman+ (COLU, BRAN)
BEMPORAD 67 PL 25B 380 +Braccini, Foa, Lubelsmey+ (PISA, BONN)
Also 67 Private Comm. Ion
BILLING 67 PL 25B 435 +Bullock, Esten, Govan+ (LOUC, OXF)
BUNIATOV 67 PL 25B 560 +Zavattini, Deinet+ (CERN, KARL)
CENCE 67 PRL 19 1393 +Peterson, Stenger, Chiu+ (HAWA, LRL)
ESTEN 67 PL 24B 115 +Govan, Knight, Miller, Tovey+ (LOUC, OXF)
FELDMAN 67 PRL 18 868 +Frati, Gleeson, Halpern+ (PENN)
FLATTE 67 PRL 18 976 (LRL)
FLATTE 67B PR 163 1441 +Wohl (LRL)
LITCHFIELD 67 PL 24B 486 +Rangan, Segar, Smith+ (RHEL, SACL)
PRICE 67 PRL 18 1207 +Crawford (LRL)
ALFF-... 66 PR 145 1072 Alff-Steinberger, Berley+ (COLU, RUTG)
CLPWY 66 PR 149 1044 (SCUC, LRL, PURD, WISC, YALE)
CRAWFORD 66 PRL 16 333 +Price (LRL)
DIGIUGNO 66 PRL 16 767 +Giorgi, Silvestri+ (NAPL, TRST, FRAS)
GROSSMAN 66 PR 146 993 +Price, Crawford (LRL)
GRUNHAUS 66 Thesis (COLU)
JAMES 66 PR 142 896 +Kraybill (YALE, BNL)
JONES 66 PL 23 597 +Binnie, Duane, Horsey, Mason+ (LOIC, RHEL)
LARRIBE 66 PL 23 600 +Leveque, Muller, Pauli+ (SACL, RHEL)
FOSTER 65 PR 138B 652 +Peters, Meer, Loeffler+ (WISC, PURD)
FOSTER 65B Athens Conf. +Good, Meer (WISC)
FOSTER 65C Thesis (WISC)
PRICE 65 PRL 15 123 +Crawford (LRL)
RITTENBERG 65 PRL 15 556 +Kalbfleisch (LRL, BNL)
FOELSCHE 64 PR 134B 1138 +Kraybill (YALE)
KRAEMER 64 PR 136B 496 +Madansky, Fields+ (JHU, NWES, WOOD)
PAULI 64 PL 13 351 +Muller (SACL)
BACCI 63 PRL 11 37 +Penso, Salvini+ (ROMA, FRAS)
CRAWFORD 63 PRL 10 546 +Lloyd, Fowler (LRL, DUKE)
Also 66B PRL 16 907 Crawford, Lloyd, Fowler (LRL, DUKE)
DELCOURT 63 PL 7 215 +Lefrancois, Perez-y-Jorba+ (ORSA)
ALFF-... 62 PRL 9 322 Alff-Steinberger, Berley, Colley+ (COLU, RUTG)
BASTIEN 62 PRL 8 114 +Berge, Dahl, Ferro-Luzzi+ (LRL)
PICKUP 62 PRL 8 329 +Robinson, Salant (CNRC, BNL)

$\rho(770)$

$I^G(J^{PC}) = 1^+(1^{--})$

Our latest mini-review on this particle can be found in the 1984 edition.

$\rho(770)$ MASS

We no longer list S-wave Breit-Wigner fits, or data with high combinatorial background.

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID
768.1±0.5 OUR AVERAGE	Includes data from the 3 datablocks that follow this one. Error includes scale factor of 1.1.

CHARGED ONLY

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
766.9±1.2 OUR AVERAGE						
768 ±9		AGUILAR-...	91	EHS		400pp
767 ±3	2935	[1] CAPRARO	87	SPEC	−	200 $\pi^- Cu \rightarrow \pi^- \pi^0 Cu$
761 ±5	967	[1] CAPRARO	87	SPEC	−	200 $\pi^- Pb \rightarrow \pi^- \pi^0 Pb$
771 ±4		HUSTON	86	SPEC	+	202 $\pi^+ A \rightarrow \pi^+ \pi^0 A$
766 ±7	6500	[2] BYERLY	73	OSPK	−	5 $\pi^- p$
766.8±1.5	9650	[3] PISUT	68	RVUE	−	1.7–3.2 $\pi^- p$, $t < 10$
767 ±6	900	[1] EISNER	67	HBC	−	4.2 $\pi^- p$, $t < 10$

NEUTRAL ONLY, PHOTOPRODUCED

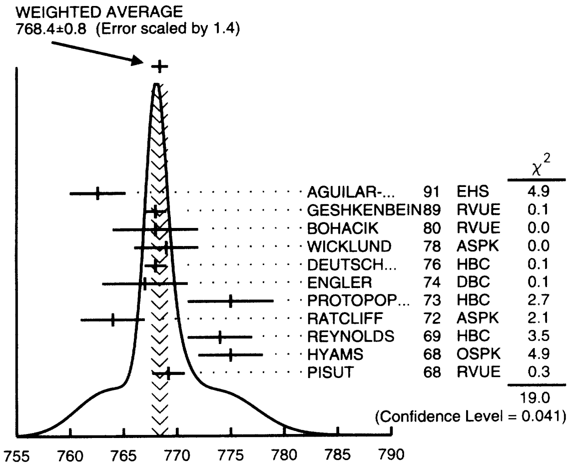
The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
768.1± 1.3 OUR AVERAGE						
767.6± 2.7		BARTALUCCI	78	CNTR	0	$\gamma p \rightarrow e^+ e^- p$
775 ± 5		GLADDING	73	CNTR	0	2.9–4.7 γp
767.0± 4.0	1930	BALLAM	72	HBC	0	2.8 γp
770.0± 4.0	2430	BALLAM	72	HBC	0	4.7 γp
765.0±10.0		ALVENSLEBEN	70	CNTR	0	γA, $t < 0.01$
767.7± 1.9	140k	BIGGS	70	CNTR	0	<4.1 $\gamma C \rightarrow \pi^+ \pi^- C$
765 ± 5.0	4000	ASBURY	67B	CNTR	0	γ + Pb

NEUTRAL ONLY, OTHER REACTIONS

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
768.4±0.8 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.						
762.6±2.6		AGUILAR-...	91	EHS		400pp
768 ±1		[4] GESHKENBEIN	89	RVUE		π form factor
768.0±4.0		[5,6] BOHACIK	80	RVUE	0	
769.0±3.0		[2] WICKLUND	78	ASPK	0	3,4,6 $\pi^\pm N$
768.0±1.0	76000	DEUTSCH...	76	HBC	0	16 $\pi^+ p$
767 ±4	4100	ENGLER	74	DBC	0	6 $\pi^+ n \rightarrow \pi^+ \pi^- p$
775.0±4.0	32000	[5] PROTOPOP...	73	HBC	0	7.1 $\pi^+ p$, $t < 0.4$
764.0±3.0	6800	RATCLIFF	72	ASPK	0	15 $\pi^- p$, $t < 0.3$
774.0±3.0	1700	REYNOLDS	69	HBC	0	2.26 $\pi^- p$
775.0±3.0	2250	HYAMS	68	OSPK	0	11.2 $\pi^- p$
769.2±1.5	13300	[7] PISUT	68	RVUE	0	1.7–3.2 $\pi^- p$, $t < 10$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
775.9±1.1		[8] BARKOV	85	OLYA	0	π form factor
777.4±2.0		[9] CHABAUD	83	ASPK	0	17 $\pi^- p$ polarized
770 ±2		[10] HEYN	80	RVUE		Pion form factor
769.5±0.7		[5,6] LANG	79	RVUE	0	
770 ±9		[6] ESTABROOKS	74	RVUE	0	17 $\pi^- p \rightarrow \pi^+ \pi^- n$
773.5±1.7	11200	[1] JACOBS	72	HBC	0	2.8 $\pi^- p$



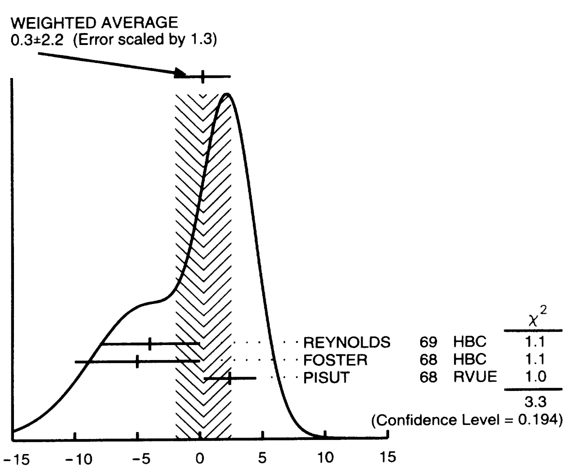
$\rho(770)^0$ mass (MeV)

[1] Mass errors enlarged by us to $\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[2] Phase shift analysis. Systematic errors added corresponding to spread of different fits.
[3] From fit of 3-parameter relativistic *P*-wave Breit-Wigner to total mass distribution. Includes BATON 68, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, BLIEDEN 65 and CARMONY 64.
[4] Includes BARKOV 85 data. Model-dependent width definition.
[5] From pole extrapolation.
[6] From phase shift analysis of GRAYER 74 data.
[7] Includes MALAMUD 69, ARMENISE 68, BACON 67, HUWE 67, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, GOLDHABER 64, ABOLINS 63.
[8] From the Gounaris-Sakurai parametrization of the pion form factor.
[9] From fit of 3-parameter relativistic Breit-Wigner to helicity-zero part of P-wave intensity. CHABAUD 83 includes data of GRAYER 74.
[10] HEYN 80 includes all spacelike and timelike F_π values until 1978.

$\rho(770)^0 - \rho(770)^\pm$ MASS DIFFERENCE

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.3±2.2 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.						
−4.0±4.0	3000	[11] REYNOLDS	69	HBC	−0	2.26 $\pi^- p$
−5 ±5	3600	[11] FOSTER	68	HBC	±0	0.0 $\overline{p}p$
2.4±2.1	22950	[12] PISUT	68	RVUE		$\pi N \rightarrow \rho N$

[11] From quoted masses of charged and neutral modes.
[12] Includes MALAMUD 69, ARMENISE 68, BATON 68, BACON 67, HUWE 67, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, BLIEDEN 65, CARMONY 64, GOLDHABER 64, ABOLINS 63.



$\rho(770)^0 - \rho(770)^\pm$ mass difference (MeV)

$\rho(770)$ RANGE PARAMETER

The range parameter R enters an energy-dependent correction to the width, of the form $(1 + q_r^2 R^2) / (1 + q^2 R^2)$, where q is the momentum of one of the pions in the $\pi\pi$ rest system. At resonance, $q = q_r$.

VALUE (GeV^{-1})	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
$\mathbf{5.3^{+0.9}_{-0.7}}$	CHABAUD	83	ASPK	0	17 $\pi^- p$ polarized

$\rho(770)$ WIDTH

We no longer list *S*-wave Breit-Wigner fits, or data with high combinatorial background.

MIXED CHARGES

VALUE (MeV)	*DOCUMENT ID*
151.5±1.2 OUR AVERAGE	Includes data from the 3 datablocks that follow this one.

CHARGED ONLY

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
The data in this block is included in the average printed for a previous datablock.						
149.1± 2.9 OUR FIT						
149.1± 2.9 OUR AVERAGE						
155 ±11	2935	[13] CAPRARO	87	SPEC	−	200 π^- Cu → $\pi^- \pi^0$ Cu
154 ±20	967	[13] CAPRARO	87	SPEC	−	200 π^- Pb → $\pi^- \pi^0$ Pb
150 ± 5		HUSTON	86	SPEC	+	202 $\pi^+ A \rightarrow \pi^+ \pi^0 A$
146 ±12	6500	[14] BYERLY	73	OSPK	−	5 $\pi^- p$
148.2± 4.1	9650	[15] PISUT	68	RVUE	−	1.7–3.2 $\pi^- p$, t <10
146 ±13	900	EISNER	67	HBC	−	4.2 $\pi^- p$, t <10

NEUTRAL ONLY, PHOTOPRODUCED

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
The data in this block is included in the average printed for a previous datablock.						
150.9± 3.0		BARTALUCCI	78	CNTR	0	$\gamma p \rightarrow e^+ e^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
147 ±11		GLADDING	73	CNTR	0	2.9–4.7 γp
155.0±12.0	2430	BALLAM	72	HBC	0	4.7 γp
145.0±13.0	1930	BALLAM	72	HBC	0	2.8 γp
140.0± 5.0		ALVENSLEBEN	70	CNTR	0	γA, t <0.01
146.1± 2.9	140k	BIGGS	70	CNTR	0	<4.1 $\gamma C \rightarrow \pi^+ \pi^- C$
160.0±10.0		LANZEROTTI	68	CNTR	0	γp
130 ± 5	4000	ASBURY	67B	CNTR	0	γ + Pb

NEUTRAL ONLY, OTHER REACTIONS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
The data in this block is included in the average printed for a previous datablock.						
152.4± 1.5 OUR FIT						
152.4± 1.5 OUR AVERAGE						
150.5± 3.0		[16] BARKOV	85	OLYA	0	π form factor
148.0± 6.0		[17,18] BOHACIK	80	RVUE	0	
152.0± 9.0		[14] WICKLUND	78	ASPK	0	3,4,6 $\pi^\pm p N$
154.0± 2.0	76000	DEUTSCH...	76	HBC	0	16 $\pi^+ p$
157.0± 8.0	6800	RATCLIFF	72	ASPK	0	15 $\pi^- p$, t <0.3
143.0± 8.0	1700	REYNOLDS	69	HBC	0	2.26 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
138 ± 1		[19] GESHKENBEIN	89	RVUE		π form factor
$160.0^{+4.1}_{-4.0}$		[20] CHABAUD	83	ASPK	0	17 $\pi^- p$ polarized
155 ± 1		[21] HEYN	80	RVUE	0	π form factor
148.0± 1.3		[17,18] LANG	79	RVUE	0	
146 ±14	4100	ENGLER	74	DBC	0	6 $\pi^+ n \rightarrow \pi^+ \pi^- p$
143 ±13		[18] ESTABROOKS	74	RVUE	0	17 $\pi^- p \rightarrow \pi^+ \pi^- n$
160.0±10.0	32000	[17] PROTOPOP...	73	HBC	0	7.1 $\pi^+ p$, t <0.4
145.0±12.0	2250	[13] HYAMS	68	OSPK	0	11.2 $\pi^- p$
163.0±15.0	13300	[22] PISUT	68	RVUE	0	1.7–3.2 $\pi^- p$, t <10

[13] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[14] Phase shift analysis. Systematic errors added corresponding to spread of different fits.
[15] From fit of 3-parameter relativistic *P*-wave Breit-Wigner to total mass distribution. Includes BATON 68, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, BLIEDEN 65 and CARMONY 64.
[16] From the Gounaris-Sakurai parametrization of the pion form factor.
[17] From pole extrapolation.
[18] From phase shift analysis of GRAYER 74 data.
[19] Includes BARKOV 85 data. Model-dependent width definition.
[20] From fit of 3-parameter relativistic Breit-Wigner to helicity-zero part of *P*-wave intensity. CHABAUD 83 includes data of GRAYER 74.
[21] HEYN 80 includes all spacelike and timelike F_π values until 1978.
[22] Includes MALAMUD 69, ARMENISE 68, BACON 67, HUWE 67, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, GOLDHABER 64, ABOLINS 63.

$\rho(770)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi\pi$	$\sim$ 100 %	
	$\rho(770)^{\pm}$ decays		
Γ_2	$\pi^{\pm}\pi^0$	$\sim$ 100 %	
Γ_3	$\pi^{\pm}\gamma$	$(4.5 \pm 0.5) \times 10^{-4}$	S=2.2
Γ_4	$\pi^{\pm}\eta$	$< 8 \times 10^{-3}$	CL=84%
Γ_5	$\pi^{\pm}\pi^+\pi^-\pi^0$	$< 2.0 \times 10^{-3}$	CL=84%
	$\rho(770)^0$ decays		
Γ_6	$\pi^+\pi^-$	$\sim$ 100 %	
Γ_7	$\pi^+\pi^-\gamma$	$(9.9 \pm 1.6) \times 10^{-3}$	
Γ_8	$\pi^0\gamma$	$(7.9 \pm 2.0) \times 10^{-4}$	
Γ_9	$\eta\gamma$	$(3.8 \pm 0.7) \times 10^{-4}$	
Γ_{10}	$\mu^+\mu^-$	[a] $(4.60 \pm 0.28) \times 10^{-5}$	
Γ_{11}	e^+e^-	[a] $(4.44 \pm 0.21) \times 10^{-5}$	
Γ_{12}	$\pi^+\pi^-\pi^0$	$< 1.2 \times 10^{-4}$	CL=90%
Γ_{13}	$\pi^+\pi^-\pi^+\pi^-$	$< 2 \times 10^{-4}$	CL=90%
Γ_{14}	$\pi^+\pi^-\pi^0\pi^0$	$< 4 \times 10^{-5}$	CL=90%

[a] The e^+e^- branching fraction is from $e^+e^- \to \pi^+\pi^-$ experiments only. The $\omega\rho$ interference is then due to $\omega\rho$ mixing only, and is expected to be small. If $e\mu$ universality holds, $\Gamma(\rho^0 \to \mu^+\mu^-) = \Gamma(\rho^0 \to e^+e^-) \times 0.99785$.

CONSTRAINED FIT INFORMATION

An overall fit to the total width and a partial width uses 9 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 = 10.2$ for 7 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_3	−100	
Γ	18	−18
	x_2	x_3

	Mode	Rate (MeV)	Scale factor
Γ_2	$\pi^{\pm}\pi^0$	149.1 ± 2.9	
Γ_3	$\pi^{\pm}\gamma$	0.068 ± 0.007	2.3

CONSTRAINED FIT INFORMATION

An overall fit to the total width, a partial width, and a branching ratio uses 8 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 = 3.3$ for 5 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

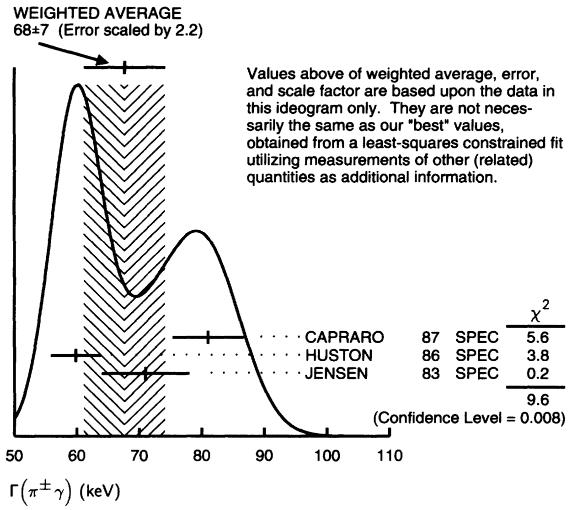
x_{10}	−80		
x_{11}	−60	0	
Γ	13	0	−21
	x_6	x_{10}	x_{11}

	Mode	Rate (MeV)
Γ_6	$\pi^+\pi^-$	152.4 ± 1.5
Γ_{10}	$\mu^+\mu^-$	[a] 0.0070 ± 0.0004
Γ_{11}	e^+e^-	[a] 0.00677 ± 0.00032

$\rho(770)$ PARTIAL WIDTHS

$\Gamma(\pi^{\pm}\gamma)$ — Γ_3

VALUE (keV)	DOCUMENT ID		TECN	CHG	COMMENT
68 ±7 OUR FIT Error includes scale factor of 2.3.					
68 ±7 OUR AVERAGE Error includes scale factor of 2.2. See the ideogram below.					
81.0±4.0±4.0	CAPRARO	87	SPEC	−	$200\ \pi^- A \to \pi^-\pi^0 A$
59.8±4.0	HUSTON	86	SPEC	+	$202\ \pi^+ A \to \pi^+\pi^0 A$
71.0±7.0	JENSEN	83	SPEC	−	$156\text{–}260\ \pi^- A \to \pi^-\pi^0 A$



$\Gamma(e^+e^-)$ — Γ_{11}

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
6.77±0.32 OUR FIT				
6.77±0.10±0.30	BARKOV	85	OLYA	$e^+e^- \to \pi^+\pi^-$

$\Gamma(\pi^0\gamma)$ — Γ_8

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
121±31	DOLINSKY	89	ND	$e^+e^- \to \pi^0\gamma$

$\Gamma(\eta\gamma)$ — Γ_9

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
62±17	[23] DOLINSKY	89	ND	$e^+e^- \to \eta\gamma$
111±22	[24] DOLINSKY	89	ND	$e^+e^- \to \eta\gamma$

[23] Solution corresponding to constructive ω-ρ interference. The quark model predicts a relative decay phase of zero.
[24] Solution corresponding to destructive ρ-ω interference.

$\rho(770)$ BRANCHING RATIOS

$\Gamma(\pi^{\pm}\eta)/\Gamma(\pi\pi)$ — Γ_4/Γ_1

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<80	84	FERBEL	66	HBC	±	$\pi^{\pm}p$ above 2.5

$\Gamma(\pi^{\pm}\pi^+\pi^-\pi^0)/\Gamma(\pi\pi)$ — Γ_5/Γ_1

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<20	84	FERBEL	66	HBC	±	$\pi^{\pm}p$ above 2.5
• • • We do not use the following data for averages, fits, limits, etc. • • •						
35±40		JAMES	66	HBC	+	$2.1\ \pi^+p$

$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ — Γ_{10}/Γ_6

VALUE (units 10^{-5})	DOCUMENT ID		TECN	COMMENT
4.60±0.28 OUR FIT				
4.6 ±0.2 ±0.2	ANTIPOV	89	SIGM	$\pi^- Cu \to \mu^+\mu^-\pi^- Cu$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$8.2^{+1.6}_{-3.6}$	[25] ROTHWELL	69	CNTR	Photoproduction
5.6 ±1.5	[26] WEHMANN	69	OSPK	$12\ \pi^-$ C, Fe
$9.7^{+3.1}_{-3.3}$	[27] HYAMS	67	OSPK	$11\ \pi^-$ Li, H

[25] Possibly large ρ-ω interference leads us to increase the minus error.
[26] Result contains 11 ± 11% correction using SU(3) for central value. The error on the correction takes account of possible ρ-ω interference and the upper limit agrees with the upper limit of $\omega \to \mu^+\mu^-$ from this experiment.
[27] HYAMS 67's mass resolution is 20 MeV. The ω region was excluded.

$\Gamma(e^+e^-)/\Gamma(\pi\pi)$ — Γ_{11}/Γ_1

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
0.41±0.05	BENAKSAS	72	OSPK	e^+e^-

$\Gamma(\eta\gamma)/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	CHG	COMMENT
3.8±0.7 OUR AVERAGE					
4.0±1.1	[28] DOLINSKY	89	ND		e^+e^-
3.6±0.9	[28] ANDREWS	77	CNTR	0	6.7–10 γCu
• • • We do not use the following data for averages, fits, limits, etc. • • •					
7.3±1.5	[29] DOLINSKY	89	ND		e^+e^-
5.4±1.1	[29] ANDREWS	77	CNTR	0	6.7–10 γCu

[28] Solution corresponding to constructive ω-ρ interference. The quark model predicts a relative decay phase of zero.
[29] Solution corresponding to destructive ω-ρ interference.

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<2	90	KURDADZE	88	OLYA	$e^+e^- \to \pi^+\pi^-\pi^+\pi^-$

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma(\pi\pi)$ — Γ_{13}/Γ_1

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<15	90	ERBE	69	HBC	0	2.5–5.8 γp
<20		CHUNG	68	HBC	0	3.2,4.2 $\pi^- p$
<20	90	HUSON	68	HLBC	0	16.0 $\pi^- p$
<80		JAMES	66	HBC	0	2.1 $\pi^+ p$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<1.2	90	VASSERMAN	88B	ND	$e^+e^- \to \pi^+\pi^-\pi^0$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma(\pi\pi)$ — Γ_{12}/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
~ 0.01		BRAMON	86	RVUE	0	$J/\psi \to \omega\pi^0$
<0.01	84	[30] ABRAMS	71	HBC	0	3.7 $\pi^+ p$

[30] Model dependent, assumes I = 1, 2, or 3 for the 3π system.

$\Gamma(\pi^+\pi^-\pi^0\pi^0)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.4	90	AULCHENKO	87C	ND	0	$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2	90	KURDADZE	86	OLYA	0	$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

$\Gamma(\pi^+\pi^-\gamma)/\Gamma_{total}$ — Γ_7/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.0099±0.0016		[31] DOLINSKY	91	ND	$e^+e^- \to \pi^+\pi^-\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0111±0.0014		[32] VASSERMAN	88	ND	$e^+e^- \to \pi^+\pi^-\gamma$
<0.005	90	[33] VASSERMAN	88	ND	$e^+e^- \to \pi^+\pi^-\gamma$

[31] Bremsstrahlung from a decay pion and for photon energy above 50 MeV.
[32] Superseded by DOLINSKY 91.
[33] Structure radiation due to quark rearrangement in the decay.

$\Gamma(\pi^0\gamma)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
7.9±2.0	DOLINSKY	89	ND	e^+e^-

$\rho(770)$ REFERENCES

AGUILAR-... 91 ZPHY C50 405 Aguilar-Benitez, Allison, Batalor+ (LEBC-EHS Collab.)
DOLINSKY 91 PRPL 202 99 +Druzhinin, Dubrovin+ (NOVO)
ANTIPOV 89 ZPHY C42 185 +Batarin+ (SERP, JINR, BGNA, MILA, TBIL)
DOLINSKY 89 ZPHY C42 511 +Druzhinin, Dubrovin, Golubev+ (NOVO)
GESHKENBEIN 89 ZPHY 45 351 (ITEP)
KURDADZE 88 JETPL 47 512 +Leltchouk, Pakhtusova, Sidorov+ (NOVO)
Translated from ZETFP 47 432.
VASSERMAN 88 SJNP 47 1035 +Golubev, Dolinsky+ (NOVO)
Translated from YAF 47 1635.
VASSERMAN 88B SJNP 48 480 +Golubev, Dolinsky+ (NOVO)
Translated from YAF 48 753.
AULCHENKO 87C YAF 87-90 Preprint +Dolinsky, Druzhinin+ (NOVO)
CAPRARO 87 NP B288 659 +Levy+ (CLER, FRAS, MILA, PISA, LCGT, TRST+)
BRAMON 86 PL B173 97 +Casulleras (BARC)
HUSTON 86 PR 33 3199 +Berg, Collick, Jonckheere+ (ROCH, FNAL, MINN)
KURDADZE 86 JETPL 43 643 +Lelchuk, Pakhtusova, Sidorov, Skrinskii+ (NOVO)
Translated from ZETFP 43 497.
BARKOV 85 NP B256 365 +Chilingarov, Eidelman, Khazin, Lelchuk+ (NOVO)
CHABAUD 83 NP B223 1 +Gorlich, Cerrada+ (CERN, CRAC, MPIM)
JENSEN 83 PR D27 26 +Berg, Biel, Collick+ (ROCH, FNAL, MINN)
BOHACIK 80 PR D21 1342 +Kuhnelt (SLOV, WIEN)
HEYN 80 ZPHY C7 169 +Lang (GRAZ)
LANG 79 PR D19 956 +Mas-Parareda (GRAZ)
BARTALUCCI 78 NC 44A 587 +Basini, Bertolucci+ (DESY, FRAS)
WICKLUND 78 PR D17 1197 +Ayres, Diebold, Greene, Kramer, Pawlicki (ANL)
ANDREWS 77 PRL 38 198 +Fukushima, Harvey, Lobkowicz, May+ (ROCH)
DEUTSCH... 76 NP B103 426 Deutschmann+ (AACH, BERL, BONN, CERN+)
ENGLER 74 PR D10 2070 +Kraemer, Toaff, Weisser, Diaz+ (CMU, CASE)
ESTABROOKS 74 NP B79 301 +Martin (DURH)
GRAYER 74 NP B75 189 +Hyams, Blum, Dietl+ (CERN, MPIM)
BYERLY 73 PR D7 637 +Anthony, Coffin, Meanley, Meyer, Rice+ (MICH)
GLADDING 73 PR D8 3721 +Russell, Tannenbaum, Weiss, Thomson (HARV)
PROTOPOP... 73 PR D7 1280 Protopopescu, Alston-Garnjost, Galtieri, Flatte+ (LBL)
BALLAM 72 PR D5 545 +Chadwick, Bingham, Milburn+ (SLAC, LBL, TUFT)
BENAKSAS 72 PL 39B 289 +Cosme, Jean-Marie, Jullian, Laplanche+ (ORSA)
JACOBS 72 PR D6 1291 (SACL)
RATCLIFF 72 PL 38B 345 +Bulos, Carnegie, Kluge, Leith, Lynch+ (SLAC)
ABRAMS 71 PR D4 653 +Barnham, Butler, Coyne, Goldhaber, Hall+ (LBL)
ALVENSLEBEN 70 PRL 24 786 +Becker, Bertram, Chen, Cohen (DESY)
BIGGS 70 PRL 24 1197 +Braben, Clifft, Gabathuler, Kitching+ (DARE)
ERBE 69 PR 188 2060 +Hilpert+ (German Bubble Chamber Collab.)
MALAMUD 69 Argonne Conf. 93 +Schlein (UCLA)
REYNOLDS 69 PR 184 1424 +Albright, Bradley, Brucker, Harms+ (FSU)
ROTHWELL 69 PRL 23 1521 +Chase, Earles, Gettner, Glass, Weinstein+ (NEAS)
WEHMANN 69 PR 178 2095 + (HARV, CASE, SLAC, CORN, MCGI)
ARMENISE 68 NC 54A 999 +Ghidini, Forino+ (BARI, BGNA, FIRZ, ORSA)
BATON 68 PR 176 1574 +Laurens (SACL)
CHUNG 68 PR 165 1491 +Dahl, Kirz, Miller (LRL)
FOSTER 68 NP B6 107 +Gavillet, Labrosse, Montanet+ (CERN, CDEF)
HUSON 68 PL 28B 208 +Lubatti, Six, Veillet+ (ORSA, MILA, UCLA)
HYAMS 68 NP B7 1 +Koch, Potter, Wilson, VonLindern+ (CERN, MPIM)
LANZEROTTI 68 PR 166 1365 +Blumenthal, Ehn, Faissler+ (HARV)
PISUT 68 NP B6 325 +Roos (CERN)
ASBURY 67B PRL 19 865 +Becker, Bertram, Joos, Jordan+ (DESY, COLU)
BACON 67 PR 157 1263 +Fickinger, Hill, Hopkins, Robinson+ (BNL)
EISNER 67 PR 164 1699 +Johnson, Klein, Peters, Sahni, Yen+ (PURD)
HUWE 67 PL 24B 252 +Marquit, Oppenheimer, Schultz, Wilson (COLU)
HYAMS 67 PL 24B 634 +Koch, Pellett, Potter, VonLindern+ (CERN, MPIM)
MILLER 67B PR 153 1423 +Gutay, Johnson, Loeffler+ (PURD)
ALFF-... 66 PR 145 1072 Alff-Steinberger, Berley+ (COLU, RUTG)
FERBEL 66 PL 21 111 (ROCH)
HAGOPIAN 66 PR 145 1128 +Selove, Alitti, Baton+ (PENN, SACL)
HAGOPIAN 66B PR 152 1183 +Pan (PENN, LRL)
JACOBS 66B UCRL 16877 (LRL)
JAMES 66 PR 142 896 +Kraybill (YALE, BNL)
WEST 66 PR 149 1089 +Boyd, Erwin, Walker (WISC)
BLIEDEN 65 PL 19 444 +Freytag, Geibel+ (CERN Missing Mass Spect. Collab.)
CARMONY 64 PRL 12 254 +Lander, Rindfleisch, Xuong, Yager (UCB)
GOLDHABER 64 PRL 12 336 +Brown, Kadyk, Shen+ (LRL, UCB)
ABOLINS 63 PRL 11 381 +Lander, Mehlhop, Nguyen, Yager (UCSD)

OTHER RELATED PAPERS

ERKAL 85 ZPHY C29 485 +Olsson (WISC)
RYBICKI 85 ZPHY C28 65 +Sakrejda (CRAC)
KURDADZE 83 JETPL 37 733 +Lelchuk, Pakhtusova+ (NOVO)
Translated from ZETFP 37 613.
ALEKSEEV 82 JETP 55 591 +Kartamyshev, Makarin+ (KIAE)
Translated from ZETF 82 1007.
KENNEY 62 PR 126 736 +Shephard, Gall (KNTY)
SAMIOS 62 PRL 9 139 +Bachman, Lea+ (BNL, CUNY, COLU, KNTY)
XUONG 62 PR 128 1849 +Lynch (LRL)
ANDERSON 61 PRL 6 365 +Bang, Burke, Carmony, Schmitz (LRL)
ERWIN 61 PRL 6 628 +March, Walker, West (WISC)

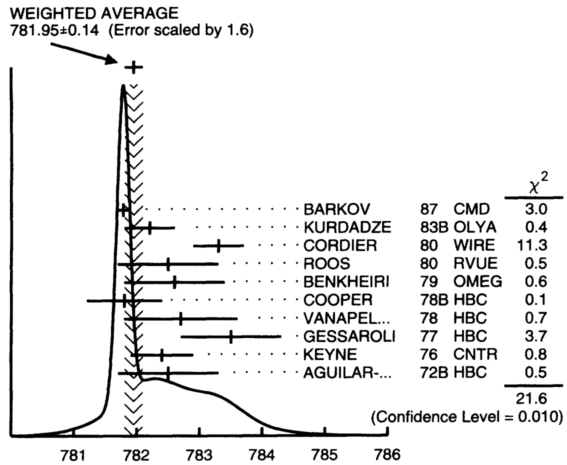
$\omega(783)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\omega(783)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
781.95±0.14 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.				
781.78±0.10		BARKOV	87	CMD	$e^+e^- \to \pi^+\pi^-\pi^0$
782.2 ±0.4		KURDADZE	83B	OLYA	e^+e^-
783.3 ±0.4		CORDIER	80	WIRE	$e^+e^- \to \pi^+\pi^-\pi^0$
782.5 ±0.8	33260	ROOS	80	RVUE	0.0–3.6 $\overline{p}p$
782.6 ±0.8	3000	BENKHEIRI	79	OMEG	9–12 $\pi^\pm p$
781.8 ±0.6	1430	COOPER	78B	HBC	0.7–0.8 $\overline{p}p \to 5\pi$
782.7 ±0.9	535	VANAPEL...	78	HBC	7.2 $\overline{p}p \to \overline{p}p\omega$
783.5 ±0.8	2100	GESSAROLI	77	HBC	11 $\pi^- p \to \omega\pi$
782.4 ±0.5	7000	[1] KEYNE	76	CNTR	$\pi^- p \to \omega n$
782.5 ±0.8	418	AGUILAR-...	72B	HBC	3.9,4.6 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
783.4 ±1.0	248	BIZZARRI	71	HBC	0.0 $p\overline{p} \to K^+K^-\omega$
781.0 ±0.6	510	BIZZARRI	71	HBC	0.0 $p\overline{p} \to K_1 K_1 \omega$
783.7 ±1.0		[2] COYNE	71	HBC	3.7 $\pi^+ p$
784.1 ±1.2	750	ABRAMOVI...	70	HBC	3.9 $\pi^- p$
783.2 ±1.6		[3] BIGGS	70B	CNTR	<4.1 $\gamma C \to \pi^+\pi^- C$
782.4 ±0.5	2400	BIZZARRI	69	HBC	0.0 $\overline{p}p$

[1] Observed by threshold-crossing technique. Mass resolution = 4.8 MeV FWHM.
[2] From best-resolution sample of COYNE 71.
[3] From ω-ρ interference in the $\pi^+\pi^-$ mass spectrum assuming ω width 12.6 MeV.



$\omega(783)$ mass (MeV)

$\omega(783)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
8.43±0.10 OUR AVERAGE					
8.4 ±0.1		[4] AULCHENKO	87	ND	e^+e^-, $\pi^+\pi^-\pi^0$
8.30±0.40		BARKOV	87	CMD	$e^+e^- \rightarrow \pi^+\pi^-\pi^0$
9.8 ±0.9		KURDADZE	83B	OLYA	e^+e^-
9.0 ±0.8		CORDIER	80	WIRE	$e^+e^- \rightarrow \pi^+\pi^-\pi^0$
9.1 ±0.8		BENAKSAS	72B	OSPK	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
12.0 ±2.0	1430	COOPER	78B	HBC	0.7–0.8 $\overline{p}p \rightarrow 5\pi$
9.4 ±2.5	2100	GESSAROLI	77	HBC	11 $\pi^- p \rightarrow \omega\pi$
10.22±0.43	20000	[5] KEYNE	76	CNTR	$\pi^- p \rightarrow \omega n$
13.3 ±2	418	AGUILAR-...	72B	HBC	3.9,4.6 $K^- p$
10.5 ±1.5		BORENSTEIN	72	HBC	2.18 $K^- p$
7.70±0.9 ±1.15	940	BROWN	72	MMS	2.5 $\pi^- p \rightarrow n$ MM
10.3 ±1.4	510	BIZZARRI	71	HBC	0.0 $p\overline{p} \rightarrow K_1 K_1 \omega$
12.8 ±3.0	248	BIZZARRI	71	HBC	0.0 $p\overline{p} \rightarrow K^+K^-\omega$
9.5 ±1.0	4270	COYNE	71	HBC	3.7 $\pi^+ p$

[4] Relativistic Breit-Wigner includes radiative corrections.
[5] Observed by threshold-crossing technique. Mass resolution = 4.8 MeV FWHM.

$\omega(783)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi^+\pi^-\pi^0$	(88.8 ±0.6) %	
Γ_2	$\pi^0\gamma$	(8.5 ±0.5) %	
Γ_3	$\pi^+\pi^-$	(2.21±0.30) %	
Γ_4	neutrals (excluding $\pi^0\gamma$)	(4.4 $^{+7.9}_{-2.9}$) $\times 10^{-3}$	
Γ_5	$\pi^0 e^+e^-$	(5.9 ±1.9) $\times 10^{-4}$	
Γ_6	$\eta\gamma$	(4.7 $^{+2.2}_{-1.8}$) $\times 10^{-4}$	S=1.1
Γ_7	$\pi^0\mu^+\mu^-$	(9.6 ±2.3) $\times 10^{-5}$	
Γ_8	e^+e^-	(7.15±0.19) $\times 10^{-5}$	
Γ_9	$\pi^+\pi^-\pi^0\pi^0$	< 2 %	CL=90%
Γ_{10}	$\pi^+\pi^-\gamma$	< 3.6 $\times 10^{-3}$	CL=95%
Γ_{11}	$\pi^+\pi^-\pi^+\pi^-$	< 1 $\times 10^{-3}$	CL=90%
Γ_{12}	$\pi^0\pi^0\gamma$	< 4 $\times 10^{-4}$	CL=90%
Γ_{13}	$\mu^+\mu^-$	< 1.8 $\times 10^{-4}$	CL=90%
Γ_{14}	$\eta\pi^0$		

CONSTRAINED FIT INFORMATION

An overall fit to 6 branching ratios uses 22 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 11.3 for 19 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	12		
x_3	−44	−5	
x_4	−69	−71	0
	x_1	x_2	x_3

$\omega(783)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ — Γ_8

VALUE (keV)	DOCUMENT ID
0.60±0.02 OUR EVALUATION	Error includes scale factor of 1.1.

$\omega(783)$ BRANCHING RATIOS

$\Gamma(\text{neutrals})/\Gamma(\pi^+\pi^-\pi^0)$ — $(\Gamma_2+\Gamma_4)/\Gamma_1$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.101±0.007 OUR FIT	Error includes scale factor of 1.1.				
0.105±0.009 OUR AVERAGE					
0.15 ±0.04	46	AGUILAR-...	72B	HBC	3.9,4.6 $K^- p$
0.10 ±0.03	19	BARASH	67B	HBC	0.0 $\overline{p}p$
0.134±0.026	850	DIGIUGNO	66B	CNTR	1.4 $\pi^- p$
0.097±0.016	348	FLATTE	66	HBC	1.8 $K^- p$
0.06 $^{+0.05}_{-0.02}$		JAMES	66	HBC	2.1 $\pi^+ p$
0.08 ±0.03	35	KRAEMER	64	DBC	1.2 $\pi^+ d$
0.11 ±0.02	20	BUSCHBECK	63	HBC	1.5 $K^- p$

$\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_3/Γ_1

See also $\Gamma(\pi^+\pi^-)/\Gamma_{total}$.

VALUE	DOCUMENT ID		TECN	COMMENT
0.0249±0.0035 OUR FIT				
0.026 ±0.005 OUR AVERAGE				
0.021 $^{+0.028}_{-0.009}$	[6] RATCLIFF	72	ASPK	15 $\pi^- p \rightarrow n2\pi$
0.028 ±0.006	BEHREND	71	ASPK	Photoproduction
0.022 $^{+0.009}_{-0.01}$	[7] ROOS	70	RVUE	

[6] Significant interference effect observed. NB of $\omega \rightarrow 3\pi$ comes from an extrapolation.
[7] ROOS 70 combines ABRAMOVICH 70 and BIZZARRI 70.

$\Gamma(\pi^0\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.096±0.006 OUR FIT				
0.096±0.006 OUR AVERAGE				
0.099±0.007	DOLINSKY	89	ND	$e^+e^- \rightarrow \pi^0\gamma$
0.084±0.013	KEYNE	76	CNTR	$\pi^- p \rightarrow \omega n$
0.109±0.025	BENAKSAS	72C	OSPK	e^+e^-
0.081±0.020	BALDIN	71	HLBC	2.9 $\pi^+ p$
0.13 ±0.04	JACQUET	69B	HLBC	

$\Gamma(\pi^+\pi^-\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_{10}/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.066	90	KALBFLEISCH	75	HBC	2.2 $K^- p$
<0.05	90	FLATTE	66	HBC	1.8 $K^- p$

$\Gamma(\pi^+\pi^-\gamma)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0036	95	WEIDENAUER	90	ASTE	$p\overline{p} \rightarrow \pi^+\pi^-\pi^+\pi^-\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.004	95	BITYUKOV	88B	SPEC	32 $\pi^- p \rightarrow \pi^+\pi^-\gamma X$

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1 × 10⁻³	90	KURDADZE	88	OLYA	$e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$

$\Gamma(\pi^+\pi^-\pi^0\pi^0)/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID		TECN	COMMENT
<2	90	KURDADZE	86	OLYA	$e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$

$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_{13}/Γ_1

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
<0.2	90	WILSON 69	OSPK	$12\ \pi^- C \rightarrow$ Fe
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.7	74	FLATTE 66	HBC	$1.8\ K^- p$
<1.2		BARBARO-... 65	HBC	$2.7\ K^- p$

$\Gamma(\pi^0\pi^0\gamma)/\Gamma(\pi^0\gamma)$ — Γ_{12}/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.005	90	DOLINSKY 89	ND	e^+e^-
<0.18	95	KEYNE 76	CNTR	$\pi^- p \rightarrow \omega n$
<0.15	90	BENAKSAS 72C	OSPK	e^+e^-
<0.14		BALDIN 71	HLBC	$2.9\ \pi^+ p$
<0.1	90	BARMIN 64	HLBC	$1.3–2.8\ \pi^- p$

$[\Gamma(\eta\gamma) + \Gamma(\eta\pi^0)]/\Gamma(\pi^+\pi^-\pi^0)$ — $(\Gamma_6+\Gamma_{14})/\Gamma_1$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.017	90	FLATTE 66	HBC	$1.8\ K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.045	95	JACQUET 69B	HLBC	

Γ(neutrals)/Γ(charged particles) — $(\Gamma_2+\Gamma_4)/(\Gamma_1+\Gamma_3)$

VALUE	DOCUMENT ID	TECN	COMMENT
0.098±0.007 OUR FIT Error includes scale factor of 1.1.			
0.124±0.021	FELDMAN 67C	OSPK	$1.2\ \pi^- p$

$\Gamma(\pi^0\pi^0\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_{12}/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00045	90	DOLINSKY 89	ND	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.08	95	JACQUET 69B	HLBC	

$\Gamma(\eta\gamma)/\Gamma(\pi^0\gamma)$ — Γ_6/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
0.0082±0.0033 OUR AVERAGE			
0.0082±0.0033	[8] DOLINSKY 89	ND	e^+e^-
0.010 ±0.045	APEL 72B	OSPK	$4–8\ \pi^- p \rightarrow n 3\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.039 ±0.007	[9] DOLINSKY 89	ND	e^+e^-

[8] Solution corresponding to constructive ω-ρ interference. The quark model predicts a relative decay phase of zero.
[9] Solution corresponding to destructive ρ-ω interference.

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
0.96±0.23	DZHELYADIN 81B	CNTR	$25–33\ \pi^- p \rightarrow \omega n$

$\Gamma(\pi^0 e^+e^-)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
5.9±1.9	43	DOLINSKY 88	ND	$e^+e^- \rightarrow \pi^0 e^+e^-$

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
0.715±0.019 OUR AVERAGE				
0.714±0.036		DOLINSKY 89	ND	e^+e^-
0.72 ±0.03		BARKOV 87	CMD	$e^+e^- \rightarrow \pi^+\pi^-\pi^0$
0.66 ±0.05		KURDADZE 84	OLYA	$e^+e^- \rightarrow$ hadrons
0.675±0.069		CORDIER 80	WIRE	$e^+e^- \rightarrow 3\pi$
0.83 ±0.10		BENAKSAS 72B	OSPK	$e^+e^- \rightarrow 3\pi$
0.77 ±0.06		[10] AUGUSTIN 69D	OSPK	$e^+e^- \rightarrow 2\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.64 ±0.04		[11] KURDADZE 83B	OLYA	e^+e^-
0.65 ±0.13	33	[12] ASTVACAT... 68	OSPK	Assume SU(3)+mixing

[10] Rescaled by us to correspond to ω width 8.4 MeV.
[11] Superseded by KURDADZE 84.
[12] Not resolved from ρ decay. Error statistical only.

Γ(neutrals)/Γ_{total} — $(\Gamma_2+\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.089±0.006 OUR FIT Error includes scale factor of 1.1.				
0.079±0.009 OUR AVERAGE				
0.073±0.018	42	BASILE 72B	CNTR	$1.67\ \pi^- p$
0.075±0.025		BIZZARRI 71	HBC	$0.0\ p\bar{p}$
0.079±0.019		DEINET 69B	OSPK	$1.5\ \pi^- p$
0.084±0.015		BOLLINI 68C	CNTR	$2.1\ \pi^- p$

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_3/Γ

See also $\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$.

VALUE	DOCUMENT ID	TECN	COMMENT
0.0221±0.0030 OUR FIT			
0.021 ±0.004 OUR AVERAGE			
0.023 ±0.005	BARKOV 85	OLYA	e^+e^-
$0.016\ ^{+0.009}_{-0.007}$	QUENZER 78	CNTR	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.010 ±0.001	[13] WICKLUND 78	ASPK	$3,4,6\ \pi^\pm N$
0.0122±0.0030	ALVENSLEBEN 71C	CNTR	Photoproduction
$0.013\ ^{+0.012}_{-0.009}$	MOFFEIT 71	HBC	$2.8,4.7\ \gamma p$
$0.0080\ ^{+0.0028}_{-0.002}$	[14] BIGGS 70B	CNTR	$4.2 \gamma C \rightarrow \pi^+\pi^- C$

[13] From a model-dependent analysis assuming complete coherence.
[14] Re-evaluated under $\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ by BEHREND 71 using more accurate $\omega \rightarrow \rho$ photoproduction cross-section ratio.

$\Gamma(\pi^0\pi^0\gamma)/\Gamma$(neutrals) — $\Gamma_{12}/(\Gamma_2+\Gamma_4)$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22±0.07		[15] DAKIN 72	OSPK	$1.4\ \pi^- p \rightarrow n$ MM
<0.19	90	DEINET 69B	OSPK	

[15] See $\Gamma(\pi^0\gamma)/\Gamma$(neutrals).

$\Gamma(\pi^0\gamma)/\Gamma$(neutrals) — $\Gamma_2/(\Gamma_2+\Gamma_4)$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.78±0.07		[16] DAKIN 72	OSPK	$1.4\ \pi^- p \rightarrow n$ MM
>0.81	90	DEINET 69B	OSPK	

[16] Error statistical only. Authors obtain good fit also assuming $\pi^0\gamma$ as the only neutral decay.

$\Gamma(\eta\gamma)/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
$4.7^{+2.2}_{-1.8}$ OUR AVERAGE Error includes scale factor of 1.1.			
7.3±2.9	[17] DOLINSKY 89	ND	e^+e^-
$3.0^{+2.5}_{-1.8}$	[17] ANDREWS 77	CNTR	$6.7–10\ \gamma$ Cu
• • • We do not use the following data for averages, fits, limits, etc. • • •			
35 ±5	[18] DOLINSKY 89	ND	e^+e^-
29.0±7.0	[18] ANDREWS 77	CNTR	$6.7–10\ \gamma$ Cu

[17] Solution corresponding to constructive ω-ρ interference. The quark model predicts a relative decay phase of zero.
[18] Solution corresponding to destructive ω-ρ interference.

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma(\mu^+\mu^-)$ — Γ_7/Γ_{13}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.2±0.6	30	[19] DZHELYADIN 79	CNTR	$25–33\ \pi^- p$

[19] Superseded by DZHELYADIN 81B result above.

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.8942±0.0062	DOLINSKY 89	ND	e^+e^-

ω(783) REFERENCES

WEIDENAUER	90	ZPHY C47 353	+Duch, Heel, Kalinowsky+	(ASTERIX Collab.)
DOLINSKY	89	ZPHY C42 511	+Druzhinin, Dubrovin, Golubev+	(NOVO)
BITYUKOV	88B	SJNP 47 800	+Borisov, Viktorov, Golovkin+	(SERP)
		Translated from YAF 47 1258.		
DOLINSKY	88	SJNP 48 277	+Druzhinin, Dubrovin, Golubev+	(NOVO)
		Translated from YAF 48 442.		
KURDADZE	88	JETPL 47 512	+Leltchouk, Pakhtusova, Sidorov+	(NOVO)
		Translated from ZETFP 47 432.		
AULCHENKO	87	PL B186 432	+Dolinsky, Druzhinin, Dubrovin+	(NOVO)
BARKOV	87	JETPL 46 164	+Vasserman, Vorobev, Ivanov	(NOVO)
		Translated from ZETFP 46 132.		
KURDADZE	86	JETPL 43 643	+Lelchuk, Pakhtusova, Sidorov, Skrinskii+	(NOVO)
		Translated from ZETFP 43 497.		
BARKOV	85	NP B256 365	+Chilingarov, Eidelman, Khazin, Lelchuk+	(NOVO)
KURDADZE	84	IYAF 84-7 Preprint	+Leltchouk, Pakhtusova, Sidorov+	(NOVO)
KURDADZE	83B	JETPL 36 274	+Pakhtusova, Sidorov+	(NOVO)
		Translated from ZETFP 36 221.		
DZHELYADIN	81B	PL 102B 296	+Golovkin, Konstantinov+	(SERP)
CORDIER	80	NP B172 13	+Delcourt, Eschstruth, Fulda+	(LALO)
ROOS	80	LNC 27 321	+Pellinen	(HELS)
BENKHEIRI	79	NP B150 268	+Eisenstein+	(EPOL, CERN, CDEF, LALO)
DZHELYADIN	79	PL 84B 143	+Golovkin, Gritsuk+	(SERP)
COOPER	78B	NP B146 1	+Gurtu+	(TATA, CERN, CDEF, MADR)
QUENZER	78	PL 76B 512	+Ribes, Rumpf, Bertrand, Bizot, Chase+	(LALO)
VANAPEL...	78	NP B133 245	VanApeldoorn, Grundeman, Harting+	(ZEEM)
WICKLUND	78	PR D17 1197	+Ayres, Diebold, Greene, Kramer, Pawlicki	(ANL)
ANDREWS	77	PRL 38 198	+Fukushima, Harvey, Lobkowicz, May+	(ROCH)
GESSAROLI	77	NP B126 382	+	(BGNA, FIRZ, GENO, MILA, OXF, PAVI)
KEYNE	76	PR D14 28	+Binnie, Carr, Debenham, Garbutt+	(LOIC, SHMP)
Also	73B	PR D8 2789	Binnie, Carr, Debenham, Duane+	(LOIC, SHMP)
KALBFLEISCH	75	PR D11 987	+Strand, Chapman	(BNL, MICH)
AGUILAR-...	72B	PR D6 29	Aguilar-Benitez, Chung, Eisner, Samios	(BNL)
APEL	72B	PL 41B 234	+Auslander, Muller, Bertolucci+	(KARL, PISA)
BASILE	72B	Phil. Conf. 153	+Bollini, Broglin, Dalpiaz, Frabetti+	(CERN)
BENAKSAS	72B	PL 42B 507	+Cosme, Jean-Marie, Jullian	(ORSA)
BENAKSAS	72C	PL 42B 511	+Cosme, Jean-Marie, Jullian, Laplanche+	(ORSA)

BORENSTEIN	72	PR D5 1559	+Danburg, Kalbfleisch+	(BNL, MICH)
BROWN	72	PL 42B 117	+Downing, Holloway, Huld, Bernstein+	(ILL, ILLC)
DAKIN	72	PR D6 2321	+Hauser, Kreisler, Mischke	(PRIN)
RATCLIFF	72	PL 38B 345	+Bulos, Carnegie, Kluge, Leith, Lynch+	(SLAC)
ALVENSLEBEN	71C	PRL 27 888	+Becker, Busza, Chen, Cohen+	(DESY)
BALDIN	71	SJNP 13 758	+Yergakov, Trebukhovsky, Shishov	(ITEP)
		Translated from YAF 13 1318.		
BEHREND	71	PRL 27 61	+Lee, Nordberg, Wehmann+	(ROCH, CORN, FNAL)
BIZZARRI	71	NP B27 140	+Montanet, Nilsson, D'Andlau+	(CERN, CDEF)
COYNE	71	NP B32 333	+Butler, Fang-Landau, MacNaughton	(LRL)
MOFFEIT	71	NP B29 349	+Bingham, Fretter+	(LRL, UCB, SLAC, TUFT)
ABRAMOVI...	70	NP B20 209	Abramovich, Blumenfeld, Bruyant+	(CERN)
BIGGS	70B	PRL 24 1201	+Clifft, Gabathuler, Kitching, Rand	(DARE)
BIZZARRI	70	PRL 25 1385	+Ciapetti, Dore, Gaspero, Guidoni+	(ROMA, SYRA)
ROOS	70	DNPL/R7 173		(CERN)
Proc. Daresbury Study Weekend No. 1.				
AUGUSTIN	69D	PL 28B 513	+Benaksas, Buon, Gracco, Haissinski+	(ORSA)
BIZZARRI	69	NP B14 169	+Foster, Gavillet, Montanet+	(CERN, CDEF)
DEINET	69B	PL 30B 426	+Menzione, Muller, Buniatov+	(KARL, CERN)
JACQUET	69B	NC 63A 743	+Nguyen-Khac, Haatuft, Halsteinslid	(EPOL, BERG)
WILSON	69	Private Comm.		(HARV)
Also	69	PR 178 2095	Wehmann+	(HARV, CASE, SLAC, CORN, MCGI)
ASTVACAT...	68	PL 27B 45	Astvacaturov, Azimov, Baldin+	(JINR, MOSU)
BOLLINI	68C	NC 56A 531	+Buhler, Dalpiaz, Massam+	(CERN, BGNA, STRB)
BARASH	67B	PR 156 1399	+Kirsch, Miller, Tan	(COLU)
FELDMAN	67C	PR 159 1219	+Frati, Gleeson, Halpern, Nussbaum+	(PENN)
DIGIUGNO	66B	NC 44A 1272	+Peruzzi, Troise+	(NAPL, FRAS, TRST)
FLATTE	66	PR 145 1050	+Huwe, Murray, Button-Shafer, Solmitz+	(LRL)
JAMES	66	PR 142 896	+Kraybill	(YALE, BNL)
BARBARO-...	65	PRL 14 279	Barbaro-Galtieri, Tripp	(LRL)
BARMIN	64	JETP 18 1289	+Dolgolenko, Krestnikov+	(ITEP)
		Translated from ZETF 45 1879.		
KRAEMER	64	PR 136B 496	+Madansky, Fields+	(JHU, NWES, WOOD)
BUSCHBECK	63	Siena Conf. 1 166	+Czapp+	(VIEN, CERN, ANIK)

OTHER RELATED PAPERS

DOLINSKY	86	PL B174 453	+Druzhinin, Dubrovin, Eidelman+	(NOVO)
KURDADZE	83	JETPL 37 733	+Lelchuk, Pakhtusova+	(NOVO)
		Translated from ZETFP 37 613.		
ALFF-...	62B	PRL 9 325	Alff-Steinberger, Berley, Colley+	(COLU, RUTG)
ARMENTEROS	62	CERN Conf. 90	+Budde+	(CERN, CDEF, EPOL)
STEVENSON	62	PR 125 687	+Alvarez, Maglich, Rosenfeld	(LRL)
MAGLICH	61	PRL 7 178	+Alvarez, Rosenfeld, Stevenson	(LRL)
PEVSNER	61	PRL 7 421	+Kraemer, Nussbaum, Richardson+	(JHU)
XUONG	61	PRL 7 327	+Lynch	(LRL)

$\eta'(958)$

$I^G(J^{PC}) = 0^+(0^{-+})$

Our latest mini-review on this particle can be found in the 1984 edition. See also the mini-review under non-$q\bar{q}$ candidates. (See the index for the page number.)

$\eta'(958)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
957.75±0.14 OUR AVERAGE					
958 ±1	340	ARMSTRONG	91B	OMEG	300 $pp \to pp\eta\pi^+\pi^-$
958.2 ±0.4	622	AUGUSTIN	90	DM2	$J/\psi \to \gamma\eta\pi^+\pi^-$
957.8 ±0.2	2420	AUGUSTIN	90	DM2	$J/\psi \to \gamma\gamma\pi^+\pi^-$
956.3 ±1.0	143 ± 12	GIDAL	87	MRK2	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
957.46±0.33		DUANE	74	MMS	$\pi^- p \to n$ MM
958.2 ±0.5	1414	DANBURG	73	HBC	2.2 $K^- p \to \Lambda X^0$
958 ±1	400	JACOBS	73	HBC	2.9 $K^- p \to \Lambda X^0$
956.1 ±1.1	3415	BASILE	71	CNTR	1.6 $\pi^- p \to n X^0$
957.4 ±1.4	535	BASILE	71	CNTR	1.6 $\pi^- p \to n X^0$
957 ±1		RITTENBERG	69	HBC	1.7–2.7 $K^- p$

$\eta'(958)$ WIDTH

We include direct measurements of the $\eta'(958)$ total width and $\gamma\gamma$ partial width together with the measured branching ratios in the fit for the partial decay rates.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.198±0.019 OUR FIT Error includes scale factor of 1.4.						
0.28 ±0.10	1000	BINNIE	79	MMS	0	$\pi^- p \to n$ MM

$\eta'(958)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi^+\pi^-\eta$	(44.1 ±1.7) %	S=1.2
Γ_2	$\rho^0\gamma$	(30.0 ±1.4) %	S=1.1
Γ_3	$\pi^0\pi^0\eta$	(20.6 ±1.2) %	S=1.2
Γ_4	$\omega\gamma$	(3.00±0.30) %	
Γ_5	$\gamma\gamma$	(2.17±0.17) %	S=1.5
Γ_6	$3\pi^0$	(1.53±0.26) $\times 10^{-3}$	S=1.1
Γ_7	$\mu^+\mu^-\gamma$	(1.06±0.27) $\times 10^{-4}$	
Γ_8	$\pi^+\pi^-\pi^0$	< 5 %	CL=90%
Γ_9	$\pi^0\rho^0$	< 4 %	CL=90%
Γ_{10}	$\pi^+\pi^-$	< 2 %	CL=90%
Γ_{11}	$\pi^0 e^+e^-$	< 1.3 %	CL=90%
Γ_{12}	ηe^+e^-	< 1.1 %	CL=90%
Γ_{13}	$\pi^+\pi^+\pi^-\pi^-$	< 1 %	CL=90%
Γ_{14}	$\pi^+\pi^+\pi^-\pi^-$ neutrals	< 1 %	CL=95%
Γ_{15}	$\pi^+\pi^+\pi^-\pi^-\pi^0$	< 1 %	CL=90%
Γ_{16}	6π	< 1 %	CL=90%
Γ_{17}	$\pi^+\pi^- e^+e^-$	< 6 $\times 10^{-3}$	CL=90%
Γ_{18}	$\pi^0\pi^0$	< 9 $\times 10^{-4}$	CL=90%
Γ_{19}	$\pi^0\gamma\gamma$	< 8 $\times 10^{-4}$	CL=90%
Γ_{20}	$4\pi^0$	< 5 $\times 10^{-4}$	CL=90%
Γ_{21}	3γ	< 9 $\times 10^{-5}$	CL=90%
Γ_{22}	$\mu^+\mu^-\pi^0$	< 6.0 $\times 10^{-5}$	CL=90%
Γ_{23}	$\mu^+\mu^-\eta$	< 1.5 $\times 10^{-5}$	CL=90%
Γ_{24}	$\pi^+\pi^-\gamma$ (including $\rho^0\gamma$)		
Γ_{25}	e^+e^-	< 2.1 $\times 10^{-7}$	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to the total width, a partial width, 2 combinations of partial widths obtained from integrated cross section, and 16 branching ratios uses 42 measurements and one constraint to determine 7 parameters. The overall fit has a $\chi^2 = 31.3$ for 36 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−57					
x_3	−62	−27				
x_4	−25	−23	33			
x_5	−18	−9	18	5		
x_6	−23	−10	35	11	6	
Γ	33	−12	−18	−2	−87	−6
	x_1	x_2	x_3	x_4	x_5	x_6

	Mode	Rate (MeV)	Scale factor
Γ_1	$\pi^+\pi^-\eta$	0.087 ±0.010	1.3
Γ_2	$\rho^0\gamma$	0.059 ±0.006	1.4
Γ_3	$\pi^0\pi^0\eta$	0.041 ±0.004	1.6
Γ_4	$\omega\gamma$	0.0059 ±0.0008	1.2
Γ_5	$\gamma\gamma$	0.00429±0.00019	1.1
Γ_6	$3\pi^0$	(3.0 ±0.6) $\times 10^{-4}$	1.2

$\eta'(958)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ — Γ_5

VALUE (keV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
4.29±0.19 OUR FIT Error includes scale factor of 1.1.					
4.30±0.27 OUR AVERAGE					
3.62±0.14±0.48		[1] BEHREND	91	CELL	$e^+e^- \to e^+e^-\eta'(958)$
4.6 ±1.1 ±0.6	23	BARU	90	MD1	$e^+e^- \to e^+e^-\pi^+\pi^-\gamma$
4.57±0.25±0.44		BUTLER	90	MRK2	$e^+e^- \to e^+e^-\eta'(958)$
4.94±0.23±0.72	547	[2] ROE	90	ASP	$e^+e^- \to e^+e^-2\gamma$
3.8 ±0.7 ±0.6	34	AIHARA	88C	TPC	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
4.8 ±0.5 ±0.5	136 ± 14	[2] WILLIAMS	88	CBAL	$e^+e^- \to e^+e^-2\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.7 ±0.6 ±0.9	143 ± 12	[3] GIDAL	87	MRK2	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
4.0 ±0.9		[4] BARTEL	85E	JADE	$e^+e^- \to e^+e^-2\gamma$

[1] Using B($\eta' \to \rho(770)\gamma$) = (0.301 ± 0.014)%.
[2] Using B($\eta' \to \gamma\gamma$) = (2.17 ± 0.17)%.
[3] Superseded by BUTLER 90.
[4] Systematic error not evaluated.

$\eta'(958)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(total)$

This combination of a partial width with the partial width into $\gamma\gamma$ and with the total width is obtained from the integrated cross section into channel(i) in the $\gamma\gamma$ annihilation.

$\Gamma(\gamma\gamma) \times \Gamma(\rho^0\gamma)/\Gamma_{total}$ — $\Gamma_5\Gamma_2/\Gamma$

VALUE (keV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.29±0.06 OUR FIT Error includes scale factor of 1.2.					
1.26±0.07 OUR AVERAGE Error includes scale factor of 1.2.					
1.09±0.04±0.13		BEHREND	91	CELL	$e^+e^- \to e^+e^-\rho(770)^0\gamma$
1.35±0.09±0.21		AIHARA	87	TPC	$e^+e^- \to e^+e^-\rho\gamma$
1.13±0.04±0.13	867 ± 30	ALBRECHT	87B	ARG	$e^+e^- \to e^+e^-\rho\gamma$

$1.53\pm0.09\pm0.21$		ALTHOFF	84E	TASS	$e^+e^- \to e^+e^-\rho\gamma$
$1.14\pm0.08\pm0.11$	243 ± 16.5	BERGER	84B	PLUT	$e^+e^- \to e^+e^-\rho\gamma$
$1.73\pm0.34\pm0.35$	95	JENNI	83	MRK2	$e^+e^- \to e^+e^-\rho\gamma$
$1.49\pm0.13\pm0.027$	213	BARTEL	82B	JADE	$e^+e^- \to e^+e^-\rho\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.85\pm0.31\pm0.24$	43	BEHREND	83B	CELL	$e^+e^- \to e^+e^-\rho\gamma$

$\Gamma(\gamma\gamma) \times \Gamma(\pi^0\pi^0\eta)/\Gamma_{total}$ — $\Gamma_5\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.88±0.07 OUR FIT	Error includes scale factor of 1.1.			
0.95±0.05±0.08	[5] KARCH	90	CBAL	$e^+e^- \to e^+e^-\eta\pi^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.00\pm0.08\pm0.10$	[5,6] ANTREASYAN	87	CBAL	$e^+e^- \to e^+e^-\eta\pi^0\pi^0$

[5] Using BR($\eta \to 2\gamma$)=(38.9 ± 0.5)%.
[6] Superseded by KARCH 90.

$\eta'(958)$ α PARAMETER

$|\text{MATRIX ELEMENT}|^2 = (1+\alpha y)^2 + \alpha^2$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.061±0.012 OUR AVERAGE				
-0.058 ± 0.013	[7] ALDE	86	GAM4	$38\ \pi^-p \to n\eta2\pi^0$
$-0.08\ \pm0.03$	[7] KALBFLEISCH	74	RVUE	$\eta' \to \eta\pi^+\pi^-$

[7] May not necessarily be the same for $\eta' \to \eta\pi^+\pi^-$ and $\eta' \to \eta\pi^0\pi^0$.

$\eta'(958)$ BRANCHING RATIOS

$\Gamma(\pi^+\pi^-\eta(\text{neutral decay}))/\Gamma_{total}$ — $0.709\Gamma_1/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.313±0.012 OUR FIT	Error includes scale factor of 1.2.				
0.314±0.026	281	RITTENBERG	69	HBC	1.7–2.7 K^-p

$\Gamma(\pi^+\pi^-\ \text{neutrals})/\Gamma_{total}$ — $(0.709\Gamma_1+0.291\Gamma_3+0.9\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.400±0.010 OUR FIT	Error includes scale factor of 1.1.				
0.36 ±0.05 OUR AVERAGE					
0.4 ±0.1	39	LONDON	66	HBC	2.2 K^-p
0.35 ±0.06	33	BADIER	65B	HBC	3 K^-p

$\Gamma(\pi^+\pi^-\eta(\text{charged decay}))/\Gamma_{total}$ — $0.291\Gamma_1/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.128±0.005 OUR FIT	Error includes scale factor of 1.2.				
0.116±0.013 OUR AVERAGE					
0.123±0.014	107	RITTENBERG	69	HBC	1.7–2.7 K^-p
0.1 ±0.04	10	LONDON	66	HBC	2.2 K^-p
0.07 ±0.04	7	BADIER	65B	HBC	3 K^-p

$[\Gamma(\pi^0\pi^0\eta\ (\text{charged decay})) + \Gamma(\omega\ (\text{charged decay})\ \gamma)]/\Gamma_{total}$ — $(0.291\Gamma_3+0.9\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.087±0.005 OUR FIT	Error includes scale factor of 1.2.				
0.045±0.029	42	RITTENBERG	69	HBC	1.7–2.7 K^-p

$\Gamma(\text{neutrals})/\Gamma_{total}$ — $(0.709\Gamma_3+0.09\Gamma_4+\Gamma_5)/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.170±0.009 OUR FIT	Error includes scale factor of 1.2.				
0.187±0.017 OUR AVERAGE					
0.185±0.022	535	BASILE	71	CNTR	1.6 $\pi^-p \to nX^0$
0.189±0.026	123	RITTENBERG	69	HBC	1.7–2.7 K^-p

$\Gamma(\rho^0\gamma)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.300±0.014 OUR FIT	Error includes scale factor of 1.1.				
0.319±0.030 OUR AVERAGE					
0.329±0.033	298	RITTENBERG	69	HBC	1.7–2.7 K^-p
0.2 ±0.1	20	LONDON	66	HBC	2.2 K^-p
0.34 ±0.09	35	BADIER	65B	HBC	3 K^-p

$\Gamma(\rho^0\gamma)/\Gamma(\pi\pi\eta)$ — $\Gamma_2/(\Gamma_1+\Gamma_3)$

VALUE	DOCUMENT ID		TECN	COMMENT
0.464±0.030 OUR FIT	Error includes scale factor of 1.1.			
0.31 ±0.15	DAVIS	68	HBC	5.5 K^-p

$\Gamma(\pi^0 e^+e^-)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.013	90	RITTENBERG	65	HBC	2.7 K^-p

$\Gamma(\eta e^+e^-)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.011	90	RITTENBERG	65	HBC	2.7 K^-p

$\Gamma(\pi^0\rho^0)/\Gamma_{total}$ — Γ_9/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.04	90	RITTENBERG	65	HBC	2.7 K^-p

$\Gamma(\pi^+\pi^-e^+e^-)/\Gamma_{total}$ — Γ_{17}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.006	90	RITTENBERG	65	HBC	2.7 K^-p

$\Gamma(6\pi)/\Gamma_{total}$ — Γ_{16}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.01	90	LONDON	66	HBC	Compilation

$\Gamma(\omega\gamma)/\Gamma(\pi^+\pi^-\eta)$ — Γ_4/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.068±0.008 OUR FIT	Error includes scale factor of 1.1.				
0.068±0.013	68	ZANFINO	77	ASPK	8.4 π^-p

$\Gamma(\rho^0\gamma)/[\Gamma(\pi^+\pi^-\eta) + \Gamma(\pi^0\pi^0\eta) + \Gamma(\omega\gamma)]$ — $\Gamma_2/(\Gamma_1+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	COMMENT
0.443±0.029 OUR FIT	Error includes scale factor of 1.1.			
0.25 ±0.14	DAUBER	64	HBC	1.95 K^-p

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0217±0.0017 OUR FIT	Error includes scale factor of 1.5.				
0.0196±0.0015 OUR AVERAGE					
0.0200±0.0018		[8] STANTON	80	SPEC	8.45 $\pi^-p \to n\pi^+\pi^-2\gamma$
0.025 ±0.007		DUANE	74	MMS	$\pi^-p \to n$ MM
0.0171±0.0033	68	DALPIAZ	72	CNTR	1.6 $\pi^-p \to nX^0$
$0.020\ ^{+0.008}_{-0.006}$	31	HARVEY	71	OSPK	3.65 $\pi^-p \to nX^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.018 ±0.002	6000	[9] APEL	79	NICE	15–40 $\pi^-p \to n2\gamma$

[8] Includes APEL 79 result.
[9] Data is included in STANTON 80 evaluation.

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_{25}/Γ

VALUE (units 10^{-7})	CL%	DOCUMENT ID		TECN	COMMENT
<2.1	90	VOROBYEV	88	ND	$e^+e^- \to \pi^+\pi^-\eta$

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	RITTENBERG	69	HBC	1.7–2.7 K^-p
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.08	95	DANBURG	73	HBC	2.2 $K^-p \to \Lambda X^0$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_8/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.05	90	RITTENBERG	69	HBC	1.7–2.7 K^-p
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.09	95	DANBURG	73	HBC	2.2 $K^-p \to \Lambda X^0$

$\Gamma(\pi^+\pi^+\pi^-\pi^-\ \text{neutrals})/\Gamma_{total}$ — Γ_{14}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.01	95	DANBURG	73	HBC	2.2 $K^-p \to \Lambda X^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.01	90	RITTENBERG	69	HBC	1.7–2.7 K^-p

$\Gamma(\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{total}$ — Γ_{15}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.01	90	RITTENBERG	69	HBC	1.7–2.7 K^-p

$\Gamma(\pi^+\pi^+\pi^-\pi^-)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.01	90	RITTENBERG	69	HBC	1.7–2.7 K^-p

$\Gamma(\rho^0\gamma)/\Gamma(\pi^+\pi^-\gamma\ (\text{including}\ \rho^0\gamma))$ — Γ_2/Γ_{24}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.08±0.08 OUR AVERAGE					
1.15±0.10	473	DANBURG	73	HBC	2.2 $K^-p \to \Lambda X^0$
1.01±0.15	137	JACOBS	73	HBC	2.9 $K^-p \to \Lambda X^0$
0.94±0.20		AGUILAR-...	70D	HBC	3.9–4.6 K^-p

$\Gamma(\pi^0\pi^0\eta\ (3\pi^0\ \text{decay}))/\Gamma_{total}$ — $0.319\Gamma_3/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.066±0.004 OUR FIT	Error includes scale factor of 1.2.				
0.11 ±0.06	4	BENSINGER	70	DBC	2.2 π^+d

$\Gamma(\rho^0\gamma)/\Gamma(\pi^+\pi^-\eta(\text{neutral decay}))$ — $\Gamma_2/0.709\Gamma_1$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.96±0.07 OUR FIT	Error includes scale factor of 1.2.				
0.99±0.11 OUR AVERAGE					
0.92±0.14	473	DANBURG	73	HBC	2.2 $K^-p \to \Lambda X^0$
1.11±0.18	192	JACOBS	73	HBC	2.9 $K^-p \to \Lambda X^0$

$\Gamma(\gamma\gamma)/\Gamma(\pi^0\pi^0\eta(\text{neutral decay}))$ — $\Gamma_5/0.709\Gamma_3$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.149±0.013 OUR FIT	Error includes scale factor of 1.7.				
0.188±0.058	16	APEL	72	OSPK	3.8 $\pi^-p \to nX^0$

$\Gamma(\mu^+\mu^-\gamma)/\Gamma(\gamma\gamma)$ — Γ_7/Γ_5

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
4.9±1.2	33	VIKTOROV	80	CNTR	25,33 $\pi^- p \to 2\mu\gamma$

$\Gamma(\mu^+\mu^-\eta)/\Gamma_{total}$ — Γ_{23}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<1.5	90	DZHELYADIN	81	CNTR	30 $\pi^- p \to \eta' n$

$\Gamma(\mu^+\mu^-\pi^0)/\Gamma_{total}$ — Γ_{22}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<6.0	90	DZHELYADIN	81	CNTR	30 $\pi^- p \to \eta' n$

$\Gamma(3\pi^0)/\Gamma(\pi^0\pi^0\eta)$ — Γ_6/Γ_3

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
74±12 OUR FIT				
74±12 OUR AVERAGE				
74±15	ALDE	87B	GAM2	38 $\pi^- p \to n6\gamma$
75±18	BINON	84	GAM2	30–40 $\pi^- p \to n6\gamma$

$\Gamma(\gamma\gamma)/\Gamma(\pi^0\pi^0\eta)$ — Γ_5/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
0.105±0.009 OUR FIT	Error includes scale factor of 1.7.			
0.112±0.002±0.006	ALDE	87B	GAM2	38 $\pi^- p \to n2\gamma$

$\Gamma(\omega\gamma)/\Gamma(\pi^0\pi^0\eta)$ — Γ_4/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
0.146±0.014 OUR FIT				
0.147±0.016	ALDE	87B	GAM2	38 $\pi^- p \to n4\gamma$

$\Gamma(3\gamma)/\Gamma(\pi^0\pi^0\eta)$ — Γ_{21}/Γ_3

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<4.6	90	ALDE	87B	GAM2	38 $\pi^- p \to n3\gamma$

$\Gamma(\pi^0\gamma\gamma)/\Gamma(\pi^0\pi^0\eta)$ — Γ_{19}/Γ_3

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<37	90	ALDE	87B	GAM2	38 $\pi^- p \to n4\gamma$

$\Gamma(\pi^0\pi^0)/\Gamma(\pi^0\pi^0\eta)$ — Γ_{18}/Γ_3

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<45	90	ALDE	87B	GAM2	38 $\pi^- p \to n4\gamma$

$\Gamma(4\pi^0)/\Gamma(\pi^0\pi^0\eta)$ — Γ_{20}/Γ_3

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<23	90	ALDE	87B	GAM2	38 $\pi^- p \to n8\gamma$

$\eta'(958)$ C-NONCONSERVING DECAY PARAMETER

See the note on η decay parameters in the Stable Particle Full Listings for definition of this parameter.

DECAY ASYMMETRY PARAMETER FOR $\pi^+\pi^-\gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.01 ±0.04 OUR AVERAGE					
−0.019±0.056		AIHARA	87	TPC	$2\gamma \to \pi^+\pi^-\gamma$
−0.069±0.078	295	GRIGORIAN	75	STRC	2.1 $\pi^- p$
0.00 ±0.10	103	KALBFLEISCH	75	HBC	2.2 $K^- p$
0.07 ±0.08	152	RITTENBERG	65	HBC	2.1–2.7 $K^- p$

$\eta'(958)$ REFERENCES

ARMSTRONG	91B	ZPHY C52 389	+Barnes+	(ATHU, BARI, BIRM, CERN, CDEF)
BEHREND	91	ZPHY C49 401	+Criegee, Field, Franke+	(CELLO Collab.)
AUGUSTIN	90	PR D42 10	+Cosme+	(DM2 Collab.)
BARU	90	ZPHY C48 581	+Blinov, Blinov+	(MD-1 Collab.)
BUTLER	90	PR D42 1368	+Boyer+	(Mark II Collab.)
KARCH	90	PL B249 353	+Antreasyan, Bartels+	(Crystal Ball Collab.)
ROE	90	PR D41 17	+Bartha, Burke, Garbincius+	(ASP Collab.)
AIHARA	88C	PR D38 1	+Alston-Garnjost+	(TPC-2γ Collab.)
VOROBYEV	88	SJNP 48 273	+Golubev, Dolinsky, Druzhinin+	(NOVO)
		Translated from YAF 48 436.		
WILLIAMS	88	PR D38 1365	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
AIHARA	87	PR D35 2650	+Alston-Garnjost+	(TPC-2γ Collab.) JP
ALBRECHT	87B	PL B199 457	+Andam, Binder+	(ARGUS Collab.)
ALDE	87B	ZPHY C36 603	+Binon, Bricman+	(LANL, BELG, SERP, LAPP)
ANTREASYAN	87	PR D36 2633	+Bartels, Besset+	(Crystal Ball Collab.)
GIDAL	87	PRL 59 2012	+Boyer, Butler, Cords, Abrams+	(LBL, SLAC, HARV)
ALDE	86	PL B177 115	+Binon, Bricman+	(SERP, BELG, LANL, LAPP)
BARTEL	85E	PL 160B 421	+Becker, Cords, Felst+	(JADE Collab.)
ALTHOFF	84E	PL 147B 487	+Braunschweig, Kirschfink, Luebelsmeyer+	(TASSO Collab.)
BERGER	84B	PL 142B 125		(AACH, BERG, DESY, GLAS, HAMB, UMD, SIEG+)
BINON	84	PL 140B 264	+Donskov, Duteil+	(SERP, BELG, LAPP, CERN)
BEHREND	83B	PL 125B 518	+D'Agostini+	(DESY, KARL, MPIM, LALO, LPNP+)
Also	82C	PL 114B 378	Behrend, Chen, Fenner, Field+	(CELLO Collab.)
JENNI	83	PR D27 1031	+Burke, Telnov, Abrams, Blocker+	(SLAC, LBL)
BARTEL	82B	PL 113B 190	+Cords+	(DESY, HAMB, HEID, LANC, MCHS+)
DZHELYADIN	81	PL 105B 239	+Golovkin, Konstantinov, Kubarovski+	(SERP)
STANTON	80	PL 92 B 353	+Edwards, Legacey+	(OSU, CARL, MCGI, TNTO)
VIKTOROV	80	SJNP 32 520	+Golovkin, Dzhelyadin, Zaitsev, Mukhin+	(SERP)
		Translated from YAF 32 1005.		
APEL	79	PL 83B 131	+Augenstein, Bertolucci	(KARL, PISA, SERP, WIEN)
BINNIE	79	PL 83B 141	+Carr, Debenham, Jones, Karami, Keyne+	(LOIC)
ZANFINO	77	PRL 38 930	+Brockman+	(CARL, MCGI, OHIO, TNTO)
GRIGORIAN	75	NP B91 232	+Ladage, Mellema, Rudnick+	(UCLA)
KALBFLEISCH	75	PR D11 987	+Strand, Chapman	(BNL, MICH)
DUANE	74	PRL 32 425	+Binnie, Camilleri, Carr+	(LOIC, SHMP)
KALBFLEISCH	74	PR D10 916		(BNL)
DANBURG	73	PR D8 3744	+Kalbfleisch, Borenstein, Chapman+	(BNL, MICH) JP
JACOBS	73	PR D8 18	+Chang, Gauthier+	(BRAN, UMD, SYRA, TUFT) JP
APEL	72	PL 40B 680	+Auslander, Muller, Bertolucci+	(KARL, PISA)
DALPIAZ	72	PL 42B 377	+Frabetti, Massam, Navarria, Zichichi	(CERN)
BASILE	71	NC 3A 371	+Bollini, Dalpiaz, Frabetti+	(CERN, BGNA, STRB)
HARVEY	71	PRL 27 885	+Marquit, Peterson, Rhoades+	(MINN, MICH)
AGUILAR-...	70D	PRL 25 1635	Aguilar-Benitez, Bassano, Samios, Barnes+	(BNL)
BENSINGER	70	PL 33B 505	+Erwin, Thompson, Walker	(WISC)
RITTENBERG	69	UCRL 18863 Thesis		(LRL) I
DAVIS	68	PL 27B 532	+Ammar, Mott, Dagan, Derrick+	(NWES, ANL)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA) IJP
BADIER	65B	PL 17 337	+Demoulin, Barloutaud+	(EPOL, SACL, AMST)
RITTENBERG	65	PRL 15 556	+Kalbfleisch	(LRL, BNL)
DAUBER	64	PRL 13 449	+Slater, Smith, Stork, Ticho	(UCLA) JP
Also	64B	Dubna Conf. 1 418	Dauber, Slater, Smith, Stork, Ticho	(UCLA)

OTHER RELATED PAPERS

BEHREND	91	ZPHY C49 401	+Criegee, Field, Franke+	(CELLO Collab.)
BICKERSTAFF	82	ZPHY C16 171	+McKellar	(MELB)
KIENZLE	65	PL 19 438	+Maglich, Levrat, Lefebvres+	(CERN)
TRILLING	65	PL 19 427	+Brown, Goldhaber, Kadyk, Scanio	(LRL)
GOLDBERG	64	PRL 12 546	+Gundzik, Lichtman, Connolly, Hart+	(SYRA, BNL)
GOLDBERG	64B	PRL 13 249	+Gundzik, Leitner, Connolly, Hart+	(SYRA, BNL)
KALBFLEISCH	64	PRL 12 527	+Alvarez, Barbaro-Galtieri+	(LRL) JP
KALBFLEISCH	64B	PRL 13 349	+Dahl, Rittenberg	(LRL) JP

$f_0(975)$

was $S(975)$

$I^G(J^{PC}) = 0^+(0^{++})$

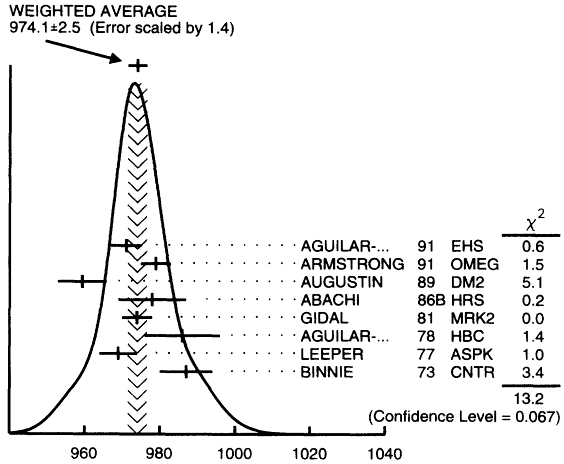
For early work using Breit-Wigner or scattering length parametrization in fits to the $K\overline{K}$ mass spectrum, see reference section and our 1972 edition.

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

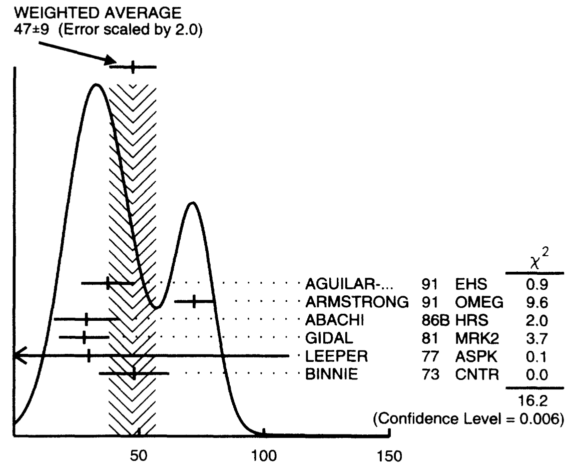
$f_0(975)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
974.1± 2.5 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.			
971.1± 4.0	[1] AGUILAR-...	91	EHS	400pp
979 ± 4	[2] ARMSTRONG	91	OMEG	300 $pp \to pp\pi\pi, ppKK$
959.4± 6.5	[1] AUGUSTIN	89	DM2	$J/\psi \to \omega\pi^+\pi^-$
978 ± 9	[1] ABACHI	86B	HRS	$e^+e^- \to \pi^+\pi^-$
974 ± 4	[2] GIDAL	81	MRK2	J/ψ decay
986 ±10	[2] AGUILAR-...	78	HBC	0.7 $\overline{p}p \to K^0_S K^0_S$
969 ± 5	[2] LEEPER	77	ASPK	2–2.4 $\pi^- p$
987 ± 7	[2] BINNIE	73	CNTR	$\pi^- p \to n$ MM
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 985	[3] MORGAN	91	RVUE	$\pi\pi(K\overline{K}) \to \pi\pi(K\overline{K})$, $J/\psi \to \phi\pi\pi(K\overline{K})$, $D_s \to \pi(\pi\pi)$
~ 969	[4] MORGAN	91	RVUE	$\pi\pi(K\overline{K}) \to \pi\pi(K\overline{K})$, $J/\psi \to \phi\pi\pi(K\overline{K})$, $D_s \to \pi(\pi\pi)$
~ 970	[5] MORGAN	91	RVUE	$\pi\pi(K\overline{K}) \to \pi\pi(K\overline{K})$, $J/\psi \to \phi\pi\pi(K\overline{K})$, $D_s \to \pi(\pi\pi)$
956 ±12	BREAKSTONE	90	SFM	$pp \to pp\pi^+\pi^-$
$985.0^{+9.0}_{-39.0}$	ETKIN	82B	MPS	23 $\pi^- p \to n2K^0_S$
985	[6] TORNQVIST	82	RVUE	
975	[6] ACHASOV	80	RVUE	
1012 ± 6	[7] GRAYER	73	ASPK	17 $\pi^- p \to \pi^+\pi^- n$
1007 ±20	[7] HYAMS	73	ASPK	17 $\pi^- p \to \pi^+\pi^- n$
997 ± 6	[7] PROTOPOP...	73	HBC	7 $\pi^+ p \to \pi^+ p\pi^+\pi^-$

[1] From invariant mass fit.
[2] From coupled channel analysis.
[3] On sheet II in a 2 pole solution.
[4] On sheet III in a 2 pole solution.
[5] On sheet II in a one pole solution. A better fit is obtained with a two pole solution.
[6] Coupled channel analysis with finite width corrections.
[7] Included in AGUILAR-BENITEZ 78 fit.



$f_0(975)$ mass (MeV)



$f_0(975)$ width (MeV)

$f_0(975)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
47 ± 9 OUR AVERAGE	Error includes scale factor of 2.0. See the ideogram below.		
37.4 ± 10.6	[8] AGUILAR-... 91	EHS	400pp
72 ± 8	[9] ARMSTRONG 91	OMEG	300 $pp \to pp\pi\pi, ppK\overline{K}$
29 ± 13	[8] ABACHI 86B	HRS	$e^+e^- \to \pi^+\pi^-$
28 ± 10	[9] GIDAL 81	MRK2	J/ψ decay
30 ± 80	[9] LEEPER 77	ASPK	2–2.4 $\pi^- p$
48 ± 14	[9] BINNIE 73	CNTR	$\pi^- p \to n$ MM
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 64	[10] MORGAN 91	RVUE	$\pi\pi(K\overline{K}) \to \pi\pi(K\overline{K})$, $J/\psi \to \phi\pi\pi(K\overline{K})$, $D_s \to \pi(\pi\pi)$
~ 66	[11] MORGAN 91	RVUE	$\pi\pi(K\overline{K}) \to \pi\pi(K\overline{K})$, $J/\psi \to \phi\pi\pi(K\overline{K})$, $D_s \to \pi(\pi\pi)$
~ 84	[12] MORGAN 91	RVUE	$\pi\pi(K\overline{K}) \to \pi\pi(K\overline{K})$, $J/\psi \to \phi\pi\pi(K\overline{K})$, $D_s \to \pi(\pi\pi)$
110 ± 30	BREAKSTONE 90	SFM	$pp \to pp\pi^+\pi^-$
120 ± 281 ± 20	ETKIN 82B	MPS	23 $\pi^- p \to n2K^0_S$
~ 400	TORNQVIST 82	RVUE	
70 to 300	ACHASOV 80	RVUE	
100 ± 80	[13] AGUILAR-... 78	HBC	0.7 $\overline{p}p \to K^0_S K^0_S$
32 ± 10	[14] GRAYER 73	ASPK	17 $\pi^- p \to \pi^+\pi^- n$
30 ± 10	[14] HYAMS 73	ASPK	17 $\pi^- p \to \pi^+\pi^- n$
54 ± 16	[14] PROTOPOP... 73	HBC	7 $\pi^+ p \to \pi^+ p\pi^+\pi^-$

[8] From invariant mass fit.
[9] From coupled channel analysis.
[10] On sheet II in a 2 pole solution.
[11] On sheet III in a 2 pole solution.
[12] On sheet II in a one pole solution. A better fit is obtained with a two pole solution.
[13] From coupled channel fit to the HYAMS 73 and PROTOPOPESCU 73 data. With a simultaneous fit to the $\pi\pi$ phase-shifts, inelasticity and to the $K^0_S K^0_S$ invariant mass.
[14] Included in AGUILAR-BENITEZ 78 fit.

$f_0(975)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\pi\pi$	(78.1 ± 2.4) %	
Γ_2	$K\overline{K}$	(21.9 ± 2.4) %	
Γ_3	$\eta\eta$		
Γ_4	$\gamma\gamma$	(1.19±0.33) × 10^{-5}	
Γ_5	e^+e^-	< 3 × 10^{-7}	90%

CONSTRAINED FIT INFORMATION

An overall fit to a branching ratio uses 3 measurements and one constraint to determine 2 parameters. The overall fit has a $\chi^2 =$ 2.0 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−100
	x_1

$f_0(975)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ — Γ_4

VALUE (KeV)	EVTS	DOCUMENT ID	TECN	COMMENT
0.56±0.11 OUR AVERAGE				
0.63±0.14		[15] MORGAN 90	RVUE	$\gamma\gamma \to \pi^+\pi^-$, $\pi^0\pi^0$
0.42±0.06±0.18	60 ± 8	[16] OEST 90	JADE	$e^+e^- \to e^+e^-\pi^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.29±0.07±0.12		[17,18] BOYER 90	MRK2	$e^+e^- \to e^+e^-\pi^+\pi^-$
0.31±0.14±0.09		[17,18] MARSISKE 90	CBAL	$e^+e^- \to e^+e^-\pi^0\pi^0$

[15] From amplitude analysis of BOYER 90 and MARSISKE 90, data corresponds to resonance parameters $m = 989$ MeV, $\Gamma = 61$ MeV.
[16] OEST 90 quote systematic errors $^{+0.08}_{-0.18}$. We use ±0.18.
[17] From analysis allowing arbitrary background unconstrained by unitarity.
[18] Data included in MORGAN 90 analysis.

$\Gamma(e^+e^-)$ — Γ_5

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
<8.4	90	VOROBYEV 88	ND	$e^+e^- \to \pi^0\pi^0$

$f_0(975)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/[\Gamma(\pi\pi) + \Gamma(K\overline{K})]$ — $\Gamma_1/(\Gamma_1+\Gamma_2)$

VALUE	DOCUMENT ID	TECN	COMMENT
0.781±0.024 OUR FIT			
$0.781^{+0.027}_{-0.023}$ OUR AVERAGE			
0.67 ±0.09	[19] LOVERRE 80	HBC	4 $\pi^- p \to K\overline{K}N$
0.81 $^{+0.09}_{-0.04}$	[19] CASON 78	STRC	7 $\pi^- p \to n2K^0_S$
0.78 ±0.03	[19] WETZEL 76	OSPK	8.9 $\pi^- p \to n2K^0_S$

[19] Measure $\pi\pi$ elasticity assuming two resonances coupled to the $\pi\pi$ and $K\overline{K}$ channels only.

$f_0(975)$ REFERENCES

AGUILAR-...	91	ZPHY C50 405	Aguilar-Benitez, Allison, Batalor+	(LEBC-EHS Collab.)
ARMSTRONG	91	ZPHY C51 351	+Benayoun+	(ATHU, BARI, BIRM, CERN, CDEF)
MORGAN	91	PL B258 444	+Pennington	(RAL, DURH)
BOYER	90	PR D42 1350	+Butler+	(Mark II Collab.)
BREAKSTONE	90	ZPHY C48 569	+	(ISU, BGNA, CERN, DORT, HEID, WARS)
MARSISKE	90	PR D41 3324	+Antreasyan+	(Crystal Ball Collab.)
MORGAN	90	ZPHY C48 623	+Pennington	(RAL, DURH)
OEST	90	ZHPY C47 343	+Olsson+	(JADE Collab.)
AUGUSTIN	89	NP B320 1	+Cosme	(DM2 Collab.)
VOROBYEV	88	SJNP 48 273	+Golubev, Dolinsky, Druzhinin+	(NOVO)
		Translated from YAF 48 436.		
ABACHI	86B	PRL 57 1990	+Derrick, Blockus+	(PURD, ANL, IND, MICH, LBL)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFT, VAND)
TORNQVIST	82	PRL 49 624		(HELS)
GIDAL	81	PL 107B 153	+Goldhaber, Guy, Millikan, Abrams+	(SLAC, LBL)
ACHASOV	80	SJNP 32 566	+Devyanin, Shestakov	(NOVO)
		Translated from YAF 32 1098.		
LOVERRE	80	ZPHY C6 187	+Armenteros, Dionisi+	(CERN, CDEF, MADR, STOH) IJP
AGUILAR-...	78	NP B140 73	Aguilar-Benitez, Cerrada+	(MADR, BOMB, CERN+)
CASON	78	PRL 41 271	+Baumbaugh, Bishop, Biswas+	(NDAM, ANL)
LEEPER	77	PR D16 2054	+Buttram, Crawley, Duke, Lamb, Peterson	(ISU)
WETZEL	76	NP B115 208	+Freudenreich, Beusch+	(ETH, CERN, LOIC)
BINNIE	73	PRL 31 1534	+Carr, Debenham, Duane, Garbutt+	(LOIC, SHMP)
GRAYER	73	Tallahassee	+Hyams, Jones, Blum, Dietl, Koch+	(CERN, MPIM)
HYAMS	73	NP B64 134	+Jones, Weilhammer, Blum, Dietl+	(CERN, MPIM)
PROTOPOP...	73	PR D7 1280	Protopopescu, Alston-Garnjost, Galtieri, Flatte+	(LBL)

OTHER RELATED PAPERS

AU	87	PR D35 1633	+Morgan, Pennington	(DURH, RAL)
AKESSON	86	NP B264 154	+Albrow, Almehed+	(Axial Field Spec. Collab.)
MENNESSIER	83	ZPHY C16 241		(MONP)
BARBER	82	ZPHY C12 1	+Dainton, Brodbeck, Brookes+	(DARE, LANC, SHEF)
ETKIN	82C	PR D25 2446	+Foley, Lai+	(BNL, CUNY, TUFT, VAND)
BIGI	62	CERN Conf. 247	+Brandt, Carrara+	(CERN)
BINGHAM	62	CERN Conf. 240	+Bloch+	(EPOL, CERN)
ERWIN	62	PRL 9 34	+Hoyer, March, Walker, Wangler	(WISC, BNL)
WANG	61	JETP 13 323	+Veksler, Vrana+	(JINR)
		Translated from ZETF 40 464.		

$a_0(980)$

was $\delta(980)$

$I^G(J^{PC}) = 1^-(0^{++})$

NOTE ON THE $a_0(980)$

A conventional $q\bar{q}$ assignment of this scalar meson still remains an intriguing question.

Its observed mass and width are inconsistent, *a priori*, with the properties expected of a member of an $L = 1$ $q\bar{q}$ nonet. However, since the mass and width are distorted by the proximity of the $K\bar{K}$ threshold, its nature can be better investigated using different experimental observations.

TORNQVIST 82 has shown that it is possible to understand the unusual experimental features of this particle within a unitarized quark model. As with the $f_0(975)$, the $a_0(980)$ can be interpreted as a normal $q\bar{q}$ resonance with a large admixture of $K\bar{K}$, $\eta\pi$, and $\eta'\pi$ continuum state.

Assuming the dominance of the decay $\eta'(958) \to \eta\pi\pi$ via a virtual $a_0(980)\pi$ intermediate state, BRAMON 80 concludes that the experimental value $\Gamma(\eta'(958) \to \eta\pi\pi) \approx 200$ keV is fully consistent with a $q\bar{q}$ interpretation. The same analysis finds additional evidence in favor of a $q\bar{q}$ interpretation of the $a_0(980)$: in fact, if the $a_0(980)$ is a $q\bar{q}$ state, one expects that the decay chain $f_1 \to a_0(980)\pi \to \eta\pi\pi$ is more important for the $f_1(1285)$ than for the $f_1(1420)$, the reverse being true if the $a_0(980)$ were a $q\bar{q}q\bar{q}$ state with a strange quark component. In practice, the $f_1(1285) \to a_0(980)\pi \to \eta\pi\pi$ is observed, while the $f_1(1420) \to a_0(980)\pi \to \eta\pi\pi$ is (practically) absent.

The main argument in favor of the interpretation of this particle as a $q\bar{q}q\bar{q}$ state is its almost complete degeneracy in mass with the isoscalar $f_0(975)$, together with the fact that the $f_0(975)$ couples much more to the $K\bar{K}$ than to the $\pi\pi$ system. A Crystal Ball measurement of the $a_0(980) \to \gamma\gamma$ suppression in the reaction $\gamma\gamma \to a_0(980) \to \eta\pi$ (ANTREASYAN 86) has reinforced this four-quark interpretation. ACHASOV 88B points out that none of the calculations performed in the framework of a $q\bar{q}$ scheme has been able to predict such a narrow $a_0(980) \to \gamma\gamma$ width as the one found by the Crystal Ball. He then argues in favor of an unusual nature of the $a_0(980)$, and shows that a four-quark model is instead able to give the correct order-of-magnitude suppression of 2γ production for both the scalar $a_0(980)$ and $f_0(975)$ mesons.

Another interesting non-$q\bar{q}$ interpretation is given by the model of WEINSTEIN 83B, 89. In this work, the $q\bar{q}q\bar{q}$ system is investigated using the nonrelativistic quark model; assuming a large hyperfine interaction, the $a_0(980)$ and $f_0(975)$ are both interpreted as $K\bar{K}$ bound states, and then the P-wave $q\bar{q}$ states are all in the 1300-MeV mass region. With this S-wave $K\bar{K}$ molecule assignment, many of the peculiar properties of the $a_0(980)$ and $f_0(975)$ (masses, widths, branching fractions and two-photon widths) appear clarified.

If the $a_0(980)$ is not the $^3P_0$ state, then this state should be observed near 1300 MeV, with partial decay widths close to the flavor symmetry predictions for an ideal nonet (TORNQVIST 90). The candidate $a_0(1320)$ reported by GAMS-4000 would have the right mass, but the signal is weak and its width is much smaller than expected.

$a_0(980)$ MASS

VALUE	DOCUMENT ID
982.7±2.0 OUR AVERAGE	Includes data from the 2 datablocks that follow this one. Error includes scale factor of 1.1.

$\eta\pi$ FINAL STATE ONLY

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.					
983.4± 2.1 OUR AVERAGE					
984 ± 4	1040	[1] ARMSTRONG 91B	OMEG		300 $pp \to pp\eta\pi^+\pi^-$
976 ± 6		ATKINSON 84E	OMEG	±	25–55 $\gamma p \to \eta\pi n$
986 ± 3	500	[2] EVANGELISTA 81	OMEG		12 $\pi^- p \to \eta\pi p$
990.0± 7.0	145	[2] GURTU 79	HBC	±	4.2 $K^- p \to \Lambda\eta 2\pi$
977.0± 7.0		GRASSLER 77	HBC	−	16 $\pi^\mp p \to p\eta 3\pi$
972 ±10	150	DEFOIX 72	HBC	±	0.7 $\bar{p}p \to 7\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
980 ±11	47	CONFORTO 78	OSPK	−	4.5 $\pi^- p \to pX^-$
978.0±16.0	50	CORDEN 78	OMEG	±	12–15 $\pi^- p \to n\eta 2\pi$
989.0± 4.0	70	WELLS 75	HBC	−	3.1–6 $K^- p \to \Lambda\eta 2\pi$
970.0±15.0	20	BARNES 69C	HBC	−	4–5 $K^- p \to \Lambda\eta 2\pi$
980 ±10		CAMPBELL 69	DBC	±	2.7 $\pi^+ d$
980.0±10.0	15	MILLER 69B	HBC	−	4.5 $K^- N \to \eta\pi\Lambda$
980.0±10.0	30	AMMAR 68	HBC	±	5.5 $K^- p \to \Lambda\eta 2\pi$

[1] From a single Breit-Wigner fit.
[2] From $f_1(1285)$ decay.

$K\bar{K}$ ONLY

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.					
976 ± 6	316	DEBILLY 80	HBC	±	1.2–2 $\bar{p}p \to f_1(1285)\omega$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1016 ±10	100	[3] ASTIER 67	HBC	±	0.0 $\bar{p}p$
1003.3± 7.0	143	[4] ROSENFELD 65	RVUE	±	

[3] ASTIER 67 includes data of BARLOW 67, CONFORTO 67, ARMENTEROS 65.
[4] Plus systematic errors.

$a_0(980)$ WIDTH

$\eta\pi$ FINAL STATE ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
57 ±11 OUR AVERAGE						
62 ±15	500	[5] EVANGELISTA	81	OMEG		$12\ \pi^- p \to \eta\pi p$
60.0±20.0	145	[5] GURTU	79	HBC	±	$4.2\ K^- p \to \Lambda\eta 2\pi$
44.0±22.0		GRASSLER	77	HBC	−	$16\ \pi^\mp p \to p\eta 3\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
95 ±14	1040	[6] ARMSTRONG	91B	OMEG		$300\ pp \to pp\eta\pi^+\pi^-$
$60\ ^{+50}_{-30}$	47	CONFORTO	78	OSPK	−	$4.5\ \pi^- p \to pX^-$
$86.0^{+60.0}_{-50.0}$	50	CORDEN	78	OMEG	±	$12\text{–}15\ \pi^- p \to n\eta 2\pi$
80 to 300		[7] FLATTE	76	RVUE	−	$4.2\ K^- p \to \Lambda\eta 2\pi$
$16.0^{+25.0}_{-16.0}$	70	WELLS	75	HBC	−	$3.1\text{–}6\ K^- p \to \Lambda\eta 2\pi$
30 ± 5	150	DEFOIX	72	HBC	±	$0.7\ \overline{p}p \to 7\pi$
40 ±15		CAMPBELL	69	DBC	±	$2.7\ \pi^+ d$
60.0±30.0	15	MILLER	69B	HBC	−	$4.5\ K^- N \to \eta\pi\Lambda$
80.0±30.0	30	AMMAR	68	HBC	±	$5.5\ K^- p \to \Lambda\eta 2\pi$

[5] From $f_1(1285)$ decay.
[6] From a single Breit-Wigner fit.
[7] Using a two-channel resonance parametrization of GAY 76B data.

$K\overline{K}$ ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 25	100	[8] ASTIER	67	HBC	±
57.0±13.0	143	[9] ROSENFELD	65	RVUE	±

[8] ASTIER 67 includes data of BARLOW 67, CONFORTO 67, ARMENTEROS 65.
[9] Plus systematic errors.

$a_0(980)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\pi$	seen
Γ_2	$K\overline{K}$	seen
Γ_3	$\rho\pi$	
Γ_4	$\pi\eta'(958)$	
Γ_5	$\gamma\gamma$	seen
Γ_6	e^+e^-	

$a_0(980)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(\eta\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_5/\Gamma$

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT
$0.24^{+0.08}_{-0.07}$ OUR AVERAGE					
0.28±0.04±0.10	44 ± 7	OEST	90	JADE	$e^+e^- \to e^+e^-\pi^0\eta$
$0.19\pm0.07^{+0.10}_{-0.07}$		ANTREASYAN	86	CBAL	$e^+e^- \to e^+e^-\pi^0\eta$

$\Gamma(\eta\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_6/\Gamma$

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<1.5	90	VOROBYEV	88	ND	$e^+e^- \to \pi^0\eta$

$a_0(980)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma(\eta\pi)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.7 ±0.3	[10] CORDEN	78	OMEG		$12\text{–}15\ \pi^- p \to n\eta 2\pi$
0.25±0.08	[10] DEFOIX	72	HBC	±	$0.7\ \overline{p} \to 7\pi$

[10] From the decay of $f_1(1285)$.

$\Gamma(\rho\pi)/\Gamma(\eta\pi)$ — Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.25	70	AMMAR	70	HBC	±	$4.1,5.5\ K^- p \to \Lambda\eta 2\pi$

$a_0(980)$ REFERENCES

ARMSTRONG	91B	ZPHY C52 389	+Barnes+	(ATHU, BARI, BIRM, CERN, CDEF)
OEST	90	ZHPY C47 343	+Olsson+	(JADE Collab.)
VOROBYEV	88	SJNP 48 273	+Golubev, Dolinsky, Druzhinin+	(NOVO)
		Translated from YAF 48 436.		
ANTREASYAN	86	PR D33 1847	+Aschman, Besset, Bienlein+	(Crystal Ball Collab.)
ATKINSON	84E	PL 138B 459	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP+)
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)
DEBILLY	80	NP B176 1	+Briand, Duboc, Levy+	(CURI, LAUS, NEUC, GLAS)
GURTU	79	NP B151 181	+Gavillet, Blokzijl+	(CERN, ZEEM, NIJM, OXF)
CONFORTO	78	LNC 23 419	+Conforto, Key+	(RHEL, TNTO, CHIC, FNAL+)
CORDEN	78	NP B144 253	+Corbett, Alexander+	(BIRM, RHEL, TELA, LOWC)
GRASSLER	77	NP B121 189	+	(AACH, BERL, BONN, CERN, CRAC, HEID+)
FLATTE	76	PL 63B 224		(CERN)
GAY	76B	PL 63B 220	+Chaloupka, Blokzijl, Heinen+	(CERN, AMST, NIJM) JP
WELLS	75	NP B101 333	+Radojicic, Roscoe, Lyons	(OXF)
DEFOIX	72	NP B44 125	+Nascimento, Bizzarri+	(CDEF, CERN)
AMMAR	70	PR D2 430	+Kropac, Davis+	(KANS, NWES, ANL, WISC)
BARNES	69C	PRL 23 610	+Chung, Eisner, Bassano, Goldberg+	(BNL, SYRA)
CAMPBELL	69	PRL 22 1204	+Lichtman, Loeffler+	(PURD)
MILLER	69B	PL 29B 255	+Kramer, Carmony+	(PURD)
Also	69	PR 188 2011	Yen, Ammann, Carmony, Elsner+	(PURD)
AMMAR	68	PRL 21 1832	+Davis, Kropac, Derrick, Fields+	(NWES, ANL)
ASTIER	67	PL 25B 294	+Montanet, Baubillier, Duboc+	(CDEF, CERN, IRAD)
Includes data of BARLOW 67, CONFORTO 67, and ARMENTEROS 65.				
BARLOW	67	NC 50A 701	+Lillestol, Montanet+	(CERN, CDEF, IRAD, LIVP)
CONFORTO	67	NP B3 469	+Marechal+	(CERN, CDEF, IPNP, LIVP)
ARMENTEROS	65	PL 17 344	+Edwards, Jacobsen+	(CERN, CDEF)
ROSENFELD	65	Oxford Conf. 58		(LRL)

OTHER RELATED PAPERS

TORNQVIST	90	NPBPS 21,196		(HELS)
WEINSTEIN	89	UTPT 89 03	+Isgur	(TNTO)
ACHASOV	88B	ZPHY C41 309	+Shestakov	(NOVO)
WEINSTEIN	83B	PR D27 588	+Isgur	(TNTO)
TORNQVIST	82	PRL 49 624		(HELS)
BRAMON	80	PL 93B 65	+Masso	(BARC)
TURKOT	63	Siena Conf. 1 661	+Collins, Fujii, Kemp+	(BNL, PITT)

$\phi(1020)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\phi(1020)$ MASS

We average mass and width values only when the systematic errors have been evaluated.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1019.413±0.008 OUR AVERAGE					
1019.7 ±0.3	2012	DAVENPORT	86	MPSF	$400\ pA \to 4KX$
1019.411±0.008	642k	[1] DIJKSTRA	86	SPEC	$100\text{–}200\ \pi^\pm, \overline{p}, p, K^\pm$, on Be
1019.7 ±0.1 ±0.1	5079	ALBRECHT	85D	ARG	$e^+e^- \to$ hadrons
1019.3 ±0.1	1500	ARENTON	82	AEMS	11.8 polar. $pp \to KK$
1019.67 ±0.17	25080	[2] PELLINEN	82	RVUE	
1019.54 ±0.12	1100	BARKOV	79B	EMUL	e^+e^-
1019.52 ±0.13		BUKIN	78C	OLYA	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1019.8 ±0.7		ARMSTRONG	86	OMEG	$85\ \pi^+/pp \to \pi^+/p4Kp$
1020.1 ±0.11	5526	[3] ATKINSON	86	OMEG	$20\text{–}70\ \gamma p$
1019.7 ±1.0		BEBEK	86	CLEO	$e^+e^- \to \Upsilon(4S)$
1020.9 ±0.2		[3] FRAME	86	OMEG	$13\ K^+p \to \phi K^+p$
1021.0 ±0.2		[3] ARMSTRONG	83B	OMEG	$18.5\ K^-p \to K^-K^+\Lambda$
1020.0 ±0.5		[3] ARMSTRONG	83B	OMEG	$18.5\ K^-p \to K^-K^+\Lambda$
1019.7 ±0.3		[3] BARATE	83	GOLI	$190\ \pi^-$ Be $\to 2\mu X$
1019.8 ±0.2 ±0.5	766	IVANOV	81	OLYA	$1\text{–}1.4\ e^+e^- \to K^+K^-$
1019.4 ±0.5	337	COOPER	78B	HBC	$0.7\text{–}0.8\ \overline{p}p \to K^0_S K^0_L$
1020.0 ±1.0	383	[3] BALDI	77	CNTR	$10\ \pi^-p \to \pi^-\phi p$
1018.9 ±0.6	800	COHEN	77	ASPK	$6\ \pi^\pm N \to K^+K^-N$
1019.7 ±0.5	454	KALBFLEISCH	76	HBC	$2.18\ K^-p \to K\overline{K}n$
1019.4 ±0.8	984	BESCH	74	CNTR	$2\ \gamma p \to pK^+K^-$
1020.3 ±0.4	100	BALLAM	73	HBC	$2.8\text{–}9.3\ \gamma p$
1019.4 ±0.7		BINNIE	73B	CNTR	$\pi^-p \to \phi n$
1019.6 ±0.5	120	[4] AGUILAR-...	72B	HBC	$3.9,4.6\ K^-p \to \Lambda K^+K^-$
1019.9 ±0.5	100	[4] AGUILAR-...	72B	HBC	$3.9,4.6\ K^-p \to K^-pK^+K^-$
1020.4 ±0.5	131	COLLEY	72	HBC	$10\ K^+p \to K^+p\phi$
1019.9 ±0.3	410	STOTTLE...	71	HBC	$2.9\ K^-p \to \Sigma/\Lambda K\overline{K}$

[1] Weighted and scaled average of 12 measurements of DIJKSTRA 86.
[2] PELLINEN 82 review includes AKERLOF 77, DAUM 81, BALDI 77, AYRES 74, DEGROOT 74.
[3] Systematic errors not evaluated.
[4] Mass errors enlarged by us to $\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

$\phi(1020)$ WIDTH

We average mass and width values only when the systematic errors have been evalutated.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
4.43±0.06 OUR FIT					
4.43±0.06 OUR AVERAGE					
4.45±0.06	271k	DIJKSTRA	86	SPEC	100 π^- Be
4.5 ±0.7	1500	ARENTON	82	AEMS	11.8 polar. $pp \to KK$
4.2 ±0.6	766	[5] IVANOV	81	OLYA	1–1.4 $e^+e^- \to K^+K^-$
4.3 ±0.6		[5] CORDIER	80	WIRE	$e^+e^- \to \pi^+\pi^-\pi^0$
4.58±0.55	1100	BARKOV	79B	EMUL	e^+e^-
4.36±0.29	3681	[5,6] BUKIN	78C	OLYA	e^+e^-
4.4 ±0.6	984	[5] BESCH	74	CNTR	$2\gamma p \to pK^+K^-$
4.67±0.72	681	[5] BALAKIN	71	OSPK	e^+e^-
4.09±0.29		BIZOT	70	OSPK	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.08±0.14	13714	KURDADZE	84	OLYA	$e^+e^- \to$ hadrons
3.6 ±0.8	337	[5] COOPER	78B	HBC	0.7–0.8 $\bar{p}p \to K^0_S K^0_L$
4.5 ±0.50	1300	[5,7] AKERLOF	77	SPEC	400 $pA \to K^+K^-X$
4.5 ±0.8	500	[5,7] AYRES	74	ASPK	3–6 $\pi^-p \to K^+K^-n$, $K^-p \to K^+K^-\Lambda/\Sigma^0$
3.81±0.37		COSME	74B	OSPK	e^+e^-
3.8 ±0.7	454	[5] BORENSTEIN	72	HBC	2.18 $K^-p \to K\bar{K}n$

[5] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[6] Number of events includes a small background contribution.
[7] Systematic errors not evaluated.

$\phi(1020)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	K^+K^-	(49.1 ±0.8) %	S=1.2
Γ_2	$K^0_L K^0_S$	(34.4 ±0.7) %	S=1.2
Γ_3	$\rho\pi$	(12.9 ±0.7) %	
Γ_4	$\pi^+\pi^-\pi^0$	(2.4 ±0.9) %	S=1.1
Γ_5	$\eta\gamma$	(1.28±0.06) %	S=1.2
Γ_6	$\pi^0\gamma$	(1.31±0.13) × 10^{-3}	
Γ_7	e^+e^-	(3.09±0.07) × 10^{-4}	
Γ_8	$\mu^+\mu^-$	(2.48±0.34) × 10^{-4}	
Γ_9	ηe^+e^-	(1.3 $^{+0.8}_{-0.6}$) × 10^{-4}	
Γ_{10}	$\pi^+\pi^-$	(8 $^{+5}_{-4}$) × 10^{-5}	S=1.5
Γ_{11}	$\omega\gamma$	< 5 %	CL=84%
Γ_{12}	$\rho\gamma$	< 2 %	CL=84%
Γ_{13}	$\pi^+\pi^-\gamma$	< 7 × 10^{-3}	CL=90%
Γ_{14}	$f_0(975)\gamma$	< 2 × 10^{-3}	CL=90%
Γ_{15}	$\pi^0\pi^0\gamma$	< 1 × 10^{-3}	CL=90%
Γ_{16}	$\pi^+\pi^-\pi^+\pi^-$	< 8.7 × 10^{-4}	CL=90%
Γ_{17}	$\eta'(958)\gamma$	< 4.1 × 10^{-4}	CL=90%
Γ_{18}	$\pi^+\pi^+\pi^-\pi^-\pi^0$	< 1.5 × 10^{-4}	CL=95%
Γ_{19}	$\pi^0e^+e^-$	< 1.2 × 10^{-4}	CL=90%
Γ_{20}	$\pi^0\eta\gamma$	< 2.5 × 10^{-3}	CL=90%
Γ_{21}	$a_0(980)\gamma$	< 5 × 10^{-3}	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to the total width, a partial width, and 9 branching ratios uses 38 measurements and one constraint to determine 6 parameters. The overall fit has a χ^2 = 24.8 for 33 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−71				
x_3	0	0			
x_4	−34	−14	−76		
x_5	−5	−2	0	0	
Γ	0	0	−24	18	0
	x_1	x_2	x_3	x_4	x_5

	Mode	Rate (MeV)	Scale factor
Γ_1	K^+K^-	2.18 ±0.05	1.1
Γ_2	$K^0_L K^0_S$	1.52 ±0.04	1.2
Γ_3	$\rho\pi$	0.570 ±0.030	
Γ_4	$\pi^+\pi^-\pi^0$	0.10 ±0.04	1.1
Γ_5	$\eta\gamma$	0.0569±0.0029	1.2

$\phi(1020)$ PARTIAL WIDTHS

$\Gamma(\rho\pi)$ — Γ_3

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0.570±0.030 OUR FIT				
0.57 ±0.03	JULLIAN	76	OSPK	e^+e^-

$\Gamma(e^+e^-)$ — Γ_7

VALUE (keV)	DOCUMENT ID
1.37±0.05 OUR EVALUATION	

$\phi(1020)$ BRANCHING RATIOS

$\Gamma(K^+K^-)/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.491±0.008 OUR FIT Error includes scale factor of 1.2.					
0.497±0.019 OUR AVERAGE					
0.45 ±0.05	321	KALBFLEISCH	76	HBC	2.18 K^-p
0.49 ±0.06	270	DEGROOT	74	HBC	4.2 $K^-p \to \Lambda\phi$
0.540±0.034		BALAKIN	71	OSPK	e^+e^-
0.486±0.044		CHATELUS	71	OSPK	e^+e^-
0.48 ±0.04	252	LINDSEY	66	HBC	2.7 K^-p

$\Gamma(K^0_L K^0_S)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.344±0.007 OUR FIT Error includes scale factor of 1.2.					
0.333±0.009 OUR AVERAGE					
0.326±0.035		DOLINSKY	91	ND	$e^+e^- \to K_S K_L$
0.310±0.024		DRUZHININ	84	ND	$e^+e^- \to K^0_L K^0_S$
0.338±0.010		KURDADZE	84	OLYA	$e^+e^- \to K_S K_L$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.27 ±0.03	133	KALBFLEISCH	76	HBC	2.18 K^-p
0.257±0.038		BALAKIN	71	OSPK	e^+e^-
0.40 ±0.04	167	LINDSEY	66	HBC	2.7 K^-p

$[\Gamma(\rho\pi) + \Gamma(\pi^+\pi^-\pi^0)]/\Gamma_{total}$ — $(\Gamma_3+\Gamma_4)/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.152±0.006 OUR FIT Error includes scale factor of 1.2.				
0.148±0.006 OUR AVERAGE Error includes scale factor of 1.1.				
0.143±0.007	DOLINSKY	91	ND	$e^+e^- \to \pi^+\pi^-\pi^0$
0.155±0.008	KURDADZE	84	OLYA	$e^+e^- \to \pi^+\pi^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.139±0.007	[8] PARROUR	76B	OSPK	e^+e^-

[8] Using total width 4.1 MeV. The $\rho\pi$ to 3π mode is more than 80%. at the 90% confidence level.

$\Gamma(K^0_L K^0_S)/\Gamma(K\bar{K})$ — $\Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.412±0.008 OUR FIT Error includes scale factor of 1.2.					
0.45 ±0.04 OUR AVERAGE					
0.44 ±0.07		LONDON	66	HBC	2.2 K^-p
0.48 ±0.07	52	BADIER	65B	HBC	3 K^-p
0.40 ±0.10	10	SCHLEIN	63	HBC	2.0 K^-p

$[\Gamma(\rho\pi) + \Gamma(\pi^+\pi^-\pi^0)]/\Gamma(K\overline{K})$ — $(\Gamma_3+\Gamma_4)/(\Gamma_1+\Gamma_2)$

VALUE	DOCUMENT ID		TECN	COMMENT
0.182±0.008 OUR FIT Error includes scale factor of 1.2.				
0.24 ±0.04 OUR AVERAGE				
0.237±0.039	CERRADA	77B	HBC	4.2 $K^- p \to \Lambda 3\pi$
0.30 ±0.15	LONDON	66	HBC	2.2 $K^- p$

$[\Gamma(\rho\pi) + \Gamma(\pi^+\pi^-\pi^0)]/\Gamma(K^0_L K^0_S)$ — $(\Gamma_3+\Gamma_4)/\Gamma_2$

VALUE	DOCUMENT ID		TECN	COMMENT
0.443±0.021 OUR FIT Error includes scale factor of 1.2.				
0.49 ±0.05 OUR AVERAGE				
0.56 ±0.13	BUKIN	78C	OLYA	e^+e^-
0.47 ±0.06	COSME	74	OSPK	e^+e^-

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
2.48±0.34 OUR AVERAGE				
2.69±0.46	HAYES	71	CNTR	Photoproduction
2.17±0.60	EARLES	70	CNTR	6.0 Bremsstr.
2.34±1.01	MOY	69	CNTR	Photoproduction

$\Gamma(\eta\gamma)/\Gamma_{total}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0128±0.0006 OUR FIT Error includes scale factor of 1.2.					
0.0128±0.0007 OUR AVERAGE Error includes scale factor of 1.2.					
0.0130±0.0006		[9] DRUZHININ	84	ND	$e^+e^- \to 3\gamma$
0.014 ±0.002		[10] DRUZHININ	84	ND	$e^+e^- \to 6\gamma$
0.0088±0.0020	290	KURDADZE	83C	OLYA	$e^+e^- \to 3\gamma$
0.0135±0.0029		ANDREWS	77	CNTR	6.7–10 γCu
0.015 ±0.004	54	[9] COSME	76	OSPK	e^+e^-

[9] From 2γ decay mode of η.
[10] From $3\pi^0$ decay mode of η.

$\Gamma(\pi^+\pi^-\gamma)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.007	90	COSME	74	OSPK	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.06	90	KALBFLEISCH	75	HBC	2.2 $K^- p$
<0.04		LINDSEY	65	HBC	2.7 $K^- p$

$\Gamma(\omega\gamma)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.05	84	LINDSEY	66	HBC	2.7 $K^- p$

$\Gamma(\rho\gamma)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	84	LINDSEY	66	HBC	2.7 $K^- p$

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
3.09±0.07 OUR AVERAGE				
3.05±0.12	KURDADZE	84	OLYA	$e^+e^- \to$ hadrons
3.00±0.21	BUKIN	78C	OLYA	e^+e^-
3.10±0.14	[11] PARROUR	76	OSPK	e^+e^-
3.3 ±0.3	COSME	74	OSPK	e^+e^-
2.81±0.25	BALAKIN	71	OSPK	e^+e^-
3.50±0.27	CHATELUS	71	OSPK	e^+e^-

[11] Using total width 4.2 MeV. They detect 3π mode and observe significant interference with ω tail. This is accounted for in the result quoted above.

$\Gamma(\pi^0\gamma)/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.31±0.13 OUR AVERAGE					
1.30±0.13		DRUZHININ	84	ND	$e^+e^- \to 3\gamma$
1.4 ±0.5	32	COSME	76	OSPK	e^+e^-

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
$0.8\ ^{+0.5}_{-0.4}$ OUR AVERAGE Error includes scale factor of 1.5.					
$0.63^{+0.37}_{-0.28}$		[12] GOLUBEV	86	ND	$e^+e^- \to \pi^+\pi^-$
$1.94^{+1.03}_{-0.81}$		[12] VASSERMAN	81	OLYA	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<6.6	95	BUKIN	78B	OLYA	e^+e^-
<4.0	95	JULLIAN	76	OSPK	e^+e^-
<2.7	95	ALVENSLEBEN	72	OSPK	γC

[12] Using $\Gamma(e^+e^-)/\Gamma_{total} = 3.1 \times 10^{-4}$.

$\Gamma(K^0_L K^0_S)/\Gamma(K^+K^-)$ — Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.700±0.024 OUR FIT Error includes scale factor of 1.2.					
0.736±0.030 OUR AVERAGE					
0.70 ±0.05		BUKIN	78C	OLYA	e^+e^-
0.82 ±0.08		LOSTY	78	HBC	4.2 $K^- p \to \phi$ hyperon
0.71 ±0.05		LAVEN	77	HBC	10 $K^- p \to K^+K^-\Lambda$
0.71 ±0.08		LYONS	77	HBC	3–4 $K^- p \to \Lambda\phi$
0.89 ±0.10	144	AGUILAR-...	72B	HBC	3.9,4.6 $K^- p$

$[\Gamma(\rho\pi) + \Gamma(\pi^+\pi^-\pi^0)]/\Gamma(K^+K^-)$ — $(\Gamma_3+\Gamma_4)/\Gamma_1$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.310±0.015 OUR FIT Error includes scale factor of 1.2.					
0.28 ±0.09	34	AGUILAR-...	72B	HBC	3.9,4.6 $K^- p$

$\Gamma(\eta e^+e^-)/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
$1.3^{+0.8}_{-0.6}$	7	GOLUBEV	85	ND	$e^+e^- \to \gamma\gamma e^+e^-$

$\Gamma(\eta'(958)\gamma)/\Gamma_{total}$ — Γ_{17}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<4.1	90	DRUZHININ	87	ND	$e^+e^- \to \gamma\eta\pi^+\pi^-$

$\Gamma(\pi^0\pi^0\gamma)/\Gamma_{total}$ — Γ_{15}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<1	90	DRUZHININ	87	ND	$e^+e^- \to 5\gamma$

$\Gamma(\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{total}$ — Γ_{18}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<1.5	95	BARKOV	88	CMD	$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0$

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma_{total}$ — Γ_{16}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<8.7	90	CORDIER	79	WIRE	$e^+e^- \to 4\pi$

$\Gamma(f_0(975)\gamma)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<2	90	DRUZHININ	87	ND	$e^+e^- \to \pi^0\pi^0\gamma$

$\Gamma(\pi^0 e^+e^-)/\Gamma_{total}$ — Γ_{19}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.2 x 10^{-4}	90	DOLINSKY	88	ND	$e^+e^- \to \pi^0 e^+e^-$

$\Gamma(\pi^0\eta\gamma)/\Gamma_{total}$ — Γ_{20}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<2.5	90	DOLINSKY	91	ND	$e^+e^- \to \pi^0\eta\gamma$

$\Gamma(a_0(980)\gamma)/\Gamma_{total}$ — Γ_{21}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<5	90	DOLINSKY	91	ND	$e^+e^- \to \pi^0\eta\gamma$

$\phi(1020)$ REFERENCES

DOLINSKY 91 PRPL 202 99 +Druzhinin, Dubrovin+ (NOVO)
BARKOV 88 SJNP 47 248 +Vasserman, Vorobyev, Ivanov+ (NOVO)
Translated from YAF 47 393.
DOLINSKY 88 SJNP 48 277 +Druzhinin, Dubrovin, Golubev+ (NOVO)
Translated from YAF 48 442.
DRUZHININ 87 ZPHY C37 1 +Dubrovin, Eidelman, Golubev+ (NOVO)
ARMSTRONG 86 PL 166B 245 +Bloodworth, Carney+ (ATHU, BARI, BIRM, CERN)
ATKINSON 86 ZPHY C30 521 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
BEBEK 86 PRL 56 1893 +Berkelman, Blucher, Cassel+ (CLEO Collab.)
DAVENPORT 86 PR 33 2519 (TUFT, ARIZ, FNAL, FSU, NDAM, VAND)
DIJKSTRA 86 ZPHY C31 375 +Bailey+ (ANIK, BRIS, CERN, CRAC, MPIM, RAL)
FRAME 86 NP B276 667 +Hughes, Lynch, Minto, McFadzean+ (GLAS)
GOLUBEV 86 SJNP 44 409 +Druzhinin, Ivanchenko, Perevedentsev+ (NOVO)
Translated from YAF 44 633.
ALBRECHT 85D PL 153B 343 +Drescher, Binder, Drews+ (ARGUS Collab.)
GOLUBEV 85 SJNP 41 756 +Druzhinin, Ivanchenko, Peryshkin+ (NOVO)
Translated from YAF 41 1183.
DRUZHININ 84 PL 144B 136 +Golubev, Ivanchenko, Peryshkin+ (NOVO)
KURDADZE 84 IYAF 84-7 Preprint +Leltchouk, Pakhtusova, Sidorov+ (NOVO)
ARMSTRONG 83B NP B224 193 + (BARI, BIRM, CERN, MILA, LPNP, PAVI)
BARATE 83 PL 121B 449 +Bareyre, Bonamy+ (SACL, LOIC, SHMP, IND)
KURDADZE 83C JETPL 38 366 +Lelchuk, Root+ (NOVO)
Translated from ZETFP 38 306.
ARENTON 82 PR D25 2241 +Ayres, Diebold, May, Swallow+ (ANL, ILL)
PELLINEN 82 PS 25 599 +Roos (HELS)
DAUM 81 PL 100B 439 +Bardsley+ (AMST, BRIS, CERN, CRAC, MPIM+)
IVANOV 81 PL 107B 297 +Kurdadze, Lelchuk, Sidorov, Skrinsky+ (NOVO)
Also 82 Private Comm. Eidelman (NOVO)
VASSERMAN 81 PL 99B 62 +Kurdadze, Sidorov, Skrinsky+ (NOVO)
CORDIER 80 NP B172 13 +Delcourt, Eschstruth, Fulda+ (LALO)
BARKOV 79B IYAF 79-93 Preprint +Zolotorev, Makarina, Mishakova+ (NOVO)
CORDIER 79 PL 81B 389 +Delcourt, Eschstruth, Fulda+ (LALO)
BUKIN 78B SJNP 27 521 +Kurdadze, Sidorov, Skrinsky+ (NOVO)
Translated from YAF 27 985.
BUKIN 78C SJNP 27 516 +Kurdadze, Serednyakov, Sidorov+ (NOVO)
Translated from YAF 27 976.

COOPER 78B NP B146 1 +Gurtu+ (TATA, CERN, CDEF, MADR)
LOSTY 78 NP B133 38 +Holmgren, Blokzijl+ (CERN, AMST, NIJM, OXF)
AKERLOF 77 PRL 39 861 +Alley, Bintinger, Ditzler+ (FNAL, MICH, PURD)
ANDREWS 77 PRL 38 198 +Fukushima, Harvey, Lobkowicz, May+ (ROCH)
BALDI 77 PL 68B 381 +Bohringer, Dorsaz, Hungerbuhler+ (GEVA)
CERRADA 77B NP B126 241 +Blockzijl, Heinen+ (AMST, CERN, NIJM, OXF)
COHEN 77 PRL 38 269 +Ayres, Diebold, Kramer, Pawlicki, Wicklund (ANL)
LAVEN 77 NP B127 43 +Otter, Klein+ (AACH, BERL, CERN, LOIC, WIEN)
LYONS 77 NP B125 207 +Cooper, Clark (OXF)
COSME 76 PL 63B 352 +Courau, Dudelzak, Grelaud, Jean-Marie+ (ORSA)
JULLIAN 76 Tbilisi 2 B19 (ORSA)
KALBFLEISCH 76 PR D13 22 +Strand, Chapman (BNL, MICH)
PARROUR 76 PL 63B 357 +Grelaud, Cosme, Courau, Dudelzak+ (ORSA)
PARROUR 76B PL 63B 362 +Grelaud, Cosme, Courau, Dudelzak+ (ORSA)
KALBFLEISCH 75 PR D11 987 +Strand, Chapman (BNL, MICH)
AYRES 74 PRL 32 1463 +Diebold, Greene, Kramer, Levine+ (ANL)
BESCH 74 NP B70 257 +Hartmann, Kose, Krautschneider, Paul+ (BONN)
COSME 74 PL 48B 155 +Jean-Marie, Jullian, Laplanche+ (ORSA)
COSME 74B PL 48B 159 +Jean-Marie, Jullian, Laplanche+ (ORSA)
DEGROOT 74 NP B74 77 +Hoogland, Jongejans, Metzger+ (AMST, NIJM)
BALLAM 73 PR D7 3150 +Chadwick, Eisenberg, Bingham+ (SLAC, LBL)
BINNIE 73B PR D8 2789 +Carr, Debenham, Duane+ (LOIC, SHMP)
AGUILAR-... 72B PR D6 29 Aguilar-Benitez, Chung, Eisner, Samios (BNL)
ALVENSLEBEN 72 PRL 28 66 +Becker, Biggs, Binkley+ (MIT, DESY)
BORENSTEIN 72 PR D5 1559 +Danburg, Kalbfleisch+ (BNL, MICH)
COLLEY 72 NP B50 1 +Jobes, Riddiford, Griffiths+ (BIRM, GLAS)
BALAKIN 71 PL 34B 328 +Budker, Pakhtusova, Sidorov, Skrinsky+ (NOVO)
CHATELUS 71 LAL 1247 Thesis (STRB)
Also 70 PL 32 416 Bizot, Buon, Chatelus, Jeanjean+ (ORSA)
HAYES 71 PR D4 899 +Imlay, Joseph, Keizer, Stein (CORN)
STOTTLE... 71 ORO 2504 170 Thesis Stottlemyer (UMD)
BIZOT 70 PL 32 416 +Buon, Chatelus, Jeanjean+ (ORSA)
Also 69 Liverpool Sym. 69 Perez-y-Jorba
EARLES 70 PRL 25 1312 +Faissler, Gettner, Lutz, Moy, Tang+ (NEAS)
MOY 69 Thesis (NEAS)
LINDSEY 66 PR 147 913 +Smith (LRL)
LONDON 66 PR 143 1034 +Rau, Goldberg, Lichtman+ (BNL, SYRA)
BADIER 65B PL 17 337 +Demoulin, Barloutaud+ (EPOL, SACL, AMST)
LINDSEY 65 PRL 15 221 +Smith (LRL)
LINDSEY 65 data included in LINDSEY 66.
SCHLEIN 63 PRL 10 368 +Slater, Smith, Stork, Ticho (UCLA)

OTHER RELATED PAPERS

GEORGIO... 85 PL 152B 428 Georgiopoulos+ (TUFT, ARIZ, FNAL, FSU, NDAM+)
ARMENTEROS 63B Siena Conf. 2 70 +Edwards, Astier+ (CERN, CDEF)
GELFAND 63B PRL 11 438 +Miller, Nussbaum, Kirsch+ (COLU, RUTG)
BERTANZA 62 PRL 9 180 +Brisson, Connolly, Hart+ (BNL, SYRA)

$h_1(1170)$ was $H(1190)$

$I^G(J^{PC}) = 0^-(1^{+-})$

$h_1(1170)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1170 ±20 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1159 ±26	[1] ANDO 91	SPEC		$8\ \pi^- p \to \pi^+\pi^-\pi^0 n$
1167 ±22	[2] TAKAMATSU 90	SPEC	0	$8\ \pi^- p \to 3\pi n$
~ 1175.0	[3] TORNQVIST 82B	RVUE		
1190 ±60	[1] DANKOWY... 81	SPEC	0	$8\ \pi p \to 3\pi n$

[1] Uses the model of BOWLER 75.
[2] This result supersedes ANDO 87.
[3] From a unitarized quark-model calculation.

$h_1(1170)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
360 ±40 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
423 ±37	[4] ANDO 91	SPEC		$8\ \pi^- p \to \pi^+\pi^-\pi^0 n$
304 ±45	[5] TAKAMATSU 90	SPEC	0	$8\ \pi^- p \to 3\pi n$
~ 365.0	[6] TORNQVIST 82B	RVUE		
320 ±50	[4] DANKOWY... 81	SPEC	0	$8\ \pi p \to 3\pi n$

[4] Uses the model of BOWLER 75.
[5] This result supersedes ANDO 87.
[6] From a unitarized quark-model calculation.

$h_1(1170)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen

$h_1(1170)$ BRANCHING RATIOS

$\Gamma(\rho\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
seen	ANDO 87	SPEC	0	$8\ \pi p \to 3\pi n$
seen	ATKINSON 84	OMEG		$20\text{–}70\ \gamma p \to \pi^+\pi^-\pi^0 p$
seen	DANKOWY... 81	SPEC		$8\ \pi p \to 3\pi n$

$h_1(1170)$ REFERENCES

ANDO 91 NP B21 98 (suppl) + (KEK, KYOT, NIRS, SAGA, TOKY, AKIT, NAGO+)
TAKAMATSU 90 Hadron 89 Conf. p 71 +Ando+ (KEK)
ANDO 87 Hadron 87 Conf. +Imai, Inaba (KEK)
ATKINSON 84 NP B231 15 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
TORNQVIST 82B NP B203 268 (HELS)
DANKOWY... 81 PRL 46 580 Dankowych+ (TNTO, BNL, CARL, MCGI, OHIO)
BOWLER 75 NP B97 227 +Game, Aitchison, Dainton (OXF, DARE)

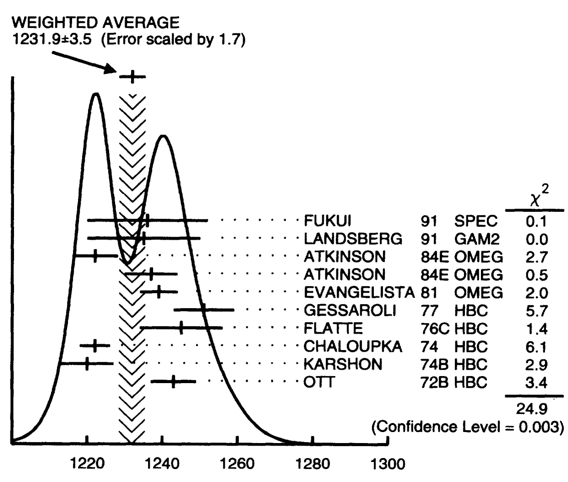
$b_1(1235)$ was $B(1235)$

$I^G(J^{PC}) = 1^+(1^{+-})$

$b_1(1235)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1232 ±10 OUR ESTIMATE		This is only an educated guess; the error given is larger than the error on the average of the published values.			
1231.9± 3.5 OUR AVERAGE		Error includes scale factor of 1.7. See the ideogram below.			
1236 ±16		FUKUI 91	SPEC		$8.95\ \pi^- p \to \omega\pi^0 n$
1235 ±15		LANDSBERG 91	GAM2		$38{,}100\ \pi^- p \to \omega\pi^0 n$
1222 ± 6		ATKINSON 84E	OMEG	±	$25\text{–}55\ \gamma p \to \omega\pi X$
1237 ± 7		ATKINSON 84E	OMEG	0	$25\text{–}55\ \gamma p \to \omega\pi X$
1239 ± 5		EVANGELISTA 81	OMEG	−	$12\ \pi^- p \to \omega\pi p$
1251.0± 8.0	450	GESSAROLI 77	HBC	−	$11\ \pi^- p \to \pi^-\omega p$
1245.0±11.0	890	FLATTE 76C	HBC	−	$4.2\ K^- p \to \pi^-\omega\Sigma^+$
1222 ± 4	1400	CHALOUPKA 74	HBC	−	$3.9\ \pi^- p$
1220 ± 7	600	KARSHON 74B	HBC	+	$4.9\ \pi^+ p$
1243 ± 6	1163	[1] OTT 72B	HBC	+	$7.1\ \pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1311 ±10		[2] TAKAMATSU 90	SPEC	0	$8\ \pi^- p \to \eta\rho n$
1190 ±10		AUGUSTIN 89	DM2	±	$e^+e^- \to 5\pi$
1213 ± 5		ATKINSON 84C	OMEG	0	$20\text{–}70\ \gamma p$
1271 ±11		COLLICK 84	SPEC	+	$200\ \pi^+ Z \to Z\pi\omega$

[1] From fit of the mass spectrum.
[2] Breit−Wigner fitting of PWA of $\eta\pi\pi$ system.



$b_1(1235)$ mass (MeV)

$b_1(1235)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
155 ± 8 OUR AVERAGE					
151 ±31		FUKUI 91	SPEC		$8.95\ \pi^- p \to \omega\pi^0 n$
160 ±30		LANDSBERG 91	GAM2		$38{,}100\ \pi^- p \to \omega\pi^0 n$
170 ±15		EVANGELISTA 81	OMEG	−	$12\ \pi^- p \to \omega\pi p$
170.0±50.0	225	BALTAY 78B	HBC	+	$15\ \pi^+ p \to p4\pi$
155.0±32.0	450	GESSAROLI 77	HBC	−	$11\ \pi^- p \to \pi^-\omega p$
182.0±45.0	890	FLATTE 76C	HBC	−	$4.2\ K^- p \to \pi^-\omega\Sigma^+$
135 ±20	1400	CHALOUPKA 74	HBC	−	$3.9\ \pi^- p$
156 ±22	600	KARSHON 74B	HBC	+	$4.9\ \pi^+ p$
$134\ ^{+23}_{-26}$	1163	[3] OTT 72B	HBC	+	$7.1\ \pi^+ p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

126 ±10	[4] TAKAMATSU	90	SPEC	0	$8\ \pi^- p \to \eta \rho n$
210 ±19	AUGUSTIN	89	DM2	±	$e^+ e^- \to 5\pi$
231 ±14	ATKINSON	84C	OMEG	0	20–70 γp
232 ±29	COLLICK	84	SPEC	+	$200\ \pi^+ Z \to Z\pi\omega$

[3] From fit of the mass spectrum.
[4] Breit–Wigner fitting of PWA of $\eta\pi\pi$ system.

$b_1(1235)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\omega\pi$ [D/S amplitude ratio $= 0.26 \pm 0.04$]	dominant	
Γ_2	$\pi^\pm\gamma$	$(1.5\pm0.4) \times 10^{-3}$	
Γ_3	$\eta\rho$	seen	
Γ_4	$\pi^+\pi^+\pi^-\pi^0$	< 50 %	84%
Γ_5	$\eta\pi$	< 25 %	90%
Γ_6	$\pi\pi$	< 15 %	90%
Γ_7	$(K\overline{K})^\pm\pi^0$	< 8 %	90%
Γ_8	$K^0_S K^0_L \pi^\pm$	< 6 %	90%
Γ_9	$K\overline{K}$	< 2 %	84%
Γ_{10}	$K^0_S K^0_S \pi^\pm$	< 2 %	90%
Γ_{11}	$\pi\phi$	< 1.5 %	84%

$b_1(1235)$ PARTIAL WIDTHS

$\Gamma(\pi^\pm\gamma)$ Γ_2

VALUE (keV)	DOCUMENT ID		TECN	CHG	COMMENT
230.0±60.0	COLLICK	84	SPEC	+	$200\ \pi^+ Z \to Z\pi\omega$

$b_1(1235)$ D-wave/S-wave AMPLITUDE RATIO IN DECAY OF $b_1(1235) \to \omega\pi$

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.260±0.035 OUR AVERAGE						
0.235±0.047		ATKINSON	84C	OMEG		20–70 γp
$0.4\ ^{+0.1}_{-0.1}$		GESSAROLI	77	HBC	−	$11\ \pi^- p \to \pi^-\omega p$
0.21 ±0.08		CHUNG	75B	HBC	+	$7.1\ \pi^+ p$
0.3 ±0.1		CHALOUPKA	74	HBC	−	3.9–7.5 $\pi^- p$
0.35 ±0.25	600	KARSHON	74B	HBC	+	$4.9\ \pi^+ p$

$b_1(1235)$ BRANCHING RATIOS

$\Gamma(\eta\rho)/\Gamma(\omega\pi)$ Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
seen	TAKAMATSU	90	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.10	ATKINSON	84D	OMEG	20–70 γp

$\Gamma(\pi^+\pi^+\pi^-\pi^0)/\Gamma(\omega\pi)$ Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.5	ABOLINS	63	HBC	+	$3.5\ \pi^+ p$

$\Gamma(\eta\pi)/\Gamma(\omega\pi)$ Γ_5/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.25	90	BALTAY	67	HBC	±	$0.0\ \overline{p}p$

$\Gamma(\pi\pi)/\Gamma(\omega\pi)$ Γ_6/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.15	90	OTT	72B	HBC	+	$7.1\ \pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.3		ADERHOLZ	64B	HBC		$4.0\ \pi^+ p$

$\Gamma((K\overline{K})^\pm\pi^0)/\Gamma(\omega\pi)$ Γ_7/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.08	90	BALTAY	67	HBC	±	$0.0\ \overline{p}p$

$\Gamma(K^0_S K^0_L \pi^\pm)/\Gamma(\omega\pi)$ Γ_8/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.06	90	BALTAY	67	HBC	±	$0.0\ \overline{p}p$

$\Gamma(K\overline{K})/\Gamma(\omega\pi)$ Γ_9/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.02		DAHL	67	HBC	−	1.6–4.2 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.08	95	BIZZARRI	69	HBC	±	$0.0\ \overline{p}p$
<0.10	90	BALTAY	67	HBC	±	$0.0\ \overline{p}p$

$\Gamma(K^0_S K^0_S \pi^\pm)/\Gamma(\omega\pi)$ Γ_{10}/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.02	90	BALTAY	67	HBC	±	$0.0\ \overline{p}p$

$\Gamma(\pi\phi)/\Gamma(\omega\pi)$ Γ_{11}/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.015		DAHL	67	HBC		1.6–4.2 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.04	95	BIZZARRI	69	HBC	±	$0.0\ \overline{p}p$

$b_1(1235)$ REFERENCES

FUKUI	91	PL B257 241	+Horikawa+	(SUGI, NAGO, KEK, KYOT, MIYA)
LANDSBERG	91	Hadron 91 Conf.	+	(SERP, BELG, LANL, LAPP, PISA, KEK)
TAKAMATSU	90	Hadron 89 Conf. p 71	+Ando+	(KEK)
AUGUSTIN	89	NP B320 1	+Cosme	(DM2 Collab.)
ATKINSON	84C	NP B243 1	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP+) JP
ATKINSON	84D	NP B242 269	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP+)
ATKINSON	84E	PL 138B 459	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP+)
COLLICK	84	PRL 53 2374	+Heppelmann, Berg+	(MINN, ROCH, FNAL)
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)
BALTAY	78B	PR D17 62	+Cautis, Cohen, Csorna+	(COLU, BING)
GESSAROLI	77	NP B126 382	+	(BGNA, FIRZ, GENO, MILA, OXF, PAVI) JP
FLATTE	76C	PL 64B 225	+Gay, Blokzijl, Metzger+	(CERN, AMST, NIJM, OXF) JP
CHUNG	75B	PR D11 2426	+Protopopescu, Lynch, Flatte+	(BNL, LBL, UCSC) JP
CHALOUPKA	74	PL 51B 407	+Ferrando, Losty, Montanet	(CERN) JP
KARSHON	74B	PR D10 3608	+Mikenberg, Eisenberg, Pitluck, Ronat+	(REHO) JP
OTT	72B	LBL-1547 Thesis		(LBL) JP
BIZZARRI	69	NP B14 169	+Foster, Gavillet, Montanet+	(CERN, CDEF)
BALTAY	67	PRL 18 93	+Franzini, Severiens, Yeh, Zanello	(COLU)
DAHL	67	PR 163 1377	+Hardy, Hess, Kirz, Miller	(LRL)
ADERHOLZ	64B	PL 10 240	+	(AACH, BERL, BIRM, BONN, HAMB, LOIC+)
ABOLINS	63	PRL 11 381	+Lander, Mehlhop, Nguyen, Yager	(UCSD)

OTHER RELATED PAPERS

BRAU	88	PR D37 2379	+Franek+	(SLAC Hybrid Facility Photon Collab.) JP
ATKINSON	84C	NP B243 1	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP+) JP
GOLDHABER	65	PRL 15 118	+Goldhaber, Kadyk, Shen	(LRL)
CARMONY	64	PRL 12 254	+Lander, Rindfleisch, Xuong, Yager	(UCB) JP
BONDAR	63B	PL 5 209	+Dodd+	(AACH, BIRM, HAMB, LOIC, MPIM)

$f_0(1240)$
was $g_S(1240)$

$I^G(J^{PC}) = 0^+(0^{++})$

OMITTED FROM SUMMARY TABLE

Seen in phase shift analysis of $K^0_S K^0_S$ system. Named g_S by ETKIN 82C. Needs confirmation.

$f_0(1240)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1240.0±10±20	ETKIN	82C	MPS	0	$23\ \pi^- p \to n 2K^0_S$

$f_0(1240)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
140.0±10±20	ETKIN	82C	MPS	0	$23\ \pi^- p \to n 2K^0_S$

$f_0(1240)$ DECAY MODES

	Mode
Γ_1	$K\overline{K}$

$f_0(1240)$ REFERENCES

ETKIN	82C	PR D25 2446	+Foley, Lai+	(BNL, CUNY, TUFT, VAND) JP

$a_1(1260)$
was $A_1(1270)$

$I^G(J^{PC}) = 1^-(1^{++})$

NOTE ON THE $a_1(1260)$

For quite some time, even the existence as a genuine resonance of this broad bump in the 3π mass spectrum was questioned. Today the $a_1(1260)$ situation appears to be satisfactorily clarified and its resonance parameters are well determined, at least if one restricts the fits to include only one resonance. For an attempt to fit the leptonic data with two resonances, see IIZUKA 89.

The experimental data may be grouped into two classes:

1) Hadronically-produced $a_1(1260)$. There are two high-statistics experiments, diffractive production from incident π^- (DAUM 80, 81B) and charge-exchange production with low-energy π^- (DANKOWYCH 81), both on hydrogen. The extraction of the $a_1(1260)$ resonance parameters from these experiments is troubled by the presence of a coherent background, attributed to the Deck effect. Both experiments performed a partial-wave analysis. The phenomenological amplitude used to explain the 1^+S0^+ data consists of a rescattered Deck amplitude (calculated from one-pion exchange and not allowed to vary) plus a direct resonance production term. Both experiments agree with an $a_1(1260)$ mass of $\simeq$ 1270 MeV, but DAUM 81B finds a width somewhat smaller than that from the charge-exchange data ($\simeq$300 MeV against $\simeq$380 MeV). Rather lower values for the $a_1(1260)$ mass and width 1122$\pm$17 MeV and 254$\pm$11 MeV were obtained with a partial-wave analysis of the $\pi^+\pi^-\pi^0$ system in a high statistics π^-p charge-exchange reaction by TAKAMATSU 90. However, in this analysis only Breit-Wigner terms are considered.

2) Four experiments have reported good data on the heavy lepton decay $\tau \to a_1(1260)\nu_\tau$, $a_1(1260) \to \rho\pi$ (RUCKSTUHL 86, SCHMIDKE 86, ALBRECHT 86B, and BAND 87). In this channel, the $a_1(1260)$ from τ decay is expected to be (almost) free from any background. The four sets of τ decays show some inconsistencies in the values quoted for the $a_1(1260)$ mass; however, according to BOWLER 86, these discrepancies can be attributed to the different assumptions and approximations made in fitting the data. Furthermore, all these τ decays seem to indicate a consistent $a_1(1260)$ width $\geq$ 400 MeV, considerably larger than the one found by DAUM 81B.

This discrepancy between the hadronic and the τ-decay results has stimulated several reanalyses of the data. BOWLER 86, TORNQVIST 87, ISGUR 89, and IVANOV 91 have studied the process $\tau \to 3\pi\nu_\tau$. (BOWLER 86 made fits to the data of ALBRECHT 86B and SCHMIDKE 86, while TORNQVIST 87, ISGUR 89, and IVANOV 91 also took into account RUCKSTUHL 86.)

BOWLER 86 assumed that the 3π state is wholly $a_1(1260)$, with no background, coherent or incoherent. His fits to the data always used the same theoretical form, with a "normal" Breit-Wigner shape and various behaviors of the $a_1(1260)$ axial coupling as a function of the 3π mass.

TORNQVIST 87 fits a modified Breit-Wigner form to the data that includes, besides $\rho\pi$ and $K^*(892)\overline{K} + \overline{K}^*(892)K$ threshold effects, an energy-dependent real part of the $a_1(1260)$ mass parameter ("running mass shift function").

ISGUR 89 deduced a full mass-dependent covariant amplitude for $\tau \to 3\pi\nu_\tau$ from theory; all the ambiguities due to the non-pointlikeness of the hadrons (such as unknown off-shell behaviors of propagators and vertices) are associated with a parametrized nonresonant background amplitude. Since this background is small anyway, the $a_1(1260)$ parameters do not depend critically on its form.

Despite these quite different approaches, all three analyses find a good overall description of all the τ-decay data with an $a_1(1260)$ mass in the range of 1230 MeV, consistent with the hadronic data; however the widths (400 MeV for BOWLER 86, 420 MeV for ISGUR 89, and 600 MeV for TORNQVIST 87) are significantly higher than those extracted from diffractive-hadronic data.

IVANOV 91, using a phenomenological meson Lagrangian based on four-quark interaction, obtained $a_1(1260)$ parameters consistent with those mentioned above.

BOWLER 88 returned to the diffractive data and investigated their consistency with an $a_1(1260)$ width $\geq$400 MeV, as required by the τ-decay data. He verified that a width of $\sim$300 MeV is a direct consequence of the particular fixed shape of the Deck amplitude as used in DAUM 81B; freeing this shape, good fits are achieved for an $a_1(1260)$ width of $\simeq$400 MeV. There is then no longer any contradiction between the hadronic and the τ-decay data, and the $a_1(1260)$ parameters are now well constrained. The best estimates found in BOWLER 88 are 1260$\pm$25 MeV for the $a_1(1260)$ mass and 396$\pm$43 MeV for its width.

$a_1(1260)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1260 ±30 OUR ESTIMATE					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1146 ±65	[1] ANDO	91	SPEC		$8\ \pi^- p \to \pi^+\pi^-\pi^0 n$
1242 ±37	[2] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
1260 ±14	[3] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
1250 ± 9	[4] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
1208 ±15	ARMSTRONG	90	OMEG	0	$300.0 pp \to pp\pi^+\pi^-\pi^0$
1122 ±17	[5] TAKAMATSU	90	SPEC	0	$8\ \pi^- p \to 3\pi n$
1220 ±15	[6] ISGUR	89	RVUE		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
1260 ±25	[7] BOWLER	88	RVUE		
1166 ±18 ±11	BAND	87	MAC		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
1164 ±41 ±23	BAND	87	MAC		$\tau^+ \to \pi^+\pi^0\pi^0\nu$
1250 ±40	[6] TORNQVIST	87	RVUE		
1046 ±11	[8] ALBRECHT	86B	ARG		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
1235 ±40	[6] BOWLER	86	RVUE		
1056 ±20 ±15	[8] RUCKSTUHL	86	DLCO		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
1194 ±14 ±10	[8] SCHMIDKE	86	MRK2		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
1240.0±80.0	[1] DANKOWY...	81	SPEC	0	$8.45\ \pi^- p \to n 3\pi$
1280.0±30.0	[1] DAUM	81B	CNTR		$63,94\ \pi^- p \to p 3\pi$
1041.0±13.0	[9] GAVILLET	77	HBC	+	$4.2\ K^- p \to \Sigma 3\pi$

[1] Uses the model of BOWLER 75.
[2] Reanalysis of RUCKSTUHL 86.
[3] Reanalysis of SCHMIDKE 86.
[4] Reanalysis of ALBRECHT 86B.
[5] Results of Breit–Wigner fitting to intensity distribution of $1 1^+ \rho S_1 +$ wave.
[6] From a combined reanalysis of ALBRECHT 86B, SCHMIDKE 86, and RUCKSTUHL 86.
[7] From a combined reanalysis of ALBRECHT 86B and DAUM 81B.
[8] Included in BOWLER 86, TORNQVIST 87, and ISGUR 89 reviews.
[9] Produced in K^- backward scattering.

$a_1(1260)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
~400 OUR ESTIMATE					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
272 ± 83	[10] ANDO	91	SPEC		$8\ \pi^- p \to \pi^+\pi^-\pi^0 n$
465 $^{+228}_{-143}$	[11] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
298 $^{+40}_{-34}$	[12] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
488 ± 32	[13] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
430 ± 50	ARMSTRONG	90	OMEG	0	$300.0 pp \to pp\pi^+\pi^-\pi^0$
254 ± 11	[18] TAKAMATSU	90	SPEC	0	$8\ \pi^- p \to 3\pi n$
420 ± 40	[14] ISGUR	89	RVUE		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
396 ± 43	[15] BOWLER	88	RVUE		
405 ± 75 ±25	BAND	87	MAC		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
419 ±108 ±57	BAND	87	MAC		$\tau^+ \to \pi^+\pi^0\pi^0\nu$
600 ±100	[14] TORNQVIST	87	RVUE		
521 ± 27	[16] ALBRECHT	86B	ARG		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
400 ±100	[14] BOWLER	86	RVUE		
476 $^{+132}_{-120}$ ±54	[16] RUCKSTUHL	86	DLCO		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
462 ± 56 ±30	[16] SCHMIDKE	86	MRK2		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
380.0±100.0	[10] DANKOWY...	81	SPEC	0	$8.45\ \pi^- p \to n 3\pi$
300.0± 50.0	[10] DAUM	81B	CNTR		$63,94\ \pi^- p \to p 3\pi$
230.0± 50.0	[17] GAVILLET	77	HBC	+	$4.2\ K^- p \to \Sigma 3\pi$

[10] Uses the model of BOWLER 75.
[11] Reanalysis of RUCKSTUHL 86.
[12] Reanalysis of SCHMIDKE 86.
[13] Reanalysis of ALBRECHT 86B.
[14] From a combined reanalysis of ALBRECHT 86B, SCHMIDKE 86, and RUCKSTUHL 86.
[15] From a combined reanalysis of ALBRECHT 86B and DAUM 81B.
[16] Included in BOWLER 86, TORNQVIST 87, and ISGUR 89 reviews.
[17] Produced in K^- backward scattering.
[18] Results of Breit–Wigner fitting to intensity distribution of $1 1^+ \rho S_1 +$ wave.

$a_1(1260)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\rho\pi$	dominant	
Γ_2	$\pi\gamma$	seen	
Γ_3	$\pi(\pi\pi)_{S\text{-wave}}$	[a] <0.7 %	90%

[a] This is only an educated guess; the error given is larger than the error on the average of the published values.

$a_1(1260)$ PARTIAL WIDTHS

$\Gamma(\pi\gamma)$ Γ_2

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
640.0±246.0	ZIELINSKI	84C	SPEC	$200\ \pi^+ Z \to Z 3\pi$

$a_1(1260)$ BRANCHING RATIOS

$\Gamma(\pi(\pi\pi)_{S\text{-wave}})/\Gamma(\rho\pi)$ Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN
0.003 ±0.003	[19] LONGACRE	82	RVUE

[19] Uses multichannel Aitchison-Bowler model (BOWLER 75). Uses data from GAVILLET 77, DAUM 80, and DANKOWYCH 81.

$a_1(1260)$ REFERENCES

ANDO 91 NP B21 98 (suppl) + (KEK, KYOT, NIRS, SAGA, TOKY, AKIT, NAGO+)
IVANOV 91 ZPHY C49 563 +Osipov, Volkov (JINR)
ARMSTRONG 90 ZPHY C48 213 +Benayoun, Beusch (WA76 Collab.)
TAKAMATSU 90 Hadron 89 Conf. p 71 +Ando+ (KEK)
ISGUR 89 PR D39 1357 +Morningstar, Reader (TNTO)
BOWLER 88 PL B209 99 (OXF)
BAND 87 PL B198 297 +Camporesi, Chadwick, Delfino+ (MAC Collab.)
TORNQVIST 87 ZPHY C36 695 (HELS)
ALBRECHT 86B ZPHY C33 7 +Donker, Gabriel, Edwards+ (ARGUS Collab.)
BOWLER 86 PL B182 400 (OXF)
RUCKSTUHL 86 PRL 56 2132 +Stroynowski, Atwood, Barish+ (DELCO Collab.)
SCHMIDKE 86 PRL 57 527 +Abrams, Matteuzzi, Amidei+ (Mark II Collab.)
ZIELINSKI 84C PRL 52 1195 +Berg, Chandlee, Cihangir+ (ROCH, MINN, FNAL)
LONGACRE 82 PR D26 83 (BNL)
DANKOWY... 81 PRL 46 580 Dankowych+ (TNTO, BNL, CARL, MCGI, OHIO)
DAUM 81B NP B182 269 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)
DAUM 80 PL 89B 281 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+) JP
GAVILLET 77 PL 69B 119 +Blockzijl, Engelen+ (AMST, CERN, NIJM, OXF) JP
BOWLER 75 NP B97 227 +Game, Aitchison, Dainton (OXF, DARE)

OTHER RELATED PAPERS

IIZUKA 89 PR D39 3357 +Koibuchi, Masuda (NAGO, IBAR, TSUK)
TORNQVIST 87 ZPHY C36 695 (HELS)
ADERHOLZ 64 PL 10 226 + (AACH, BERL, BIRM, BONN, DESY, HAMB+)
GOLDHABER 64 PRL 12 336 +Brown, Kadyk, Shen+ (LRL, UCB)
LANDER 64 PRL 13 346A +Abolins, Carmony, Hendricks, Xuong+ (UCSD) JP
BELLINI 63 NC 29 896 +Fiorini, Herz, Negri, Ratti (MILA)

$f_2(1270)$

$I^G(J^{PC}) = 0^+(2^{++})$

See also minireview under non-$q\bar{q}$ candidates.

$f_2(1270)$ MASS

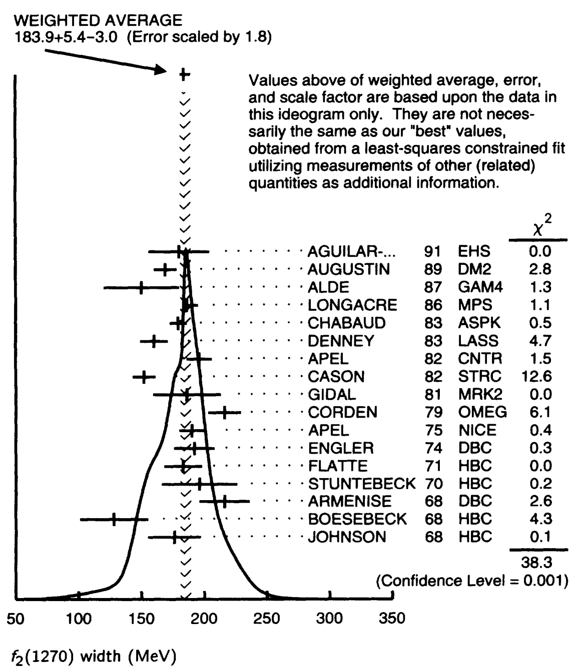
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1275 ± 5 OUR ESTIMATE					
1274.9± 1.2 OUR AVERAGE					
1269.7± 5.2	5730	AUGUSTIN	89	DM2	$e^+e^- \to 5\pi$
1283 ± 8	400 ± 50	[1] ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$
1274 ± 5		[1] AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
1283.0± 6.0		[2] LONGACRE	86	MPS	$22\ \pi^- p \to n 2K^0_S$
1276.0± 7.0		COURAU	84	DLCO	$e^+e^- \to e^+e^-\pi^+\pi^-$
1273.3± 2.3		[3] CHABAUD	83	ASPK	$17\ \pi^- p$ polarized
1280.0± 4.0		[4] CASON	82	STRC	$8\ \pi^+ p \to p\pi^+ 2\pi^0$
1281.0± 7.0	11600 ± 1000	GIDAL	81	MRK2	J/ψ decay
1282.0± 5.0		[5] CORDEN	79	OMEG	$12–15\ \pi^- p \to n 2\pi$
1269 ± 4	10k	APEL	75	NICE	$40\ \pi^- p \to n 2\pi^0$
1272 ± 4	4600	ENGLER	74	DBC	$6\ \pi^+ n \to \pi^+\pi^- p$
1277.0± 4.0	5300	FLATTE	71	HBC	$7.0\ \pi^+ p$
1273.0± 8.0		[1] STUNTEBECK	70	HBC	$8\ \pi^- p$, $5.4\ \pi^+ d$
1265 ± 8		BOESEBECK	68	HBC	$8\ \pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1281 ± 6		ADAMO	91	OBLX	$\bar{n} p \to \pi^+\pi^+\pi^-$
1262 ±11		AGUILAR-...	91	EHS	$400 pp$
1275 ±10		AKER	91	CBAR	$0.0\ \bar{p} p \to 3\pi^0$
1220 ±10		BREAKSTONE	90	SFM	$pp \to pp\pi^+\pi^-$
1288.0±12.0		ABACHI	86B	HRS	$e^+e^- \to \pi^+\pi^-$
1284.0±30.0	3k	BINON	83	GAM2	$38\ \pi^- p \to n 2\eta$
1280.0±20.0	3k	APEL	82	CNTR	$25\ \pi^- p \to n 2\pi^0$
1284.0±10.0	16000	DEUTSCH...	76	HBC	$16\ \pi^+ p$
1258.0±10.0	600	TAKAHASHI	72	HBC	$8\ \pi^- p \to n 2\pi$
1275.0±13.0		ARMENISE	70	HBC	$9\ \pi^+ n \to p\pi^+\pi^-$
1261 ± 5	1960	[1] ARMENISE	68	DBC	$5.1\ \pi^+ n \to p\pi^+ MM^-$
1270 ±10	360	[1] ARMENISE	68	DBC	$5.1\ \pi^+ n \to p\pi^0$ MM
1268.0± 6.0		[6] JOHNSON	68	HBC	$3.7–4.2\ \pi^- p$
1276 ±11		RABIN	67	HBC	$8.5\ \pi^+ p$

[1] Mass errors enlarged by us to $\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[2] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.
[3] From an energy-independent partial-wave analysis.
[4] From an amplitude analysis of $\pi^+\pi^- \to \pi^0\pi^0$ scattering data.
[5] From an amplitude analysis of $\pi^+\pi^- \to \pi^+\pi^-$ scattering data.
[6] JOHNSON 68 includes BONDAR 63, LEE 64, DERADO 65, EISNER 67.

$f_2(1270)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
185 ±20 OUR ESTIMATE					
184.7± 2.8 OUR FIT Error includes scale factor of 1.6.					
$183.9^{+5.4}_{-3.0}$ OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.					
180 ±24		AGUILAR-...	91	EHS	400 pp
169.0± 9.0	5730	[7] AUGUSTIN	89	DM2	$e^+e^- \rightarrow 5\pi$
150 ±30	400 ± 50	[7] ALDE	87	GAM4	100 $\pi^- p \rightarrow 4\pi^0 n$
$186.0^{+9.0}_{-2.0}$		[8] LONGACRE	86	MPS	22 $\pi^- p \rightarrow n2K^0_S$
$179.2^{+6.9}_{-6.6}$		[9] CHABAUD	83	ASPK	17 $\pi^- p$ polarized
160.0±11.0		DENNEY	83	LASS	10 $\pi^+ N$
196.0±10.0	3k	APEL	82	CNTR	25 $\pi^- p \rightarrow n2\pi^0$
152.0± 9.0		[10] CASON	82	STRC	8 $\pi^+ p \rightarrow p\pi^+ 2\pi^0$
186.0±27.0	11600 ± 1000	GIDAL	81	MRK2	J/ψ decay
216.0±13.0		[11] CORDEN	79	OMEG	12–15 $\pi^- p \rightarrow n2\pi$
190 ±10	10k	APEL	75	NICE	40 $\pi^- p \rightarrow n2\pi^0$
192 ±16	4600	ENGLER	74	DBC	6 $\pi^+ n \rightarrow \pi^+\pi^- p$
183.0±15.0	5300	FLATTE	71	HBC	7 $\pi^+ p \rightarrow \Delta^{++} f_2$
196.0±30.0		[7] STUNTEBECK	70	HBC	8 $\pi^- p$, 5.4 $\pi^+ d$
216 ±20	1960	[7] ARMENISE	68	DBC	5.1 $\pi^+ n \rightarrow p\pi^+ MM^-$
128 ±27		[7] BOESEBECK	68	HBC	8 $\pi^+ p$
176.0±21.0		[7,12] JOHNSON	68	HBC	3.7–4.2 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
206 ±19		ADAMO	91	OBLX	$\bar{n}p \rightarrow \pi^+\pi^+\pi^-$
200 ±10		AKER	91	CBAR	0.0 $\bar{p}p \rightarrow 3\pi^0$
240.0±40.0	3k	BINON	83	GAM2	38 $\pi^- p \rightarrow n2\eta$
187.0±30.0	650	[7] ANTIPOV	77	CIBS	25 $\pi^- p \rightarrow p3\pi$
225.0±38.0	16000	DEUTSCH...	76	HBC	16 $\pi^+ p$
166.0±28.0	600	[7] TAKAHASHI	72	HBC	8 $\pi^- p \rightarrow n2\pi$
173.0±53.0		[7] ARMENISE	70	HBC	9 $\pi^+ n \rightarrow p\pi^+\pi^-$
155 ±17		RABIN	67	HBC	8.5 $\pi^+ p$

[7] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[8] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.
[9] From an energy-independent partial-wave analysis.
[10] From an amplitude analysis of $\pi^+\pi^- \rightarrow \pi^0\pi^0$ scattering data.
[11] From an amplitude analysis of $\pi^+\pi^- \rightarrow \pi^+\pi^-$ scattering data.
[12] JOHNSON 68 includes BONDAR 63, LEE 64, DERADO 65, EISNER 67.



$f_2(1270)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi\pi$	$(84.9\ ^{+2.5}_{-1.3})$ %	S=1.3
Γ_2	$\pi^+\pi^-2\pi^0$	$(6.9\ ^{+1.5}_{-2.7})$ %	S=1.4
Γ_3	$K\bar{K}$	(4.6 ±0.5) %	S=2.9
Γ_4	$2\pi^+2\pi^-$	(2.8 ±0.4) %	S=1.2
Γ_5	$\eta\eta$	(4.5 ±1.0) $\times 10^{-3}$	S=2.4
Γ_6	$4\pi^0$	(3.0 ±1.0) $\times 10^{-3}$	
Γ_7	$\gamma\gamma$	(1.39±0.20) $\times 10^{-5}$	S=1.1
Γ_8	$\eta\pi\pi$	< 8 $\times 10^{-3}$	CL=95%
Γ_9	$K^0K^-\pi^+$ + c.c.	< 3.4 $\times 10^{-3}$	CL=95%
Γ_{10}	e^+e^-	< 9 $\times 10^{-9}$	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to the total width, 4 partial widths, a combination of partial widths obtained from integrated cross sections, and 6 branching ratios uses 38 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 69.4$ for 31 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−92						
x_3	12	−39					
x_4	11	−36	1				
x_5	2	−9	0	0			
x_6	0	−6	0	0	0		
x_7	7	−2	−15	1	0	0	
Γ	−82	76	−12	−9	−3	0	−9
	x_1	x_2	x_3	x_4	x_5	x_6	x_7

	Mode	Rate (MeV)	Scale factor
Γ_1	$\pi\pi$	$156.8\ ^{+3.2}_{-1.3}$	
Γ_2	$\pi^+\pi^-2\pi^0$	$12.7\ ^{+2.9}_{-5.1}$	1.4
Γ_3	$K\bar{K}$	8.6 ±0.8	3.0
Γ_4	$2\pi^+2\pi^-$	5.2 ±0.7	1.2
Γ_5	$\eta\eta$	0.83 ±0.19	2.4
Γ_6	$4\pi^0$	0.55 ±0.18	
Γ_7	$\gamma\gamma$	0.0026±0.0004	1.1

$f_2(1270)$ PARTIAL WIDTHS

$\Gamma(\pi\pi)$ — Γ_1

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$156.8^{+3.2}_{-1.3}$ OUR FIT				
$157.0^{+6.0}_{-1.0}$	[14] LONGACRE	86	MPS	22 $\pi^- p \rightarrow n2K^0_S$

$\Gamma(K\bar{K})$ — Γ_3

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
8.6 ±0.8 OUR FIT Error includes scale factor of 3.0.				
$9.0\ ^{+0.7}_{-0.3}$	[14] LONGACRE	86	MPS	22 $\pi^- p \rightarrow n2K^0_S$

$\Gamma(\eta\eta)$ — Γ_5

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0.83±0.19 OUR FIT Error includes scale factor of 2.4.				
1.0 ±0.1	[14] LONGACRE	86	MPS	22 $\pi^- p \rightarrow n2K^0_S$

$\Gamma(\gamma\gamma)$ — Γ_7

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT
2.6 ±0.4 OUR FIT Error includes scale factor of 1.1.					
2.8 ±0.4 OUR AVERAGE					
3.10±0.35±0.35		[13] BLINOV	91	MD1	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-$
2.35±0.65		[15] MORGAN	90	RVUE	$\gamma\gamma \rightarrow \pi^+\pi^-, \pi^0\pi^0$

• • • We do not use the following data for averages, fits, limits, etc. • • •

$2.27\pm0.47\pm0.11$		ADACHI	90D	TOPZ	$e^+e^- \to e^+e^-\pi^+\pi^-$
$3.15\pm0.04\pm0.39$		BOYER	90	MRK2	$e^+e^- \to e^+e^-\pi^+\pi^-$
$3.19\pm0.16^{+0.29}_{-0.28}$		MARSISKE	90	CBAL	$e^+e^- \to e^+e^-\pi^0\pi^0$
$3.19\pm0.09^{+0.22}_{-0.38}$	2177 ± 47	OEST	90	JADE	$e^+e^- \to e^+e^-\pi^0\pi^0$
$3.0\ \pm0.1\ \pm0.5$		[16] BEHREND	88D	CELL	$e^+e^- \to e^+e^-\pi^+\pi^-$
$3.2\ \pm0.1\ \pm0.4$		[17] AIHARA	86B	TPC	$e^+e^- \to e^+e^-\pi^+\pi^-$
$2.5\ \pm0.1\ \pm0.5$		BEHREND	84B	CELL	$e^+e^- \to e^+e^-\pi^+\pi^-$
$2.85\pm0.25\pm0.5$		[18] BERGER	84	PLUT	$e^+e^- \to e^+e^-2\pi$
$2.70\pm0.05\pm0.20$		COURAU	84	DLCO	$e^+e^- \to e^+e^-\pi^+\pi^-$
$2.52\pm0.13\pm0.38$		[19] SMITH	84C	MRK2	$e^+e^- \to e^+e^-\pi^+\pi^-$
$2.3\ \pm0.2\ \pm0.5$		FRAZER	83	JADE	$e^+e^- \to e^+e^-\pi^+\pi^-$
$2.7\ \pm0.2\ \pm0.6$		EDWARDS	82F	CBAL	$e^+e^- \to e^+e^-2\pi^0$
$2.9\ ^{+0.6}_{-0.4}\ \pm0.6$		[20] EDWARDS	82F	CBAL	$e^+e^- \to e^+e^-2\pi^0$
$3.2\ \pm0.2\ \pm0.6$		BRANDELIK	81B	TASS	$e^+e^- \to e^+e^-\pi^+\pi^-$
$3.6\ \pm0.3\ \pm0.5$		ROUSSARIE	81	MRK2	$e^+e^- \to e^+e^-\pi^+\pi^-$
$2.3\ \pm0.8$		[21] BERGER	80B	PLUT	e^+e^-

[13] In the unitarized model of Lyth.

$\Gamma(e^+e^-)$ — Γ_{10}

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<1.7	90	VOROBYEV	88	ND	$e^+e^- \to \pi^0\pi^0$

[14] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.
[15] Error includes spread of different solutions. Data of MARK2 and CRYSTAL BALL used in the analysis. Authors report strong correlations with $\gamma\gamma$ width of $f_0(1400)$: $\Gamma(f_2) + 1/4\ \Gamma(f^0) = 3.6 \pm 0.3$ KeV.
[16] Not used, since quoted as preliminary.
[17] Radiative corrections modify the partial widths; for instance the COURAU 84 value becomes 2.66 ± 0.21 in the calculation of LANDRO 86.
[18] Using the MENNESSIER 83 model.
[19] Superseded by BOYER 90.
[20] If helicity = 2 assumption is not made.
[21] Using mass, width and $B(f_2(1270) \to 2\pi)$ from PDG 78.

$f_2(1270)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ — $\Gamma_3\Gamma_7/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.119±0.018 OUR FIT Error includes scale factor of 1.2.				
0.091±0.007±0.027	[22] ALBRECHT	90G	ARG	$e^+e^- \to e^+e^-K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.104\pm0.007\pm0.072$	[23] ALBRECHT	90G	ARG	$e^+e^- \to e^+e^-K^+K^-$

[22] Using an incoherent background.
[23] Using a coherent background.

$f_2(1270)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.849^{+0.025}_{-0.013}$ OUR FIT Error includes scale factor of 1.3.					
0.837±0.020 OUR AVERAGE					
0.849 ± 0.025		CHABAUD	83	ASPK	$17\ \pi^-p$ polarized
$0.85\ \pm0.05$	250	BEAUPRE	71	HBC	$8\ \pi^+p \to \Delta^{++}f_2$
$0.8\ \ \pm0.04$	600	OH	70	HBC	$1.26\ \pi^-p \to \pi^+\pi^-n$

$\Gamma(\pi^+\pi^-2\pi^0)/\Gamma(\pi\pi)$ — Γ_2/Γ_1

Should be twice $\Gamma(2\pi^+2\pi^-)/\Gamma(\pi\pi)$ if decay is $\rho\rho$. (See ASCOLI 68D.)

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.081^{+0.019}_{-0.034}$ OUR FIT Error includes scale factor of 1.4.					
0.15 ±0.06	600	EISENBERG	74	HBC	$4.9\ \pi^+p \to \Delta^{++}f_2$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.07		EMMS	75D	DBC	$4\ \pi^+n \to pf_2$

$\Gamma(K\overline{K})/\Gamma(\pi\pi)$ — Γ_3/Γ_1

We average only experiments which either take into account $f_2(1270)$-$a_2(1320)$ interference explicitly or demonstrate that $a_2(1320)$ production is negligible.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.055±0.006 OUR FIT Error includes scale factor of 2.9.					
$0.040^{+0.005}_{-0.006}$ OUR AVERAGE					
$0.037^{+0.008}_{-0.021}$		ETKIN	82B	MPS	$23\ \pi^-p \to n2K^0_S$
0.045 ± 0.009		CHABAUD	81	ASPK	$17\ \pi^-p$ polarized
0.039 ± 0.008		LOVERRE	80	HBC	$4\ \pi^-p \to K\overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.036 ± 0.005		[24] COSTA...	80	OMEG	1–$2.2\ \pi^-p \to K^+K^-n$
0.030 ± 0.005		[25] MARTIN	79	RVUE	
0.027 ± 0.009		[26] POLYCHRO...	79	STRC	$7\ \pi^-p \to n2K^0_S$
0.025 ± 0.015		EMMS	75D	DBC	$4\ \pi^+n \to pf_2$
0.031 ± 0.012	20	ADERHOLZ	69	HBC	$8\ \pi^+p \to K^+K^-\pi^+p$

[24] Re-evaluated by CHABAUD 83.
[25] Includes PAWLICKI 77 data.
[26] Takes into account the $f_2(1270) - f_2'(1525)$ interference.

$\Gamma(2\pi^+2\pi^-)/\Gamma(\pi\pi)$ — Γ_4/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.033±0.005 OUR FIT Error includes scale factor of 1.2.					
0.033±0.004 OUR AVERAGE Error includes scale factor of 1.1.					
0.024 ± 0.006	160	EMMS	75D	DBC	$4\ \pi^+n \to pf_2$
0.051 ± 0.025	70	EISENBERG	74	HBC	$4.9\ \pi^+p \to \Delta^{++}f_2$
$0.043^{+0.007}_{-0.011}$	285	LOUIE	74	HBC	$3.9\ \pi^-p \to nf_2$
0.037 ± 0.007	154	ANDERSON	73	DBC	$6\ \pi^+n \to pf_2$
0.047 ± 0.013		OH	70	HBC	$1.26\ \pi^-p \to \pi^+\pi^-n$

$\Gamma(\eta\eta)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
4.5±1.0 OUR FIT Error includes scale factor of 2.4.				
3.1±0.8 OUR AVERAGE Error includes scale factor of 1.3.				
2.8 ± 0.7	ALDE	86D	GAM4	$100\ \pi^-p \to 2\eta n$
5.2 ± 1.7	BINON	83	GAM2	$38\ \pi^-p \to 2\eta n$

$\Gamma(\eta\eta)/\Gamma(\pi\pi)$ — Γ_5/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	95	EDWARDS	82F	CBAL	$e^+e^- \to e^+e^-2\eta$
<0.016	95	EMMS	75D	DBC	$4\ \pi^+n \to pf_2$
<0.09	95	EISENBERG	74	HBC	$4.9\ \pi^+p \to \Delta^{++}f_2$

$\Gamma(4\pi^0)/\Gamma_{total}$ — Γ_6/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0030±0.0010 OUR FIT					
0.003 ±0.001	400 ± 50	ALDE	87	GAM4	$100\ \pi^-p \to 4\pi^0n$

$\Gamma(\eta\pi\pi)/\Gamma(\pi\pi)$ — Γ_8/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.010	95	EMMS	75D	DBC	$4\ \pi^+n \to pf_2$

$\Gamma(K^0K^-\pi^+ + \text{c.c.})/\Gamma(\pi\pi)$ — Γ_9/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.004	95	EMMS	75D	DBC	$4\ \pi^+n \to pf_2$

$f_2(1270)$ REFERENCES

ADAMO	91	Hadron 91 Conf.	+Agnello, Balestra+	(OBELIX Collab.)
AGUILAR-...	91	ZPHY C50 405	Aguilar-Benitez, Allison, Batalor+	(LEBC-EHS Collab.)
AKER	91	PL B260 249	+Amsler, Peters+	(CBAR Collab.)
BLINOV	91	INP 91-71 Preprint	+Bondar, Bukin+	(NOVO)
ADACHI	90D	PL B234 185	+Doser+	(TOPAZ Collab.)
ALBRECHT	90G	ZPHY C48 183	+Ehrlichmann, Harder+	(ARGUS Collab.)
BOYER	90	PR D42 1350	+Butler+	(Mark II Collab.)
BREAKSTONE	90	ZPHY C48 569	+	(ISU, BGNA, CERN, DORT, HEID, WARS)
MARSISKE	90	PR D41 3324	+Antreasyan+	(Crystal Ball Collab.)
MORGAN	90	ZPHY C48 623	+Pennington	(RAL, DURH)
OEST	90	ZHPY C47 343	+Olsson+	(JADE Collab.)
AUGUSTIN	89	NP B320 1	+Cosme	(DM2 Collab.)
BEHREND	88D	Munich 88 Conference	+	(CELLO Collab.)
VOROBYEV	88	SJNP 48 273	+Golubev, Dolinsky, Druzhinin+	(NOVO)
		Translated from YAF 48 436.		
ALDE	87	PL B198 286	+Binon, Bricman+	(LANL, BRUX, SERP, LAPP)
AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
ABACHI	86B	PRL 57 1990	+Derrick, Blockus+	(PURD, ANL, IND, MICH, LBL)
AIHARA	86B	PRL 57 404	+Alston-Garnjost+	(TPC-2γ Collab.)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN)
LANDRO	86	PL B172 445	+Mork, Olsen	(UTRO)
LONGACRE	86	PL B177 223	+Etkin+	(BNL, BRAN, CUNY, DUKE, NDAM)
BEHREND	84B	ZPHY C23 223	+Fenner, Schachter, Schroeder+	(CELLO Collab.)
BERGER	84	ZPHY C26 199	+Klovning, Burger+	(PLUTO Collab.)
COURAU	84	PL 147B 227	+Johnson, Sherman, Atwood, Baillon+	(CIT, SLAC)
SMITH	84C	PR D30 851	+Burke, Abrams, Blocker, Levi+	(SLAC, LBL, HARV)
BINON	83	NC 78A 313	+Donskov, Duteil+	(BELG, LAPP, SERP, CERN)
Also	83B	SJNP 38 561	Binon, Gouanere+	(BELG, LAPP, SERP, CERN)
CHABAUD	83	NP B223 1	+Gorlich, Cerrada+	(CERN, CRAC, MPIM)
DENNEY	83	PR D28 2726	+Cranley, Firestone, Chapman+	(IOWA, MICH)
FRAZER	83	Aachen Conf.		(UCSD)
MENNESSIER	83	ZPHY C16 241		(MONP)
APEL	82	NP B201 197	+Augenstein+	(KARL, PISA, SERP, WIEN, CERN)
CASON	82	PRL 48 1316	+Biswas, Baumbaugh, Bishop+	(NDAM, ANL)
EDWARDS	82F	PL 110B 82	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFT, VAND)
BRANDELIK	81B	ZPHY C10 117	+Boerner+	(TASSO Collab.)
CHABAUD	81	APP B12 575	+Niczyporuk, Becker+	(CERN, CRAC, MPIM)

GIDAL	81	PL 107B 153	+Goldhaber, Guy, Millikan, Abrams+ (SLAC, LBL)
ROUSSARIE	81	PL 105B 304	+Burke, Abrams, Alam+ (SLAC, LBL)
BERGER	80B	PL 94B 254	+Genzer+ (AACH, BERG, DESY, HAMB, UMD+)
COSTA...	80	NP B175 402	Costa De Beauregard+ (BARI, BONN, CERN+)
LOVERRE	80	ZPHY C6 187	+Armenteros, Dionisi+ (CERN, CDEF, MADR, STOH)
CORDEN	79	NP B157 250	+Dowell, Garvey+ (BIRM, RHEL, TELA, LOWC)
MARTIN	79	NP B158 520	+Ozmutlu (DURH)
POLYCHRO...	79	PR D19 1317	Polychronakos, Cason, Bishop+ (NDAM, ANL)
PDG	78	PL 75B	Bricman+
ANTIPOV	77	NP B119 45	+Busnello, Damgaard, Kienzle+ (SERP, GEVA)
PAWLICKI	77	PR D15 3196	+Ayres, Cohen, Diebold, Kramer, Wicklund (ANL)
DEUTSCH...	76	NP B103 426	Deutschmann+ (AACH, BERL, BONN, CERN+)
APEL	75	PL 57B 398	+Augenstein+ (KARL, PISA, SERP, WIEN, CERN)
EMMS	75D	NP B96 155	+Kinson, Stacey, Votruba+ (BIRM, DURH, RHEL)
EISENBERG	74	PL 52B 239	+Engler, Haber, Karshon+ (REHO)
ENGLER	74	PR D10 2070	+Kraemer, Toaff, Weisser, Diaz+ (CMU, CASE)
LOUIE	74	PL 48B 385	+Alitti, Gandois, Chaloupka+ (SACL, CERN)
ANDERSON	73	PRL 31 562	+Engler, Kraemer, Toaff, Diaz+ (CMU, CASE)
TAKAHASHI	72	PR D6 1266	+Barish+ (TOHO, PENN, NDAM, ANL)
BEAUPRE	71	NP B28 77	+Deutschmann, Graessler+ (AACH, BERL, CERN)
FLATTE	71	PL 34B 551	+Alston-Garnjost, Barbaro-Galtieri+ (LBL)
ARMENISE	70	LNC 4 199	+Ghidini, Foring, Cartacci+ (BARI, BGNA, FIRZ)
OH	70	PR D1 2494	+Garfinkel, Morse, Walker, Prentice (WISC, TNTO) JP
STUNTEBECK	70	PL 32B 391	+Kenney, Deery, Biswas, Cason+ (NDAM)
ADERHOLZ	69	NP B11 259	+Bartsch+ (AACH, BERL, CERN, JAGL, WARS)
ARMENISE	68	NC 54A 999	+Ghidini, Forino+ (BARI, BGNA, FIRZ, ORSA)
ASCOLI	68D	PRL 21 1712	+Crawley, Mortara+ (ILL)
BOESEBECK	68	NP B4 501	+Deutschmann+ (AACH, BERL, CERN)
JOHNSON	68	PR 176 1651	+Poirier, Biswas, Gutay+ (NDAM, PURD, SLAC)
EISNER	67	PR 164 1699	+Johnson, Klein, Peters, Sahni, Yen+ (PURD)
RABIN	67	Thesis	(RUTG)
DERADO	65	PRL 14 872	+Kenney, Poirier, Shephard (NDAM)
LEE	64	PRL 12 342	+Roe, Sinclair, VanderVelde (MICH)
BONDAR	63	PL 5 153	+ (AACH, BIRM, BONN, DESY, LOIC, MPIM)

$f_1(1285)$

was $D(1285)$

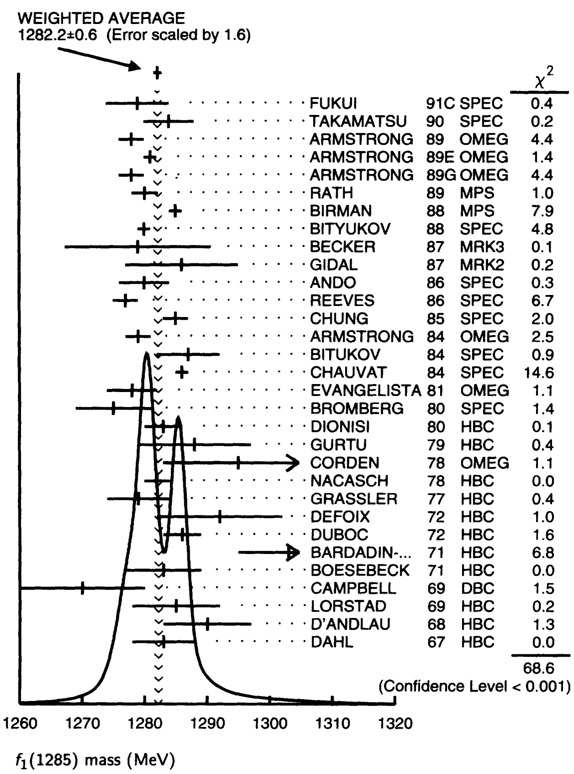
$I^G(J^{PC}) = 0^+(1^{++})$

See also minireview under non-$q\overline{q}$ candidates.

$f_1(1285)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1282 ± 5 OUR ESTIMATE					
1282.2± 0.6 OUR AVERAGE		Error includes scale factor of 1.6. See the ideogram below.			
1279 ± 5		FUKUI 91C	SPEC		$8.95\ \pi^- p \to \eta\pi^+\pi^- n$
1284 ± 4		TAKAMATSU 90	SPEC	0	$8\ \pi^- p \to K\overline{K}\pi n$
1278 ± 2	140 ± 12	ARMSTRONG 89	OMEG		$300\ pp \to K\overline{K}\pi pp$
1281 ± 1		ARMSTRONG 89E	OMEG		$300\ pp \to pp2(\pi^+\pi^-)$
1278 ± 2		ARMSTRONG 89G	OMEG		$85\ \pi^+ p \to 4\pi\pi p,\ pp \to 4\pi pp$
1280.1± 2.1	60 ± 20	RATH 89	MPS		$21.4\ \pi^- p \to K^0_S K^0_S \pi^0 n$
1285 ± 1	4750 ± 100	[1] BIRMAN 88	MPS		$8\ \pi^- p \to K^+\overline{K}^0\pi^- n$
1280 ± 1	504 ± 84	BITYUKOV 88	SPEC		$32.5\ \pi^- p \to K^+K^-\pi^0 n$
1279 ± 6 ±10	16 ± 6	BECKER 87	MRK3		$e^+e^- \to \phi K\overline{K}\pi$
1286 ± 9		GIDAL 87	MRK2		$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
1280 ± 4		ANDO 86	SPEC		$8\ \pi^- p \to n\eta\pi^+\pi^-$
1277.0± 2.0	420	REEVES 86	SPEC		$6.6\ p\overline{p} \to KK\pi X$
1285.0± 2.0		CHUNG 85	SPEC		$8\ \pi^- p \to NK\overline{K}\pi$
1279.0± 2.0	604	ARMSTRONG 84	OMEG		$85\ \pi^+ p \to K\overline{K}\pi\pi p,\ pp \to K\overline{K}\pi pp$
1287.0± 5.0	353	BITUKOV 84	SPEC		$32\ \pi^- p \to K^+K^-\pi^0 n$
1286.0± 1.0		CHAUVAT 84	SPEC		ISR 31.5 pp
1278 ± 4		EVANGELISTA 81	OMEG		$12\ \pi^- p \to \eta\pi p$
1275.0± 6.0	31	BROMBERG 80	SPEC		$100\ \pi^- p \to K\overline{K}\pi X$
1283.0± 3.0	103	DIONISI 80	HBC		$4\ \pi^- p \to K\overline{K}\pi n$
1288.0± 9.0	200	GURTU 79	HBC		$4.2\ K^- p \to n\eta 2\pi$
1295.0±12.0	85	CORDEN 78	OMEG		$12–15\ \pi^- p \to n5\pi$
1282.0± 2.0	320	NACASCH 78	HBC		$0.7,0.76\ \overline{p}p \to K\overline{K}3\pi$
1279.0± 5.0	210	GRASSLER 77	HBC		$16\ \pi^{\mp} p$
1292 ±10	150	DEFOIX 72	HBC		$0.7\ \overline{p}p \to 7\pi$
1286 ± 3	180	DUBOC 72	HBC		$1.2\ \overline{p}p \to 2K4\pi$
1303.0± 8.0		BARDADIN-... 71	HBC		$8\ \pi^+ p \to p6\pi$
1283.0± 6.0		BOESEBECK 71	HBC		$16.0\ \pi p \to p5\pi$
1270.0±10.0		CAMPBELL 69	DBC		$2.7\ \pi^+ d$
1285 ± 7		LORSTAD 69	HBC		$0.7\ \overline{p}p$, 4,5-body
1290 ± 7		D'ANDLAU 68	HBC		$1.2\ \overline{p}p$, 5–6 body
1283.0± 5.0		DAHL 67	HBC		$1.6–4.2\ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1264 ± 8		AUGUSTIN 90	DM2		$J/\psi \to \gamma\eta\pi^+\pi^-$
~1279		[2] TORNQVIST 82B	RVUE		
~1275.0	46	[3] STANTON 79	CNTR		$8.5\ \pi^- p \to n2\gamma 2\pi$
1271.0±10.0	34	CORDEN 78	OMEG		$12–15\ \pi^- p \to K^+K^-\pi n$
1280 ± 3	500	[4] THUN 72	MMS		$13.4\ \pi^- p$

[1] From partial wave analysis of $K^+\overline{K}^0\pi^-$ system.
[2] From a unitarized quark-model calculation.
[3] From phase shift analysis of $\eta\pi^+\pi^-$ system.
[4] Seen in the missing mass spectrum.



$f_1(1285)$ WIDTH

Only experiments giving width error less than 20 MeV are kept for averaging.

VALUE (MeV)	CL%	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
24 ± 3 OUR ESTIMATE						
24.2± 1.1 OUR AVERAGE			Error includes scale factor of 1.1.			
22 ± 5			TAKAMATSU 90	SPEC	0	$8\ \pi^- p \to K\overline{K}\pi n$
25 ± 4		140 ± 12	ARMSTRONG 89	OMEG		$300\ pp \to K\overline{K}\pi pp$
31 ± 5			ARMSTRONG 89E	OMEG		$300\ pp \to pp2(\pi^+\pi^-)$
41 ±12			ARMSTRONG 89G	OMEG		$85\ \pi^+ p \to 4\pi\pi p,\ pp \to 4\pi pp$
17.9±10.9		60 ± 20	RATH 89	MPS		$21.4\ \pi^- p \to K^0_S K^0_S \pi^0 n$
22 ± 2		4750 ± 100	[5] BIRMAN 88	MPS		$8\ \pi^- p \to K^+\overline{K}^0\pi^- n$
25 ± 4		504 ± 84	BITYUKOV 88	SPEC		$32.5\ \pi^- p \to K^+K^-\pi^0 n$
$14\ ^{+20}_{-14}$ ±10		16 ± 6	BECKER 87	MRK3		$e^+e^- \to \phi K\overline{K}\pi$
19 ± 5			ANDO 86	SPEC		$8\ \pi^- p \to n\eta\pi^+\pi^-$

32.0± 8.0		420	REEVES 86	SPEC		6.6 $p\overline{p} \to K K \pi X$
22.0± 2.0			CHUNG 85	SPEC		8 $\pi^- p \to N K \overline{K} \pi$
32.0± 3.0		604	ARMSTRONG 84	OMEG		85 $\pi^+ p \to K \overline{K} \pi \pi p$, $pp \to K \overline{K} \pi p p$
24.0± 3.0			CHAUVAT 84	SPEC		ISR 31.5 pp
26 ±12			EVANGELISTA 81	OMEG		12 $\pi^- p \to \eta \pi p$
29.0±10.0		103	DIONISI 80	HBC		4 $\pi^- p \to K \overline{K} \pi n$
25.0±15.0		200	GURTU 79	HBC		4.2 $K^- p \to n \eta 2\pi$
28.3± 6.7		320	NACASCH 78	HBC		0.7,0.76 $\overline{p} p \to K \overline{K} 3\pi$
24.0±18.0		210	GRASSLER 77	HBC		16 $\pi^{\mp} p$
10.0±10.0			BOESEBECK 71	HBC		16.0 $\pi p \to p 5\pi$
30.0±15.0			CAMPBELL 69	DBC		2.7 $\pi^+ d$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
44 ±20			AUGUSTIN 90	DM2		$J/\psi \to \gamma \eta \pi^+ \pi^-$
<20	90		TAKAMATSU 90	SPEC	0	8.95 $\pi^- p \to \eta \pi^+ \pi^- n$
~ 10.0			STANTON 79 [6]	CNTR		8.5 $\pi^- p \to n 2\gamma 2\pi$
28 ± 5		150	DEFOIX 72 [7]	HBC		0.7 $\overline{p} p \to 7\pi$
46 ± 9		180	DUBOC 72 [7]	HBC		1.2 $\overline{p} p \to 2K 4\pi$
37 ± 5		500	THUN 72 [8]	MMS		13.4 $\pi^- p$
60 ±15			LORSTAD 69 [7]	HBC		0.7 $\overline{p} p$, 4,5-body
35.0±10.0			DAHL 67 [7]	HBC		1.6–4.2 $\pi^- p$

[5] From partial wave analysis of $K^+ \overline{K}^0 \pi^-$ system.
[6] From phase shift analysis of $\eta \pi^+ \pi^-$ system.
[7] Resolution is not unfolded.
[8] Seen in the missing mass spectrum.

$f_1(1285)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	4π	(38 ±4) %	S=1.1
Γ_2	$\rho \pi \pi$	dominates 4π	
Γ_3	$\rho^0 \pi^+ \pi^-$		
Γ_4	$\eta \pi \pi$	(50 ±5) %	S=1.1
Γ_5	$a_0(980)\pi$	(37 ±7) %	
Γ_6	$2\pi^+ 2\pi^-$		
Γ_7	$K \overline{K} \pi$	(11.9±1.4) %	S=1.1
Γ_8	$\phi \gamma$	(10 ±4) × 10^{-4}	
Γ_9	$\gamma \gamma^*$	(11 ±3) × 10^{-5}	
Γ_{10}	$4\pi^0$	< 7 × 10^{-4}	CL=90%
Γ_{11}	$\gamma \rho^0$	> 4 × 10^{-3}	CL=90%
Γ_{12}	$\gamma \gamma$		
Γ_{13}	$K \overline{K}^*(892)$	not seen	

CONSTRAINED FIT INFORMATION

An overall fit to 3 branching ratios uses 8 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 6.2 for 6 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle \delta x_i \delta x_j \right\rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_4	−96	
x_7	39	−62
	x_1	x_4

$f_1(1285)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(\eta\pi\pi) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ — $\Gamma_4\Gamma_{12}/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID	TECN	COMMENT
<0.62	95	GIDAL 87	MRK2	$e^+ e^- \to e^+ e^- \eta \pi^+ \pi^-$

$\Gamma(\eta\pi\pi) \times \Gamma(\gamma\gamma^*)/\Gamma_{total}$ — $\Gamma_4\Gamma_9/\Gamma$

VALUE (keV)	EVTS	DOCUMENT ID	TECN	COMMENT
1.4 ±0.4 OUR AVERAGE Error includes scale factor of 1.4.				
1.18±0.25±0.20	26	AIHARA 88B [9,10]	TPC	$e^+ e^- \to e^+ e^- \eta \pi^+ \pi^-$
2.30±0.61±0.42		GIDAL 87 [9,11]	MRK2	$e^+ e^- \to e^+ e^- \eta \pi^+ \pi^-$

[9] Assuming a ρ-pole form factor.
[10] Published value multiplied by $\eta\pi\pi$ branching ratio 0.49.
[11] Published value divided by 2 and multiplied by the $\eta\pi\pi$ branching ratio 0.49.

$f_1(1285)$ BRANCHING RATIOS

The $f_1(1285)$ branching ratios fit is made with the assumptions that the $f_1(1285) \to 4\pi$ decay is all $\rho\pi\pi$ and that the $\pi\pi$ pair has $I = 1$.

$\Gamma(K\overline{K}\pi)/\Gamma(4\pi)$ — Γ_7/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.31±0.04 OUR FIT Error includes scale factor of 1.1.			
0.32±0.04 OUR AVERAGE Error includes scale factor of 1.2.			
0.28±0.05	ARMSTRONG 89E [12]	OMEG	300 $pp \to pp f_1(1285)$
0.37±0.03±0.05	ARMSTRONG 89G [13]	OMEG	85 $\pi p \to 4\pi X$

[12] Assuming $\rho\pi\pi$ and $a_0(980)\pi$ intermediate states.
[13] 4π consistent with being entirely $\rho\pi\pi$.

$\Gamma(K\overline{K}\pi)/\Gamma(\eta\pi\pi)$ — Γ_7/Γ_4

VALUE	DOCUMENT ID	TECN	COMMENT
0.24±0.05 OUR FIT Error includes scale factor of 1.1.			
0.23±0.06 OUR AVERAGE Error includes scale factor of 1.2.			
0.42±0.15	GURTU 79	HBC	4.2 $K^- p$
0.5 ±0.2	CORDEN 78	OMEG	12–15 $\pi^- p$
0.20±0.08	DEFOIX 72 [14]	HBC	0.7 $\overline{p} p \to 7\pi$
0.16±0.08	CAMPBELL 69	DBC	2.7 $\pi^+ d$

[14] $K\overline{K}$ system characterized by the $I = 1$ threshold enhancement. (See under $a_0(980)$).

$\Gamma(a_0(980)\pi)/\Gamma(\eta\pi\pi)$ — Γ_5/Γ_4

VALUE	DOCUMENT ID	TECN	COMMENT
0.74±0.12 OUR AVERAGE			
0.72±0.15	GURTU 79	HBC	4.2 $K^- p$
0.6 $^{+0.3}_{-0.2}$	CORDEN 78	OMEG	12–15 $\pi^- p$
1.0 ±0.3	GRASSLER 77	HBC	16 $\pi^{\mp} p$

$\Gamma(4\pi)/\Gamma(\eta\pi\pi)$ — Γ_1/Γ_4

VALUE	DOCUMENT ID	TECN	COMMENT
0.76±0.16 OUR FIT Error includes scale factor of 1.1.			
0.83±0.24 OUR AVERAGE			
0.64±0.40	GURTU 79	HBC	4.2 $K^- p$
0.93±0.30	GRASSLER 77 [15]	HBC	16 $\pi^{\mp} p$

[15] Assuming $\rho\pi\pi$ and $a_0(980)\pi$ intermediate states.

$\Gamma(K\overline{K}^*(892))/\Gamma_{total}$ — Γ_{13}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
not seen	NACASCH 78	HBC	0.7,0.76 $\overline{p} p \to K\overline{K} 3\pi$

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma(2\pi^+2\pi^-)$ — $\frac{1}{3}\Gamma_3/\Gamma_6$

VALUE	DOCUMENT ID	TECN	COMMENT
1.0±0.4	GRASSLER 77	HBC	16 GeV $\pi^{\pm} p$

$\Gamma(\rho\pi\pi)/\Gamma(\eta\pi\pi)$ — Γ_2/Γ_4

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.4	95	CORDEN 78 [16]	OMEG	12–15 $\pi^- p$

[16] Note that CORDEN 78 and GRASSLER 77 are in disagreement.

$\Gamma(4\pi^0)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<7	90	ALDE 87	GAM4	100 $\pi^- p \to 4\pi^0 n$

$\Gamma(\phi\gamma)/\Gamma(K\overline{K}\pi)$ — Γ_8/Γ_7

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	COMMENT
0.82±0.21±0.20	19 ± 5	BITYUKOV 88	SPEC	32.5 $\pi^- p \to K^+ K^- \pi^0 n$

$\Gamma(\gamma\rho^0)/\Gamma(K\overline{K}\pi)$ — Γ_{11}/Γ_7

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
>0.035	90	COFFMAN 90 [17]	MRK3	$J/\psi \to \gamma\gamma\pi^+\pi^-$

[17] Using $B(J/\psi \to \gamma f_1(1285) \to \gamma\gamma\rho^0)$=0.25 × 10^{-4} and $B(J/\psi \to \gamma f_1(1285) \to \gamma K\overline{K}\pi)$=<0.72 × 10^{-3}.

$\Gamma(\gamma\rho^0)/\Gamma(2\pi^+2\pi^-)$ — Γ_{11}/Γ_6

VALUE	DOCUMENT ID	TECN	COMMENT
0.45±0.18	COFFMAN 90 [18]	MRK3	$J/\psi \to \gamma\gamma\pi^+\pi^-$

[18] Using $B(J/\psi \to \gamma f_1(1285) \to \gamma\gamma\rho^0)$=0.25 × 10^{-4} and $B(J/\psi \to \gamma f_1(1285) \to \gamma 2\pi^+ 2\pi^-)$=0.55 × 10^{-4} given by MIR 88.

$\Gamma(\gamma\rho^0)/\Gamma(a_0(980)\pi)$ — Γ_{11}/Γ_5

VALUE	DOCUMENT ID	TECN	COMMENT
0.10±0.03±0.02	BURCHELL 91 [19]	MRK3	$J/\psi \to \gamma\eta\pi^+\pi^-$

[19] Uses a result from COFFMAN 90, and includes an unknown branching ratio for $a_0(980) \to \eta\pi$.

$\Gamma(\gamma\rho^0)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.05	95	BITYUKOV 91B	SPEC	32 $\pi^- p \to \pi^+\pi^-\gamma n$

$f_1(1285)$ REFERENCES

BITYUKOV 91B SJNP +Borisov, Viktorov+ (SERP)
Translated from YAF 54 529.
BURCHELL 91 NP B21 132 (suppl) (Mark III Collab.)
FUKUI 91C PL B267 293 + (SUGI, NAGO, KEK, KYOT, MIYA, AKIT)
AUGUSTIN 90 PR D42 10 +Cosme+ (DM2 Collab.)
COFFMAN 90 PR D41 1410 +De Jongh+ (Mark III Collab.)
TAKAMATSU 90 Hadron 89 Conf. p 71 +Ando+ (KEK)
ARMSTRONG 89 PL B221 216 +Benayoun+ (CERN, CDEF, BIRM, BARI, ATHU, LPNP) JPC
ARMSTRONG 89E PL B228 536 +Benayoun (ATHU, BARI, BIRM, CERN, CDEF, LPNP)
ARMSTRONG 89G ZPHY C43 55 +Bloodworth (CERN, BIRM, BARI, ATHU, LPNP)
RATH 89 PR D40 693 +Cason+ (NDAM, BRAN, BNL, CUNY, DUKE)
AIHARA 88B PL B209 107 +Alston-Garnjost+ (TPC-2γ Collab.)
BIRMAN 88 PRL 61 1557 +Chung, Peaslee+ (BNL, FSU, IND, SMAS) JP
BITYUKOV 88 PL B203 327 +Borisov, Dorofeev+ (SERP)
MIR 88 Photon-Photon 88 Conf., 126 (Mark III Collab.)
ALDE 87 PL B198 286 +Binon, Bricman+ (LANL, BRUX, SERP, LAPP)
BECKER 87 PRL 59 186 +Blaylock, Bolton, Brown+ (Mark III Collab.)
GIDAL 87 PRL 59 2012 +Boyer, Butler, Cords, Abrams+ (LBL, SLAC, HARV)
ANDO 86 PRL 57 1296 +Imai+ (KEK, KYOT, NIRS, SAGA, TOKY, TSUK+) IJP
REEVES 86 PR 34 1960 +Chung, Crittenden+ (FLOR, BNL, IND, SMAS) JP
CHUNG 85 PRL 55 779 +Fernow, Boehnlein+ (BNL, FLOR, IND, SMAS) JP
ARMSTRONG 84 PL 146B 273 +Bloodworth, Burns+ (ATHU, BARI, BIRM, CERN) JP
BITUKOV 84 PL 144B 133 +Dorofeev, Dzhelyadin, Golovkin, Kulik+ (SERP)
CHAUVAT 84 PL 148B 382 +Meritet, Bonino+ (CERN, UDCF, UCLA, SACL)
TORNQVIST 82B NP B203 268 (HELS)
EVANGELISTA 81 NP B178 197 + (BARI, BONN, CERN, DARE, LIVP+)
BROMBERG 80 PR D22 1513 +Haggerty, Abrams, Dzierba (CIT, FNAL, ILLC, IND)
DIONISI 80 NP B169 1 +Gavillet+ (CERN, MADR, CDEF, STOH)
GURTU 79 NP B151 181 +Gavillet, Blokzijl+ (CERN, ZEEM, NIJM, OXF)
STANTON 79 PRL 42 346 +Brockman+ (OSU, CARL, MCGI, TNTO) JP
CORDEN 78 NP B144 253 +Corbett, Alexander+ (BIRM, RHEL, TELA, LOWC) JP
NACASCH 78 NP B135 203 +Defoix, Dobrzynski+ (PARI, MADR, CERN)
GRASSLER 77 NP B121 189 + (AACH, BERL, BONN, CERN, CRAC, HEID+)
DEFOIX 72 NP B44 125 +Nascimento, Bizzarri+ (CDEF, CERN)
DUBOC 72 NP B46 429 +Goldberg, Makowski, Donald+ (LPNP, LIVP)
THUN 72 PRL 28 1733 +Blieden, Finocchiaro, Bowen+ (STON, NEAS)
BARDADIN-... 71 PR D4 2711 Bardadin-Otwinowska, Hofmokl+ (WARS)
BOESEBECK 71 PL 34B 659 (AACH, BERL, BONN, CERN, CRAC, HEID, WARS)
CAMPBELL 69 PRL 22 1204 +Lichtman, Loeffler+ (PURD)
LORSTAD 69 NP B14 63 +D'Andlau, Astier+ (CDEF, CERN) JP
D'ANDLAU 68 NP B5 693 +Astier, Barlow+ (CDEF, CERN, IRAD, LIVP) IJP
DAHL 67 PR 163 1377 +Hardy, Hess, Kirz, Miller (LRL) IJP

——— OTHER RELATED PAPERS ———

AIHARA 88C PR D38 1 +Alston-Garnjost+ (TPC-2γ Collab.) JPC
ASTON 85 PR D32 2255 +Carnegie, Dunwoodie+ (SLAC, CARL, CNRC)
ATKINSON 84E PL 138B 459 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
GAVILLET 82 ZPHY C16 119 +Armenteros+ (CERN, CDEF, PADO, ROMA)
D'ANDLAU 65 PL 17 347 +Barlow, Adamson+ (CDEF, CERN, IRAD, LIVP)
MILLER 65 PRL 14 1074 +Chung, Dahl, Hess, Hardy, Kirz+ (LRL, UCB)

$\eta(1295)$
was $\eta(1275)$

$I^G(J^{PC}) = 0^+(0^{-+})$

See also the mini-review under non-$q\bar{q}$ candidates. (See the index for the page number.)

$\eta(1295)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1295±4	FUKUI	91C	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 1275	STANTON	79	CNTR	8.4 $\pi^- p \to n\eta 2\pi$

$\eta(1295)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
53±6	FUKUI	91C	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 70	STANTON	79	CNTR	8.4 $\pi^- p \to n\eta 2\pi$

$\eta(1295)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\pi^+\pi^-$	seen
Γ_2	$a_0(980)\pi$	seen
Γ_3	$\gamma\gamma$	

$\eta(1295)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(\eta\pi^+\pi^-) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.6	90	AIHARA	88C	TPC	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
<0.3		ANTREASYAN	87	CBAL	$e^+e^- \to e^+e^-\eta\pi\pi$

$\eta(1295)$ BRANCHING RATIOS

$\Gamma(a_0(980)\pi)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	BIRMAN	88	MPS	8 $\pi^- p \to K^+\overline{K}^0\pi^- n$
large	ANDO	86	SPEC	8 $\pi^- p \to n\eta\pi^+\pi^-$
large	STANTON	79	CNTR	8.4 $\pi^- p \to n\eta 2\pi$

$\eta(1295)$ REFERENCES

FUKUI 91C PL B267 293 + (SUGI, NAGO, KEK, KYOT, MIYA, AKIT)
AIHARA 88C PR D38 1 +Alston-Garnjost+ (TPC-2γ Collab.)
BIRMAN 88 PRL 61 1557 +Chung, Peaslee+ (BNL, FSU, IND, SMAS) JP
ANTREASYAN 87 PR D36 2633 +Bartels, Besset+ (Crystal Ball Collab.)
ANDO 86 PRL 57 1296 +Imai+ (KEK, KYOT, NIRS, SAGA, TOKY, TSUK+) IJP
STANTON 79 PRL 42 346 +Brockman+ (OSU, CARL, MCGI, TNTO) JP

$\pi(1300)$

$I^G(J^{PC}) = 1^-(0^{-+})$

$\pi(1300)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1300 ±100 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1190 ± 30	ZIELINSKI	84	SPEC	200 $\pi^+ Z \to Z3\pi$
1240 ± 30	BELLINI	82	SPEC	40 $\pi^- A \to A3\pi$
1273.0± 50.0	[1] AARON	81	RVUE	
1342 ± 20	BONESINI	81	OMEG	12 $\pi^- p \to p3\pi$
~ 1400	DAUM	81B	SPEC	63,94 $\pi^- p$

[1] Uses multichannel Aitchison-Bowler model (BOWLER 75). Uses data from DAUM 80 and DANKOWYCH 81.

$\pi(1300)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
200 to 600 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
440 ± 80	ZIELINSKI	84	SPEC	200 $\pi^+ Z \to Z3\pi$
360 ±120	BELLINI	82	SPEC	40 $\pi^- A \to A3\pi$
580.0±100.0	[2] AARON	81	RVUE	
220 ± 70	BONESINI	81	OMEG	12 $\pi^- p \to p3\pi$
~ 600	DAUM	81B	SPEC	63,94 $\pi^- p$

[2] Uses multichannel Aitchison-Bowler model (BOWLER 75). Uses data from DAUM 80 and DANKOWYCH 81.

$\pi(1300)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen
Γ_2	$\pi(\pi\pi)_{S\text{-wave}}$	seen
Γ_3	$f_0(1400)\pi$	

$\pi(1300)$ BRANCHING RATIOS

$\Gamma(\pi(\pi\pi)_{S\text{-wave}})/\Gamma(\rho\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2.12	[3] AARON	81	RVUE

[3] Uses multichannel Aitchison-Bowler model (BOWLER 75). Uses data from DAUM 80 and DANKOWYCH 81.

$\pi(1300)$ REFERENCES

ZIELINSKI 84 PR D30 1855 +Berg, Chandlee, Cihangir+ (ROCH, MINN, FNAL)
BELLINI 82 PRL 48 1697 +Frabetti, Ivanshin, Litkin+ (MILA, BGNA, JINR)
AARON 81 PR D24 1207 +Longacre (NEAS, BNL)
BONESINI 81 PL 103B 75 +Donald+ (MILA, LIVP, DARE, CERN, BARI, BONN)
DANKOWY... 81 PRL 46 580 Dankowych+ (TNTO, BNL, CARL, MCGI, OHIO)
DAUM 81B NP B182 269 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)
DAUM 80 PL 89B 281 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)
BOWLER 75 NP B97 227 +Game, Aitchison, Dainton (OXF, DARE)

$a_0(1320)$

$I^G(J^{PC}) = 1^-(0^{++})$

OMITTED FROM SUMMARY TABLE

Intensity peaking at the mass of the $a_2(1320)$ and with a comparable width. Needs confirmation.

$a_0(1320)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1320 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1322±30	BOUTEMEUR	90	GAM4	100 $\pi^- p \to 4\gamma n$

$a_0(1320)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
130±30	BOUTEMEUR	90	GAM4	100 $\pi^- p \to 4\gamma n$

$a_0(1320)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\pi^0$	seen
Γ_2	$\eta'\pi^0$	

$a_0(1320)$ BRANCHING RATIOS

$\Gamma(\eta\pi^0)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	BOUTEMEUR	90	GAM4	100 $\pi^- p \to 4\gamma n$

$\Gamma(\eta'\pi^0)/\Gamma(\eta\pi^0)$ — Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.40	95	BOUTEMEUR	90	GAM4	100 $\pi^- p \to 4\gamma n$

$a_0(1320)$ REFERENCES

BOUTEMEUR 90 Hadron 89 Conf. p 119+Poulet (SERP, BELG, LANL, LAPP, PISA, KEK)

$a_2(1320)$
was $A_2(1320)$

$I^G(J^{PC}) = 1^-(2^{++})$

$a_2(1320)$ MASS

3π AND $K^\pm K^0_S$ MODES

VALUE (MeV)	DOCUMENT ID
1318.2±0.7 OUR AVERAGE	Includes data from the 2 datablocks that follow this one. Error includes scale factor of 1.1.

3π MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1318.5± 1.4 OUR AVERAGE		Error includes scale factor of 1.2.				
1315 ± 8		ANDO	91	SPEC		8 $\pi^- p \to \pi^+\pi^-\pi^0 n$
1320 ±10		ANDO	91	SPEC		8 $\pi^- p \to \pi^+\pi^-\pi^0 n$
1310 ± 5		ARMSTRONG	90	OMEG	0	300.0 $pp \to pp\pi^+\pi^-\pi^0$
1323.8± 2.3	4022	AUGUSTIN	89	DM2	±	$J/\psi \to \rho^\pm a_2^\mp$
1320.6± 3.1	3562	AUGUSTIN	89	DM2	0	$J/\psi \to \rho^0 a_2^0$
1317.0± 2.0	25000	[1] DAUM	80C	SPEC	−	63,94 $\pi^- p \to 3\pi p$
1320.0±10.0	1097	[1] BALTAY	78B	HBC	+0	15 $\pi^+ p \to p4\pi$
1306.0± 8.0		FERRERSORIA	78	OMEG	−	9 $\pi^- p \to p3\pi$
1318 ± 7	1600	[1] EMMS	75	DBC	0	4 $\pi^+ n \to p(3\pi)^0$
1315 ± 5		[1] ANTIPOV	73C	CNTR	−	25,40 $\pi^- p \to p\eta\pi^-$
1306 ± 9	1580	CHALOUPKA	73	HBC	−	3.9 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1310 ± 2		[1] EVANGELISTA	81	OMEG	−	12 $\pi^- p \to 3\pi p$
1343.0±11.0	490	BALTAY	78B	HBC	0	15 $\pi^+ p \to \Delta 3\pi$
1309 ± 5	5000	BINNIE	71	MMS	−	$\pi^- p$ near a_2 threshold
1299.0± 6.0	28000	BOWEN	71	MMS	−	5 $\pi^- p$
1300 ± 6.0	24000	BOWEN	71	MMS	+	5 $\pi^+ p$
1309.0± 4.0	17000	BOWEN	71	MMS	−	7 $\pi^- p$
1306.0± 4.0	941	ALSTON-...	70	HBC	+	7.0 $\pi^+ p \to 3\pi p$

[1] From a fit to $J^P = 2^+$ $\rho\pi$ partial wave.

$K^\pm K^0_S$ MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1318.1± 0.7 OUR AVERAGE						
1319.0± 5.0	4700	[2,3] CLELAND	82B	SPEC	+	50 $\pi^+ p \to K^0_S K^+ p$
1324.0± 6.0	5200	[2,3] CLELAND	82B	SPEC	−	50 $\pi^- p \to K^0_S K^- p$
1320.0± 2.0	4000	CHABAUD	80	SPEC	−	17 $\pi^- A \to K^0_S K^- A$
1312.0± 4.0	11000	CHABAUD	78	SPEC	−	9.8 $\pi^- p \to K^- K^0_S p$
1316.0± 2.0	4730	CHABAUD	78	SPEC	−	18.8 $\pi^- p \to K^- K^0_S p$
1318 ± 1		[2,4] MARTIN	78D	SPEC	−	10 $\pi^- p \to K^0_S K^- p$
1320.0± 2.0	2724	MARGULIE	76	SPEC	−	23 $\pi^- p \to K^- K^0_S p$
1313.0± 4.0	730	FOLEY	72	CNTR	−	20.3 $\pi^- p \to K^- K^0_S p$
1319.0± 3.0	1500	[4] GRAYER	71	ASPK	−	17.2 $\pi^- p \to K^- K^0_S p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1330.0±11.0	1000	[2,3] CLELAND	82B	SPEC	+	30 $\pi^+ p \to K^0_S K^+ p$
1324.0± 5.0	350	HYAMS	78	ASPK	+	12.7 $\pi^+ p \to K^+ K^0_S p$

[2] From a fit to $J^P = 2^+$ partial wave.
[3] Number of events evaluated by us.
[4] Systematic error in mass scale subtracted.

$\eta\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1336.2±1.7	2561	DELFOSSE	81	SPEC	+	$\pi^\pm p \to p\pi^\pm\eta$
1330.7±2.4	1653	DELFOSSE	81	SPEC	−	$\pi^\pm p \to p\pi^\pm\eta$
1324 ±8	6200	[5,6] CONFORTO	73	OSPK	−	6 $\pi^- p \to p\,MM^-$
1323 ±8	1000	[5] KEY	73	OSPK	−	6 $\pi^- p \to p\pi^-\eta$

[5] Error includes 5 MeV systematic mass-scale error.
[6] Missing mass with enriched MMS $= \eta\pi^-$, $\eta = 2\gamma$.

$a_2(1320)$ WIDTH

3π MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
103.3± 2.1 OUR AVERAGE						
100 ±10		ANDO	91	SPEC		8 $\pi^- p \to \pi^+\pi^-\pi^0 n$
104 ±16		ANDO	91	SPEC		8 $\pi^- p \to \pi^+\pi^-\pi^0 n$
120 ±10		ARMSTRONG	90	OMEG	0	300.0 $pp \to pp\pi^+\pi^-\pi^0$
107.0± 9.7	4022	AUGUSTIN	89	DM2	±	$J/\psi \to \rho^\pm a_2^\mp$
118.5±12.5	3562	AUGUSTIN	89	DM2	0	$J/\psi \to \rho^0 a_2^0$
97 ± 5		[7] EVANGELISTA	81	OMEG	−	12 $\pi^- p \to 3\pi p$
96.0± 9.0	25000	[7] DAUM	80C	SPEC	−	63,94 $\pi^- p \to 3\pi p$
110.0±15.0	1097	[7] BALTAY	78B	HBC	+0	15 $\pi^+ p \to p4\pi$
112 ±18	1600	[7] EMMS	75	DBC	0	4 $\pi^+ n \to p(3\pi)^0$
122 ±14	1200	[7,8] WAGNER	75	HBC	0	7 $\pi^+ p \to \Delta^{++}(3\pi)^0$
115 ±15		[7] ANTIPOV	73C	CNTR	−	25,40 $\pi^- p \to p\eta\pi^-$
99 ±15	1580	CHALOUPKA	73	HBC	−	3.9 $\pi^- p$
105.0± 5.0	28000	BOWEN	71	MMS	−	5 $\pi^- p$
99.0± 5.0	24000	BOWEN	71	MMS	+	5 $\pi^+ p$
103.0± 5.0	17000	BOWEN	71	MMS	−	7 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
115.0±14.0	490	BALTAY	78B	HBC	0	15 $\pi^+ p \to \Delta 3\pi$
72 ±16	5000	BINNIE	71	MMS	−	$\pi^- p$ near a_2 threshold
79.0±12.0	941	ALSTON-...	70	HBC	+	7.0 $\pi^+ p \to 3\pi p$

[7] From a fit to $J^P = 2^+$ $\rho\pi$ partial wave.
[8] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

$K^\pm K^0_S$ AND $\eta\pi$ MODES

VALUE (MeV)	DOCUMENT ID
110 ±5 OUR ESTIMATE	
110.5±2.1 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.

$K^{\pm} K^0_S$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.					
109.8± 2.4 OUR AVERAGE					
112.0±20.0	4700	[9,10] CLELAND 82B	SPEC	+	$50\ \pi^+ p \rightarrow K^0_S K^+ p$
120.0±25.0	5200	[9,10] CLELAND 82B	SPEC	−	$50\ \pi^- p \rightarrow K^0_S K^- p$
106.0± 4.0	4000	CHABAUD 80	SPEC	−	$17\ \pi^- A \rightarrow K^0_S K^- A$
126.0±11.0	11000	CHABAUD 78	SPEC	−	$9.8\ \pi^- p \rightarrow K^- K^0_S p$
101.0± 8.0	4730	CHABAUD 78	SPEC	−	$18.8\ \pi^- p \rightarrow K^- K^0_S p$
113 ± 4		[9,11] MARTIN 78D	SPEC	−	$10\ \pi^- p \rightarrow K^0_S K^- p$
105.0± 8.0	2724	[11] MARGULIE 76	SPEC	−	$23\ \pi^- p \rightarrow K^- K^0_S p$
113.0±19.0	730	FOLEY 72	CNTR	−	$20.3\ \pi^- p \rightarrow K^- K^0_S p$
123.0±13.0	1500	[11] GRAYER 71	ASPK	−	$17.2\ \pi^- p \rightarrow K^- K^0_S p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
121.0±51.0	1000	[9,10] CLELAND 82B	SPEC	+	$30\ \pi^+ p \rightarrow K^0_S K^+ p$
110.0±18.0	350	HYAMS 78	ASPK	+	$12.7\ \pi^+ p \rightarrow K^+ K^0_S p$

[9] From a fit to $J^P = 2^+$ partial wave.
[10] Number of events evaluated by us.
[11] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

$\eta\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.					
113 ±4 OUR AVERAGE					
112.2±5.7	2561	DELFOSSE 81	SPEC	+	$\pi^{\pm} p \rightarrow p \pi^{\pm} \eta$
116.6±7.7	1653	DELFOSSE 81	SPEC	−	$\pi^{\pm} p \rightarrow p \pi^{\pm} \eta$
108 ±9	1000	KEY 73	OSPK	−	$6\ \pi^- p \rightarrow p \pi^- \eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
104 ±9	6200	[12] CONFORTO 73	OSPK	−	$6\ \pi^- p \rightarrow p\ MM^-$

[12] Model dependent.

$a_2(1320)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\rho\pi$	(70.1±2.7) %	S=1.2
Γ_2	$\eta\pi$	(14.5±1.2) %	
Γ_3	$\omega\pi\pi$	(10.6±3.2) %	S=1.3
Γ_4	$K\overline{K}$	(4.9±0.8) %	
Γ_5	$\pi^{\pm}\gamma$	(2.7±0.5) $\times 10^{-3}$	
Γ_6	$\gamma\gamma$	(9.5±0.9) $\times 10^{-6}$	
Γ_7	$\pi^+\pi^-\pi^-$	< 8 %	CL=90%
Γ_8	$\eta'(958)\pi$	< 1.0 %	CL=95%
Γ_9	e^+e^-	< 2.3 $\times 10^{-7}$	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to 5 branching ratios uses 18 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 9.3 for 15 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle \delta x_i \delta x_j \right\rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	10		
x_3	−89	−46	
x_4	−1	−2	−24
	x_1	x_2	x_3

$a_2(1320)$ PARTIAL WIDTHS

$\Gamma(\pi^{\pm}\gamma)$ — Γ_5

VALUE (keV)	DOCUMENT ID	TECN	CHG	COMMENT
295± 60	CIHANGIR 82	SPEC	+	$200\ \pi^+ A$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
461±110	[12] MAY 77	SPEC	±	$9.7\ \gamma A$

$\Gamma(\gamma\gamma)$ — Γ_6

VALUE (keV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1.04±0.09 OUR AVERAGE					
1.26±0.26±0.18	36	BARU 90	MD1		$e^+e^- \rightarrow e^+e^-\pi^+\pi^-\gamma\gamma$
1.00±0.07±0.15	415	BEHREND 90C	CELL	0	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-\pi^0$
1.03±0.13±0.21		BUTLER 90	MRK2		$e^+e^- \rightarrow e^+e^-\pi^+\pi^-\pi^0$
1.01±0.14±0.22	85 ± 9	OEST 90	JADE		$e^+e^- \rightarrow e^+e^-\pi^0\eta$
0.90±0.27±0.15	56	[13] ALTHOFF 86	TASS	0	$e^+e^- \rightarrow e^+e^-3\pi$
1.14±0.20±0.26		[14] ANTREASYAN 86	CBAL	0	$e^+e^- \rightarrow e^+e^-\pi^0\eta$
1.06±0.18±0.19		BERGER 84C	PLUT	0	$e^+e^- \rightarrow e^+e^-3\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.81\pm0.19^{+0.42}_{-0.11}$	35	[13] BEHREND 83B	CELL	0	$e^+e^- \rightarrow e^+e^-3\pi$
0.84±0.07±0.15		[13] FRAZER 83	JADE	0	$e^+e^- \rightarrow e^+e^-3\pi$
0.77±0.18±0.27	22	[14] EDWARDS 82F	CBAL	0	$e^+e^- \rightarrow e^+e^-\pi^0\eta$

[13] From $\rho\pi$ decay mode.
[14] From $\eta\pi^0$ decay mode.

$\Gamma(e^+e^-)$ — Γ_9

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
<25	90	VOROBYEV 88	ND	$e^+e^- \rightarrow \pi^0\eta$

$a_2(1320)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ — $\Gamma_4\Gamma_6/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
0.126±0.007±0.028	[15] ALBRECHT 90G	ARG	$e^+e^- \rightarrow e^+e^-K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.081±0.006±0.027	[16] ALBRECHT 90G	ARG	$e^+e^- \rightarrow e^+e^-K^+K^-$

[15] Using an incoherent background.
[16] Using a coherent background.

$a_2(1320)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma(\rho\pi)$ — Γ_4/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.070±0.012 OUR FIT					
0.078±0.017		CHABAUD 78	RVUE		
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.056±0.014	50	[17] CHALOUPKA 73	HBC	−	$3.9\ \pi^- p$
0.097±0.018	113	[17] ALSTON-... 71	HBC	+	$7.0\ \pi^+ p$
0.06 ±0.03		[17] ABRAMOVI... 70B	HBC	−	$3.93\ \pi^- p$
0.054±0.022		[17] CHUNG 68	HBC	−	$3.2\ \pi^- p$

[17] Included in CHABAUD 78 review.

$\Gamma(\eta\pi)/[\Gamma(\rho\pi) + \Gamma(\eta\pi) + \Gamma(K\overline{K})]$ — $\Gamma_2/(\Gamma_1+\Gamma_2+\Gamma_4)$

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.162±0.012 OUR FIT					
0.140±0.028 OUR AVERAGE					
0.13 ±0.04		ESPIGAT 72	HBC	±	$0.0\ \overline{p}p$
0.15 ±0.04	34	BARNHAM 71	HBC	+	$3.7\ \pi^+ p$

$\Gamma(\eta\pi)/\Gamma(\rho\pi)$ — Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.207±0.018 OUR FIT					
0.213±0.020 OUR AVERAGE					
0.18 ±0.05		FORINO 76	HBC		$11\ \pi^- p$
0.22 ±0.05	52	ANTIPOV 73	CNTR	−	$40\ \pi^- p$
0.211±0.044	149	CHALOUPKA 73	HBC	−	$3.9\ \pi^- p$
0.246±0.042	167	ALSTON-... 71	HBC	+	$7.0\ \pi^+ p$
0.25 ±0.09	15	BOECKMANN 70	HBC	+	$5.0\ \pi^+ p$
0.23 ±0.08	22	ASCOLI 68	HBC	−	$5\ \pi^- p$
0.12 ±0.08		CHUNG 68	HBC	−	$3.2\ \pi^- p$
0.22 ±0.09		CONTE 67	HBC	−	$11.0\ \pi^- p$

$\Gamma(\eta'(958)\pi)/\Gamma_{total}$ — Γ_8/Γ

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.006	95	ALDE 91C	GAM2		$38\ \pi^- p \rightarrow \eta'\pi^0 n$
<0.02	97	BARNHAM 71	HBC	+	$3.7\ \pi^+ p$
0.004±0.004		BOESEBECK 68	HBC	+	$8\ \pi^+ p$

$\Gamma(\eta'(958)\pi)/\Gamma(\rho\pi)$ — Γ_8/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.011	90	EISENSTEIN 73	HBC	−	$5\ \pi^- p$
<0.04		ALSTON-... 71	HBC	+	$7.0\ \pi^+ p$
$0.04\ ^{+0.03}_{-0.04}$		BOECKMANN 70	HBC	0	$5.0\ \pi^+ p$

$\Gamma(K\overline{K})/[\Gamma(\rho\pi) + \Gamma(\eta\pi) + \Gamma(K\overline{K})]$ — $\Gamma_4/(\Gamma_1+\Gamma_2+\Gamma_4)$

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.054±0.009 OUR FIT						
0.048±0.012 OUR AVERAGE						
0.05 ±0.02		TOET	73	HBC	+	$5\ \pi^+ p$
0.09 ±0.04		TOET	73	HBC	0	$5\ \pi^+ p$
0.03 ±0.02	8	DAMERI	72	HBC	−	$11\ \pi^- p$
0.06 ±0.03	17	BARNHAM	71	HBC	+	$3.7\ \pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.020±0.004		[18] ESPIGAT	72	HBC	±	$0.0\ \overline{p}p$

[18] Not averaged because of discrepancy between masses from $K\overline{K}$ and $\rho\pi$ modes.

$\Gamma(\pi^+\pi^-\pi^-)/\Gamma(\rho\pi)$ — Γ_7/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.12	90	ABRAMOVI...	70B	HBC	−	$3.93\ \pi^- p$

$\Gamma(\pi^\pm\gamma)/\Gamma_{total}$ — Γ_5/Γ

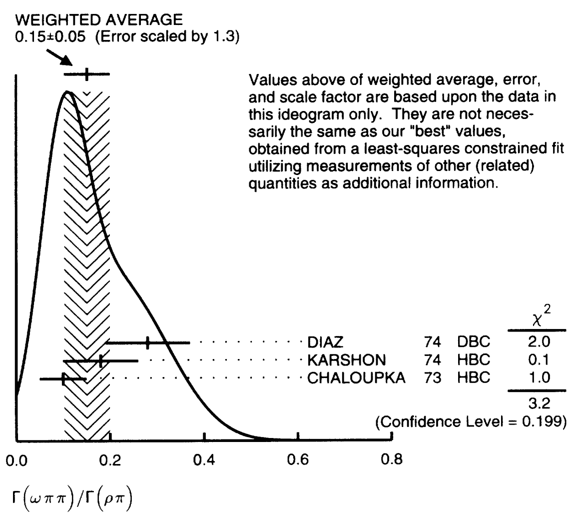
VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.005^{+0.005}_{-0.003}$	[19] EISENBERG	72	HBC	$4.3,5.25,7.5\ \gamma p$

[19] Pion-exchange model used in this estimation.

$\Gamma(\omega\pi\pi)/\Gamma(\rho\pi)$ — Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.15±0.05 OUR FIT Error includes scale factor of 1.3.						
0.15±0.05 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.						
0.28±0.09	60	DIAZ	74	DBC	0	$6\ \pi^+ n$
0.18±0.08		[20] KARSHON	74	HBC		Avg. of above two
0.10±0.05	279	CHALOUPKA	73	HBC	−	$3.9\ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.29±0.08	140	[20] KARSHON	74	HBC	0	$4.9\ \pi^+ p$
0.10±0.04	60	[20] KARSHON	74	HBC	+	$4.9\ \pi^+ p$
0.19±0.08		DEFOIX	73	HBC	0	$0.7\ \overline{p}p$

[20] KARSHON 74 suggest an additional $I = 0$ state strongly coupled to $\omega\pi\pi$ which could explain discrepancies in branching ratios and masses. We use a central value and a systematic spread.



$\Gamma(\eta'(958)\pi)/\Gamma(\eta\pi)$ — Γ_8/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.07	95	BOUTEMEUR	90	GAM4	$100\ \pi^- p \to 4\gamma n$

$a_2(1320)$ REFERENCES

ALDE 91C IHEP 91-88 +Binon+ (SERP, BELG, LANL, LAPP, PISA, KEK)
ANDO 91 NP B21 98 (suppl) + (KEK, KYOT, NIRS, SAGA, TOKY, AKIT, NAGO+)
ALBRECHT 90G ZPHY C48 183 +Ehrlichmann, Harder+ (ARGUS Collab.)
ARMSTRONG 90 ZPHY C48 213 +Benayoun, Beusch (WA76 Collab.)
BARU 90 ZPHY C48 581 +Blinov, Blinov+ (MD-1 Collab.)
BEHREND 90C ZPHY C46 583 +Criegee+ (CELLO Collab.)
BOUTEMEUR 90 Hadron 89 Conf. p 119+Poulet (SERP, BELG, LANL, LAPP, PISA, KEK)
BUTLER 90 PR D42 1368 +Boyer+ (Mark II Collab.)
OEST 90 ZHPY C47 343 +Olsson+ (JADE Collab.)
AUGUSTIN 89 NP B320 1 +Cosme (DM2 Collab.)
VOROBYEV 88 SJNP 48 273 +Golubev, Dolinsky, Druzhinin+ (NOVO)
Translated from YAF 48 436.
ALTHOFF 86 ZPHY C31 537 +Boch, Foster, Bernardi+ (TASSO Collab.)
ANTREASYAN 86 PR D33 1847 +Aschman, Besset, Bienlein+ (Crystal Ball Collab.)
BERGER 84C PL 149B 427 +Klovning, Burger+ (PLUTO Collab.)
BEHREND 83B PL 125B 518 +D'Agostini+ (DESY, KARL, MPIM, LALO, LPNP+)
FRAZER 83 Aachen Conf. (UCSD)
CIHANGIR 82 PL 117B 123 +Berg, Biel, Chandlee+ (FNAL, MINN, ROCH)
CLELAND 82B NP B208 228 +Delfosse, Dorsaz, Gloor (DURH, GEVA, LAUS, PITT)
EDWARDS 82F PL 110B 82 +Partridge, Peck+ (CIT, HARV, PRIN, STAN, SLAC)
DELFOSSE 81 NP B183 349 +Guisan, Martin, Muhlemann, Weill+ (GEVA, LAUS)
EVANGELISTA 81 NP B178 197 + (BARI, BONN, CERN, DARE, LIVP+)
CHABAUD 80 NP B175 189 +Hyams, Papadopoulou+ (CERN, MPIM, AMST)
DAUM 80C PL 89B 276 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+) JP
BALTAY 78B PR D17 62 +Cautis, Cohen, Csorna+ (COLU, BING)
CHABAUD 78 NP B145 349 +Hyams, Jones, Weilhammer, Blum+ (CERN, MPIM)
FERRERSORIA 78 PL 74B 287 +Treille+ (ORSA, CERN, CDEF, LPNP)
HYAMS 78 NP B146 303 +Jones, Weilhammer, Blum+ (CERN, MPIM, ATEN)
MARTIN 78D PL 74B 417 +Ozmutlu, Baldi, Bohringer, Dorsaz+ (DURH, GEVA) JP
MAY 77 PR D16 1983 +Abramson, Andrews, Busnello+ (ROCH, CORN)
FORINO 76 NC 35A 465 +Gessaroli+ (BGNA, FIRZ, GENO, MILA, OXF, PAVI)
MARGULIE 76 PR D14 667 +Kramer, Foley, Love, Lindenbaum+ (BNL, CUNY)
EMMS 75 PL 58B 117 +Jones, Kinson, Stacey, Bell+ (BIRM, DURH, RHEL) JP
WAGNER 75 PL 58B 201 +Tabak, Chew (LBL) JP
DIAZ 74 PRL 32 260 +Dibianca, Fickinger, Anderson+ (CASE, CMU)
KARSHON 74 PRL 32 852 +Mikenberg, Pitluck, Eisenberg, Ronat+ (REHO)
ANTIPOV 73 NP B63 175 +Ascoli, Busnello, Focacci+ (CERN, SERP) JP
ANTIPOV 73C NP B63 153 +Ascoli, Busnello, Focacci+ (CERN, SERP) JP
CHALOUPKA 73 PL 44B 211 +Dobrzynski, Ferrando, Losty+ (CERN)
CONFORTO 73 PL 45B 154 +Mobley, Key+ (EFI, FNAL, TNTO, WISC)
DEFOIX 73 PL 43B 141 +Dobrzynski, Espigat, Nascimento+ (CDEF)
EISENSTEIN 73 PR D7 278 +Schultz, Ascoli, Ioffredo+ (ILL)
KEY 73 PRL 30 503 +Conforto, Mobley+ (TNTO, EFI, FNAL, WISC)
TOET 73 NP B63 248 +Thuan, Major+ (NIJM, BONN, DURH, TORI)
DAMERI 72 NC 9A 1 +Borzatta, Goussu+ (GENO, MILA, SACL)
EISENBERG 72 PR D5 15 +Ballam, Dagan+ (REHO, SLAC, TELA)
ESPIGAT 72 NP B36 93 +Ghesquiere, Lillestol, Montanet (CERN, CDEF)
FOLEY 72 PR D6 747 +Love, Ozaki, Platner, Lindenbaum+ (BNL, CUNY)
ALSTON-... 71 PL 34B 156 Alston-Garnjost, Barbaro, Buhl, Derenzo+ (LRL)
BARNHAM 71 PRL 26 1494 +Abrams, Butler, Coyne, Goldhaber, Hall+ (LBL)
BINNIE 71 PL 36B 257 +Camilleri, Duane, Faruqi, Burton+ (LOIC, SHMP)
BOWEN 71 PRL 26 1663 +Earles, Faissler, Blieden+ (NEAS, STON)
GRAYER 71 PL 34B 333 +Hyams, Jones, Schlein, Blum+ (CERN, MPIM)
ABRAMOVI... 70B NP B23 466 Abramovich, Blumenfeld, Bruyant+ (CERN) JP
ALSTON-... 70 PL 33B 607 Alston-Garnjost, Barbaro, Buhl, Derenzo+ (LRL)
BOECKMANN 70 NP B16 221 +Major+ (BONN, DURH, NIJM, EPOL, TORI)
ASCOLI 68 PRL 20 1321 +Crawley, Mortara, Shapiro, Bridges+ (ILL) JP
BOESEBECK 68 NP B4 501 +Deutschmann+ (AACH, BERL, CERN)
CHUNG 68 PR 165 1491 +Dahl, Kirz, Miller (LRL)
CONTE 67 NC 51A 175 +Tomasini, Cords+ (GENO, HAMB, MILA, SACL)

OTHER RELATED PAPERS

JENNI 83 PR D27 1031 +Burke, Telnov, Abrams, Blocker+ (SLAC, LBL)
BEHREND 82C PL 114B 378 +Chen, Fenner, Field+ (CELLO Collab.)
ABOLINS 65 Athens Conf. +Carmony, Lander, Xuong, Yager (UCSD) I
ADERHOLZ 65 PR 138B 897 (AACH, BERL, BIRM, BONN, HAMB, LOIC, MPIM)
ALITTI 65 PL 15 69 +Baton, Deler, Crussard+ (SACL, BGNA) JP
CHUNG 65 PRL 15 325 +Dahl, Hardy, Hess, Jacobs, Kirz (LRL)
FORINO 65B PL 19 68 +Gessaroli+ (BGNA, BARI, FIRZ, ORSA, SACL)
LEFEBVRES 65 PL 19 434 +Levrat+ (CERN Missing Mass Spect. Collab.)
SEIDLITZ 65 PRL 15 217 +Dahl, Miller (LRL)
ADERHOLZ 64 PL 10 226 + (AACH, BERL, BIRM, BONN, DESY, HAMB+)
CHUNG 64 PRL 12 621 +Dahl, Hardy, Hess, Kalbfleisch, Kirz (LRL)
GOLDHABER 64B Dubna Conf. 1 480 +Goldhaber, O'Halloran, Shen (LRL)
Also 64 PRL 12 336 Goldhaber, Brown, Kadyk, Shen+ (LRL, UCB)
LANDER 64 PRL 13 346A +Abolins, Carmony, Hendricks, Xuong+ (UCSD)

$h_1(1380)$

$I^G(J^{PC}) = ?^-(1^{+?})$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the $K^0_S K^\pm \pi^\mp$ system. Evidence for $K^*\overline{K} + \overline{K}^* K$ decays (ASTON 88C). Needs confirmation.

$h_1(1380)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1380±20	ASTON	88C	LASS	$11\ K^- p \to K^0_S K^\pm \pi^\mp \Lambda$

$h_1(1380)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
80±30	ASTON	88C	LASS	$11\ K^- p \to K^0_S K^\pm \pi^\mp \Lambda$

$h_1(1380)$ DECAY MODES

	Mode
Γ_1	$K\overline{K}^*(892) +$ c.c.

$h_1(1380)$ REFERENCES

ASTON 88C PL B201 573 +Awaji, Bienz+ (SLAC, NAGO, CINC, TOKY)

$\omega(1390)$

$I^G(J^{PC}) = 0^-(1^{--})$

See also $\omega(1600)$.

$\omega(1390)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1394±17 OUR AVERAGE			
1440±70	[1] DONNACHIE 91	RVUE	
1391±18	DONNACHIE 89	RVUE	$e^+e^- \rightarrow \rho\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1425±25	GOVORKOV 88	RVUE	

[1] Using data from BISELLO 91B.

$\omega(1390)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
229±40 OUR AVERAGE			
240±70	[2] DONNACHIE 91	RVUE	
224±49	DONNACHIE 89	RVUE	$e^+e^- \rightarrow \rho\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
300±25	GOVORKOV 88	RVUE	

[2] Using data from BISELLO 91B.

$\omega(1390)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	dominant
Γ_2	$\omega\pi\pi$	
Γ_3	e^+e^-	

$\omega(1390)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(\rho\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
137±40	DONNACHIE 89	RVUE	$e^+e^- \rightarrow \rho\pi$

$\Gamma(\omega\pi\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_2\Gamma_3/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID	TECN	COMMENT
<41	68	DONNACHIE 89	RVUE	$e^+e^- \rightarrow \omega 2\pi$

$\omega(1390)$ REFERENCES

BISELLO 91B NP B21 111 (suppl) (DM2 Collab.)
DONNACHIE 91 ZPHY C51 689 +Clegg (MCHS, LANC)
DONNACHIE 89 ZPHY C42 663 +Clegg (CERN, MCHS)
GOVORKOV 88 SJNP 48 150 (JINR)
Translated from YAF 48 237.

OTHER RELATED PAPERS

ATKINSON 87 ZPHY C34 157 + (BONN, CERN, GLAS, LANC, MCHS, LPNP)
ATKINSON 84 NP B231 15 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
ATKINSON 83B PL 127B 132 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)

$f_0(1400)$
was $\epsilon(1300)$

$I^G(J^{PC}) = 0^+(0^{++})$

NOTE ON S–WAVE $\pi\pi$, $K\overline{K}$, AND $\eta\eta$ INTERACTIONS

In this note we discuss results on the nonstrange $I^G J^{PC} = 0^+0^{++}$ partial wave (S wave) coupled to the $\pi\pi$, $K\overline{K}$, and $\eta\eta$ systems.

Up to the ρ meson region, the $I = 0$ S–wave phase shift δ_0^0 is (qualitatively) uniquely determined: it rises monotonically and reaches 60° to 70° near 700 MeV. In the early phase shift analyses, based on $\pi^+\pi^- \rightarrow \pi^+\pi^-$ data, two solutions for δ_0^0 were found in the 700–900 MeV region. One solution indicated a resonance under the ρ meson with mass and width similar to those of the ρ meson, the old $\epsilon(800)$; the other gave an approximately energy–independent phase shift of about 90°, with no resonance. Today, a narrow $\epsilon(800)$ seems to be ruled out: our present knowledge of the low (and high) energy behavior of δ_0^0 may still be summarized by Fig. 1, which shows the CERN–Munich phase shift data (GRAYER 74) together with a fit of AU 87.

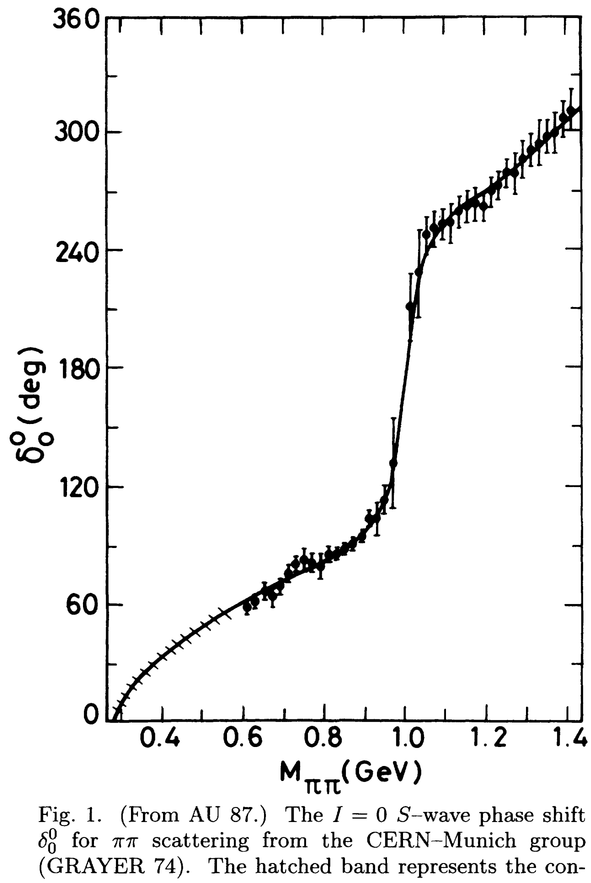


Fig. 1. (From AU 87.) The $I = 0$ S–wave phase shift δ_0^0 for $\pi\pi$ scattering from the CERN–Munich group (GRAYER 74). The hatched band represents the continuation down to the threshold provided by the Roy equations. The curve shows a fit typical of all the AU 87 solutions.

Without polarization information, reactions of the type $\pi N \rightarrow \pi\pi N$ cannot be analyzed unambiguously since there are more helicity amplitudes than observables. Thus additional assumptions are necessary.

No evidence for a narrow ϵ resonance was obtained in an amplitude analysis (ESTABROOKS 74) of the largest $\pi^- p$ (unpolarized) $\rightarrow \pi^+\pi^- n$ experiment (HYAMS 73, GRAYER 74); the analysis assumed both spin and phase coherence. The advent of $\pi^- p$ (polarized) $\rightarrow \pi^+\pi^- n$ data (BECKER 79) made both assumptions unnecessary. Analyzing their data, BECKER 79B confirmed that there is no resonance in δ_0^0 below 900 MeV.

CASON 83 disagreed with these results: In an amplitude analysis of the reaction $\pi^+\pi^- \rightarrow \pi^0\pi^0$, with the assumption of one-pion exchange dominance, he concluded that the only way to make $\pi^+\pi^- \rightarrow \pi^0\pi^0$ and $\pi^+\pi^- \rightarrow \pi^+\pi^-$ data self-consistent is with a resonant phase shift. However, the phase variation is not well represented by a narrow Breit–Wigner. The conclusion of CASON 83 disagrees with other unextrapolated $\pi^0\pi^0$ data, which appear to rule out the existence of an $\epsilon(800)$.

The first measurement of $\pi^+ n$ (polarized)$\rightarrow \pi^+\pi^- p$ on a polarized deuteron target is now adding new information. An amplitude analysis by SVEC 92 suggests the existence of a scalar state at 750 MeV with a width of 100–150 MeV, quite contrary to the conclusions of BECKER 79B.

The region of elastic $\pi\pi$ scattering is known to extend to about 990 MeV, near the $K\overline{K}$ threshold; beyond 1 GeV we have to consider the two channels $\pi\pi$ and $K\overline{K}$, and beyond 1100 MeV the $\eta\eta$ channel also opens up. In addition, the solutions have inherent ambiguities related to the Barrelet zeroes of the amplitudes. Thus HYAMS 75 finds four solutions in the region 1.0 to 1.8 GeV, ESTABROOKS 74 finds eight solutions, and CORDEN 79, extending the $\pi\pi$ analysis to 2.08 GeV, finds another set of eight solutions. Many of these solutions have been ruled out by imposing continuity in various forms as well as analyticity and unitarity (FROGGATT 75, 77, COMMON 76, MARTIN 78C).

A partial wave analysis performed by AKESSON 86 on the reaction $pp \rightarrow pp\pi^+\pi^-$, with the two pions produced centrally, shows that the $\pi\pi$ S wave dominates up to 1.6 GeV; furthermore, no room is left for other scalar mesons besides the $f_0(975)$ and $f_0(1400)$. A coupled-channel analysis ($\pi\pi$ and $K\overline{K}$) together with $\pi\pi$ scattering data and $J/\psi \rightarrow \phi\pi\pi$, $\phi K\overline{K}$ and $D_s^\pm \rightarrow \pi\pi\pi$ decays agrees with this (MORGAN 91). Even a solution with three resonances near 1 GeV has been suggested (AU 87; see Fig. 2 for a typical Argand plot).

Independent evidence for the $f_0(1400)$ comes from studies of the $K\overline{K}$ and $\eta\eta$ systems. In the reaction $\pi^- p \rightarrow K_S^0 K_S^0 n$, the S wave is large in the 1300-MeV region (WETZEL 76, LOVERRE 80, ETKIN 82B), with evidence for a bump. Moreover, the Y_0^2 moment shows a large negative excursion, indicating S-D interference (CASON 76, WETZEL 76, POLYCHRONAKOS 79, GOTTESMAN 80, LOVERRE 80, ETKIN 82B). The main problem is the isospin of the bump; if OPE were the only mechanism, $I = 0$ would be assured. The high

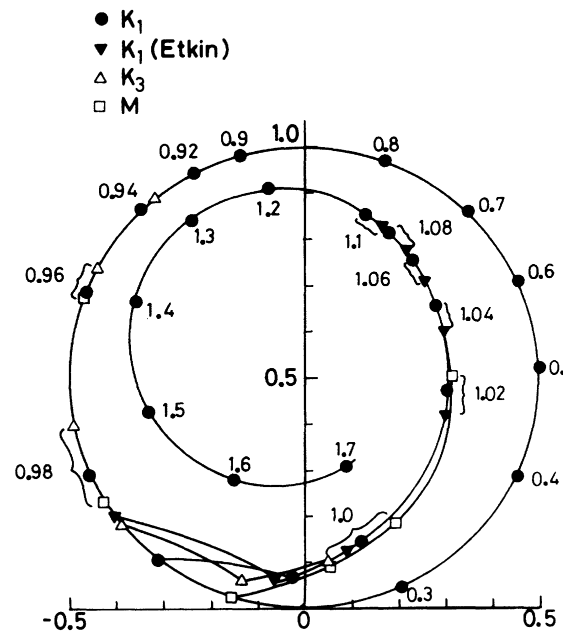


Fig. 2. (From AU 87.) The $\pi\pi$ $I = 0$ S-wave amplitude shown in an Argand plot comparing the solutions K_1 (•), K_1 (ETKIN 82B) (▼), K_3 (△), and M (□). The last three are shown only where they differ from solution K_1. The corresponding energies in GeV are displayed on the plot.

statistics experiment (ETKIN 82B) in the restricted t' region below 0.1 GeV^2 strongly favors OPE dominance and assigns the observed effects to the $I^G = 0^+$ state. A simplified scheme of amplitude analysis in the range 1.6–2.4 GeV has been applied to the same reaction $\pi^- p \rightarrow K_S^0 K_S^0 n$ at 40 GeV (BOLONKIN 88). The S-wave intensity shows clear evidence for a large structure at about 1400 MeV, together with another small signal in the region of the $f_2(1720)$. The mass of the $f_0(1400)$ agrees with the finding of ETKIN 82B in the same channel.

The reaction $\pi^- p \rightarrow \eta\eta N$ at 100 GeV has been analyzed in a search for scalar glueball candidates (ALDE 86D). A partial wave analysis shows a bump near threshold in the S-wave amplitude which is naturally associated with the $f_0(1400)$, although its mass is somewhat lower than that of the state decaying into $\pi\pi$ and $K\overline{K}$.

The mass and the width of the $f_0(1400)$ are difficult to extract from partial wave analyses and also to define in any simple way, since the Breit–Wigner shape is completely distorted by hadronic mass renormalization effects from the $\pi\pi$, $K\overline{K}$, and $\eta\eta$ channels.

The interpretation of the 0^{++} mesons as members of the $q\overline{q}$ 0^{++} nonet may appear controversial, due to some unconventional experimental properties of such states; to solve this problem, several extensive coupled-channel analyses of $I = 0$ S-wave $\pi\pi$ and $K\overline{K}$ final states have been performed. Rather standard properties for the scalar mesons are obtained by TORNQVIST 82, who finds that they can be understood as conventional $q\overline{q}$ states; the $f_0(975)$ and $f_0(1400)$ have large components of $q\bar{q}q\bar{q}$ in the form of virtual two–meson continua (mainly $K\overline{K}$). ACHASOV 84 disagrees with these conclusions and finds instead that the two scalar mesons can both be interpreted as $q\bar{q}q\bar{q}$ states. WEINSTEIN 83B, 89 on the other hand interpret the $f_0(975)$ as a $K\overline{K}$ molecule bound by the hyperfine interaction, leaving the $f_0(1400)$ as a $^3P_0$ $q\bar{q}$ state. In contrast, MORGAN 91 gives evidence, based on a model–independent test, that the $f_0(975)$ is not a molecule.

$f_0(1400)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
~ 1400 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1472 ±12	ARMSTRONG	91	OMEG	$300\ pp \to pp\pi\pi, ppK\overline{K}$
1440 ±20	CHEN	91	MRK3	$J/\psi \to \gamma\pi^+\pi^-, \gamma K\overline{K}$
1275 ±20	BREAKSTONE	90	SFM	$pp \to pp\pi^+\pi^-$
1440 ±50	BOLONKIN	88	SPEC	$40\ \pi^- p \to K^0_S K^0_S n$
1420.0±20.0	AKESSON	86	SPEC	$pp \to pp\pi^+\pi^-$
1220.0±40.0	ALDE	86D	GAM4	$100\ \pi^- p \to n2\eta$
1463.0± 9.0	ETKIN	82B	MPS	$23\ \pi^- p \to n2K^0_S$
1470.0±10 ±20	[1] ETKIN	82C	MPS	$23\ \pi^- p \to n2K^0_S$
~ 1237	TORNQVIST	82	RVUE	
1425 ±15	WICKLUND	80	SPEC	$6\ \pi N \to K^+K^-N$
~ 1300	POLYCHRO...	79	STRC	$7\ \pi^- p \to n2K^0_S$
1256.0	FROGGATT	77	RVUE	$\pi^+\pi^-$ channel

[1] Fit includes interference with the $f_0(1240)$ resonance.

$f_0(1400)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
150 to 400 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
195 ± 33	ARMSTRONG	91	OMEG	$300\ pp \to pp\pi\pi, ppK\overline{K}$
160 ± 40	CHEN	91	MRK3	$J/\psi \to \gamma\pi^+\pi^-, \gamma K\overline{K}$
285 ± 60	BREAKSTONE	90	SFM	$pp \to pp\pi^+\pi^-$
250 ± 80	BOLONKIN	88	SPEC	$40\ \pi^- p \to K^0_S K^0_S n$
460.0± 50.0	AKESSON	86	SPEC	$pp \to pp\pi^+\pi^-$
320.0± 40.0	ALDE	86D	GAM4	$100\ \pi^- p \to n2\eta$
$118.0^{+138.0}_{-16.0}$	ETKIN	82B	MPS	$23\ \pi^- p \to n2K^0_S$
140.0± 10 ±20	[2] ETKIN	82C	MPS	$23\ \pi^- p \to n2K^0_S$
~ 1400	TORNQVIST	82	RVUE	
160 ± 30	WICKLUND	80	SPEC	$6\ \pi N \to K^+K^-N$
~ 150	POLYCHRO...	79	STRC	$7\ \pi^- p \to n2K^0_S$
~ 400	[3] FROGGATT	77	RVUE	$\pi^+\pi^-$ channel

[2] Fit includes interference with the $f_0(1240)$ resonance.

[3] Width defined as distance between 45 and 135° phase shift.

$f_0(1400)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	$(93.6^{+1.9}_{-1.5})$ %
Γ_2	$K\overline{K}$	(7.5±0.9) %
Γ_3	$\eta\eta$	seen
Γ_4	$\gamma\gamma$	seen
Γ_5	e^+e^-	not seen

$f_0(1400)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ Γ_4

VALUE (KeV)	DOCUMENT ID		TECN	COMMENT
5.4±2.3	[4] MORGAN	90	RVUE	$\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$

[4] Error includes spread of different solutions. Authors report strong correlation with $\gamma\gamma$ width of $f_2(1270)$.

$\Gamma(e^+e^-)$ Γ_5

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<20	90	VOROBYEV	88	ND	$e^+e^- \to \pi^0\pi^0$

$f_0(1400)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.936^{+0.019}_{-0.015}}$	GORLICH	80	ASPK	$17,18\ \pi^- p$ polarized
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 0.93	TORNQVIST	82	RVUE	
0.93	LOVERRE	80	HBC	$4\ \pi^- p \to K\overline{K}N$
0.73	HYAMS	75	ASPK	$17.2\ \pi^- p \to n\pi^+\pi^-$

$\Gamma(K\overline{K})/\Gamma(\pi\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.08 ±0.01	COSTA...	80	OMEG	$10\ \pi^- p \to K^+K^-n$

$f_0(1400)$ REFERENCES

ARMSTRONG	91	ZPHY C51 351	+Benayoun+	(ATHU, BARI, BIRM, CERN, CDEF)
CHEN	91	Hadron 91 Conf. SLAC-PUB-5669		(Mark III Collab.)
BREAKSTONE	90	ZPHY C48 569	+	(ISU, BGNA, CERN, DORT, HEID, WARS)
MORGAN	90	ZPHY C48 623	+Pennington	(RAL, DURH)
BOLONKIN	88	NP B309 426	+Bloshenko, Gorin+	(ITEP, SERP)
VOROBYEV	88	SJNP 48 273 Translated from YAF 48 436.	+Golubev, Dolinsky, Druzhinin+	(NOVO)
AKESSON	86	NP B264 154	+Albrow, Almehed+	(Axial Field Spec. Collab.)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFT, VAND)
ETKIN	82C	PR D25 2446	+Foley, Lai+	(BNL, CUNY, TUFT, VAND)
TORNQVIST	82	PRL 49 624		(HELS)
COSTA...	80	NP B175 402	Costa De Beauregard+	(BARI, BONN, CERN+)
GORLICH	80	NP B174 16	+Niczyporuk+	(CRAC, MPIM, CERN, ZEEM)
LOVERRE	80	ZPHY C6 187	+Armenteros, Dionisi+	(CERN, CDEF, MADR, STOH) IJP
WICKLUND	80	PRL 45 1469	+Ayres, Cohen, Diebold, Pawlicki	(ANL)
POLYCHRO...	79	PR D19 1317	Polychronakos, Cason, Bishop+	(NDAM, ANL) IJP
FROGGATT	77	NP B129 89	+Petersen	(GLAS, NORD)
HYAMS	75	NP B100 205	+Jones, Weilhammer, Blum, Dietl+	(CERN, MPIM)

OTHER RELATED PAPERS

SVEC	92	PR D45 55	+de Lesquen, van Rossum	(MCGI, SACL)
MORGAN	91	PL B258 444	+Pennington	(RAL, DURH)
WEINSTEIN	89	UTPT 89 03	+Isgur	(TNTO)
ALDE	88	PL B201 160	+Bellazzini, Binon+	(SERP, BELG, LANL, LAPP, PISA)
AU	87	PR D35 1633	+Morgan, Pennington	(DURH, RAL)
ACHASOV	84	ZPHY C22 53	+Devyanin, Shestakov	(NOVO)
CASON	83	PR D28 1586	+Cannata, Baumbaugh, Bishop+	(NDAM, ANL)
WEINSTEIN	83B	PR D27 588	+Isgur	(TNTO)
BECKER	79	NP B151 46	+Blanar, Blum+	(MPIM, CERN, ZEEM, CRAC)
BECKER	79B	NP B150 301	+Blanar, Blum+	(MPIM, CERN, ZEEM, CRAC)
CORDEN	79	NP B157 250	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC) JP
CASON	76	PRL 36 1485	+Polychronakos, Bishop, Biswas+	(NDAM, ANL) IJ
WETZEL	76	NP B115 208	+Freudenreich, Beusch+	(ETH, CERN, LOIC)
ESTABROOKS	74	NP B79 301	+Martin	(DURH)
GRAYER	74	NP B75 189	+Hyams, Blum, Dietl+	(CERN, MPIM)
HYAMS	73	NP B64 134	+Jones, Weilhammer, Blum, Dietl+	(CERN, MPIM)

$\hat{\rho}(1405)$

$I^G(J^{PC}) = 1^-(1^{-+})$

OMITTED FROM SUMMARY TABLE

Seen by ALDE 88B in $\pi^- p \to \eta\pi^0 n$ amplitude analysis. Needs confirmation.

See also the mini-review under non-$q\bar{q}$ candidates. (See the index for the page number.)

$\hat{\rho}(1405)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1406±20	[1] ALDE	88B	GAM4	0	$100\ \pi^- p \to \eta\pi^0 n$

[1] Seen in the P_0-wave intensity of the $\eta\pi^0$ system.

$\hat{\rho}(1405)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
180±20	[2] ALDE	88B	GAM4	0	$100\ \pi^- p \to \eta\pi^0 n$

[2] Seen in the P_0-wave intensity of the $\eta\pi^0$ system.

$\hat{\rho}(1405)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\pi^0$	seen
Γ_2	$\rho\pi$	not seen
Γ_3	$\eta'\pi$	

$\hat{\rho}(1405)$ BRANCHING RATIOS

$\Gamma(\eta\pi^0)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	[3] ALDE	88B	GAM4	0	$100\ \pi^- p \rightarrow \eta\pi^0 n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
not seen	[4] APEL	81	NICE	0	$40\ \pi^- p \rightarrow \eta\pi^0 n$

[3] Seen in the P_0-wave intensity of the $\eta\pi^0$ system.
[4] A general fit allowing S, D, and P waves (including m=0) is not done because of limited statistics.

$\Gamma(\rho\pi)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		COMMENT
not seen	[5] ZIELINSKI	86	$200\ \pi^+$ Cu,Pb $\rightarrow \pi^+\pi^+\pi^-$ X

[5] A general fit allowing S, D, and P waves (including m=0) is not done because of limited statistics.

$\Gamma(\eta'\pi)/\Gamma(\eta\pi^0)$ Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.80	95	BOUTEMEUR	90	GAM4	$100\ \pi^- p \rightarrow 4\gamma n$

$\hat{\rho}(1405)$ REFERENCES

BOUTEMEUR 90 Hadron 89 Conf. p 119+Poulet (SERP, BELG, LANL, LAPP, PISA, KEK)
ALDE 88B PL B205 397 +Binon, Boutemeur+ (SERP, BELG, LANL, LAPP) IGJPC
ZIELINSKI 86 Berkeley HEP 1 736 +Berg+ (ROCH, MINN, FNAL)
APEL 81 NP B193 269 +Augenstein, Bertolucci, Donskov+ (SERP, CERN)

OTHER RELATED PAPERS

IDDIR 88 PL B205 564 +Le Yaouanc, Ono+ (LPTP, TOKY)
TUAN 88 PL B213 537 +Ferbel, Dalitz (HAWA, ROCH, OXF)
ZIELINSKI 87 ZPHY C34 255 (ROCH)
ZIELINSKI 86 Berkeley HEP 1 736 +Berg+ (ROCH, MINN, FNAL)

$f_1(1420)$
was $E(1420)$

$I^G(J^{PC}) = 0^+(1^{++})$

See also minireview under non-$q\overline{q}$ candidates.

NOTE ON THE $f_1(1420)$

This particle is the axial–vector component of the old puzzling E/ι, which has caused much trouble.

In hadron–induced reactions, the $f_1(1420)$ is observed in centrally produced $K\overline{K}\pi$ systems (DIONISI 80, ARMSTRONG 84, 89) obtained with π and p beams. A Dalitz–plot analysis gives its quantum numbers and the dominant decay mode. For instance, ARMSTRONG 89 finds that the signal is totally consistent with being an 1^{++} state, with a dominant quasi–two–body S–wave decay mode into $K^*(892)\overline{K}$; furthermore, no 0^{-+} or 1^{+-} waves are required to describe the data. A G parity of +1 is suggested by the positive interference between the two overlapping $K^*(892)$ (ARMSTRONG 84). No significant signals in the $\eta\pi\pi$ or 4π decay modes are found by ARMSTRONG 89G in centrally produced 4π systems. All of this is in line with the previous observations made in $\overline{p}p$ annihilations.

In $\gamma\gamma$ fusion from e^+e^- annihilations, a signal at about 1420 MeV is seen only in single tag events (AIHARA 86C, GIDAL 87B, BEHREND 89, HILL 89) where one of the two photons is off the mass shell; by contrast, it is totally absent in the untagged events where both photons are real and hence they cannot produce a spin–1 meson because of the Yang–Landau theorem. This clearly implies $J = 1$ and $C = +1$. As for the parity, AIHARA 88B, 88C (same analysis as AIHARA 86C, with 25% more statistics) and BEHREND 89 all find angular distributions with positive parity preferred, but negative parity not excluded.

Although some uncertainties still remain, these two experimental observations (the state seen in hadronic interactions and the one seen in spacelike virtual photon fusion from e^+e^- annihilations) are often identified since there are more similarities than differences. In particular, all experiments agree that this state shows up only in $K^*(892)\overline{K}$. The same conclusions are obtained with partial wave analysis applied to the J/ψ radiative decay, J/$\psi \rightarrow \gamma K\overline{K}\pi$ (BAI 90C, AUGUSTIN 91).

BITYUKOV 88 studied the radiative decay $1^{++} \rightarrow \phi\gamma$. Since the ϕ is (almost) a pure $s\overline{s}$ state, the $\phi\gamma$ decay seems to be a good analyser to extract the $s\overline{s}$ component in the wave function of the decaying meson. Seeing the $f_1(1285)$ but not the $f_1(1420)$ in the $\phi\gamma$ mass spectrum, BITYUKOV 88 concludes that the $f_1(1420)$ cannot be the $s\overline{s}$ isoscalar member of the axial–vector $q\overline{q}$ nonet of the $f_1(1285)$. On the other hand, AIHARA 88C argues that, assuming they both belong to the same nonet and using several hypotheses, the octet–singlet mixing angle obtained is compatible with the $f_1(1420)$ being mostly $s\overline{s}$ and the $f_1(1285)$ being mostly $(u\overline{u}+d\overline{d})/\sqrt{2}$, although both require large admixtures of other $q\overline{q}$ components.

Arguments in favor of the possibility that the $f_1(1420)$ is a hybrid $q\overline{q}g$ meson or a four–quark state are put forward by ISHIDA 89 and by CALDWELL 90, respectively.

LONGACRE 90 argues that this particle is inconsistent with a QCD arrangement of quarks and gluons. He then develops a final-state rescattering mechanism with successive interactions between a K, a $\overline{K}$, and a π. The $f_1(1420)$ would then be a molecular state formed by the π orbiting in a P wave around an S–wave $K\overline{K}$ state.

$f_1(1420)$ MASS

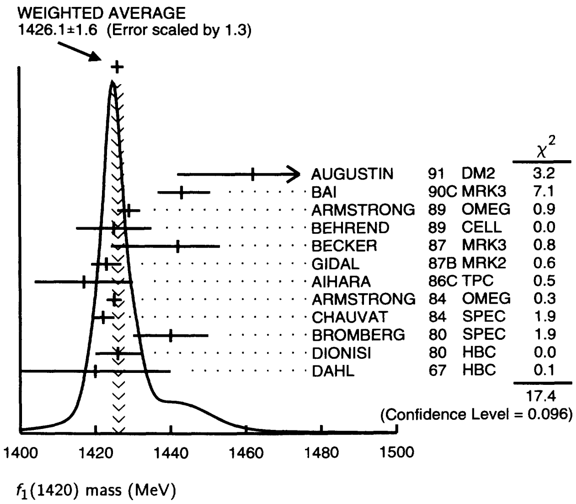
PRODUCED IN $p\overline{p}$ ANNIHILATION

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1414.9± 3.5 OUR AVERAGE		Error includes scale factor of 1.2.			
1417.5± 4		NACASCH	78	HBC	0.7,0.76 $\overline{p}p$
1398 ±10	170	DEFOIX	72	HBC	0.7 $\overline{p}p \rightarrow 7\pi$
1406 ± 7	280	DUBOC	72	HBC	1.2 $\overline{p}p \rightarrow 2K4\pi$
1420 ± 7	310	LORSTAD	69	HBC	0.7 $\overline{p}p$
1423.0±10.0		FRENCH	67	HBC	3–4 $\overline{p}p$

PRODUCED IN OTHER REACTIONS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1426.1± 1.6 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.			
1462 ±20		[1] AUGUSTIN	91	DM2	$J/\psi \rightarrow \gamma K\overline{K}\pi$
1443 $^{+7}_{-6}$ $^{+3}_{-2}$	1100	BAI	90C	MRK3	$J/\psi \rightarrow \gamma K^0_S K^\pm\pi^\mp$
1429 ± 3	389 ± 27	ARMSTRONG	89	OMEG	300 $pp \rightarrow K\overline{K}\pi pp$
1425 ±10	17	BEHREND	89	CELL	$\gamma\gamma \rightarrow K^0_S K^\pm\pi^\mp$
1442 ± 5.0$^{+10.0}_{-17.0}$	111$^{+31}_{-26}$	BECKER	87	MRK3	e^+e^-, $\omega K\overline{K}\pi$
1423 ± 4		GIDAL	87B	MRK2	$e^+e^- \rightarrow e^+e^- K\overline{K}\pi$
1417.0±13.0	13	AIHARA	86C	TPC	$e^+e^- \rightarrow e^+e^- K\overline{K}\pi$
1425.0± 2.0	1520	ARMSTRONG	84	OMEG	85 π^+p, $pp \rightarrow (\pi^+, p)(K\overline{K}\pi)$
1422.0± 3.0		CHAUVAT	84	SPEC	ISR 31.5 pp
1440.0±10.0		[2] BROMBERG	80	SPEC	100 $\pi^-p \rightarrow K\overline{K}\pi$X
1426.0± 6.0	221	DIONISI	80	HBC	4 $\pi^-p \rightarrow K\overline{K}\pi n$
1420 ±20		DAHL	67	HBC	1.6–4.2 π^-p

[1] From fit to the $K^*(892)K$ 1^{++} partial wave.
[2] Mass error increased to account for $a_0(980)$ mass cut uncertainties.



$f_1(1420)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
56.0± 3.0 OUR AVERAGE					
129 ±41		[3] AUGUSTIN	91	DM2	$J/\psi \to \gamma K \overline{K} \pi$
68 $^{+29}_{-18}$ $^{+8}_{-9}$	1100	BAI	90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm \pi^\mp$
58 ± 8	389 ± 27	ARMSTRONG	89	OMEG	$300\ pp \to K \overline{K} \pi pp$
42 ±22	17	BEHREND	89	CELL	$\gamma\gamma \to K^0_S K^\pm \pi^\mp$
40 $^{+17}_{-13}$ ±5	111^{+31}_{-26}	BECKER	87	MRK3	$e^+ e^-, \omega K \overline{K} \pi$
$35.0^{+47.0}_{-20.0}$	13	AIHARA	86C	TPC	$e^+ e^- \to e^+ e^- K \overline{K} \pi$
62.0± 5.0	1520	ARMSTRONG	84	OMEG	$85\ \pi^+ p, pp \to (\pi^+, p)\ (K \overline{K} \pi)$
47.0±10.0		CHAUVAT	84	SPEC	ISR 31.5 pp
62.0±14.0		BROMBERG	80	SPEC	$100\ \pi^- p \to K \overline{K} \pi X$
40.0±15.0	221	DIONISI	80	HBC	$4\ \pi^- p \to K \overline{K} \pi n$
53 ±20.0		NACASCH	78	HBC	$0.7, 0.76\ \overline{p} p$
50 ±10	170	DEFOIX	72	HBC	$0.7\ \overline{p} p \to 7\pi$
50 ±12	280	DUBOC	72	HBC	$1.2\ \overline{p} p \to 2K 4\pi$
60 ±20	310	LORSTAD	69	HBC	$0.7\ \overline{p} p$
60.0±20.0		DAHL	67	HBC	$1.6–4.2\ \pi^- p$
45 ±20		FRENCH	67	HBC	$3–4\ \overline{p} p$

[3] From fit to the $K^*(892) K\ 1^{++}$ partial wave.

$f_1(1420)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K \overline{K} \pi$	dominant
Γ_2	$\eta \pi \pi$	possibly seen
Γ_3	$a_0(980) \pi$	possibly seen
Γ_4	$\pi \pi \rho$	
Γ_5	$K \overline{K}^*(892)$ + c.c.	
Γ_6	4π	
Γ_7	$\gamma\gamma^*$	

$f_1(1420)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K \overline{K} \pi) \times \Gamma(\gamma\gamma^*)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_7/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
1.7±0.4 OUR AVERAGE					
3.0±0.9±0.7		[4,5] BEHREND	89	CELL	$e^+ e^- \to e^+ e^- K^0_S K \pi$
$2.3^{+1.0}_{-0.9}$±0.8		HILL	89	JADE	$e^+ e^- \to e^+ e^- K^\pm K^0_S \pi^\mp$
1.3±0.5±0.3		AIHARA	88B	TPC	$e^+ e^- \to e^+ e^- K^\pm K^0_S \pi^\mp$
1.6±0.7±0.3		[4,6] GIDAL	87B	MRK2	$e^+ e^- \to e^+ e^- K \overline{K} \pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<8.0	95	JENNI	83	MRK2	$e^+ e^- \to e^+ e^- K \overline{K} \pi$

[4] Assume a ρ-pole form factor.
[5] A ϕ - pole form factor gives considerably smaller widths.
[6] Published value divided by 2.

$f_1(1420)$ BRANCHING RATIOS

$\Gamma(K \overline{K}^*(892) + \text{c.c.})/\Gamma(K \overline{K} \pi)$ — Γ_5/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.76±0.06	BROMBERG	80	SPEC	$100\ \pi^- p \to K \overline{K} \pi X$
0.86±0.12	DIONISI	80	HBC	$4\ \pi^- p \to K \overline{K} \pi n$

$\Gamma(\pi \pi \rho)/\Gamma(K \overline{K} \pi)$ — Γ_4/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.3	95	CORDEN	78	OMEG	$12–15\ \pi^- p$
<2.0		DAHL	67	HBC	$1.6–4.2\ \pi^- p$

$\Gamma(\eta \pi \pi)/\Gamma(K \overline{K} \pi)$ — Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.1	95	ARMSTRONG	91B	OMEG	$300\ pp \to pp \eta \pi^+ \pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.35±0.75		KOPKE	89	MRK3	$J/\psi \to \omega \eta \pi \pi (K \overline{K} \pi)$
<0.6	90	GIDAL	87	MRK2	$e^+ e^- \to e^+ e^- \eta \pi^+ \pi^-$
<0.5	95	CORDEN	78	OMEG	$12–15\ \pi^- p$
1.5 ±0.8		DEFOIX	72	HBC	$0.7\ \overline{p} p$

$\Gamma(a_0(980) \pi)/\Gamma(\eta \pi \pi)$ — Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen in either mode	ANDO	86	SPEC	$8\ \pi^- p$
not seen in either mode	CORDEN	78	OMEG	$12–15\ \pi^- p$
0.4±0.2	DEFOIX	72	HBC	$0.7\ \overline{p} p \to 7\pi$

$\Gamma(4\pi)/\Gamma(K \overline{K}^*(892) + \text{c.c.})$ — Γ_6/Γ_5

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.90	95	DIONISI	80	HBC	$4\ \pi^- p$

$\Gamma(K \overline{K} \pi)/[\Gamma(a_0(980)\pi) + \Gamma(K \overline{K}^*(892) + \text{c.c.})]$ — $\Gamma_1/(\Gamma_3+\Gamma_5)$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.65±0.27	[7] DIONISI	80	HBC	$4\ \pi^- p$

[7] Calculated using $\Gamma(K\overline{K})/\Gamma(\eta\pi) = 0.24 \pm 0.07$ for $a_0(980)$ fractions.

$\Gamma(a_0(980)\pi)/\Gamma(K \overline{K}^*(892) + \text{c.c.})$ — Γ_3/Γ_5

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.04	68	ARMSTRONG	84	OMEG	$85\ \pi^+ p$

$\Gamma(4\pi)/\Gamma(K \overline{K} \pi)$ — Γ_6/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.62	95	ARMSTRONG	89G	OMEG	$85\ \pi p \to 4\pi X$

$f_1(1420)$ REFERENCES

ARMSTRONG	91B	ZPHY C52 389	+Barnes+	(ATHU, BARI, BIRM, CERN, CDEF)
AUGUSTIN	91	PR D (to be pub.)	+Cosme	(DM2 Collab.)
BAI	90C	PRL 65 2507	+Blaylock+	(Mark III Collab.)
ARMSTRONG	89	PL B221 216	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, LPNP) JPC
ARMSTRONG	89G	ZPHY C43 55	+Bloodworth	(CERN, BIRM, BARI, ATHU, LPNP)
BEHREND	89	ZPHY C42 367	+Criegee+	(CELLO Collab.)
HILL	89	ZPHY C42 355	+Olsson+	(JADE Collab.) JP
KOPKE	89	PRPL 174 67	+Wermes+	(CERN)
AIHARA	88B	PL B209 107	+Alston-Garnjost+	(TPC-2γ Collab.)
BECKER	87	PRL 59 186	+Blaylock, Bolton, Brown+	(Mark III Collab.) JP
GIDAL	87	PRL 59 2012	+Boyer, Butler, Cords, Abrams+	(LBL, SLAC, HARV)
GIDAL	87B	PRL 59 2016	+Boyer, Butler, Cords, Abrams+	(LBL, SLAC, HARV)
AIHARA	86C	PRL 57 2500	+Alston-Garnjost+	(TPC-2γ Collab.) JP
ANDO	86	PRL 57 1296	+Imai+	(KEK, KYOT, NIRS, SAGA, TOKY, TSUK+)
ARMSTRONG	84	PL 146B 273	+Bloodworth, Burns+	(ATHU, BARI, BIRM, CERN) JP
CHAUVAT	84	PL 148B 382	+Meritet, Bonino+	(CERN, UDCF, UCLA, SACL)
JENNI	83	PR D27 1031	+Burke, Telnov, Abrams, Blocker+	(SLAC, LBL)
BROMBERG	80	PR D22 1513	+Haggerty, Abrams, Dzierba	(CIT, FNAL, ILLC, IND)
DIONISI	80	NP B169 1	+Gavillet+	(CERN, MADR, CDEF, STOH) IJP
CORDEN	78	NP B144 253	+Corbett, Alexander+	(BIRM, RHEL, TELA, LOWC)
NACASCH	78	NP B135 203	+Defoix, Dobrzynski+	(PARI, MADR, CERN)
DEFOIX	72	NP B44 125	+Nascimento, Bizzarri+	(CDEF, CERN)
DUBOC	72	NP B46 429	+Goldberg, Makowski, Donald+	(LPNP, LIVP)
LORSTAD	69	NP B14 63	+D'Andlau, Astier+	(CDEF, CERN) JP
DAHL	67	PR 163 1377	+Hardy, Hess, Kirz, Miller	(LRL) IJP
Also	65	PRL 14 1074	Miller, Chung, Dahl, Hess, Hardy, Kirz+	(LRL, UCB)
FRENCH	67	NC 52A 438	+Kinson, McDonald, Riddiford+	(CERN, BIRM)

OTHER RELATED PAPERS

CALDWELL	90	Hadron 89 Conf. p 127		(UCSB)
ISHIDA	89	PTP 82 119	+Oda, Sawazaki, Yamada	(TNIH)
AIHARA	88C	PR D38 1	+Alston-Garnjost+	(TPC-2γ Collab.) JPC
BITYUKOV	88	PL B203 327	+Borisov, Dorofeev+	(SERP)
PROTOPOP...	87B	Hadron 87 Conf.	Protopopescu, Chung	(BNL)

$f_2(1430)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

This entry lists nearby peaks observed in the D wave of the $K\overline{K}$ and $\pi^+\pi^-$ systems.

$f_2(1430)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1430 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1421 ± 5	AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
1480.0±50.0	AKESSON	86	SPEC	$pp \to pp\pi^+\pi^-$
$1436.0^{+26.0}_{-16.0}$	DAUM	84	CNTR	17–18 $\pi^- p \to K^+K^- n$
1412.0± 3.0	DAUM	84	CNTR	63 $\pi^- p \to K^0_S K^0_S n$, $K^+K^- n$
$1439.0^{+5.0}_{-6.0}$	[1] BEUSCH	67	OSPK	5,7,12 $\pi^- p \to K^0_S K^0_S n$

[1] Not seen by WETZEL 76.

$f_2(1430)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
30 ± 9	AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
150.0±40.0	AKESSON	86	SPEC	$pp \to pp\pi^+\pi^-$
$81.0^{+56.0}_{-29.0}$	DAUM	84	CNTR	17–18 $\pi^- p \to K^+K^- n$
14.0± 6.0	DAUM	84	CNTR	63 $\pi^- p \to K^0_S K^0_S n$, $K^+K^- n$
$43.0^{+17.0}_{-18.0}$	[2] BEUSCH	67	OSPK	5,7,12 $\pi^- p \to K^0_S K^0_S n$

[2] Not seen by WETZEL 76.

$f_2(1430)$ DECAY MODES

	Mode
Γ_1	$K\overline{K}$
Γ_2	$\pi\pi$

$f_2(1430)$ REFERENCES

AUGUSTIN 87 ZPHY C36 369 +Cosme+ (LALO, CLER, FRAS, PADO)
AKESSON 86 NP B264 154 +Albrow, Almehed+ (Axial Field Spec. Collab.)
DAUM 84 ZPHY C23 339 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+) JP
WETZEL 76 NP B115 208 +Freudenreich, Beusch+ (ETH, CERN, LOIC)
BEUSCH 67 PL 25B 357 +Fischer, Gobbi, Astbury+ (ETH, CERN)

$\eta(1440)$
was $\iota(1440)$

$I^G(J^{PC}) = 0^+(0^{-+})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

NOTE ON THE $\eta(1440)$

The first observation of a meson with $I^G J^{PC} = 0^+0^{-+}$ in the 1400-MeV mass region was made with $p\overline{p}$ annihilations at rest (BAILLON 67) in the channel $\eta(1440) \to K\overline{K}\pi$. It was seen to decay equally into $a_0(980)\pi$ and $\overline{K}^*(892)K$.

The $\eta(1440)$ has since also been seen in other hadronic reactions: In a partial-wave analysis of the $\eta\pi^+\pi^-$ system, confirming the decay $\eta(1440) \to a_0(980)\pi$ (FUKUI 91C); in a partial-wave analysis of the $K\overline{K}\pi$ system (CHUNG 85, BIRMAN 88); in 6-GeV $p\overline{p}$ annihilations (REEVES 86); and in non-peripherally selected $\pi^- p \to K^0_S K^0_S \pi^0 n$ (RATH 89). RATH 89 favors the interpretation that there are two narrow η resonances in the 1410–1480 MeV region.

Neither the $\eta(1440)$ nor the $f_1(1420)$ are observed in the $s\overline{s}$-enriched peripheral reaction $K^- p \to K\overline{K}\pi\Lambda$ at 11 GeV/c (ASTON 87), which speaks against an $s\overline{s}$ interpretation of either state. Moreover, the $\eta(1440)$ is not seen by ARMSTRONG 84, 89 either, who studied $K\overline{K}\pi$ central production in $\pi^+ p \to \pi^+(K\overline{K}\pi)p$ and $pp \to p(K\overline{K}\pi)p$ at 85 and 300 GeV/c [but the $f_1(1420)$ is seen]. This agrees with earlier results (DIONISI 80, DEFOIX 72, DUBOC 72, LORSTAD 69, etc.).

The $\eta(1440)$ is also seen as a broad enhancement in $J/\psi(1S)$ radiative decay. In the $K\overline{K}\pi$ channel, however, its mass is higher than observed in hadronic interactions, and its width is larger. It has been shown (TOKI 87, BAI 90C) that two resonances (with $M \approx 1420$ MeV and $M \approx 1490$ MeV) give a better description of the data. Moreover, the $\eta\pi^+\pi^-$ channel peaks near 1400 MeV (AUGUSTIN 90, BURCHELL 91). All these results suggest the existence of two overlapping states (favored by RATH 89 in hadronic production), one around 1400 MeV decaying into both $K\overline{K}\pi$ and $\eta\pi\pi$, the other one around 1490 MeV seen only in $K\overline{K}\pi$. Other possible decay modes, in $\pi\pi\gamma$ and 4π, are not sufficiently well established to clarify the situation.

There is considerable confusion on the partial decay modes: The $K\overline{K}\pi$ final state is usually dominated by $\overline{K}^*(892)K$ and/or $a_0(980)\pi$ contributions, but it is impossible to quote any reliable $\overline{K}^*K$ and $a_0\pi$ branching ratios, since the analyses are highly model dependent and the experiments do not agree.

We continue to list under the $\eta(1440)$ all the results on the 0^{-+} system in the 1380–1490 MeV region, but keep in mind that it is likely that there is more than one resonance present in these observations. The masses and widths are given separately according to the various decay modes.

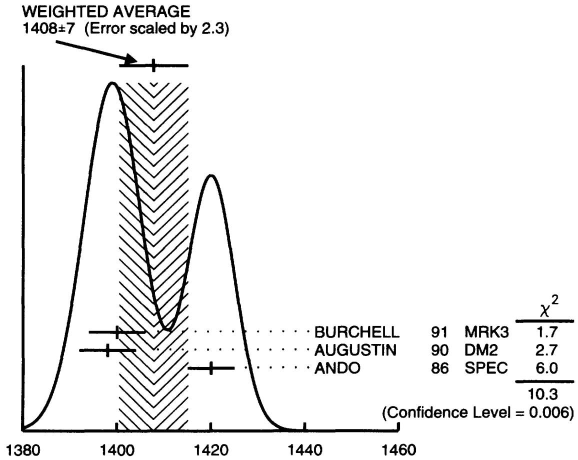
$\eta(1440)$ MASS

VALUE (MeV)	DOCUMENT ID
1420±20 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

$\eta\pi\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1408±7 OUR AVERAGE	Error includes scale factor of 2.3. See the ideogram below.				
1400±6		[1] BURCHELL	91	MRK3	$J/\psi \to \gamma\eta\pi^+\pi^-$
1398±6	261 ± 24	[2] AUGUSTIN	90	DM2	$J/\psi \to \gamma\eta\pi^+\pi^-$
1420±5		ANDO	86	SPEC	8 $\pi^- p \to n\eta\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1388±4		FUKUI	91C	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$

[1] From fit to the $a_0(980)\pi$ 0^{-+} partial wave.
[2] Best fit with a single Breit Wigner.



$\eta(1440)$ mass, $\eta\pi\pi$ mode (MeV)

$\pi\pi\gamma$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1401±18	[3,4] AUGUSTIN 90	DM2	$J/\psi \to \pi^+\pi^-\gamma\gamma$
1440±20	[4] COFFMAN 90	MRK3	$J/\psi \to \pi^+\pi^- 2\gamma$

[3] Best fit with a single Breit Wigner.
[4] This peak in the $\gamma\rho$ channel may not be related to the $\eta(1440)$.

4π MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1489±12	3270	[5] BISELLO 89B	DM2	$J/\psi \to 4\pi\gamma$

[5] Estimated by us from various fits.

$K\overline{K}\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1419.9± 1.0 OUR AVERAGE		Error includes scale factor of 1.2.		
1421 ±14		[6] AUGUSTIN 91	DM2	$J/\psi \to \gamma K\overline{K}\pi$
1416 ± 8 $^{+7}_{-5}$	700	[7] BAI 90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
1424 ± 4		TAKAMATSU 90	SPEC	$8\ \pi^- p \to n K^0_S K^\pm\pi^\mp$
1413 ± 8	500	DUCH 89	ASTE	$\overline{p}p \to \pi^+\pi^- K^\pm\pi^\mp K^0$
1419 ± 1	8800 ± 200	[8,9] BIRMAN 88	MPS	$8\ \pi^- p \to K^+\overline{K}^0\pi^- n$
1424 ± 3	620	[9,10] REEVES 86	SPEC	$6.6\ p\overline{p} \to K\overline{K}\pi X$
1421 ± 2		CHUNG 85	SPEC	$8\ \pi^- p \to K\overline{K}\pi n$
1425 ± 7	800	[9,11] BAILLON 67	HBC	$0.0\ \overline{p}p \to K\overline{K}\pi\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1459 ± 5		[8] AUGUSTIN 91	DM2	$J/\psi \to \gamma K\overline{K}\pi$
1445 ± 8	693 ± 30	[9] AUGUSTIN 90	DM2	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
1433 ± 8	296 ± 20	[9] AUGUSTIN 90	DM2	$J/\psi \to \gamma K^+ K^- \pi^0$
1490 $^{+14}_{-8}$ $^{+3}_{-16}$	1100	[6] BAI 90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
1443 ± 5		[6] TAKAMATSU 90	SPEC	$8\ \pi^- p \to n K^*(892) K$
1475 ± 4		[12] RATH 89	MPS	$21.4\ \pi^- p \to n K^0_S K^0_S \pi^0$
1452.8± 6.8	170 ± 15	[9] RATH 89	MPS	$21.4\ \pi^- p \to K^0_S K^0_S \pi^0 n$
1412.8± 5.4		RATH 89	MPS	$21.4\ \pi^- p \to n K^0_S K^0_S \pi^0$
1454 ± 3		WISNIEWSKI 87	MRK3	$J/\psi \to K\overline{K}\pi\gamma$
1440 $^{+20}_{-15}$	174	EDWARDS 82E	CBAL	$J/\psi \to \gamma K^+ K^- \pi^0$
1440 $^{+10}_{-15}$		SCHARRE 80	MRK2	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$

[6] From fit to the $K^*(892) K$ 0^{-+} partial wave.
[7] From fit to the $a_0(980)\pi$ 1^{++} partial wave. cannot rule out a $a_0(980)\pi$ 1^{++} partial wave.
[8] From fit to the $a_0(980)\pi$ 0^{-+} partial wave.
[9] Best fit with a single Breit Wigner.
[10] From fit of the 0^{-+} partial wave , mainly $a_0(980)\pi$.
[11] From best fit of 0^{-+} partial wave , 50% $K^*(892)K$, 50% $a_0(980)\pi$.
[12] From fit to the $a_0(980)\pi$ 0^{-+} partial wave , but $a_0(980)\pi$ 1^{++} cannot be excluded. The fit is also consistent with one resonance at 1453 MeV.

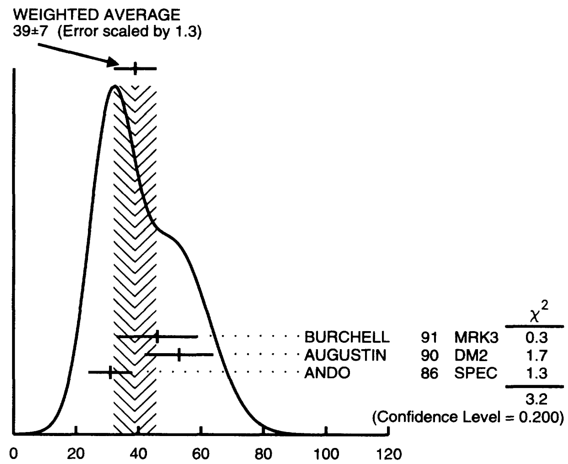
$\eta(1440)$ WIDTH

VALUE (MeV)	DOCUMENT ID
60±30 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

$\eta\pi\pi$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
39± 7 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.		
46±13	[13] BURCHELL 91	MRK3	$J/\psi \to \gamma\eta\pi^+\pi^-$
53±11	[14] AUGUSTIN 90	DM2	$J/\psi \to \gamma\eta\pi^+\pi^-$
31± 7	ANDO 86	SPEC	$8\ \pi^- p \to n\eta\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
59± 4	FUKUI 91C	SPEC	$8.95\ \pi^- p \to \eta\pi^+\pi^- n$

[13] From fit to the $a_0(980)\pi$ 0^{-+} partial wave.
[14] From $\eta\pi^+\pi^-$ mass distribution - mainly $a_0(980)\pi$ - no spin-parity determination available.



$\eta(1440)$ width $\eta\pi\pi$ mode (MeV)

$\pi\pi\gamma$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
174±44	AUGUSTIN 90	DM2	$J/\psi \to \pi^+\pi^-\gamma\gamma$
60±30	[15] COFFMAN 90	MRK3	$J/\psi \to \pi^+\pi^- 2\gamma$

[15] This peak in the $\gamma\rho$ channel may not be related to the $\eta(1440)$.

4π MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
144±13	3270	[16] BISELLO 89B	DM2	$J/\psi \to 4\pi\gamma$

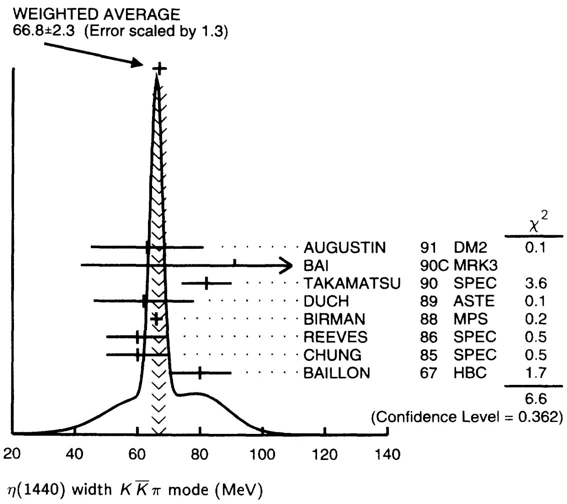
[16] Estimated by us from various fits.

$K\overline{K}\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
66.8± 2.3 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.		
63 ±18		AUGUSTIN 91	DM2	$J/\psi \to \gamma K\overline{K}\pi$
91 $^{+67}_{-31}$ $^{+15}_{-38}$		BAI 90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
82 ± 8		TAKAMATSU 90	SPEC	$8\ \pi^- p \to n K^0_S K^\pm\pi^\mp$
62 ±16	500	DUCH 89	ASTE	$\overline{p}p \to K\overline{K}\pi\pi\pi$
66 ± 2	8800 ± 200	BIRMAN 88	MPS	$8\ \pi^- p \to K^+\overline{K}^0\pi^- n$
60 ±10	620	[17] REEVES 86	SPEC	$6.6\ p\overline{p} \to K K\pi X$
60 ±10		CHUNG 85	SPEC	$8\ \pi^- p \to K\overline{K}\pi n$
80 ±10	800	[18] BAILLON 67	HBC	$0.0\ \overline{p}p \to K\overline{K}\pi\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
75 ± 9		[19] AUGUSTIN 91	DM2	$J/\psi \to \gamma K\overline{K}\pi$
75 ± 9	693 ± 30	[19] AUGUSTIN 90	DM2	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
93 ±14	296 ± 20	AUGUSTIN 90	DM2	$J/\psi \to \gamma K^+ K^- \pi^0$
105 ±10	693 ± 30	AUGUSTIN 90	DM2	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
54 $^{+37}_{-21}$ $^{+13}_{-24}$		[20] BAI 90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
59 ± 4		[20] TAKAMATSU 90	SPEC	$9\ \pi^- p \to n\eta\pi^+\pi^-$
57 ± 8		TAKAMATSU 90	SPEC	$8\ \pi^- p \to n K^*(892) K$
51 ±13		[21] RATH 89	MPS	$21.4\ \pi^- p \to n K^0_S K^0_S \pi^0$
99.9±11.4	170 ± 15	[22] RATH 89	MPS	$21.4\ \pi^- p \to K^0_S K^0_S \pi^0 n$
19 ± 7		RATH 89	MPS	$21.4\ \pi^- p \to n K^0_S K^0_S \pi^0$
160 ±11		WISNIEWSKI 87	MRK3	$J/\psi \to K\overline{K}\pi\gamma$
55 $^{+20}_{-30}$	174	EDWARDS 82E	CBAL	$J/\psi \to \gamma K^+ K^- \pi^0$
50 $^{+30}_{-20}$		SCHARRE 80	MRK2	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$

[17] From best fit to 0^{-+} partial wave , 50% $K^*(892)K$, 50% $a_0(980)\pi$.
[18] From fit to the 0^{-+} partial wave , mainly $a_0(980)\pi$.

[19] From fit to the $a_0(980)\pi$ 0^{-+} partial wave.
[20] From fit to the $K^*(892)K$ 0^{-+} partial wave.
[21] From fit to the $a_0(980)\pi$ 0^{-+} partial wave , but $a_0(980)\pi$ 1^{++} cannot be excluded. The fit is also consistent with one resonance at 1453 MeV.
[22] Best fit with a single Breit Wigner.



$\eta(1440)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}\pi$	seen
Γ_2	$\eta\pi\pi$	seen
Γ_3	$a_0(980)\pi$	seen
Γ_4	$\pi\pi\rho$	
Γ_5	$K\overline{K}^*(892)$ + c.c.	
Γ_6	4π	seen
Γ_7	$\gamma\gamma$	
Γ_8	$\rho^0\gamma$	

$\eta(1440)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_7/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
<1.2	95	BEHREND	89	CELL	$\gamma\gamma \to K^0_S K^\pm \pi^\mp$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.6	95	AIHARA	86D	TPC	$e^+e^- \to e^+e^- K^0_S K^\pm \pi^\mp$
<2.2	95	ALTHOFF	85B	TASS	$e^+e^- \to e^+e^- K\overline{K}\pi$
<8.0	95	JENNI	83	MRK2	$e^+e^- \to e^+e^- K\overline{K}\pi$

$\Gamma(\eta\pi\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\Gamma_2\Gamma_7/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.3	ANTREASYAN	87	CBAL	$e^+e^- \to e^+e^-\eta\pi\pi$

$\Gamma(\rho^0\gamma) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\Gamma_8\Gamma_7/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.5	95	ALTHOFF	84E	TASS	$e^+e^- \to e^+e^-\pi^+\pi^-\gamma$

$\eta(1440)$ BRANCHING RATIOS

$\Gamma(\eta\pi\pi)/\Gamma(K\overline{K}\pi)$ Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.5	90	EDWARDS	83B	CBAL	$J/\psi \to \eta\pi\pi\gamma$
<1.1	90	SCHARRE	80	MRK2	$J/\psi \to \eta\pi\pi\gamma$
<1.5	95	FOSTER	68B	HBC	$0.0\ \overline{p}p$

$\Gamma(a_0(980)\pi)/\Gamma(K\overline{K}\pi)$ Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
~0.8	500	[23] DUCH	89	ASTE	$\overline{p}p \to \pi^+\pi^- K^\pm\pi^\mp K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~0.75		[23] REEVES	86	SPEC	$6.6\ p\overline{p} \to KK\pi X$

[23] Assuming that the $a_0(980)$ decays only into $K\overline{K}$.

$\Gamma(K\overline{K}^*(892) + \text{c.c.})/\Gamma(K\overline{K}\pi)$ Γ_5/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.50±0.10	BAILLON	67	HBC	$0.0\ \overline{p}p \to K\overline{K}\pi\pi\pi$

$\Gamma(K\overline{K}^*(892) + \text{c.c.})/[\Gamma(a_0(980)\pi) + \Gamma(K\overline{K}^*(892) + \text{c.c.})]$ $\Gamma_5/(\Gamma_3+\Gamma_5)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.25	90	EDWARDS	82E	CBAL	$J/\psi \to K^+K^-\pi^0\gamma$

$\Gamma(\rho^0\gamma)/\Gamma(K\overline{K}\pi)$ Γ_8/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.0152±0.0038	[24] COFFMAN	90	MRK3	$J/\psi \to \gamma\gamma\pi^+\pi^-$

[24] Using $B(J/\psi \to \gamma\eta(1440) \to \gamma K K\pi)=4.2 \times 10^{-3}$ and $B(J/\psi \to \gamma\eta(1440) \to \gamma\gamma\rho^0)=6.4 \times 10^{-5}$ and assuming that the $\gamma\rho^0$ signal does not come from the $f_1(1420)$.

$\eta(1440)$ REFERENCES

AUGUSTIN	91	PR D (to be pub.)	+Cosme	(DM2 Collab.)
BURCHELL	91	NP B21 132 (suppl)		(Mark III Collab.)
FUKUI	91C	PL B267 293	+	(SUGI, NAGO, KEK, KYOT, MIYA, AKIT)
AUGUSTIN	90	PR D42 10	+Cosme+	(DM2 Collab.)
BAI	90C	PRL 65 2507	+Blaylock+	(Mark III Collab.)
COFFMAN	90	PR D41 1410	+De Jongh+	(Mark III Collab.)
TAKAMATSU	90	Hadron 89 Conf. p 71	+Ando+	(KEK)
BEHREND	89	ZPHY C42 367	+Criegee+	(CELLO Collab.)
BISELLO	89B	PR D39 701	Busetto+	(DM2 Collab.)
DUCH	89	ZPHY 45 223	+Heel, Bailey+	(ASTERIX Collab.) JP
RATH	89	PR D40 693	+Cason+	(NDAM, BRAN, BNL, CUNY, DUKE)
BIRMAN	88	PRL 61 1557	+Chung, Peaslee+	(BNL, FSU, IND, SMAS) JP
ANTREASYAN	87	PR D36 2633	+Bartels, Besset+	(Crystal Ball Collab.)
WISNIEWSKI	87	Hadron 87 Conf.		(Mark III Collab.)
AIHARA	86D	PRL 57 51	+Alston-Garnjost+	(TPC-2γ Collab.)
ANDO	86	PRL 57 1296	+Imai+	(KEK, KYOT, NIRS, SAGA, TOKY, TSUK+) IJP
REEVES	86	PR 34 1960	+Chung, Crittenden+	(FLOR, BNL, IND, SMAS) JP
ALTHOFF	85B	ZPHY C29 189	+Braunschweig, Kirschfink+	(TASSO Collab.)
CHUNG	85	PRL 55 779	+Fernow, Boehnlein+	(BNL, FLOR, IND, SMAS) JP
ALTHOFF	84E	PL 147B 487	+Braunschweig, Kirschfink, Luebelsmeyer+	(TASSO Collab.)
EDWARDS	83B	PRL 51 859	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
JENNI	83	PR D27 1031	+Burke, Telnov, Abrams, Blocker+	(SLAC, LBL)
EDWARDS	82E	PRL 49 259	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
Also	83	PRL 50 219	Edwards, Partridge+	(CIT, HARV, PRIN, STAN+)
SCHARRE	80	PL 97B 329	+Trilling, Abrams, Alam, Blocker+	(SLAC, LBL)
FOSTER	68B	NP B8 174	+Gavillet, Labrosse, Montanet+	(CERN, CDEF)
BAILLON	67	NC 50A 393	+Edwards, D'Andlau, Astier+	(CERN, CDEF, IRAD)

OTHER RELATED PAPERS

AHMAD	89	NP B (PROC.)8 50	+Amsler, Auld+	(ASTERIX Collab.)
ARMSTRONG	89	PL B221 216	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, LPNP)
ZIEMINSKA	88	AIP Conf.		(IND)
ARMSTRONG	87	ZPHY C34 23	+Bloodworth+	(CERN, BIRM, BARI, ATHU, LPNP)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, TOKY)
PROTOPOP...	87B	Hadron 87 Conf.	Protopopescu, Chung	(BNL)
TOKI	87	Hadron 87 Conf.		(TOKY)
ARMSTRONG	84	PL 146B 273	+Bloodworth, Burns+	(ATHU, BARI, BIRM, CERN)
DIONISI	80	NP B169 1	+Gavillet+	(CERN, MADR, CDEF, STOH)
DEFOIX	72	NP B44 125	+Nascimento, Bizzarri+	(CDEF, CERN)
DUBOC	72	NP B46 429	+Goldberg, Makowski, Donald+	(LPNP, LIVP)
LORSTAD	69	NP B14 63	+D'Andlau, Astier+	(CDEF, CERN)

$\rho(1450)$

$I^G(J^{PC}) = 1^+(1^{--})$

See the mini-review under the $\rho(1700)$.

$\rho(1450)$ MASS

VALUE (MeV)	DOCUMENT ID
1465±25 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.
1451± 8 OUR AVERAGE	Includes data from the 4 datablocks that follow this one.

MIXED MODES

VALUE (MeV)	DOCUMENT ID		TECN
The data in this block is included in the average printed for a previous datablock.			
1465±25	DONNACHIE	87	RVUE
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1425±25	GOVORKOV	88	RVUE

$\eta\rho^0$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
1470±20	ANTONELLI	88	DM2	$e^+e^- \to \eta\pi^+\pi^-$
1446±10	FUKUI	88	SPEC	$8.95\ \pi^-p \to \eta\pi^+\pi^-n$

$\pi^+\pi^-$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
1424±25	BISELLO	89	DM2	$e^+e^- \to \pi^+\pi^-$

$\omega\pi$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
1463±25	[1] DONNACHIE 91	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1250	[2] ASTON 80C	OMEG	20–70 $\gamma p \rightarrow \omega\pi^0 p$
1290±40	[2] BARBER 80C	SPEC	3–5 $\gamma p \rightarrow \omega\pi^0 p$

[1] Using data from BISELLO 91B, DOLINSKY 86 and ALBRECHT 87L.
[2] Not separated from $b_1(1235)$, not pure $J^P = 1^-$ effect.

$\pi^+\pi^-\pi^+\pi^-$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1449±4	[3] ARMSTRONG 89E	OMEG	300 $pp \rightarrow pp2(\pi^+\pi^-)$

[3] Not clear whether this observation has I=1 or 0.

$\phi\pi$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1480±40	[4] BITYUKOV 87	SPEC	0	32.5 $\pi^- p \rightarrow \phi\pi^0 n$

[4] See the minireview for $\rho(1700)$ and ACHASOV 88 for a non-exotic interpretation. DONNACHIE 91 suggests this is a different particle.

$\rho(1450)$ WIDTH

VALUE (MeV)	DOCUMENT ID
310±60 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

$\omega\pi$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
311± 62	[5] DONNACHIE 91	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
300	[6] ASTON 80C	OMEG	20–70 $\gamma p \rightarrow \omega\pi^0 p$
320±100	[6] BARBER 80C	SPEC	3–5 $\gamma p \rightarrow \omega\pi^0 p$

[5] Using data from BISELLO 91B, DOLINSKY 86 and ALBRECHT 87L.
[6] Not separated from $b_1(1235)$, not pure $J^P = 1^-$ effect.

MIXED MODES

VALUE (MeV)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
240±25	GOVORKOV 88	RVUE
220±25	DONNACHIE 87	RVUE

$\eta\rho^0$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
230±30	ANTONELLI 88	DM2	$e^+e^- \rightarrow \eta\pi^+\pi^-$
60±15	FUKUI 88	SPEC	8.95 $\pi^- p \rightarrow \eta\pi^+\pi^- n$

$\pi^+\pi^-$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
269±31	BISELLO 89	DM2	$e^+e^- \rightarrow \pi^+\pi^-$

$\pi^+\pi^-\pi^+\pi^-$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
78±18	[7] ARMSTRONG 89E	OMEG	300 $pp \rightarrow pp2(\pi^+\pi^-)$

[7] Not clear whether this observation has I=1 or 0.

$\phi\pi$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
130±60	[8] BITYUKOV 87	SPEC	0	32.5 $\pi^- p \rightarrow \phi\pi^0 n$

[8] See the minireview for $\rho(1700)$ and ACHASOV 88 for a non-exotic interpretation. DONNACHIE 91 suggests this is a differentparticle.

$\rho(1450)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	seen
Γ_2	4π	seen
Γ_3	e^+e^-	seen
Γ_4	$\eta\rho$	<4 %
Γ_5	$\phi\pi$	<1 %
Γ_6	$\omega\pi$	
Γ_7	$K\overline{K}$	

$\rho(1450)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(\pi\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.12	[9] DIEKMAN 88	RVUE	$e^+e^- \rightarrow \pi^+\pi^-$

[9] Using total width = 235 MeV.

$\Gamma(\eta\rho) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_4\Gamma_3/\Gamma$

VALUE (eV)	DOCUMENT ID	TECN	COMMENT
91±19	ANTONELLI 88	DM2	$e^+e^- \rightarrow \eta\pi^+\pi^-$

$\Gamma(\phi\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_5\Gamma_3/\Gamma$

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
<70	90	[10] AULCHENKO 87B	ND	$e^+e^- \rightarrow K_S^0 K_L^0 \pi^0$

[10] Using mass 1480 ± 40 MeV and total width 130 ± 60 MeV of BITYUKOV 87.

$\rho(1450)$ BRANCHING RATIOS

$\Gamma(\eta\rho)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE	DOCUMENT ID	TECN
<0.04	DONNACHIE 87B	RVUE

$\Gamma(\phi\pi)/\Gamma(\omega\pi)$ — Γ_5/Γ_6

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
>0.5	95	BITYUKOV 87	SPEC	0	32.5 $\pi^- p \rightarrow \phi\pi^0 n$

$\Gamma(\omega\pi)/\Gamma(4\pi)$ — Γ_6/Γ_2

VALUE	DOCUMENT ID	TECN
<0.14	CLEGG 88	RVUE

$\Gamma(\eta\rho)/\Gamma(\omega\pi)$ — Γ_4/Γ_6

VALUE	DOCUMENT ID	TECN	COMMENT
~ 0.24	[11] DONNACHIE 91	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
>2	FUKUI 91	SPEC	8.95 $\pi^- p \rightarrow \omega\pi^0 n$

$\Gamma(\omega\pi)/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE	DOCUMENT ID	TECN
~ 0.21	[11] DONNACHIE 91	RVUE

$\Gamma(\pi\pi)/\Gamma(\omega\pi)$ — Γ_1/Γ_6

VALUE	DOCUMENT ID	TECN
~ 0.24	[11] DONNACHIE 91	RVUE

$\Gamma(\phi\pi)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	DOCUMENT ID	TECN
<0.01	[11] DONNACHIE 91	RVUE

$\Gamma(K\overline{K})/\Gamma(\omega\pi)$ — Γ_7/Γ_6

VALUE	DOCUMENT ID	TECN
<0.08	[11] DONNACHIE 91	RVUE

[11] Using data from BISELLO 91B, DOLINSKY 86 and ALBRECHT 87L.

$\rho(1450)$ REFERENCES

BISELLO	91B	NP B21 111 (suppl)		(DM2 Collab.)
DONNACHIE	91	ZPHY C51 689	+Clegg	(MCHS, LANC)
FUKUI	91	PL B257 241	+Horikawa+	(SUGI, NAGO, KEK, KYOT, MIYA)
ARMSTRONG	89E	PL B228 536	+Benayoun	(ATHU, BARI, BIRM, CERN, CDEF, LPNP)
BISELLO	89	PL B220 321	+Busetto+	(DM2 Collab.)
ACHASOV	88	PL B207 199	+Kozhevnikov	(NOVO)
ANTONELLI	88	PL B212 133	+Baldini+	(DM2 Collab.)
CLEGG	88	ZPHY C40 313	+Donnachie	(MCHS, LANC)
DIEKMAN	88	PRPL 159 101		(BONN)
FUKUI	88	PL B202 441	+Horikawa+	(SUGI, NAGO, KEK, KYOT, MIYA)
GOVORKOV	88	SJNP 48 150 Translated from YAF 48 237.		(JINR)
ALBRECHT	87L	PL B185 223	+Binder, Boeckmann, Glaser+	(ARGUS Collab.)
AULCHENKO	87B	JETPL 45 145 Translated from ZETFP 45 118.	+Dolinsky, Druzhinin, Dubrovin+	(NOVO)
BITYUKOV	87	PL B188 383	+Dzhelyadin, Dorofeev, Golovkin+	(SERP)
DONNACHIE	87	ZPHY C33 407	+Mirzaie	(MCHS)
DONNACHIE	87B	ZPHY C34 257	+Clegg	(MCHS, LANC)
DOLINSKY	86	PL B174 453	+Druzhinin, Dubrovin, Eidelman+	(NOVO)
ASTON	80C	PL 92B 211		(BONN, CERN, EPOL, GLAS, LANC, MCHS+)
BARBER	80C	ZPHY C4 169	+Dainton, Brodbeck, Brookes+	(DARE, LANC, SHEF)

OTHER RELATED PAPERS

BRAU	88	PR D37 2379	+Franek+	(SLAC Hybrid Facility Photon Collab.)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, TOKY)
KURDADZE	86	JETPL 43 643	+Lelchuk, Pakhtusova, Sidorov, Skrinskii+	(NOVO)
		Translated from ZETFP 43 497.		
BARKOV	85	NP B256 365	+Chilingarov, Eidelman, Khazin, Lelchuk+	(NOVO)
BISELLO	85	LAL 85-15	+Augustin, Ajaltouni+	(PADO, LALO, CLER, FRAS)
ABE	84B	PRL 53 751	+Bacon, Ballam+	(SLAC Hybrid Facility Photon Collab.)
ATKINSON	84C	NP B243 1	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP+)
CORDIER	82	PL 109B 129	+Bisello, Bizot, Buon, Delcourt	(LALO)
KILLIAN	80	PR D21 3005	+Treadwell, Ahrens, Berkelman, Cassel+	(CORN)
COSME	76	PL 63B 352	+Courau, Dudelzak, Grelaud, Jean-Marie+	(ORSA)
BINGHAM	72B	PL 41B 635	+Rabin, Rosenfeld, Smadja+	(LBL, UCB, SLAC)
FRENKIEL	72	NP B47 61	+Ghesquiere, Lillestol, Chung+	(CDEF, CERN)
LAYSSAC	71	NC 6A 134	+Renard	(MONP)

$f_1(1510)$ was $D(1530)$

$I^G(J^{PC}) = 0^+(1^{++})$

See also minireview under non-$q\overline{q}$ candidates.

$f_1(1510)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1512 ± 4	600 ± 200	[1] BIRMAN	88	MPS	$8\ \pi^- p \rightarrow K^+ \overline{K}^0 \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1530 ±10		ASTON	88C	LASS	$11\ K^- p \rightarrow K^0_S K^{\pm} \pi^{\mp} \Lambda$
1526.0± 6.0	271	GAVILLET	82	HBC	$4.2\ K^- p \rightarrow \Lambda K K \pi$

[1] From partial wave analysis of $K^+ \overline{K}^0 \pi^-$ state.

$f_1(1510)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
35 ±15	600 ± 200	[2] BIRMAN	88	MPS	$8\ \pi^- p \rightarrow K^+ \overline{K}^0 \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
100 ±40		ASTON	88C	LASS	$11\ K^- p \rightarrow K^0_S K^{\pm} \pi^{\mp} \Lambda$
107.0±15.0	271	GAVILLET	82	HBC	$4.2\ K^- p \rightarrow \Lambda K K \pi$

[2] From partial wave analysis of $K^+ \overline{K}^0 \pi^-$ state.

$f_1(1510)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K \overline{K}^*(892)$ + c.c.	seen

$f_1(1510)$ REFERENCES

ASTON	88C	PL B201 573	+Awaji, Bienz+	(SLAC, NAGO, CINC, TOKY) JP
BIRMAN	88	PRL 61 1557	+Chung, Peaslee+	(BNL, FSU, IND, SMAS) JP
GAVILLET	82	ZPHY C16 119	+Armenteros+	(CERN, CDEF, PADO, ROMA)

$f_2(1520)$

$I^G(J^{PC}) = 0^+(2^{++})$

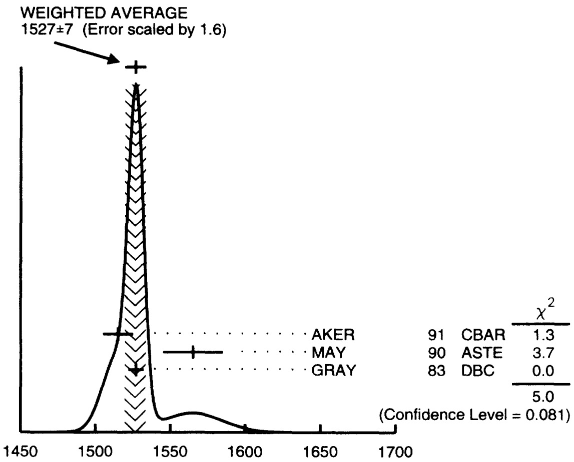
OMITTED FROM SUMMARY TABLE

Seen in antiproton-nucleon annihilation at rest into 3π. See also minireview under non-$q\overline{q}$ candidates.

$f_2(1520)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1527± 7 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.					
1515±10		AKER	91	CBAR		$0.0\ \overline{p} p \rightarrow 3\pi^0$
1565±20		MAY	90	ASTE		$\overline{p} p \rightarrow \pi^+ \pi^- \pi^0$
1527± 5	435 ± 45	[1] GRAY	83	DBC	0	$0.0\ \overline{p} N \rightarrow 3\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1540±15		ADAMO	91	OBLX		$\overline{n} p \rightarrow \pi^+ \pi^+ \pi^-$
1477± 5		BRIDGES	86B	DBC	0	$\overline{p} N \rightarrow 3\pi^- 2\pi^+$

[1] No fit of the Dalitz plot has been made. J=0 is cautiously suggested, but J=2 is not excluded.



$f_2(1520)$ mass (MeV)

$f_2(1520)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
118±10 OUR AVERAGE	Error includes scale factor of 1.1.					
120±10		AKER	91	CBAR		$0.0\ \overline{p} p \rightarrow 3\pi^0$
170±40		MAY	90	ASTE		$\overline{p} p \rightarrow \pi^+ \pi^- \pi^0$
101±19	435 ± 45	[2,3] GRAY	83	DBC	0	$0.0\ \overline{p} N \rightarrow 3\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
132±37		ADAMO	91	OBLX		$\overline{n} p \rightarrow \pi^+ \pi^+ \pi^-$
116± 9		BRIDGES	86B	DBC	0	$\overline{p} N \rightarrow 3\pi^- 2\pi^+$

[2] No fit of the Dalitz plot has been made.
[3] Width error enlarged by us to $4\Gamma/N^{1/2}$.

$f_2(1520)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi^+ \pi^-$	seen
Γ_2	$\rho^0 \rho^0$	
Γ_3	$\pi^0 \pi^0$	

$f_2(1520)$ BRANCHING RATIOS

$\Gamma(\pi^+ \pi^-)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	MAY	89	ASTE		$\overline{p} p \rightarrow \pi^+ \pi^- \pi^0$
seen	GRAY	83	DBC	0	$0.0\ \overline{p} N \rightarrow 3\pi$

$\Gamma(\pi^+ \pi^-)/\Gamma(\rho^0 \rho^0)$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.042±0.013	BRIDGES	86B	DBC	0	$\overline{p} N \rightarrow 3\pi^- 2\pi^+$

$\Gamma(\pi^0 \pi^0)/\Gamma_{total}$ Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	AKER	91	CBAR	$0.0\ \overline{p} p \rightarrow 3\pi^0$

$f_2(1520)$ REFERENCES

ADAMO	91	Hadron 91 Conf.	+Agnello, Balestra+	(OBELIX Collab.)
AKER	91	PL B260 249	+Amsler, Peters+	(CBAR Collab.)
MAY	90	ZPHY C46 203	+Duch, Heel+	(ASTERIX Collab.)
MAY	89	PL B225 450	+Duch, Heel+	(ASTERIX Collab.) IJP
BRIDGES	86B	PRL 56 215	+Daftari, Kalogeropoulos, Debbe+	(SYRA, CASE)
GRAY	83	PR D27 307	+Kalogeropoulos, Nandy, Roy, Zenone	(SYRA)

$f_0(1525)$

$I^G(J^{PC}) = 0^+(0^{++})$

OMITTED FROM SUMMARY TABLE

This entry contains evidence for $K\overline{K}$ S-wave intensity peaking at the mass of the $f_2'(1525)$ and with a comparable width. Needs confirmation.

$f_0(1525)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1525 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 1525	ASTON	88D	LASS	11 $K^- p \to K^0_S K^0_S \Lambda$
~ 1525	BAUBILLIER	83		8 $K^- p \to K^+ K^- \Lambda$

$f_0(1525)$ WIDTH

VALUE (MeV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 90	BAUBILLIER	83	8 $K^- p \to K^+ K^- \Lambda$

$f_0(1525)$ REFERENCES

ASTON	88D	NP B301 525	+Awaji, Bienz+	(SLAC, NAGO, CINC, TOKY)
BAUBILLIER	83	ZPHY C17 309	+	(BIRM, CERN, GLAS, MSU, LPNP)

$f_2'(1525)$
was $f'(1525)$

$I^G(J^{PC}) = 0^+(2^{++})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$f_2'(1525)$ MASS

VALUE (MeV)	DOCUMENT ID
1525±5 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

PRODUCED BY PION BEAM

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1547.0^{+10.0}_{-2.0}$		[1] LONGACRE	86	MPS	22 $\pi^- p \to K^0_S K^0_S n$
1496.0^{+9}_{-8}		[2] CHABAUD	81	ASPK	6 $\pi^- p \to K^+ K^- n$
1497.0^{+8}_{-9}		CHABAUD	81	ASPK	18.4 $\pi^- p \to K^+ K^- n$
1492.0±29.0		GORLICH	80	ASPK	17 $\pi^- p$ polarized $\to K^+ K^- n$
1502.0±25.0		[3] CORDEN	79	OMEG	12–15 $\pi^- p \to \pi^+ \pi^- n$
1480.0	14	CRENNELL	66	HBC	6.0 $\pi^- p \to K^0_S K^0_S n$

PRODUCED BY $K^\pm$ BEAM

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1524.5±1.4 OUR AVERAGE	Includes data from the datablock that follows this one. Error includes scale factor of 1.1.				
1526.8±4.3		ASTON	88D	LASS	11 $K^- p \to K^0_S K^0_S \Lambda$
1529.0±3.0		ARMSTRONG	83B	OMEG	18.5 $K^- p \to K^- K^+ \Lambda$
1521.0±6.0	650	AGUILAR-...	81B	HBC	4.2 $K^- p \to \Lambda K^+ K^-$
1521.0±3.0	572	ALHARRAN	81	HBC	8.25 $K^- p \to \Lambda K \overline{K}$
1522.0±6.0	123	BARREIRO	77	HBC	4.15 $K^- p \to \Lambda K^0_S K^0_S$
1528 ±7	166	EVANGELISTA	77	OMEG	10 $K^- p \to K^+ K^- (\Lambda,\Sigma)$
1527.0±3.0	120	BRANDENB...	76C	ASPK	13 $K^- p \to K^+ K^- (\Lambda,\Sigma)$
1519 ±7	100	AGUILAR-...	72B	HBC	3.9,4.6 $K^- p \to K\overline{K}(\Lambda,\Sigma)$

PRODUCED IN e^+e^- ANNIHILATION

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1519 ± 5 OUR AVERAGE	Error includes scale factor of 1.1.			
1531.6±10.0	AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+ K^-$
1515 ± 5	[4] FALVARD	88	DM2	$J/\psi \to \phi K^+ K^-$
1525 ±10 ±10	BALTRUSAIT...	87	MRK3	$J/\psi \to \gamma K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1496 ± 2	[5] FALVARD	88	DM2	$J/\psi \to \phi K^+ K^-$

[1] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.
[2] CHABAUD 81 is a reanalysis of PAWLICKI 77 data.
[3] From an amplitude analysis where the $f_2'(1525)$ width and elasticity are in complete disagreement with the values obtained from $K\overline{K}$ channel, making the solution dubious.
[4] From an analysis ignoring interference with $f_0(1710)$.
[5] From an analysis including interference with $f_0(1710)$.

$f_2'(1525)$ WIDTH

VALUE (MeV)	DOCUMENT ID		COMMENT
76±10 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.		
85± 5 OUR FIT			
76±10	PDG	90	For fitting

PRODUCED BY PION BEAM

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$108.0^{+5.0}_{-2.0}$	[6] LONGACRE	86	MPS	22 $\pi^- p \to K^0_S K^0_S n$
69.0^{+22}_{-16}	[7] CHABAUD	81	ASPK	6 $\pi^- p \to K^+ K^- n$
137.0^{+23}_{-21}	CHABAUD	81	ASPK	18.4 $\pi^- p \to K^+ K^- n$
$150.0^{+83.0}_{-50.0}$	GORLICH	80	ASPK	17 $\pi^- p$ polarized $\to K^+ K^- n$
165.0±42.0	[8] CORDEN	79	OMEG	12–15 $\pi^- p \to \pi^+ \pi^- n$
$92.0^{+39.0}_{-22.0}$	[9] POLYCHRO...	79	STRC	7 $\pi^- p \to n K^0_S K^0_S$

PRODUCED BY $K^\pm$ BEAM

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
78 ± 5 OUR AVERAGE	Includes data from the datablock that follows this one.				
90.2±11.8		ASTON	88D	LASS	11 $K^- p \to K^0_S K^0_S \Lambda$
83.0±15.0		ARMSTRONG	83B	OMEG	18.5 $K^- p \to K^- K^+ \Lambda$
85.0±16.0	650	AGUILAR-...	81B	HBC	4.2 $K^- p \to \Lambda K^+ K^-$
$80.0^{+14.0}_{-11.0}$	572	ALHARRAN	81	HBC	8.25 $K^- p \to \Lambda K\overline{K}$
72.0±25.0	166	EVANGELISTA	77	OMEG	10 $K^- p \to K^+ K^- (\Lambda,\Sigma)$
69 ±22	100	AGUILAR-...	72B	HBC	3.9,4.6 $K^- p \to K\overline{K}(\Lambda,\Sigma)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$62.0^{+19.0}_{-14.0}$	123	BARREIRO	77	HBC	4.15 $K^- p \to \Lambda K^0_S K^0_S$
61.0± 8.0	120	BRANDENB...	76C	ASPK	13 $K^- p \to K^+ K^- (\Lambda,\Sigma)$

PRODUCED IN e^+e^- ANNIHILATION

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
67 ± 9 OUR AVERAGE				
102.6±29.7	AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+ K^-$
62 ±10	[10] FALVARD	88	DM2	$J/\psi \to \phi K^+ K^-$
85 ±35	BALTRUSAIT...	87	MRK3	$J/\psi \to \gamma K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
100 ± 3	[11] FALVARD	88	DM2	$J/\psi \to \phi K^+ K^-$

[6] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.
[7] CHABAUD 81 is a reanalysis of PAWLICKI 77 data.
[8] From an amplitude analysis where the $f_2'(1525)$ width and elasticity are in complete disagreement with the values obtained from $K\overline{K}$ channel, making the solution dubious.
[9] From a fit to the D with $f_2(1270)$-$f_2'(1525)$ interference. Mass fixed at 1516 MeV.
[10] From an analysis ignoring interference with $f_0(1710)$.
[11] From an analysis including interference with $f_0(1710)$.

$f_2'(1525)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}$	$(71.2\ ^{+2.0}_{-2.5})$ %
Γ_2	$\eta\eta$	$(27.9\ ^{+2.5}_{-2.0})$ %
Γ_3	$\pi\pi$	$(8.2 \pm 1.6) \times 10^{-3}$
Γ_4	$\gamma\gamma$	$(1.23 \pm 0.22) \times 10^{-6}$
Γ_5	$K\overline{K}^*(892)$ + c.c.	
Γ_6	$\pi\pi\eta$	
Γ_7	$\pi K\overline{K}$	
Γ_8	$\pi^+\pi^+\pi^-\pi^-$	

CONSTRAINED FIT INFORMATION

An overall fit to the total width, 4 partial widths, a combination of partial widths obtained from integrated cross sections, and 2 branching ratios uses 13 measurements and one constraint to determine 5 parameters. The overall fit has a $\chi^2 = 10.0$ for 9 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta p_i \delta p_j\right\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−100			
x_3	−6	−2		
x_4	−29	29	0	
Γ	61	−61	2	−39
	x_1	x_2	x_3	x_4

	Mode	Rate (MeV)
Γ_1	$K\overline{K}$	61 ± 5
Γ_2	$\eta\eta$	$23.9\ ^{+2.2}_{-1.2}$
Γ_3	$\pi\pi$	0.70 ± 0.14
Γ_4	$\gamma\gamma$	$(1.05 \pm 0.17) \times 10^{-4}$

$f_2'(1525)$ PARTIAL WIDTHS

$\Gamma(K\overline{K})$ — Γ_1

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
61 ±5 OUR FIT				
$\mathbf{63.0^{+6.0}_{-5.0}}$	[12] LONGACRE	86	MPS	$22\ \pi^- p \to K^0_S K^0_S n$

$\Gamma(\pi\pi)$ — Γ_3

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0.70±0.14 OUR FIT				
$\mathbf{1.4\ ^{+1.0}_{-0.5}}$	[12] LONGACRE	86	MPS	$22\ \pi^- p \to K^0_S K^0_S n$

$\Gamma(\eta\eta)$ — Γ_2

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$\mathbf{23.9^{+2.2}_{-1.2}}$ **OUR FIT**				
$\mathbf{24.0^{+3.0}_{-1.0}}$	[12] LONGACRE	86	MPS	$22\ \pi^- p \to K^0_S K^0_S n$

$\Gamma(\gamma\gamma)$ — Γ_4

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.105±0.017 OUR FIT				
$\mathbf{0.107^{+0.029}_{-0.022}}$ **OUR AVERAGE**				
$0.11\ ^{+0.03}_{-0.02} \pm 0.02$	BEHREND	89C	CELL	$e^+e^- \to e^+e^- K^0_S K^0_S$
$0.10\ ^{+0.04}_{-0.03}\ ^{+0.03}_{-0.02}$	BERGER	88	PLUT	$e^+e^- \to e^+e^- K^0_S K^0_S$

[12] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.

$f_2'(1525)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{\rm total}$ — $\Gamma_1\Gamma_4/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.075 ±0.012 OUR FIT				
0.074 ±0.016 OUR AVERAGE				
0.067 ±0.008 ±0.015	[13] ALBRECHT	90G	ARG	$e^+e^- \to e^+e^- K^+K^-$
0.12 ±0.07 ±0.04	[13] AIHARA	86B	TPC	$e^+e^- \to e^+e^- K^+K^-$
0.11 ±0.02 ±0.04	[13] ALTHOFF	83	TASS	$e^+e^- \to e^+e^- K\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0314±0.0050±0.0077	[14] ALBRECHT	90G	ARG	$e^+e^- \to e^+e^- K^+K^-$

[13] Using an incoherent background.
[14] Using a coherent background.

$f_2'(1525)$ BRANCHING RATIOS

$\Gamma(\eta\eta)/\Gamma(K\overline{K})$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.39^{+0.05}_{-0.04}}$ **OUR FIT**				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.11±0.04	[15] PROKOSHKIN	91	GAM4	$300\ \pi^- p \to \pi^- p \eta\eta$
<0.50	BARNES	67	HBC	$4.6,5.0\ K^- p$

[15] Combining results of GAM4 with those of WA76 on $K\overline{K}$ central production and results of CBAL, MRK3 and DM2 on $J/\psi \to \gamma\eta\eta$.

$\Gamma(\pi\pi)/\Gamma_{\rm total}$ — Γ_3/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.0082±0.0016 OUR FIT					
0.0075±0.0016 OUR AVERAGE					
0.007 ±0.002		COSTA...	80	OMEG	$10\ \pi^- p \to K^+K^- n$
$0.027\ ^{+0.071}_{-0.013}$		[16] GORLICH	80	ASPK	$17,18\ \pi^- p$
0.0075±0.0025		[16,17] MARTIN	79	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.06	95	AGUILAR-...	81B	HBC	$4.2\ K^- p \to \Lambda K^+ K^-$
0.19 ±0.03		CORDEN	79	OMEG	$12\text{–}15\ \pi^- p \to \pi^+\pi^- n$
<0.045	95	BARREIRO	77	HBC	$4.15\ K^- p \to \Lambda K^0_S K^0_S$
0.012 ±0.004		[16] PAWLICKI	77	SPEC	$6\ \pi N \to K^+K^- N$
<0.063	90	BRANDENB...	76C	ASPK	$13\ K^- p \to K^+K^-(\Lambda,\Sigma)$
<0.0086		[16] BEUSCH	75B	OSPK	$8.9\ \pi^- p \to K^0 \overline{K}{}^0 n$

[16] Assuming that the $f_2'(1525)$ is produced by an one-pion exchange production mechanism.
[17] MARTIN 79 uses the PAWLICKI 77 data with different input value of the $f_2'(1525) \to K\overline{K}$ branching ratio.

$\Gamma(\pi\pi)/\Gamma(K\overline{K})$ — Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.0115±0.0022 OUR FIT				
0.075 ±0.035	AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$

$\Gamma(\pi\pi\eta)/\Gamma(K\overline{K})$ — Γ_6/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.41	95	AGUILAR-...	72B	HBC	$3.9,4.6\ K^- p$
<0.3	67	AMMAR	67	HBC	

$\left[\Gamma(K\overline{K}^*(892) + \text{c.c.}) + \Gamma(\pi K\overline{K})\right]/\Gamma(K\overline{K})$ — $(\Gamma_5+\Gamma_7)/\Gamma_1$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.35	95	AGUILAR-...	72B	HBC	$3.9,4.6\ K^- p$
<0.4	67	AMMAR	67	HBC	

$\Gamma(\pi^+\pi^+\pi^-\pi^-)/\Gamma(K\overline{K})$ — Γ_8/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.32	95	AGUILAR-...	72B	HBC	$3.9,4.6\ K^- p$

$\Gamma(\eta\eta)/\Gamma_{\rm total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10 ±0.03	[18] PROKOSHKIN	91	GAM4	$300\ \pi^- p \to \pi^- p \eta\eta$

[18] Combining results of GAM4 with those of WA76 on $K\overline{K}$ central production and results of CBAL, MRK3 and DM2 on $J/\psi \to \gamma\eta\eta$.

$f_2'(1525)$ REFERENCES

PROKOSHKIN	91	Singapore Conf. Translated from SPD 36 155.		(GAM2 Collab.)
ALBRECHT	90G	ZPHY C48 183	+Ehrlichmann, Harder+	(ARGUS Collab.)
PDG	90	PL B239	Hernandez, Stone, Porter+	(IFIC, BOST, CIT+)
BEHREND	89C	ZPHY C43 91	+Criegee, Dainton+	(CELLO Collab.)
ASTON	88D	NP B301 525	+Awaji, Bienz+	(SLAC, NAGO, CINC, TOKY)
AUGUSTIN	88	PRL 60 2238	+Calcaterra+	(DM2 Collab.)
BERGER	88	ZPHY C37 329	+Genzel, Lackas+	(PLUTO Collab.)
FALVARD	88	PR D38 2706	+Ajaltouni+	(CLER, FRAS, LALO, PADO)
AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
BALTRUSAIT...	87	PR D35 2077	Baltrusaitis, Coffman, Dubois+	(Mark III Collab.)
AIHARA	86B	PRL 57 404	+Alston-Garnjost+	(TPC-2γ Collab.)
LONGACRE	86	PL B177 223	+Etkin+	(BNL, BRAN, CUNY, DUKE, NDAM)
ALTHOFF	83	PL 121B 216	+Brandelik, Boerner, Burkhardt+	(TASSO Collab.)
ARMSTRONG	83B	NP B224 193	+	(BARI, BIRM, CERN, MILA, LPNP, PAVI)
AGUILAR-...	81B	ZPHY C8 313	Aguilar-Benitez, Albajar+	(CERN, CDEF, MADR+)
ALHARRAN	81	NP B191 26	+Baubillier+	(BIRM, CERN, GLAS, MICH, LPNP)
CHABAUD	81	APP B12 575	+Niczyporuk, Becker+	(CERN, CRAC, MPIM)
COSTA...	80	NP B175 402	Costa De Beauregard+	(BARI, BONN, CERN+)
GORLICH	80	NP B174 16	+Niczyporuk+	(CRAC, MPIM, CERN, ZEEM)
CORDEN	79	NP B157 250	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC) JP
MARTIN	79	NP B158 520	+Ozmutlu	(DURH)
POLYCHRO...	79	PR D19 1317	Polychronakos, Cason, Bishop+	(NDAM, ANL)
BARREIRO	77	NP B121 237	+Diaz, Gay, Hemingway+	(CERN, AMST, NIJM, OXF)
EVANGELISTA	77	NP B127 384	+	(BARI, BONN, CERN, DARE, GLAS+)
PAWLICKI	77	PR D15 3196	+Ayres, Cohen, Diebold, Kramer, Wicklund	(ANL) IJP
BRANDENB...	76C	NP B104 413	Brandenburg, Carnegie, Cashmore+	(SLAC)
BEUSCH	75B	PL 60B 101	+Birman, Websdale, Wetzel	(CERN, ETH)
AGUILAR-...	72B	PR D6 29	Aguilar-Benitez, Chung, Eisner, Samios	(BNL)
AMMAR	67	PRL 19 1071	+Davis, Hwang, Dagan, Derrick+	(NWES, ANL) JP
BARNES	67	PRL 19 964	+Dornan, Goldberg, Leitner+	(BNL, SYRA) IJPC
CRENNELL	66	PRL 16 1025	+Kalbfleisch, Lai, Scarr, Schumann+	(BNL) I

OTHER RELATED PAPERS

JENNI	83	PR D27 1031	+Burke, Telnov, Abrams, Blocker+	(SLAC, LBL)
ARMSTRONG	82	PL 110B 77	+Baubillier+	(BARI, BIRM, CERN, MILA, LPNP+)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFT, VAND)
LUKE	82	DESY 82/073		(DESY)
ABRAMS	67B	PRL 18 620	+Kehoe, Glasser, Sechi-Zorn, Wolsky	(UMD)
BARNES	65	PRL 15 322	+Culwick, Guidoni, Kalbfleisch, Goz+	(BNL, SYRA)

$f_0(1590)$

$I^G(J^{PC}) = 0^+(0^{++})$

See also the mini-review under non-$q\bar{q}$ candidates. (See the index for the page number.)

$f_0(1590)$ MASS

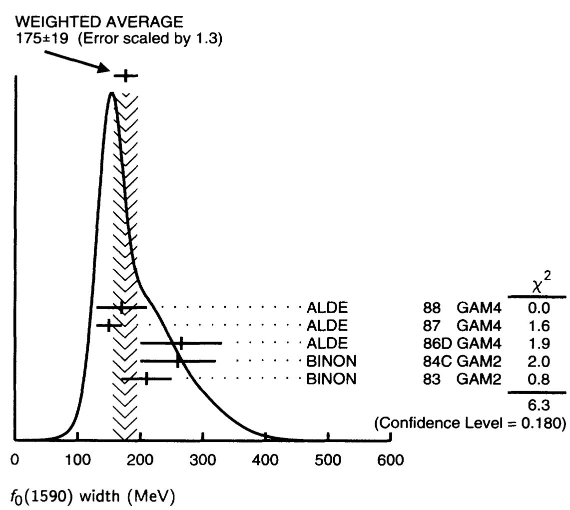
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1587 ±11	**OUR AVERAGE**				
1610 ±20		ALDE	88	GAM4	$300\ \pi^- N \to \pi^- N 2\eta$
1570 ±20	600 ± 70	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$
1575.0±45.0		[1] ALDE	86D	GAM4	$100\ \pi^- p \to 2\eta n$
1568.0±33.0		BINON	84C	GAM2	$38\ \pi^- p \to \eta\eta' n$
1592.0±25.0		BINON	83	GAM2	$38\ \pi^- p \to 2\eta n$

[1] From central value and spread of two solutions.

$f_0(1590)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
175 ±19	**OUR AVERAGE**	Error includes scale factor of 1.3. See the ideogram below.			
170 ±40		ALDE	88	GAM4	$300\ \pi^- N \to \pi^- N 2\eta$
150 ±20	600 ± 70	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$
265.0±65.0		[2] ALDE	86D	GAM4	$100\ \pi^- p \to 2\eta n$
260.0±60.0		BINON	84C	GAM2	$38\ \pi^- p \to \eta\eta' n$
210.0±40.0		BINON	83	GAM2	$38\ \pi^- p \to 2\eta n$

[2] From central value and spread of two solutions.



$f_0(1590)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\eta'(958)$	dominant
Γ_2	$\eta\eta$	large
Γ_3	$4\pi^0$	large
Γ_4	$\pi^0\pi^0$	
Γ_5	$K\bar{K}$	

$f_0(1590)$ BRANCHING RATIOS

$\Gamma(\eta\eta'(958))/\Gamma(\eta\eta)$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
2.7±0.8	BINON	84C	GAM2	$38\ \pi^- p \to \eta\eta' n$

$\Gamma(\eta\eta)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
large	ALDE	88	GAM4	$300\ \pi^- N \to \eta\eta\pi^- N$
large	BINON	83	GAM2	$38\ \pi^- p \to 2\eta n$

$\Gamma(4\pi^0)/\Gamma(\eta\eta)$ Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.8 ±0.3	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$

$\Gamma(\pi^0\pi^0)/\Gamma(\eta\eta)$ Γ_4/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.17	90	PROKOSHKIN	90	GAM4	$300\ \pi^- p \to \pi^- 2\pi^0 p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.3		[3] BINON	83	GAM2	$38\ \pi^- p \to 2\eta n$

[3] Superseded by PROKOSHKIN 90.

$\Gamma(K\bar{K})/\Gamma(\eta\eta)$ Γ_5/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.6		BINON	83	GAM2	$38\ \pi^- p \to 2\eta n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.4	90	[4] PROKOSHKIN	91	GAM4	$300\ \pi^- p \to \pi^- p\eta\eta$

[4] Combining results of GAM4 with those of WA76 on $K\bar{K}$ central production.

$f_0(1590)$ REFERENCES

PROKOSHKIN	91	Singapore Conf. Translated from SPD 36 155.		(GAM2 Collab.)
PROKOSHKIN	90	Hadron 89 Conf. p 27		(SERP, BELG, LANL, LAPP, PISA, KEK)
ALDE	88	PL B201 160	+Bellazzini, Binon+	(SERP, BELG, LANL, LAPP, PISA) JP
ALDE	87	PL B198 286	+Binon, Bricman+	(LANL, BRUX, SERP, LAPP)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN) IGJP
BINON	84C	NC 80A 363	+Bricman, Donskov+	(BELG, LAPP, SERP, CERN)
BINON	83	NC 78A 313	+Donskov, Duteil+	(BELG, LAPP, SERP, CERN) IGJP
Also	83B	SJNP 38 561	Binon, Gouanere+	(BELG, LAPP, SERP, CERN)

OTHER RELATED PAPERS

SLAUGHTER	88	MPL A3 1361	(LANL)

$\omega(1600)$

$I^G(J^{PC}) = 0^-(1^{--})$

See also $\omega(1390)$.

$\omega(1600)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1594 ±12		DONNACHIE	89	RVUE		$e^+e^- \to \rho\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1625 ±25		GOVORKOV	88	RVUE		
1670 ±20		ATKINSON	83B	OMEG		$20\text{–}70\ \gamma p \to 3\pi X$
1657 ±13		CORDIER	81	DM1		$e^+e^- \to \omega 2\pi$
1679 ±34	21	ESPOSITO	80	FRAM		$e^+e^- \to 3\pi$
1652.0±17.0		COSME	79	OSPK	0	$e^+e^- \to 3\pi$

$\omega(1600)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
100 ±30		DONNACHIE	89	RVUE		$e^+e^- \to \rho\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
250 ±25		GOVORKOV	88	RVUE		
160 ±20		ATKINSON	83B	OMEG		$20\text{–}70\ \gamma p \to 3\pi X$
136 ±46		CORDIER	81	DM1		$e^+e^- \to \omega 2\pi$
99 ±49	21	ESPOSITO	80	FRAM		$e^+e^- \to 3\pi$
42.0±17.0		COSME	79	OSPK	0	$e^+e^- \to 3\pi$

$\omega(1600)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen
Γ_2	$\omega\pi\pi$	seen
Γ_3	e^+e^-	seen

$\omega(1600)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(\rho\pi) \times \Gamma(e^+e^-)/\Gamma_{total}$ $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
96±35	DONNACHIE	89	RVUE	$e^+e^- \to \rho\pi$

$\Gamma(\omega\pi\pi) \times \Gamma(e^+e^-)/\Gamma_{total}$ $\Gamma_2\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
56±31	DONNACHIE	89	RVUE	$e^+e^- \to \omega 2\pi$

$\omega(1600)$ REFERENCES

DONNACHIE 89 ZPHY C42 663 +Clegg (CERN, MCHS)
GOVORKOV 88 SJNP 48 150 (JINR)
Translated from YAF 48 237.
ATKINSON 83B PL 127B 132 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
CORDIER 81 PL 106B 155 +Bisello, Bizot, Buon, Delcourt, Mane (ORSA)
ESPOSITO 80 LNC 28 195 +Marini, Patteri+ (FRAS, NAPL, PADO, ROMA)
COSME 79 NP B152 215 +Dudelzak, Grelaud, Jean-Marie, Jullian+ (IPN)

OTHER RELATED PAPERS

ATKINSON 87 ZPHY C34 157 + (BONN, CERN, GLAS, LANC, MCHS, LPNP)
ATKINSON 84 NP B231 15 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)

$X(1600)$

$I^G(J^{PC}) = 2^+(2^{++})$

OMITTED FROM SUMMARY TABLE

Observed in the reaction $\gamma\gamma \rightarrow \rho^0\rho^0$ near threshold. The large ratio of cross-sections $\sigma(\gamma\gamma \rightarrow \rho^0\rho^0) / \sigma(\gamma\gamma \rightarrow \rho^+\rho^-) \approx 4$ and the dominance of the $J^P = 2^+$ wave in the reaction $\gamma\gamma \rightarrow \rho^0\rho^0$ is a signature consistent with the production of an exotic ($I = 2$) resonance. Needs confirmation.

$X(1600)$ MASS

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
1600±100	[1] ALBRECHT	91F	ARG	0	$10.2\ e^+e^- \rightarrow e^+e^-2(\pi^+\pi^-)$

[1] Our estimate.

$X(1600)$ WIDTH

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
400±200	[2] ALBRECHT	91F	ARG	0	$10.2\ e^+e^- \rightarrow e^+e^-2(\pi^+\pi^-)$

[2] Our estimate.

$X(1600)$ REFERENCES

ALBRECHT 91F ZPHY C50 1 +Appuan, Paulini, Funk+ (ARGUS Collab.)

OTHER RELATED PAPERS

ALBRECHT 89M PL B217 205 +Bockmann+ (ARGUS Collab.)
BEHREND 89D PL B218 494 +Criegee+ (CELLO Collab.)

$f_2(1640)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

Seen by ALDE 89B in $\omega\omega$ mass distribution. Needs confirmation.

$f_2(1640)$ MASS

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
1635±7		[1] ALDE	90	GAM2	$38\ \pi^- p \rightarrow n\omega\omega$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1647±7		ADAMO	91	OBLX	$\bar{n}p \rightarrow 3\pi^+2\pi^-$
1643±7	90	ALDE	89B	GAM2	$38\ \pi^- p \rightarrow n\omega\omega$

[1] This result supersedes ALDE 89B.

$f_2(1640)$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
<70	90	ALDE	89B	GAM2	$38\ \pi^- p \rightarrow n\omega\omega$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
58±20		ADAMO	91	OBLX	$\bar{n}p \rightarrow 3\pi^+2\pi^-$

$f_2(1640)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\omega\omega$	seen

$f_2(1640)$ BRANCHING RATIOS

$\Gamma(\omega\omega)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	ALDE	89B	GAM2	$38\ \pi^- p \rightarrow n\omega\omega$

$f_2(1640)$ REFERENCES

ADAMO 91 Hadron 91 Conf. +Agnello, Balestra+ (OBELIX Collab.)
ALDE 90 PL B241 600 +Binon+ (SERP, BELG, LANL, LAPP, PISA, KEK)
ALDE 89B PL B216 451 +Binon, Bricman+ (SERP, BELG, LANL, LAPP, TBIL) IGJPC

$X(1650)$

$I^G(J^{PC}) = 1^-(?^{??})$

OMITTED FROM SUMMARY TABLE

$X(1650)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1650±50	BOUTEMEUR	90	GAM4	$100\ \pi^- p \rightarrow 4\gamma n$

$X(1650)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
150±50	BOUTEMEUR	90	GAM4	$100\ \pi^- p \rightarrow 4\gamma n$

$X(1650)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta'\pi^0$	seen

$X(1650)$ REFERENCES

BOUTEMEUR 90 Hadron 89 Conf. p 119+Poulet (SERP, BELG, LANL, LAPP, PISA, KEK)

$\omega_3(1670)$

$I^G(J^{PC}) = 0^-(3^{--})$

$\omega_3(1670)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1668 ± 5 OUR AVERAGE					
1685.0±20.0	60	BAUBILLIER	79	HBC	$8.2\ K^- p$ backward
1673.0±12.0	430	[1,2] BALTAY	78E	HBC	$15\ \pi^+ p \rightarrow \Delta 3\pi$
1650.0±12.0		CORDEN	78B	OMEG	$8–12\ \pi^- p \rightarrow N3\pi$
1669 ±11	600	[2] WAGNER	75	HBC	$7\ \pi^+ p \rightarrow \Delta^{++}3\pi$
1678 ±14	500	DIAZ	74	DBC	$6\ \pi^+ n \rightarrow p3\pi^0$
1660 ±13	200	DIAZ	74	DBC	$6\ \pi^+ n \rightarrow p\omega\pi^0\pi^0$
1679 ±17	200	MATTHEWS	71D	DBC	$7.0\ \pi^+ n \rightarrow p3\pi^0$
1670 ±20		KENYON	69	DBC	$8\ \pi^+ n \rightarrow p3\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1700.0	110	[1] CERRADA	77B	HBC	$4.2\ K^- p \rightarrow \Lambda 3\pi$
1695.0±20.0		BARNES	69B	HBC	$4.6\ K^- p \rightarrow \omega 2\pi$ X
1636 ±20		ARMENISE	68B	DBC	$5.1\ \pi^+ n \rightarrow p3\pi^0$

[1] Phase rotation seen for $J^P = 3^-$ $\rho\pi$ wave.
[2] From a fit to $I(J^P) = 0(3^-)$ $\rho\pi$ partial wave.

$\omega_3(1670)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
166 ±15 OUR ESTIMATE		This is only an educated guess; the error given is larger than the error on the average of the published values.			
173 ±11 OUR AVERAGE					
160.0±80.0	60	[3] BAUBILLIER	79	HBC	$8.2\ K^- p$ backward
173.0±16.0	430	[4,5] BALTAY	78E	HBC	$15\ \pi^+ p \rightarrow \Delta 3\pi$
253.0±39.0		CORDEN	78B	OMEG	$8–12\ \pi^- p \rightarrow N3\pi$
173 ±28	600	[3,5] WAGNER	75	HBC	$7\ \pi^+ p \rightarrow \Delta^{++}3\pi$
167 ±40	500	DIAZ	74	DBC	$6\ \pi^+ n \rightarrow p3\pi^0$
122 ±39	200	DIAZ	74	DBC	$6\ \pi^+ n \rightarrow p\omega\pi^0\pi^0$
155 ±40	200	[3] MATTHEWS	71D	DBC	$7.0\ \pi^+ n \rightarrow p3\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
90 ±20		BARNES	69B	HBC	$4.6\ K^- p \rightarrow \omega 2\pi$
100 ±40		KENYON	69	DBC	$8\ \pi^+ n \rightarrow p3\pi^0$
112 ±60		ARMENISE	68B	DBC	$5.1\ \pi^+ n \rightarrow p3\pi^0$

[3] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[4] Phase rotation seen for $J^P = 3^-$ $\rho\pi$ wave.
[5] From a fit to $I(J^P) = 0(3^-)$ $\rho\pi$ partial wave.

$\omega_3(1670)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen
Γ_2	$\omega\pi\pi$	seen
Γ_3	$b_1(1235)\pi$	possibly seen

$\omega_3(1670)$ BRANCHING RATIOS

$\Gamma(\omega\pi\pi)/\Gamma(\rho\pi)$ Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.71 ± 0.27	100	DIAZ	74	DBC	$6\ \pi^+ n \rightarrow p5\pi^0$

$\Gamma(b_1(1235)\pi)/\Gamma(\rho\pi)$ Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
possibly seen	DIAZ	74	DBC	$6\ \pi^+ n \rightarrow p5\pi^0$

$\Gamma(b_1(1235)\pi)/\Gamma(\omega\pi\pi)$ Γ_3/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.75	68	BAUBILLIER	79	HBC	$8.2\ K^- p$ backward

$\omega_3(1670)$ REFERENCES

BAUBILLIER	79	PL 89B 131	+	(BIRM, CERN, GLAS, MSU, LPNP)
BALTAY	78E	PRL 40 87	+Cautis, Kalelkar	(COLU) JP
CORDEN	78B	NP B138 235	+Corbett, Alexander+	(BIRM, RHEL, TELA, LOWC)
CERRADA	77B	NP B126 241	+Blockzijl, Heinen+	(AMST, CERN, NIJM, OXF) JP
WAGNER	75	PL 58B 201	+Tabak, Chew	(LBL) JP
DIAZ	74	PRL 32 260	+Dibianca, Fickinger, Anderson+	(CASE, CMU)
MATTHEWS	71D	PR D3 2561	+Prentice, Yoon, Carroll+	(TNTO, WISC)
BARNES	69B	PRL 23 142	+Chung, Eisner, Flaminio+	(BNL)
KENYON	69	PRL 23 146	+Kinson, Scarr+	(BNL, UCND, ORNL)
ARMENISE	68B	PL 26B 336	+Forino, Cartacci+	(BARI, BGNA, FIRZ, ORSA)

OTHER RELATED PAPERS

MATTHEWS	71	LNC 1 361	+Prentice, Yoon, Carroll+	(TNTO, WISC)
ARMENISE	70	LNC 4 199	+Ghidini, Foring, Cartacci+	(BARI, BGNA, FIRZ)

$\pi_2(1670)$ was $A_3(1680)$

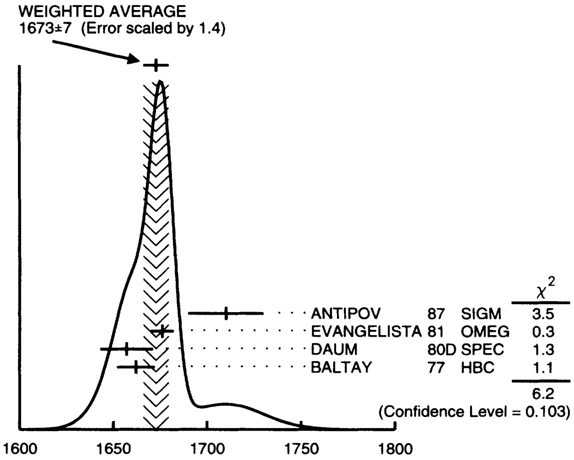
$I^G(J^{PC}) = 1^-(2^{-+})$

Our latest mini-review on this particle can be found in the 1984 edition.

$\pi_2(1670)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1670 ±20	**OUR ESTIMATE**	This is only an educated guess; the error given is larger than the error on the average of the published values.				
1673 ± 7	**OUR AVERAGE**	Error includes scale factor of 1.4. See the ideogram below.				
1710 ±20	700 ± 150	ANTIPOV	87	SIGM	−	$50\ \pi^- \mathrm{Cu} \rightarrow \mu^+\mu^-\pi^- \mathrm{Cu}$
1676 ± 6		[1] EVANGELISTA	81	OMEG	−	$12\ \pi^- p \rightarrow 3\pi p$
1657.0±14.0		[1,2] DAUM	80D	SPEC	−	$63–94\ \pi p \rightarrow 3\pi X$
1662.0±10.0	2000	[1] BALTAY	77	HBC	+	$15\ \pi^+ p \rightarrow p3\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1742 ±31 ±49		ANTREASYAN	90	CBAL		$e^+e^- \rightarrow e^+e^-\pi^0\pi^0\pi^0$
1710.0±20.0		[3] DAUM	81B	SPEC	−	$63,94\ \pi^- p$
1640 ±10	575	KALELKAR	75	HBC	+	$15\ \pi^+ p \rightarrow p\pi^+ f_2$
1660 ±10		[1] ASCOLI	73	HBC	−	$5–25\ \pi^- p \rightarrow p\pi_2$

[1] From a fit to $J^P = 2^-$ S-wave $f_2(1270)\pi$ partial wave.
[2] Clear phase rotation seen in 2^-S, 2^-P, 2^-D waves. We quote central value and spread of single-resonance fits to three channels.
[3] From a two-resonance fit to four 2^-0^+ waves. This should not be averaged with all the single resonance fits.



$\pi_2(1670)$ mass (MeV)

$\pi_2(1670)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
250 ±20	**OUR ESTIMATE**	This is only an educated guess; the error given is larger than the error on the average of the published values.				
240 ±15	**OUR AVERAGE**	Error includes scale factor of 1.1.				
170 ±80	700 ± 150	ANTIPOV	87	SIGM	−	$50\ \pi^- \mathrm{Cu} \rightarrow \mu^+\mu^-\pi^- \mathrm{Cu}$
260 ±20		[4] EVANGELISTA	81	OMEG	−	$12\ \pi^- p \rightarrow 3\pi p$
219.0±20.0		[4,5] DAUM	80D	SPEC	−	$63–94\ \pi p \rightarrow 3\pi X$
285.0±60.0	2000	[4] BALTAY	77	HBC	+	$15\ \pi^+ p \rightarrow p3\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
236 ±49 ±36		ANTREASYAN	90	CBAL		$e^+e^- \rightarrow e^+e^-\pi^0\pi^0\pi^0$
312.0±50.0		[6] DAUM	81B	SPEC	−	$63,94\ \pi^- p$
240 ±30	575	KALELKAR	75	HBC	+	$15\ \pi^+ p \rightarrow p\pi^+ f_2$
270 ±60		[4] ASCOLI	73	HBC	−	$5–25\ \pi^- p \rightarrow p\pi_2$

[4] From a fit to $J^P = 2^-$ $f_2(1270)\pi$ partial wave.
[5] Clear phase rotation seen in 2^-S, 2^-P, 2^-D waves. We quote central value and spread of single-resonance fits to three channels.
[6] From a two-resonance fit to four 2^-0^+ waves. This should not be averaged with all the single resonance fits.

$\pi_2(1670)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$f_2(1270)\pi$	(56.2±3.2) %	
Γ_2	$\rho\pi$	(31 ±4) %	
Γ_3	$f_0(1400)\pi$	(8.7±3.4) %	
Γ_4	$K\overline{K}^*(892)$ + c.c.	(4.2±1.4) %	
Γ_5	$\eta\pi$	< 5 %	90%
Γ_6	$\pi^\pm 2\pi^+ 2\pi^-$	< 5 %	90%
Γ_7	$\pi^\pm\pi^+\pi^-$		
Γ_8	$\gamma\gamma$	(5.4±1.1) × 10^{-3}	

CONSTRAINED FIT INFORMATION

An overall fit to 4 branching ratios uses 6 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 1.9 for 3 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

	x_1	x_2	x_3
x_2	−53		
x_3	−29	−59	
x_4	−8	−21	−9

$\pi_2(1670)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ — Γ_8

VALUE (KeV)	DOCUMENT ID		TECN	CHG	COMMENT
1.35±0.26 OUR AVERAGE					
1.41±0.23±0.28	ANTREASYAN	90	CBAL	0	$e^+e^- \rightarrow e^+e^-\pi^0\pi^0\pi^0$
1.3 ±0.3 ±0.2	[7] BEHREND	90C	CELL	0	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.8 ±0.3 ±0.12	[8] BEHREND	90C	CELL	0	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-\pi^0$

[7] Incoherent Ansatz.
[8] Constructive interference between $f_2(1270)$,$\rho\pi$ and background.

$\pi_2(1670)$ BRANCHING RATIOS

$\Gamma(\rho\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$ — $\frac{1}{2}\Gamma_2/(0.567\Gamma_1+\frac{1}{2}\Gamma_2+0.624\Gamma_3)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.29±0.04 OUR FIT					
0.29±0.05	[9] DAUM	81B	SPEC		63,94 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.3	BARTSCH	68	HBC	+	8 $\pi^+ p \rightarrow 3\pi p$
<0.4	FERBEL	68	RVUE	±	

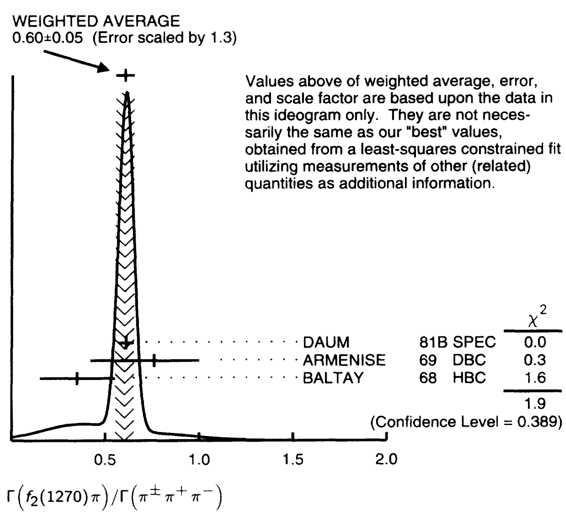
[9] From a two-resonance fit to four 2^-0^+ waves.

$\Gamma(f_2(1270)\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$ — $0.567\Gamma_1/(0.567\Gamma_1+\frac{1}{2}\Gamma_2+0.624\Gamma_3)$

(With $f_2(1270) \rightarrow \pi^+\pi^-$.)

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.604±0.035 OUR FIT					
0.60 ±0.05 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.				
0.61 ±0.04	[10] DAUM	81B	SPEC		63,94 $\pi^- p$
0.76 $^{+0.24}_{-0.34}$	ARMENISE	69	DBC	+	5.1 $\pi^+ d \rightarrow d3\pi$
0.35 ±0.20	BALTAY	68	HBC	+	7–8.5 $\pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.59	BARTSCH	68	HBC	+	8 $\pi^+ p \rightarrow 3\pi p$

[10] From a two-resonance fit to four 2^-0^+ waves.



$\Gamma(\eta\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$ — $\Gamma_5/(0.567\Gamma_1+\frac{1}{2}\Gamma_2+0.624\Gamma_3)$

(All η decays.)

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.09	BALTAY	68	HBC	+	7–8.5 $\pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.10	CRENNELL	70	HBC	−	6 $\pi^- p \rightarrow f_2\pi^- N$

$\Gamma(\pi^\pm 2\pi^+ 2\pi^-)/\Gamma(\pi^\pm\pi^+\pi^-)$ — $\Gamma_6/(0.567\Gamma_1+\frac{1}{2}\Gamma_2+0.624\Gamma_3)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.10	CRENNELL	70	HBC	−	6 $\pi^- p \rightarrow f_2\pi^- N$
<0.1	BALTAY	68	HBC	+	7,8.5 $\pi^+ p$

$\Gamma(f_0(1400)\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$ — $0.624\Gamma_3/(0.567\Gamma_1+\frac{1}{2}\Gamma_2+0.624\Gamma_3)$

(With $f_0(1400) \rightarrow \pi^+\pi^-$.)

VALUE	DOCUMENT ID		TECN	COMMENT
0.10±0.04 OUR FIT				
0.10±0.05	[11] DAUM	81B	SPEC	63,94 $\pi^- p$

[11] From a two-resonance fit to four 2^-0^+ waves.

$\Gamma(K\overline{K}^*(892) + \text{c.c.})/\Gamma(f_2(1270)\pi)$ — Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.075±0.025 OUR FIT					
0.075±0.025	[12] ARMSTRONG	82B	OMEG	−	16 $\pi^- p \rightarrow K^+K^-\pi^- p$

[12] From a partial-wave analysis of $K^+K^-\pi^-$ system.

D-wave/S-wave RATIO FOR $\pi_2(1670) \rightarrow f_2(1270)\pi$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22±0.10	[13] DAUM	81B	SPEC	63,94 $\pi^- p$

[13] From a two-resonance fit to four 2^-0^+ waves.

$\pi_2(1670)$ REFERENCES

ANTREASYAN	90	ZPHY C48 561	+Bartels, Besset+	(Crystal Ball Collab.)
BEHREND	90C	ZPHY C46 583	+Criegee+	(CELLO Collab.)
ANTIPOV	87	EPL 4 403	+Batarin+	(SERP, JINR, INRM, TBIL, BGNA, MILA)
ARMSTRONG	82B	NP B202 1	+Baccari	(AACH, BARI, BONN, CERN, GLAS+)
DAUM	81B	NP B182 269	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)
Also	81B	NP B186 594	Evangelista	
DAUM	80D	PL 89B 285	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+) JP
BALTAY	77	PRL 39 591	+Cautis, Kalelkar	(COLU) JP
KALELKAR	75	Nevis 207 Thesis		(COLU)
ASCOLI	73	PR D7 669		(ILL, TNTO, GENO, HAMB, MILA, SACL) JP
CRENNELL	70	PRL 24 781	+Karshon, Lai, Scarr, Sims	(BNL)
ARMENISE	69	LNC 2 501	+Ghidini, Forino, Cartacci+	(BARI, BGNA, FIRZ)
BALTAY	68	PRL 20 887	+Kung, Yeh, Ferbel+	(COLU, ROCH, RUTG, YALE) I
BARTSCH	68	NP B7 345	+Keppel, Kraus+	(AACH, BERL, CERN) JP
FERBEL	68	Phil. Conf. 335		(ROCH)

OTHER RELATED PAPERS

CHEN	83B	PR D28 2304	+Fenker+	(ARIZ, FNAL, FLOR, NDAM, TUFT+)
LEEDOM	83	PR D27 1426	+DeBonte, Gaidos, Key, Wong+	(PURD, TNTO)
BELLINI	82B	NP B199 1	+	(CERN, MILA, JINR, BGNA, HELS, PAVI, WARS+)
FOCACCI	66	PRL 17 890	+Kienzle, Levrat, Maglich, Martin	(CERN)
LEVRAT	66	PL 22 714	+Tolstrup+	(CERN Missing Mass Spect. Collab.)
LUBATTI	66	Berkeley Thesis		(LRL)
VETLITSKY	66	PL 21 579	+Guszavin, Kliger, Zolganov+	(ITEP)
FORINO	65B	PL 19 68	+Gessaroli+	(BGNA, BARI, FIRZ, ORSA, SACL)

$\phi(1680)$

$I^G(J^{PC}) = 0^-(1^{--})$

First identified using Dalitz plot analysis of $e^+e^- \rightarrow K K^*(892)$ (BIZOT 80, DELCOURT 81). We do not list anymore ω radial excitations under this particle. See also $\omega(1390)$ and $\omega(1600)$.

$\phi(1680)$ MASS

e^+e^- PRODUCTION

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1680±50 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.				
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1657±27	367	BISELLO	91C	DM2	$e^+e^- \rightarrow K^0_S K^\pm\pi^\mp$
1655±17		[1] BISELLO	88B	DM2	$e^+e^- \rightarrow K^+K^-$
1680±10		[2] BUON	82	DM1	$e^+e^- \rightarrow$ hadrons
1677±12		[3] MANE	82	DM1	$e^+e^- \rightarrow K^0_S K\pi$

PHOTOPRODUCTION

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1726±22	BUSENITZ	89	TPS	$\gamma p \rightarrow K^+K^- X$
1760±20	ATKINSON	85C	OMEG	20–70 $\gamma p \rightarrow K\overline{K} X$
1690±10	ASTON	81F	OMEG	25–70 $\gamma p \rightarrow K^+K^- X$

[1] From global fit including ρ, ω, ϕ and $\rho(1700)$ assume mass 1570 MeV and width 510 MeV for ρ radial excitation.
[2] From global fit of ρ, ω, ϕ and their radial excitations to channels $\omega\pi^+\pi^-$, K^+K^-, $K^0_S K^0_L$, $K^0_S K^\pm\pi^\mp$. Assume mass 1570 MeV and width 510 MeV for ρ radial excitations, mass 1570 and width 500 MeV for ω radial excitation.
[3] Fit to one channel only, neglecting interference with ω, $\rho(1700)$.

$\phi(1680)$ WIDTH

e^+e^- PRODUCTION

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
150±50 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.				
• • • We do not use the following data for averages, fits, limits, etc. • • •					
146±55	367	BISELLO	91C	DM2	$e^+e^- \rightarrow K^0_S K^\pm\pi^\mp$
207±45		[4] BISELLO	88B	DM2	$e^+e^- \rightarrow K^+K^-$
185±22		[5] BUON	82	DM1	$e^+e^- \rightarrow$ hadrons
102±36		[6] MANE	82	DM1	$e^+e^- \rightarrow K^0_S K\pi$

PHOTOPRODUCTION

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
121±47	BUSENITZ	89	TPS	$\gamma p \to K^+ K^- X$
80±40	ATKINSON	85C	OMEG	20–70 $\gamma p \to K \overline{K} X$
100±40	ASTON	81F	OMEG	25–70 $\gamma p \to K^+ K^- X$

[4] From global fit including ρ, ω, ϕ and $\rho(1700)$ assume mass 1570 MeV and width 510 MeV for ρ radial excitation.
[5] From global fit of ρ, ω, ϕ and their radial excitations to channels $\omega\pi^+\pi^-$, K^+K^-, $K^0_S K^0_L$, $K^0_S K^\pm \pi^\mp$. Assume mass 1570 MeV and width 510 MeV for ρ radial excitation, mass 1570 and width 500 MeV for ω radial excitation.
[6] Fit to one channel only, neglecting interference with ω, $\rho(1700)$.

$\phi(1680)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}^*(892)$ + c.c.	dominant
Γ_2	$K\overline{K}$	seen
Γ_3	e^+e^-	seen
Γ_4	$\omega\pi\pi$	possibly seen
Γ_5	$K^0_S K\pi$	seen
Γ_6	$K^+K^-\pi^0$	

$\phi(1680)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

This combination of a partial width with the partial width into e^+e^- and with the total width is obtained from the integrated cross section into channel (I) in e^+e^- annihilation. We list only data that have not been used to determine the partial width $\Gamma(I)$ or the branching ratio $\Gamma(I)$/total.

$\Gamma(K\overline{K}^*(892) + \text{c.c.}) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.48 ±0.14	367	BISELLO	91C	DM2	$e^+e^- \to K^0_S K^\pm \pi^\mp$
0.413±0.033		[7] BIZOT	80	DM1	e^+e^-

$\Gamma(K\overline{K}) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_2\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.053±0.035	[7] BIZOT	80	DM1	e^+e^-

$\Gamma(\omega\pi\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_4\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 0.017	[7] BIZOT	80	DM1	e^+e^-

[7] Model dependent.

$\phi(1680)$ BRANCHING RATIOS

$\Gamma(K\overline{K}^*(892) + \text{c.c.})/\Gamma(K^0_S K\pi)$ — Γ_1/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
dominant	MANE	82	DM1	$e^+e^- \to K^0_S K^\pm \pi^\mp$

$\Gamma(K\overline{K})/\Gamma(K\overline{K}^*(892) + \text{c.c.})$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.07 ±0.01	BUON	82	DM1	e^+e^-

$\Gamma(\omega\pi\pi)/\Gamma(K\overline{K}^*(892) + \text{c.c.})$ — Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
<0.10	BUON	82	DM1	e^+e^-

$\phi(1680)$ REFERENCES

BISELLO 91C ZPHY C52 227 +Busetto, Castro, Nigro, Pescara+ (DM2 Collab.)
BUSENITZ 89 PR D40 1 +Olszewski, Callahan+ (ILL, FNAL)
BISELLO 88B ZPHY C39 13 +Busetto+ (PADO, CLER, FRAS, LALO)
ATKINSON 85C ZPHY C27 233 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
BUON 82 PL 118B 221 +Bisello, Bizot, Cordier, Delcourt+ (LALO, MONP)
MANE 82 PL 112B 178 +Bisello, Bizot, Buon, Delcourt, Fayard+ (LALO)
ASTON 81F PL 104B 231 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)
DELCOURT 81 PL 99B 257 +Bisello, Bizot, Buon, Cordier, Mane (ORSA)
BIZOT 80 Madison Conf. 546 +Bisello, Buon, Cordier, Delcourt+ (LALO, USTL)

OTHER RELATED PAPERS

ATKINSON 86C ZPHY C30 541 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
ATKINSON 84 NP B231 15 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
ATKINSON 84B NP B231 1 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
ATKINSON 83C NP B229 269 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
CORDIER 81 PL 106B 155 +Bisello, Bizot, Buon, Delcourt, Mane (ORSA)
MANE 81 PL 99B 261 +Bisello, Bizot, Buon, Cordier, Delcourt (ORSA)
ASTON 80F NP B174 269 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)

$\rho_3(1690)$
was $g(1690)$

$I^G(J^{PC}) = 1^+(3^{--})$

$\rho_3(1690)$ MASS

We include only high statistics experiments in the average for the 2π, $K\overline{K}$, and $K\overline{K}\pi$ modes.

2π, $K\overline{K}$, AND $K\overline{K}\pi$ MODES

VALUE (MeV)	DOCUMENT ID
1691 ±5 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.
1691.4±2.7 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.

2π MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1686 ± 4 OUR AVERAGE						
1677 ±14		EVANGELISTA	81	OMEG	−	12 $\pi^- p \to 2\pi p$
1679.0±11.0	476	BALTAY	78B	HBC	0	15 $\pi^+ p \to \pi^+\pi^- n$
1678.0±12.0	175	[1] ANTIPOV	77	CIBS	0	25 $\pi^- p \to p 3\pi$
1690 ± 7	600	[1] ENGLER	74	DBC	0	6 $\pi^+ n \to \pi^+\pi^- p$
1693 ± 8		[2] GRAYER	74	ASPK	0	17 $\pi^- p \to \pi^+\pi^- n$
1678 ±12		MATTHEWS	71C	DBC	0	7 $\pi^+ N$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1734.0±10.0		[3] CORDEN	79	OMEG		12–15 $\pi^- p \to n 2\pi$
1692 ±12		[2,4] ESTABROOKS	75	RVUE		17 $\pi^- p \to \pi^+\pi^- n$
1737.0±23.0		ARMENISE	70	DBC	0	9 $\pi^+ N$
1650.0±35.0	122	BARTSCH	70B	HBC	+	8 $\pi^+ p \to N 2\pi$
1687 ±21		STUNTEBECK	70	HDBC	0	8 $\pi^- p$, 5.4 $\pi^+ d$
1683 ±13		ARMENISE	68	DBC	0	5.1 $\pi^+ d$
1670.0±30.0		GOLDBERG	65	HBC	0	6 $\pi^+ d$, 8 $\pi^- p$

[1] Mass errors enlarged by us to $\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[2] Uses same data as HYAMS 75
[3] From a phase shift solution containing a $f'_2(1525)$ width two times larger than the $K\overline{K}$ result.
[4] From phase-shift analysis. Error takes account of spread of different phase-shift solutions.

$K\overline{K}$ AND $K\overline{K}\pi$ MODES

The data in this block is included in the average printed for a previous datablock.

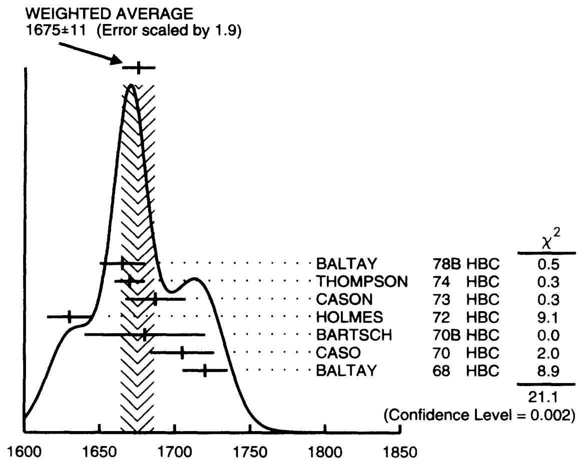
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1696 ± 4 OUR AVERAGE						
1699.0± 5.0		ALPER	80	CNTR	0	62 $\pi^- p \to K^+ K^- n$
1698 ±12	6k	[5,6] MARTIN	78D	SPEC		10 $\pi p \to K^0_S K^- p$
1692 ± 6		BLUM	75	ASPK	0	18.4 $\pi^- p \to n K^+ K^-$
1690.0±16.0		ADERHOLZ	69	HBC	+	8 $\pi^+ p \to K\overline{K}\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1694.0± 8.0		[7] COSTA...	80	OMEG		10 $\pi^- p \to K^+ K^- n$

[5] From a fit to $J^P = 3^-$ partial wave.
[6] Systematic error on mass scale subtracted.
[7] They cannot distinguish between $\rho_3(1690)$ and $\omega_3(1670)$.

$(4\pi)^\pm$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1675 ±11 OUR AVERAGE		Error includes scale factor of 1.9. See the ideogram below.				
1665.0±15.0	177	BALTAY	78B	HBC	+	15 $\pi^+ p \to p 4\pi$
1670 ±10		THOMPSON	74	HBC	+	13 $\pi^+ p$
1687 ±20		CASON	73	HBC	−	8,18.5 $\pi^- p$
1630 ±15		HOLMES	72	HBC	+	10–12 $K^+ p$
1680.0±40.0	144	BARTSCH	70B	HBC	+	8 $\pi^+ p \to N 4\pi$
1705.0±21.0		CASO	70	HBC	−	11.2 $\pi^- p \to n \rho 2\pi$
1720 ±15		BALTAY	68	HBC	+	7, 8.5 $\pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1694 ± 6		[8] EVANGELISTA	81	OMEG	−	12 $\pi^- p \to p 4\pi$
1718 ±10		[9] EVANGELISTA	81	OMEG	−	12 $\pi^- p \to p 4\pi$
1673 ± 9		[10] EVANGELISTA	81	OMEG	−	12 $\pi^- p \to p 4\pi$
1733 ± 9	66	[11] KLIGER	74	HBC	−	4.5 $\pi^- p \to p 4\pi$
1685 ±14		[11] CASON	73	HBC	−	8,18.5 $\pi^- p$
1689.0±20.0	102	[11] BARTSCH	70B	HBC	+	8 $\pi^+ p \to N 2\rho$

[8] From $\rho^-\rho^0$ mode, not independent of the other two EVANGELISTA 81 entries.
[9] From $a_2(1320)^-\pi^0$ mode, not independent of the other two EVANGELISTA 81 entries.
[10] From $a_2(1320)^0\pi^-$ mode, not independent of the other two EVANGELISTA 81 entries.
[11] From $\rho^\pm\rho^0$ mode.



$\rho_3(1690)$ mass, $(4\pi)^{\pm}$ mode (MeV)

$\omega\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1681 ± 6 OUR AVERAGE					
1690 ±20	LANDSBERG	91	GAM2		38,100 $\pi^- p \to \omega\pi^0 n$
1690 ±15	EVANGELISTA	81	OMEG	−	12 $\pi^- p \to \omega\pi p$
1666.0±14.0	GESSAROLI	77	HBC		11 $\pi^- p \to \omega\pi p$
1686 ± 9	THOMPSON	74	HBC	+	13 $\pi^+ p$
1654 ±24	BARNHAM	70	HBC	+	10 $K^+ p \to \omega\pi X$

$\eta\pi^+\pi^-$ MODE

(For difficulties with MMS experiments, see the $a_2(1320)$ mini-review in the 1973 edition.)

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1680 ±15	FUKUI	88	SPEC	0	8.95 $\pi^- p \to \eta\pi^+\pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1700.0±47.0	[12] ANDERSON	69	MMS	−	16 $\pi^- p$ backward
1632 ±15	[12,13] FOCACCI	66	MMS	−	7–12 $\pi^- p \to p$ MM
1700 ±15	[12,13] FOCACCI	66	MMS	−	7–12 $\pi^- p \to p$ MM
1748 ±15	[12,13] FOCACCI	66	MMS	−	7–12 $\pi^- p \to p$ MM

[12] Seen in 2.5–3 GeV/c $\overline{p}p$. $2\pi^+2\pi^-$, with 0, 1, 2 $\pi^+\pi^-$ pairs in ρ band not seen by OREN 74 (2.3 GeV/c $\overline{p}p$) with more statistics. (Jan. 1976)

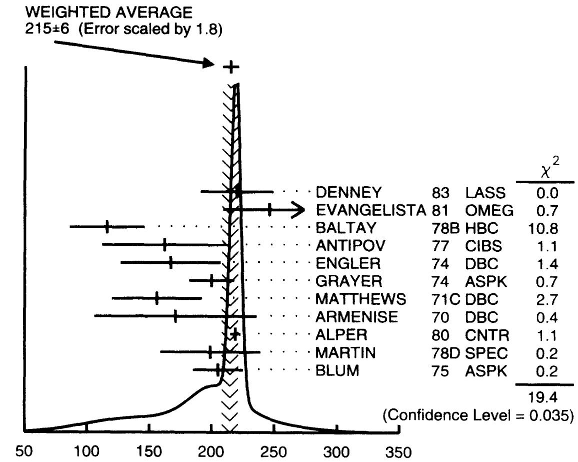
[13] Not seen by BOWEN 72.

$\rho_3(1690)$ WIDTH

We include only high statistics experiments in the average for the 2π, $K\overline{K}$, $K\overline{K}\pi$ modes.

2π, $K\overline{K}$, AND $K\overline{K}\pi$ MODES

VALUE (MeV)	DOCUMENT ID
215±20 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.
215± 6 OUR AVERAGE	Includes data from the 2 datablocks that follow this one. Error includes scale factor of 1.8. See the ideogram below.



$\rho_3(1690)$ width, 2π, $K\overline{K}$, and $K\overline{K}\pi$ modes (MeV)

2π MODE

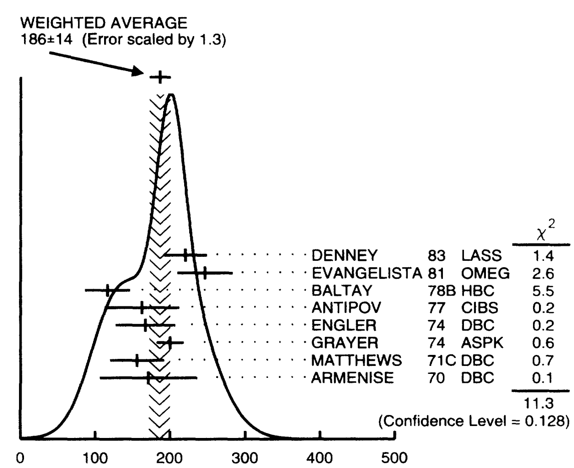
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.						
186 ±14 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.						
220 ±29		DENNEY	83	LASS		10 $\pi^+ N$
246 ±37		EVANGELISTA	81	OMEG	−	12 $\pi^- p \to 2\pi p$
116.0±30.0	476	BALTAY	78B	HBC	0	15 $\pi^+ p \to \pi^+\pi^- n$
162.0±50.0	175	[14] ANTIPOV	77	CIBS	0	25 $\pi^- p \to p3\pi$
167 ±40	600	ENGLER	74	DBC	0	6 $\pi^+ n \to \pi^+\pi^- p$
200 ±18		[15] GRAYER	74	ASPK	0	17 $\pi^- p \to \pi^+\pi^- n$
156 ±36		MATTHEWS	71C	DBC	0	7 $\pi^+ N$
171.0±65.0		ARMENISE	70	DBC	0	9 $\pi^+ d$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
322.0±35.0		[16] CORDEN	79	OMEG		12–15 $\pi^- p \to n2\pi$
240 ±30		[15,17] ESTABROOKS	75	RVUE		17 $\pi^- p \to \pi^+\pi^- n$
180.0±30.0	122	BARTSCH	70B	HBC	+	8 $\pi^+ p \to N2\pi$
267 $^{+72}_{-46}$		STUNTEBECK	70	HDBC	0	8 $\pi^- p$, 5.4 $\pi^+ d$
188 ±49		ARMENISE	68	DBC	0	5.1 $\pi^+ d$
180.0±40.0		GOLDBERG	65	HBC	0	6 $\pi^+ d$, 8 $\pi^- p$

[14] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

[15] Uses same data as HYAMS 75 and BECKER 79.

[16] From a phase shift solution containing a $f_2'(1525)$ width two times larger than the $K\overline{K}$ result.

[17] From phase-shift analysis. Error takes account of spread of different phase-shift solutions.



$\rho_3(1690)$ width, 2π mode (MeV)

$K\overline{K}$ AND $K\overline{K}\pi$ MODES

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.						
218 ± 4 OUR AVERAGE						
219.0± 4.0		ALPER	80	CNTR	0	62 $\pi^- p \to K^+ K^- n$
199 ±40	6000	[18] MARTIN	78D	SPEC		10 $\pi p \to K^0_S K^- p$
205 ±20		BLUM	75	ASPK	0	18.4 $\pi^- p \to n K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
186.0±11.0		[19] COSTA...	80	OMEG		10 $\pi^- p \to K^+ K^- n$
112.0±60.0		ADERHOLZ	69	HBC	+	8 $\pi^+ p \to K\overline{K}\pi$

[18] From a fit to $J^P = 3^-$ partial wave.
[19] They cannot distinguish between $\rho_3(1690)$ and $\omega_3(1670)$.

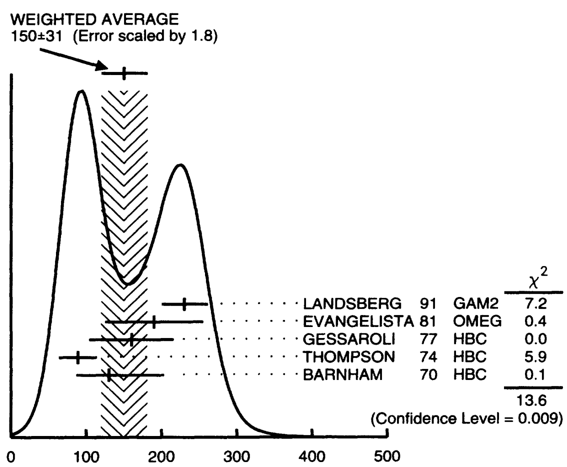
$(4\pi)^{\pm}$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
119 ±13 OUR AVERAGE						
105.0±30.0	177	BALTAY	78B	HBC	+	15 $\pi^+ p \to p 4\pi$
106 ±25		THOMPSON	74	HBC	+	13 $\pi^+ p$
169 $^{+70}_{-48}$		CASON	73	HBC	−	8,18.5 $\pi^- p$
130 ±30		HOLMES	72	HBC	+	10–12 $K^+ p$
135.0±30.0	144	BARTSCH	70B	HBC	+	8 $\pi^+ p \to N 4\pi$
100 ±35		BALTAY	68	HBC	+	7, 8.5 $\pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
123 ±13		[20] EVANGELISTA	81	OMEG	−	12 $\pi^- p \to p 4\pi$
230 ±28		[21] EVANGELISTA	81	OMEG	−	12 $\pi^- p \to p 4\pi$
184 ±33		[22] EVANGELISTA	81	OMEG	−	12 $\pi^- p \to p 4\pi$
150	66	[23] KLIGER	74	HBC	−	4.5 $\pi^- p \to p 4\pi$
125 $^{+83}_{-35}$		[23] CASON	73	HBC	−	8,18.5 $\pi^- p$
180.0±30.0	90	[23] BARTSCH	70B	HBC	+	8 $\pi^+ p \to N a_2 \pi$
160.0±30.0	102	BARTSCH	70B	HBC	+	8 $\pi^+ p \to N 2\rho$

[20] From $\rho^- \rho^0$ mode, not independent of the other two EVANGELISTA 81 entries.
[21] From $a_2(1320)^- \pi^0$ mode, not independent of the other two EVANGELISTA 81 entries.
[22] From $a_2(1320)^0 \pi^-$ mode, not independent of the other two EVANGELISTA 81 entries.
[23] From $\rho^{\pm} \rho^0$ mode.

$\omega\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
150 ±31 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.					
230 ±30	LANDSBERG	91	GAM2		38,100 $\pi^- p \to \omega \pi^0 n$
190 ±65	EVANGELISTA	81	OMEG	−	12 $\pi^- p \to \omega \pi p$
160.0±56.0	GESSAROLI	77	HBC		11 $\pi^- p \to \omega \pi p$
89 ±25	THOMPSON	74	HBC	+	13 $\pi^+ p$
130 $^{+73}_{-43}$	BARNHAM	70	HBC	+	10 $K^+ p \to \omega \pi X$



$\rho_3(1690)$ width, $\omega\pi$ mode (MeV)

$\eta\pi^+\pi^-$ MODE

(For difficulties with MMS experiments, see the $a_2(1320)$ mini-review in the 1973 edition.)

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
106 ±27	FUKUI	88	SPEC	0	8.95 $\pi^- p \to \eta \pi^+ \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
195.0	[24] ANDERSON	69	MMS	−	16 $\pi^- p$ backward
< 21	[24,25] FOCACCI	66	MMS	−	7–12 $\pi^- p \to p$ MM
< 30	[24,25] FOCACCI	66	MMS	−	7–12 $\pi^- p \to p$ MM
< 38	[24,25] FOCACCI	66	MMS	−	7–12 $\pi^- p \to p$ MM

[24] Seen in 2.5–3 GeV/c $\overline{p}p$. $2\pi^+ 2\pi^-$, with 0, 1, 2 $\pi^+\pi^-$ pairs in ρ^0 band not seen by OREN 74 (2.3 GeV/c $\overline{p}p$) with more statistics. (Jan. 1979)
[25] Not seen by BOWEN 72.

$\rho_3(1690)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor
Γ_1	4π	(71.1 ±1.9) %	
Γ_2	$\pi\pi$	(23.6 ±1.3) %	
Γ_3	$K\overline{K}\pi$	(3.8 ±1.2) %	
Γ_4	$K\overline{K}$	(1.58±0.26) %	1.2
Γ_5	$\eta\pi^+\pi^-$	seen	
Γ_6	$\pi\pi\rho$ Excluding 2ρ and $a_2(1320)\pi$.		
Γ_7	$a_2(1320)\pi$		
Γ_8	$\omega\pi$		
Γ_9	$\rho\rho$		
Γ_{10}	$\phi\pi$		
Γ_{11}	$\eta\pi$		
Γ_{12}	$\pi^{\pm}\pi^+\pi^-\pi^0$		
Γ_{13}	$\pi^{\pm} 2\pi^+ 2\pi^- \pi^0$		

CONSTRAINED FIT INFORMATION

An overall fit to 5 branching ratios uses 10 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 14.7 for 7 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−77		
x_3	−74	17	
x_4	−15	2	0
	x_1	x_2	x_3

$\rho_3(1690)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.236±0.013 OUR FIT					
0.243±0.013 OUR AVERAGE					
0.259 $^{+0.018}_{-0.019}$	BECKER	79	ASPK	0	17 $\pi^- p$ polarized
0.23 ±0.02	CORDEN	79	OMEG		12–15 $\pi^- p \to n 2\pi$
0.22 ±0.04	[26] MATTHEWS	71C	HDBC	0	7 $\pi^+ n \to \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.245±0.006	[27] ESTABROOKS	75	RVUE		17 $\pi^- p \to \pi^+\pi^- n$

[26] One-pion-exchange model used in this estimation.
[27] From phase-shift analysis of HYAMS 75 data.

$\Gamma(\pi\pi)/\Gamma(\pi^{\pm}\pi^+\pi^-\pi^0)$ — Γ_2/Γ_{12}

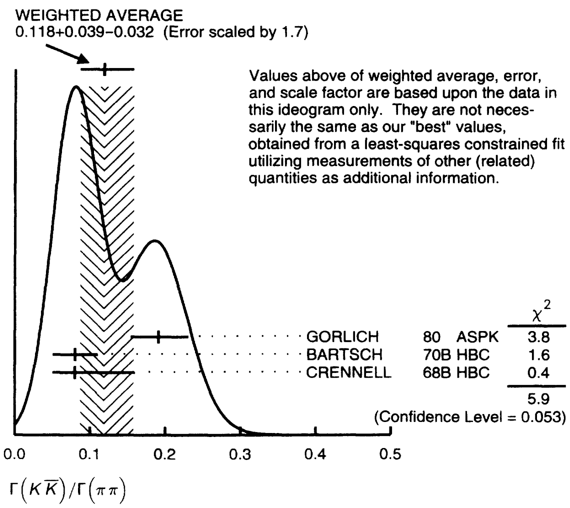
VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.35±0.11	CASON	73	HBC	−	8,18.5 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.2	HOLMES	72	HBC	+	10–12 $K^+ p$
<0.12	BALLAM	71B	HBC	−	16 $\pi^- p$

$\Gamma(\pi\pi)/\Gamma(4\pi)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.332±0.026 OUR FIT Error includes scale factor of 1.1.					
0.30 ±0.10	BALTAY	78B	HBC	0	15 $\pi^+ p \to p 4\pi$

$\Gamma(K\overline{K})/\Gamma(\pi\pi)$ — Γ_4/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.067±0.011 OUR FIT Error includes scale factor of 1.2.					
$\mathbf{0.118^{+0.039}_{-0.032}}$ **OUR AVERAGE** Error includes scale factor of 1.7. See the ideogram below.					
$0.191^{+0.040}_{-0.037}$	GORLICH	80	ASPK	0	17,18 $\pi^- p$ polarized
0.08 ±0.03	BARTSCH	70B	HBC	+	8 $\pi^+ p$
$0.08\ ^{+0.08}_{-0.03}$	CRENNELL	68B	HBC		6.0 $\pi^- p$



$\Gamma(K\overline{K}\pi)/\Gamma(\pi\pi)$ — Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.16±0.05 OUR FIT					
0.16±0.05	[28] BARTSCH	70B	HBC	+	8 $\pi^+ p$

[28] Increased by us to correspond to $B(\rho_3(1690) \to \pi\pi)=0.24$.

$[\Gamma(\pi\pi\rho) + \Gamma(a_2(1320)\pi) + \Gamma(\rho\rho)]/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — $(\Gamma_6+\Gamma_7+\Gamma_9)/\Gamma_{12}$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.94±0.09 OUR AVERAGE					
0.96±0.21	BALTAY	78B	HBC	+	15 $\pi^+ p \to p4\pi$
0.88±0.15	BALLAM	71B	HBC	−	16 $\pi^- p$
1 ±0.15	BARTSCH	70B	HBC	+	8 $\pi^+ p$
consistent with 1	CASO	68	HBC	−	11 $\pi^- p$

$\Gamma(\rho\rho)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_9/Γ_{12}

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.12±0.11		BALTAY	78B	HBC	+	15 $\pi^+ p \to p4\pi$
0.56	66	KLIGER	74	HBC	−	4.5 $\pi^- p \to p4\pi$
0.13±0.09		[29] THOMPSON	74	HBC	+	13 $\pi^+ p$
0.7 ±0.15		BARTSCH	70B	HBC	+	8 $\pi^+ p$

[29] $\rho\rho$ and $a_2(1320)\pi$ modes are indistinguishable.

$\Gamma(\rho\rho)/[\Gamma(\pi\pi\rho) + \Gamma(a_2(1320)\pi) + \Gamma(\rho\rho)]$ — $\Gamma_9/(\Gamma_6+\Gamma_7+\Gamma_9)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.48±0.16	CASO	68	HBC	−	11 $\pi^- p$

$\Gamma(a_2(1320)\pi)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_7/Γ_{12}

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.66±0.08	BALTAY	78B	HBC	+	15 $\pi^+ p \to p4\pi$
0.36±0.14	[30] THOMPSON	74	HBC	+	13 $\pi^+ p$
not seen	CASON	73	HBC	−	8,18.5 $\pi^- p$
0.6 ±0.15	BARTSCH	70B	HBC	+	8 $\pi^+ p$
0.6	BALTAY	68	HBC	+	7,8.5 $\pi^+ p$

[30] $\rho\rho$ and $a_2(1320)\pi$ modes are indistinguishable.

$\Gamma(\omega\pi)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_8/Γ_{12}

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
0.23±0.05 OUR AVERAGE Error includes scale factor of 1.2.						
0.33±0.07		THOMPSON	74	HBC	+	13 $\pi^+ p$
0.12±0.07		BALLAM	71B	HBC	−	16 $\pi^- p$
0.25±0.10		BALTAY	68	HBC	+	7,8.5 $\pi^+ p$
0.25±0.10		JOHNSTON	68	HBC	−	7.0 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.11	95	BALTAY	78B	HBC	+	15 $\pi^+ p \to p4\pi$
<0.09		KLIGER	74	HBC	−	4.5 $\pi^- p \to p4\pi$

$\Gamma(\phi\pi)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_{10}/Γ_{12}

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.11	BALTAY	68	HBC	+	7,8.5 $\pi^+ p$

$\Gamma(\pi^\pm 2\pi^+ 2\pi^- \pi^0)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_{13}/Γ_{12}

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.15	BALTAY	68	HBC	+	7,8.5 $\pi^+ p$

$\Gamma(\eta\pi)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_{11}/Γ_{12}

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.02	THOMPSON	74	HBC	+	13 $\pi^+ p$

$\Gamma(K\overline{K})/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.0158±0.0026 OUR FIT Error includes scale factor of 1.2.					
0.0130±0.0024 OUR AVERAGE					
0.013 ±0.003	COSTA...	80	OMEG	0	10 $\pi^- p \to K^+ K^- n$
0.013 ±0.004	[31] MARTIN	78B	SPEC	−	10 $\pi p \to K^0_S K^- p$

[31] From $(\Gamma_2\Gamma_4)^{1/2} = 0.056 \pm 0.034$ assuming $B(\rho_3(1690) \to \pi\pi) = 0.24$.

$\Gamma(\omega\pi)/[\Gamma(\omega\pi) + \Gamma(\rho\rho)]$ — $\Gamma_8/(\Gamma_8+\Gamma_9)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.22±0.08	CASON	73	HBC	−	8,18.5 $\pi^- p$

$\Gamma(\eta\pi^+\pi^-)/\Gamma_{total}$ — Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	FUKUI	88	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$

$\rho_3(1690)$ REFERENCES

LANDSBERG 91 Hadron 91 Conf. + (SERP, BELG, LANL, LAPP, PISA, KEK)
FUKUI 88 PL B202 441 +Horikawa+ (SUGI, NAGO, KEK, KYOT, MIYA)
DENNEY 83 PR D28 2726 +Cranley, Firestone, Chapman+ (IOWA, MICH)
EVANGELISTA 81 NP B178 197 + (BARI, BONN, CERN, DARE, LIVP+)
ALPER 80 PL 94B 422 +Becker+ (AMST, CERN, CRAC, MPIM, OXF+)
COSTA... 80 NP B175 402 Costa De Beauregard+ (BARI, BONN, CERN+)
GORLICH 80 NP B174 16 +Niczyporuk+ (CRAC, MPIM, CERN, ZEEM)
BECKER 79 NP B151 46 +Blanar, Blum+ (MPIM, CERN, ZEEM, CRAC)
CORDEN 79 NP B157 250 +Dowell, Garvey+ (BIRM, RHEL, TELA, LOWC) JP
BALTAY 78B PR D17 62 +Cautis, Cohen, Csorna+ (COLU, BING)
MARTIN 78B NP B140 158 +Ozmutlu, Baldi, Bohringer, Dorsaz+ (DURH, GEVA)
MARTIN 78D PL 74B 417 +Ozmutlu, Baldi, Bohringer, Dorsaz+ (DURH, GEVA)
ANTIPOV 77 NP B119 45 +Busnello, Damgaard, Kienzle+ (SERP, GEVA)
GESSAROLI 77 NP B126 382 + (BGNA, FIRZ, GENO, MILA, OXF, PAVI)
BLUM 75 PL 57B 403 +Chabaud, Dietl, Garelick, Grayer+ (CERN, MPIM) JP
ESTABROOKS 75 NP B95 322 +Martin (DURH)
HYAMS 75 NP B100 205 +Jones, Weilhammer, Blum, Dietl+ (CERN, MPIM)
ENGLER 74 PR D10 2070 +Kraemer, Toaff, Weisser, Diaz+ (CMU, CASE)
GRAYER 74 NP B75 189 +Hyams, Blum, Dietl+ (CERN, MPIM)
KLIGER 74 SJNP 19 428 +Beketov, Grechko, Guzhavin, Dubovikov+ (ITEP)
Translated from YAF 19 839.
OREN 74 NP B71 189 +Cooper, Fields, Rhines, Allison+ (ANL, OXF)
THOMPSON 74 NP B69 220 +Gaidos, McIlwain, Miller, Mulera+ (PURD)
CASON 73 PR D7 1971 +Biswas, Kenney, Madden+ (NDAM)
BOWEN 72 PRL 29 890 +Earles, Faissler, Blieden+ (NEAS, STON)
HOLMES 72 PR D6 3336 +Ferbel, Slattery, Werner (ROCH)
BALLAM 71B PR D3 2606 +Chadwick, Guiragossian, Johnson+ (SLAC)
MATTHEWS 71C NP B33 1 +Prentice, Yoon, Carroll+ (TNTO, WISC) JP
ARMENISE 70 LNC 4 199 +Ghidini, Foring, Cartacci+ (BARI, BGNA, FIRZ)
BARNHAM 70 PRL 24 1083 +Colley, Jobes, Kenyon, Pathak, Riddiford (BIRM)
BARTSCH 70B NP B22 109 +Kraus, Tsanos, Grote+ (AACH, BERL, CERN)
CASO 70 LNC 3 707 +Conte, Tomasini+ (GENO, HAMB, MILA, SACL)
STUNTEBECK 70 PL 32B 391 +Kenney, Deery, Biswas, Cason+ (NDAM)
ADERHOLZ 69 NP B11 259 +Bartsch+ (AACH, BERL, CERN, JAGL, WARS)
ANDERSON 69 PRL 22 1390 +Collins+ (BNL, CMU)
ARMENISE 68 NC 54A 999 +Ghidini, Forino+ (BARI, BGNA, FIRZ, ORSA) I
BALTAY 68 PRL 20 887 +Kung, Yeh, Ferbel+ (COLU, ROCH, RUTG, YALE) I
CASO 68 NC 54A 983 +Conte, Cords, Diaz+ (GENO, HAMB, MILA, SACL)
CRENNELL 68B PL 28B 136 +Karshon, Lal, Scarr, Skillicorn (BNL)
JOHNSTON 68 PRL 20 1414 +Prentice, Steenberg, Yoon (TNTO, WISC) IJP
FOCACCI 66 PRL 17 890 +Kienzle, Levrat, Maglich, Martin (CERN)
GOLDBERG 65 PL 17 354 + (CERN, EPOL, ORSA, MILA, CEA, SACL)

OTHER RELATED PAPERS

BARNETT 83B PL 120B 455 +Blockus, Burka, Chien, Christian+ (JHU)
EHRLICH 66 PR 152 1194 +Selove, Yuta (PENN)
LEVRAT 66 PL 22 714 +Tolstrup+ (CERN Missing Mass Spect. Collab.)
SEGUINOT 66 PL 19 712 +Martin+ (CERN Missing Mass Spect. Collab.)
BELLINI 65 NC 40A 948 +DiCorato, Duimio, Fiorini (MILA)
DEUTSCH... 65 PL 18 351 Deutschmann+ (AACH, BERL, CERN)
FORINO 65 PL 19 65 +Gessaroli+ (BGNA, ORSA, SACL)

$\rho(1700)$

$I^G(J^{PC}) = 1^+(1^{--})$

NOTE ON THE $\rho(1450)$ AND THE $\rho(1700)$

In our 1988 edition, we replaced the old $\rho(1600)$ entry with two new ones, the $\rho(1450)$ and the $\rho(1700)$, because there was emerging evidence that the 1600-MeV mass region actually contains two ρ–like resonances. ERKAL 86 had pointed out this possibility with a theoretical analysis on the consistency of 2π and 4π electromagnetic form factors and the $\pi\pi$ scattering length. DONNACHIE 87, with a full analysis of the data in the annihilation reactions $e^+e^- \to \pi^+\pi^-$, $2\pi^+2\pi^-$, and $\pi^+\pi^-\pi^0\pi^0$, and in the photoproduction reactions $\gamma p \to \pi^+\pi^- p$, $2\pi^+2\pi^- p$, and $\pi^+\pi^-\pi^0\pi^0 p$, had also argued that to obtain a consistent picture it was necessary to postulate two resonances, whose masses and widths could be fixed reasonably well. This picture was supported by the analysis of DONNACHIE 87B of $J^P = 1^-$ $\eta\rho^0$ mass spectra obtained in photoproduction and in e^+e^- annihilations; the analysis showed the need for a contribution from a ρ meson with a mass of about 1470 MeV, but could say little about a higher mass resonance (actually the data could be explained without it). Confirmation of the decay $\rho(1450) \to \omega\pi$, and a tight constraint on the mass due to strong interference with the $\rho(770)$ tail, was found by DONNACHIE 91 in an analysis of the reaction $e^+e^- \to \omega\pi$.

The analysis of DONNACHIE 87 was extended by CLEGG 88 to include new data on 4π systems produced in e^+e^- annihilation and in τ decay (4π τ–lepton decays and 4π annihilation reactions can be related by the Conserved Vector Current assumption). These systems were successfully analysed in terms of interfering contributions from two ρ–like states and from the tail of the $\rho(770)$ decaying into two–body states. While specific conclusions on $\rho(1450) \to 4\pi$ were obtained, the quality of the data used by CLEGG 88 prevented any conclusion on $\rho(1700) \to 4\pi$ decay.

An analysis by CLEGG 90 of 6π mass spectra from e^+e^- annihilation and from diffractive photoproduction provides evidence for two ρ mesons at about 2.1 and 1.8 GeV that decay strongly into 6π states. While the former is a candidate for a new resonance, the latter could be a manifestation of the $\rho(1700)$, distorted by threshold effects.

Independent evidence for two 1^- states is provided by KILLIAN 80 in 4π electroproduction at $\langle Q^2 \rangle = 1$ $(\text{GeV}/c)^2$, and by FUKUI 88 in a high-statistics sample of the $\eta\pi\pi$ system in $\pi^- p$ charge exchange.

This scenario with two overlapping resonances is supported by other data. BISELLO 89 measured the pion form factor in the energy interval 1.35–2.4 GeV with significant statistics (280 $e^+e^- \to \pi^+\pi^-$ events with very low background); a deep minimum is observed around 1.6 GeV, and the best fit to the form factor is obtained with the hypothesis of ρ–like resonances at 1420 and 1770 MeV with widths about 250 MeV. ANTONELLI 88 found that the $e^+e^- \to \eta\pi^+\pi^-$ cross section (with three different η decay modes) is better fitted with two fully interfering Breit–Wigners, with parameters in fair agreement with those of DONNACHIE 87 and BISELLO 89.

These experimental results (although ANTONELLI 88 is statistically less significant than BISELLO 89) have also resolved the disagreement between DONNACHIE 87 and FUKUI 88 on the $\rho(1450)$ width in favor of the DONNACHIE 87 value. From this point of view, the two experiments can be considered as solid confirmation of the $\rho(1450)$.

Several observations on the $\omega\pi$ system in the 1200-MeV region (FRENKIEL 72, COSME 76, BARBER 80C, ATKINSON 84C, BRAU 88) may be interpreted in terms of either $J^P = 1^-$ $\rho(770) \to \pi\omega$ production (LAYSSAC 71) or $J^P = 1^+$ $b_1(1235)$ production (BRAU 88). We argue that no special entry for a $\rho(1250)$ is needed. For completeness, the relevant observations are listed under the $\rho(1450)$.

$\rho(1700)$ MASS

$\eta\rho^0$ AND MIXED MODES

VALUE (MeV)	DOCUMENT ID
1700±20 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.
1712±13 OUR AVERAGE	Includes data from the 2 datablocks that follow this one. Error includes scale factor of 1.2.

MIXED MODES

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1700±25	DONNACHIE	87	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1625±25	GOVORKOV	88	RVUE	
1580±20	[1] BUON	82	DM1	$e^+e^- \to$ hadrons

$\eta\rho^0$ MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1740±20	ANTONELLI	88	DM2	$e^+e^- \to \eta\pi^+\pi^-$
1701±15	FUKUI	88	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$

$\pi^+\pi^-$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1768 ±21	BISELLO	89	DM2	$e^+e^- \to \pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1546 ±26	GESHKENBEIN	89	RVUE	
1650	[2] ERKAL	85	RVUE	20–70 $\gamma p \to \gamma\pi$
1550 ±70	ABE	84B	HYBR	20 $\gamma p \to \pi^+\pi^- p$
1590 ±20	[3] ASTON	80	OMEG	20–70 $\gamma p \to p 2\pi$
1600.0±10.0	[4] ATIYA	79B	SPEC	50 $\gamma C \to C 2\pi$
$1598.0^{+24.0}_{-22.0}$	BECKER	79	ASPK	17 $\pi^- p$ polarized
1659 ±25	[2] LANG	79	RVUE	
1575	[2] MARTIN	78C	RVUE	17 $\pi^- p \to \pi^+\pi^- n$
1610 ±30	[2] FROGGATT	77	RVUE	17 $\pi^- p \to \pi^+\pi^- n$
1590 ±20	[5] HYAMS	73	ASPK	17 $\pi^- p \to \pi^+\pi^- n$

$K\overline{K}$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1582±36	1600	CLELAND	82B	SPEC	±	50 $\pi p \to K^0_S K^\pm p$

$2(\pi^+\pi^-)$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1520± 30		[3] ASTON	81E	OMEG	20–70 $\gamma p \to p 4\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1570± 20		[6] CORDIER	82	DM1	$e^+e^- \to 2(\pi^+\pi^-)$
1654± 25		[7] DIBIANCA	81	DBC	$\pi^+ d \to p p 2(\pi^+\pi^-)$
1666± 39		[6] BACCI	80	FRAG	$e^+e^- \to 2(\pi^+\pi^-)$
1780	34	KILLIAN	80	SPEC	11 $e^- p \to 2(\pi^+\pi^-)$
1500		[8] ATIYA	79B	SPEC	50 $\gamma C \to C 4\pi^\pm$
1570± 60	65	[9] ALEXANDER	75	HBC	7.5 $\gamma p \to p 4\pi$
1550± 60		[3] CONVERSI	74	OSPK	$e^+e^- \to 2(\pi^+\pi^-)$
1550± 50	160	SCHACHT	74	STRC	5.5–9 $\gamma p \to p 4\pi$
1450±100	340	SCHACHT	74	STRC	9–18 $\gamma p \to p 4\pi$
1430± 50	400	BINGHAM	72B	HBC	9.3 $\gamma p \to p 4\pi$

$\pi^+\pi^-\pi^0\pi^0$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1660±30	ATKINSON 85B	OMEG	20–70 γp

$3(\pi^+\pi^-)$ AND $2(\pi^+\pi^-\pi^0)$ MODES

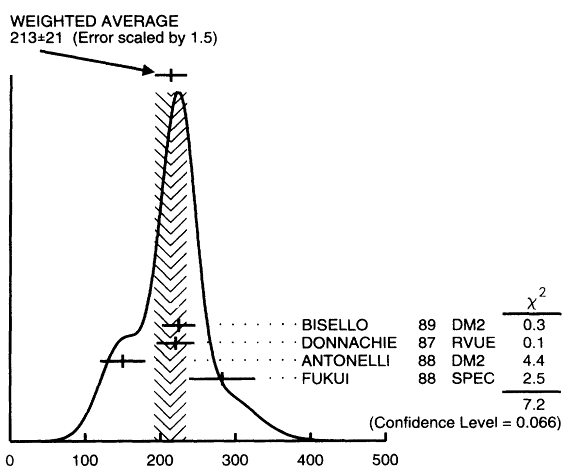
VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1783±15	CLEGG 90	RVUE	$e^+e^- \rightarrow 3(\pi^+\pi^-)2(\pi^+\pi^-\pi^0)$

[1] From global fit of ρ, ω, ϕ and their radial excitations to channels $\omega\pi^+\pi^-$, K^+K^-, $K^0_S K^0_L$, $K^0_S K^\pm\pi^\mp$.
[2] From phase shift analysis of HYAMS 73 data.
[3] Simple relativistic Breit-Wigner fit with constant width.
[4] An additional 40 MeV uncertainty in both the mass and width is present due to the choice of the background shape.
[5] Included in BECKER 79 analysis.
[6] Simple relativistic Breit-Wigner fit with model dependent width.
[7] One peak fit result.
[8] Parameters roughly estimated, not from a fit.
[9] Skew mass distribution compensated by Ross-Stodolsky factor.

$\rho(1700)$ WIDTH

$\eta\rho^0$, $\pi^+\pi^-$, AND MIXED MODES

VALUE (MeV)	DOCUMENT ID
235±50 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.
213±21 OUR AVERAGE	Includes data from the 3 datablocks that follow this one. Error includes scale factor of 1.5. See the ideogram below.



$\rho(1700)$ width, $\eta\rho^0$, $\pi^+\pi^-$, and mixed modes (MeV)

MIXED MODES

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
220±25	DONNACHIE 87	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
250±25	GOVORKOV 88	RVUE	
340±80	[10] BUON 82	DM1	$e^+e^- \rightarrow$ hadrons

$\eta\rho^0$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
150±30	ANTONELLI 88	DM2	$e^+e^- \rightarrow \eta\pi^+\pi^-$
282±44	FUKUI 88	SPEC	8.95 $\pi^-p \rightarrow \eta\pi^+\pi^-n$

$\pi^+\pi^-$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
224 ± 22	BISELLO 89	DM2	$e^+e^- \rightarrow \pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
620 ± 60	GESHKENBEIN 89	RVUE	
<315	[11] ERKAL 85	RVUE	20–70 $\gamma p \rightarrow \gamma\pi$
280 $^{+30}_{-80}$	ABE 84B	HYBR	20 $\gamma p \rightarrow \pi^+\pi^-p$
230.0± 80.0	[12] ASTON 80	OMEG	20–70 $\gamma p \rightarrow p2\pi$
283.0± 14.0	[13] ATIYA 79B	SPEC	50 $\gamma C \rightarrow C2\pi$
175.0$^{+98.0}_{-53.0}$	BECKER 79	ASPK	17 π^-p polarized
232 ± 34	[11] LANG 79	RVUE	
340	[11] MARTIN 78C	RVUE	17 $\pi^-p \rightarrow \pi^+\pi^-n$
300 ±100	[11] FROGGATT 77	RVUE	17 $\pi^-p \rightarrow \pi^+\pi^-n$
180 ± 50	[14] HYAMS 73	ASPK	17 $\pi^-p \rightarrow \pi^+\pi^-n$

$K\overline{K}$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
265±120	1600	CLELAND 82B	SPEC	±	50 $\pi p \rightarrow K^0_S K^\pm p$

$2(\pi^+\pi^-)$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
400± 50		[12] ASTON 81E	OMEG	20–70 $\gamma p \rightarrow p4\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
510± 40		[15] CORDIER 82	DM1	$e^+e^- \rightarrow 2(\pi^+\pi^-)$
400±146		[16] DIBIANCA 81	DBC	$\pi^+d \rightarrow pp2(\pi^+\pi^-)$
700±160		[15] BACCI 80	FRAG	$e^+e^- \rightarrow 2(\pi^+\pi^-)$
100	34	KILLIAN 80	SPEC	11 $e^-p \rightarrow 2(\pi^+\pi^-)$
600		[17] ATIYA 79B	SPEC	50 $\gamma C \rightarrow C4\pi^\pm$
340±160	65	[18] ALEXANDER 75	HBC	7.5 $\gamma p \rightarrow p4\pi$
360±100		[12] CONVERSI 74	OSPK	$e^+e^- \rightarrow 2(\pi^+\pi^-)$
400±120	160	[19] SCHACHT 74	STRC	5.5–9 $\gamma p \rightarrow p4\pi$
850±200	340	[19] SCHACHT 74	STRC	9–18 $\gamma p \rightarrow p4\pi$
650±100	400	BINGHAM 72B	HBC	9.3 $\gamma p \rightarrow p4\pi$

$\pi^+\pi^-\pi^0\pi^0$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
300±50	ATKINSON 85B	OMEG	20–70 γp

$3(\pi^+\pi^-)$ AND $2(\pi^+\pi^-\pi^0)$ MODES

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
285±20	CLEGG 90	RVUE	$e^+e^- \rightarrow 3(\pi^+\pi^-)2(\pi^+\pi^-\pi^0)$

[10] From global fit of ρ, ω, ϕ and their radial excitations to channels $\omega\pi^+\pi^-$, K^+K^-, $K^0_S K^0_L$, $K^0_S K^\pm\pi^\mp$.
[11] From phase shift analysis of HYAMS 73 data.
[12] Simple relativistic Breit-Wigner fit with constant width.
[13] An additional 40 MeV uncertainty in both the mass and width is present due to the choice of the background shape.
[14] Included in BECKER 79 analysis.
[15] Simple relativistic Breit-Wigner fit with model-dependent width.
[16] One peak fit result.
[17] Parameters roughly estimated, not from a fit.
[18] Skew mass distribution compensated by Ross-Stodolsky factor.
[19] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

$\rho(1700)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi\pi$	dominant
Γ_2	$\rho^0\pi^+\pi^-$	large
Γ_3	$\rho^0\pi^0\pi^0$	
Γ_4	$\rho^\pm\pi^\mp\pi^0$	large
Γ_5	$2(\pi^+\pi^-)$	large
Γ_6	$\pi^+\pi^-$	seen
Γ_7	$K\overline{K}^*(892)$ + c.c.	seen
Γ_8	$\eta\rho$	seen
Γ_9	$K\overline{K}$	seen
Γ_{10}	e^+e^-	seen
Γ_{11}	$\rho^0\rho^0$	
Γ_{12}	$\pi\omega$	

$\rho(1700)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

This combination of a partial width with the partial width into e^+e^- and with the total width is obtained from the cross-section into channel$_i$ in e^+e^- annihilation.

$\Gamma(2(\pi^+\pi^-)) \times \Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_5\Gamma_{10}/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
2.64±0.18 OUR AVERAGE			
2.6 ±0.2	DELCOURT 81B	DM1	$e^+e^- \rightarrow 2(\pi^+\pi^-)$
2.83±0.42	BACCI 80	FRAG	$e^+e^- \rightarrow 2(\pi^+\pi^-)$

$\Gamma(\pi^+\pi^-) \times \Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_6\Gamma_{10}/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.13	[20] DIEKMAN 88	RVUE	$e^+e^- \rightarrow \pi^+\pi^-$

[20] Using total width = 220 MeV.

$\Gamma(K\overline{K}^*(892) + \text{c.c.}) \times \Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_7\Gamma_{10}/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.305±0.071	[21] BIZOT 80	DM1	e^+e^-

$\Gamma(\eta\rho) \times \Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_8\Gamma_{10}/\Gamma$

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
7 ±3	ANTONELLI	88	DM2	$e^+e^- \rightarrow \eta\pi^+\pi^-$

$\Gamma(K\overline{K}) \times \Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_9\Gamma_{10}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.035±0.029	[21] BIZOT	80	DM1	e^+e^-

$\Gamma(\rho\pi\pi) \times \Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_1\Gamma_{10}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.510±0.090	[21] BIZOT	80	DM1	e^+e^-

[21] Model dependent.

$\rho(1700)$ BRANCHING RATIOS

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_6/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.287^{+0.043}_{-0.042}$	BECKER	79	ASPK	17 $\pi^- p$ polarized
0.15 to 0.30	[22] MARTIN	78C	RVUE	17 $\pi^- p \rightarrow \pi^+\pi^- n$
<0.20	[23] COSTA...	77B	RVUE	$e^+e^- \rightarrow 2\pi, 4\pi$
0.30 ±0.05	[22] FROGGATT	77	RVUE	17 $\pi^- p \rightarrow \pi^+\pi^- n$
<0.15	[24] EISENBERG	73	HBC	5 $\pi^+ p \rightarrow \Delta^{++} 2\pi$
0.25 ±0.05	[25] HYAMS	73	ASPK	17 $\pi^- p \rightarrow \pi^+\pi^- n$
0.20 ±0.05	MONTANET	73	HBC	0.0 $\overline{p}p$

[22] From phase shift analysis of HYAMS 73 data.
[23] Estimate using unitarity, time reversal invariance, Breit-Wigner.
[24] Estimated using one-pion-exchange model.
[25] Included in BECKER 79 analysis.

$\Gamma(\pi^+\pi^-)/\Gamma(2(\pi^+\pi^-))$ — Γ_6/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.13±0.05	ASTON	80	OMEG	20–70 $\gamma p \rightarrow p2\pi$
<0.14	[26] DAVIER	73	STRC	6–18 $\gamma p \rightarrow p4\pi$
<0.2	[27] BINGHAM	72B	HBC	9.3 $\gamma p \rightarrow p2\pi$

[26] Upper limit is estimate.
[27] 2σ upper limit.

$\Gamma(K\overline{K}^*(892) + c.c.)/\Gamma(2(\pi^+\pi^-))$ — Γ_7/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.15±0.03	[28] DELCOURT	81B	DM1	$e^+e^- \rightarrow \overline{K}K\pi$

[28] Assuming $\rho(1700)$ and ω radial excitations to be degenerate in mass.

$\Gamma(\eta\rho)/\Gamma_{total}$ — Γ_8/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.04		DONNACHIE	87B	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.02	58	ATKINSON	86B	OMEG	20–70 γp

$\Gamma(\eta\rho)/\Gamma(2(\pi^+\pi^-))$ — Γ_8/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.123±0.027	DELCOURT	82	DM1	$e^+e^- \rightarrow \pi^+\pi^-$ MM
~ 0.1	ASTON	80	OMEG	20–70 γp

$\Gamma(\pi^+\pi^-$ neutrals$)/\Gamma(2(\pi^+\pi^-))$ — $(\Gamma_3+\Gamma_4+0.709\Gamma_8)/\Gamma_5$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.6±0.4	[29] BALLAM	74	HBC	9.3 γp

[29] Upper limit. Background not subtracted.

$\Gamma(K\overline{K})/\Gamma(2(\pi^+\pi^-))$ — Γ_9/Γ_5

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.015±0.010		[30] DELCOURT	81B	DM1		$e^+e^- \rightarrow \overline{K}K$
<0.04	95	BINGHAM	72B	HBC	0	9.3 γp

[30] Assuming $\rho(1700)$ and ω radial excitations to be degenerate in mass.

$\Gamma(K\overline{K})/\Gamma(K\overline{K}^*(892) + c.c.)$ — Γ_9/Γ_7

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.052±0.026	BUON	82	DM1	$e^+e^- \rightarrow$ hadrons

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma(2(\pi^+\pi^-))$ — Γ_2/Γ_5

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1.0		DELCOURT	81B	DM1	$e^+e^- \rightarrow 2(\pi^+\pi^-)$
0.7 ±0.1	500	SCHACHT	74	STRC	5.5–18 $\gamma p \rightarrow p4\pi$
0.80		[31] BINGHAM	72B	HBC	9.3 $\gamma p \rightarrow p4\pi$

[31] The $\pi\pi$ system is in S-wave.

$\Gamma(\rho^0\pi^0\pi^0)/\Gamma(\rho^\pm\pi^\mp\pi^0)$ — Γ_3/Γ_4

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.10	ATKINSON	85B	OMEG		20–70 γp
<0.15	ATKINSON	82	OMEG	0	20–70 $\gamma p \rightarrow p4\pi$

$\rho(1700)$ REFERENCES

CLEGG 90 ZPHY C45 677 +Donnachie (LANC, MCHS)
BISELLO 89 PL B220 321 +Busetto+ (DM2 Collab.)
GESHKENBEIN 89 ZPHY 45 351 (ITEP)
ANTONELLI 88 PL B212 133 +Baldini+ (DM2 Collab.)
DIEKMAN 88 PRPL 159 101 (BONN)
FUKUI 88 PL B202 441 +Horikawa+ (SUGI, NAGO, KEK, KYOT, MIYA)
GOVORKOV 88 SJNP 48 150 (JINR)
Translated from YAF 48 237.
DONNACHIE 87 ZPHY C33 407 +Mirzaie (MCHS)
DONNACHIE 87B ZPHY C34 257 +Clegg (MCHS, LANC)
ATKINSON 86B ZPHY C30 531 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
ATKINSON 85B ZPHY C26 499 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
ERKAL 85 ZPHY C29 485 +Olsson (WISC)
ABE 84B PRL 53 751 +Bacon, Ballam+ (SLAC Hybrid Facility Photon Collab.)
ATKINSON 82 PL 108B 55 + (BONN, CERN, GLAS, LANC, MCHS, CURI+)
BUON 82 PL 118B 221 +Bisello, Bizot, Cordier, Delcourt+ (LALO, MONP)
CLELAND 82B NP B208 228 +Delfosse, Dorsaz, Gloor (DURH, GEVA, LAUS, PITT)
CORDIER 82 PL 109B 129 +Bisello, Bizot, Buon, Delcourt (LALO)
DELCOURT 82 PL 113B 93 +Bisello, Bizot, Buon, Cordier, Mane (LALO)
ASTON 81E NP B189 15 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)
DELCOURT 81B Bonn Conf. 205 (ORSA)
Also 82 PL 109B 129 Cordier, Bisello, Bizot, Buon, Delcourt (LALO)
DIBIANCA 81 PR D23 595 +Fickinger, Malko, Dado, Engler+ (CASE, CMU)
ASTON 80 PL 92B 215 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)
BACCI 80 PL 95B 139 +DeZorzi, Penso, Baldini-Celio+ (ROMA, FRAS)
BIZOT 80 Madison Conf. 546 +Bisello, Buon, Cordier, Delcourt+ (LALO, USTL)
KILLIAN 80 PR D21 3005 +Treadwell, Ahrens, Berkelman, Cassel+ (CORN)
ATIYA 79B PRL 43 1691 +Holmes, Knapp, Lee, Seto+ (COLU, ILL, FNAL)
BECKER 79 NP B151 46 +Blanar, Blum+ (MPIM, CERN, ZEEM, CRAC)
LANG 79 PR D19 956 +Mas-Parareda (GRAZ)
MARTIN 78C ANP 114 1 +Pennington (CERN)
COSTA... 77B PL 71B 345 Costa De Beauregard, Pire, Truong (EPOL)
FROGGATT 77 NP B129 89 +Petersen (GLAS, NORD)
ALEXANDER 75 PL 57B 487 +Benary, Gandsman, Lissauer+ (TELA)
BALLAM 74 NP B76 375 +Chadwick, Bingham, Fretter+ (SLAC, LBL, MPIM)
CONVERSI 74 PL 52B 493 +Paoluzi, Ceradini, Grilli+ (ROMA, FRAS)
SCHACHT 74 NP B81 205 +Derado, Fries, Park, Yount (MPIM)
DAVIER 73 NP B58 31 +Derado, Fries, Liu, Mozley, Odian, Park+ (SLAC)
EISENBERG 73 PL 43B 149 +Karshon, Mikenberg, Pitluck+ (REHO)
HYAMS 73 NP B64 134 +Jones, Weilhammer, Blum, Dietl+ (CERN, MPIM)
MONTANET 73 Erice School 518 (CERN)
BINGHAM 72B PL 41B 635 +Rabin, Rosenfeld, Smadja+ (LBL, UCB, SLAC) IGJP

OTHER RELATED PAPERS

ACHASOV 88C PLB 209 373 +Kozhevnikov (NOVO)
BRAU 88 PR D37 2379 +Franek+ (SLAC Hybrid Facility Photon Collab.) JP
CLEGG 88 ZPHY C40 313 +Donnachie (MCHS, LANC)
ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, TOKY)
ERKAL 86 ZPHY C31 615 +Olsson (WISC)
BARKOV 85 NP B256 365 +Chilingarov, Eidelman, Khazin, Lelchuk+ (NOVO)
BISELLO 85 LAL 85-15 +Augustin, Ajaltouni+ (PADO, LALO, CLER, FRAS)
ATKINSON 84C NP B243 1 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+) JP
ATKINSON 83B PL 127B 132 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
ATKINSON 83C NP B229 269 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
AUGUSTIN 83 LAL 83-21 +Ayach, Bisello, Baldini+ (LALO, PADO, FRAS)
SHAMBROO 82 PR D26 1 +Wilson, Anderson, Francis+ (HARV, EFI, ILL, OXF)
BARBER 80C ZPHY C4 169 +Dainton, Brodbeck, Brookes+ (DARE, LANC, SHEF)
KILLIAN 80 PR D21 3005 +Treadwell, Ahrens, Berkelman, Cassel+ (CORN)
COSME 76 PL 63B 352 +Courau, Dudelzak, Grelaud, Jean-Marie+ (ORSA)
FRENKIEL 72 NP B47 61 +Ghesquiere, Lillestol, Chung+ (CDEF, CERN)
ALVENSLEBEN 71 PRL 26 273 +Becker, Bertram, Chen+ (DESY, MIT) G
BRAUN 71 NP B30 213 +Fridman, Gerber, Givernaud+ (STRB) G
BULOS 71 PRL 26 149 +Busza, Kehoe, Beniston+ (SLAC, UMD, IBM, LBL) G
LAYSSAC 71 NC 6A 134 +Renard (MONP)

$X(1700)$
was $\eta(1700)$

$I^G(J^{PC}) = \text{even}^+(?^{?+})$

OMITTED FROM SUMMARY TABLE

Enhancement seen in the $\eta\pi\pi$ system produced in the radiative decay of the $J/\psi(1S)$. May contain significant substructure. Relation to other enhancements seen in radiative $J/\psi(1S)$ decay unclear (see HITLIN 83). Tentatively called $X(1700)$ by us.

$X(1700)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1700.0±45	EDWARDS	83B	CBAL	$J/\psi \to \eta\gamma 2\pi$

$X(1700)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
520±110	EDWARDS	83B	CBAL	$J/\psi \to \eta\gamma 2\pi$

$X(1700)$ REFERENCES

EDWARDS	83B	PRL 51 859	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
HITLIN	83	Cornell Conf. 746		(CIT)

$f_0(1710)$
was $\theta(1690)$

$I^G(J^{PC}) = 0^+(0^{++})$
J needs confirmation.

NOTE ON THE $f_0(1710)$

The $f_0(1710)$ is seen in the "gluon rich" radiative decay $J/\psi(1S) \to \gamma f_0(1710)$; therefore $C = +$. It decays into $\eta\eta$ and $K^0_S K^0_S$, which implies $I^G J^{PC} = 0^+(\text{even})^{++}$. In an amplitude analysis of the $K\overline{K}$ and $\pi^+\pi^-$ systems produced in J/ψ radiative decay, CHEN 91 finds a large spin-zero component for this particle (although a small component of spin two for the $K\overline{K}$ sample is not completely ruled out). This resonance is also observed in $K\overline{K}$ systems recoiling against ϕ and ω in hadronic $J/\psi(1S)$ decay [however, $J/\psi(1S) \to \omega f_0(1710)$ is rather controversial, according to FALVARD 88]. The $f_0(1710)$ is not seen in the radiative decay $J/\psi(1S) \to \gamma\rho^0\rho^0$ (BISELLO 89B), in agreement with the indication (BALTRUSAITIS 85G) that the $\rho\rho$ enhancement in this region is $J^P = 0^-$, hence unrelated to the $f_0(1710)$.

Clear evidence is seen for the first time in hadroproduction (ARMSTRONG 89D, 300 GeV/c pp central production of the $K\overline{K}$ system), both in K^+K^- and $K^0_S K^0_S$. Mass and width determinations are complicated since the mass spectra are dominated by the overlap with $f_2'(1525)$. The apparently large disagreement between the widths found by ARMSTRONG 89D in the two different channels ($\approx$ 180 MeV in K^+K^- and $\approx$ 100 MeV in $K^0_S K^0_S$) can be explained by the arbitrariness of the polynomial–exponential background shape which leads to a large systematic error for the width. Note that this resonance is not observed in the exclusive hypercharge-exchange reaction $K^-p \to K^0_S K^0_S \Lambda$ (ASTON 88D).

A partial-wave analysis of the $K^0_S K^0_S$ system (BOLONKIN 88) finds a D_0 wave ($J^{PC} = 2^{++}$) behavior near 1700 MeV, but its width ($\approx$ 30 MeV) is much narrower than the width observed in $J/\psi(1S)$ decays and in hadroproduction.

Note that this particle was named $f_2(1720)$ until the 1990 edition; see also the "Note on Non-$q\overline{q}$ Mesons."

$f_0(1710)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1709 ± 5 OUR AVERAGE				
1710 ±20	CHEN	91	MRK3	$J/\psi \to \gamma\pi^+\pi^-, \gamma K\overline{K}$
1713 ±10	ARMSTRONG	89D	OMEG	$300\ pp \to ppK^+K^-$
1706 ±10	ARMSTRONG	89D	OMEG	$300\ pp \to ppK^0_S K^0_S$
1707.0±10.0	AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+K^-$
1698 ±15	AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
1720 ±10 ±10	BALTRUSAIT...	87	MRK3	$J/\psi \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1700 ±15	BOLONKIN	88	SPEC	$40\ \pi^-p \to K^0_S K^0_S n$
1720 ±60	BOLONKIN	88	SPEC	$40\ \pi^-p \to K^0_S K^0_S n$
1638 ±10	[1] FALVARD	88	DM2	$J/\psi \to \phi K^+K^-$
1690 ± 4	[2] FALVARD	88	DM2	$J/\psi \to \phi K^+K^-$
1730 $^{+2}_{-10}$	[3,4] LONGACRE	86	MPS	$22\ \pi^-p \to n2K^0_S$
1742.0±15.0	WILLIAMS	84	MPSF	$200\ \pi^-N \to 2K^0_S X$
1670 ±50	BLOOM	83	CBAL	$J/\psi \to \gamma 2\eta$
1650 ±50	BURKE	82	MRK2	$J/\psi \to \gamma 2\rho$
1730.0±10 ±20	ETKIN	82C	MPS	$23\ \pi^-p \to n2K^0_S$
1708.0±30.0	FRANKLIN	82	MRK2	$e^+e^- \to \gamma K^+K^-$

[1] From an analysis ignoring interference with $f_2'(1525)$.
[2] From an analysis including interference with $f_2'(1525)$.
[3] From a partial-wave analysis of data using a K-matrix formalism with 5 poles, but assuming spin 2.
[4] Fit with constrained inelasticity.

$f_0(1710)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
146 ± 12 OUR AVERAGE	Error includes scale factor of 1.1.			
186 ± 30	CHEN	91	MRK3	$J/\psi \to \gamma\pi^+\pi^-, \gamma K\overline{K}$
181 ± 30	ARMSTRONG	89D	OMEG	$300\ pp \to ppK^+K^-$
104 ± 30	ARMSTRONG	89D	OMEG	$300\ pp \to ppK^0_S K^0_S$
166.4± 33.2	AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+K^-$
136 ± 28	AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
130 ± 20	BALTRUSAIT...	87	MRK3	$J/\psi \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
30 ± 20	BOLONKIN	88	SPEC	$40\ \pi^-p \to K^0_S K^0_S n$
350 ±150	BOLONKIN	88	SPEC	$40\ \pi^-p \to K^0_S K^0_S n$
148 ± 17	[5] FALVARD	88	DM2	$J/\psi \to \phi K^+K^-$
184 ± 6	[6] FALVARD	88	DM2	$J/\psi \to \phi K^+K^-$
122 $^{+74}_{-15}$	[7,8] LONGACRE	86	MPS	$22\ \pi^-p \to n2K^0_S$
57.0± 38.0	WILLIAMS	84	MPSF	$200\ \pi^-N \to 2K^0_S X$
160 ± 80	BLOOM	83	CBAL	$J/\psi \to \gamma 2\eta$
200 ±100	BURKE	82	MRK2	$J/\psi \to \gamma 2\rho$
200.0 $^{+156.0}_{-9.0}$	[9] ETKIN	82B	MPS	$23\ \pi^-p \to n2K^0_S$
156.0± 60.0	FRANKLIN	82	MRK2	$e^+e^- \to \gamma K^+K^-$

[5] From an analysis ignoring interference with $f_2'(1525)$.
[6] From an analysis including interference with $f_2'(1525)$.
[7] From a partial-wave analysis of data using a K-matrix formalism with 5 poles, but assuming spin 2.
[8] Fit with constrained inelasticity.
[9] From an amplitude analysis of the $K^0_S K^0_S$ system.

$f_0(1710)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}$	seen
Γ_2	$\eta\eta$	
Γ_3	$\pi\pi$	seen
Γ_4	$\rho\rho$	possibly seen
Γ_5	$\gamma\gamma$	

$f_0(1710)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\qquad \Gamma_1\Gamma_5/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
<0.11	95	[10] BEHREND	89C	CELL	$\gamma\gamma \to K^0_S K^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.48	95	ALBRECHT	90G	ARG	$\gamma\gamma \to K^+K^-$
<0.28	95	[10] ALTHOFF	85B	TASS	$\gamma\gamma \to K\overline{K}\pi$

[10] Assuming helicity 2.

$f_0(1710)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.38^{+0.09}_{-0.19}$	[11,12] LONGACRE 86	MPS	$22\ \pi^- p \to n2K^0_S$

$\Gamma(\eta\eta)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.18^{+0.03}_{-0.13}$	[11,12] LONGACRE 86	MPS	$22\ \pi^- p \to n2K^0_S$

$\Gamma(\pi\pi)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.039^{+0.002}_{-0.024}$	[11,12] LONGACRE 86	MPS	$22\ \pi^- p \to n2K^0_S$

$\Gamma(\pi\pi)/\Gamma(K\overline{K})$ — Γ_3/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.39±0.14	ARMSTRONG 91	OMEG	$300\ pp \to pp\pi\pi, ppKK$

[11] From a partial-wave analysis of data using a K-matrix formalism with 5 poles, but assuming spin 2.
[12] Fit with constrained inelasticity.

$f_0(1710)$ REFERENCES

ARMSTRONG 91 ZPHY C51 351 +Benayoun+ (ATHU, BARI, BIRM, CERN, CDEF)
CHEN 91 Hadron 91 Conf. (Mark III Collab.)
SLAC-PUB-5669
ALBRECHT 90G ZPHY C48 183 +Ehrlichmann, Harder+ (ARGUS Collab.)
ARMSTRONG 89D PL B227 186 +Benayoun (ATHU, BARI, BIRM, CERN, CDEF)
BEHREND 89C ZPHY C43 91 +Criegee, Dainton+ (CELLO Collab.)
AUGUSTIN 88 PRL 60 2238 +Calcaterra+ (DM2 Collab.)
BOLONKIN 88 NP B309 426 +Bloshenko, Gorin+ (ITEP, SERP)
FALVARD 88 PR D38 2706 +Ajaltouni+ (CLER, FRAS, LALO, PADO)
AUGUSTIN 87 ZPHY C36 369 +Cosme+ (LALO, CLER, FRAS, PADO)
BALTRUSAIT... 87 PR D35 2077 Baltrusaitis, Coffman, Dubois+ (Mark III Collab.)
LONGACRE 86 PL B177 223 +Etkin+ (BNL, BRAN, CUNY, DUKE, NDAM)
ALTHOFF 85B ZPHY C29 189 +Braunschweig, Kirschfink+ (TASSO Collab.)
WILLIAMS 84 PR D30 877 +Diamond+ (VAND, NDAM, TUFT, ARIZ, FNAL+)
BLOOM 83 ARNS 33 143 +Peck (SLAC, CIT)
BURKE 82 PRL 49 632 +Trilling, Abrams, Alam, Blocker+ (LBL, SLAC)
ETKIN 82B PR D25 1786 +Foley, Lai+ (BNL, CUNY, TUFT, VAND)
ETKIN 82C PR D25 2446 +Foley, Lai+ (BNL, CUNY, TUFT, VAND)
FRANKLIN 82 SLAC-254 (SLAC)

OTHER RELATED PAPERS

CHEN 91 Hadron 91 Conf. (Mark III Collab.)
SLAC-PUB-5669
PROKOSHKIN 91 Singapore Conf. (GAM2 Collab.)
Translated from SPD 36 155.
BISELLO 89B PR D39 701 Busetto+ (DM2 Collab.)
ASTON 88D NP B301 525 +Awaji, Bienz+ (SLAC, NAGO, CINC, TOKY)
AKESSON 86 NP B264 154 +Albrow, Almehed+ (Axial Field Spec. Collab.)
ARMSTRONG 86B PL 167B 133 +Bloodworth, Carney+ (ATHU, BARI, BIRM, CERN)
BALTRUSAIT... 86B PR D33 1222 Baltrusaitis, Coffman, Hauser+ (Mark III Collab.)
ALTHOFF 83 PL 121B 216 +Brandelik, Boerner, Burkhardt+ (TASSO Collab.)
BARNETT 83B PL 120B 455 +Blockus, Burka, Chien, Christian+ (JHU)
ALTHOFF 82 ZPHY C16 13 +Boerner, Burkhardt+ (TASSO Collab.)
BARNES 82 PL 116B 365 +Close (RHEL)
BARNES 82B NP B198 360 +Close, Monaghan (RHEL, OXF)
TANIMOTO 82 PL 116B 198 (BIEL)

$X(1740)$

$I^G = 0^+$

OMITTED FROM SUMMARY TABLE

Seen in hadronic interactions at large momentum transfer and with small cross sections $J^P = 0^+$ or 2^+.

$X(1740)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1744 ±15	[1] ALDE 91	GAM2	$38\ \pi^- p \to \eta\eta X$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1755.0± 8.0	ALDE 86C	GAM2	$38\ \pi^- p \to n2\eta$

[1] ALDE 91 combines all the GAMS-2000 data.

$X(1740)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<80	ALDE 91	GAM2	$38\ \pi^- p \to \eta\eta X$
<50	ALDE 86C	GAM2	$38\ \pi^- p \to n2\eta$

$X(1740)$ DECAY MODES

	Mode
Γ_1	$\eta\eta$
Γ_2	$\pi^0\pi^0$
Γ_3	$\eta\eta'$

$X(1740)$ BRANCHING RATIOS

$\Gamma(\pi^0\pi^0)/\Gamma(\eta\eta)$ — Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1	90	ALDE 91	GAM2	$38\ \pi^- p \to \eta\eta X$

$\Gamma(\eta\eta')/\Gamma(\eta\eta)$ — Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1	90	ALDE 91	GAM2	$38\ \pi^- p \to \eta\eta X$

$X(1740)$ REFERENCES

ALDE 91 PL B (to be pub.) + (GAM2 Collab.)
Translated from YAF 54 745.
ALDE 86C PL B182 105 +Binon, Bricman+ (SERP, BELG, LANL, LAPP)

$\eta(1760)$

$I^G(J^{PC}) = 0^+(0^{-+})$

OMITTED FROM SUMMARY TABLE

Seen at DCI in the 4π system. Needs confirmation.

$\eta(1760)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1760±11	320	[1] BISELLO 89B	DM2	$J/\psi \to 4\pi\gamma$

[1] Estimated by us from various fits.

$\eta(1760)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
60±16	320	[2] BISELLO 89B	DM2	$J/\psi \to 4\pi\gamma$

[2] Estimated by us from various fits.

$\eta(1760)$ REFERENCES

BISELLO 89B PR D39 701 Busetto+ (DM2 Collab.)

$\pi(1770)$

$I^G(J^{PC}) = 1^-(0^{-+})$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the diffractively produced 3π system. Needs confirmation.

$\pi(1770)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1770±30	1100	BELLINI 82	SPEC	−	$40\ \pi^- A \to 3\pi A$

$\pi(1770)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
310±50	1100	BELLINI 82	SPEC	−	$40\ \pi^- A \to 3\pi A$

$\pi(1770)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$f_0(1400)\pi$	dominant
Γ_2	$\rho\pi$	not seen

$\pi(1770)$ BRANCHING RATIOS

$\Gamma(f_0(1400)\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
dominant	BELLINI	82	SPEC	−	40 $\pi^- A \to 3\pi A$

$\Gamma(\rho\pi)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
not seen	BELLINI	82	SPEC	−	40 $\pi^- A \to 3\pi A$

$\pi(1770)$ REFERENCES

BELLINI 82 PRL 48 1697 +Frabetti, Ivanshin, Litkin+ (MILA, BGNA, JINR)

$\pi(1775)$

$I^G(J^{PC}) = 1^-(?^{-+})$

OMITTED FROM SUMMARY TABLE

Seen by CONDO 91 in the charge exchange photoproduction reactions $\gamma p \to (p\pi^+)(\pi^+\pi^-\pi^-)$, $\gamma p \to n\pi^+\pi^+\pi^-$.

$\pi(1775)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1776±13 OUR AVERAGE				
1763±20	CONDO	91	SHF	$\gamma p \to (p\pi^+)(\pi^+\pi^-\pi^-)$
1787±18	CONDO	91	SHF	$\gamma p \to n\pi^+\pi^+\pi^-$

$\pi(1775)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
155±40 OUR AVERAGE				
192±60	CONDO	91	SHF	$\gamma p \to (p\pi^+)(\pi^+\pi^-\pi^-)$
118±60	CONDO	91	SHF	$\gamma p \to n\pi^+\pi^+\pi^-$

$\pi(1775)$ DECAY MODES

	Mode
Γ_1	$\rho\pi$
Γ_2	$f_2(1270)\pi$

$\pi(1775)$ BRANCHING RATIOS

$\Gamma(\rho\pi)/\Gamma(f_2(1270)\pi)$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
1.43±0.26 OUR AVERAGE				
1.3 ±0.3	CONDO	91	SHF	$\gamma p \to (p\pi^+)(\pi^+\pi^-\pi^-)$
1.8 ±0.5	CONDO	91	SHF	$\gamma p \to n\pi^+\pi^+\pi^-$

$\pi(1775)$ REFERENCES

CONDO 91 PR D43 2787 +Handler+ (SLAC Hybrid Collab.)

$f_2(1810)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

From an amplitude analysis of the K^+K^- system seen in $\pi^- p \to K^+K^- n$ at 10 GeV/c. Confirmed by LONGACRE 86. Seen also in $\pi^+\pi^- \to 2\pi^0$ amplitude analysis (CASON 82), in the partial-wave analysis of the $\eta\eta$ system (ALDE 86D) and in the $4\pi^0$ mass spectrum (ALDE 88).

$f_2(1810)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1810 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1858.0^{+18.0}_{-71.0}$	[1] LONGACRE	86	MPS	Compilation
1799.0±15.0	CASON	82	STRC	8 $\pi^+ p \to p\pi^+ 2\pi^0$
$1857.0^{+35.0}_{-24.0}$	[2] COSTA...	80	OMEG	10 $\pi^- p \to K^+K^- n$

[1] From a partial-wave analysis of data using a K-matrix formalism with 5 poles. Includes compilation of several other experiments.
[2] Error increased by spread of two solutions. Included in LONGACRE 86 global analysis.

$f_2(1810)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$388.0^{+15.0}_{-21.0}$	[3] LONGACRE	86	MPS	Compilation
$280.0^{+42.0}_{-35.0}$	CASON	82	STRC	8 $\pi^+ p \to p\pi^+ 2\pi^0$
$185.0^{+102.0}_{-139.0}$	[4] COSTA...	80	OMEG	10 $\pi^- p \to K^+K^- n$

[3] From a partial-wave analysis of data using a K-matrix formalism with 5 poles. Includes compilation of several other experiments.
[4] Error increased by spread of two solutions. Included in LONGACRE 86 global analysis.

$f_2(1810)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	$(21.0^{+2.0}_{-3.0})$ %
Γ_2	$\eta\eta$	$(8.0^{+28.0}_{-3.0}) \times 10^{-3}$
Γ_3	$4\pi^0$	
Γ_4	K^+K^-	$(3.0^{+19.0}_{-2.0}) \times 10^{-3}$

$f_2(1810)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.21^{+0.02}_{-0.03}$	[5] LONGACRE	86	MPS	Compilation
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.44 ±0.03	[6] CASON	82	STRC	8 $\pi^+ p \to p\pi^+ 2\pi^0$

$\Gamma(\eta\eta)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.008^{+0.028}_{-0.003}$	[5] LONGACRE	86	MPS	Compilation

$\Gamma(K^+K^-)/\Gamma_{total}$ Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.003^{+0.019}_{-0.002}$	[5] LONGACRE	86	MPS	Compilation
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	COSTA...	80	OMEG	10 $\pi^- p \to K^+K^- n$

[5] From a partial-wave analysis of data using a K-matrix formalism with 5 poles. Includes compilation of several other experiments.
[6] Included in LONGACRE 86 global analysis.

$f_2(1810)$ REFERENCES

ALDE 88 PL B201 160 +Bellazzini, Binon+ (SERP, BELG, LANL, LAPP, PISA)
ALDE 86D NP B269 485 +Binon, Bricman+ (BELG, LAPP, SERP, CERN)
LONGACRE 86 PL B177 223 +Etkin+ (BNL, BRAN, CUNY, DUKE, NDAM)
CASON 82 PRL 48 1316 +Biswas, Baumbaugh, Bishop+ (NDAM, ANL)
COSTA... 80 NP B175 402 Costa De Beauregard+ (BARI, BONN, CERN+)

OTHER RELATED PAPERS

AKER 91 PL B260 249 +Amsler, Peters+ (CBAR Collab.)
CASON 83 PR D28 1586 +Cannata, Baumbaugh, Bishop+ (NDAM, ANL)
ETKIN 82B PR D25 1786 +Foley, Lai+ (BNL, CUNY, TUFT, VAND)

$X(1814)$

$I^G(J^{PC}) = 1^-(?^{??})$

OMITTED FROM SUMMARY TABLE

Observed in coherent production of a carbon nucleus. $J^{PC} = 1^{++}$ and 2^{-+} preferred.

$X(1814)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1814±10±23	426 ± 57	BITYUKOV	91	VES	36 $\pi^- N \to \pi^- \eta\eta N$

$X(1814)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
205±18±32	426 ± 57	BITYUKOV	91	VES	36 $\pi^- N \to \pi^- \eta\eta N$

$X(1814)$ DECAY MODES

	Mode
Γ_1	$\pi\eta\eta$
Γ_2	$\pi\eta\eta'(958)$

$X(1814)$ BRANCHING RATIOS

$\Gamma(\pi\eta\eta'(958))/\Gamma(\pi\eta\eta)$ Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.3 ±0.1	426 ± 57	BITYUKOV	91	VES	36 $\pi^- N \to \pi^- \eta\eta N$

$X(1814)$ REFERENCES

BITYUKOV 91 PL B268 137 +Borisov+ (SERP, TBIL)

$\phi_3(1850)$

was $X(1850)$
was $\phi_J(1850)$

$I^G(J^{PC}) = 0^-(3^{--})$

Seen in the $K\overline{K}$ and $K\overline{K}\pi$ mass distributions.

$\phi_3(1850)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1854 ± 7 OUR AVERAGE					
1855 ±10		ASTON	88E	LASS	11 $K^- p \to K^- K^+ \Lambda$, $K^0_S K^\pm \pi^\mp \Lambda$
$1870.0^{+30.0}_{-20.0}$	430	ARMSTRONG	82	OMEG	18.5 $K^- p \to K^- K^+ \Lambda$
1850.0±10.0	123	ALHARRAN	81B	HBC	8.25 $K^- p \to K\overline{K}\Lambda$

$\phi_3(1850)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
87^{+28}_{-23} OUR AVERAGE	Error includes scale factor of 1.2.				
64 ±31		ASTON	88E	LASS	11 $K^- p \to K^- K^+ \Lambda$, $K^0_S K^\pm \pi^\mp \Lambda$
$160.0^{+90.0}_{-50.0}$	430	ARMSTRONG	82	OMEG	18.5 $K^- p \to K^- K^+ \Lambda$
$80.0^{+40.0}_{-30.0}$	123	ALHARRAN	81B	HBC	8.25 $K^- p \to K\overline{K}\Lambda$

$\phi_3(1850)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}$	seen
Γ_2	$K\overline{K}^*(892)$ + c.c.	seen

$\phi_3(1850)$ BRANCHING RATIOS

$\Gamma(K\overline{K}^*(892) + \text{c.c.})/\Gamma(K\overline{K})$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
$0.55^{+0.85}_{-0.45}$	ASTON	88E	LASS	11 $K^- p \to K^- K^+ \Lambda$, $K^0_S K^\pm \pi^\mp \Lambda$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.8 ±0.4	ALHARRAN	81B	HBC	8.25 $K^- p \to K\overline{K}\pi\Lambda$

$\phi_3(1850)$ REFERENCES

ASTON 88E PL B208 324 +Awaji, Biewz+ (SLAC, NAGO, CINC, TOKY) IGJPC
ARMSTRONG 82 PL 110B 77 +Baubillier+ (BARI, BIRM, CERN, MILA, LPNP+) JP
ALHARRAN 81B PL 101B 357 +Amirzadeh+ (BIRM, CERN, GLAS, MICH, LPNP)

OTHER RELATED PAPERS

CORDIER 82B PL 110B 335 +Bisello, Bizot, Buon, Delcourt, Fayard+ (LALO)
ASTON 80B PL 92B 219 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)

$\eta_2(1870)$

$I^G(J^{PC}) = 0^+(2^{-+})$

OMITTED FROM SUMMARY TABLE

Reported by FEINDT 91 at the SINGAPORE 91 conference. Based on CELLO and CRYSTAL BALL results.

$\eta_2(1870)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1861±40 OUR AVERAGE				
1876±35±45	FEINDT	91	CBAL	$\gamma\gamma \to \eta\pi^0\pi^0$
1850±50	FEINDT	91	CELL	$\gamma\gamma \to \eta\pi^+\pi^-$

$\eta_2(1870)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
229± 90±33	FEINDT	91	CBAL	$\gamma\gamma \to \eta\pi^0\pi^0$
~ 360	FEINDT	91	CELL	$\gamma\gamma \to \eta\pi^+\pi^-$

$\eta_2(1870)$ DECAY MODES

	Mode
Γ_1	$\eta\pi\pi$
Γ_2	$a_2(1320)\pi$
Γ_3	$f_0(975)\pi$

$\eta_2(1870)$ REFERENCES

FEINDT 91 Singapore Conf. 537

OTHER RELATED PAPERS

KARCH 90 PL B249 353 +Antreasyan, Bartels+ (Crystal Ball Collab.)

$X(1910)$

$I^G(J^{PC}) = 0^+(?^{?+})$

OMITTED FROM SUMMARY TABLE

We list here several bumps seen in the mass distributions of different final states.

$X(1910)$ MASS

VALUE (MeV)	DOCUMENT ID
≈ 1910 OUR ESTIMATE	

$X(1910)$ $4\pi^0$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1806±10	1600 ± 100	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$
1870±40		ALDE	86D	GAM4	$100\ \pi^- p \to 4\gamma n$

$X(1910)$ $\omega\omega$ MODE

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1924±14		[1] ALDE	90	GAM2	$38\ \pi^- p \to n\omega\omega$
1956±20	90	ALDE	89B	GAM2	$38\ \pi^- p \to n\omega\omega$

[1] This result supersedes ALDE 89B.

$X(1910)$ $\eta\eta'$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1911±10	[2] ALDE	91B	GAM2	$38\ \pi^- p \to \eta\eta' n$

[2] This result supersedes ALDE 89, PROKOSHKIN 90

$X(1910)$ WIDTH

VALUE (MeV)	DOCUMENT ID
≈ 100 OUR ESTIMATE	

$X(1910)$ $4\pi^0$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
190±20	1600 ± 100	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$
250±30		ALDE	86D	GAM4	$100\ \pi^- p \to 4\gamma n$

$X(1910)$ $\omega\omega$ MODE

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
91±50		[3] ALDE	90	GAM2	$38\ \pi^- p \to n\omega\omega$
220±60	90	ALDE	89B	GAM2	$38\ \pi^- p \to n\omega\omega$

[3] This result supersedes ALDE 89B.

$X(1910)$ $\eta\eta'$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
90±35	[4] ALDE	91B	GAM2	$38\ \pi^- p \to \eta\eta' n$

[4] This result supersedes ALDE 89, PROKOSHKIN 90

$X(1910)$ DECAY MODES

	Mode
Γ_1	$4\pi^0$
Γ_2	$\pi\pi$
Γ_3	$\pi^0\pi^0$
Γ_4	$K^0_S K^0_S$
Γ_5	$\eta\eta$
Γ_6	$\omega\omega$
Γ_7	$\eta\eta'$
Γ_8	$\eta\pi\pi$

$X(1910)$ BRANCHING RATIOS

$\Gamma(\pi^0\pi^0)/\Gamma(4\pi^0)$ — Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.25	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$

$\Gamma(4\pi^0)/\Gamma(\eta\eta)$ — Γ_1/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.8±0.3	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$

$\Gamma(\omega\omega)/\Gamma_{total}$ — Γ_6/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	ALDE	89B	GAM2	$38\ \pi^- p \to n\omega\omega$

$\Gamma(\pi^0\pi^0)/\Gamma(\eta\eta')$ — Γ_3/Γ_7

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.1	ALDE	89	GAM2	$38\pi^- p \to n\eta\eta'$

$\Gamma(\eta\eta)/\Gamma(\eta\eta')$ — Γ_5/Γ_7

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	90	[5] ALDE	91B	GAM2	$38\pi^- p \to n\eta\eta'$

[5] This result supersedes ALDE 89, PROKOSHKIN 90

$\Gamma(K^0_S K^0_S)/\Gamma(\eta\eta')$ — Γ_4/Γ_7

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.066	90	BALOSHIN	86	SPEC	$40\pi p \to K^0_S K^0_S n$

$X(1910)$ REFERENCES

ALDE 91B SJNP 54 +Binon+ (SERP, BELG, LANL, LAPP, PISA, KEK)
Translated from YAF 54 751.
ALDE 90 PL B241 600 +Binon+ (SERP, BELG, LANL, LAPP, PISA, KEK)
PROKOSHKIN 90 Hadron 89 Conf. p 27 (SERP, BELG, LANL, LAPP, PISA, KEK)
ALDE 89 PL B216 447 +Binon, Bricman, Donskov+ (SERP, BELG, LANL, LAPP)
ALDE 89B PL B216 451 +Binon, Bricman+ (SERP, BELG, LANL, LAPP, TBIL)
ALDE 87 PL B198 286 +Binon, Bricman+ (LANL, BRUX, SERP, LAPP)
ALDE 86D NP B269 485 +Binon, Bricman+ (BELG, LAPP, SERP, CERN)
BALOSHIN 86 SJNP 43 959 +Barkov, Bolonkin, Vladimirskii, Grigoriev+ (ITEP)
Translated from YAF 43 1487.

$X(1950)$

$I^G(J^{PC}) = ?^?(?^{??})$

OMITTED FROM SUMMARY TABLE

Seen by (BIENZ 90) in a $K^*(892)\,\overline{K}^*(892)$ effective mass distribution; $J^{PC} = 0^{-+}$ is disfavored. Needs confirmation.

$X(1950)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1950±15	ASTON	91	LASS	0	$11\ K^- p \to \Lambda K \overline{K} \pi\pi$

$X(1950)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
250±50	ASTON	91	LASS	0	$11\ K^- p \to \Lambda K \overline{K} \pi\pi$

$X(1950)$ DECAY MODES

	Mode
Γ_1	$K^*(892)\overline{K}^*(892)$

$X(1950)$ BRANCHING RATIOS

$\Gamma(K^*(892)\overline{K}^*(892))/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	ASTON	91	LASS	0	$11\ K^- p \to \Lambda K \overline{K} \pi\pi$

$X(1950)$ REFERENCES

ASTON 91 NP B21 5 (suppl) +Awaji+ (LASS Collab.)
BIENZ 90 SLAC 369 (LASS Collab.)

OTHER RELATED PAPERS

BIENZ 90 SLAC 369 (LASS Collab.)
ALBRECHT 88N PL B212 528 + (ARGUS Collab.)
ALBRECHT 87Q PL B198 255 +Binder+ (ARGUS Collab.)
ARMSTRONG 87C ZPHY C34 33 +Bloodworth+ (CERN, BIRM, BARI, ATHU, LPNP)

$f_2(2010)$
was $g_T(2010)$

$I^G(J^{PC}) = 0^+(2^{++})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$f_2(2010)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2011 $^{+62}_{-76}$	[1] ETKIN	88	MPS	$22\ \pi^- p \rightarrow \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1980 ± 20	[2] BOLONKIN	88	SPEC	$40\ \pi^- p \rightarrow K^0_S K^0_S n$
$2050.0^{+\ 90.0}_{-\ 50.0}$	ETKIN	85	MPS	$22\ \pi^- p \rightarrow 2\phi n$
$2120.0^{+\ 20.0}_{-120.0}$	LINDENBAUM	84	RVUE	
2160.0 ± 50.0	ETKIN	82	MPS	$16\ \pi^- p \rightarrow 2\phi n$

[1] Includes data of ETKIN 85. The percentage of the resonance going into $\phi\phi$ 2^{++} S_2, D_2, and D_0 is 98^{+1}_{-3}, 0^{+1}_{-0}, and 2^{+2}_{-1}, respectively.
[2] Statistically very weak, only 1.4 s.d.

$f_2(2010)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
202 $^{+67}_{-62}$	[3] ETKIN	88	MPS	$22\ \pi^- p \rightarrow \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
145 ± 50	[4] BOLONKIN	88	SPEC	$40\ \pi^- p \rightarrow K^0_S K^0_S n$
$200.0^{+160.0}_{-\ 50.0}$	ETKIN	85	MPS	$22\ \pi^- p \rightarrow 2\phi n$
$300.0^{+150.0}_{-\ 50.0}$	LINDENBAUM	84	RVUE	
310.0 ± 70.0	ETKIN	82	MPS	$16\ \pi^- p \rightarrow 2\phi n$

[3] Includes data of ETKIN 85.
[4] Statistically very weak, only 1.4 s.d.

$f_2(2010)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\phi\phi$	seen

$f_2(2010)$ REFERENCES

BOLONKIN	88	NP B309 426	+Bloshenko, Gorin+	(ITEP, SERP)
ETKIN	88	PL B201 568	+Foley, Lindenbaum+	(BNL, CUNY)
ETKIN	85	PL 165B 217	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
LINDENBAUM	84	CNPP 13 285		(CUNY)
ETKIN	82	PRL 49 1620	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
Also	83	Brighton Conf. 351	Lindenbaum	(BNL, CUNY)

OTHER RELATED PAPERS

ARMSTRONG	89B	PL B221 221	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, LPNP)
GREEN	86	PRL 56 1639	+Lai+	(FNAL, ARIZ, FSU, NDAM, TUFT, VAND+)
BOOTH	84	NP B242 51	+Ballance, Carroll, Donald+	(LIVP, GLAS, CERN)

$a_4(2040)$

$I^G(J^{PC}) = 1^-(4^{++})$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the $K\overline{K}$ and $\pi^+\pi^-\pi^0$ systems. Needs confirmation.

$a_4(2040)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2037 ±26 OUR AVERAGE					
2040.0 ± 30.0	[1] CLELAND	82B	SPEC	±	$50\ \pi p \rightarrow K^0_S K^{\pm} p$
2030.0 ± 50.0	[2] CORDEN	78C	OMEG	0	$15\ \pi^- p \rightarrow 3\pi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1903.0 ± 10.0	[3] BALDI	78	SPEC	−	$10\ \pi^- p \rightarrow p K^0_S K^-$

[1] From an amplitude analysis.
[2] $J^P = 4^+$ is favored, though $J^P = 2^+$ cannot be excluded.
[3] From a fit to the Y^0_8 moment. Limited by phase space.

$a_4(2040)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
427 ±120 OUR AVERAGE					
380.0 ± 150.0	[4] CLELAND	82B	SPEC	±	$50\ \pi p \rightarrow K^0_S K^{\pm} p$
510.0 ± 200.0	[5] CORDEN	78C	OMEG	0	$15\ \pi^- p \rightarrow 3\pi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
166.0 ± 43.0	[6] BALDI	78	SPEC	−	$10\ \pi^- p \rightarrow p K^0_S K^-$

[4] From an amplitude analysis.
[5] $J^P = 4^+$ is favored, though $J^P = 2^+$ cannot be excluded.
[6] From a fit to the Y^0_8 moment. Limited by phase space.

$a_4(2040)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}$	seen
Γ_2	$\pi^+\pi^-\pi^0$	seen

$a_4(2040)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	BALDI	78	SPEC	±	$10\ \pi^- p \rightarrow K^0_S K^- p$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	CORDEN	78C	OMEG	0	$15\ \pi^- p \rightarrow 3\pi n$

$a_4(2040)$ REFERENCES

CLELAND	82B	NP B208 228	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
BALDI	78	PL 74B 413	+Bohringer, Dorsaz, Hungerbuhler+	(GEVA) JP
CORDEN	78C	NP B136 77	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC) JP

OTHER RELATED PAPERS

DELFOSSE	81	NP B183 349	+Guisan, Martin, Muhlemann, Weill+	(GEVA, LAUS)

$a_3(2050)$
was $A(2050)$

$I^G(J^{PC}) = 1^-(3^{++})$

OMITTED FROM SUMMARY TABLE

Formerly called A_4 or π. Needs confirmation.

$a_3(2050)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2080±40	208	KALELKAR	75	HBC	+	$15\ \pi^+ p \to p\pi^+\rho_3$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
~ 2100		ANTIPOV	77	CIBS	−	$25\ \pi^- p \to p\pi^-\rho_3$
2214±15		BALTAY	77	HBC	0	$15\ \pi^- p \to \Delta^{++} 3\pi$

$a_3(2050)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
340±80	208	KALELKAR	75	HBC	+	$15\ \pi^+ p \to p\pi^+\rho_3$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
~ 500		ANTIPOV	77	CIBS	−	$25\ \pi^- p \to p\pi^-\rho_3$
355±21		BALTAY	77	HBC	0	$15\ \pi^- p \to \Delta^{++} 3\pi$

$a_3(2050)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	3π	
Γ_2	$\rho_3(1690)\pi$	dominant

$a_3(2050)$ BRANCHING RATIOS

$\Gamma(\rho_3(1690)\pi)/\Gamma(3\pi)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
dominant	KALELKAR	75	HBC	+	$15\ \pi^+ p \to p 3\pi$

$a_3(2050)$ REFERENCES

ANTIPOV 77 NP B119 45 +Busnello, Damgaard, Kienzle+ (SERP, GEVA)
BALTAY 77 PRL 39 591 +Cautis, Kalelkar (COLU) JP
KALELKAR 75 Nevis 207 Thesis (COLU)

OTHER RELATED PAPERS

HARRIS 81 ZPHY C9 275 +Dunn, Lubatti, Moriyasu, Podolsky+ (SEAT, UCB)
HUSON 68 PL 28B 208 +Lubatti, Six, Veillet+ (ORSA, MILA, UCLA)
DANYSZ 67B NC 51A 801 +French, Simak (CERN)

$f_4(2050)$
was $h(2030)$

$I^G(J^{PC}) = 0^+(4^{++})$

$f_4(2050)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2049 ±10 OUR AVERAGE		Error includes scale factor of 1.2.			
2060 ±20		ALDE	90	GAM2	$38\ \pi^- p \to n\omega\omega$
2038 ±30		AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
2086 ±15		BALTRUSAIT...	87	MRK3	$J/\psi \to \gamma\pi^+\pi^-$
2000.0±60.0		ALDE	86D	GAM4	$100\ \pi^- p \to n2\eta$
2020.0±20.0	40k	[1] BINON	84B	GAM2	$38\ \pi^- p \to n2\pi^0$
2015.0±28.0		[1] CASON	82	STRC	$8\ \pi^+ p \to p\pi^+ 2\pi^0$
2031.0^{+25}_{-36}		ETKIN	82B	MPS	$23\ \pi^- p \to n2K^0_S$
2020 ±30	700	APEL	75	NICE	$40\ \pi^- p \to n2\pi^0$
2050 ±25		BLUM	75	ASPK	$18.4\ \pi^- p \to nK^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1978.0± 5.0		[2] ALPER	80	CNTR	$62\ \pi^- p \to K^+K^- n$
2040.0±10.0		[2] ROZANSKA	80	SPRK	$18\ \pi^- p \to p\bar{p}n$
1935.0±13.0		[2] CORDEN	79	OMEG	$12\text{–}15\ \pi^- p \to n2\pi$
1988.0± 7.0		EVANGELISTA	79B	OMEG	$10\ \pi^- p \to K^+K^- n$
1922.0±14.0		[3] ANTIPOV	77	CIBS	$25\ \pi^- p \to p3\pi$

[1] From amplitude analysis of reaction $\pi^+\pi^- \to 2\pi^0$.
[2] $I(J^P) = 0(4^+)$ from amplitude analysis assuming one-pion exchange.
[3] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

$f_4(2050)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
203 ± 12 OUR AVERAGE					
170 ± 60		ALDE	90	GAM2	$38\ \pi^- p \to n\omega\omega$
304 ± 60		AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
210 ± 63		BALTRUSAIT...	87	MRK3	$J/\psi \to \gamma\pi^+\pi^-$
400.0±100.0		ALDE	86D	GAM4	$100\ \pi^- p \to n2\eta$
240.0± 40.0	40k	[4] BINON	84B	GAM2	$38\ \pi^- p \to n2\pi^0$
190.0± 14.0		DENNEY	83	LASS	$10\ \pi^+ n/\pi^+ p$
$186.0^{+103.0}_{-58.0}$		[4] CASON	82	STRC	$8\ \pi^+ p \to p\pi^+ 2\pi^0$
305.0^{+36}_{-119}		ETKIN	82B	MPS	$23\ \pi^- p \to n2K^0_S$
180 ± 60	700	APEL	75	NICE	$40\ \pi^- p \to n2\pi^0$
$225\ ^{+120}_{-70}$		BLUM	75	ASPK	$18.4\ \pi^- p \to nK^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
243.0± 16.0		[5] ALPER	80	CNTR	$62\ \pi^- p \to K^+K^- n$
140.0± 15.0		[5] ROZANSKA	80	SPRK	$18\ \pi^- p \to p\bar{p}n$
263.0± 57.0		[5] CORDEN	79	OMEG	$12\text{–}15\ \pi^- p \to n2\pi$
100.0± 28.0		EVANGELISTA	79B	OMEG	$10\ \pi^- p \to K^+K^- n$
107.0± 56.0		[6] ANTIPOV	77	CIBS	$25\ \pi^- p \to p3\pi$

[4] From amplitude analysis of reaction $\pi^+\pi^- \to 2\pi^0$.
[5] $I(J^P) = 0(4^+)$ from amplitude analysis assuming one-pion exchange.
[6] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

$f_4(2050)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\omega\omega$	(25 ±6) %
Γ_2	$\pi\pi$	(17.0±1.5) %
Γ_3	$K\bar{K}$	$(6.8^{+3.4}_{-1.8}) \times 10^{-3}$
Γ_4	$\eta\eta$	$(2.1\pm0.8) \times 10^{-3}$
Γ_5	$4\pi^0$	< 1.2 %
Γ_6	$\gamma\gamma$	

$f_4(2050)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\bar{K}) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_3\Gamma_6/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.29	95	ALTHOFF	85B	TASS	$\gamma\gamma \to K\bar{K}\pi$

$\Gamma(\pi\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_2\Gamma_6/\Gamma$

VALUE (keV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.1	95	13 ± 4	OEST	90	JADE	$e^+e^- \to e^+e^-\pi^0\pi^0$

$f_4(2050)$ BRANCHING RATIOS

$\Gamma(\omega\omega)/\Gamma(\pi\pi)$ — Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
1.5 ±0.3	ALDE	90	GAM2	$38\ \pi^- p \to n\omega\omega$

$\Gamma(\pi\pi)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.170±0.015 OUR AVERAGE				
0.18 ±0.03	[7] BINON	83C	GAM2	$38\ \pi^- p \to n4\gamma$
0.16 ±0.03	[7] CASON	82	STRC	$8\ \pi^+ p \to p\pi^+ 2\pi^0$
0.17 ±0.02	[7] CORDEN	79	OMEG	$12\text{–}15\ \pi^- p \to n2\pi$

[7] Assuming one pion exchange.

$\Gamma(K\bar{K})/\Gamma(\pi\pi)$ — Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.04\ ^{+0.02}_{-0.01}}$	ETKIN	82B	MPS	$23\ \pi^- p \to n2K^0_S$

$\Gamma(\eta\eta)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
2.1±0.8	ALDE	86D	GAM4	$100\ \pi^- p \to n4\gamma$

$\Gamma(4\pi^0)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
<0.012	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$

$f_4(2050)$ REFERENCES

ALDE	90	PL B241 600	+Binon+	(SERP, BELG, LANL, LAPP, PISA, KEK)
OEST	90	ZHPY C47 343	+Olsson+	(JADE Collab.)
ALDE	87	PL B198 286	+Binon, Bricman+	(LANL, BRUX, SERP, LAPP)
AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
BALTRUSAIT...	87	PR D35 2077	Baltrusaitis, Coffman, Dubois+	(Mark III Collab.)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN)
ALTHOFF	85B	ZPHY C29 189	+Braunschweig, Kirschfink+	(TASSO Collab.)
BINON	84B	LNC 39 41	+Donskov, Duteil, Gouanere+	(SERP, BELG, LAPP)
BINON	83C	SJNP 38 723	+Gouanere, Donskov, Duteil+	(SERP, BRUX+)
		Translated from YAF 38 1199.		
DENNEY	83	PR D28 2726	+Cranley, Firestone, Chapman+	(IOWA, MICH)
CASON	82	PRL 48 1316	+Biswas, Baumbaugh, Bishop+	(NDAM, ANL)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFT, VAND)
ALPER	80	PL 94B 422	+Becker+	(AMST, CERN, CRAC, MPIM, OXF+)
ROZANSKA	80	NP B162 505	+Blum, Dietl, Grayer, Lorenz+	(MPIM, CERN)
CORDEN	79	NP B157 250	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC) JP
EVANGELISTA	79B	NP B154 381	+	(BARI, BONN, CERN, DARE, GLAS, LIVP+)
ANTIPOV	77	NP B119 45	+Busnello, Damgaard, Kienzle+	(SERP, GEVA)
APEL	75	PL 57B 398	+Augenstein+	(KARL, PISA, SERP, WIEN, CERN) JP
BLUM	75	PL 57B 403	+Chabaud, Dietl, Garelick, Grayer+	(CERN, MPIM) JP

OTHER RELATED PAPERS

CASON	83	PR D28 1586	+Cannata, Baumbaugh, Bishop+	(NDAM, ANL)
GOTTESMAN	80	PR D22 1503	+Jacobs+	(SYRA, BRAN, BNL, CINC)
WAGNER	74	London Conf. 2 27		(MPIM)

$\eta(2100)$

$I^G(J^{PC}) = 0^+(0^{-+})$

OMITTED FROM SUMMARY TABLE

Seen by BISELLO 89B in the radiative decay $J/\psi \rightarrow \gamma\rho\rho$ and by BISELLO 86B and BAI 90B in $J/\psi \rightarrow \gamma\phi\phi$. $J^P = 0^-$ strongly favoured in both modes.

$\eta(2100)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
≈ 2100 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2230±25±15		BAI	90B MRK3	$J/\psi \rightarrow \gamma K^+K^-K^+K^-$
2214±20±13		BAI	90B MRK3	$J/\psi \rightarrow \gamma K^+K^-K^0_S K^0_L$
2103±50	586	[1] BISELLO	89B DM2	$J/\psi \rightarrow 4\pi\gamma$
~ 2220		BISELLO	86B DM2	$J/\psi \rightarrow \gamma K^+K^-K^+K^-$

[1] Estimated by us from various fits.

$\eta(2100)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
$167^{+\ 50}_{-\ 60}$ OUR AVERAGE				
$150^{+300}_{-\ 60}\pm60$		BAI	90B MRK3	$J/\psi \rightarrow \gamma K^+K^-K^+K^-$
187± 75	586	[2] BISELLO	89B DM2	$J/\psi \rightarrow 4\pi\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 80		BISELLO	86B DM2	$J/\psi \rightarrow \gamma K^+K^-K^+K^-$

[2] Estimated by us from various fits.

$\eta(2100)$ REFERENCES

BAI	90B	PRL 65 1309	+Blaylock+	(Mark III Collab.)
BISELLO	89B	PR D39 701	Busetto+	(DM2 Collab.)
BISELLO	86B	PL B179 294	+Busetto, Castro, Limentani+	(DM2 Collab.)

$\pi_2(2100)$ was $A(2100)$

$I^G(J^{PC}) = 1^-(2^{-+})$

OMITTED FROM SUMMARY TABLE

Seen in the $\rho\pi$, $f_0(1400)\pi$, and $f_2(1270)\pi$ $J^P = 2^-$ waves of the diffractively produced 3π system. Needs confirmation.

$\pi_2(2100)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2100±150	[1] DAUM 81B	CNTR	63,94 $\pi^- p \rightarrow 3\pi X$

[1] From a two-resonance fit to four 2^-0^+ waves.

$\pi_2(2100)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
651±50	[2] DAUM 81B	CNTR	63,94 $\pi^- p \rightarrow 3\pi X$

[2] From a two-resonance fit to four 2^-0^+ waves.

$\pi_2(2100)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	3π	seen
Γ_2	$\rho\pi$	seen
Γ_3	$f_2(1270)\pi$	seen
Γ_4	$f_0(1400)\pi$	seen

$\pi_2(2100)$ BRANCHING RATIOS

$\Gamma(\rho\pi)/\Gamma(3\pi)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.19±0.05	[3] DAUM 81B	CNTR	63,94 $\pi^- p$

$\Gamma(f_2(1270)\pi)/\Gamma(3\pi)$ — Γ_3/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.36±0.09	[3] DAUM 81B	CNTR	63,94 $\pi^- p$

$\Gamma(f_0(1400)\pi)/\Gamma(3\pi)$ — Γ_4/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.45±0.07	[3] DAUM 81B	CNTR	63,94 $\pi^- p$

D-wave/S-wave RATIO FOR $\pi_2(2100) \rightarrow f_2(1270)\pi$

VALUE	DOCUMENT ID	TECN	COMMENT
0.39±0.23	[3] DAUM 81B	CNTR	63,94 $\pi^- p$

[3] From a two-resonance fit to four 2^-0^+ waves.

$\pi_2(2100)$ REFERENCES

DAUM	81B	NP B182 269	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)

$\rho(2110)$

$I^G(J^{PC}) = 1^+(1^{--})$

OMITTED FROM SUMMARY TABLE

Seen in $e^+e^- \rightarrow 3(\pi^+\pi^-)$, $2(\pi^+\pi^-\pi^0)$ and $\gamma p \rightarrow p\omega\pi^+\pi^-\pi^0$. Seen also in $\pi^- p \rightarrow \omega\pi^0 n$. Needs confirmation.

$\rho(2110)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2138±30 OUR AVERAGE				
2153±37	BIAGINI 91	RVUE		$e^+e^- \rightarrow \pi^+\pi^-$, K^+K^-
2110±50	[1] CLEGG 90	RVUE	0	$e^+e^- \rightarrow 3(\pi^+\pi^-), 2(\pi^+\pi^-\pi^0)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2200±20	ALDE 91D	GAM2		38,100 $\pi^- p \rightarrow \omega\pi^0 n$
2280±50	ATKINSON 85	OMEG	0	20–70 $\gamma p \rightarrow p\omega\pi^+\pi^-\pi^0$

[1] Includes ATKINSON 85.

ρ(2110) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
397± 60 OUR AVERAGE					
389± 79	BIAGINI	91	RVUE		$e^+e^- \to \pi^+\pi^-$, K^+K^-
410±100	[2] CLEGG	90	RVUE	0	$e^+e^- \to 3(\pi^+\pi^-), 2(\pi^+\pi^-\pi^0)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
260± 50	ALDE	91D	GAM2		38,100 $\pi^- p \to \omega\pi^0 n$
440±110	ATKINSON	85	OMEG	0	20–70 $\gamma p \to p\omega\pi^+\pi^-\pi^0$

[2] Includes ATKINSON 85.

ρ(2110) REFERENCES

ALDE 91D IHEP 91-115 Preprint Binon+ (SERP, BELG, LANL, LAPP, PISA, KEK)
BIAGINI 91 NC 104A 363 +Dubnicka+ (FRAS, PRAG)
CLEGG 90 ZPHY C45 677 +Donnachie (LANC, MCHS)
ATKINSON 85 ZPHY C29 333 + (BONN, CERN, GLAS, LANC, MCHS, IPNP+)

$f_2(2150)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

This entry was previously called T_0. Contains results only from formation experiments. For production experiments see the $\overline{N}N$(1100–3600) entry. See also $\rho(2150)$, $\rho_3(2250)$, $f_4(2300)$, $\rho_5(2350)$.

f_2(2150) MASS

VALUE (MeV)	DOCUMENT ID
≈ 2150 OUR ESTIMATE	

$\overline{p}p \to \pi\pi$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2170.0	[1] MARTIN	80B	RVUE	
~ 2150.0	[1] MARTIN	80C	RVUE	
~ 2150.0	[2] DULUDE	78B	OSPK	1–2 $\overline{p}p \to \pi^0\pi^0$

[1] $I(J^P) = 0(2^+)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[2] $I^G(J^P) = 0^+(2^+)$ from partial-wave amplitude analysis.

S-CHANNEL $\overline{p}p$ or $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2190.0	[3] CUTTS	78B	CNTR		0.97–3 $\overline{p}p \to \overline{N}N$
2155.0±15.0	[3,4] COUPLAND	77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
2193 ± 2	[3,5] ALSPECTOR	73	CNTR		$\overline{p}p$ S channel

[3] Isospins 0 and 1 not separated.
[4] From a fit to the total elastic cross section.
[5] Referred to as T or T region by ALSPECTOR 73.

f_2(2150) WIDTH

$\overline{p}p \to \pi\pi$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 250.0	[6] MARTIN	80B	RVUE	
~ 250.0	[6] MARTIN	80C	RVUE	
~ 250.0	[7] DULUDE	78B	OSPK	1–2 $\overline{p}p \to \pi^0\pi^0$

[6] $I(J^P) = 0(2^+)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[7] $I^G(J^P) = 0^+(2^+)$ from partial-wave amplitude analysis.

S-CHANNEL $\overline{p}p$ or $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
135.0±75.0	[8,9] COUPLAND	77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
98 ± 8	[9] ALSPECTOR	73	CNTR		$\overline{p}p$ S channel

[8] From a fit to the total elastic cross section.
[9] Isospins 0 and 1 not separated.

f_2(2150) DECAY MODES

	Mode
Γ_1	$\pi\pi$

f_2(2150) REFERENCES

MARTIN 80B NP B176 355 +Morgan (LOUC, RHEL) JP
MARTIN 80C NP B169 216 +Pennington (DURH) JP
CUTTS 78B PR D17 16 +Good, Grannis, Green, Lee+ (STON, WISC)
DULUDE 78B PL 79B 335 +Lanou, Massimo, Peaslee+ (BROW, MIT, BARI) JP
COUPLAND 77 PL 71B 460 +Eisenhandler, Gibson, Astbury+ (LOQM, RHEL)
ALSPECTOR 73 PRL 30 511 +Cohen, Cvijanovich+ (RUTG, UPNJ)

OTHER RELATED PAPERS

FIELDS 71 PRL 27 1749 +Cooper, Rhines, Allison (ANL, OXF)
YOH 71 PRL 26 922 +Barish, Caroll, Lobkowicz+ (CIT, BNL, ROCH)

$\rho(2150)$

$I^G(J^{PC}) = 1^+(1^{--})$

OMITTED FROM SUMMARY TABLE

This entry was previously called $T_1(2190)$. Contains results only from formation experiments. For production experiments see the $\overline{N}N$(1100–3600) entry. See also $f_2(2150)$, $\rho_3(2250)$, $f_4(2300)$, $\rho_5(2350)$.

Our latest mini-review on this particle can be found in the 1984 edition.

ρ(2150) MASS

VALUE (MeV)	DOCUMENT ID
≈ 2150 OUR ESTIMATE	

$\overline{p}p \to \pi\pi$

VALUE (MeV)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 2170.0	[1] MARTIN	80B	RVUE
~ 2100.0	[1] MARTIN	80C	RVUE

S-CHANNEL $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2190.0	[2] CUTTS	78B	CNTR		0.97–3 $\overline{p}p \to \overline{N}N$
2155.0±15.0	[2,3] COUPLAND	77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
2193 ± 2	[2,4] ALSPECTOR	73	CNTR		$\overline{p}p$ S channel
2190 ±10	[5] ABRAMS	70	CNTR		S channel $\overline{p}N$

[1] $I(J^P) = 1(1^-)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[2] Isospins 0 and 1 not separated.
[3] From a fit to the total elastic cross section.
[4] Referred to as T or T region by ALSPECTOR 73.
[5] Seen as bump in $I = 1$ state. See also COOPER 68. PEASLEE 75 confirm $\overline{p}p$ results of ABRAMS 70, no narrow structure.

ρ(2150) WIDTH

$\overline{p}p \to \pi\pi$

VALUE (MeV)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 250.0	[6] MARTIN	80B	RVUE
~ 200.0	[6] MARTIN	80C	RVUE

S-CHANNEL $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
135.0±75.0	[7,8] COUPLAND	77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
98 ± 8	[8] ALSPECTOR	73	CNTR		$\overline{p}p$ S channel
~ 85	[9] ABRAMS	70	CNTR		S channel $\overline{p}N$

[6] $I(J^P) = 1(1^-)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[7] From a fit to the total elastic cross section.
[8] Isospins 0 and 1 not separated.
[9] Seen as bump in $I = 1$ state. See also COOPER 68. PEASLEE 75 confirm $\overline{p}p$ results of ABRAMS 70, no narrow structure.

ρ(2150) REFERENCES

MARTIN 80B NP B176 355 +Morgan (LOUC, RHEL) JP
MARTIN 80C NP B169 216 +Pennington (DURH) JP
CUTTS 78B PR D17 16 +Good, Grannis, Green, Lee+ (STON, WISC)
COUPLAND 77 PL 71B 460 +Eisenhandler, Gibson, Astbury+ (LOQM, RHEL)
PEASLEE 75 PL 57B 189 +Demarzo, Guerriero+ (CANB, BARI, BROW, MIT)
ALSPECTOR 73 PRL 30 511 +Cohen, Cvijanovich+ (RUTG, UPNJ)
ABRAMS 70 PR D1 1917 +Cool, Giacomelli, Kycia, Leontic, Li+ (BNL)
COOPER 68 PRL 20 1059 +Hyman, Manner, Musgrave+ (ANL)

OTHER RELATED PAPERS

BRICMAN 69 PL 29B 451 +Ferro-Luzzi, Bizard+ (CERN, CAEN, SACL)
ABRAMS 67C PRL 18 1209 +Cool, Giacomelli, Kycia, Leontic, Li+ (BNL)

$f_2(2175)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

Seen in central production of $\eta\eta$ system.

$f_2(2175)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
≈ 2175 OUR ESTIMATE			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2175±20	PROKOSHKIN 90	GAM4	300 $\pi^- N \rightarrow \pi^- N 2\eta$, 450$pN \rightarrow pN2\eta$

$f_2(2175)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
150±35	PROKOSHKIN 90	GAM4	300 $\pi^- N \rightarrow \pi^- N 2\eta$, 450$pN \rightarrow pN2\eta$

$f_2(2175)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\eta$	seen

$f_2(2175)$ BRANCHING RATIOS

$\Gamma(\eta\eta)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID
• • • We do not use the following data for averages, fits, limits, etc. • • •	
seen	PROKOSHKIN 90

$f_2(2175)$ REFERENCES

PROKOSHKIN 90 Hadron 89 Conf. p 27 (SERP, BELG, LANL, LAPP, PISA, KEK)

$X(2200)$

$I^G(J^{PC}) = ?^?(\text{even}^{++})$

OMITTED FROM SUMMARY TABLE

Seen at DCI in the $K^0_S K^0_S$ system. Not seen in Υ radiative decays (BARU 89). Needs confirmation.

$X(2200)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2197±17	AUGUSTIN 88	DM2	0	$J/\psi \rightarrow \gamma K^0_S K^0_S$

$X(2200)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
201±51	AUGUSTIN 88	DM2	0	$J/\psi \rightarrow \gamma K^0_S K^0_S$

$X(2200)$ REFERENCES

BARU 89 ZPHY C42 505 +Beilin, Blinov+ (NOVO)
AUGUSTIN 88 PRL 60 2238 +Calcaterra+ (DM2 Collab.)

$f_4(2220)$
was $\xi(2220)$

$I^G(J^{PC}) = 0^+(4^{++})$

OMITTED FROM SUMMARY TABLE

This state has been seen at SPEAR in the $K\overline{K}$ systems (K^+K^- and $K^0_S K^0_S$) produced in the radiative decay of $J/\psi(1S)$. Seen in $\eta\eta'$ (ALDE 86B), in $K^0_S K^0_S$ (ASTON 88D), and in K^+K^- (ASTON 88F). Needs confirmation. Not seen in Υ radiative decays nor in B inclusive decay (BEHRENDS 84). Not seen in $\overline{p}p \rightarrow K^+K^-$ formation experiment (SCULLI 87). Not seen at DCI in either K^+K^- or $K^0_S K^0_S$ systems (AUGUSTIN 88).

$f_4(2220)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
2225± 6 OUR AVERAGE				
2209^{+17}_{-15}±10		ASTON 88F	LASS	11 $K^- p \rightarrow K^+K^-\Lambda$
2230±20		BOLONKIN 88	SPEC	40 $\pi^- p \rightarrow K^0_S K^0_S n$
2220±10	41	ALDE 86B	GAM4	38–100 $\pi p \rightarrow n\eta\eta'$
2230± 6±14	93	BALTRUSAIT...86D	MRK3	$e^+e^- \rightarrow \gamma K^+K^-$
2232± 7± 7	23	BALTRUSAIT...86D	MRK3	$e^+e^- \rightarrow \gamma K^0_S K^0_S$

$f_4(2220)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
38^{+15}_{-13} OUR AVERAGE				
60^{+107}_{-57}		ASTON 88F	LASS	11 $K^- p \rightarrow K^+K^-\Lambda$
80± 30		BOLONKIN 88	SPEC	40 $\pi^- p \rightarrow K^0_S K^0_S n$
26^{+20}_{-16}±17	93	BALTRUSAIT...86D	MRK3	$e^+e^- \rightarrow \gamma K^+K^-$
18^{+23}_{-15}±10	23	BALTRUSAIT...86D	MRK3	$e^+e^- \rightarrow \gamma K^0_S K^0_S$

$f_4(2220)$ DECAY MODES

	Mode
Γ_1	$K\overline{K}$
Γ_2	$\gamma\gamma$
Γ_3	$\eta\eta'(958)$

$f_4(2220)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ $\Gamma_1\Gamma_2/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID	TECN	COMMENT
<0.086	95	[1] ALBRECHT 90G	ARG	$\gamma\gamma \rightarrow K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.0	95	[2] ALTHOFF 85B	TASS	$\gamma\gamma$, $K\overline{K}\pi$

[1] Assuming $J^P = 2^+$

[2] True for $J^P = 0^+$ and $J^P = 2^+$.

$f_4(2220)$ REFERENCES

ALBRECHT 90G ZPHY C48 183 +Ehrlichmann, Harder+ (ARGUS Collab.)
ASTON 88D NP B301 525 +Awaji, Bienz+ (SLAC, NAGO, CINC, TOKY)
ASTON 88F PL B215 199 +Awaji+ (SLAC, NAGO, CINC, TOKY) JP
AUGUSTIN 88 PRL 60 2238 +Calcaterra+ (DM2 Collab.)
BOLONKIN 88 NP B309 426 +Bloshenko, Gorin+ (ITEP, SERP)
SCULLI 87 PRL 58 1715 +Christenson, Kreiter, Nemethy, Yamin (NYU, BNL)
ALDE 86B PL B177 120 +Binon, Bricman+ (SERP, BELG, LANL, LAPP)
BALTRUSAIT... 86D PRL 56 107 Baltrusaitis (CIT, UCSC, ILL, SLAC, WASH)
ALTHOFF 85B ZPHY C29 189 +Braunschweig, Kirschfink+ (TASSO Collab.)
BEHRENDS 84 PL 137B 277 +Chadwich, Chauveau, Gentile+ (CLEO Collab.)

OTHER RELATED PAPERS

BARDIN 87 PL B195 292 +Burgun+ (SACL, FERR, CERN, PADO, TORI)
YAOUANC 85 ZPHY C28 309 +Oliver, Pene, Raynal, Ono (ORSA, TOKY)
GODFREY 84 PL 141B 439 +Kokoski, Isgur (TNTO)
SHATZ 84 PL 138B 209 (CIT)
WILLEY 84 PRL 52 585 (PITT)
EINSWEILER 83 Brighton Conf. 348 (Mark III Collab.)
HITLIN 83 Cornell Conf. 746 (CIT)

$\rho_3(2250)$

$I^G(J^{PC}) = 1^+(3^{--})$

OMITTED FROM SUMMARY TABLE

Contains results only from formation experiments. For production experiments see the $\overline{N}N(1100–3600)$ entry. See also $\rho(2150)$, $f_2(2150)$, $f_4(2300)$, $\rho_5(2350)$.

$\rho_3(2250)$ MASS

VALUE (MeV)	DOCUMENT ID
≈ 2250 OUR ESTIMATE	

$\overline{p}p \to \pi\pi$ or $K\overline{K}$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2250.0	[1] MARTIN	80B	RVUE		
~ 2300.0	[1] MARTIN	80C	RVUE		
~ 2140.0	[2] CARTER	78B	CNTR	0	0.7–2.4 $\overline{p}p \to K^-K^+$
~ 2150.0	[3] CARTER	77	CNTR	0	0.7–2.4 $\overline{p}p \to \pi\pi$

[1] $I(J^P) = 1(3^-)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[2] $I = 0, 1$. $J^P = 3^-$ from Barrelet-zero analysis.
[3] $I(J^P) = 1(3^-)$ from amplitude analysis.

S-CHANNEL $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2190.0	[4] CUTTS	78B	CNTR		0.97–3 $\overline{p}p \to \overline{N}N$
2155.0±15.0	[4,5] COUPLAND	77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
2193 ± 2	[4,6] ALSPECTOR	73	CNTR		$\overline{p}p$ S channel
2190 ± 10	[7] ABRAMS	70	CNTR		S channel $\overline{p}N$

[4] Isospins 0 and 1 not separated.
[5] From a fit to the total elastic cross section.
[6] Referred to as T or T region by ALSPECTOR 73.
[7] Seen as bump in $I = 1$ state. See also COOPER 68. PEASLEE 75 confirm $\overline{p}p$ results of ABRAMS 70, no narrow structure.

$\rho_3(2250)$ WIDTH

$\overline{p}p \to \pi\pi$ or $K\overline{K}$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250.0	[8] MARTIN	80B	RVUE		
~ 200.0	[8] MARTIN	80C	RVUE		
~ 150.0	[9] CARTER	78B	CNTR	0	0.7–2.4 $\overline{p}p \to K^-K^+$
~ 200.0	[10] CARTER	77	CNTR	0	0.7–2.4 $\overline{p}p \to \pi\pi$

[8] $I(J^P) = 1(3^-)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[9] $I = 0, 1$. $J^P = 3^-$ from Barrelet-zero analysis.
[10] $I(J^P) = 1(3^-)$ from amplitude analysis.

S-CHANNEL $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
135.0±75.0	[11,12] COUPLAND	77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
98 ± 8	[12] ALSPECTOR	73	CNTR		$\overline{p}p$ S channel
~ 85	[13] ABRAMS	70	CNTR		S channel $\overline{p}N$

[11] From a fit to the total elastic cross section.
[12] Isospins 0 and 1 not separated.
[13] Seen as bump in $I = 1$ state. See also COOPER 68. PEASLEE 75 confirm $\overline{p}p$ results of ABRAMS 70, no narrow structure.

$\rho_3(2250)$ REFERENCES

MARTIN	80B	NP B176 355	+Morgan	(LOUC, RHEL) JP
MARTIN	80C	NP B169 216	+Pennington	(DURH) JP
CARTER	78B	NP B141 467		(LOQM)
CUTTS	78B	PR D17 16	+Good, Grannis, Green, Lee+	(STON, WISC)
CARTER	77	PL 67B 117	+Coupland, Eisenhandler, Astbury+	(LOQM, RHEL) JP
COUPLAND	77	PL 71B 460	+Eisenhandler, Gibson, Astbury+	(LOQM, RHEL)
PEASLEE	75	PL 57B 189	+Demarzo, Guerriero+	(CANB, BARI, BROW, MIT)
ALSPECTOR	73	PRL 30 511	+Cohen, Cvijanovich+	(RUTG, UPNJ)
ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)
COOPER	68	PRL 20 1059	+Hyman, Manner, Musgrave+	(ANL)

OTHER RELATED PAPERS

MARTIN	79B	PL 86B 93	+Pennington	(DURH)
CARTER	78	NP B132 176		(LOQM) JP
CARTER	77B	PL 67B 122		(LOQM) JP
CARTER	77C	NP B127 202	+Coupland, Atkinson+	(LOQM, DARE, RHEL)
MONTANET	77	Boston Conf. 260		(CERN)
ZEMANY	76	NP B103 537	+MingMa, Mountz, Smith	(MSU)
BERTANZA	74	NC 23A 209	+Bigi, Casali, Lariccia+	(PISA, PADO, TORI)
BETTINI	73	NC 15A 563	+Alston-Garnjost, Bigi+	(PADO, LBL, PISA, TORI)
DONNACHIE	73	LNC 7 285	+Thomas	(MCHS)
NICHOLSON	73	PR D7 2572	+Delorme, Carroll+	(CIT, ROCH, BNL)
FIELDS	71	PRL 27 1749	+Cooper, Rhines, Allison	(ANL, OXF)
YOH	71	PRL 26 922	+Barish, Caroll, Lobkowicz+	(CIT, BNL, ROCH)
ABRAMS	67C	PRL 18 1209	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)

$f_2(2300)$ was $g'_T(2300)$

$I^G(J^{PC}) = 0^+(2^{++})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$f_2(2300)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2297 ±28	[1] ETKIN	88	MPS	22 $\pi^-p \to \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2220 ±15 ±20	WISNIEWSKI	87	MRK3	$J/\psi \to 2K^+2K^-\gamma$
2206 ±20 ±25	WISNIEWSKI	87	MRK3	$J/\psi \to 2K^0K^+K^-\gamma$
2231.0±10.0	BOOTH	86	OMEG	85 π^- Be $\to 2\phi$Be
$2220.0^{+90.0}_{-20.0}$	LINDENBAUM	84	RVUE	
2320.0±40.0	ETKIN	82	MPS	16 $\pi^-p \to 2\phi n$

[1] Includes data of ETKIN 85. The percentage of the resonance going into $\phi\phi$ 2^{++} S_2, D_2, and D_0 is 6^{+15}_{-5}, 25^{+18}_{-14}, and 69^{+16}_{-27}, respectively.

$f_2(2300)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
149 ±41	[2] ETKIN	88	MPS	22 $\pi^-p \to \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
114 ±45 ±35	WISNIEWSKI	87	MRK3	$J/\psi \to 2K^+2K^-\gamma$
150 ±46 ±35	WISNIEWSKI	87	MRK3	$J/\psi \to 2K^0K^+K^-\gamma$
133.0±50.0	BOOTH	86	OMEG	85 π^- Be $\to 2\phi$Be
200.0±50.0	LINDENBAUM	84	RVUE	
220.0±70.0	ETKIN	82	MPS	16 $\pi^-p \to 2\phi n$

[2] Includes data of ETKIN 85.

$f_2(2300)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\phi\phi$	seen

$f_2(2300)$ REFERENCES

ETKIN	88	PL B201 568	+Foley, Lindenbaum+	(BNL, CUNY)
WISNIEWSKI	87	Hadron 87 Conf.		(Mark III Collab.)
BOOTH	86	NP B273 677	+Carroll, Donald, Edwards+	(LIVP, GLAS, CERN)
ETKIN	85	PL 165B 217	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
LINDENBAUM	84	CNPP 13 285		(CUNY)
ETKIN	82	PRL 49 1620	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
Also	83	Brighton Conf. 351	Lindenbaum	(BNL, CUNY)

OTHER RELATED PAPERS

ARMSTRONG	89B	PL B221 221	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, LPNP)
GREEN	86	PRL 56 1639	+Lai+	(FNAL, ARIZ, FSU, NDAM, TUFT, VAND+)
BOOTH	84	NP B242 51	+Ballance, Carroll, Donald+	(LIVP, GLAS, CERN)

$f_4(2300)$

$I^G(J^{PC}) = 0^+(4^{++})$

OMITTED FROM SUMMARY TABLE

This entry was previously called $U_0(2350)$. Contains results only from formation experiments. For production experiments see the $\overline{N}N(1100–3600)$ entry. See also $\rho(2150)$, $f_2(2150)$, $\rho_3(2250)$, $\rho_5(2350)$.

$f_4(2300)$ MASS

VALUE (MeV)	DOCUMENT ID
≈ 2300 OUR ESTIMATE	

$\overline{p}p \to \pi\pi$ or $\overline{K}K$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2300	[1] MARTIN	80B	RVUE	
~ 2300	[1] MARTIN	80C	RVUE	
~ 2340	[2] CARTER	78B	CNTR	0.7–2.4 $\overline{p}p \to K^-K^+$
~ 2330	DULUDE	78B	OSPK	1–2 $\overline{p}p \to \pi^0\pi^0$
~ 2310	[3] CARTER	77	CNTR	0.7–2.4 $\overline{p}p \to \pi\pi$

[1] $I(J^P) = 0(4^+)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[2] $I(J^P) = 0(4^+)$ from Barrelet-zero analysis.
[3] $I(J^P) = 0(4^+)$ from amplitude analysis.

S-CHANNEL $\overline{p}p$ or $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2380.0	[4] CUTTS	78B	CNTR	0.97–3 $\overline{p}p \rightarrow \overline{N}N$
2345 ±15.0	[4,5] COUPLAND	77	CNTR	0.7–2.4 $\overline{p}p \rightarrow \overline{p}p$
2359 ± 2	[4,6] ALSPECTOR	73	CNTR	$\overline{p}p$ *S* channel
2375 ±10	ABRAMS	70	CNTR	*S* channel $\overline{N}N$

[4] Isospins 0 and 1 not separated.
[5] From a fit to the total elastic cross section.
[6] Referred to as *U* or *U* region by ALSPECTOR 73.

$f_4(2300)$ WIDTH

$\overline{p}p \rightarrow \pi\pi$ or $\overline{K}K$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 200	[7] MARTIN	80C	RVUE	
~ 150	[8] CARTER	78B	CNTR	0.7–2.4 $\overline{p}p \rightarrow K^-K^+$
~ 210	[9] CARTER	77	CNTR	0.7–2.4 $\overline{p}p \rightarrow \pi\pi$

[7] $I(J^P) = 0(4^+)$ from simultaneous analysis of $p\overline{p} \rightarrow \pi^-\pi^+$ and $\pi^0\pi^0$.
[8] $I(J^P) = 0(4^+)$ from Barrelet-zero analysis.
[9] $I(J^P) = 0(4^+)$ from amplitude analysis.

S-CHANNEL $\overline{p}p$ or $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$135.0^{+150.0}_{-65.0}$	[10,11] COUPLAND	77	CNTR	0.7–2.4 $\overline{p}p \rightarrow \overline{p}p$
165^{+18}_{-8}	[11] ALSPECTOR	73	CNTR	$\overline{p}p$ *S* channel
~ 190	ABRAMS	70	CNTR	*S* channel $\overline{N}N$

[10] From a fit to the total elastic cross section.
[11] Isospins 0 and 1 not separated.

$f_4(2300)$ REFERENCES

MARTIN	80B	NP B176 355	+Morgan	(LOUC, RHEL) JP
MARTIN	80C	NP B169 216	+Pennington	(DURH) JP
CARTER	78B	NP B141 467		(LOQM)
CUTTS	78B	PR D17 16	+Good, Grannis, Green, Lee+	(STON, WISC)
DULUDE	78B	PL 79B 335	+Lanou, Massimo, Peaslee+	(BROW, MIT, BARI) JP
CARTER	77	PL 67B 117	+Coupland, Eisenhandler, Astbury+	(LOQM, RHEL) JP
COUPLAND	77	PL 71B 460	+Eisenhandler, Gibson, Astbury+	(LOQM, RHEL)
ALSPECTOR	73	PRL 30 511	+Cohen, Cvijanovich+	(RUTG, UPNJ)
ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)

OTHER RELATED PAPERS

FIELDS	71	PRL 27 1749	+Cooper, Rhines, Allison	(ANL, OXF)
YOH	71	PRL 26 922	+Barish, Caroll, Lobkowicz+	(CIT, BNL, ROCH)
BRICMAN	69	PL 29B 451	+Ferro-Luzzi, Bizard+	(CERN, CAEN, SACL)

$f_2(2340)$
was $g''_T(2340)$

$I^G(J^{PC}) = 0^+(2^{++})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$f_2(2340)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2339 ±55	[1] ETKIN	88	MPS	$22\ \pi^- p \rightarrow \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2392.0±10.0	BOOTH	86	OMEG	$85\ \pi^-$ Be $\rightarrow 2\phi$Be
2360.0±20.0	LINDENBAUM	84	RVUE	

[1] Includes data of ETKIN 85. The percentage of the resonance going into $\phi\phi\ 2^{++}\ S_2$, D_2, and D_0 is 37 ± 19, 4^{+12}_{-4}, and 59^{+21}_{-19}, respectively.

$f_2(2340)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
319^{+81}_{-69}	[2] ETKIN	88	MPS	$22\ \pi^- p \rightarrow \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
198.0± 50.0	BOOTH	86	OMEG	$85\ \pi^-$ Be $\rightarrow 2\phi$Be
$150.0^{+150.0}_{-50.0}$	LINDENBAUM	84	RVUE	

[2] Includes data of ETKIN 85.

$f_2(2340)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\phi\phi$	seen

$f_2(2340)$ REFERENCES

ETKIN	88	PL B201 568	+Foley, Lindenbaum+	(BNL, CUNY)
BOOTH	86	NP B273 677	+Carroll, Donald, Edwards+	(LIVP, GLAS, CERN)
ETKIN	85	PL 165B 217	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
LINDENBAUM	84	CNPP 13 285		(CUNY)

OTHER RELATED PAPERS

ARMSTRONG	89B	PL B221 221	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, LPNP)
GREEN	86	PRL 56 1639	+Lai+	(FNAL, ARIZ, FSU, NDAM, TUFT, VAND+)
BOOTH	84	NP B242 51	+Ballance, Carroll, Donald+	(LIVP, GLAS, CERN)

$\rho_5(2350)$

$I^G(J^{PC}) = 1^+(5^{--})$

OMITTED FROM SUMMARY TABLE

This entry was previously called $U_1(2400)$. Contains results only from formation experiments. For production experiments see the $\overline{N}N(1100–3600)$ entry. See also $\rho(2150)$, $f_2(2150)$, $\rho_3(2250)$, $f_4(2300)$.

$\rho_5(2350)$ MASS

VALUE (MeV)	DOCUMENT ID
≈ 2350 OUR ESTIMATE	

$\overline{p}p \rightarrow \pi\pi$ or $\overline{K}K$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2300	[1] MARTIN	80B	RVUE		
~ 2250	[1] MARTIN	80C	RVUE		
~ 2500	[2] CARTER	78B	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow K^-K^+$
~ 2480	[3] CARTER	77	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow \pi\pi$

[1] $I(J^P) = 1(5^-)$ from simultaneous analysis of $p\overline{p} \rightarrow \pi^-\pi^+$ and $\pi^0\pi^0$.
[2] $I = 0(1)$; $J^P = 5^-$ from Barrelet-zero analysis.
[3] $I(J^P) = 1(5^-)$ from amplitude analysis.

S-CHANNEL $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2380	[4] CUTTS	78B	CNTR		0.97–3 $\overline{p}p \rightarrow \overline{N}N$
2345.0±15.0	[4,5] COUPLAND	77	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow \overline{p}p$
2359 ± 2	[4,6] ALSPECTOR	73	CNTR		$\overline{p}p$ *S* channel
2350 ±10	[7] ABRAMS	70	CNTR		*S* channel $\overline{N}N$
2360.0±25.0	[8] OH	70B	HDBC	−0	$\overline{p}(pn)$, $K^* K 2\pi$

[4] Isospins 0 and 1 not separated.
[5] From a fit to the total elastic cross section.
[6] Referred to as *U* or *U* region by ALSPECTOR 73.
[7] For $I = 1\ \overline{N}N$.
[8] No evidence for this bump seen in the $\overline{p}p$ data of CHAPMAN 71B. Narrow state not confirmed by OH 73 with more data.

$\rho_5(2350)$ WIDTH

$\overline{p}p \rightarrow \pi\pi$ or $\overline{K}K$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250	[9] MARTIN	80B	RVUE		
~ 300	[9] MARTIN	80C	RVUE		
~ 150	[10] CARTER	78B	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow K^-K^+$
~ 210	[11] CARTER	77	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow \pi\pi$

[9] $I(J^P) = 1(5^-)$ from simultaneous analysis of $p\overline{p} \rightarrow \pi^-\pi^+$ and $\pi^0\pi^0$.
[10] $I = 0(1)$; $J^P = 5^-$ from Barrelet-zero analysis.
[11] $I(J^P) = 1(5^-)$ from amplitude analysis.

S-CHANNEL $\overline{N}N$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$135.0^{+150.0}_{-65.0}$	12,13 COUPLAND 77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
165^{+18}_{-8}	13 ALSPECTOR 73	CNTR		$\overline{p}p$ S channel
< 60.0	14 OH 70B	HDBC	−0	$\overline{p}(pn)$, $K^* K 2\pi$
~ 140	ABRAMS 67C	CNTR		S channel $\overline{p}N$

[12] From a fit to the total elastic cross section.
[13] Isospins 0 and 1 not separated.
[14] No evidence for this bump seen in the $\overline{p}p$ data of CHAPMAN 71B. Narrow state not confirmed by OH 73 with more data.

$\rho_5(2350)$ REFERENCES

MARTIN 80B NP B176 355 +Morgan (LOUC, RHEL) JP
MARTIN 80C NP B169 216 +Pennington (DURH) JP
CARTER 78B NP B141 467 (LOQM)
CUTTS 78B PR D17 16 +Good, Grannis, Green, Lee+ (STON, WISC)
CARTER 77 PL 67B 117 +Coupland, Eisenhandler, Astbury+ (LOQM, RHEL) JP
COUPLAND 77 PL 71B 460 +Eisenhandler, Gibson, Astbury+ (LOQM, RHEL)
ALSPECTOR 73 PRL 30 511 +Cohen, Cvijanovich+ (RUTG, UPNJ)
OH 73 NP B51 57 +Eastman, MingMa, Parker, Smith+ (MSU)
CHAPMAN 71B PR D4 1275 +Green, Lys, Murphy, Ring+ (MICH)
ABRAMS 70 PR D1 1917 +Cool, Giacomelli, Kycia, Leontic, Li+ (BNL)
OH 70B PRL 24 1257 +Parker, Eastman, Smith, Sprafka, Ma (MSU)
ABRAMS 67C PRL 18 1209 +Cool, Giacomelli, Kycia, Leontic, Li+ (BNL)

OTHER RELATED PAPERS

CASO 70 LNC 3 707 +Conte, Tomasini+ (GENO, HAMB, MILA, SACL)
BRICMAN 69 PL 29B 451 +Ferro-Luzzi, Bizard+ (CERN, CAEN, SACL)

$a_6(2450)$

$I^G(J^{PC}) = 1^-(6^{++})$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the $K\overline{K}$ system. Needs confirmation.

$a_6(2450)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2450±130	1 CLELAND 82B	SPEC	±	50 $\pi p \to K^0_S K^\pm p$

[1] From an amplitude analysis.

$a_6(2450)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
400±250	2 CLELAND 82B	SPEC	±	50 $\pi p \to K^0_S K^\pm p$

[2] From an amplitude analysis.

$a_6(2450)$ DECAY MODES

	Mode
Γ_1	$K\overline{K}$

$a_6(2450)$ REFERENCES

CLELAND 82B NP B208 228 +Delfosse, Dorsaz, Gloor (DURH, GEVA, LAUS, PITT)

$f_6(2510)$ was $r(2510)$

$I^G(J^{PC}) = 0^+(6^{++})$

OMITTED FROM SUMMARY TABLE

Seen in $\pi^0\pi^0$. Needs confirmation.

$f_6(2510)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2510.0±30.0	BINON 84B	GAM2	38 $\pi^- p \to n 2\pi^0$

$f_6(2510)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
240.0±60.0	BINON 84B	GAM2	23 $\pi^- p \to n 2\pi^0$

$f_6(2510)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	(6.0±1.0) %

$f_6(2510)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.06 ±0.01	1 BINON 83C	GAM2	38 $\pi^- p \to n 4\gamma$

[1] Assuming one pion exchange.

$f_6(2510)$ REFERENCES

BINON 84B LNC 39 41 +Donskov, Duteil, Gouanere+ (SERP, BELG, LAPP) JP
BINON 83C SJNP 38 723 +Gouanere, Donskov, Duteil+ (SERP, BRUX+)
Translated from YAF 38 1199.

$X(3100)$

$I^G(J^{PC}) = ?^?(?^{??})$

OMITTED FROM SUMMARY TABLE

Narrow peak observed in several ($\Lambda\overline{p}$ + pions) and ($\overline{\Lambda}p$ + pions) states. Not seen by BOEHNLEIN 91. If due to strong decays, this state has exotic quantum numbers (B=0,Q=+1,S=−1 for $\Lambda\overline{p}\pi^+\pi^+$ and $I \geq 3/2$ for $\Lambda\overline{p}\pi^-$). See also under non-$q\overline{q}$ candidates. (See the index for the page number.)

$X(3100)$ MASS

VALUE (MeV)	DOCUMENT ID
≈ 3100 OUR ESTIMATE	

3-BODY DECAYS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3060±30	KEKELIDZE 90	BIS2	$X(3100) \to \Lambda\overline{p}\pi^+$
3040±30	KEKELIDZE 90	BIS2	$X(3100) \to \overline{\Lambda}p\pi^-$
3070±30	KEKELIDZE 90	BIS2	$X(3100) \to \Lambda\overline{p}\pi^-$
3040±30	KEKELIDZE 90	BIS2	$X(3100) \to \overline{\Lambda}p\pi^+$

4-BODY DECAYS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3060±25	KEKELIDZE 90	BIS2	$X(3100) \to \Lambda\overline{p}\pi^+\pi^\pm$
3045±25	KEKELIDZE 90	BIS2	$X(3100) \to \overline{\Lambda}p\pi^-\pi^\pm$
3105±30	BOURQUIN 86	SPEC	$X(3100) \to \Lambda\overline{p}\pi^+\pi^+$
3115±30	BOURQUIN 86	SPEC	$X(3100) \to \Lambda\overline{p}\pi^+\pi^-$

5-BODY DECAYS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3095±30	BOURQUIN 86	SPEC	$X(3100) \to \Lambda\overline{p}\pi^+\pi^+\pi^-$

X(3100) WIDTH

3-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
55 ± 15	KEKELIDZE	90	BIS2	$X(3100) \to \Lambda\bar{p}\pi^+$
40 ± 15	KEKELIDZE	90	BIS2	$X(3100) \to \bar{\Lambda}p\pi^-$
70 ± 25	KEKELIDZE	90	BIS2	$X(3100) \to \Lambda\bar{p}\pi^-$
35 ± 15	KEKELIDZE	90	BIS2	$X(3100) \to \bar{\Lambda}p\pi^+$

4-BODY DECAYS

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
30 ± 10		KEKELIDZE	90	BIS2	$X(3100) \to \Lambda\bar{p}\pi^+\pi^\pm$
30 ± 15		KEKELIDZE	90	BIS2	$X(3100) \to \bar{\Lambda}p\pi^-\pi^\pm$
<30	90	BOURQUIN	86	SPEC	$X(3100) \to \Lambda\bar{p}\pi^+\pi^+$
<80	90	BOURQUIN	86	SPEC	$X(3100) \to \Lambda\bar{p}\pi^+\pi^-$

5-BODY DECAYS

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<30	90	BOURQUIN	86	SPEC	$X(3100) \to \Lambda\bar{p}\pi^+\pi^+\pi^-$

X(3100) DECAY MODES

	Mode
Γ_1	$X(3100)^0 \to \Lambda\bar{p}\pi^+$
Γ_2	$X(3100)^{--} \to \Lambda\bar{p}\pi^-$
Γ_3	$X(3100)^- \to \Lambda\bar{p}\pi^+\pi^-$
Γ_4	$X(3100)^+ \to \Lambda\bar{p}\pi^+\pi^+$
Γ_5	$X(3100)^0 \to \Lambda\bar{p}\pi^+\pi^+\pi^-$

X(3100) REFERENCES

BOEHNLEIN 91 NP B21 174 (suppl) +Chung+ (FLOR, BNL, IND, RICE, SMAS)
KEKELIDZE 90 Hadron 89 Conf. p 551+Aleev+ (BIS-2 Collab.)
BOURQUIN 86 PL B172 113 +Brown+ (GEVA, RAL, HEID, LAUS, BRIS, CERN)

OTHER RELATED PAPERS

BOEHNLEIN 91 NP B21 174 (suppl) +Chung+ (FLOR, BNL, IND, RICE, SMAS)

X(3250)

$I^G(J^{PC}) = ?^?(?^{??})$

OMITTED FROM SUMMARY TABLE

Narrow peak observed in several final states with hidden strangeness ($\Lambda\bar{p}K^+$, $\Lambda\bar{p}K^+\pi^\pm$, $K^0 p\bar{p}K^\pm$). See also under non-$q\bar{q}$ candidates. (See the index for the page number.)

X(3250) MASS

VALUE (MeV)	DOCUMENT ID
≈ 3250 OUR ESTIMATE	

3-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3230 ± 30	KEKELIDZE	90	SPEC	$X(3250) \to \Lambda\bar{p}K^+$
3250 ± 30	KEKELIDZE	90	SPEC	$X(3250) \to \bar{\Lambda}pK^-$

4-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3240 ± 30	KEKELIDZE	90	SPEC	$X(3250) \to \Lambda\bar{p}K^+\pi^\pm$
3220 ± 30	KEKELIDZE	90	SPEC	$X(3250) \to \bar{\Lambda}pK^-\pi^\pm$
3270 ± 30	KEKELIDZE	90	SPEC	$X(3250) \to K^0 p\bar{p}K^\pm$

X(3250) WIDTH

3-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
35 ± 15	KEKELIDZE	90	SPEC	$X(3250) \to \Lambda\bar{p}K^+$
20 ± 10	KEKELIDZE	90	SPEC	$X(3250) \to \bar{\Lambda}pK^-$

4-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
25 ± 10	KEKELIDZE	90	SPEC	$X(3250) \to \Lambda\bar{p}K^+\pi^\pm$
55 ± 20	KEKELIDZE	90	SPEC	$X(3250) \to \bar{\Lambda}pK^-\pi^\pm$
50 ± 20	KEKELIDZE	90	SPEC	$X(3250) \to K^0 p\bar{p}K^\pm$

X(3250) DECAY MODES

	Mode
Γ_1	$\Lambda\bar{p}K^+$
Γ_2	$\Lambda\bar{p}K^+\pi^\pm$
Γ_3	$K^0 p\bar{p}K^\pm$

X(3250) REFERENCES

KEKELIDZE 90 Hadron 89 Conf. p 551+Aleev+ (BIS-2 Collab.)

OTHER LIGHT UNFLAVORED MESONS ($S = C = B = 0$)

$e^+e^-(1100\text{–}2200)$

$I^G(J^{PC}) = ?^?(1^{--})$

OMITTED FROM SUMMARY TABLE

This entry contains nonstrange vector mesons coupled to e^+e^- (photon) between the ϕ and $J/\psi(1S)$ mass regions. See also $\omega(1390)$, $\rho(1450)$, $\omega(1600)$, $\phi(1680)$, and $\rho(1700)$.

$e^+e^-(1100\text{–}2200)$ MASSES AND WIDTHS

We do not use the following data for averages, fits, limits, etc.

VALUE (MeV)	DOCUMENT ID
1100 to 2200 OUR LIMIT	

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$1097.0^{+16.0}_{-19.0}$	BARTALUCCI	79	OSPK	$7\ \gamma p \to e^+e^-p$
$31.0^{+24.0}_{-20.0}$	BARTALUCCI	79	OSPK	$7\ \gamma p \to e^+e^-p$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
~ 1830.0	PETERSON	78	SPEC	$\gamma p \to K^+K^-p$
~ 120.0	PETERSON	78	SPEC	$\gamma p \to K^+K^-p$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
~ 1820	[1] SPINETTI	79	RVUE	$e^+e^- \to 4\pi^\pm 2\gamma$
~ 30	[1] SPINETTI	79	RVUE	$e^+e^- \to 4\pi^\pm 2\gamma$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
~ 2130	[2] ESPOSITO	78	FRAM	$e^+e^- \to K^*(892)^+ \ldots$
~ 30	[2] ESPOSITO	78	FRAM	$e^+e^- \to K^*(892)^+ \ldots$

[1] Integrated cross section of BACCI 77, BARBIELLINI 77, ESPOSITO 77.
[2] Not seen by DELCOURT 79.

$e^+e^-(1100\text{–}2200)$ REFERENCES

BARTALUCCI 79 NC 49A 207 +Basini, Bertolucci+ (DESY, FRAS)
DELCOURT 79 PL 86B 395 +Derado, Bertrand, Bisello, Bizot, Buon+ (LALO)
SPINETTI 79 Batavia Conf. 506 (FRAS)
ESPOSITO 78 LNC 22 305 +Felicetti (FRAS, NAPL, PADO, ROMA)
PETERSON 78 PR D18 3955 +Dixon, Ehrlich, Galik, Larson (CORN, HARV)
BACCI 77 PL 68B 393 +DeZorzi, Penso, Stella, Baldini+ (ROMA, FRAS)
BARBIELLINI 77 PL 68B 397 +Barletta+ (FRAS, NAPL, PISA, SANI)
ESPOSITO 77 PL 68B 389 +Felicetti, Marini+ (FRAS, NAPL, PADO, ROMA)

OTHER RELATED PAPERS

BACCI 76 PL 64B 356 +Bidoli, Penso, Stella, Baldini+ (ROMA, FRAS)
BACCI 75 PL 58B 481 +Bidoli, Penso, Stella+ (ROMA, FRAS)

$\overline{N}N$(1100–3600)

OMITTED FROM SUMMARY TABLE

This entry contains various high mass, nonstrange structures coupled to the baryon-antibaryon system, as well as quasi-nuclear bound states below threshold.

$\overline{N}N$(1100–3600) MASSES AND WIDTHS

We do not use the following data for averages, fits, limits etc.

VALUE (MeV)	DOCUMENT ID
1100 to 3600 OUR LIMIT	

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1107±4	DAFTARI 87	DBC	0	0. $\overline{p}n \to \rho^-\pi^+\pi^-$
111±8±15	DAFTARI 87	DBC	0	0. $\overline{p}n \to \rho^-\pi^+\pi^-$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1167 ±7	[1] CHIBA 91	CNTR		$\overline{p}d \to \gamma X$
1191.0±9.9	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$
1210 ±5.0	[1,2,3,4] RICHTER 83	CNTR	0	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1325 ±5	[1] CHIBA 91	CNTR		$\overline{p}d \to \gamma X$
1329.2±7.6	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1390.9±6.3	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$
1395	[1,3,4,5] PAVLOPO... 78	CNTR		Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
~ 1410	BETTINI 66	DBC	0	0. $\overline{p}N \to 5\pi$
~ 100	BETTINI 66	DBC	0	0. $\overline{p}N \to 5\pi$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1468± 6	[6] BRIDGES 86B	DBC	0	0. $\overline{p}N \to 2\pi^-\pi^+\pi^0$
88±18	[6] BRIDGES 86B	DBC	0	0. $\overline{p}N \to 2\pi^-\pi^+\pi^0$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1479 ±5	[1] CHIBA 91	CNTR		$\overline{p}d \to \gamma X$
1478.4±8.9	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$
1477 ±5	[6] BRIDGES 86B	DBC	−	0. $\overline{p}N \to 3\pi^-2\pi^+$
116 ±9	[6] BRIDGES 86B	DBC	−	0. $\overline{p}N \to 3\pi^-2\pi^+$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1512 ± 7	[1] CHIBA 91	CNTR		$\overline{p}d \to \gamma X$
1523.8± 3.6	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$
1522 ± 7	[6] BRIDGES 86B	DBC	0	0. $\overline{p}N \to 2\pi^-\pi^+$
59 ±12	[6] BRIDGES 86B	DBC	0	0. $\overline{p}N \to 2\pi^-\pi^+$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1577.8± 3.4	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$
1594 ± 9	[6] BRIDGES 86B	DBC	−	0. $\overline{p}N \to 2\pi^-\pi^+\pi^0$
81 ±12	[6] BRIDGES 86B	DBC	−	0. $\overline{p}N \to 2\pi^-\pi^+\pi^0$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1633.6±4.1	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$
$1637.1^{+5.6}_{-7.3}$	ADIELS 84	CNTR		$\overline{p}$He

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1638±3.0	[1,2,3,4] RICHTER 83	CNTR	0	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
$1644.0^{+5.6}_{-7.3}$	ADIELS 84	CNTR	$\overline{p}$He

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1646	[1,3,4,5] PAVLOPO... 78	CNTR	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
$1687.1^{+5.0}_{-4.3}$	ADIELS 84	CNTR	$\overline{p}$He
1684	[1,3,4,5] PAVLOPO... 78	CNTR	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1693±2	[1] CHIBA 91	CNTR		$\overline{p}d \to \gamma X$
1694±2.0	[1,2,3,4] RICHTER 83	CNTR	0	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1713.0±2.6	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1731.0±1.5	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1771±1.0	[1,3,4,7] RICHTER 83	CNTR	0	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1856.6±5	BRIDGES 86D	SPEC	0	0. $\overline{p}d \to \pi\pi N$
20 ±5	BRIDGES 86D	SPEC	0	0. $\overline{p}d \to \pi\pi N$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1873±2.5	BRIDGES 86D	SPEC	0	0. $\overline{p}d \to \pi\pi N$
< 5	BRIDGES 86D	SPEC	0	0. $\overline{p}d \to \pi\pi N$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1897.0±17.0	[8] ABASHIAN 76	STRC	8 $\pi^- p \to p3\pi$
110.0±82.0	[8] ABASHIAN 76	STRC	8 $\pi^- p \to p3\pi$
1897 ± 1	KALOGERO... 75	DBC	$\overline{p}n$ annihilation near threshold
25 ± 6	KALOGERO... 75	DBC	$\overline{p}n$ annihilation near threshold

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
~ 1920.0	[9] EVANGELISTA 79	OMEG	10,16 $\pi^- p \to \overline{p}p$
~ 190.0	EVANGELISTA 79	OMEG	10,16 $\pi^- p \to \overline{p}p$

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
$1937.3^{+1.3}_{-0.7}$		[10] FRANKLIN 87	SPEC		0.586 $\overline{p}p$
< 3.0		[10] FRANKLIN 87	SPEC		0.586 $\overline{p}p$
1930.0± 2.0		[11] ASTON 80D	OMEG		$\gamma p \to p\overline{p}X$
12.0± 7.0		[11] ASTON 80D	OMEG		$\gamma p \to p\overline{p}X$
1940.0± 1.0	36	DAUM 80E	CNTR	0	93 $pp \to \overline{p}p + X$
~ 6.0		DAUM 80E	CNTR		93 $pp \to \overline{p}p + X$
1949 ±10		[12] DEFOIX 80	HBC	0	$\overline{p}p \to 5\pi$
80 ±20		[12] DEFOIX 80	HBC	0	$\overline{p}p \to 5\pi$
1939.0± 2.0		[13] HAMILTON 80B	CNTR	0	S channel $\overline{p}p$
22.0± 6.0		[13] HAMILTON 80B	CNTR	0	S channel $\overline{p}p$
1935.5± 1.0		SAKAMOTO 79	HBC	0	0.37–0.73 $\overline{p}p$
2.8± 1.4		SAKAMOTO 79	HBC	0	0.37–0.73 $\overline{p}p$
1939.0± 3.0		BRUCKNER 77	SPEC	0	0.4–0.85 $\overline{p}p$
< 4.0		BRUCKNER 77	SPEC	0	0.4–0.85 $\overline{p}p$
1935.9± 1.0		[14] CHALOUPKA 76	HBC	0	$\overline{p}p$ total,elastic
$8.8^{+4.3}_{-3.2}$		[15] CHALOUPKA 76	HBC	0	$\overline{p}p$ total,elastic
1942 ± 5		[16] D'ANDLAU 75	HBC	0	0.175–0.750 $\overline{p}p$
57.5± 5		[17] D'ANDLAU 75	HBC	0	0.175–0.750 $\overline{p}p$
$1934.4^{+2.6}_{-1.4}$		[18] KALOGERO... 75	DBC	−	$\overline{p}N$ annihilation
11^{+11}_{-4}		[19] KALOGERO... 75	DBC	−	$\overline{p}N$ annihilation
1932 ± 2		[14] CARROLL 74	CNTR		S channel $\overline{p}p \to d$
9^{+4}_{-3}		[15] CARROLL 74	CNTR		S channel $\overline{p}p \to d$
1968		[20] BENVENUTI 71	HBC	0	0.1–0.8 $\overline{p}p$
35		[20] BENVENUTI 71	HBC	0	0.1–0.8 $\overline{p}p$
1940 ± 8		CLINE 70	HBC	0	0.25–0.74 $\overline{p}p$
49 ± 9		CLINE 70	HBC	0	0.25–0.74 $\overline{p}p$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1949±10	[21] DEFOIX 80	HBC	0	0.0–1.2 $\overline{p}p \to 5\pi$
80±20	[21] DEFOIX 80	HBC	0	0.0–1.2 $\overline{p}p \to 5\pi$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2022.0± 6.0	[22] AZOOZ 83	HYBR	+	6 $\overline{p}p \to p\overline{n}3\pi$
14.0±13.0	[22] AZOOZ 83	HYBR	+	6 $\overline{p}p \to p\overline{n}3\pi$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2023.0± 5.0	BODENKAMP 83	SPEC	0	$\gamma p \to \overline{p}pp$
27.0±12.0	BODENKAMP 83	SPEC	0	$\gamma p \to \overline{p}pp$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2026.0± 5.0	[22] AZOOZ 83	HYBR	−	4 $\overline{p}p \to \overline{p}n3\pi$
20.0±11.0	[22] AZOOZ 83	HYBR	−	4 $\overline{p}p \to \overline{p}n3\pi$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2080±10	[23] KREYMER 80	STRC	0	13 $\pi^- d \to p\overline{p}n(n)$
110±20	[23] KREYMER 80	STRC	0	13 $\pi^- d \to p\overline{p}n(n)$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2090.0±20.0	[24] KREYMER 80	STRC	13 $\pi^- d \to np\overline{p}\pi^- p$
170.0±50.0	[24] KREYMER 80	STRC	13 $\pi^- d \to np\overline{p}\pi^- p$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
~ 2110.0	[25] EVANGELISTA 79	OMEG	10,16 $\pi^- p \to \overline{p}p$
~ 330.0	[25] EVANGELISTA 79	OMEG	10,16 $\pi^- p \to \overline{p}p$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2110.0±10.0	[26] ROZANSKA 80	SPRK	18 $\pi^- p \to p\overline{p}n$
190.0±10.0	[26] ROZANSKA 80	SPRK	18 $\pi^- p \to p\overline{p}n$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2141	[27] DONALD 73	HBC	0	$\overline{p}p$ S channel
14	[27] DONALD 73	HBC	0	$\overline{p}p$ S channel

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2180.0±10.0	[28] ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$
270.0±10.0	[28] ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2207±13	[29] ALLES-...	67B	HBC	0	5.7 $\overline{p}p$
62±52	[29] ALLES-...	67B	HBC	0	5.7 $\overline{p}p$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$2210.0^{+79.0}_{-21.0}$	EVANGELISTA	79B	OMEG	10 $\pi^- p \rightarrow K^+ K^- n$
~ 203.0	EVANGELISTA	79B	OMEG	10 $\pi^- p \rightarrow K^+ K^- n$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
~ 2260.0	[30] EVANGELISTA	79	OMEG	10,16 $\pi^- p \rightarrow \overline{p}p$
~ 440.0	[30] EVANGELISTA	79	OMEG	10,16 $\pi^- p \rightarrow \overline{p}p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2307.0± 6.0	ALPER	80	CNTR	0	62 $\pi^- p \rightarrow K^+ K^- n$
245.0±20.0	ALPER	80	CNTR	0	62 $\pi^- p \rightarrow K^+ K^- n$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2380.0±10.0	[31] ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$
380.0±20.0	[31] ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2450.0±10.0	[32] ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$
280.0±20.0	[32] ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2480.0±30.0	[33] CARTER	77	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow \pi\pi$
210.0±25.0	[33] CARTER	77	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow \pi\pi$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
~ 2500.0	[34] CARTER	78B	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow K^- K^+$
~ 150.0	[34] CARTER	78B	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow K^- K^+$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2710.0±20.0	ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$
170.0±40.0	ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2850.0±5.0	[35] BRAUN	76	DBC	–	5.5 $\overline{p}d \rightarrow N\overline{N}\pi$
< 39	[35] BRAUN	76	DBC	–	5.5 $\overline{p}d \rightarrow N\overline{N}\pi$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
3370±10	[36] ALEXANDER	72	HBC	0	6.94 $\overline{p}p$
150±40	[36] ALEXANDER	72	HBC	0	6.94 $\overline{p}p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
3600±20	[36] ALEXANDER	72	HBC	0	6.94 $\overline{p}p$
140±20	[36] ALEXANDER	72	HBC	0	6.94 $\overline{p}p$

[1] Not seen by GRAF 91.
[2] Not seen by CHIBA 88, ANGELOPOULOS 86, ADIELS 86.
[3] They looked for radiative transitions to bound $p\overline{p}$ states, mono-energetic γ rays detected.
[4] Observed widths consistent with experimental resolution.
[5] Not seen by ADIELS 86.
[6] From analysis of difference of π^- and π^+ spectra.
[7] Not seen by CHIBA 88, ANGELOPOULOS 86.
[8] Produced backwards.
[9] $I(J^P) = 1(1^-)$ from a mass dependent partial-wave analysis taking solution A.
[10] From reanalysis of data from JASTRZEMBSKI 81.
[11] Not seen by BUSENITZ 89.
[12] From energy dependence of 5π cross section. $I^G = 1^-$ from observation of $\omega\rho$ decay. $P = +$ and $J > 1$. $a_2(1320)\pi\pi$ also seen.
[13] $I = 0$ favored, $J = 0$ or 1, seen in total $\overline{p}p$ total cross section. Primarily from annihilation reactions. Not seen in $\overline{p}d$ total and annihilation cross sections.
[14] Narrow bump seen in total $\overline{p}p$, $\overline{p}d$ cross sections. Isospin uncertain. Not seen in $\overline{p}p$ charge exchange by ALSTON-GARNJOST 75, CHALOUPKA 76. Integrated cross section three times larger than BRUCKNER 77.
[15] Narrow bump seen in total $\overline{p}p$, $\overline{p}d$ cross sections. Isospin uncertain. Not seen in $\overline{p}p$ charge exchange by ALSTON-GARNJOST 75, CHALOUPKA 76. Integrated cross section three times larger than BRUCKNER 77. Not seen by CLOUGH 84.
[16] From energy dependence of far backward elastic scattering. Some indication of additional structure.
[17] From energy dependence of far backward elastic scattering. Some indication of additional structure.
[18] Not seen by ALBERI 79 with comparable statistics.
[19] Not seen by ALBERI 79 with comparable statistics.
[20] Seen as a bump in the $\overline{p}p \rightarrow K^0_S K^0_L$ cross section with $J^{PC} = 1^{--}$.
[21] Isospin 1 favored.
[22] Not seen by BIONTA 80, CARROLL 80, HAMILTON 80, BANKS 81, CHUNG 81, BARNETT 83.
[23] Neutron spectator. See also $np\overline{p}\pi^-(p)$ channel following.
[24] Proton spectator. See also $p\overline{p}n(n)$ channel above.
[25] $I(J^P) = 1(3^-)$ from a mass dependent partial-wave analysis taking solution A.
[26] $I(J^P) = 1(3^-)$ from amplitude analysis assuming one-pion exchange.
[27] Seen in final state $\omega\pi^+\pi^-$.
[28] $I(J^P) = 0(2^+)$ from amplitude analysis assuming one-pion exchange.
[29] ALLES-BORELLI 67B see neutral mode only $\pi^+\pi^-\pi^0$.
[30] $I(J^P) = 0(4^+)$ from a mass dependent partial-wave analysis taking solution A.
[31] $I(J^P) = 0(4^+)$ from amplitude analysis assuming one-pion exchange.
[32] $I(J^P) = 1(5^-)$ from amplitude analysis assuming one-pion exchange.
[33] $I(J^P) = 1(5^-)$ from amplitude analysis of $\overline{p}p \rightarrow \pi\pi$.
[34] I=0,1 $J^P = 5^-$ from Barrelet-zero analysis.
[35] Decays to $\overline{N}N$ and $\overline{N}N\pi$. Not seen by BARNETT 83.
[36] Decays to $4\pi^+ 4\pi^-$.

$\overline{N}N(1100\text{–}3600)$ REFERENCES

CHIBA	91	PR D44 1933	+Fujitani+	(FUKI, INUS, KEK, KYOT, OSAK, TOKY)
GRAF	91	PR D44 1945	+Fero, Gee+	(UCI, PENN, NMSU, KARL, ATHU)
BUSENITZ	89	PR D40 1	+Olszewski, Callahan+	(ILL, FNAL)
CHIBA	88	PL B202 447	+Doi	(FUKI, INUS, KEK, KYOT, OSAK, TOKY)
CHIBA	87	PR D36 3321	+Doi+	(FUKI, INUS, KEK, KYOT, OSAK, TOKY)
DAFTARI	87	PRL 58 859	+Gray, Kalogeropoulos, Roy	(SYRA)
FRANKLIN	87	PL B184 81		
ADIELS	86	PL B182 405	+Backenstoss+	(STOH, BASL, LASL, THES, CERN)
ANGELOPO...	86	PL B178 441	Angelopoulos+	(ATHU, UCI, KARL, NMSU, PENN)
BRIDGES	86B	PRL 56 215	+Daftari, Kalogeropoulos, Debbe+	(SYRA, CASE)
BRIDGES	86D	PL B180 313	+Brown, Daftari+	(SYRA, BNL, CASE, UMD, COLU)
ADIELS	84	PL 138B 235	+Backenstoss+	(BASL, KARL, STOH, STRB, THES)
CLOUGH	84	PL 146B 299	+Beard, Bugg+	(SURR, LOQM, ANIK, TRST, GEVA)
AZOOZ	83	PL 122B 471	+Butterworth	(LOIC, RHEL, SACL, SLAC, TOHO+)
BARNETT	83	PR D27 493	+Blockus, Burka, Chien, Christian+	(JHU)
BODENKAMP	83	PL 133B 275	+Fries, Behrend, Fenner+	(KARL, DESY)
RICHTER	83	PL 126B 284	+Adiels	(BASL, KARL, STOH, STRB, THES)
BANKS	81	PL 100B 191	+Booth, Campbell, Armstrong+	(LIVP, CERN)
CHUNG	81	PRL 46 395	+Bensinger+	(BNL, BRAN, CINC, FSU, SMAS)
JASTRZEM...	81	PR D23 2784	Jastrzembski, Mandelkern+	(TEMP, UCI, UNM)
ALPER	80	PL 94B 422	+Becker+	(AMST, CERN, CRAC, MPIM, OXF+)
ASTON	80D	PL 93B 517		(BONN, CERN, EPOL, GLAS, LANC, MCHS, ORSA+)
BIONTA	80	PRL 44 909	+Carroll, Edelstein+	(BNL, CMU, FNAL, SMAS)
CARROLL	80	PRL 44 1572	+Chiang, Johnson, Cester, Webb+	(BNL, PRIN)
DAUM	80E	PL 90B 475	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
DEFOIX	80	NP B162 12	+Dobrzynski, Angelini, Bigi+	(CDEF, PISA)
HAMILTON	80	PRL 44 1179	+Pun, Tripp, Lazarus+	(LBL, BNL, MTHO)
HAMILTON	80B	PRL 44 1182	+Pun, Tripp, Lazarus+	(LBL, BNL, MTHO)
KREYMER	80	PR D22 36	+Baggett, Fieguth+	(IND, PURD, SLAC, VAND)
ROZANSKA	80	NP B162 505	+Blum, Dietl, Grayer, Lorenz+	(MPIM, CERN)
ALBERI	79	PL 83B 247	+Alvear, Castelli, Poropat+	(TRST, CERN, IFRJ)
EVANGELISTA	79	NP B153 253	+	(BARI, BONN, CERN, DARE, GLAS, LIVP+)
EVANGELISTA	79B	NP B154 381	+	(BARI, BONN, CERN, DARE, GLAS, LIVP+)
SAKAMOTO	79	NP B158 410	+Hashimoto, Sai, Yamamoto+	(TOKY)
CARTER	78B	NP B141 467		(LOQM)
PAVLOPO...	78	PL 72B 415	Pavlopoulos+	(KARL, BASL, CERN, STOH, STRB)
BRUCKNER	77	PL 67B 222	+Granz, Ingham, Kilian+	(MPIH, HEID, CERN)
CARTER	77	PL 67B 117	+Coupland, Eisenhandler, Astbury+	(LOQM, RHEL) JP
ABASHIAN	76	PR D13 5	+Watson, Gelfand, Buttram+	(ILL, ANL, CHIC, ISU)
BRAUN	76	PL 60B 481	+Brick, Fridman, Gerber, Juillot, Maurer+	(STRB)
CHALOUPKA	76	PL 61B 487	+	(CERN, LIVP, MONS, PADO, ROMA, TRST)
ALSTON-...	75	PRL 35 1685	Alston-Garnjost, Kenney, Pollard, Ross, Tripp+	(LBL, MHCO)
D'ANDLAU	75	PL 58B 223	+Cohen-Ganouna, Laloum, Lutz, Petri	(CDEF, PISA)
KALOGERO...	75	PRL 34 1047	Kalogeropoulos, Tzanakos	(SYRA)
CARROLL	74	PRL 32 247	+Chiang, Kycia, Li, Mazur, Michael+	(BNL)
DONALD	73	NP B61 333	+Edwards, Gibbins, Briand, Duboc+	(LIVP, LPNP)
ALEXANDER	72	NP B45 29	+Bar-Nir, Benary, Dagan+	(TELA)
BENVENUTI	71	PRL 27 283	+Cline, Rutz, Reeder, Scherer	(WISC)
CLINE	70	Preprint	+English, Reeder	(WISC)
ALLES-...	67B	NC 50A 776	Alles-Borelli, French, Frisk+	(CERN, BONN) G
BETTINI	66	NC 42A 695	+Cresti, Limentani, Bertanza, Bigi+	(PADO, PISA)

OTHER RELATED PAPERS

TANIMORI	90	PR D41 744	+Ishimoto+	(KEK, TOKY, KYOT, TOHO, HIRO)
LIU	87	PRL 58 2288	+Kiu, Li	(STON)
ARMSTRONG	86C	PL B175 383	+Chu, Clement, Elinon+	(BNL, HOUS, PENN, RICE)
BRIDGES	86	PRL 56 211	+Brown+	(BLSU, BNL, CASE, COLU, UMD, SYRA)
BRIDGES	86C	PRL 57 1534	+Daftari, Kalogeropoulos+	(SYRA) JP
DOVER	86	PRL 57 1207	+	(BNL) JP
ANGELOPO...	85	PL 159B 210	Angelopoulos+	(ATHU, UCI, UNM, PENN, TEMP)
BODENKAMP	85	NP B255 717	+Fries, Behrend, Hesse+	(KARL, DESY)
AZOOZ	84	NP B244 277	+Butterworth	(LOIC, RHEL, SACL, SLAC, TOHO+)

$X(1900\text{–}3600)$

OMITTED FROM SUMMARY TABLE

NOTE ON THE $X(1900\text{–}3600)$ REGION

The high-mass region is covered nearly continuously with evidence for peaks of various widths having various decay modes. As a satisfactory grouping into particles is not yet possible, we list all the $Y = 0$ bumps coupled neither to $\overline{N}N$ nor to e^+e^-, and having $M > 1900$ MeV, together, ordered by increasing mass.

The narrow peaks observed in a missing-mass-spectrometer experiment at 1929, 2195, and 2382 MeV, called respectively S, T, and U by the authors (CHIKOVANI 66, FOCACCI 66), were not seen by ANTIPOV 72, who performed a similar experiment at 25 and 40 GeV/c.

$X(1900–3600)$ MASSES AND WIDTHS

We do not use the following data for averages, fits, limits, etc.

VALUE (MeV)	DOCUMENT ID
1900 to 3600 OUR LIMIT	

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1870.0 ± 40.0	[1] ALDE	86D	GAM4	0	$100\ \pi^- p \to 2\eta X$
250.0 ± 30.0	[1] ALDE	86D	GAM4	0	$100\ \pi^- p \to 2\eta X$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1898 ± 18	100	THOMPSON	74	HBC	+	$13\ \pi^+ p \to 2\rho X$
108^{+41}_{-27}	100	THOMPSON	74	HBC	+	$13\ \pi^+ p \to 2\rho X$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1900 ± 40	100	BOESEBECK	68	HBC	+	$8\ \pi^+ p \to \pi^+\pi^0 X$
216 ± 105	100	BOESEBECK	68	HBC	+	$8\ \pi^+ p \to \pi^+\pi^0 X$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1901 ± 13	ARMSTRONG	89E	OMEG	$300\ pp \to pp2(\pi^+\pi^-)$
312 ± 61	ARMSTRONG	89E	OMEG	$300\ pp \to pp2(\pi^+\pi^-)$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1929 ± 14	FOCACCI	66	MMS	−	$3–12\ \pi^- p$
22 ± 2	FOCACCI	66	MMS	−	$3–12\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1970 ± 10	CHLIAPNIK...	80	HBC	0	$32\ K^+ p \to 2K^0_S 2\pi X$
40 ± 20	CHLIAPNIK...	80	HBC	0	$32\ K^+ p \to 2K^0_S 2\pi X$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1973.0 ± 15.0	30	CASO	70	HBC	−	$11.2\ \pi^- p \to \rho 2\pi$
80.0	30	CASO	70	HBC	−	$11.2\ \pi^- p \to \rho 2\pi$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2070	50	TAKAHASHI	72	HBC	$8\ \pi^- p \to N 2\pi$
160	50	TAKAHASHI	72	HBC	$8\ \pi^- p \to N 2\pi$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2100.0 ± 40.0	[2] ALDE	86D	GAM4	0	$100\ \pi^- p \to 2\eta X$
250.0 ± 40.0	[2] ALDE	86D	GAM4	0	$100\ \pi^- p \to 2\eta X$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2141.0 ± 12.0	389	GREEN	86	MPSF	$400\ pA \to 4K X$
49.0 ± 28.0	389	GREEN	86	MPSF	$400\ pA \to 4K X$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2190.0 ± 10.0	CLAYTON	67	HBC	±	$2.5\ \overline{p}p \to a_2, \omega$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2195 ± 15	FOCACCI	66	MMS	−	$3–12\ \pi^- p$
39 ± 14	FOCACCI	66	MMS	−	$3–12\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2207.0 ± 22.0	[3] CASO	70	HBC	−	$11.2\ \pi^- p$
130.0	[3] CASO	70	HBC	−	$11.2\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2280.0 ± 50.0	ATKINSON	85	OMEG	0	$20–70\ \gamma p \to p\omega\pi^+\pi^-\pi^0$
440.0 ± 110.0	ATKINSON	85	OMEG	0	$20–70\ \gamma p \to p\omega\pi^+\pi^-\pi^0$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2300.0 ± 100.0	ATKINSON	84F	OMEG	±0	$20–70\ \gamma p \to \rho f$
~ 250.0	ATKINSON	84F	OMEG	±0	$20–70\ \gamma p \to \rho f$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2330 ± 30	ATKINSON	88	OMEG	0	$25–50\ \gamma p \to \rho^\pm\rho^0\pi^\mp$
435 ± 75	ATKINSON	88	OMEG	0	$25–50\ \gamma p \to \rho^\pm\rho^0\pi^\mp$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2340 ± 20	126	[4] BALTAY	75	HBC	+	$15\ \pi^+ p \to p5\pi$
180 ± 60	126	[4] BALTAY	75	HBC	+	$15\ \pi^+ p \to p5\pi$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2382 ± 24	FOCACCI	66	MMS	−	$3–12\ \pi^- p$
62 ± 6	FOCACCI	66	MMS	−	$3–12\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2500.0 ± 32.0	ANDERSON	69	MMS	−	$16\ \pi^- p$ backward
87.0	ANDERSON	69	MMS	−	$16\ \pi^- p$ backward

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2620 ± 20	550	BAUD	69	MMS	−	$8–10\ \pi^- p$
85 ± 30	550	BAUD	69	MMS	−	$8–10\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2676.0 ± 27.0	[3] CASO	70	HBC	−	$11.2\ \pi^- p$
150.0	[3] CASO	70	HBC	−	$11.2\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2747 ± 32	DENNEY	83	LASS	$10\ \pi^+ N$
195 ± 75	DENNEY	83	LASS	$10\ \pi^+ N$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2800 ± 20	640	BAUD	69	MMS	−	$8–10\ \pi^- p$
46 ± 10	640	BAUD	69	MMS	−	$8–10\ \pi^- p$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2820 ± 10	15	[5] SABAU	71	HBC	+	$8\ \pi^+ p$
50 ± 10	15	[5] SABAU	71	HBC	+	$8\ \pi^+ p$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2880 ± 20	230	BAUD	69	MMS	−	$8–10\ \pi^- p$
< 15	230	BAUD	69	MMS	−	$8–10\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
3025.0 ± 20.0	BAUD	70	MMS	−	$10.5–13\ \pi^- p$
~ 25.0	BAUD	70	MMS	−	$10.5–13\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
3075.0 ± 20.0	BAUD	70	MMS	−	$10.5–13\ \pi^- p$
~ 25.0	BAUD	70	MMS	−	$10.5–13\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
3145.0 ± 20.0	BAUD	70	MMS	−	$10.5–15\ \pi^- p$
< 10.0	BAUD	70	MMS	−	$10.5–15\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
3475.0 ± 20.0	BAUD	70	MMS	−	$14–15.5\ \pi^- p$
~ 30.0	BAUD	70	MMS	−	$14–15.5\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
3535.0 ± 20.0	BAUD	70	MMS	−	$14–15.5\ \pi^- p$
~ 30.0	BAUD	70	MMS	−	$14–15.5\ \pi^- p$

[1] Seen in $J = 2$ wave in one of the two ambiguous solutions.
[2] Seen in $J = 0$ wave in one of the two ambiguous solutions.
[3] Seen in $\rho^-\pi^+\pi^-$ (ω and η antiselected in 4π system).
[4] Dominant decay into $\rho^0\rho^0\pi^+$. BALTAY 78 finds confirmation in $2\pi^+\pi^-2\pi^0$ events which contain $\rho^+\rho^0\pi^0$ and $2\rho^+\pi^-$.
[5] Seen in $(K\overline{K}\pi\pi)$ mass distribution.

$X(1900–3600)$ REFERENCES

ARMSTRONG	89E	PL B228 536	+Benayoun	(ATHU, BARI, BIRM, CERN, CDEF, LPNP)
ATKINSON	88	ZPHY C38 535	+Axon+	(BONN, CERN, GLAS, LANC, MCHS, LPNP)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN)
GREEN	86	PRL 56 1639	+Lai+	(FNAL, ARIZ, FSU, NDAM, TUFT, VAND+)
ATKINSON	85	ZPHY C29 333	+	(BONN, CERN, GLAS, LANC, MCHS, IPNP+)
ATKINSON	84F	NP B239 1	+	(BONN, CERN, GLAS, LANC, MCHS, IPNP+)
DENNEY	83	PR D28 2726	+Cranley, Firestone, Chapman+	(IOWA, MICH) J
CHLIAPNIK...	80	ZPHY C3 285	Chliapnikov, Gerdyukov+	(SERP, BRUX, MONS)
BALTAY	78	PR D17 52	+Cautis, Cohen, Csorna, Kalelkar+	(COLU, BING)
BALTAY	75	PRL 35 891	+Cautis, Cohen, Kalelkar, Pisello+	(COLU, BING)
THOMPSON	74	NP B69 220	+Gaidos, McIlwain, Miller, Mulera+	(PURD)
TAKAHASHI	72	PR D6 1266	+Barish+	(TOHO, PENN, NDAM, ANL)
SABAU	71	LNC 1 514	+Uretsky	(BUCH, ANL)
BAUD	70	PL 31B 549	+Benz+	(CERN Boson Spectrometer Collab.)
CASO	70	LNC 3 707	+Conte, Tomasini+	(GENO, HAMB, MILA, SACL)
ANDERSON	69	PRL 22 1390	+Collins+	(BNL, CMU)
BAUD	69	PL 30B 129	+Benz+	(CERN Boson Spectrometer Collab.)
BOESEBECK	68	NP B4 501	+Deutschmann+	(AACH, BERL, CERN)
CLAYTON	67	Heidelberg Conf. 57	+Mason, Muirhead, Filippas+	(LIVP, ATHU)
FOCACCI	66	PRL 17 890	+Kienzle, Levrat, Maglich, Martin	(CERN)

OTHER RELATED PAPERS

ANTIPOV	72	PL 40 147	+Kienzle, Landsberg+	(SERP)
CHIKOVANI	66	PL 22 233	+Kienzle, Maglich+	(SERP)

STRANGE MESONS
($S = \pm 1$, $C = B = 0$)

$K^+ = u\bar{s}$, $K^0 = d\bar{s}$, $\overline{K}^0 = \bar{d}s$, $K^- = \bar{u}s$, similarly for K^*'s

$K^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

$K^{\pm}$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
493.646±0.009 OUR FIT					
493.646±0.009 OUR AVERAGE					
493.636±0.011	GALL	88	CNTR	−	Kaonic atoms
493.640±0.054	LUM	81	CNTR	−	Kaonic atoms
493.670±0.029	BARKOV	79	EMUL	±	$e^+e^- \rightarrow K^+K^-$
493.657±0.020	CHENG	75	CNTR	−	Kaonic atoms
493.691±0.040	BACKENSTO...	73	CNTR	−	Kaonic atoms
• • • We do not use the following data for averages, fits, limits, etc. • • •					
493.662±0.19	KUNSELMAN	74	CNTR	−	Kaonic atoms
493.78 ±0.17	GREINER	65	EMUL	+	
493.7 ±0.3	BARKAS	63	EMUL	−	
493.9 ±0.2	COHEN	57	RVUE	+	

$K^+ - K^-$ MASS DIFFERENCE

Test of *CPT*.

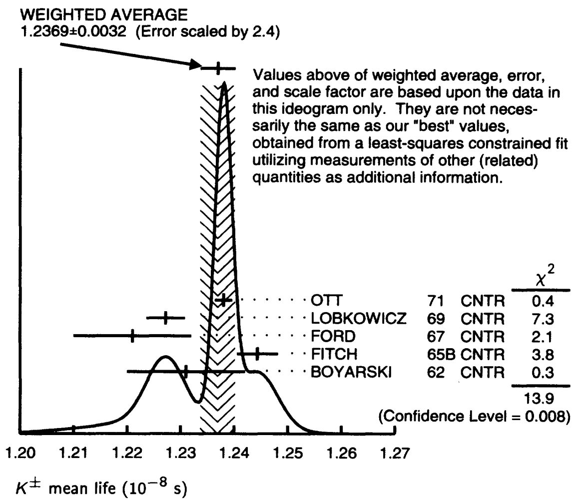
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG
−0.032±0.090	1.5M	[1] FORD	72	ASPK	±

[1] FORD 72 uses $m(\pi^+) - m(\pi^-) = +28 \pm 70$ keV.

$K^{\pm}$ MEAN LIFE

VALUE (10^{-8} s)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.2371±0.0029 OUR FIT	Error includes scale factor of 2.2.					
1.2369±0.0032 OUR AVERAGE	Error includes scale factor of 2.4. See the ideogram below.					
1.2380±0.0016	3M	OTT	71	CNTR	+	Stopping K
1.2272±0.0036		LOBKOWICZ	69	CNTR	+	K in flight
1.221 ±0.011		FORD	67	CNTR	±	
1.2443±0.0038		FITCH	65B	CNTR	+	K at rest
1.231 ±0.011		BOYARSKI	62	CNTR	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.25 $^{+0.22}_{-0.17}$		[2] BARKAS	61	EMUL		
1.27 $^{+0.36}_{-0.23}$	51	[2] BHOWMIK	61	EMUL		
1.31 ±0.08	293	NORDIN	61	HBC	−	
1.24 ±0.07		NORDIN	61	RVUE	−	
1.38 ±0.24	33	[2] FREDEN	60B	EMUL		
1.21 ±0.06		BURROWES	59	CNTR		
1.60 ±0.3	52	[2] EISENBERG	58	EMUL		
0.95 $^{+0.36}_{-0.25}$		[2] ILOFF	56	EMUL		

[2] Old experiments with large errors excluded from averaging.



($K^+ - K^-$) / AVERAGE, MEAN LIFE DIFFERENCE

This quantity is a measure of *CPT* invariance in weak interactions.

VALUE (%)	DOCUMENT ID		TECN
0.11 ±0.09 OUR AVERAGE	Error includes scale factor of 1.2.		
0.090±0.078	LOBKOWICZ	69	CNTR
0.47 ±0.30	FORD	67	CNTR

K^+ DECAY MODES

K^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\mu^+\nu_\mu$		(63.51±0.19) %	S=1.2
Γ_2	$e^+\nu_e$		(1.55±0.07) × 10^{-5}	
Γ_3	$\pi^+\pi^0$		(21.17±0.16) %	S=1.1
Γ_4	$\pi^+\pi^+\pi^-$		(5.59±0.05) %	S=2.0
Γ_5	$\pi^+\pi^0\pi^0$		(1.73±0.04) %	S=1.2
Γ_6	$\pi^0\mu^+\nu_\mu$ Called $K_{\mu3}$.		(3.18±0.08) %	S=1.6
Γ_7	$\pi^0 e^+\nu_e$ Called K_{e3}.		(4.82±0.06) %	S=1.3
Γ_8	$\pi^0\pi^0 e^+\nu_e$		(2.1 ±0.4) × 10^{-5}	
Γ_9	$\pi^+\pi^- e^+\nu_e$		(3.91±0.17) × 10^{-5}	
Γ_{10}	$\pi^+\pi^-\mu^+\nu_\mu$		(1.4 ±0.9) × 10^{-5}	
Γ_{11}	$\pi^0\pi^0\pi^0 e^+\nu_e$		< 3.5 × 10^{-6}	CL=90%
Γ_{12}	$\pi^+\gamma\gamma$	[a]	< 1 × 10^{-6}	CL=90%
Γ_{13}	$\pi^+ 3\gamma$	[a]	< 1.0 × 10^{-4}	CL=90%
Γ_{14}	$e^+\nu_e\nu\bar{\nu}$		< 6 × 10^{-5}	CL=90%
Γ_{15}	$\mu^+\nu_\mu\nu\bar{\nu}$		< 6.0 × 10^{-6}	CL=90%
Γ_{16}	$\mu^+\nu_\mu e^+ e^-$		(1.06±0.32) × 10^{-6}	
Γ_{17}	$e^+\nu_e e^+ e^-$		(2.1 $^{+2.1}_{-1.1}$) × 10^{-7}	
Γ_{18}	$\mu^+\nu_\mu\mu^+\mu^-$		< 4.1 × 10^{-7}	CL=90%
Γ_{19}	$\mu^+\nu_\mu\gamma$	[a,b]	(5.50±0.28) × 10^{-3}	
Γ_{20}	$\pi^+\pi^0\gamma$	[a,b]	(2.75±0.15) × 10^{-4}	
Γ_{21}	$\pi^+\pi^0\gamma$ (DE)	[a,c]	(1.8 ±0.4) × 10^{-5}	
Γ_{22}	$\pi^+\pi^+\pi^-\gamma$	[a,b]	(1.04±0.31) × 10^{-4}	
Γ_{23}	$\pi^+\pi^0\pi^0\gamma$	[a,b]	(7.4 $^{+5.5}_{-2.9}$) × 10^{-6}	
Γ_{24}	$\pi^0\mu^+\nu_\mu\gamma$	[a,b]	< 6.1 × 10^{-5}	CL=90%
Γ_{25}	$\pi^0 e^+\nu_e\gamma$	[a,b]	(2.62±0.20) × 10^{-4}	
Γ_{26}	$\pi^0 e^+\nu_e\gamma$ (SD)	[d]	< 5.3 × 10^{-5}	CL=90%
	$\Delta S = \Delta Q$ (*SQ*), Lepton number (*L*), Lepton Family number (*LF*) violating modes or Flavor-Changing neutral current (*FC*) modes			
Γ_{27}	$\pi^+\pi^+ e^-\bar{\nu}_e$	*SQ*	< 1.2 × 10^{-8}	CL=90%
Γ_{28}	$\pi^+\pi^+\mu^-\bar{\nu}_\mu$	*SQ*	< 3.0 × 10^{-6}	CL=95%
Γ_{29}	$\pi^+ e^+ e^-$	*FC*	(2.7 ±0.5) × 10^{-7}	
Γ_{30}	$\pi^+\mu^+\mu^-$	*FC*	< 2.3 × 10^{-7}	CL=90%
Γ_{31}	$\pi^+\nu\bar{\nu}$	*FC*	< 3.4 × 10^{-8}	CL=90%
Γ_{32}	$\mu^-\nu e^+ e^+$	*LF*	< 2.0 × 10^{-8}	CL=90%
Γ_{33}	$\mu^+\nu_e$	*LF*	< 4 × 10^{-3}	CL=90%

Γ_{34}	$\pi^+\mu^+e^-$	LF	< 2.1	$\times 10^{-10}$	CL=90%
Γ_{35}	$\pi^+\mu^-e^+$	LF	< 7	$\times 10^{-9}$	CL=90%
Γ_{36}	$\pi^-\mu^+e^+$	L	< 7	$\times 10^{-9}$	CL=90%
Γ_{37}	$\pi^-e^+e^+$	L	< 1.0	$\times 10^{-8}$	CL=90%
Γ_{38}	$\pi^-\mu^+\mu^+$	L	< 1.5	$\times 10^{-4}$	CL=90%
Γ_{39}	$\mu^+\overline{\nu}_e$	L	< 3.3	$\times 10^{-3}$	CL=90%
Γ_{40}	$\pi^0e^+\overline{\nu}_e$	L	< 3	$\times 10^{-3}$	CL=90%
Γ_{41}	$\pi^+\gamma$				

[a] See the Listings below for the energy limits used in this measurement.

[b] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.

[c] Direct-emission branching fraction.

[d] Structure-dependent part.

CONSTRAINED FIT INFORMATION

An overall fit to the mean life, 2 partial widths, and 20 branching ratios uses 59 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 74.9$ for 52 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i\delta p_j\rangle/(\delta p_i\cdot\delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_3	−63						
x_4	−36	−15					
x_5	−24	−5	21				
x_6	−43	−20	13	0			
x_7	−44	−19	35	5	40		
x_8	−3	−1	2	0	2	6	
Γ	7	3	−20	−4	−3	−7	0
	x_1	x_3	x_4	x_5	x_6	x_7	x_8

	Mode	Rate (10^8 s^{-1})	Scale factor
Γ_1	$\mu^+\nu_\mu$	0.5134 ±0.0020	1.4
Γ_3	$\pi^+\pi^0$	0.1711 ±0.0013	1.1
Γ_4	$\pi^+\pi^+\pi^-$	0.0452 ±0.0004	1.9
Γ_5	$\pi^+\pi^0\pi^0$	0.01400±0.00032	1.2
Γ_6	$\pi^0\mu^+\nu_\mu$ Called $K_{\mu3}$.	0.0257 ±0.0007	1.6
Γ_7	$\pi^0e^+\nu_e$ Called K_{e3}.	0.0390 ±0.0005	1.3
Γ_8	$\pi^0\pi^0e^+\nu_e$	$(1.70\ ^{+0.34}_{-0.29})\times 10^{-5}$	

$K^{\pm}$ DECAY RATES

$\Gamma(\mu^+\nu_\mu)$ — Γ_1

VALUE (10^6 s^{-1})	DOCUMENT ID		TECN	CHG
51.34±0.20 OUR FIT Error includes scale factor of 1.4.				
51.2 ±0.8	FORD	67	CNTR	±

$\Gamma(\pi^+\pi^+\pi^-)$ — Γ_4

VALUE (10^6 s^{-1})	EVTS	DOCUMENT ID		TECN	CHG
4.52 ±0.04 OUR FIT Error includes scale factor of 1.9.					
4.511±0.024		[3] FORD	70	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.529±0.032	3.2M	[3] FORD	70	ASPK	
4.496±0.030		[3] FORD	67	CNTR	±

[3] First FORD 70 value is second FORD 70 combined with FORD 67.

$(\Gamma(K^+) - \Gamma(K^-)) / \Gamma(K)$

$K^+ \to \mu^+\nu_\mu$ RATE DIFFERENCE

Test of *CPT* conservation.

VALUE (%)	DOCUMENT ID		TECN
−0.54±0.41	FORD	67	CNTR

$K^+ \to \pi^+\pi^+\pi^-$ RATE DIFFERENCE

Test of *CP* conservation.

VALUE (%)	EVTS	DOCUMENT ID		TECN	CHG
0.07±0.12 OUR AVERAGE					
0.08±0.12		[4] FORD	70	ASPK	
−0.50±0.90		FLETCHER	67	OSPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.02±0.16		[5] SMITH	73	ASPK	±
0.10±0.14	3.2M	[4] FORD	70	ASPK	
−0.04±0.21		[4] FORD	67	CNTR	

[4] First FORD 70 value is second FORD 70 combined with FORD 67.

[5] SMITH 73 value of $K^{\pm} \to \pi^{\pm}\pi^+\pi^-$ rate difference is derived from SMITH 73 value of $K^{\pm} \to \pi^{\pm}2\pi^0$ rate difference.

$K^+ \to \pi^+\pi^0\pi^0$ RATE DIFFERENCE

Test of *CP* conservation.

VALUE (%)	EVTS	DOCUMENT ID		TECN	CHG
0.0 ±0.6 OUR AVERAGE					
0.08±0.58		SMITH	73	ASPK	±
−1.1 ±1.8	1802	HERZO	69	OSPK	

$K^+ \to \pi^+\pi^0$ RATE DIFFERENCE

Test of *CPT* conservation.

VALUE (%)	DOCUMENT ID		TECN
0.8±1.2	HERZO	69	OSPK

$K^+ \to \pi^+\pi^0\gamma$ RATE DIFFERENCE

Test of *CP* conservation.

VALUE (%)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.9± 3.3 OUR AVERAGE						
0.8± 5.8	2461	SMITH	76	WIRE	±	E_π 55–90 MeV
1.0± 4.0	4000	ABRAMS	73B	ASPK	±	E_π 51–100 MeV
0.0±24.0	24	EDWARDS	72	OSPK		E_π 58–90 MeV

K^+ BRANCHING RATIOS

$\Gamma(\mu^+\nu_\mu)/\Gamma_{total}$ — Γ_1/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
63.51±0.19 OUR FIT Error includes scale factor of 1.2.						
63.24±0.44	62k	CHIANG	72	OSPK	+	1.84 GeV/c K^+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
56.9 ±2.6		[6] ALEXANDER	57	EMUL	+	
58.5 ±3.0		[6] BIRGE	56	EMUL	+	

[6] Old experiments not included in averaging.

$\Gamma(\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$ — Γ_1/Γ_4

VALUE	EVTS	DOCUMENT ID		TECN	CHG
11.36±0.12 OUR FIT Error includes scale factor of 1.8.					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
10.38±0.82	427	[7] YOUNG	65	EMUL	+

[7] Deleted from overall fit because YOUNG 65 constrains his results to add up to 1. Only YOUNG 65 measured $(\mu\nu)$ directly.

$\Gamma(e^+\nu_e)/\Gamma_{total}$ — Γ_2/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$2.1^{+1.8}_{-1.3}$		4	BOWEN	67B	OSPK	+
<160.0	95		BORREANI	64	HBC	+

$\Gamma(e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ — Γ_2/Γ_1

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	CHG
2.45±0.11 OUR AVERAGE					
2.51±0.15	404	HEINTZE	76	SPEC	+
2.37±0.17	534	HEARD	75B	SPEC	+
2.42±0.42	112	CLARK	72	OSPK	+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.8\ ^{+0.8}_{-0.6}$	8	MACEK	69	ASPK	+
$1.9\ ^{+0.7}_{-0.5}$	10	BOTTERILL	67	ASPK	+

$\Gamma(\pi^+\pi^0)/\Gamma_{total}$ — Γ_3/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
21.17±0.16 OUR FIT Error includes scale factor of 1.1.						
21.18±0.28	16k	CHIANG	72	OSPK	+	1.84 GeV/c K^+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
21.0 ±0.6		CALLAHAN	65	HLBC		See $\Gamma(\pi^+\pi^0)/\Gamma(\pi^+\pi^+\pi^-)$
21.6 ±0.6		TRILLING	65B	RVUE		
23.2 ±2.2		[8] ALEXANDER	57	EMUL	+	
27.7 ±2.7		[8] BIRGE	56	EMUL	+	

[8] Earlier experiments not averaged.

$\Gamma(\pi^+\pi^0)/\Gamma(\mu^+\nu_\mu)$ — Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	CHG
0.3333±0.0032 OUR FIT Error includes scale factor of 1.1.				
0.331 ±0.005 OUR AVERAGE Error includes scale factor of 1.2.				
0.3355±0.0057		[9] WEISSENBE... 76	SPEC	+
0.305 ±0.018	1600	ZELLER 69	ASPK	+
0.3277±0.0065	4517	[10] AUERBACH 67	OSPK	+
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.328 ±0.005	25k	[9] WEISSENBE... 74	STRC	+

[9] WEISSENBERG 76 revises WEISSENBERG 74.
[10] AUERBACH 67 changed from 0.3253 ± 0.0065. See comment with ratio $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\mu^+\nu_\mu)$.

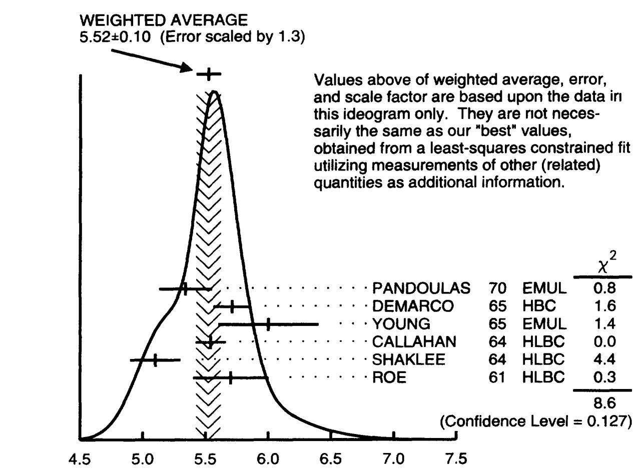
$\Gamma(\pi^+\pi^0)/\Gamma(\pi^+\pi^+\pi^-)$ — Γ_3/Γ_4

VALUE	EVTS	DOCUMENT ID	TECN	CHG
3.79±0.05 OUR FIT Error includes scale factor of 1.5.				
3.84±0.27 OUR AVERAGE Error includes scale factor of 1.9.				
3.96±0.15	1045	CALLAHAN 66	FBC	+
3.24±0.34	134	YOUNG 65	EMUL	+

$\Gamma(\pi^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
5.59±0.05 OUR FIT Error includes scale factor of 2.0.					
5.52±0.10 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.					
5.34±0.21	693	[11] PANDOULAS 70	EMUL	+	
5.71±0.15		DEMARCO 65	HBC		
6.0 ±0.4	44	YOUNG 65	EMUL	+	
5.54±0.12	2332	CALLAHAN 64	HLBC	+	
5.1 ±0.2	540	SHAKLEE 64	HLBC	+	
5.7 ±0.3		ROE 61	HLBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5.56±0.20	2330	[12] CHIANG 72	OSPK	+	1.84 GeV/c K^+
5.2 ±0.3		[13] TAYLOR 59	EMUL	+	
6.8 ±0.4		[13] ALEXANDER 57	EMUL	+	
5.6 ±0.4		[13] BIRGE 56	EMUL	+	

[11] Includes events of TAYLOR 59.
[12] Value is not independent of CHIANG 72 $\Gamma(\mu^+\nu_\mu)/\Gamma_{total}$, $\Gamma(\pi^+\pi^0)/\Gamma_{total}$, $\Gamma(\pi^+\pi^0\pi^0)/\Gamma_{total}$, $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma_{total}$, and $\Gamma(\pi^0 e^+\nu_e)/\Gamma_{total}$.
[13] Earlier experiments not averaged.

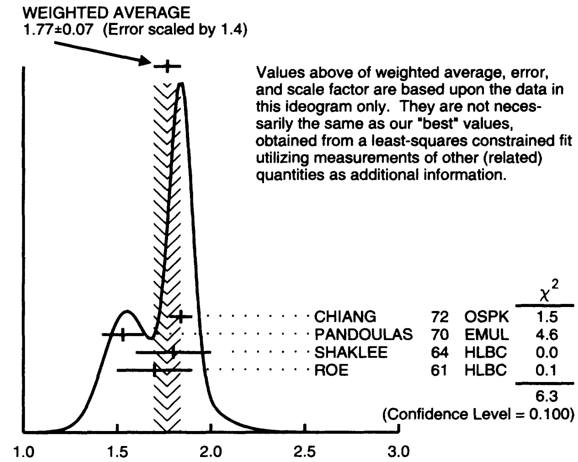


$\Gamma(\pi^+\pi^+\pi^-)/\Gamma_{total}$ (units 10^{-2})

$\Gamma(\pi^+\pi^0\pi^0)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1.73±0.04 OUR FIT Error includes scale factor of 1.2.					
1.77±0.07 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.					
1.84±0.06	1307	CHIANG 72	OSPK	+	1.84 GeV/c K^+
1.53±0.11	198	[14] PANDOULAS 70	EMUL	+	
1.8 ±0.2	108	SHAKLEE 64	HLBC	+	
1.7 ±0.2		ROE 61	HLBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.5 ±0.2		[15] TAYLOR 59	EMUL	+	
2.2 ±0.4		[15] ALEXANDER 57	EMUL	+	
2.1 ±0.5		[15] BIRGE 56	EMUL	+	

[14] Includes events of TAYLOR 59.
[15] Earlier experiments not averaged.



$\Gamma(\pi^+\pi^0\pi^0)/\Gamma_{total}$ (units 10^{-2})

$\Gamma(\pi^+\pi^0\pi^0)/\Gamma(\pi^+\pi^0)$ — Γ_5/Γ_3

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.0819±0.0020 OUR FIT Error includes scale factor of 1.2.					
0.081 ±0.005	574	[16] LUCAS 73B	HBC	−	Dalitz pairs only

[16] LUCAS 73B gives N($\pi 2\pi^0$) = 574 ± 5.9%, N(2π) = 3564 ± 3.1%. We quote 0.5N($\pi 2\pi^0$)/N(2π) where 0.5 is because only Dalitz pair π^0's were used.

$\Gamma(\pi^+\pi^0\pi^0)/\Gamma(\pi^+\pi^+\pi^-)$ — Γ_5/Γ_4

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.310±0.007 OUR FIT Error includes scale factor of 1.2.					
0.304±0.009 OUR AVERAGE					
0.303±0.009	2027	BISI 65	BC	+	HBC+HLBC
0.393±0.099	17	YOUNG 65	EMUL	+	

$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
3.18±0.08 OUR FIT Error includes scale factor of 1.6.					
3.33±0.16	2345	CHIANG 72	OSPK	+	1.84 GeV/c K^+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.8 ±0.4		[17] TAYLOR 59	EMUL	+	
5.9 ±1.3		[17] ALEXANDER 57	EMUL	+	
2.8 ±1.0		[17] BIRGE 56	EMUL	+	

[17] Earlier experiments not averaged.

$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\mu^+\nu_\mu)$ — Γ_6/Γ_1

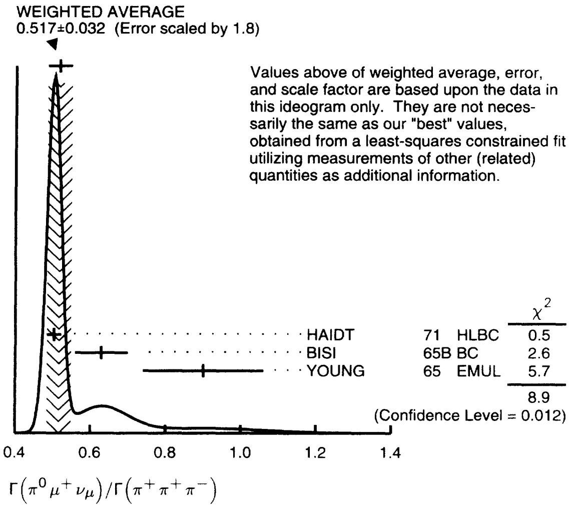
VALUE	EVTS	DOCUMENT ID	TECN	CHG
0.0501±0.0014 OUR FIT Error includes scale factor of 1.6.				
0.0488±0.0026 OUR AVERAGE				
0.054 ±0.009	240	ZELLER 69	ASPK	+
0.0480±0.0037	424	[18] GARLAND 68	OSPK	+
0.0486±0.0040	307	[19] AUERBACH 67	OSPK	+

[18] GARLAND 68 changed from 0.055 ± 0.004 in agreement with μ-spectrum calculation of GAILLARD 70 appendix B. L.G.Pondrom, (private communication 73).
[19] AUERBACH 67 changed from 0.0602 ± 0.0046 by erratum which brings the μ-spectrum calculation into agreement with GAILLARD 70 appendix B.

$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$ — Γ_6/Γ_4

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.569±0.015 OUR FIT Error includes scale factor of 1.6.					
0.517±0.032 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.					
0.503±0.019	1505	[20] HAIDT 71	HLBC	+	
0.63 ±0.07	2845	[21] BISI 65B	BC	+	HBC+HLBC
0.90 ±0.16	38	YOUNG 65	EMUL	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.510±0.017	1505	[20] EICHTEN 68	HLBC	+	

[20] HAIDT 71 is a reanalysis of EICHTEN 68.
[21] Error enlarged for background problems. See GAILLARD 70.



$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^0e^+\nu_e)$ — Γ_6/Γ_7

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.660±0.016 OUR FIT	Error includes scale factor of 1.5.					
0.680±0.013 OUR AVERAGE						
0.705±0.063	554	[22] LUCAS	73B	HBC	−	Dalitz pairs only
0.698±0.025	3480	[23] CHIANG	72	OSPK	+	1.84 GeV/c K^+
0.667±0.017	5601	BOTTERILL	68B	ASPK	+	
0.703±0.056	1509	[24] CALLAHAN	66B	HLBC		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.670±0.014		[25] HEINTZE	77	SPEC	+	
0.67 ±0.12		WEISSENBE...	76	SPEC	+	
0.608±0.014	1585	[26] BRAUN	75	HLBC	+	
0.596±0.025		[27] HAIDT	71	HLBC	+	
0.604±0.022	1398	[27] EICHTEN	68	HLBC		

[22] LUCAS 73B gives $N(K_{\mu3}) = 554 \pm 7.6\%$, $N(K_{e3}) = 786 \pm 3.1\%$. We divide.

[23] CHIANG 72 $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^0e^+\nu_e)$ is statistically independent of CHIANG 72 $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma_{total}$ and $\Gamma(\pi^0e^+\nu_e)/\Gamma_{total}$.

[24] From CALLAHAN 66B we use only the $K_{\mu3}/K_{e3}$ ratio and do not include in the fit the ratios $K_{\mu3}/(\pi\pi^+\pi^0)$ and $K_{e3}/(\pi\pi^+\pi^0)$, since they show large disagreements with the rest of the data.

[25] HEINTZE 77 value from fit to λ_0. Assumes μ-e universality.

[26] BRAUN 75 value is from form factor fit. Assumes μ-e universality.

[27] HAIDT 71 is a reanalysis of EICHTEN 68. Only individual ratios included in fit (see $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$ and $\Gamma(\pi^0e^+\nu_e)/\Gamma(\pi^+\pi^+\pi^-)$).

$[\Gamma(\pi^+\pi^0) + \Gamma(\pi^0\mu^+\nu_\mu)]/\Gamma_{total}$ — $(\Gamma_3+\Gamma_6)/\Gamma$

We combine these two modes for experiments measuring them in xenon bubble chamber because of difficulties of separating them there.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	CHG
24.35±0.16 OUR FIT	Error includes scale factor of 1.1.				
24.6 ±1.0 OUR AVERAGE	Error includes scale factor of 1.4.				
25.4 ±0.9	886	SHAKLEE	64	HLBC	+
23.4 ±1.1		ROE	61	HLBC	+

$\Gamma(\pi^0e^+\nu_e)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
4.82±0.06 OUR FIT	Error includes scale factor of 1.3.					
4.85±0.09 OUR AVERAGE						
4.86±0.10	3516	CHIANG	72	OSPK	+	1.84 GeV/c K^+
4.7 ±0.3	429	SHAKLEE	64	HLBC	+	
5.0 ±0.5		ROE	61	HLBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
5.1 ±1.3		[28] ALEXANDER	57	EMUL	+	
3.2 ±1.3		[28] BIRGE	56	EMUL	+	

[28] Earlier experiments not averaged.

$\Gamma(\pi^0e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ — Γ_7/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	CHG
0.0759±0.0011 OUR FIT	Error includes scale factor of 1.4.				
0.0752±0.0024 OUR AVERAGE					
0.069 ±0.006	350	ZELLER	69	ASPK	+
0.0775±0.0033	960	BOTTERILL	68C	ASPK	+
0.069 ±0.006	561	GARLAND	68	OSPK	+
0.0791±0.0054	295	[29] AUERBACH	67	OSPK	+

[29] AUERBACH 67 changed from 0.0797 ± 0.0054. See comment with ratio $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\mu^+\nu_\mu)$. The value 0.0785 ± 0.0025 given in AUERBACH 67 is an average of AUERBACH 67 $\Gamma(\pi^0e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ and CESTER 66 $\Gamma(\pi^0e^+\nu_e)/[\Gamma(\mu^+\nu_\mu) + \Gamma(\pi^+\pi^0)]$.

$\Gamma(\pi^0e^+\nu_e)/\Gamma(\pi^+\pi^0)$ — Γ_7/Γ_3

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.228±0.004 OUR FIT	Error includes scale factor of 1.3.					
0.221±0.012	786	[30] LUCAS	73B	HBC	−	Dalitz pairs only

[30] LUCAS 73B gives $N(K_{e3}) = 786 \pm 3.1\%$, $N(2\pi) = 3564 \pm 3.1\%$. We divide.

$\Gamma(\pi^0e^+\nu_e)/\Gamma(\pi^+\pi^+\pi^-)$ — Γ_7/Γ_4

VALUE	EVTS	DOCUMENT ID		TECN	CHG
0.863±0.011 OUR FIT	Error includes scale factor of 1.3.				
0.860±0.014 OUR AVERAGE					
0.867±0.027	2768	BARMIN	87	XEBC	+
0.856±0.040	2827	BRAUN	75	HLBC	+
0.850±0.019	4385	[31] HAIDT	71	HLBC	+
0.94 ±0.09	854	BELLOTTI	67B	HLBC	
0.90 ±0.06	230	BORREANI	64	HBC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.846±0.021	4385	[31] EICHTEN	68	HLBC	+
0.90 ±0.16	37	YOUNG	65	EMUL	+

[31] HAIDT 71 is a reanalysis of EICHTEN 68.

$\Gamma(\pi^0e^+\nu_e)/[\Gamma(\mu^+\nu_\mu) + \Gamma(\pi^+\pi^0)]$ — $\Gamma_7/(\Gamma_1+\Gamma_3)$

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	CHG
5.69±0.08 OUR FIT	Error includes scale factor of 1.4.				
6.01±0.15 OUR AVERAGE					
5.92±0.65		[32] WEISSENBE...	76	SPEC	+
6.16±0.22	5110	ESCHSTRUTH	68	OSPK	+
5.89±0.21	1679	CESTER	66	OSPK	+

[32] Value calculated from WEISSENBERG 76 ($\pi^0e\nu$), ($\mu\nu$), and ($\pi\pi^0$) values to eliminate dependence on our 1974 ($\pi2\pi^0$) and ($\pi\pi^+\pi^-$) fractions.

$\Gamma(\pi^0\pi^0e^+\nu_e)/\Gamma(\pi^0e^+\nu_e)$ — Γ_8/Γ_7

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	CHG
$4.3^{+0.9}_{-0.7}$ OUR FIT						
$4.1^{+1.0}_{-0.7}$ OUR AVERAGE						
$4.2^{+1.0}_{-0.9}$		25	BOLOTOV	86B	CALO	−
$3.8^{+5.0}_{-1.2}$		2	LJUNG	73	HLBC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<37.0	90	0	ROMANO	71	HLBC	+

$\Gamma(\pi^0\pi^0e^+\nu_e)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	CHG
2.1 ±0.4 OUR FIT					
2.54±0.89	10	BARMIN	88B	HLBC	+

$\Gamma(\pi^+\pi^-e^+\nu_e)/\Gamma(\pi^+\pi^+\pi^-)$ — Γ_9/Γ_4

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	CHG
6.99±0.30 OUR AVERAGE	Error includes scale factor of 1.2.				
7.21±0.32	30k	ROSSELET	77	SPEC	+
7.36±0.68	500	BOURQUIN	71	ASPK	
7.0 ±0.9	106	SCHWEINB...	71	HLBC	+
5.83±0.63	269	ELY	69	HLBC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
6.7 ±1.5	69	BIRGE	65	FBC	+

$\Gamma(\pi^+\pi^-\mu^+\nu_\mu)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.77^{+0.54}_{-0.50}$	1	CLINE	65	FBC	+

$\Gamma(\pi^+\pi^-\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$ — Γ_{10}/Γ_4

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	CHG
2.57±1.55	7	BISI	67	DBC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2.5	1	GREINER	64	EMUL	+

$\Gamma(\pi^0\pi^0\pi^0e^+\nu_e)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	CHG
<3.5	90	0	BOLOTOV	88	SPEC	−

$\Gamma(\pi^+\gamma\gamma)/\Gamma_{total}$ — Γ_{12}/Γ

All values given here assume a phase space pion energy spectrum.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
< 0.01	90	0	ATIYA	90B	CALO		$T\pi$ 117–127 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •							
< 0.084	90	0	ASANO	82	CNTR	+	$T\pi$ 117–127 MeV
−0.42 ±0.52		0	ABRAMS	77	SPEC	+	$T\pi$ <92 MeV
< 0.35	90	0	LJUNG	73	HLBC	+	6–102,114–127 MeV
< 0.5	90	0	KLEMS	71	OSPK	+	$T\pi$ <117 MeV
−0.1 ±0.6			CHEN	68	OSPK	+	$T\pi$ 60–90 MeV

$\Gamma(\pi^+ 3\gamma)/\Gamma_{total}$ — Γ_{13}/Γ

Values given here assume a phase space pion energy spectrum.

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<1.0	90	ASANO	82	CNTR	+	$T(\pi)$ 117–127 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<3.0	90	KLEMS	71	OSPK	+	$T(\pi)$ >117 MeV

$\Gamma(e^+ \nu_e \nu \overline{\nu})/\Gamma(e^+ \nu_e)$ — Γ_{14}/Γ_2

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG
<3.8	90	0	HEINTZE	79	SPEC	+

$\Gamma(\mu^+ \nu_\mu \nu \overline{\nu})/\Gamma_{total}$ — Γ_{15}/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	CHG
<6.0	90	0	[33] PANG	73	CNTR	+

[33] PANG 73 assumes μ spectrum from ν-ν interaction of BARDIN 70.

$\Gamma(\mu^+ \nu_\mu e^+ e^-)/\Gamma(\pi^+ \pi^- e^+ \nu_e)$ — Γ_{16}/Γ_9

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
27. ±8.	14	[34] DIAMANT-...	76	SPEC	+	Extrapolated BR
• • • We do not use the following data for averages, fits, limits, etc. • • •						
3.3±0.9	14	[34] DIAMANT-...	76	SPEC	+	$m(ee)$ >140

[34] DIAMANT-BERGER 76 quotes this result times our 1975 $\pi^+ \pi^- e \nu$ BR ratio. The first DIAMANT-BERGER 76 value is the second value extrapolated to 0 to include low mass e pairs.

$\Gamma(e^+ \nu_e e^+ e^-)/\Gamma(\pi^+ \pi^- e^+ \nu_e)$ — Γ_{17}/Γ_9

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	CHG
$0.54^{+0.54}_{-0.27}$	4	DIAMANT-...	76	SPEC	+

$\Gamma(\mu^+ \nu_\mu \mu^+ \mu^-)/\Gamma_{total}$ — Γ_{18}/Γ

VALUE (units 10^{-7})	CL%	DOCUMENT ID		TECN	CHG
<4.1	90	ATIYA	89	CNTR	+

$\Gamma(\mu^+ \nu_\mu \gamma)/\Gamma_{total}$ — Γ_{19}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
5.50±0.28 OUR AVERAGE						
6.6 ±1.5		[35,36] DEMIDOV	90	HLBC		P(μ) < 231.5 MeV/c
6.0 ±0.9		BARMIN	88	HLBC	+	P(μ) <231.5 MeV/c
5.4 ±0.3		[37] AKIBA	85	SPEC		P(μ) <231.5 MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •						
3.5 ±0.8		[36,38] DEMIDOV	90	HLBC		E(γ) > 20 MeV
3.2 ±0.5	57	[39] BARMIN	88	HLBC	+	$E(\gamma)$ >20 MeV
5.8 ±3.5	12	WEISSENBE...	74	STRC	+	$E(\gamma)$ >9 MeV

[35] P(μ) cut given in DEMIDOV 90 paper, 235.1 MeV/c, is a misprint according to authors (private communication).
[36] DEMIDOV 90 quotes only inner bremsstrahlung (IB) part.
[37] Assumes μ-e universality and uses constraints from $K \to e \nu \gamma$.
[38] Not independent of above DEMIDOV 90 value. Cuts differ.
[39] Not independent of above BARMIN 88 value. Cuts differ.

$\Gamma(\pi^+ \pi^0 \gamma)/\Gamma_{total}$ — Γ_{20}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2.75±0.15 OUR AVERAGE							
2.71±0.45		140	BOLOTOV	87	WIRE	−	$T\pi^-$ 55–90 MeV
2.87±0.32		2461	SMITH	76	WIRE	±	$T\pi^\pm$ 55–90 MeV
2.71±0.19		2100	ABRAMS	72	ASPK	±	$T\pi^+$ 55–90 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$1.5\ ^{+1.1}_{-0.6}$			[40] LJUNG	73	HLBC	+	$T\pi^+$ 55–80 MeV
$2.6\ ^{+1.5}_{-1.1}$			[40] LJUNG	73	HLBC	+	$T\pi^+$ 55–90 MeV
$6.8\ ^{+3.7}_{-2.1}$		17	[40] LJUNG	73	HLBC	+	$T\pi^+$ 55–102 MeV
2.4 ±0.8		24	EDWARDS	72	OSPK		$T\pi^+$ 58–90 MeV
<1.0		0	[41] MALTSEV	70	HLBC	+	$T\pi^+$ <55 MeV
<1.9	90	0	EMMERSON	69	OSPK		$T\pi^+$ 55–80 MeV
2.2 ±0.7		18	CLINE	64	FBC	+	$T\pi^+$ 55–80 MeV

[40] The LJUNG 73 values are not independent.
[41] MALTSEV 70 selects low π^+ energy to enhance direct emission contribution.

$\Gamma(\pi^+ \pi^0 \gamma\ \text{(DE)})/\Gamma_{total}$ — Γ_{21}/Γ

Direct emission part of $\Gamma(\pi^+ \pi^0 \gamma)/\Gamma_{total}$.

VALUE (units 10^{-5})	DOCUMENT ID		TECN	CHG	COMMENT
1.8 ±0.4 OUR AVERAGE					
$2.05\pm0.46^{+0.39}_{-0.23}$	BOLOTOV	87	WIRE	−	$T\pi^-$ 55–90 MeV
2.3 ±3.2	SMITH	76	WIRE	±	$T\pi^\pm$ 55–90 MeV
1.56±0.35±0.5	ABRAMS	72	ASPK	±	$T\pi^\pm$ 55–90 MeV

$\Gamma(\pi^+ \pi^+ \pi^- \gamma)/\Gamma_{total}$ — Γ_{22}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.04±0.31 OUR AVERAGE						
1.10±0.48	7	BARMIN	89	XEBC		$E(\gamma)$ > 5 MeV
1.0 ±0.4		STAMER	65	EMUL	+	$E(\gamma)$ >11 MeV

$\Gamma(\pi^+ \pi^0 \pi^0 \gamma)/\Gamma(\pi^+ \pi^0 \pi^0)$ — Γ_{23}/Γ_5

VALUE (units 10^{-4})	DOCUMENT ID		TECN	CHG	COMMENT
$4.3^{+3.2}_{-1.7}$	BOLOTOV	85	SPEC	−	$E(\gamma)$ > 10 MeV

$\Gamma(\pi^0 \mu^+ \nu_\mu \gamma)/\Gamma_{total}$ — Γ_{24}/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
<6.1	90	0	LJUNG	73	HLBC	+	$E(\gamma)$ >30 MeV

$\Gamma(\pi^0 e^+ \nu_e \gamma)/\Gamma(\pi^0 e^+ \nu_e)$ — Γ_{25}/Γ_7

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.54±0.04 OUR AVERAGE Error includes scale factor of 1.1.						
0.46±0.08	82	[42] BARMIN	91	XEBC		E(γ) > 10 MeV, 0.6 < cos$\theta_e\ \gamma$ < 0.9
0.56±0.04	192	[43] BOLOTOV	86B	CALO	−	$E(\gamma)$ >10 MeV
0.76±0.28	13	[44] ROMANO	71	HLBC		$E(\gamma)$ >10 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.51±0.25	82	[42] BARMIN	91	XEBC		E(γ) > 10 MeV, cos$\theta_e\ \gamma$ < 0.98
0.48±0.20	16	[45] LJUNG	73	HLBC	+	$E(\gamma)$ >30 MeV
$0.22^{+0.15}_{-0.10}$		[45] LJUNG	73	HLBC	+	$E(\gamma)$ >30 MeV
0.53±0.22		[44] ROMANO	71	HLBC	+	$E(\gamma)$ >30 MeV
1.2 ±0.8		BELLOTTI	67	HLBC	+	$E(\gamma)$ >30 MeV

[42] BARMIN 91 quotes branching ratio $\Gamma(K \to e\pi^0 \nu\gamma)/\Gamma_{all}$. The measured normalization is $[\Gamma(K \to e\pi^0\nu) + \Gamma(K \to \pi^+\pi^+\pi^-)]$. For comparison with other experiments we used $\Gamma(K \to e\pi^0\nu)/\Gamma_{all} = 0.0482$ to calculate the values quoted here.
[43] cos$\theta(e\gamma)$ between 0.6 and 0.9.
[44] Both ROMANO 71 values are for cos$\theta(e\gamma)$ between 0.6 and 0.9. Second value is for comparison with second LJUNG 73 value. We use lowest $E(\gamma)$ cut for Summary Table value. See ROMANO 71 for E_γ dependence.
[45] First LJUNG 73 value is for cos$\theta(e\gamma)$ <0.9, second value is for cos$\theta(e\gamma)$ between 0.6 and 0.9 for comparison with ROMANO 71.

$\Gamma(\pi^0 e^+ \nu_e \gamma\ \text{(SD)})/\Gamma_{total}$ — Γ_{26}/Γ

Structure-dependent part.

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	CHG
<5.3	90	BOLOTOV	86B	CALO	−

$\Gamma(\pi^+ \pi^+ e^- \overline{\nu}_e)/\Gamma_{total}$ — Γ_{27}/Γ

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-7})	CL%	EVTS	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 9.0	95	0	SCHWEINB...	71	HLBC	+
< 6.9	95	0	ELY	69	HLBC	+
<20.	95		BIRGE	65	FBC	+

$\Gamma(\pi^+ \pi^+ e^- \overline{\nu}_e)/\Gamma(\pi^+ \pi^- e^+ \nu_e)$ — Γ_{27}/Γ_9

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN
< 3	90	3	[46] BLOCH	76	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<130.	95	0	BOURQUIN	71	ASPK

[46] BLOCH 76 quotes 3.6×10^{-4} at CL = 95%, we convert.

$\Gamma(\pi^+ \pi^+ \mu^- \overline{\nu}_\mu)/\Gamma_{total}$ — Γ_{28}/Γ

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	CHG
<3.0	95	0	BIRGE	65	FBC	+

$\Gamma(\pi^+ e^+ e^-)/\Gamma_{total}$ — Γ_{29}/Γ

Test for ΔS = 1 weak neutral current. Allowed by combined first-order weak and electromagnetic interactions.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •							
< 1.7	90		CENCE	74	ASPK	+	Three track evts
< 0.27	90		CENCE	74	ASPK	+	Two track events
<32.0	90		BEIER	72	OSPK	±	
< 4.4	90		BISI	67	DBC	+	
< 0.88	90		CLINE	67B	FBC	+	
< 2.45	90	1	CAMERINI	64	FBC	+	

$\Gamma(\pi^+ e^+ e^-)/\Gamma(\pi^+ \pi^- e^+ \nu_e)$ — Γ_{29}/Γ_9

Test for ΔS = 1 weak neutral current. Allowed by higher-order electroweak interactions.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG
7.0±1.3	41	[47] BLOCH	75	SPEC	+

[47] BLOCH 75 quotes this result multiplied by our 1974 $\pi^+ \pi^- e \nu$ BR fraction.

$\Gamma(\pi^+\mu^+\mu^-)/\Gamma_{total}$ — Γ_{30}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE (units 10^{-7})	CL%	DOCUMENT ID		TECN	CHG
< 2.3	90	ATIYA	89	CNTR	+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<24	90	BISI	67	DBC	+
<30	90	CAMERINI	65	FBC	+

$\Gamma(\pi^+\nu\overline{\nu})/\Gamma_{total}$ — Γ_{31}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE (units 10^{-8})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
< 3.4	90		ATIYA	90	CNTR	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
< 14	90		ASANO	81B	CNTR	+	$T(\pi)$ 116–127 MeV
< 94	90		[48] CABLE	73	CNTR	+	$T(\pi)$ 60–105 MeV
< 56	90		[48] CABLE	73	CNTR	+	$T(\pi)$ 60–127 MeV
<5700	90	0	[49] LJUNG	73	HLBC	+	
< 140	90		[48] KLEMS	71	OSPK	+	$T(\pi)$ 117–127 MeV

[48] KLEMS 71 and CABLE 73 assume π spectrum same as K_{e3} decay. Second CABLE 73 limit combines CABLE 73 and KLEMS 71 data for vector interaction.
[49] LJUNG 73 assumes vector interaction.

$\Gamma(\mu^-\nu e^+e^+)/\Gamma(\pi^+\pi^-e^+\nu_e)$ — Γ_{32}/Γ_9

Test of lepton family number conservation.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	CHG
<0.5	90	0	[50] DIAMANT-...	76	SPEC	+

[50] DIAMANT-BERGER 76 quotes this result times our 1975 $\pi^+\pi^-e\nu$ BR ratio.

$\Gamma(\mu^+\nu_e)/\Gamma_{total}$ — Γ_{33}/Γ

Forbidden by lepton family number conservation.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
<0.004	90	0	LYONS	81	HLBC	0	200 GeV K^+ narrow band ν beam
• • • We do not use the following data for averages, fits, limits, etc. • • •							
<0.012	90		COOPER	82	HLBC		Wideband ν beam

$\Gamma(\pi^+\mu^+e^-)/\Gamma_{total}$ — Γ_{34}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-10})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
< 2.1	90	0	LEE	90	SPEC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
<11	90	0	CAMPAGNARI	88	SPEC	+	In LEE 90
<48	90	0	DIAMANT-...	76	SPEC	+	

$\Gamma(\pi^+\mu^-e^+)/\Gamma_{total}$ — Γ_{35}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-9})	CL%	EVTS	DOCUMENT ID		TECN	CHG
< 7	90	0	[51] DIAMANT-...	76	SPEC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<28	90		[51] BEIER	72	OSPK	±

[51] Measurement actually applies to the sum of the $\pi^+\mu^-e^+$ and $\pi^-\mu^+e^+$ modes.

$\Gamma(\pi^-\mu^+e^+)/\Gamma_{total}$ — Γ_{36}/Γ

Test of total lepton number conservation.

VALUE (units 10^{-9})	CL%	EVTS	DOCUMENT ID		TECN	CHG
< 7	90	0	[52] DIAMANT-...	76	SPEC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<28	90		[52] BEIER	72	OSPK	±

[52] Measurement actually applies to the sum of the $\pi^+\mu^-e^+$ and $\pi^-\mu^+e^+$ modes.

$\Gamma(\pi^+e^+\mu^-)/\Gamma_{total}$ — Γ_{42}/Γ

VALUE (units 10^{-8})	CL%	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.4	90	BEIER	72	OSPK	±

$\Gamma(\pi^-e^+e^+)/\Gamma_{total}$ — Γ_{37}/Γ

Test of total lepton number conservation.

VALUE (units 10^{-5})	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.5	CHANG	68	HBC	−

$\Gamma(\pi^-e^+e^+)/\Gamma(\pi^+\pi^-e^+\nu_e)$ — Γ_{37}/Γ_9

Test of total lepton number conservation.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	CHG
<2.5	90	0	[53] DIAMANT-...	76	SPEC	+

[53] DIAMANT-BERGER 76 quotes this result times our 1975 BR ratio.

$\Gamma(\pi^-\mu^+\mu^+)/\Gamma_{total}$ — Γ_{38}/Γ

Forbidden by total lepton number conservation.

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN
<1.5	90	[54] LITTENBERG	92	HBC

[54] LITTENBERG 92 is from retroactive data analysis of CHANG 68 bubble chamber data.

$\Gamma(\mu^+\overline{\nu}_e)/\Gamma_{total}$ — Γ_{39}/Γ

Forbidden by total lepton number conservation.

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<3.3	90	COOPER	82	HLBC	Wideband ν beam

$\Gamma(\pi^0e^+\overline{\nu}_e)/\Gamma_{total}$ — Γ_{40}/Γ

Forbidden by total lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.003	90	COOPER	82	HLBC	Wideband ν beam

$\Gamma(\pi^+\gamma)/\Gamma_{total}$ — Γ_{41}/Γ

Violates angular momentum conservation. Not listed in Summary Table.

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.4	90	ASANO	82	CNTR	+
<4.0	90	[55] KLEMS	71	OSPK	+

[55] Test of model of Selleri, Nuovo Cimento **60A** 291 (1969).

K^+ LONGITUDINAL POLARIZATION OF EMITTED μ^+

$K^+ \to \mu^+\nu$

Tests for right-handed currents in strangeness-changing decay.

VALUE	DOCUMENT ID		TECN	CHG
−0.97 ±0.04 OUR AVERAGE				
−0.970±0.047	YAMANAKA	86	SPEC	+
−1.0 ±0.1	CUTTS	69	SPRK	+
−0.96 ±0.12	COOMBES	57	CNTR	+

NOTE ON DALITZ PLOT PARAMETERS FOR $K \to 3\pi$ DECAYS

The Dalitz plot distribution for $K^\pm \to \pi^\pm\pi^\pm\pi^\mp$, $K^\pm \to \pi^0\pi^0\pi^\pm$, and $K_L^0 \to \pi^+\pi^-\pi^0$ can be parameterized by a series expansion such as that introduced by Weinberg.[1] We use the form

$$\left|M\right|^2 \propto 1 + g\frac{(s_3 - s_0)}{m_{\pi^+}^2} + h\left[\frac{s_3 - s_0}{m_{\pi^+}^2}\right]^2 + j\,\frac{(s_2 - s_1)}{m_{\pi^+}^2} + k\left[\frac{s_2 - s_1}{m_{\pi^+}^2}\right]^2 + \cdots\ , \qquad (1)$$

where $m_{\pi^+}^2$ has been introduced to make the coefficients g, h, j, and k dimensionless, and

$$s_i = (P_K - P_i)^2 = (m_K - m_i)^2 - 2m_K T_i\ ,\ i = 1,2,3,$$

$$s_0 = \frac{1}{3}\sum_i s_i = \frac{1}{3}(m_K^2 + m_1^2 + m_2^2 + m_3^2)\ .$$

Here the P_i are four-vectors, m_i and T_i are the mass and kinetic energy of the i^{th} pion, and the index 3 is used for the odd pion.

The coefficient g is a measure of the slope in the variable s_3 (or T_3) of the Dalitz plot, while h and k measure the quadratic dependence on s_3 and $(s_2 - s_1)$, respectively. The coefficient j is related to the asymmetry of the plot and must be zero if CP invariance holds. Note also that if CP is good, g, h, and k must be the same for $K^+ \to \pi^+\pi^+\pi^-$ as for $K^- \to \pi^-\pi^-\pi^+$.

Since different experiments use different forms for $\left|M\right|^2$, in order to compare the experiments we have converted to g, h, j, and k whatever coefficients have been measured. Where such conversions have been done, the measured coefficient a_y, a_t, a_u, or a_v is given in the comment at the right. For definitions of these coefficients, details of this conversion, and discussion of the data, see the April 1982 version of this note.[2]

See also the review of Devlin and Dickey,[3] which contains an analysis of $K \to 2\pi$ and $K \to 3\pi$ data in terms of transition amplitudes with appropriate energy dependence.

References

1. S. Weinberg, Phys. Rev. Lett. **4**, 87 (1960).
2. Particle Data Group, Phys. Lett. **111B**, 69 (1982).
3. T.J. Devlin and J.O. Dickey, Rev. Mod. Phys. **51**, 237 (1979).

ENERGY DEPENDENCE OF $K^{\pm}$ DALITZ PLOT

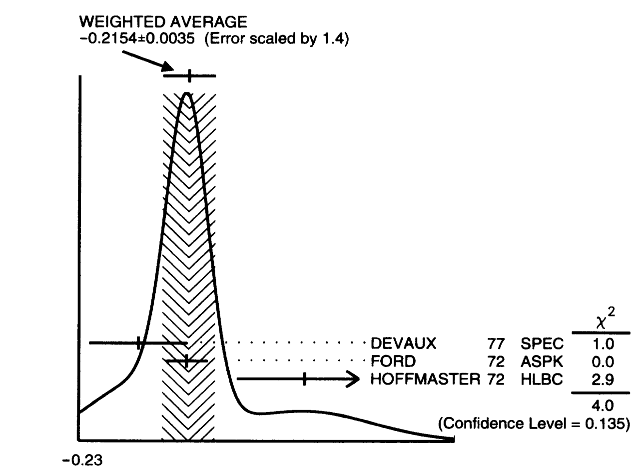
$|\text{matrix element}|^2 = 1 + gu + hu^2 + kv^2$
where $u = (s_3 - s_0) / m^2(\pi)$ and $v = (s_1 - s_2) / m^2(\pi)$

LINEAR COEFFICIENT g_{τ^+} FOR $K^+ \to \pi^+\pi^+\pi^-$

Some experiments use Dalitz variables x and y. In the comments we give a_y = coefficient of y term. See note above on "Dalitz Plot Parameters for $K \to 3\pi$ Decays." For discussion of the conversion of a_y to g, see the earlier version of the same note in the Review published in Physics Letters **111B** 70 (1982).

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
−0.2154±0.0035 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.				
−0.2221±0.0065	225k	DEVAUX	77	SPEC	+	a_y=.2814 ± .0082
−0.2157±0.0028	750k	FORD	72	ASPK	+	a_y=.2734 ± .0035
−0.200 ±0.009	39819	[56] HOFFMASTER	72	HLBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−0.196 ±0.012	17898	[57] GRAUMAN	70	HLBC	+	a_y=0.228 ± 0.030
−0.218 ±0.016	9994	[58] BUTLER	68	HBC	+	a_y=0.277 ± 0.020
−0.22 ±0.024	5428	[58,59] ZINCHENKO	67	HBC	+	a_y=0.28 ± 0.03

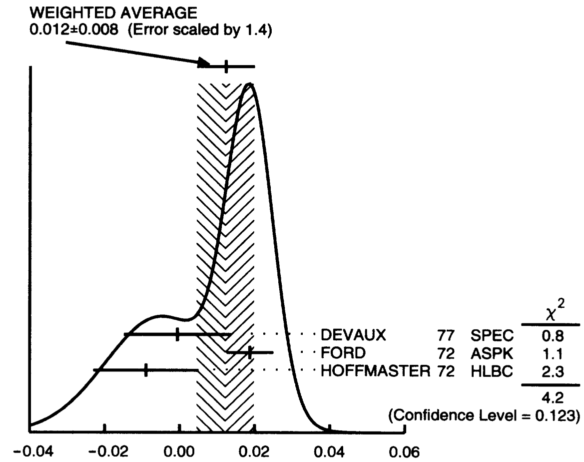
[56] HOFFMASTER 72 includes GRAUMAN 70 data.
[57] Emulsion data added — all events included by HOFFMASTER 72
[58] Experiments with large errors not included in average.
[59] Also includes DBC events.



Linear energy dependence for $K^+ \to \pi^+\pi^+\pi^-$

QUADRATIC COEFFICIENT h FOR $K^+ \to \pi^+\pi^+\pi^-$

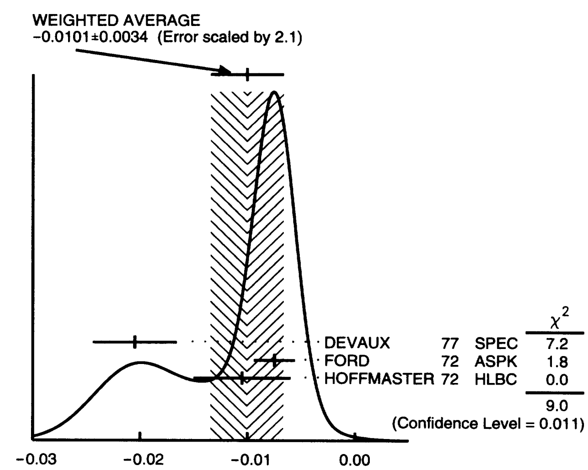
VALUE	EVTS	DOCUMENT ID		TECN	CHG
0.012 ±0.008 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.			
−0.0006±0.0143	225k	DEVAUX	77	SPEC	+
0.0187±0.0062	750k	FORD	72	ASPK	+
−0.009 ±0.014	39819	HOFFMASTER	72	HLBC	+



Quadratic coefficient h for $K^+ \to \pi^+\pi^+\pi^-$

QUADRATIC COEFFICIENT k FOR $K^+ \to \pi^+\pi^+\pi^-$

VALUE	EVTS	DOCUMENT ID		TECN	CHG
−0.0101±0.0034 OUR AVERAGE		Error includes scale factor of 2.1. See the ideogram below.			
−0.0205±0.0039	225k	DEVAUX	77	SPEC	+
−0.0075±0.0019	750k	FORD	72	ASPK	+
−0.0105±0.0045	39819	HOFFMASTER	72	HLBC	+



Quadratic coefficient k for $K^+ \to \pi^+\pi^+\pi^-$

LINEAR COEFFICIENT g_{τ^-} FOR $K^- \to \pi^-\pi^-\pi^+$

Some experiments use Dalitz variables x and y. In the comments we give a_y = coefficient of y term. See note above on "Dalitz Plot Parameters for $K \to 3\pi$ Decays." For discussion of the conversion of a_y to g, see the earlier version of the same note in the Review published in Physics Letters **111B** 70 (1982).

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
−0.217 ±0.007 OUR AVERAGE		Error includes scale factor of 2.5.				
−0.2186±0.0028	750k	FORD	72	ASPK	−	a_y=.2770 ± .0035
−0.193 ±0.010	50919	MAST	69	HBC	−	a_y=0.244 ± 0.013
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−0.199 ±0.008	81k	[60] LUCAS	73	HBC	−	a_y=0.252 ± 0.011
−0.190 ±0.023	5778	[61,62] MOSCOSO	68	HBC	−	a_y=0.242 ± 0.029
−0.220 ±0.035	1347	[63] FERRO-LUZZI	61	HBC	−	a_y=0.28 ± 0.045

[60] Quadratic dependence is required by K^0_L experiments. For comparison we average only those $K^{\pm}$ experiments which quote quadratic fit values.
[61] Experiments with large errors not included in average.
[62] Also includes DBC events.
[63] No radiative corrections included.

QUADRATIC COEFFICIENT h FOR $K^- \to \pi^-\pi^-\pi^+$

VALUE	EVTS	DOCUMENT ID		TECN	CHG
0.010 ±0.006 OUR AVERAGE					
0.0125±0.0062	750k	FORD	72	ASPK	−
−0.001 ±0.012	50919	MAST	69	HBC	−

QUADRATIC COEFFICIENT k FOR $K^- \to \pi^-\pi^-\pi^+$

VALUE	EVTS	DOCUMENT ID		TECN	CHG
−0.0084±0.0019 OUR AVERAGE					
−0.0083±0.0019	750k	FORD	72	ASPK	−
−0.014 ±0.012	50919	MAST	69	HBC	−

$(g_{\tau^+} - g_{\tau^-}) / (g_{\tau^+} + g_{\tau^-})$

A nonzero value for this quantity indicates *CP* violation.

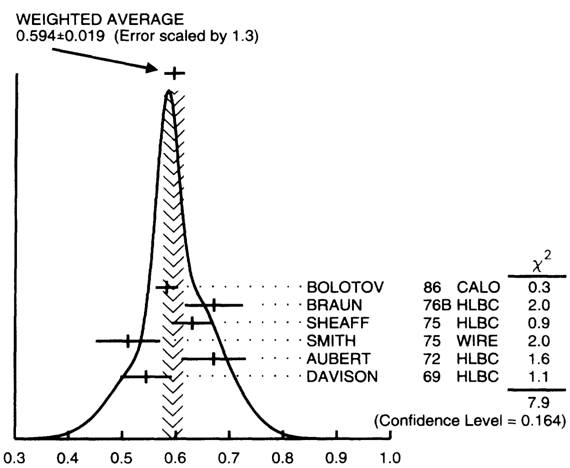
VALUE (%)	EVTS	DOCUMENT ID		TECN
−0.70±0.53	3.2M	FORD	70	ASPK

LINEAR COEFFICIENT g FOR $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$

Unless otherwise stated, all experiments include terms quadratic in $(s_3 - s_0) / m^2(\pi^+)$. See mini-review above.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.594±0.019 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.					
0.582±0.021	43k	BOLOTOV	86	CALO	−	
0.670±0.054	3263	BRAUN	76B	HLBC	+	
0.630±0.038	5635	SHEAFF	75	HLBC	+	
0.510±0.060	27k	SMITH	75	WIRE	+	
0.67 ±0.06	1365	AUBERT	72	HLBC	+	
0.544±0.048	4048	DAVISON	69	HLBC	+	Also emulsion
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.806±0.220	4639	[64] BERTRAND	76	EMUL	+	
0.484±0.084	574	[65] LUCAS	73B	HBC	−	Dalitz pairs only
0.527±0.102	198	[64] PANDOULAS	70	EMUL	+	
0.586±0.098	1874	[65] BISI	65	HLBC	+	Also HBC
0.48 ±0.04	1792	[65] KALMUS	64	HLBC	+	

[64] Experiments with large errors not included in average.
[65] Authors give linear fit only.



Linear energy dependence for $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$

QUADRATIC COEFFICIENT h FOR $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$

See mini-review above.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.035±0.015 OUR AVERAGE						
0.037±0.024	43k	BOLOTOV	86	CALO	−	
0.152±0.082	3263	BRAUN	76B	HLBC	+	
0.041±0.030	5635	SHEAFF	75	HLBC	+	
0.009±0.040	27k	SMITH	75	WIRE	+	
−0.01 ±0.08	1365	AUBERT	72	HLBC	+	
0.026±0.050	4048	DAVISON	69	HLBC	+	Also emulsion
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.164±0.121	4639	[66] BERTRAND	76	EMUL	+	
0.018±0.124	198	[66] PANDOULAS	70	EMUL	+	

[66] Experiments with large errors not included in average.

NOTE ON $K^{\pm}_{\ell 3}$ AND $K^0_{\ell 3}$ FORM FACTORS

Assuming that only the vector current contributes to $K \to \pi\ell\nu$ decays, we write the matrix element as

$$M \propto f_+(t)\left[(P_K + P_\pi)_\mu \bar{\ell}\gamma_\mu(1+\gamma_5)\nu\right] + f_-(t)\left[m_\ell \bar{\ell}(1+\gamma_5)\nu\right] \ , \qquad (1)$$

where P_K and P_π are the four-momenta of the K and π mesons, m_ℓ is the lepton mass, and f_+ and f_- are dimensionless form factors which can depend only on $t = (P_K - P_\pi)^2$, the square of the four-momentum transfer to the leptons. If time-reversal invariance holds, f_+ and f_- are relatively real. $K_{\mu 3}$ experiments measure f_+ and f_-, while K_{e3} experiments are sensitive only to f_+ because the small electron mass makes the f_- term negligible.

(a) $K_{\mu 3}$ *experiments.* Analyses of $K_{\mu 3}$ data frequently assume a linear dependence of f_+ and f_- on t, i.e.,

$$f_\pm(t) = f_\pm(0)\left[1 + \lambda_\pm(t/m_\pi^2)\right] \ . \qquad (2)$$

Most $K_{\mu 3}$ data are adequately described by Eq. (2) for f_+ and a constant f_- (i.e., $\lambda_- = 0$). There are two equivalent parametrizations commonly used in these analyses:

(1) $\lambda_+, \xi(0)$ *parametrization.* Analyses of $K_{\mu 3}$ data often introduce the ratio of the two form factors

$$\xi(t) = f_-(t)/f_+(t) \ .$$

The $K_{\mu 3}$ decay distribution is then described by the two parameters λ_+ and $\xi(0)$ (assuming time reversal invariance and $\lambda_- = 0$). These parameters can be determined by three different methods:

Method A. By studying the Dalitz plot or the pion spectrum of $K_{\mu 3}$ decay. The Dalitz plot density is (see, *e.g.*, Chounet *et al.*[1]):

$$\rho(E_\pi, E_\mu) \propto f_+^2(t)\left[A + B\xi(t) + C\xi(t)^2\right] \ ,$$

where

$$A = m_K\left(2E_\mu E_\nu - m_K E'_\pi\right) + m_\mu^2\left(\frac{1}{4}E'_\pi - E_\nu\right) \ ,$$

$$B = m_\mu^2\left(E_\nu - \frac{1}{2}E'_\pi\right) \ ,$$

$$C = \frac{1}{4}m_\mu^2 E'_\pi \ ,$$

$$E'_\pi = E_\pi^{\max} - E_\pi = \left(m_K^2 + m_\pi^2 - m_\mu^2\right)/2m_K - E_\pi \ .$$

Here E_π, E_μ, and E_ν are, respectively, the pion, muon, and neutrino energies in the kaon center of mass. The density ρ is fit to the data to determine the values of $\lambda_+, \xi(0)$, and their correlation.

Method B. By measuring the $K_{\mu 3}/K_{e3}$ branching ratio and comparing it with the theoretical ratio (see, *e.g.*, Fearing *et al.*[2]) as given in terms of λ_+ and $\xi(0)$, assuming μ-e universality:

$$\Gamma(K^{\pm}_{\mu 3})/\Gamma(K^{\pm}_{e3}) = 0.6457 + 1.4115\lambda_+ + 0.1264\xi(0) + 0.0192\xi(0)^2 + 0.0080\lambda_+\xi(0) \ ,$$

$$\Gamma(K^0_{\mu 3})/\Gamma(K^0_{e3}) = 0.6452 + 1.3162\lambda_+ + 0.1264\xi(0) + 0.0186\xi(0)^2 + 0.0064\lambda_+\xi(0) \ .$$

This cannot determine λ_+ and $\xi(0)$ simultaneously but simply fixes a relationship between them.

Method C. By measuring the muon polarization in $K_{\mu 3}$ decay. In the rest frame of the K, the μ is expected to be polarized in the direction $\mathbf{A}$ with $\mathbf{P} = \mathbf{A}/\left|\mathbf{A}\right|$, where $\mathbf{A}$ is given (Cabibbo and Maksymowicz[3]) by

$$\mathbf{A} = a_1(\xi)\mathbf{p}_\mu$$
$$-a_2(\xi)\left[\frac{\mathbf{p}_\mu}{m_\mu}\left(m_K - E_\pi + \frac{\mathbf{p}_\pi \cdot \mathbf{p}_\mu}{\left|\mathbf{p}_\mu\right|^2}(E_\mu - m_\mu)\right) + \mathbf{p}_\pi\right]$$
$$+m_K \mathrm{Im}\xi(t)(\mathbf{p}_\pi \times \mathbf{p}_\mu) \ .$$

If time-reversal invariance holds, ξ is real, and thus there is no polarization perpendicular to the K-decay plane. Polarization experiments measure the weighted average of $\xi(t)$ over the t range of the experiment, where the weighting accounts for the variation with t of the sensitivity to $\xi(t)$.

(2) λ_+, λ_0 parametrization. Most of the more recent $K_{\mu 3}$ analyses have parameterized in terms of the form factors f_+ and f_0 which are associated with vector and scalar exchange, respectively, to the lepton pair. f_0 is related to f_+ and f_- by

$$f_0(t) = f_+(t) + \left[t/(m_K^2 - m_\pi^2)\right] f_-(t) \ .$$

Here $f_0(0)$ must equal $f_+(0)$ unless $f_-(t)$ diverges at $t = 0$. The earlier assumption that f_+ is linear in t and f_- is constant leads to f_0 linear in t:

$$f_0(t) = f_0(0)\left[1 + \lambda_0(t/m_\pi^2)\right] \ .$$

With the assumption that $f_0(0) = f_+(0)$, the two parametrizations, $(\lambda_+, \xi(0))$ and (λ_+, λ_0) are equivalent as long as correlation information is retained. (λ_+, λ_0) correlations tend to be less strong than $(\lambda_+, \xi(0))$ correlations.

The experimental results for $\xi(0)$ and its correlation with λ_+ are listed in the $K^{\pm}$ and K_L^0 sections of the Full Listings in section $\xi_{\rm A}$, $\xi_{\rm B}$, or $\xi_{\rm C}$ depending on whether method A, B, or C discussed above was used. The corresponding values of λ_+ are also listed.

Because recent experiments tend to use the (λ_+, λ_0) parametrization, we include a subsection for λ_0 results. Wherever possible we have converted $\xi(0)$ results into λ_0 results and vice versa.

See the 1982 version of this note[4] for additional discussion of the $K_{\mu 3}^0$ parameters, correlations, and conversion between parametrizations, and also for a comparison of the experimental results.

(b) K_{e3} experiments. Analysis of K_{e3} data is simpler than that of $K_{\mu 3}$ because the second term of the matrix element assuming a pure vector current [Eq. (1) above] can be neglected. Here f_+ is usually assumed to be linear in t, and the linear coefficient λ_+ of Eq. (2) is determined.

If we remove the assumption of a pure vector current, then the matrix element for the decay, in addition to the terms in Eq. (2), would contain

$$+2m_K\, f_S\, \bar{\ell}(1 + \gamma_5)\nu$$
$$+(2f_T/m_K)(P_K)_\lambda(P_\pi)_\mu\, \bar{\ell}\, \sigma_{\lambda\mu}(1 + \gamma_5)\nu \ ,$$

where f_S is the scalar form factor, and f_T is the tensor form factor. In the case of the K_{e3} decays where the f_- term can be neglected, experiments have yielded limits on $|f_S/f_+|$ and $|f_T/f_+|$.

References

1. L.M. Chounet, J.M. Gaillard, and M.K. Gaillard, Phys. Reports **4C**, 199 (1972).
2. H.W. Fearing, E. Fischbach, and J. Smith, Phys. Rev. **D2**, 542 (1970).
3. N. Cabibbo and A. Maksymowicz, Phys. Lett. **9**, 352 (1964).
4. Particle Data Group, Phys. Lett. **111B**, 73 (1982).

$K_{\ell 3}^{\pm}$ FORM FACTORS

In the form factor comments, the following symbols are used.

f_+ and f_- are form factors for the vector matrix element.
f_S and f_T refer to the scalar and tensor term.
$f_0 = f_+ + f_- t/(m^2(K) - m^2(\pi))$.
λ_+, λ_-, and λ_0 are the linear expansion coefficients of f_+, f_-, and f_0.
λ_+ refers to the $K_{\mu 3}$ value except in the K_{e3} sections.
$d\xi(0)/d\lambda_+$ is the correlation between $\xi(0)$ and λ_+ in $K_{\mu 3}$.
$d\lambda_0/d\lambda_+$ is the correlation between λ_0 and λ_+ in $K_{\mu 3}$.
t = momentum transfer to the π in units of $m^2(\pi)$.
DP = Dalitz plot analysis.
PI = π spectrum analysis.
MU = μ spectrum analysis.
POL= μ polarization analysis.
BR = $K_{\mu 3}/K_{e3}$ branching ratio analysis.
E = positron or electron spectrum analysis.
RC = radiative corrections.

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN K_{e3} DECAY)

For radiative correction of K_{e3} Dalitz plot, see GINSBERG 67 and BECHERRAWY 70.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.0286±0.0022 OUR AVERAGE						
0.0284±0.0027±0.0020	32k	[67] AKIMENKO	91	SPEC		PI, no RC
0.029 ±0.004	62k	[68] BOLOTOV	88	SPEC		PI, no RC
0.027 ±0.008		[69] BRAUN	73B	HLBC	+	DP, no RC
0.029 ±0.011	4017	CHIANG	72	OSPK	+	DP, RC negligible
0.027 ±0.010	2707	STEINER	71	HLBC	+	DP, uses RC
0.045 ±0.015	1458	BOTTERILL	70	OSPK		PI, uses RC
0.08 ±0.04	960	BOTTERILL	68C	ASPK	+	e^+, uses RC
$-0.02\ ^{+0.08}_{-0.12}$	90	EISLER	68	HLBC	+	PI, uses RC
$0.045\ ^{+0.017}_{-0.018}$	854	BELLOTTI	67B	FBC	+	DP, uses RC
+0.016 ±0.016	1393	IMLAY	67	OSPK	+	DP, no RC
$+0.028\ ^{+0.013}_{-0.014}$	515	KALMUS	67	FBC	+	e^+, PI, no RC
−0.04 ±0.05	230	BORREANI	64	HBC	+	e^+, no RC
−0.010 ±0.029	407	JENSEN	64	XEBC	+	PI, no RC
+0.036 ±0.045	217	BROWN	62B	XEBC	+	PI, no RC
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.025 ±0.007		[70] BRAUN	74	HLBC	+	$K_{\mu 3}/K_{e3}$ vs. t

[67] AKIMENKO 91 state that radiative corrections would raise λ_+ by 0.0013.
[68] BOLOTOV 88 state radiative corrections of GINSBERG 67 would raise λ_+ by 0.002.
[69] BRAUN 73B states that radiative corrections of GINSBERG 67 would lower λ_+^e by 0.002 but that radiative corrections of BECHERRAWY 70 disagrees and would raise λ_+^e by 0.005.
[70] BRAUN 74 is a combined $K_{\mu 3}$-K_{e3} result. It is not independent of BRAUN 73C ($K_{\mu 3}$) and BRAUN 73B (K_{e3}) form factor results.

$\xi_A = f_-/f_+$ (determined from $K_{\mu 3}$ spectra)

The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	$d\xi(0)/d\lambda_+$	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
−0.35±0.15 OUR EVALUATION			From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).				
−0.27±0.25	−17	3973	WHITMAN	80	SPEC	+	DP
−0.8 ±0.8	−20	490	[71] ARNOLD	74	HLBC	+	DP
−0.57±0.24	−9	6527	[72] MERLAN	74	ASPK	+	DP
−0.36±0.40	−19	1897	[73] BRAUN	73C	HLBC	+	DP
−0.62±0.28	−12	4025	[74] ANKENBRA...	72	ASPK	+	PI
+0.45±0.28	−15	3480	[75] CHIANG	72	OSPK	+	DP
−1.1 ±0.56	−29	3240	[76] HAIDT	71	HLBC	+	DP
−0.5 ±0.8	−26	2041	[77] KIJEWSKI	69	OSPK	+	PI
+0.72±0.93	−17	444	CALLAHAN	66B	FBC	+	PI

• • • We do not use the following data for averages, fits, limits, etc. • • •

$-0.5\ \pm0.9$	none	78	EISLER	68 HLBC	+	PI, $\lambda_+=0$
$0.0\ ^{+1.1}_{-0.9}$		2648	[78] CALLAHAN	66B FBC	+	μ, $\lambda_+=0$
$+0.7\ \pm0.5$		87	GIACOMELLI	64 EMUL	+	MU+BR,$\lambda_+=0$
-0.08 ± 0.7			[79] JENSEN	64 XEBC	+	DP+BR
$+1.8\ \pm0.6$		76	BROWN	62B XEBC	+	DP+BR, $\lambda_+=0$

[71] ARNOLD 74 figure 4 was used to obtain ξ_A and $d\xi(0)/d\lambda_+$.

[72] MERLAN 74 figure 5 was used to obtain $d\xi(0)/d\lambda_+$.

[73] BRAUN 73C gives $\xi(t) = -0.34 \pm 0.20$, $d\xi(t)/d\lambda_+ = -14$ for $\lambda_+ = 0.027$, $t = 6.6$. We calculate above $\xi(0)$ and $d\xi(0)/d\lambda_+$ for their $\lambda_+ = 0.025 \pm 0.017$.

[74] ANKENBRANDT 72 figure 3 was used to obtain $d\xi(0)/d\lambda_+$.

[75] CHIANG 72 figure 10 was used to obtain $d\xi(0)/d\lambda_+$. Fit had $\lambda_- = \lambda_+$ but would not change for $\lambda_- = 0$. L.Pondrom, (private communication 74).

[76] HAIDT 71 table 8 (Dalitz plot analysis) gives $d\xi(0)/d\lambda_+ = (-1.1{+}0.5)/(0.050{-}0.029) = -29$, error raised from 0.50 to agree with $d\xi(0) = 0.20$ for fixed λ_+.

[77] KIJEWSKI 69 figure 17 was used to obtain $d\xi(0)/d\lambda_+$ and errors.

[78] CALLAHAN 66 table 1 (π analysis) gives $d\xi(0)/d\lambda_+ = (0.72{-}0.05)/(0{-}0.04) = -17$, error raised from 0.80 to agree with $d\xi(0) = 0.37$ for fixed λ_+. t unknown.

[79] JENSEN 64 gives $\lambda_+^{\mu} = \lambda_+^{e} = -0.020 \pm 0.027$. $d\xi(0)/d\lambda_+$ unknown. Includes SHAKLEE 64 $\xi_B(K_{\mu3}/K_{e3})$.

$\xi_B = f_-/f_+$ (determined from $K_{\mu3}/K_{e3}$)

The $K_{\mu3}/K_{e3}$ branching ratio fixes a relationship between $\xi(0)$ and λ_+. We quote the author's $\xi(0)$ and associated λ_+ but do not average because the λ_+ values differ. The fit result and scale factor given below are not obtained from these ξ_B values. Instead they are obtained directly from the fitted $K_{\mu3}/K_{e3}$ ratio $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^0 e^+\nu_e)$, with the exception of HEINTZE 77. The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
−0.35±0.15 OUR EVALUATION		From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
-0.12 ± 0.12	55k	[80] HEINTZE	77 CNTR	+	$\lambda_+=0.029$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.0\ \pm0.15$	5825	CHIANG	72 OSPK	+	$\lambda_+=0.03$, fig.10
-0.81 ± 0.27	1505	[81] HAIDT	71 HLBC	+	$\lambda_+=0.028$, fig.8
-0.35 ± 0.22		[82] BOTTERILL	70 OSPK	+	$\lambda_+=0.045\pm0.015$
$+0.91\pm0.82$		ZELLER	69 ASPK	+	$\lambda_+=0.023$
-0.08 ± 0.15	5601	[82] BOTTERILL	68B ASPK	+	$\lambda_+=0.023\pm0.008$
-0.60 ± 0.20	1398	[81] EICHTEN	68 HLBC	+	See note
$+1.0\ \pm0.6$	986	GARLAND	68 OSPK	+	$\lambda_+=0$
$+0.75\pm0.50$	306	AUERBACH	67 OSPK	+	$\lambda_+=0$
$+0.4\ \pm0.4$	636	CALLAHAN	66B FBC	+	$\lambda_+=0$
$+0.6\ \pm0.5$		BISI	65B HBC	+	$\lambda_+=0$
$+0.8\ \pm0.6$	500	CUTTS	65 OSPK	+	$\lambda_+=0$
$-0.17^{+0.75}_{-0.99}$		SHAKLEE	64 XEBC	+	$\lambda_+=0$

[80] Calculated by us from λ_0 and λ_+ given below.

[81] EICHTEN 68 has $\lambda_+ = 0.023 \pm 0.008$, $t = 4$, independent of λ_-. Replaced by HAIDT 71.

[82] BOTTERILL 70 is re-evaluation of BOTTERILL 68B with different λ_+.

$\xi_C = f_-/f_+$ (determined from μ polarization in $K_{\mu3}$)

The μ polarization is a measure of $\xi(t)$. No assumptions on λ_{+-} necessary, t (weighted by sensitivity to $\xi(t)$) should be specified. In λ_+, $\xi(0)$ parametrization this is $\xi(0)$ for $\lambda_+=0$. $d\xi/d\lambda = \xi t$. For radiative correction to muon polarization in $K_{\mu3}$, see GINSBERG 71. The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
−0.35±0.15 OUR EVALUATION		From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
-0.25 ± 1.20	1585	[83] BRAUN	75 HLBC	+	POL, t=4.2
-0.95 ± 0.3	3133	[84] CUTTS	69 OSPK	+	Total pol. t=4.0
$-1.0\ \pm0.3$	6000	[85] BETTELS	68 HLBC	+	Total pol. t=4.9
• • • We do not use the following data for averages, fits, limits, etc. • • •					
-0.64 ± 0.27	40k	[86] MERLAN	74 ASPK	+	POL, $d\xi(0)/d\lambda_+ = +1.7$
$-1.4\ \pm1.8$	397	[87] CALLAHAN	66B FBC	+	Total pol.
$-0.7\ ^{+0.9}_{-3.3}$	2950	[87] CALLAHAN	66B FBC	+	Long. pol.
$+1.2\ ^{+2.4}_{-1.8}$	2100	[87] BORREANI	65 HLBC	+	Polarization
-4.0 to $+1.7$	500	[87] CUTTS	65 OSPK	+	Long. pol.

[83] BRAUN 75 $d\xi(0)/d\lambda_+ = \xi t = -0.25 \times 4.2 = -1.0$.

[84] CUTTS 69 $t = 4.0$ was calculated from figure 8. $d\xi(0)/d\lambda_+ = \xi t = -0.95 \times 4 = -3.8$.

[85] BETTELS 68 $d\xi(0)/d\lambda_+ = \xi t = -1.0 \times 4.9 = -4.9$.

[86] MERLAN 74 polarization result (figure 5) not possible. See discussion of polarization experiments in note on "$K_{\ell3}$ Form Factors" in the 1982 edition of this Review [Physics Letters **111B** (1982)].

[87] t value not given.

IMAGINARY PART OF ξ

Test of T reversal invariance.

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
−0.017±0.025 OUR AVERAGE					
-0.016 ± 0.025	20M	CAMPBELL	81 CNTR	+	Pol.
$-0.3\ ^{+0.3}_{-0.4}$	3133	CUTTS	69 OSPK	+	Total pol. fig.7
$-0.1\ \pm0.3$	6000	BETTELS	68 HLBC	+	Total pol.
$0.0\ \pm1.0$	2648	CALLAHAN	66B FBC	+	MU
$+1.6\ \pm1.3$	397	CALLAHAN	66B FBC	+	Total pol.
$0.5\ ^{+1.4}_{-0.5}$	2950	CALLAHAN	66B FBC	+	Long. pol.
• • • We do not use the following data for averages, fits, limits, etc. • • •					
-0.010 ± 0.019	32M	[88] BLATT	83 CNTR		Polarization

[88] Combined result of MORSE 80 ($K^0_{\mu3}$) and CAMPBELL 81 ($K^+_{\mu3}$).

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN $K_{\mu3}$ DECAY)

See also the corresponding entries and footnotes in sections ξ_A, ξ_C, and λ_0. For radiative correction of $K_{\mu3}$ Dalitz plot, see GINSBERG 70 and BECHERRAWY 70.

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.033±0.008 OUR EVALUATION		From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
$+0.050\pm0.013$	3973	WHITMAN	80 SPEC	+	DP
0.025 ± 0.030	490	ARNOLD	74 HLBC	+	DP
0.027 ± 0.019	6527	MERLAN	74 ASPK	+	DP
0.025 ± 0.017	1897	BRAUN	73C HLBC	+	DP
0.024 ± 0.019	4025	[89] ANKENBRA...	72 ASPK	+	PI
-0.006 ± 0.015	3480	CHIANG	72 OSPK	+	DP
0.050 ± 0.018	3240	HAIDT	71 HLBC	+	DP
0.009 ± 0.026	2041	KIJEWSKI	69 OSPK	+	PI
$0.0\ \pm0.05$	444	CALLAHAN	66B FBC	+	PI

[89] ANKENBRANDT 72 λ_+ from figure 3 to match $d\xi(0)/d\lambda_+$. Text gives 0.024 ± 0.022.

λ_0 (LINEAR ENERGY DEPENDENCE OF f_0 IN $K_{\mu3}$ DECAY)

Wherever possible, we have converted the above values of $\xi(0)$ into values of λ_0 using the associated λ_+^{μ} and $d\xi/d\lambda$.

VALUE	$d\lambda_0/d\lambda_+$	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.004±0.007 OUR EVALUATION			From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
$+0.029\pm0.011$	-0.37	3973	WHITMAN	80 SPEC	+	DP
$+0.019\pm0.010$	$+0.03$	55k	[90] HEINTZE	77 SPEC	+	BR
$+0.008\pm0.097$	$+0.92$	1585	[91] BRAUN	75 HLBC	+	POL
-0.040 ± 0.040	-0.62	490	ARNOLD	74 HLBC	+	DP
-0.019 ± 0.015	$+0.27$	6527	[92] MERLAN	74 ASPK	+	DP
-0.008 ± 0.020	-0.53	1897	[93] BRAUN	73C HLBC	+	DP
-0.026 ± 0.013	$+0.03$	4025	[94] ANKENBRA...	72 ASPK	+	PI
$+0.030\pm0.014$	-0.21	3480	[94] CHIANG	72 OSPK	+	DP
-0.039 ± 0.029	-1.34	3240	[94] HAIDT	71 HLBC	+	DP
-0.056 ± 0.024	$+0.69$	3133	[91] CUTTS	69 OSPK	+	POL
-0.031 ± 0.045	-1.10	2041	[94] KIJEWSKI	69 OSPK	+	PI
-0.063 ± 0.024	$+0.60$	6000	[91] BETTELS	68 HLBC	+	POL
$+0.058\pm0.036$	-0.37	444	[94] CALLAHAN	66B FBC	+	PI
• • • We do not use the following data for averages, fits, limits, etc. • • •						
-0.017 ± 0.011			[95] BRAUN	74 HLBC	+	$K_{\mu3}/K_{e3}$ vs. t

[90] HEINTZE 77 uses $\lambda_+ = 0.029 \pm 0.003$. $d\lambda_0/d\lambda_+$ estimated by us.

[91] λ_0 value is for $\lambda_+ = 0.03$ calculated by us from $\xi(0)$ and $d\xi(0)/d\lambda_+$.

[92] MERLAN 74 λ_0 and $d\lambda_0/d\lambda_+$ were calculated by us from ξ_A, λ_+^{μ}, and $d\xi(0)/d\lambda_+$. Their figure 6 gives $\lambda_0 = -0.025 \pm 0.012$ and no $d\lambda_0/d\lambda_+$.

[93] This value and error are taken from BRAUN 75 but correspond to the BRAUN 73C λ_+^{μ} result. $d\lambda_0/d\lambda_+$ is from BRAUN 73C $d\xi(0)/d\lambda_+$ in ξ_A above.

[94] λ_0 calculated by us from $\xi(0)$, λ_+^{μ}, and $d\xi(0)/d\lambda_+$.

[95] BRAUN 74 is a combined $K_{\mu3}$-K_{e3} result. It is not independent of BRAUN 73C ($K_{\mu3}$) and BRAUN 73B (K_{e3}) form factor results.

$|f_S/f_+|$ FOR K_{e3} DECAY

Ratio of scalar to f_+ couplings.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.084±0.023 OUR AVERAGE			Error includes scale factor of 1.2.			
$0.070\pm0.016\pm0.016$		32k	AKIMENKO	91 SPEC		λ_+, f_S, f_T, ϕ fit
$0.00\ \pm0.10$		2827	BRAUN	75 HLBC	+	
$0.14\ ^{+0.03}_{-0.04}$		2707	STEINER	71 HLBC	+	λ_+, f_S, f_T, ϕ fit
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.13	90	4017	CHIANG	72 OSPK	+	
<0.23	90		BOTTERILL	68C ASPK		
<0.18	90		BELLOTTI	67B HLBC		
<0.30	95		KALMUS	67 HLBC	+	

$|f_T/f_+|$ FOR K_{e3} DECAY

Ratio of tensor to f_+ couplings.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.38±0.11 OUR AVERAGE Error includes scale factor of 1.1.							
$0.53^{+0.09}_{-0.10}\pm0.10$		32k	AKIMENKO	91	SPEC		λ_+, f_S, f_T, ϕ fit
0.07 ± 0.37		2827	BRAUN	75	HLBC	+	
$0.24^{+0.16}_{-0.14}$		2707	STEINER	71	HLBC	+	λ_+, f_S, f_T, ϕ fit
• • • We do not use the following data for averages, fits, limits, etc. • • •							
<0.75	90	4017	CHIANG	72	OSPK	+	
<0.58	90		BOTTERILL	68C	ASPK		
<0.58	90		BELLOTTI	67B	HLBC		
<1.1	95		KALMUS	67	HLBC	+	

f_T/f_+ FOR $K_{\mu3}$ DECAY

Ratio of tensor to f_+ couplings.

VALUE	EVTS	DOCUMENT ID		TECN
0.02±0.12	1585	BRAUN	75	HLBC

DECAY FORM FACTORS FOR $K^{\pm} \rightarrow \pi^+\pi^- e^{\pm}\nu$

Given in ROSSELET 77, BEIER 73, and BASILE 71C.

DECAY FORM FACTOR FOR $K^{\pm} \rightarrow \pi^0\pi^0 e^{\pm}\nu$

Given in BOLOTOV 86B and BARMIN 88B.

$K^{\pm} \rightarrow \ell^{\pm}\nu\gamma$ FORM FACTORS

For definitions of the axial-vector F_A and vector F_V form factor, see the "Note on $\pi^{\pm} \rightarrow \ell^{\pm}\nu\gamma$ and $K^{\pm} \rightarrow \ell^{\pm}\nu\gamma$ Form Factors" in the $\pi^{\pm}$ section. In the kaon literature, often different definitions $a_K = F_A/m_K$ and $v_K = F_V/m_K$ are used.

$F_A + F_V$, SUM OF AXIAL-VECTOR AND VECTOR FORM FACTOR FOR $K \rightarrow e\nu_e\gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.148±0.010 OUR AVERAGE					
0.147 ± 0.011	51	[96] HEINTZE	79	SPEC	$K \rightarrow e\nu\gamma$
$0.150^{+0.018}_{-0.023}$	56	[97] HEARD	75	SPEC	$K \rightarrow e\nu\gamma$

[96] HEINTZE 79 quotes absolute value of $|F_A + F_V|\sin\theta_C$. We use $\sin\theta_C = V_{us} = 0.2205$.

[97] HEARD 75 quotes absolute value of $|F_A + F_V|\sin\theta_C$. We use $\sin\theta_C = V_{us} = 0.2205$.

$F_A + F_V$, SUM OF AXIAL-VECTOR AND VECTOR FORM FACTOR FOR $K \rightarrow \mu\nu_\mu\gamma$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
< 0.23	90	[98] AKIBA	85	SPEC	$K \rightarrow \mu\nu\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−1.2 to 1.1	90	DEMIDOV	90	SPEC	$K \rightarrow \mu\nu\gamma$

[98] AKIBA 85 quotes absolute value.

$F_A - F_V$, DIFFERENCE OF AXIAL-VECTOR AND VECTOR FORM FACTOR FOR $K \rightarrow e\nu_e\gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
<0.49	90	[99] HEINTZE	79	SPEC	$K \rightarrow e\nu\gamma$

[99] HEINTZE 79 quotes $|F_A - F_V| < \sqrt{11}\,|F_A + F_V|$.

$F_A - F_V$, DIFFERENCE OF AXIAL-VECTOR AND VECTOR FORM FACTOR FOR $K \rightarrow \mu\nu_\mu\gamma$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
−2.2 to 0.3 OUR EVALUATION					
−2.2 to 0.6	90	DEMIDOV	90	SPEC	$K \rightarrow \mu\nu\gamma$
−2.5 to 0.3	90	AKIBA	85	SPEC	$K \rightarrow \mu\nu\gamma$

$K^{\pm}$ REFERENCES

LITTENBERG 92 PRL 68 443 +Shrock (BNL, STON)
AKIMENKO 91 PL B259 225 +Beloussov+ (SERP, JINR, TBIL, BRAT, SOFU, KOSI)
BARMIN 91 SJNP 53 606 +Barylov, Davidenko, Demidov+ (ITEP)
Translated from YAF 53 981.
ATIYA 90 PRL 64 21 +Chiang, Frank, Haggerty, Ito, Kycia+ (BNL-787 Collab.)
ATIYA 90B PRL 65 1188 +Chiang, Frank, Haggerty, Ito, Kycia+ (BNL-787 Collab.)
DEMIDOV 90 SJNP 52 1006 +Dobrokhotov, Lyublev, Nikitenko+ (ITEP)
Translated from YAF 52 1595.
LEE 90 PRL 64 165 +Alliegro, Campagnari+ (BNL, FNAL, PSI, WASH, YALE)
ATIYA 89 PRL 63 2177 +Chiang, Frank, Haggerty, Ito, Kycia+ (BNL-787 Collab.)
BARMIN 89 SJNP 50 421 +Barylov, Davidenko, Demidov, Dolgolenko+ (ITEP)
Translated from YAF 50 679.
BARMIN 88 SJNP 47 643 +Barylov, Davidenko, Demidov, Dolgolenko+ (ITEP)
Translated from YAF 47 1011.
BARMIN 88B SJNP 48 1032 +Barylov, Davidenko, Demidov, Dolgolenko+ (ITEP)
Translated from YAF 48 1719.
BOLOTOV 88 JETPL 47 7 +Gninenko, Dzhilkibaev, Isakov, Klubakov+ (ASCI)
Translated from ZETFP 47 8.
CAMPAGNARI 88 PRL 61 2062 +Alliegro, Chaloupka+ (BNL, FNAL, PSI, WASH, YALE)
GALL 88 PRL 60 186 +Austin+ (BOST, MIT, WILL, CIT, CMU, WYOM)
BARMIN 87 SJNP 45 62 +Barylov, Davidenko, Demidov+ (ITEP)
Translated from YAF 45 97.
BOLOTOV 87 SJNP 45 1023 +Gninenko, Dzhilkibaev, Isakov, Klubakov+ (INRM)
Translated from YAF 45 1652.
BOLOTOV 86 SJNP 44 73 +Gninenko, Dzhilkibaev, Isakov+ (INRM)
Translated from YAF 44 117.
BOLOTOV 86B SJNP 44 68 +Gninenko, Dzhilkibaev, Isakov+ (INRM)
Translated from YAF 44 108.
YAMANAKA 86 PR D34 85 +Hayano, Taniguchi, Ishikawa+ (KEK, TOKY)
Also 84 PRL 52 329 Hayano, Yamanaka, Taniguchi+ (TOKY, KEK)
AKIBA 85 PR D32 2911 +Ishikawa, Iwasaki+ (TOKY, TINT, TSUK, KEK)
BOLOTOV 85 JETPL 42 481 +Gninenko, Dzhilkibaev, Isakov+ (INRM)
Translated from ZETFP 42 390.
BLATT 83 PR D27 1056 +Adair, Black, Campbell+ (YALE, BNL)
ASANO 82 PL 113B 195 +Kikutani, Kurokawa, Miyachi+ (KEK, TOKY, OSAK)
COOPER 82 PL 112B 97 +Guy, Michette, Tyndel, Venus (RL)
PDG 82 PL 111B Roos, Porter, Aguilar-Benitez+ (HELS, CIT, CERN)
PDG 82B PL 111B 70 Roos, Porter, Aguilar-Benitez+ (HELS, CIT, CERN)
ASANO 81B PL 107B 159 +Kikutani, Kurokawa, Miyachi+ (KEK, TOKY, OSAK)
CAMPBELL 81 PRL 47 1032 +Black, Blatt, Kasha, Schmidt+ (YALE, BNL)
Also 83 PR D27 1056 Blatt, Adair, Black, Campbell+ (YALE, BNL)
LUM 81 PR D23 2522 +Wiegand, Kessler, Deslattes, Seki+ (LBL, NBS+)
LYONS 81 ZPHY C10 215 +Albajar, Myatt (OXF)
MORSE 80 PR D21 1750 +Leipuner, Larsen, Schmidt, Blatt+ (BNL, YALE)
WHITMAN 80 PR D21 652 +Abrams, Carroll, Kycia, Li+ (ILLC, BNL, ILL)
BARKOV 79 NP B148 53 +Vasserman, Zolotorev, Krupin+ (NOVO, KIAE)
HEINTZE 79 NP B149 365 +Heinzelmann, Igo-Kemenes+ (HEID, CERN)
ABRAMS 77 PR D15 22 +Carroll, Kycia, Li, Michael, Mockett+ (BNL)
DEVAUX 77 NP B126 11 +Bloch, Diamant-Berger, Maillard+ (SACL, GEVA)
HEINTZE 77 PL 70B 482 +Heinzelmann, Igo-Kemenes+ (HEID, CERN)
ROSSELET 77 PR D15 574 +Extermann, Fischer, Guisan+ (GEVA, SACL)
BERTRAND 76 NP B114 387 +Sacton+ (BRUX, UBEL, DUUC, LOUC, WARS)
BLOCH 76 PL 60B 393 +Bunce, Devaux, Diamant-Berger+ (GEVA, SACL)
BRAUN 76B LNC 17 521 +Martyn, Erriquez+ (AACH, BARI, BELG, CERN)
DIAMANT-... 76 PL 62B 485 Diamant-Berger, Bloch, Devaux+ (SACL, GEVA)
HEINTZE 76 PL 60B 302 +Heinzelmann, Igo-Kemenes, Mundhenke+ (HEID)
SMITH 76 NP B109 173 +Booth, Renshall, Jones+ (GLAS, LIVP, OXF, RHEL)
WEISSENBE... 76 NP B115 55 Weissenberg, Egorov, Minervina+ (ITEP, LEBD)
BLOCH 75 PL 56B 201 +Brehin, Bunce, Devaux+ (SACL, GEVA)
BRAUN 75 NP B89 210 +Cornelssen+ (AACH, BARI, BRUX, CERN)
CHENG 75 NP A254 381 +Asano, Chen, Dugan, Hu, Wu+ (COLU, YALE)
HEARD 75 PL 55B 324 +Heintze, Heinzelmann+ (CERN, HEID)
HEARD 75B PL 55B 327 +Heintze, Heinzelmann+ (CERN, HEID)
SHEAFF 75 PR D12 2570 (WISC)
SMITH 75 NP B91 45 +Booth, Renshall, Jones+ (GLAS, LIVP, OXF, RHEL)
ARNOLD 74 PR D9 1221 +Roe, Sinclair (MICH)
BRAUN 74 PL 51B 393 +Cornelssen, Martyn+ (AACH, BARI, BRUX, CERN)
CENCE 74 PR D10 776 +Harris, Jones, Morgado+ (HAWA, LBL, WISC)
Also 73 Thesis unpub. Clarke (WISC)
KUNSELMAN 74 PR C9 2469 (WYOM)
MERLAN 74 PR D9 107 +Kasha, Wanderer, Adair+ (YALE, BNL, LASL)
WEISSENBE... 74 PL 48B 474 Weissenberg, Egorov, Minervina+ (ITEP, LEBD)
ABRAMS 73B PRL 30 500 +Carroll, Kycia, Li, Menes, Michael+ (BNL)
BACKENSTO... 73 PL 43B 431 Backenstoss+ (CERN, KARL, HEID, STOH)
BEIER 73 PRL 30 399 +Buchholz, Mann, Parker, Roberts (PENN)
BRAUN 73B PL 47B 185 +Cornelssen (AACH, BARI, BRUX, CERN)
Also 75 NP B89 210 Braun, Cornelssen+ (AACH, BARI, BRUX, CERN)
BRAUN 73C PL 47B 182 +Cornelssen (AACH, BARI, BRUX, CERN)
Also 75 NP B89 210 Braun, Cornelssen+ (AACH, BARI, BRUX, CERN)
CABLE 73 PR D8 3807 +Hildebrand, Pang, Stiening (EFI, LBL)
LJUNG 73 PR D8 1307 +Cline (WISC)
Also 72 PRL 28 523 Ljung (WISC)
Also 72 PRL 28 1287 Cline, Ljung (WISC)
Also 69 PRL 23 326 Camerini, Ljung, Sheaff, Cline (WISC)
LUCAS 73 PR D8 719 +Taft, Willis (YALE)
LUCAS 73B PR D8 727 +Taft, Willis (YALE)
PANG 73 PR D8 1989 +Hildebrand, Cable, Stiening (EFI, ARIZ, LBL)
Also 72 PL 40B 699 Cable, Hildebrand, Pang, Stiening (EFI, LBL)
SMITH 73 NP B60 411 +Booth, Renshall, Jones+ (GLAS, LIVP, OXF, RHEL)
ABRAMS 72 PRL 29 1118 +Carroll, Kycia, Li, Menes, Michael+ (BNL)
ANKENBRA... 72 PRL 28 1472 Ankenbrandt, Larsen+ (BNL, LASL, FNAL, YALE)
AUBERT 72 NC 12A 509 +Heusse, Pascaud, Vialle+ (ORSA, BRUX, EPOL)
BEIER 72 PRL 29 678 +Buchholz, Mann, Parker (PENN)
CHIANG 72 PR D6 1254 +Rosen, Shapiro, Handler, Olsen+ (ROCH, WISC)
CLARK 72 PRL 29 1274 +Cork, Elioff, Kerth, McReynolds, Newton+ (LBL)
EDWARDS 72 PR D5 2720 +Beier, Bertram, Herzo, Koester+ (ILL)
FORD 72 PL 38B 335 +Piroue, Remmel, Smith, Souder (PRIN)
HOFFMASTER 72 NP B36 1 +Koller, Taylor+ (STEV, SETO, LEHI)
BASILE 71C PL 36B 619 +Brehin, Diamant-Berger, Kunz+ (SACL, GEVA)
BOURQUIN 71 PL 36B 615 +Boymond, Extermann, Marasco+ (GEVA, SACL)
GINSBERG 71 PR D4 2893 (MIT)
HAIDT 71 PR D3 10 (AACH, BARI, CERN, EPOL, NIJM+)
Also 69 PL 29B 691 Haidt+ (AACH, BARI, CERN, EPOL, NIJM, ORSA+)
KLEMS 71 PR D4 66 +Hildebrand, Stiening (CHIC, LRL)
Also 70 PRL 24 1086 Klems, Hildebrand, Stiening (LRL, CHIC)
Also 70B PRL 25 473 Klems, Hildebrand, Stiening (LRL, CHIC)
OTT 71 PR D3 52 +Pritchard (LOQM)
ROMANO 71 PL 36B 525 +Renton, Aubert, Burban-Lutz (BARI, CERN, ORSA)
SCHWEINB... 71 PL 36B 246 Schweinberger (AACH, BELG, CERN, NIJM+)
STEINER 71 PL 36B 521 (AACH, BARI, CERN, EPOL, ORSA, NIJM, PADO+)
BARDIN 70 PL 32B 121 +Bilenky, Pontecorvo (JINR)
BECHERRAWY 70 PR D1 1452 (ROCH)
BOTTERILL 70 PL 31B 325 +Brown, Clegg, Corbett, Culligan+ (OXF)
FORD 70 PRL 25 1370 +Piroue, Remmel, Smith, Souder (PRIN)
GAILLARD 70 CERN 70-14 +Chounet (CERN, ORSA)
GINSBERG 70 PR D1 229 (HAIF)
GRAUMAN 70 PR D1 1277 +Koller, Taylor, Pandoulas+ (STEV, SETO, LEHI)
Also 69 PRL 23 737 Grauman, Koller, Taylor+ (STEV, SETO, LEHI)
MALTSEV 70 SJNP 10 678 +Pestova, Solodovnikova, Fadeev+ (JINR)
Translated from YAF 10 1195.
PANDOULAS 70 PR D2 1205 +Taylor, Koller, Grauman+ (STEV, SETO)
CUTTS 69 PR 184 1380 +Stiening, Wiegand, Deutsch (LRL, MIT)
Also 68 PRL 20 955 Cutts, Stiening, Wiegand, Deutsch (LRL, MIT)
DAVISON 69 PR 180 1333 +Bacastow, Barkas, Evans, Fung, Porter+ (UCR)
ELY 69 PR 180 1319 +Gidal, Hagopian, Kalmus+ (LOUC, WISC, LRL)
EMMERSON 69 PRL 23 393 +Quirk (OXF)
HERZO 69 PR 186 1403 +Banner, Beier, Bertram, Edwards+ (ILL)
KIJEWSKI 69 UCRL 18433 Thesis (LBL)
LOBKOWICZ 69 PR 185 1676 +Melissinos, Nagashima, Tewksbury+ (ROCH, BNL)
Also 66 PRL 17 548 Lobkowicz, Melissinos, Nagashima+ (ROCH, BNL)
MACEK 69 PRL 22 32 +Mann, McFarlane, Roberts+ (PENN, TEMP)
MAST 69 PR 183 1200 +Gershwin, Alston-Garnjost, Bangerter+ (LRL)
SELLERI 69 NC 60A 291
ZELLER 69 PR 182 1420 +Haddock, Helland, Pahl+ (UCLA, LRL)
BETTELS 68 NC 56A 1106 (AACH, BARI, BERG, CERN, EPOL, NIJM, ORSA+)
Also 71 PR D3 10 Haidt (AACH, BARI, CERN, EPOL, NIJM+)
BOTTERILL 68B PRL 21 766 +Brown, Clegg, Corbett+ (OXF)
BOTTERILL 68C PR 174 1661 +Brown, Clegg, Corbett+ (OXF)
BUTLER 68 UCRL 18420 +Bland, Goldhaber, Goldhaber, Hirata+ (LRL)
CHANG 68 PRL 20 510 +Yodh, Ehrlich, Plano+ (UMD, RUTG)
CHEN 68 PRL 20 73 +Cutts, Kijewski, Stiening+ (LRL, MIT)
EICHTEN 68 PL 27B 586 (AACH, BARI, CERN, EPOL, ORSA, PADO, VALE)
EISLER 68 PR 169 1090 +Fung, Marateck, Meyer, Plano (RUTG)
ESCHSTRUTH 68 PR 165 1487 +Franklin, Hughes+ (PRIN, PENN)
GARLAND 68 PR 167 1225 +Tsipis, Devons, Rosen+ (COLU, RUTG, WISC)
MOSCOSO 68 Thesis (ORSA)
AUERBACH 67 PR 155 1505 +Dobbs, Mann+ (PENN, PRIN)
Also 74 PR D9 3216 Auerbach
Erratum.

BELLOTTI 67 Heidelberg Conf. +Pullia (MILA)
BELLOTTI 67B NC 52A 1287 +Fiorini, Pullia (MILA)
Also 66B PL 20 690 Bellotti, Fiorini, Pullia+ (MILA)
BISI 67 PL 25B 572 +Cester, Chiesa, Vigone (TORI)
BOTTERILL 67 PRL 19 982 +Brown, Corbett, Culligan+ (OXF)
Also 68 PR 171 1402 Botterill, Brown, Clegg, Corbett+ (OXF)
BOWEN 67B PR 154 1314 +Mann, McFarlane, Hughes+ (PPA)
CLINE 67B Herceg Novi Tbl. 4
Proc. International School on Elementary Particle Physics.
FLETCHER 67 PRL 19 98 +Beier, Edwards+ (ILL)
FORD 67 PRL 18 1214 +Lemonick, Nauenberg, Piroue (PRIN)
GINSBERG 67 PR 162 1570 (MASB)
IMLAY 67 PR 160 1203 +Eschstruth, Franklin+ (PRIN)
KALMUS 67 PR 159 1187 +Kernan (LRL)
ZINCHENKO 67 Rutgers Thesis (RUTG)
CALLAHAN 66 NC 44A 90 (WISC)
CALLAHAN 66B PR 150 1153 +Camerini+ (WISC, LRL, UCR, BARI)
CESTER 66 PL 21 343 +Eschstruth, Oneill+ (PPA)
See footnote 1 in AUERBACH 67.
Also 67 PR 155 1505 Auerbach, Dobbs, Mann+ (PENN, PRIN)
BIRGE 65 PR 139B 1600 +Ely, Gidal, Camerini, Cline+ (LRL, WISC)
BISI 65 NC 35 768 +Borreani, Cester, Ferraro+ (TORI)
BISI 65B PR 139B 1068 +Borreani, Marzari-Chiesa, Rinaudo+ (TORI)
BORREANI 65 PR 140B 1686 +Gidal, Rinaudo, Caforio+ (BARI, TORI)
CALLAHAN 65 PRL 15 129 +Cline (WISC)
CAMERINI 65 NC 37 1795 +Cline, Gidal, Kalmus, Kernan (WISC, LRL)
CLINE 65 PL 15 293 +Fry (WISC)
CUTTS 65 PR 138B 969 +Elioff, Stiening (LRL)
DEMARCO 65 PR 140B 1430 +Grosso, Rinaudo (TORI, CERN)
FITCH 65B PR 140B 1088 +Quarles, Wilkins (PRIN, MTHO)
GREINER 65 ARNS 15 67 (LRL)
STAMER 65 PR 138B 440 +Huetter, Koller, Taylor, Grauman (STEV)
TRILLING 65B UCRL 16473 (LRL)
Updated from 1965 Argonne Conference, page 5.
YOUNG 65 UCRL 16362 Thesis (LRL)
Also 67 PR 156 1464 Young, Osborne, Barkas (LRL)
BORREANI 64 PL 12 123 +Rinaudo, Werbrouck (TORI)
CALLAHAN 64 PR 136B 1463 +March, Stark (WISC)
CAMERINI 64 PRL 13 318 +Cline, Fry, Powell (WISC, LRL)
CLINE 64 PRL 13 101 +Fry (WISC)
GIACOMELLI 64 NC 34 1134 +Monti, Quareni+ (BGNA, MUNI)
GREINER 64 PRL 13 284 +Osborne, Barkas (LRL)
JENSEN 64 PR 136B 1431 +Shaklee, Roe, Sinclair (MICH)
KALMUS 64 PRL 13 99 +Kernan, Pu, Powell, Dowd (LRL, WISC)
SHAKLEE 64 PR 136B 1423 +Jensen, Roe, Sinclair (MICH)
BARKAS 63 PRL 11 26 +Dyer, Heckman (LRL)
BOYARSKI 62 PR 128 2398 +Loh, Niemela, Ritson (MIT)
BROWN 62B PRL 8 450 +Kadyk, Trilling, Roe+ (LRL, MICH)
BARKAS 61 PR 124 1209 +Dyer, Mason, Norris, Nickols, Smit (LRL)
BHOWMIK 61 NC 20 857 +Jain, Mathur (DELH)
FERRO-LUZZI 61 NC 22 1087 +Miller, Murray, Rosenfeld+ (LRL)
NORDIN 61 PR 123 2166 (LRL)
ROE 61 PRL 7 346 +Sinclair, Brown, Glaser+ (MICH, LRL)
FREDEN 60B PR 118 564 +Gilbert, White (LRL)
BURROWES 59 PRL 2 117 +Caldwell, Frisch, Hill+ (MIT)
TAYLOR 59 PR 114 359 +Harris, Orear, Lee, Baumel (COLU)
EISENBERG 58 NC 8 663 +Koch, Lohrmann, Nikolic+ (BERN)
ALEXANDER 57 NC 6 478 +Johnston, Oceallaigh (DUUC)
COHEN 57 Fund. Cons. Phys. +Crowe, Dumond (NAAS, LRL, CIT)
COOMBES 57 PR 108 1348 +Cork, Galbraith, Lambertson, Wenzel (LBL)
BIRGE 56 NC 4 834 +Perkins, Peterson, Stork, Whitehead (LRL)
ILOFF 56 PR 102 927 +Goldhaber, Lannutti, Gilbert+ (LRL)

OTHER RELATED PAPERS

BRYMAN 89 IJMP A4 79 (TRIU)
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HAIDT 69B PL 29B 696 + (AACH, BARI, CERN, EPOL, NIJM, ORSA+)
CRONIN 68B Vienna Conf. 241 (PRIN)
Rapporteur talk.
WILLIS 67 Heidelberg Conf. 273 (YALE)
Rapporteur talk.
CABIBBO 66 Berkeley Conf. 33 (CERN)
ADAIR 64 PL 12 67 +Leipuner (YALE, BNL)
CABIBBO 64 PL 9 352 +Maksymowicz (CERN)
Also 64B PL 11 360 Cabibbo, Maksymowicz (CERN)
Also 65 PL 14 72 Cabibbo, Maksymowicz (CERN)
BIRGE 63 PRL 11 35 +Ely, Gidal, Camerini+ (LRL, WISC, BARI)
BLOCK 62B CERN Conf. 371 +Lendinara, Monari (NWES, BGNA)
BRENE 61 NP 22 553 +Egardt, Qvist (NORD)

K^0

$I(J^P) = \frac{1}{2}(0^-)$

K^0 MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
497.671±0.031 OUR FIT					
497.676±0.030 OUR AVERAGE					
497.661±0.033	3713	BARKOV	87B	CMD	$e^+e^- \rightarrow K^0_L K^0_S$
497.742±0.085	780	BARKOV	85B	CMD	$e^+e^- \rightarrow K^0_L K^0_S$
497.44 ±0.50		FITCH	67	OSPK	
498.9 ±0.5	4500	BALTAY	66	HBC	K^0 from $\overline{p}p$
497.44 ±0.33	2223	KIM	65B	HBC	K^0 from $\overline{p}p$
498.1 ±0.4		CHRISTENS...	64	OSPK	

$K^0 - K^{\pm}$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
4.024±0.032 OUR FIT						
3.92 ±0.14 OUR AVERAGE						
3.95 ±0.21	417	HILL	68B	DBC	+	$K^+d \rightarrow K^0pp$
3.90 ±0.25	9	BURNSTEIN	65	HBC	−	
3.71 ±0.35	7	KIM	65B	HBC	−	$K^-p \rightarrow n\overline{K}^0$
5.4 ±1.1		CRAWFORD	59	HBC	+	
3.9 ±0.6		ROSENFELD	59	HBC	−	

K^0 REFERENCES

BARKOV 87B SJNP 46 630 +Vasserman, Vorobev, Ivanov+ (NOVO)
Translated from YAF 46 1088.
BARKOV 85B JETPL 42 138 +Blinov, Vasserman+ (NOVO)
Translated from ZETFP 42 113.
HILL 68B PR 168 1534 +Robinson, Sakitt, Canter (BNL, CMU)
FITCH 67 PR 164 1711 +Roth, Russ, Vernon (PRIN)
BALTAY 66 PR 142 932 +Sandweiss, Stonehill+ (YALE, BNL)
BURNSTEIN 65 PR 138B 895 +Rubin (UMD)
KIM 65B PR 140B 1334 +Kirsch, Miller (COLU)
CHRISTENS... 64 PRL 13 138 Christenson, Cronin, Fitch, Turlay (PRIN)
CRAWFORD 59 PRL 2 112 +Cresti, Good, Stevenson, Ticho (LRL)
ROSENFELD 59 PRL 2 110 +Solmitz, Tripp (LRL)

K^0_S

$I(J^P) = \frac{1}{2}(0^-)$

K^0_S MEAN LIFE

For earlier measurements, beginning with BOLDT 58B, see our our 1986 edition, Physics Letters **170B** 130 (1986).

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
0.8922±0.0020 OUR AVERAGE					
0.8920±0.0044	214k	GROSSMAN	87	SPEC	E=100–350 GeV
0.881 ±0.009	26k	ARONSON	76	SPEC	
0.8913±0.0032		[1] CARITHERS	75	SPEC	
0.8937±0.0048	6M	GEWENIGER	74B	ASPK	
0.8958±0.0045	50k	[2] SKJEGGEST...	72	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.905 ±0.007		[3] ARONSON	82B	SPEC	E=30–110 GeV
0.867 ±0.024	2173	[4] FACKLER	73	OSPK	
0.856 ±0.008	19994	[5] DONALD	68B	HBC	
0.872 ±0.009	20000	[5,6] HILL	68	DBC	
0.866 ±0.016		[5] ALFF-...	66B	OSPK	
0.843 ±0.013	5000	[5] KIRSCH	66	HBC	

[1] CARITHERS 75 value is for $K^0_L - K^0_S$ mass difference $\Delta(m) = 0.5348 \pm 0.0021$. The $\Delta(m)$ dependence of the total decay rate (inverse mean life) is $\Gamma(K^0_S) = [(1.122 \pm 0.004) + 0.16(\Delta(m) - 0.5348)/\Delta(m)]10^{10}$/s. Value would not change with our current $\Delta(m) = 0.5349 \pm 0.0022$.

[2] HILL 68 has been changed by the authors from the published value (0.865 ± 0.009) because of a correction in the shift due to η_{+-}. SKJEGGESTAD 72 and HILL 68 give detailed discussions of systematics encountered in this type of experiment.

[3] ARONSON 82 find that K^0_S mean life may depend on the kaon energy.

[4] FACKLER 73 does not include systematic errors.

[5] Pre-1971 experiments are excluded from the average because of disagreement with later more precise experiments.

[6] HILL 68 has been changed by the authors from the published value (0.865 ± 0.009) because of a correction in the shift due to η_{+-}. SKJEGGESTAD 72 and HILL 68 give detailed discussions of systematics encountered in this type of experiment.

K^0_S DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi^+\pi^-$		(68.61±0.28) %	S=1.2
Γ_2	$\pi^0\pi^0$		(31.39±0.28) %	S=1.2
Γ_3	$\pi^+\pi^-\gamma$	[a,b]	(1.85±0.10) × 10^{-3}	
Γ_4	$\gamma\gamma$		(2.4 ±1.2) × 10^{-6}	
Γ_5	$\pi^+\pi^-\pi^0$		< 4.9 × 10^{-5}	CL=90%
Γ_6	$3\pi^0$		< 3.7 × 10^{-5}	CL=90%
	Flavor-Changing neutral current (*FC*) modes			
Γ_7	$\mu^+\mu^-$	*FC*	< 3.2 × 10^{-7}	CL=90%
Γ_8	e^+e^-	*FC*	< 1.0 × 10^{-5}	CL=90%
Γ_9	$\pi^0e^+e^-$	*FC*	< 4.5 × 10^{-5}	CL=90%

[a] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.

[b] See the Listings below for the energy limits used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to 3 branching ratios uses 17 measurements and one constraint to determine 2 parameters. The overall fit has a $\chi^2 =$ 16.5 for 16 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−100
	x_1

K^0_S BRANCHING RATIOS

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.6861±0.0028 OUR FIT Error includes scale factor of 1.2.					
0.671 ±0.010 OUR AVERAGE					
0.670 ±0.010	3447	[7] DOYLE	69	HBC	$\pi^- p \to \Lambda K^0$
0.70 ±0.08		COLUMBIA	60B	HBC	
0.68 ±0.04		CRAWFORD	59B	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.740 ±0.024		[7] ANDERSON	62B	HBC	

[7] Anderson result not published, events added to Doyle sample.

$\Gamma(\pi^+\pi^-)/\Gamma(\pi^0\pi^0)$ — Γ_1/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
2.186±0.028 OUR FIT Error includes scale factor of 1.2.					
2.197±0.026 OUR AVERAGE					
2.11 ±0.09	1315	EVERHART	76	WIRE	$\pi^- p \to \Lambda K^0$
2.169±0.094	16k	COWELL	74	OSPK	$\pi^- p \to \Lambda K^0$
2.16 ±0.08	4799	HILL	73	DBC	$K^+ d \to K^0 pp$
2.22 ±0.10	3068	[8] ALITTI	72	HBC	$K^+ p \to \pi^+ p K^0$
2.22 ±0.08	6380	MORSE	72B	DBC	$K^+ n \to K^0 p$
2.10 ±0.11	701	[9] NAGY	72	HLBC	$K^+ n \to K^0 p$
2.22 ±0.095	6150	[10] BALTAY	71	HBC	$K p \to K^0$ neutrals
2.282±0.043	7944	[11] MOFFETT	70	OSPK	$K^+ n \to K^0 p$
2.10 ±0.06	3700	MORFIN	69	HLBC	$K^+ n \to K^0 p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.12 ±0.17	267	[9] BOZOKI	69	HLBC	
2.285±0.055	3016	[11] GOBBI	69	OSPK	$K^+ n \to K^0 p$

[8] The directly measured quantity is $K^0_S \to \pi^+\pi^-$/all $K^0 = 0.345 \pm 0.005$.

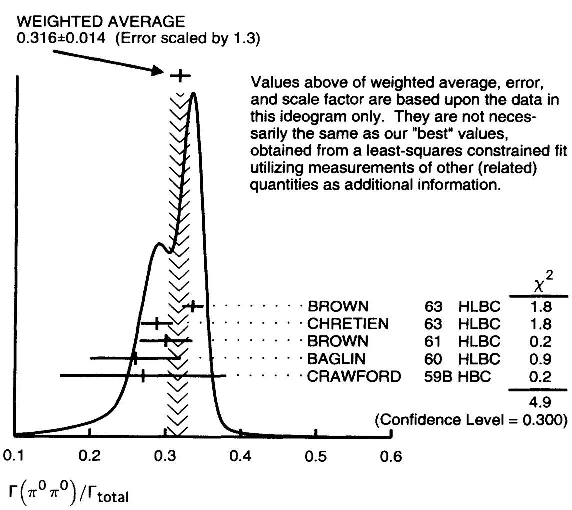
[9] NAGY 72 is a final result which includes BOZOKI 69.

[10] The directly measured quantity is $K^0_S \to \pi^+\pi^-$/all $\overline{K}^0 = 0.345 \pm 0.005$.

[11] MOFFETT 70 is a final result which includes GOBBI 69.

$\Gamma(\pi^0\pi^0)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN
0.3139±0.0028 OUR FIT Error includes scale factor of 1.2.				
0.316 ±0.014 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.				
0.335 ±0.014	1066	BROWN	63	HLBC
0.288 ±0.021	198	CHRETIEN	63	HLBC
0.30 ±0.035		BROWN	61	HLBC
0.26 ±0.06		BAGLIN	60	HLBC
0.27 ±0.11		CRAWFORD	59B	HBC



$\Gamma(\pi^+\pi^-\gamma)/\Gamma(\pi^+\pi^-)$ — Γ_3/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.70±0.14 OUR AVERAGE					
2.68±0.15		[12] TAUREG	76	SPEC	p_γ >50 MeV/c
2.8 ±0.6		[13] BURGUN	73	HBC	p_γ >50 MeV/c
3.3 ±1.2	10	WEBBER	70	HBC	p_γ >50 MeV/c
no ratio given	27	BELLOTTI	66	HBC	p_γ >50 MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.0 ±0.6	29	[14] BOBISUT	74	HLBC	p_γ >40 MeV/c

[12] TAUREG 76 find direct emission contribution <0.06, CL = 90%.

[13] BURGUN 73 estimates that direct emission contribution is 0.3 ± 0.6.

[14] BOBISUT 74 not included in average because p_γ cut differs. Estimates direct emission contribution to be 0.5 or less, CL = 95%.

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.0024±0.0012		19	BURKHARDT	87	NA31	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 0.013	90		BALATS	89	SPEC	
< 0.133	90		BARMIN	86B	XEBC	
< 0.2	90		VASSERMAN	86	CALO	$\phi \to K^0_S K^0_L$
< 0.4	90	0	BARMIN	73B	HLBC	
< 0.71	90	0	[15] BANNER	72B	OSPK	
< 2.0	90	0	MORSE	72B	DBC	
< 2.2	90	0	[15] REPELLIN	71	OSPK	
<21.0	90	0	[15] BANNER	69	OSPK	

[15] These limits are for maximum interference in K^0_S-K^0_L to 2γ's

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<0.49	90	BARMIN	85	HLBC	K^+ 850 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.85	90	METCALF	72	ASPK	

$\Gamma(3\pi^0)/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN
<0.37	90	BARMIN	83	HLBC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<4.3	90	BARMIN	73	HLBC

$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ — Γ_7/Γ_1

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN
< 0.047	90	GJESDAL	73	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<20.0	90	BOHM	69	OSPK
< 1.07	90	HYAMS	69B	OSPK
<32.6	90	[16] STUTZKE	69	OSPK
<10.0	90	BOTT-...	67	OSPK

[16] Value calculated by us, using 2.3 instead of 1 event, 90% CL.

$\Gamma(e^+e^-)/\Gamma(\pi^+\pi^-)$ — Γ_8/Γ_1

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN
< 1.5	90	BARMIN	86	XEBC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<16.0	90	[17] BITSADZE	86	CALO
<50.0	90	BOHM	69	OSPK

[17] Use B($\pi^+\pi^-$) = 0.6861.

$\Gamma(\pi^0 e^+e^-)/\Gamma_{total}$ — Γ_9/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN
<4.5	90	GIBBONS	88	F731

NOTE ON CP VIOLATION IN $K_S \to 3\pi$

(by T. Nakada, Paul Scherrer Institute and L. Wolfenstein, Carnegie-Mellon University)

The possible final states for the decay $K^0 \to \pi^+\pi^-\pi^0$ have isospin I = 0, 1, 2, and 3. The I = 0 and I = 2 states have $CP = +1$ and K_S can decay into them without violating CP symmetry, but they are expected to be strongly suppressed by centrifugal barrier effects. The I = 1 and I = 3 states, which have no centrifugal barrier, have $CP = -1$ so that the K_S decay to these requires CP violation.

In order to see CP violation in $K_S \to \pi^+\pi^-\pi^0$, it is necessary to observe the inteference between K_S and K_L decay, which determines the amplitude ratio

$$\eta_{+-0} = \frac{A(K_S \to \pi^+\pi^-\pi^0)}{A(K_L \to \pi^+\pi^-\pi^0)} .$$

If η_{+-0} is obtained from an integration over the whole Dalitz plot, there is no contribution from the $I = 0$ and $I = 2$ final states and a nonzero value of η_{+-0} is entirely due to CP violation.

Only $I = 1$ and $I = 3$ states, which are $CP = -1$, are allowed for $K^0 \to \pi^0\pi^0\pi^0$ decays and the decay of K_S into $3\pi^0$ is an unambiguous sign of CP violation. Similarly to η_{+-0}, η_{000} is defined as

$$\eta_{000} = \frac{A(K_S \to \pi^0\pi^0\pi^0)}{A(K_L \to \pi^0\pi^0\pi^0)} .$$

If one assumes that CPT invariance holds and that there are no transitions to $I = 3$ (or to nonsymmetric $I = 1$ states), it can be shown that

$$\eta_{+-0} = \eta_{000}$$
$$= \epsilon + i\frac{\text{Im } a_1}{\text{Re } a_1} .$$

With the Wu-Yang phase convention, a_1 is the weak decay amplitude for K^0 into $I = 1$ final states; ϵ is determined from CP violation in $K_L \to 2\pi$ decays. The real parts of η_{+-0} and η_{000} are equal to $\text{Re}(\epsilon)$. Since currently-known upper limits on $|\eta_{+-0}|$ and $|\eta_{000}|$ are much larger than $|\epsilon|$, they can be interpreted as upper limits on $\text{Im}(\eta_{+-0})$ and $\text{Im}(\eta_{000})$.

CP-VIOLATION PARAMETERS IN K_S^0 DECAY

$\text{Im}(\eta_{+-0})^2$

where η_{+-0} = A($K_S^0 \to \pi^+\pi^-\pi^0$, *CP*-violating) / A($K_L^0 \to \pi^+\pi^-\pi^0$). *CPT* assumed valid (i.e. $\text{Re}(\eta_{+-0}) = 0$).

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.12	90	384	METCALF	72	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.23	90	601	[18] BARMIN	85	HLBC	K^+ 850 MeV
<1.2	90	192	BALDO-...	75	HLBC	
<0.71	90	148	MALLARY	73	OSPK	Re(A)=−0.05 ± 0.17
<0.66	90	180	JAMES	72	HBC	
<1.2	90	99	JONES	72	OSPK	
<1.2	90	99	CHO	71	DBC	
<1.0	90	98	JAMES	71	HBC	Incl. in JAMES 72
<1.2	95	50	[19] MEISNER	71	HBC	CL=90% not avail.
<0.8	90	71	WEBBER	70	HBC	
<0.45	90		BEHR	66	HLBC	
<3.8	90	18	ANDERSON	65	HBC	Incl. in WEBBER 70

[18] BARMIN 85 find $\text{Re}(\eta_{+-0}) = (0.05 \pm 0.17)$ and $\text{Im}(\eta_{+-0}) = (0.15 \pm 0.33)$. Includes events of BALDO-CEOLIN 75.
[19] These authors find Re(A) = 2.75 ± 0.65, above value at Re(A) = 0.

$\text{Im}(\eta_{000})^2$

where η_{000} = A($K_S^0 \to 3\pi^0$) / A($K_L^0 \to 3\pi^0$). See text header for section "$\text{Im}(\eta_{+-0})^2$" above. This limit determines branching ratio $\Gamma(3\pi^0)/\Gamma_{total}$ above.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.1	90	632	[20] BARMIN	83	HLBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.28	90		[21] GJESDAL	74B	SPEC	Indirect meas.
<1.2	90	22	BARMIN	73	HLBC	

[20] BARMIN 83 find $\text{Re}(\eta_{000}) = (-0.08 \pm 0.18)$ and $\text{Im}(\eta_{000}) = (-0.05 \pm 0.27)$. Assuming *CPT* invariance they obtain the limit quoted above.
[21] GJESDAL 74B uses $K2\pi$, $K_{\mu 3}$, and K_{e3} decay results, unitarity, and *CPT*. Calculates $|(\eta_{000})| = 0.26 \pm 0.20$. We convert to upper limit.

K_S^0 REFERENCES

BALATS 89 SJNP 49 828 +Berezin, Bogdanov, Vishnevskii, Vishnyakov+ (ITEP)
Translated from YAF 49 1332.
GIBBONS 88 PRL 61 2661 +Papadimitriou+ (FNAL-731 Collab.)
BURKHARDT 87 PL B199 139 + (CERN, EDIN, MANZ, LALO, PISA, SIEG)
GROSSMAN 87 PRL 59 18 +Heller, James, Shupe+ (MINN, MICH, RUTG)
BARMIN 86 SJNP 44 622 +Barylov, Davidenko, Demidov+ (ITEP)
Translated from YAF 44 965.
BARMIN 86B NC 96A 159 +Barylov, Chistyakova, Chuvilo+ (ITEP, PADO)
BITSADZE 86 PL 167B 138 +Budagov (BRAT, SOFI, SERP, TBIL, JINR, BAKU+)
PDG 86B PL 170B 130 Aguilar-Benitez, Porter+ (CERN, CIT+)
VASSERMAN 86 JETPL 43 588 +Golubev, Gluskin, Druzhinin+ (NOVO)
Translated from ZETFP 43 457.
BARMIN 85 NC 85A 67 +Barylov, Chistyakova, Chuvilo+ (ITEP, PADO)
Also 85B SJNP 41 759 Barmin, Barylov, Volkov+ (ITEP)
Translated from YAF 41 1187.
BARMIN 83 PL 128B 129 +Barylov, Chistyakova, Chuvilo+ (ITEP, PADO)
Also 84 SJNP 39 269 Barmin, Barylov, Golubchikov+ (ITEP, PADO)
Translated from YAF 39 428.
ARONSON 82 PRL 48 1078 +Bernstein+ (BNL, CHIC, STAN, WISC)
ARONSON 82B PRL 48 1306 +Bock, Cheng, Fischbach (BNL, CHIC, PURD)
Also 82B PL 116B 73 Fischbach, Cheng+ (PURD, BNL, CHIC)
Also 83 PR D28 476 Aronson, Bock, Cheng+ (BNL, CHIC, PURD)
Also 83B PR D28 495 Aronson, Bock, Cheng+ (BNL, CHIC, PURD)
ARONSON 76 NC 32A 236 +McIntyre, Roehrig+ (WISC, EFI, UCSD, ILLC)
EVERHART 76 PR D14 661 +Kraus, Lande, Long, Lowenstein+ (PENN)
TAUREG 76 PL 65B 92 +Zech, Dydak, Navarria+ (HEID, CERN, DORT)
BALDO-... 75 NC 25A 688 Baldo-Ceolin, Bobisut, Calimani+ (PADO, WISC)
CARITHERS 75 PRL 34 1244 +Modis, Nygren, Pun+ (COLU, NYU)
BOBISUT 74 LNC 11 646 +Huzita, Mattioli, Puglierin (PADO)
COWELL 74 PR D10 2083 +Lee-Franzini, Orcutt, Franzini+ (STON, COLU)
GEWENIGER 74B PL 48B 487 +Gjesdal, Presser+ (CERN, HEID)
GJESDAL 74B PL 52B 119 +Presser, Steffen+ (CERN, HEID)
BARMIN 73 PL 46B 465 +Barylov, Davidenko, Demidov+ (ITEP)
BARMIN 73B PL 47B 463 +Barylov, Davidenko, Demidov+ (ITEP)
BURGUN 73 PL 46B 481 +Bertranet, Lesquoy, Muller, Pauli+ (SACL, CERN)
FACKLER 73 PRL 31 847 +Frisch, Martin, Smoot, Sompayrac (MIT)
GJESDAL 73 PL 44B 217 +Presser, Steffen, Steinberger+ (CERN, HEID)
HILL 73 PR D8 1290 +Sakitt, Samios, Burris, Engler+ (BNL, CMU)
MALLARY 73 PR D7 1953 +Binnie, Gallivan, Gomez, Peck, Sciulli+ (CIT)
ALITTI 72 PL 39B 568 +Lesquoy, Muller (SACL)
BANNER 72B PRL 29 237 +Cronin, Hoffman, Knapp, Shochet (PRIN)
JAMES 72 NP B49 1 +Montanet, Paul, Saetre+ (CERN, SACL, OSLO)
JONES 72 NC 9A 151 +Abashian, Graham, Mantsch, Orr, Smith+ (ILL)
METCALF 72 PL 40B 703 +Neuhofer, Niebergall+ (CERN, IPN, WIEN)
MORSE 72B PRL 28 388 +Nauenberg, Bierman, Sager+ (COLO, PRIN, UMD)
NAGY 72 NP B47 94 +Telbisz, Vestergombi (BUDA)
Also 69 PL 30B 498 Bozoki, Fenyves, Gombosi, Nagy+ (BUDA)
SKJEGGEST... 72 NP B48 343 Skjeggestad, James+ (OSLO, CERN, SACL)
BALTAY 71 PRL 27 1678 +Bridgewater, Cooper, Gershwin, Habibi+ (COLU)
Also 71 Nevis 187 Thesis Cooper (COLU)
CHO 71 PR D3 1557 +Dralle, Canter, Engler, Fisk+ (CMU, BNL, CASE)
JAMES 71 PL 35B 265 +Montanet, Paul, Pauli+ (CERN, SACL, OSLO)
MEISNER 71 PR D3 59 +Mann, Hertzbach, Kofler+ (MASA, BNL, YALE)
REPELLIN 71 PL 36B 603 +Wolff, Chollet, Gaillard, Jane+ (ORSA, CERN)
MOFFETT 70 BAPS 15 512 +Gobbi, Green, Hakel, Rosen (ROCH)
WEBBER 70 PR D1 1967 +Solmitz, Crawford, Alston-Garnjost (LRL)
Also 69 UCRL 19226 Thesis Webber (LRL)
BANNER 69 PR 188 2033 +Cronin, Liu, Pilcher (PRIN)
BOHM 69 Thesis (AACH)
BOZOKI 69 PL 30B 498 +Fenyves, Gombosi, Nagy+ (BUDA)
DOYLE 69 UCRL 18139 Thesis (LRL)
GOBBI 69 PRL 22 682 +Green, Hakel, Moffett, Rosen+ (ROCH)
HYAMS 69B PL 29B 521 +Koch, Potter, VonLindern, Lorenz+ (CERN, MPIM)
MORFIN 69 PRL 23 660 +Sinclair (MICH)
STUTZKE 69 PR 177 2009 +Abashian, Jones, Mantsch, Orr, Smith (ILL)
DONALD 68B PL 27B 58 +Edwards, Nisar+ (LIVP, CERN, IPNP, CDEF)
HILL 68 PR 171 1418 +Robinson, Sakitt+ (BNL, CMU)
BOTT-... 67 PL 24B 194 Bott-Bodenhausen, DeBouard, Cassel+ (CERN)
ALFF-... 66B PL 21 595 Alff-Steinberger, Heuer, Kleinknecht+ (CERN)
BEHR 66 PL 22 540 +Brisson, Petiau+ (EPOL, MILA, PADO, ORSA)
BELLOTTI 66 NC 45A 737 +Pullia, Baldo-Ceolin+ (MILA, PADO)
KIRSCH 66 PR 147 939 +Schmidt (COLU)
ANDERSON 65 PRL 14 475 +Crawford, Golden, Stern, Binford+ (LRL, WISC)
BROWN 63 PR 130 769 +Kadyk, Trilling, Roe+ (LRL, MICH)
CHRETIEN 63 PR 131 2208 + (BRAN, BROW, HARV, MIT)
ANDERSON 62B CERN Conf. 836 +Crawford+ (LRL)
BROWN 61 NC 19 1155 +Bryant, Burnstein, Glaser, Kadyk+ (MICH)
BAGLIN 60 NC 18 1043 +Bloch, Brisson, Hennessy+ (EPOL)
COLUMBIA 60B Rochester Conf. 727 Schwartz+ (COLU)
CRAWFORD 59B PRL 2 266 +Cresti, Douglass, Good, Ticho+ (LRL)
BOLDT 58B PRL 1 150 +Caldwell, Pal (MIT)

OTHER RELATED PAPERS

TRILLING 65B UCRL 16473 (LRL)
Updated from 1965 Argonne Conference, page 115.
CRAWFORD 62 CERN Conf. 827 (LRL)
FITCH 61 NC 22 1160 +Piroue, Perkins (PRIN, LASL)
GOOD 61 PR 124 1223 +Matsen, Muller, Piccioni+ (LRL)
BIRGE 60 Rochester Conf. 601 +Ely+ (LRL, WISC)
MULLER 60 PRL 4 418 +Birge, Fowler, Good, Piccioni+ (LRL, BNL)

K^0_L

$I(J^P) = \frac{1}{2}(0^-)$

$m(K^0_L) - m(K^0_S)$

For earlier measurements, beginning with GOOD 61 and FITCH 61, see our our 1986 edition, Physics Letters **170B** 132 (1986).

VALUE (10^{10} $\hbar$ s^{-1})	DOCUMENT ID		TECN	COMMENT
0.5351±0.0024 OUR AVERAGE				
0.5340±0.00255±0.0015	[1] GEWENIGER	74C	SPEC	Gap method
0.5334±0.0040 ±0.0015	[1] GJESDAL	74	SPEC	Charge asymmetry
0.542 ±0.006	CULLEN	70	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.482 ±0.014	[2] ARONSON	82B	SPEC	E=30–110 GeV
0.534 ±0.007	[3] CARNEGIE	71	ASPK	Gap method
0.542 ±0.006	[3] ARONSON	70	ASPK	Gap method

[1] These two experiments have a common systematic error due to the uncertainty in the momentum scale, as pointed out in WAHL 89.
[2] ARONSON 82 find that $\Delta(m)$ may depend on the kaon energy.
[3] ARONSON 70 and CARNEGIE 71 use K^0_S mean life = $(0.862 \pm 0.006) \times 10^{-10}$ s. We have not attempted to adjust these values for the subsequent change in the K^0_S mean life or in η_{+-}.

K^0_L MEAN LIFE

VALUE (10^{-8} s)	EVTS	DOCUMENT ID		TECN
5.17 ±0.04 OUR FIT				
5.15 ±0.04 OUR AVERAGE				
5.154±0.044	0.4M	VOSBURGH	72	CNTR
5.15 ±0.14		DEVLIN	67	CNTR
• • • We do not use the following data for averages, fits, limits, etc. • • •				
5.0 ±0.5		[4] LOWYS	67	HLBC
6.1 $^{+1.5}_{-1.2}$	1700	ASTBURY	65C	CNTR
5.3 ±0.6		FUJII	64	OSPK
5.1 $^{+2.4}_{-1.3}$	15	DARMON	62	FBC
8.1 $^{+3.2}_{-2.4}$	34	BARDON	58	CNTR

[4] Sum of partial decay rates.

K^0_L DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$3\pi^0$		(21.6 ±0.8) %	S=1.5
Γ_2	$\pi^+\pi^-\pi^0$		(12.38±0.21) %	S=1.5
Γ_3	$\pi^\pm\mu^\mp\nu$ Called $K_{\mu3}$.	[a]	(27.0 ±0.4) %	S=1.3
Γ_4	$\pi^-\mu^+\nu_\mu$			
Γ_5	$\pi^+\mu^-\overline{\nu}_\mu$			
Γ_6	$\pi^\pm e^\mp\nu$ Called K_{e3}.	[a]	(38.7 ±0.5) %	S=1.4
Γ_7	$\pi^- e^+\nu_e$			
Γ_8	$\pi^+ e^-\overline{\nu}_e$			
Γ_9	2γ		(5.70±0.27) × 10^{-4}	S=1.9
Γ_{10}	$\pi^0 2\gamma$		(2.0 ±0.5) × 10^{-6}	
Γ_{11}	$\pi^0\pi^\pm e^\mp\nu$	[a]	(6.2 ±2.0) × 10^{-5}	
Γ_{12}	($\pi\mu$ atom) ν		(1.05±0.11) × 10^{-7}	
Γ_{13}	$\pi^\pm e^\mp\nu_e\gamma$	[b,c]	(1.3 ±0.8) %	
Γ_{14}	$\pi^+\pi^-\gamma$	[b,c]	(4.41±0.32) × 10^{-5}	

Charge conjugation × Parity (CP) or Lepton Family number (LF) violating modes, or Flavor-Changing neutral current (FC) modes

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_{15}	$\pi^+\pi^-$	CP	(2.03±0.04) × 10^{-3}	S=1.2
Γ_{16}	$\pi^0\pi^0$	CP	(9.09±0.35) × 10^{-4}	S=1.8
Γ_{17}	$\pi^0\nu\overline{\nu}$	CP,FC	< 7.6 × 10^{-3}	CL=90%
Γ_{18}	$e^\pm\mu^\mp$	LF [a]	< 9.4 × 10^{-11}	CL=90%
Γ_{19}	$\mu^+\mu^-$	FC	(7.3 ±0.4) × 10^{-9}	
Γ_{20}	$\mu^+\mu^-\gamma$	FC	(2.8 ±2.8) × 10^{-7}	
Γ_{21}	$\pi^0\mu^+\mu^-$	CP,FC	< 1.2 × 10^{-6}	CL=90%
Γ_{22}	e^+e^-	FC	< 1.6 × 10^{-10}	CL=90%
Γ_{23}	$e^+e^-\gamma$	FC	(9.1 ±0.5) × 10^{-6}	
Γ_{24}	$e^+e^-\gamma\gamma$	FC	(6.6 ±3.2) × 10^{-7}	
Γ_{25}	$\pi^0 e^+e^-$	CP,FC	< 5.5 × 10^{-9}	CL=90%
Γ_{26}	$\pi^+\pi^-e^+e^-$	FC	< 2.5 × 10^{-6}	CL=90%
Γ_{27}	$\mu^+\mu^-e^+e^-$	FC	< 4.9 × 10^{-6}	CL=90%
Γ_{28}	$e^+e^-e^+e^-$	FC	(4.0 ±3.0) × 10^{-8}	

[a] The value is for the sum of the charge states indicated.
[b] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.
[c] See the Listings below for the energy limits used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to the mean life, 4 partial widths, and 12 branching ratios uses 53 measurements and one constraint to determine 8 parameters. The overall fit has a χ^2 = 54.8 for 46 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

	x_1	x_2	x_3	x_6	x_9	x_{15}	x_{16}
x_2	−35						
x_3	−78	6					
x_6	−86	7	46				
x_9	−1	12	−3	−3			
x_{15}	−28	44	13	15	33		
x_{16}	−7	19	1	1	76	45	
Γ	2	−4	0	0	−1	−2	−1

	Mode		Rate (10^8 s^{-1})	Scale factor
Γ_1	$3\pi^0$		0.0419±0.0016	1.4
Γ_2	$\pi^+\pi^-\pi^0$		0.0239±0.0004	1.4
Γ_3	$\pi^\pm\mu^\mp\nu$ Called $K_{\mu3}$.	[a]	0.0522±0.0008	1.2
Γ_6	$\pi^\pm e^\mp\nu$ Called K_{e3}.	[a]	0.0749±0.0011	1.3
Γ_9	2γ		(1.10 ±0.05) × 10^{-4}	1.9
Γ_{15}	$\pi^+\pi^-$		(3.92 ±0.08) × 10^{-4}	1.2
Γ_{16}	$\pi^0\pi^0$		(1.76 ±0.07) × 10^{-4}	1.7

K^0_L DECAY RATES

$\Gamma(3\pi^0)$ — Γ_1

VALUE (10^6 s^{-1})	EVTS	DOCUMENT ID		TECN	COMMENT
4.19±0.16 OUR FIT Error includes scale factor of 1.4.					
5.22$^{+1.03}_{-0.84}$	54	BEHR	66	HLBC	Assumes CP

$\Gamma(\pi^+\pi^-\pi^0)$ — Γ_2

VALUE (10^6 s^{-1})	EVTS	DOCUMENT ID		TECN	COMMENT
2.39±0.04 OUR FIT Error includes scale factor of 1.4.					
2.38±0.09 OUR AVERAGE					
2.32$^{+0.13}_{-0.15}$	192	BALDO-...	75	HLBC	Assumes CP
2.35±0.20	180	[5] JAMES	72	HBC	Assumes CP
2.71±0.28	99	CHO	71	DBC	Assumes CP
2.12±0.33	50	MEISNER	71	HBC	Assumes CP
2.20±0.35	53	WEBBER	70	HBC	Assumes CP
2.62$^{+0.28}_{-0.27}$	136	BEHR	66	HLBC	Assumes CP
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.5 ±0.3	98	[5] JAMES	71	HBC	Assumes CP
3.26±0.77	18	ANDERSON	65	HBC	
1.4 ±0.4	14	FRANZINI	65	HBC	

In the fit this rate is well determined by the mean life and the branching ratio $\Gamma(\pi^+\pi^-\pi^0)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$. For this reason the discrepancy between the $\Gamma(\pi^+\pi^-\pi^0)$ measurements does not affect the scale factor of the overall fit.

[5] JAMES 72 is a final measurement and includes JAMES 71.

$\Gamma(\pi^\pm\mu^\mp\nu)$ — Γ_3

VALUE (10^6 s^{-1})	EVTS	DOCUMENT ID		TECN
5.22±0.08 OUR FIT Error includes scale factor of 1.2.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.54$^{+1.24}_{-1.08}$	19	LOWYS	67	HLBC

$\Gamma(\pi^\pm e^\mp\nu)$ — Γ_6

VALUE (10^6 s^{-1})	EVTS	DOCUMENT ID		TECN	COMMENT
7.49±0.11 OUR FIT Error includes scale factor of 1.3.					
7.7 ±0.5 OUR AVERAGE					
7.81±0.56	620	CHAN	71	HBC	
7.52$^{+0.85}_{-0.72}$		AUBERT	65	HLBC	ΔS=ΔQ,CP assumed

$\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)$ — $(\Gamma_2+\Gamma_3+\Gamma_6)$

$K^0_L \to$ charged.

VALUE (10^6 s^{-1})	EVTS	DOCUMENT ID	TECN
15.10±0.19 OUR FIT Error includes scale factor of 1.3.			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
15.1 ±1.9	98	AUERBACH 66B	OSPK

$\Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)$ — $(\Gamma_3+\Gamma_6)$

VALUE (10^6 s^{-1})	EVTS	DOCUMENT ID	TECN	COMMENT
12.70±0.18 OUR FIT Error includes scale factor of 1.3.				
11.9 ±0.6 OUR AVERAGE Error includes scale factor of 1.2.				
12.4 ±0.7	410	[6] BURGUN 72	HBC	$K^+p \to K^0 p\pi^+$
13.1 ±1.3	252	[6] WEBBER 71	HBC	$K^-p \to n\overline{K}^0$
11.6 ±0.9	393	[6,7] CHO 70	DBC	$K^+n \to K^0 p$
$9.85^{+1.15}_{-1.05}$	109	[6] FRANZINI 65	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
8.47±1.69	126	[6] MANN 72	HBC	$K^-p \to n\overline{K}^0$
10.3 ±0.8	335	[7] HILL 67	DBC	$K^+n \to K^0 p$

[6] Assumes $\Delta S = \Delta Q$ rule.
[7] CHO 70 includes events of HILL 67.

K^0_L BRANCHING RATIOS

$\Gamma(3\pi^0)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_1/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.75±0.08 OUR FIT Error includes scale factor of 1.4.				
1.81±0.13 OUR AVERAGE				
1.80±0.13	1010	BUDAGOV 68	HLBC	
2.0 ±0.6	188	ALEKSANYAN 64B	FBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.65±0.07	883	BARMIN 72B	HLBC	Error statistical only

$\Gamma(3\pi^0)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ — $\Gamma_1/(\Gamma_2+\Gamma_3+\Gamma_6)$

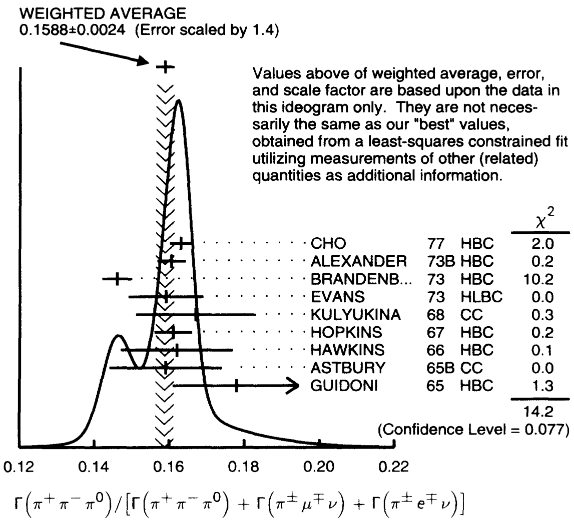
VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.277±0.013 OUR FIT Error includes scale factor of 1.5.				
0.260±0.011 OUR AVERAGE				
0.251±0.014	549	BUDAGOV 68	HLBC	ORSAY measur.
0.277±0.021	444	BUDAGOV 68	HLBC	Ecole polytec.meas
$0.31\ ^{+0.07}_{-0.06}$	29	KULYUKINA 68	CC	
0.24 ±0.08	24	ANIKINA 64	CC	

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID
0.1238±0.0021 OUR FIT Error includes scale factor of 1.5.	

$\Gamma(\pi^+\pi^-\pi^0)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ — $\Gamma_2/(\Gamma_2+\Gamma_3+\Gamma_6)$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.1586±0.0026 OUR FIT Error includes scale factor of 1.6.				
0.1588±0.0024 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.				
0.163 ±0.003	6499	CHO 77	HBC	
0.1605±0.0038	1590	ALEXANDER 73B	HBC	
0.146 ±0.004	3200	BRANDENB... 73	HBC	
0.159 ±0.010	558	EVANS 73	HLBC	
0.167 ±0.016	1402	KULYUKINA 68	CC	
0.161 ±0.005		HOPKINS 67	HBC	
0.162 ±0.015	126	HAWKINS 66	HBC	
0.159 ±0.015	326	ASTBURY 65B	CC	
0.178 ±0.017	566	GUIDONI 65	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.15\ ^{+0.03}_{-0.04}$	66	ASTBURY 65	CC	
0.144 ±0.004	1729	HOPKINS 65	HBC	See HOPKINS 67
0.151 ±0.020	79	ADAIR 64	HBC	
$0.157\ ^{+0.03}_{-0.04}$	75	LUERS 64	HBC	
0.185 ±0.038	59	ASTIER 61	CC	



$\Gamma(\pi^\pm\mu^\mp\nu)/\Gamma(\pi^\pm e^\mp\nu)$ — Γ_3/Γ_6

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.697±0.010 OUR FIT				
0.697±0.010 OUR AVERAGE				
0.702±0.011	33k	CHO 80	HBC	
0.662±0.037	10k	WILLIAMS 74	ASPK	
0.741±0.044	6700	BRANDENB... 73	HBC	
0.662±0.030	1309	EVANS 73	HLBC	
0.71 ±0.05	770	BUDAGOV 68	HLBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.68 ±0.08	3548	BASILE 70	OSPK	
0.71 ±0.04	569	[8] BEILLIERE 69	HLBC	
0.648±0.030	1309	EVANS 69	HLBC	Repl. by EVANS 73
0.67 ±0.13		[9] KULYUKINA 68	CC	
0.82 ±0.10		DEBOUARD 67	OSPK	
0.7 ±0.2	273	HAWKINS 67	HBC	
0.81 ±0.08		HOPKINS 67	HBC	
0.81 ±0.19		ADAIR 64	HBC	

[8] BEILLIERE 69 is a scanning experiment using same exposure as BUDAGOV 68.
[9] KULYUKINA 68 $\Gamma(\pi^\pm\mu^\mp\nu)/\Gamma(\pi^\pm e^\mp\nu)$ is not measured independently from $\Gamma(\pi^+\pi^-\pi^0)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ and $\Gamma(\pi^\pm e^\mp\nu)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$.

$\Gamma(\pi^\pm\mu^\mp\nu)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ — $\Gamma_3/(\Gamma_2+\Gamma_3+\Gamma_6)$

VALUE	EVTS	DOCUMENT ID	TECN
0.3456±0.0030 OUR FIT			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.335 ±0.055	330	[10] KULYUKINA 68	CC
$0.39\ ^{+0.08}_{-0.10}$	172	[10] ASTBURY 65	CC
0.356 ±0.07	251	[10] LUERS 64	HBC

[10] This mode not measured independently from $\Gamma(\pi^+\pi^-\pi^0)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ and $\Gamma(\pi^\pm e^\mp\nu)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$.

$\Gamma(\pi^\pm e^\mp\nu)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ — $\Gamma_6/(\Gamma_2+\Gamma_3+\Gamma_6)$

VALUE	EVTS	DOCUMENT ID	TECN
0.4958±0.0032 OUR FIT Error includes scale factor of 1.1.			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.498 ±0.052	500	KULYUKINA 68	CC
$0.46\ ^{+0.08}_{-0.10}$	202	ASTBURY 65	CC
0.487 ±0.05	153	LUERS 64	HBC
0.46 ±0.11	24	NYAGU 61	CC

$\Gamma(\pi^\pm e^\mp\nu)/[\Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ — $\Gamma_6/(\Gamma_3+\Gamma_6)$

VALUE	EVTS	DOCUMENT ID	TECN
0.5893±0.0033 OUR FIT			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.415 ±0.120	320	ASTIER 61	CC

$[\Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]/\Gamma_{total}$ — $(\Gamma_3+\Gamma_6)/\Gamma$

VALUE	DOCUMENT ID
0.656±0.007 OUR FIT Error includes scale factor of 1.5.	

$\Gamma(2\gamma)/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
5.70±0.27 OUR FIT	Error includes scale factor of 1.9.				
4.9 ±0.5 OUR AVERAGE					
4.54±0.84		[11] BANNER	72B	OSPK	
4.5 ±1.0	23	ENSTROM	71	OSPK	K^0_L 1.5–9 GeV/c
5.5 ±1.1	90	KUNZ	68	OSPK	Norm.to 3 π(C+N)
6.7 ±2.2	32	TODOROFF	67	OSPK	Repl. CRIEGEE 66
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5.0 ±1.0		[12] REPELLIN	71	OSPK	
7.4 ±1.6	33	[13] CRONIN	67	OSPK	
1.3 ±0.6		[14] CRIEGEE	66	OSPK	

[11] This value uses $(\eta_{00}/\eta_{+-})^2 = 1.05 \pm 0.14$. In general, $\Gamma(2\gamma)/\Gamma_{\text{total}} = [(4.32 \pm 0.55) \times 10^{-4}]\,[(\eta_{00}/\eta_{+-})^2]$.

[12] Assumes regeneration amplitude in copper at 2 GeV is 22 mb. To evaluate for a given regeneration amplitude and error, multiply by (regeneration amplitude/22mb)^2.

[13] CRONIN 67 replaced by KUNZ 68.

[14] CRIEGEE 66 replaced by TODOROFF 67.

$\Gamma(2\gamma)/\Gamma(3\pi^0)$ — Γ_9/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.64±0.16 OUR FIT	Error includes scale factor of 1.7.				
2.24±0.22 OUR AVERAGE					
2.13±0.43	28	BARMIN	71	HLBC	
2.24±0.28	115	BANNER	69	OSPK	
2.5 ±0.7	16	ARNOLD	68B	HLBC	Vacuum decay

$\Gamma(2\gamma)/\Gamma(\pi^0\pi^0)$ — Γ_9/Γ_{16}

VALUE	EVTS	DOCUMENT ID		TECN
0.627±0.019 OUR FIT	Error includes scale factor of 2.2.			
0.632±0.004±0.008	110k	BURKHARDT	87	NA31

$\Gamma(\pi^0 2\gamma)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
2.0 ±0.5 OUR AVERAGE						
1.86±0.60±0.60		60	PAPADIMITR...91		F731	$m_{\gamma\gamma} > 280$ MeV
2.1 ±0.6		14	BARR	90C	NA31	$m_{\gamma\gamma} > 280$ MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 5.1	90		PAPADIMITR...91		F731	$m_{\gamma\gamma} < 264$ MeV
< 2.7	90		PAPADIMITR...89		F731	In PAPADIM-ITRIOU 89
<230	90	0	BANNER	69	OSPK	

$\Gamma(\pi^0\pi^\pm e^\mp\nu)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN
0.062±0.020		16	CARROLL	80C	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.2	90		[15] DONALDSON	74	SPEC

[15] DONALDSON 74 uses $K^0_L \to \pi^+\pi^-\pi^0$/(all K^0_L) decays = 0.126.

$\Gamma((\pi\mu\ \text{atom})\,\nu)/\Gamma(\pi^\pm\mu^\mp\nu)$ — Γ_{12}/Γ_3

VALUE (units 10^{-7})	EVTS	DOCUMENT ID		TECN
3.90±0.39	155	[16] ARONSON	86	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	18	COOMBES	76	WIRE

[16] ARONSON 86 quote theoretical value of $(4.31 \pm 0.08) \times 10^{-7}$.

$\Gamma(\pi^\pm e^\mp\nu_e\gamma)/\Gamma(\pi^\pm e^\mp\nu)$ — Γ_{13}/Γ_6

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
3.3±2.0	10	PEACH	71	HLBC	γ KE >15 MeV

$\Gamma(\pi^+\pi^-\gamma)/\Gamma_{\text{total}}$ — Γ_{14}/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.0441±0.0032		1062	[17] CARROLL	80B	SPEC	E_γ >20 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.0152±0.0016		516	[18] CARROLL	80B	SPEC	E_γ >20 MeV
0.0289±0.0028		546	[19] CARROLL	80B	SPEC	
< 3.2	90		BOBISUT	74	HLBC	E_γ >40 MeV
0.062 ±0.021		24	[20] DONALDSON	74C	SPEC	
< 0.46	90		WOO	74	SPEC	
< 0.4	90		THATCHER	68	OSPK	E_γ 20–170 MeV
< 5.0		0	BELLOTTI	66	HLBC	E_γ 40–130 MeV
< 3.0		1	NEFKENS	66	OSPK	E_γ 120 MeV
<15.0			ANIKINA	65	CC	

[17] Both components. Uses $K^0_L \to \pi^+\pi^-\pi^0$/(all K^0_L) decays = 0.1239.

[18] Internal Bremsstrahlung component only.

[19] Direct γ emission component only.

[20] Uses $K^0_L \to \pi^+\pi^-\pi^0$/(all K^0_L) decays = 0.126.

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{15}/Γ

Violates CP conservation.

VALUE (units 10^{-3})	DOCUMENT ID	
2.03 ±0.04 OUR FIT	Error includes scale factor of 1.2.	
2.101±0.065	[21] ETAFIT	92

[21] This ETAFIT value is computed from fitted values of $|\eta_{+-}|$, the K^0_L and K^0_S lifetimes, and the $K^0_S \to \pi^+\pi^-$ branching fraction. See the discussion in the "Note on CP violation in K^0_L decay."

$\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_{15}/Γ_2

Violates CP conservation.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
1.639±0.032 OUR FIT	Error includes scale factor of 1.1.				
1.64 ±0.04	4200	MESSNER	73	ASPK	$\eta_{+-} = 2.23$

$\Gamma(\pi^+\pi^-)/[\Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ — $\Gamma_{15}/(\Gamma_3+\Gamma_6)$

Violates CP conservation.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
3.09±0.06 OUR FIT	Error includes scale factor of 1.2.				
3.09±0.10 OUR AVERAGE					
3.13±0.14	1687	COUPAL	85	SPEC	η_{+-}=2.28 ± 0.06
3.04±0.14	2703	DEVOE	77	SPEC	η_{+-}=2.25 ± 0.05
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.51±0.23	309	[22] DEBOUARD	67	OSPK	η_{+-}=2.00 ± 0.09
2.35±0.19	525	[22] FITCH	67	OSPK	η_{+-}=1.94 ± 0.08

[22] Old experiments excluded from fit. See subsection on η_{+-} in section on "PARAMETERS FOR $K^0_L \to 2\pi$ DECAY" below for average η_{+-} of these experiments and for note on discrepancy.

$\Gamma(\pi^+\pi^-)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ — $\Gamma_{15}/(\Gamma_2+\Gamma_3+\Gamma_6)$

Violates CP conservation.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.60 ±0.05 OUR FIT	Error includes scale factor of 1.1.				
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.60 ±0.07	4200	[23] MESSNER	73	ASPK	η_{+-} = 2.23 ± 0.05
1.93 ±0.26		[24] BASILE	66	OSPK	η_{+-} = 1.92 ± 0.13
1.993±0.080		[24] BOTT-...	66	OSPK	η_{+-} = 1.95 ± 0.04
2.08 ±0.35	54	[24] GALBRAITH	65	OSPK	η_{+-} = 1.99 ± 0.16
2.0 ±0.4	45	[24] CHRISTENS...	64	OSPK	η_{+-} = 1.95 ± 0.20

[23] From same data as $\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ MESSNER 73, but with different normalization.

[24] Old experiments excluded from fit. See subsection on η_{+-} in section on "PARAMETERS FOR $K^0_L \to 2\pi$ DECAY" below for average η_{+-} of these experiments and for note on discrepancy.

$\Gamma(\pi^0\pi^0)/\Gamma_{\text{total}}$ — Γ_{16}/Γ

Violates CP conservation.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.909±0.035 OUR FIT	Error includes scale factor of 1.8.				
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.5 ±0.8	189	[25] GAILLARD	69	OSPK	η_{00}=3.6 ± 0.6
1.2 $^{+1.5}_{-1.2}$	7	[26] CRIEGEE	66	OSPK	

[25] Latest result of this experiment given by FAISSNER 70 $\Gamma(\pi^0\pi^0)/\Gamma(3\pi^0)$.

[26] CRIEGEE 66 experiment not designed to measure $2\pi^0$ decay mode.

$\Gamma(\pi^0\pi^0)/\Gamma(3\pi^0)$ — Γ_{16}/Γ_1

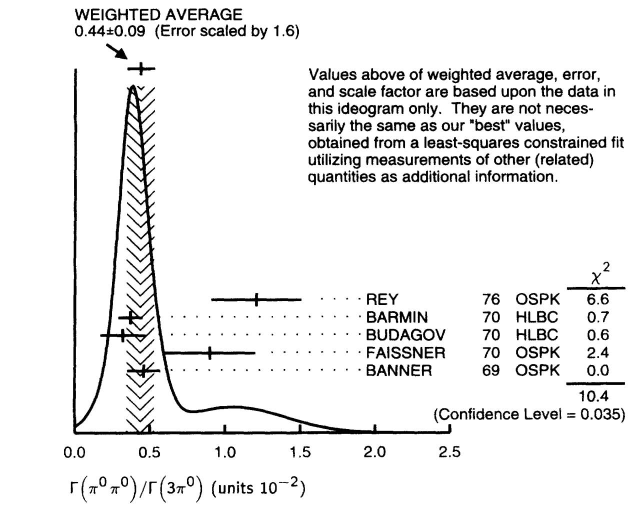
Violates CP conservation.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
0.420±0.023 OUR FIT	Error includes scale factor of 1.6.				
0.44 ±0.09 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.				
1.21 ±0.30	150	[27] REY	76	OSPK	η_{00}=3.8 ± 0.5
0.37 ±0.08	29	BARMIN	70	HLBC	η_{00}=2.02 ± 0.23
0.32 ±0.15	30	BUDAGOV	70	HLBC	η_{00}=1.9 ± 0.5
0.90 ±0.30	172	[28] FAISSNER	70	OSPK	η_{00}=3.2 ± 0.5
0.46 ±0.11	57	BANNER	69	OSPK	η_{00}=2.2 ± 0.3
not seen		BARTLETT	68	OSPK	See η_{00} below
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.31 ±0.31	133	[27] CENCE	69	OSPK	η_{00}=3.7 ± 0.5
1.89 ±0.31	109	[29] CRONIN	67	OSPK	η_{00}=4.9 ± 0.5
1.36 ±0.18		[29] CRONIN	67B	OSPK	η_{00}=3.92 ± 0.3

[27] CENCE 69 events are included in REY 76.

[28] FAISSNER 70 contains same $2\pi^0$ events as GAILLARD 69 $\Gamma(\pi^0\pi^0)/\Gamma_{\text{total}}$.

[29] CRONIN 67B is further analysis of CRONIN 67, now both withdrawn.



$\Gamma(\pi^0\pi^0)/\Gamma(\pi^+\pi^-)$ — Γ_{16}/Γ_{15}

Violates *CP* conservation.

VALUE	DOCUMENT ID	
0.448 ±0.015 OUR FIT Error includes scale factor of 2.4.		
0.4518±0.0066	[30] ETAFIT	92

[30] This ETAFIT value is computed from fitted values of $|\eta_{00}\ /\ \eta_{+-}|$ and the $\Gamma(K^0_S \to \pi^+\pi^-)\ /\ \Gamma(K^0_S \to \pi^0\pi^0)$ branching fraction. See the discussion in the "Note on *CP* violation in K^0_L decay."

$\Gamma(\pi^0\nu\overline{\nu})/\Gamma_{total}$ — Γ_{17}/Γ

Violates *CP* in leading order. Test of direct *CP* violation since the indirect *CP*-violating and *CP*-conserving contributions are expected to be suppressed. Test of $\Delta S = 1$ weak neutral current.

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN
<7.6	90	[31] LITTENBERG	89	RVUE

[31] LITTENBERG 89 is from retroactive data analysis of CRONIN 67.

$\Gamma(e^\pm\mu^\mp)/\Gamma_{total}$ — Γ_{18}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-10})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 0.94	90	0	AKAGI	91	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 4.3	90		INAGAKI	89	SPEC	In AKAGI 91
< 2.2	90		MATHIAZHA...	89	SPEC	
< 19	90		SCHAFFNER	89	SPEC	
<110	90		COUSINS	88	SPEC	
< 67	90		GREENLEE	88	SPEC	Repl. by SCHAFFNER 89
< 15.7	90		[32] CLARK	71	ASPK	

[32] Possible (but unknown) systematic errors. See note on CLARK 71 $\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ entry.

$\Gamma(e^\pm\mu^\mp)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ — $\Gamma_{18}/(\Gamma_2+\Gamma_3+\Gamma_6)$

Test of lepton family number conservation.

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 0.1	90	BOTT-...	67	OSPK
< 0.08	90	FITCH	67	OSPK
< 1.0	90	CARPENTER	66	OSPK
<10.0		ANIKINA	65	CC

$\Gamma(\mu^+\mu^-)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ — $\Gamma_{19}/(\Gamma_2+\Gamma_3+\Gamma_6)$

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 2.0	90	BOTT-...	67	OSPK
< 35.0	90	FITCH	67	OSPK
<250.0	90	ALFF-...	66B	OSPK
<100.0		ANIKINA	65	CC

$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ — Γ_{19}/Γ_{15}

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
3.62±0.18 OUR AVERAGE						
3.9 ±0.3 ±0.2		178	[33] AKAGI	91B	SPEC	
3.45±0.18±0.13		368	[34] HEINSON	91	SPEC	
$4.0\ ^{+1.4}_{-0.9}$		15	SHOCHET	79	SPEC	
$4.2\ ^{+5.1}_{-2.6}$		3	[35] FUKUSHIMA	76	SPEC	
$5.8\ ^{+2.3}_{-1.5}$		9	[36] CARITHERS	73	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
4.12±0.54		54	INAGAKI	89	SPEC	In AKAGI 91B
2.8 ±0.3 ±0.2		87	MATHIAZHA...	89B	SPEC	In HEINSON 91
< 1.53	90	0	[37] CLARK	71	SPEC	
< 18.	90	0	DARRIULAT	70	SPEC	
<140.	90	0	FOETH	69	SPEC	

[33] AKAGI 91B give this number multiplied by the 1990 PDG average for $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma(\text{total})$.

[34] HEINSON 91 give $\Gamma(K^0_L \to \mu\mu)/\Gamma_{total}$. We divide out the $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma_{total}$ PDG average which they used.

[35] FUKUSHIMA 76 errors are at CL = 90%.

[36] CARITHERS 73 errors are at CL = 68%, W.Carithers, (private communication 79).

[37] CLARK 71 limit raised from 1.2×10^{-6} by FIELD 74 reanalysis. Not in agreement with subsequent experiments. So not averaged.

$\Gamma(\mu^+\mu^-\gamma)/\Gamma_{total}$ — Γ_{20}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	CHG
0.28±0.28		1	[38] CARROLL	80D	SPEC	±0
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<7.81	90		[39] DONALDSON	74	SPEC	

[38] Uses $K^0_L \to \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.1239.

[39] Uses $K^0_L \to \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.126.

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{total}$ — Γ_{21}/Γ

Violates *CP* in leading order. Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID		TECN
<0.12	90	0	[40] CARROLL	80D	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<5.66	90		[41] DONALDSON	74	SPEC

[40] Uses $K^0_L \to \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.1239.

[41] Uses $K^0_L \to \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.126.

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_{22}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-10})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 1.6	90	1	AKAGI	91	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 5.6	90		INAGAKI	89	SPEC	In AKAGI 91
< 3.2	90		MATHIAZHA...	89	SPEC	
< 110	90		COUSINS	88	SPEC	
< 45	90		GREENLEE	88	SPEC	Repl. by JASTRZEMBSKI 88
< 12	90		JASTRZEM...	88	SPEC	
< 15.7	90		[42] CLARK	71	ASPK	
<1500	90	0	FOETH	69	ASPK	

[42] Possible (but unknown) systematic errors. See note on CLARK 71 $\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ entry.

$\Gamma(e^+e^-)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ — $\Gamma_{22}/(\Gamma_2+\Gamma_3+\Gamma_6)$

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 23.0	90	BOTT-...	67	OSPK
< 200.0	90	ALFF-...	66B	OSPK
<1000.0		ANIKINA	65	CC

$\Gamma(e^+e^-\gamma)/\Gamma_{total}$ — Γ_{23}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	CHG
9.1±0.5 OUR AVERAGE						
9.2±0.5±0.5		1053	BARR	90B	NA31	
$9.1\pm0.4^{+0.6}_{-0.5}$		919	OHL	90B	B845	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
17.4±8.7		4	[43] CARROLL	80D	SPEC	±0
<27	90	0	[44] BARMIN	72	HLBC	

[43] Uses $K^0_L \to \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.1239.

[44] Uses $K^0_L \to 3\pi^0/\text{total} = 0.214$.

$\Gamma(e^+e^-\gamma\gamma)/\Gamma_{total}$ — Γ_{24}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-7})	DOCUMENT ID		TECN	COMMENT
6.6±3.2	MORSE	92	B845	$E_\gamma > 5$ MeV

$\Gamma(\pi^0 e^+ e^-)/\Gamma_{total}$ — Γ_{25}/Γ

Violates *CP* in leading order. Direct and indirect *CP*-violating contributions are expected to be comparable and to dominate the *CP*-conserving part. Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-9})	CL%	EVTS	DOCUMENT ID		TECN
< 7.5	90	0	BARKER	90	F731
< 5.5	90	0	OHL	90	B845
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 40	90		BARR	88	NA31
< 320	90		JASTRZEM...	88	SPEC
<2300	90	0	[45] CARROLL	80D	SPEC

[45] Uses $K^0_L \rightarrow \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.1239.

$\Gamma(\pi^+\pi^- e^+ e^-)/\Gamma_{total}$ — Γ_{26}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN
< 2.5	90	0	BALATS	83	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 8.81	90		[46] DONALDSON	76	SPEC
<30			ANIKINA	73	STRC

[46] Uses $K^0_L \rightarrow \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.126.

$\Gamma(\mu^+\mu^- e^+ e^-)/\Gamma_{total}$ — Γ_{27}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN
<4.9	90	BALATS	83	SPEC

$\Gamma(e^+ e^- e^+ e^-)/\Gamma_{total}$ — Γ_{28}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-8})	CL%	EVTS	DOCUMENT ID		TECN
4 ±3		2	BARR	91	NA31
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<260	90		BALATS	83	SPEC

ENERGY DEPENDENCE OF K^0_L DALITZ PLOT

For discussion, see note on Dalitz plot parameters in the $K^\pm$ section of the Full Listings above. For definitions of a_v, a_t, a_u, and a_y, see the earlier version of the same note in the 1982 edition of this Review published in Physics Letters **111B** 70 (1982).

$$|\text{matrix element}|^2 = 1 + gu + hu^2 + jv + kv^2$$

where $u = (s_3 - s_0)\ /\ m^2(\pi)$ and $v = (s_1 - s_2)\ /\ m^2(\pi)$

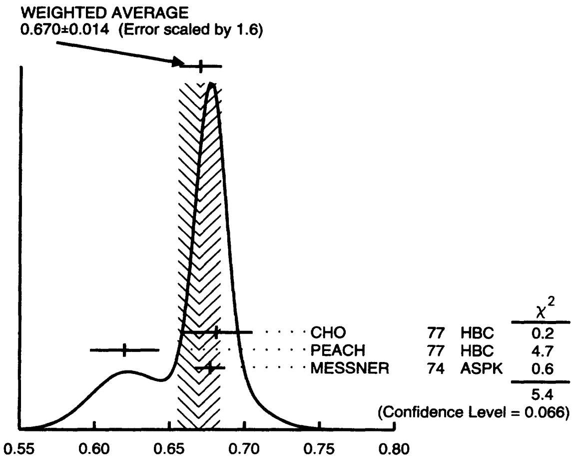
LINEAR COEFFICIENT g FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.670±0.014 OUR AVERAGE		Error includes scale factor of 1.6. See the ideogram below.			
0.681±0.024	6499	CHO	77	HBC	
0.620±0.023	4709	PEACH	77	HBC	
0.677±0.010	509k	MESSNER	74	ASPK	$a_y = -0.917 \pm 0.013$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.69 ±0.07	192	[47] BALDO-...	75	HLBC	
0.590±0.022	56k	[47] BUCHANAN	75	SPEC	$a_u = -0.277 \pm 0.010$
0.619±0.027	20k	[47,48] BISI	74	ASPK	$a_t = -0.282 \pm 0.011$
0.612±0.032		[47] ALEXANDER	73B	HBC	
0.73 ±0.04	3200	[47] BRANDENB...	73	HBC	
0.50 ±0.11	180	[47] JAMES	72	HBC	
0.608±0.043	1486	[47] KRENZ	72	HLBC	$a_t = -0.277 \pm 0.018$
0.688±0.074	384	[47] METCALF	72	ASPK	$a_t = -0.31 \pm 0.03$
0.650±0.012	29k	[47] ALBROW	70	ASPK	$a_y = -0.858 \pm 0.015$
0.593±0.022	36k	[47,49] BUCHANAN	70	SPEC	$a_u = -0.278 \pm 0.010$
0.664±0.056	4400	[47] SMITH	70	OSPK	$a_t = -0.306 \pm 0.024$
0.400±0.045	2446	[47] BASILE	68B	OSPK	$a_t = -0.188 \pm 0.020$
0.649±0.044	1350	[47] HOPKINS	67	HBC	$a_t = -0.294 \pm 0.018$
0.428±0.055	1198	[47] NEFKENS	67	OSPK	$a_u = -0.204 \pm 0.025$
0.64 ±0.17	280	[47] ANIKINA	66	CC	$a_v = -8.2^{+0.9}_{-1.3}$
0.70 ±0.12	126	[47] HAWKINS	66	HBC	$a_v = -8.6 \pm 0.7$
0.32 ±0.13	66	[47] ASTBURY	65	CC	$a_v = -5.5 \pm 1.5$
0.51 ±0.09	310	[47] ASTBURY	65B	CC	$a_v = -7.3^{+0.6}_{-0.8}$
0.55 ±0.23	79	[47] ADAIR	64	HBC	$a_v = -7.6 \pm 1.7$
0.51 ±0.20	77	[47] LUERS	64	HBC	$a_v = -7.3 \pm 1.6$

[47] Quadratic dependence required by some experiments. (See sections on "QUADRATIC COEFFICIENT h" and "QUADRATIC COEFFICIENT k" below.) Correlations prevent us from averaging results of fits not including g, h, and k terms.

[48] BISI 74 value comes from quadratic fit with quad. term consistent with zero. g error is thus larger than if linear fit were used.

[49] BUCHANAN 70 result revised by BUCHANAN 75 to include radiative correlations and to use more reliable K^0_L momentum spectrum of second experiment (had same beam).



Linear coeff. g for $K^0_L \rightarrow \pi^+\pi^-\pi^0$ matrix element squared

QUADRATIC COEFFICIENT h FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN
0.079±0.007 OUR AVERAGE				
0.095±0.032	6499	CHO	77	HBC
0.048±0.036	4709	PEACH	77	HBC
0.079±0.007	509k	MESSNER	74	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.011±0.018	29k	[50] ALBROW	70	ASPK
0.043±0.052	4400	[50] SMITH	70	OSPK

See notes in section "LINEAR COEFFICIENT g FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$ |MATRIX ELEMENT|^2" above.

[50] Quadratic coefficients h and k required by some experiments. (See section on "QUADRATIC COEFFICIENT k" below.) Correlations prevent us from averaging results of fits not including g, h, and k terms.

QUADRATIC COEFFICIENT k FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN
0.0098±0.0018 OUR AVERAGE				
0.024 ±0.010	6499	CHO	77	HBC
−0.008 ±0.012	4709	PEACH	77	HBC
0.0097±0.0018	509k	MESSNER	74	ASPK

LINEAR COEFFICIENT j FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$ (*CP*-VIOLATING TERM)

Listed in *CP*-violation section below.

K^0_L FORM FACTORS

For discussion, see note on form factors in the $K^\pm$ section of the Full Listings above.

In the form factor comments, the following symbols are used.

- f_+ and f_- are form factors for the vector matrix element.
- f_S and f_T refer to the scalar and tensor term.
- $f_0 = f_+ + f_- t/(m^2(K) - m^2(\pi))$.
- λ_+, λ_-, and λ_0 are the linear expansion coefficients of f_+, f_-, and f_0.
- λ_+ refers to the $K_{\mu 3}$ value except in the K_{e3} sections.
- $d\xi(0)/d\lambda_+$ is the correlation between $\xi(0)$ and λ_+ in $K_{\mu 3}$.
- $d\lambda_0/d\lambda_+$ is the correlation between λ_0 and λ_+ in $K_{\mu 3}$.
- t = momentum transfer to the π in units of $m^2(\pi)$.
- DP = Dalitz plot analysis.
- PI = π spectrum analysis.
- MU = μ spectrum analysis.
- POL= μ polarization analysis.
- BR = $K_{\mu 3}/K_{e3}$ branching ratio analysis.
- E = positron or electron spectrum analysis.
- RC = radiative corrections.

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN K_{e3} DECAY)

For radiative correction of K_{e3} DP, see GINSBERG 67 and BECHERRAWY 70.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0300±0.0016 OUR AVERAGE		Error includes scale factor of 1.2.			
0.0306±0.0034	74k	BIRULEV	81	SPEC	DP
0.025 ±0.005	12k	[51] ENGLER	78B	HBC	DP
0.0348±0.0044	18k	HILL	78	STRC	DP
0.0312±0.0025	500k	GJESDAL	76	SPEC	DP
0.0270±0.0028	25k	BLUMENTHAL	75	SPEC	DP
0.044 ±0.006	24k	BUCHANAN	75	SPEC	DP
0.040 ±0.012	2171	WANG	74	OSPK	DP
0.045 ±0.014	5600	ALBROW	73	ASPK	DP

0.019 ± 0.013	1871	BRANDENB... 73	HBC	PI transv.
0.022 ± 0.014	1910	NEUHOFER 72	ASPK	PI
0.023 ± 0.005	42k	BISI 71	ASPK	DP
0.05 ± 0.01	16k	CHIEN 71	ASPK	DP, no RC
0.02 ± 0.013	1000	ARONSON 68	OSPK	PI
$+0.023 \pm 0.012$	4800	BASILE 68	OSPK	DP, no RC
-0.01 ± 0.02	762	FIRESTONE 67	HBC	DP, no RC
$+0.01 \pm 0.015$	531	KADYK 67	HBC	e,PI, no RC
$+0.08 {}^{+0.10}_{-0.08}$	240	LOWYS 67	FBC	PI
$+0.15 \pm 0.08$	577	FISHER 65	OSPK	DP, no RC
$+0.07 \pm 0.06$	153	LUERS 64	HBC	DP, no RC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.029 ± 0.005	19k	[51] CHO 80	HBC	DP
0.0286 ± 0.0049	26k	BIRULEV 79	SPEC	Repl. by BIRULEV 81
0.032 ± 0.0042	48k	BIRULEV 76	SPEC	Repl. by BIRULEV 81

[51] ENGLER 78B uses an unique K_{e3} subset of CHO 80 events and is less subject to systematic effects.

$\xi_a = f_-/f_+$ (determined from $K_{\mu 3}$ spectra)

The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	$d\xi(0)/d\lambda_+$	EVTS	DOCUMENT ID	TECN	COMMENT
-0.11 ± 0.09 OUR EVALUATION			From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).		
-0.10 ± 0.09	-12	150k	[52] BIRULEV 81	SPEC	DP
$+0.26 \pm 0.16$	-13	14k	[53] CHO 80	HBC	DP
$+0.13 \pm 0.23$	-20	16k	[53] HILL 79	STRC	DP
-0.25 ± 0.22	-5.9	32k	[54] BUCHANAN 75	SPEC	DP
-0.11 ± 0.07	-17	1.6M	[55] DONALDSON 74B	SPEC	DP
-1.00 ± 0.45	-20	1385	[56] PEACH 73	HLBC	DP
-1.5 ± 0.7	-28	9086	[57] ALBROW 72	ASPK	DP
$+1.2 \pm 0.8$	-18	1341	[58] CARPENTER 66	OSPK	DP
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$+0.50 \pm 0.61$	unknown	16k	[59] DALLY 72	ASPK	DP
-3.9 ± 0.4		3140	[60] BASILE 70	OSPK	DP, indep of λ_+
$-0.68 {}^{+0.12}_{-0.20}$	-26	16k	[59] CHIEN 70	ASPK	DP

[52] BIRULEV 81 error, $d\xi(0)/d\lambda_+$ calculated by us from λ_0, λ_+. $d\lambda_0/d\lambda_+ = 0$ used.

[53] HILL 79 and CHO 80 calculated by us from λ_0, λ_+, and $d\lambda_0/d\lambda_+$.

[54] BUCHANAN 75 is calculated by us from λ_0, λ_+ and $d\lambda_0/d\lambda_+$ because their appendix A value -0.20 ± 22 assumes $\xi(t)$ constant, i.e. $\lambda_- = \lambda_+$.

[55] DONALDSON 74B gives $\xi = -0.11 \pm 0.02$ not including systematics. Above error and $d\xi(0)/d\lambda_+$ were calculated by us from λ_0 and λ_+ errors (which include systematics) and $d\lambda_0/d\lambda_+$.

[56] PEACH 73 gives $\xi(0) = -0.95 \pm 0.45$ for $\lambda_+ = \lambda_- = 0.025$. The above value is for $\lambda_- = 0$. K.Peach, private communication (1974).

[57] ALBROW 72 fit has λ_- free, gets $\lambda_- = -0.030 \pm 0.060$ or $\Lambda = +0.15^{+0.17}_{-0.11}$.

[58] CARPENTER 66 $\xi(0)$ is for $\lambda_+ = 0$. $d\xi(0)/d\lambda_+$ is from figure 9.

[59] CHIEN 70 errors are statistical only. $d\xi(0)/d\lambda_+$ from figure 4. DALLY 72 is a reanalysis of CHIEN 70. The DALLY 72 result is not compatible with assumption $\lambda_- = 0$ so not included in our fit. The nonzero λ_- value and the relatively large λ_+ value found by DALLY 72 come mainly from a single low t bin (figures 1,2). The (f_+,ξ) correlation was ignored. We estimate from figure 2 that fixing $\lambda_- = 0$ would give $\xi(0) = -1.4 \pm 0.3$ and would add 10 to χ^2. $d\xi(0)/d\lambda_+$ is not given.

[60] BASILE 70 is incompatible with all other results. Authors suggest that efficiency estimates might be responsible.

$\xi_b = f_-/f_+$ (determined from $K_{\mu 3}/K_{e3}$)

The $K_{\mu 3}/K_{e3}$ branching ratio fixes a relationship between $\xi(0)$ and λ_+. We quote the author's $\xi(0)$ and associated λ_+ but do not average because the λ_+ values differ. The fit result and scale factor given below are not obtained from these ξ_b values. Instead they are obtained directly from the authors $K_{\mu 3}/K_{e3}$ branching ratio via the fitted $K_{\mu 3}/K_{e3}$ ratio $(\Gamma(\pi^\pm \mu^\mp \nu)/\Gamma(\pi^\pm e^\mp \nu))$. The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
-0.11 ± 0.09 OUR EVALUATION		From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).		
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.5 ± 0.4	6700	BRANDENB... 73	HBC	BR, $\lambda_+ = 0.019 \pm 0.013$
-0.08 ± 0.25	1309	[61] EVANS 73	HLBC	BR, $\lambda_+ = 0.02$
-0.5 ± 0.5	3548	BASILE 70	OSPK	BR, $\lambda_+ = 0.02$
$+0.45 \pm 0.28$	569	BEILLIERE 69	HLBC	BR, $\lambda_+ = 0$
-0.22 ± 0.30	1309	[61] EVANS 69	HLBC	
$+0.2 {}^{+0.8}_{-1.2}$		KULYUKINA 68	CC	BR, $\lambda_+ = 0$
$+1.1 \pm 1.1$	389	ADAIR 64	HBC	BR, $\lambda_+ = 0$
$+0.66 {}^{+0.9}_{-1.3}$		LUERS 64	HBC	BR, $\lambda_+ = 0$

[61] EVANS 73 replaces EVANS 69.

$\xi_c = f_-/f_+$ (determined from μ polarization in $K_{\mu 3}$)

The μ polarization is a measure of $\xi(t)$. No assumptions on λ_{+-} necessary, t (weighted by sensitivity to $\xi(t)$) should be specified. In λ_+, $\xi(0)$ parametrization this is $\xi(0)$ for $\lambda_+ = 0$. $d\xi/d\lambda = \xi t$. For radiative correction to μ polarization in $K_{\mu 3}$, see GINSBERG 73. The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
-0.11 ± 0.09 OUR EVALUATION		From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).		
$+0.178 \pm 0.105$	207k	[62] CLARK 77	SPEC	POL, $d\xi(0)/d\lambda_+ = +0.68$
-0.385 ± 0.105	2.2M	[63] SANDWEISS 73	CNTR	POL, $d\xi(0)/d\lambda_+ = -6$
$-1.81 {}^{+0.50}_{-0.26}$		[64] LONGO 69	CNTR	POL, t=3.3
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-1.6 ± 0.5	638	[65] ABRAMS 68B	OSPK	Polarization
-1.2 ± 0.5	2608	[65] AUERBACH 66B	OSPK	Polarization

[62] CLARK 77 $t = +3.80$, $d\xi(0)/d\lambda_+ = \xi(t)t = 0.178 \times 3.80 = +0.68$.

[63] SANDWEISS 73 is for $\lambda_+ = 0$ and $t = 0$.

[64] LONGO 69 $t = 3.3$ calculated from $d\xi(0)/d\lambda_+ = -6.0$ (table 1) divided by $\xi = -1.81$.

[65] t value not given.

IMAGINARY PART OF ξ

Test of T reversal invariance.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
-0.007 ± 0.026 OUR AVERAGE				
0.009 ± 0.030	12M	MORSE 80	CNTR	Polarization
0.35 ± 0.30	207k	[66] CLARK 77	SPEC	POL, t=0
-0.085 ± 0.064	2.2M	[67] SANDWEISS 73	CNTR	POL, t=0
-0.02 ± 0.08		LONGO 69	CNTR	POL, t=3.3
-0.2 ± 0.6		ABRAMS 68B	OSPK	Polarization
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.012 ± 0.026		SCHMIDT 79	CNTR	Repl. by MORSE 80

[66] CLARK 77 value has additional $\xi(0)$ dependence $+0.21\mathrm{Re}[\xi(0)]$.

[67] SANDWEISS 73 value corrected from value quoted in their paper due to new value of $\mathrm{Re}(\xi)$. See footnote 4 of SCHMIDT 79.

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN $K_{\mu 3}$ DECAY)

See also the corresponding entries and notes in section "$\xi_A = f_-/f_+$" above and section "λ_0 (LINEAR ENERGY DEPENDENCE OF f_0 IN $K_{\mu 3}$ DECAY)" below. For radiative correction of $K_{\mu 3}$ Dalitz plot see GINSBERG 70 and BECHERRAWY 70.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.034 ± 0.005 OUR EVALUATION		From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).		
0.0427 ± 0.0044	150k	BIRULEV 81	SPEC	DP
0.028 ± 0.010	14k	CHO 80	HBC	DP
0.028 ± 0.011	16k	HILL 79	STRC	DP
0.046 ± 0.030	32k	BUCHANAN 75	SPEC	DP
0.030 ± 0.003	1.6M	DONALDSON 74B	SPEC	DP
0.085 ± 0.015	9086	ALBROW 72	ASPK	DP
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0337 ± 0.0033	129k	DZHORD... 77	SPEC	Repl. by BIRULEV 81
0.046 ± 0.008	82k	ALBRECHT 74	WIRE	Repl. by BIRULEV 81
0.11 ± 0.04	16k	DALLY 72	ASPK	DP
0.07 ± 0.02	16k	CHIEN 70	ASPK	Repl. by DALLY 72

λ_0 (LINEAR ENERGY DEPENDENCE OF f_0 IN $K_{\mu 3}$ DECAY)

Wherever possible, we have converted the above values of $\xi(0)$ into values of λ_0 using the associated λ_+^{μ} and $d\xi(0)/d\lambda_+$.

VALUE	$d\lambda_0/d\lambda_+$	EVTS	DOCUMENT ID	TECN	COMMENT
0.025 ± 0.006 OUR EVALUATION			From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).		
0.0341 ± 0.0067	unknown	150k	[68] BIRULEV 81	SPEC	DP
$+0.050 \pm 0.008$	-0.11	14k	CHO 80	HBC	DP
$+0.039 \pm 0.010$	-0.67	16k	HILL 79	STRC	DP
$+0.047 \pm 0.009$	1.06	207k	[69] CLARK 77	SPEC	POL
$+0.025 \pm 0.019$	$+0.5$	32k	[70] BUCHANAN 75	SPEC	DP
$+0.019 \pm 0.004$	-0.47	1.6M	[71] DONALDSON 74B	SPEC	DP
-0.060 ± 0.038	-0.71	1385	[72] PEACH 73	HLBC	DP
-0.018 ± 0.009	$+0.49$	2.2M	[69] SANDWEISS 73	CNTR	POL
-0.043 ± 0.052	-1.39	9086	[73] ALBROW 72	ASPK	DP
$-0.140 {}^{+0.043}_{-0.022}$	$+0.49$		[69] LONGO 69	CNTR	POL
$+0.08 \pm 0.07$	-0.54	1371	[69] CARPENTER 66	OSPK	DP
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.041 ± 0.008		14k	[74] CHO 80	HBC	BR, λ_+=0.028
$+0.0485 \pm 0.0076$		47k	DZHORD... 77	SPEC	In BIRULEV 81
$+0.024 \pm 0.011$		82k	ALBRECHT 74	WIRE	In BIRULEV 81
$+0.06 \pm 0.03$		6700	[75] BRANDENB... 73	HBC	BR, $\lambda_+ = 0.019 \pm 0.013$
-0.067 ± 0.227	unknown	16k	[76] DALLY 72	ASPK	DP
-0.333 ± 0.034	$+1.$	3140	[77] BASILE 70	OSPK	DP

[68] BIRULEV 81 gives $d\lambda_0/d\lambda_+ = -1.5$, giving an unreasonably narrow error ellipse which dominates all other results. We use $d\lambda_0/d\lambda_+ = 0$.

[69] λ_0 value is for $\lambda_+ = 0.03$ calculated by us from $\xi(0)$ and $d\xi(0)/d\lambda_+$.

[70] BUCHANAN 75 value is from their appendix A and uses only $K_{\mu 3}$ data. $d\lambda_0/d\lambda_+$ was obtained by private communication, C.Buchanan, 1976.
[71] DONALDSON 74B $d\lambda_0/d\lambda_+$ obtained from figure 18.
[72] PEACH 73 assumes $\lambda_+ = 0.025$. Calculated by us from $\xi(0)$ and $d\xi(0)/d\lambda_+$.
[73] ALBROW 72 λ_0 is calculated by us from ξ_A, λ_+ and $d\xi(0)/d\lambda_+$. They give $\lambda_0 = -0.043 \pm 0.039$ for $\lambda_- = 0$. We use our larger calculated error.
[74] CHO 80 BR result not independent of their Dalitz plot result.
[75] Fit for λ_0 does not include this value but instead includes the $K_{\mu 3}/K_{e3}$ result from this experiment.
[76] DALLY 72 gives $f_0 = 1.20 \pm 0.35$, $\lambda_0 = -0.080 \pm 0.272$, $\lambda_0{}' = -0.006 \pm 0.045$, but with a different definition of λ_0. Our quoted λ_0 is his λ_0/f_0. We cannot calculate true λ_0 error without his (λ_0,f_0) correlations. See also note on DALLY 72 in section ξ_A.
[77] BASILE 70 λ_0 is for $\lambda_+ = 0$. Calculated by us from ξ_A with $d\xi(0)/d\lambda_+ = 0$. BASILE 70 is incompatible with all other results. Authors suggest that efficiency estimates might be responsible.

$|f_S/f_+|$ FOR K_{e3} DECAY

Ratio of scalar to f_+ couplings.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.04	68	25k	BLUMENTHAL	75	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.095	95	18k	HILL	78	STRC	
<0.07	68	48k	BIRULEV	76	SPEC	See also BIRULEV 81
<0.19	95	5600	ALBROW	73	ASPK	
<0.15	68		KULYUKINA	67	CC	

$|f_T/f_+|$ FOR K_{e3} DECAY

Ratio of tensor to f_+ couplings.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.23	68	25k	BLUMENTHAL	75	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.40	95	18k	HILL	78	STRC	
<0.34	68	48k	BIRULEV	76	SPEC	See also BIRULEV 81
<1.0	95	5600	ALBROW	73	ASPK	
<1.0	68		KULYUKINA	67	CC	

$|f_T/f_+|$ FOR $K_{\mu 3}$ DECAY

Ratio of tensor to f_+ couplings.

VALUE	DOCUMENT ID		TECN
0.12±0.12	BIRULEV	81	SPEC

α_{K^*} DECAY FORM FACTOR FOR $K_L \to e^+e^-\gamma$

α_{K^*} is the constant in the model of BERGSTROM 83 which measures the relative strength of the vector-vector transition $K_L \to K^*\gamma$ with $K^* \to \rho, \omega, \phi \to \gamma^*$ and the pseudoscalar-pseudoscalar transition $K_L \to \pi, \eta, \eta' \to \gamma\gamma^*$.

VALUE	DOCUMENT ID		TECN
−0.28 ±0.08 OUR AVERAGE			
−0.28 ±0.13	BARR	90B	NA31
$-0.280^{+0.099}_{-0.090}$	OHL	90B	B845

NOTE ON CP VIOLATION IN K_L^0 DECAY

(by L. Wolfenstein, Carnegie-Mellon University and T. Trippe, LBL)

Experimentally Measured Parameters

CP violation has been observed in the semi-leptonic decays $K_L^0 \to \pi^\mp \ell^\pm \nu$ and in the nonleptonic decay $K_L^0 \to 2\pi$. The experimental numbers that have been measured are[1]

$$\delta = \frac{\Gamma(K_L^0 \to \pi^-\ell^+\nu) - \Gamma(K_L^0 \to \pi^+\ell^-\nu)}{\Gamma(K_L^0 \to \pi^-\ell^+\nu) + \Gamma(K_L^0 \to \pi^+\ell^-\nu)} \tag{1a}$$

$$\eta_{+-} = A(K_L^0 \to \pi^+\pi^-)/A(K_S^0 \to \pi^+\pi^-) = |\eta_{+-}|\, e^{i\phi_{+-}} \tag{1b}$$

$$\eta_{00} = A(K_L^0 \to \pi^0\pi^0)/A(K_S^0 \to \pi^0\pi^0) = |\eta_{00}|\, e^{i\phi_{00}} \ . \tag{1c}$$

Thus there are five real numbers, three magnitudes, and two phases. We list $\delta(\mu)$ for $K_L^0 \to \pi\mu\nu$ and $\delta(e)$ for $K_L^0 \to \pi e\nu$ separately and a weighted average δ. Experimentally for the $K_L^0 \to \pi^0\pi^0$ decay the quantities directly measured (and also of greatest theoretical interest) are $|\eta_{00}/\eta_{+-}|$ and $\phi_{00} - \phi_{+-}$.

Analysis Based on CPT Invariance[2]

CP violation can occur either in the $K^0 - \overline{K}^0$ mixing or in the decay amplitudes. Assuming CPT invariance, the CP violation in the mixing is described by a single parameter ϵ:

$$|K_L^0\rangle = \left[(1+\epsilon)\,|\,K^0\,\rangle - (1-\epsilon)\,|\,\overline{K}^0\,\rangle\right] \Big/ \left[2(1+|\,\epsilon\,|^2)\right]^{1/2} \tag{2a}$$

$$|K_S^0\rangle = \left[(1+\epsilon)\,|\,K^0\,\rangle + (1-\epsilon)\,|\,\overline{K}^0\,\rangle\right] \Big/ \left[2(1+|\,\epsilon\,|^2)\right]^{1/2} \ . \tag{2b}$$

The decay amplitudes are written

$$\langle\, I=0\,|\,T\,|\,K^0\rangle = e^{i\delta_0}A_0 \tag{3a}$$

$$\langle\, I=2\,|\,T\,|\,K^0\rangle = e^{i\delta_2}A_2 \tag{3b}$$

where δ_I are the $\pi\pi$ scattering phase shifts at the K^0 mass and I is the isospin of the final state. CP violation is measured by (Im A_I/Re A_I). One can then write

$$\eta_{+-} = \epsilon + \epsilon' \tag{4a}$$

$$\eta_{00} = \epsilon - 2\epsilon' \tag{4b}$$

where

$$\epsilon' = \frac{i}{\sqrt{2}}\, e^{i(\delta_2-\delta_0)}\, \frac{\text{Re}\, A_2}{\text{Re}\, A_0}\left[\frac{\text{Im}\, A_2}{\text{Re}\, A_2} - \frac{\text{Im}\, A_0}{\text{Re}\, A_0}\right] \tag{5}$$

neglecting small corrections of order ϵ' times Re(A_2/A_0). Only two of the three quantities ϵ, (Im A_I/Re A_I) are meaningful because of the ambiguity in defining the phase of K^0. The standard phase convention due to Wu and Yang[3] sets Im $A_0 = 0$. A nonzero value of ϵ' would provide definite evidence for CP violation in the decay amplitudes independent of phase convention.

By applying CPT invariance and unitarity it is possible to relate δ to ϵ and to determine the phases of ϵ. If one assumes the $\Delta S = \Delta Q$ rule (see below "Note on the $\Delta S = \Delta Q$ rule in K^0 Decay") the expression for δ becomes

$$\delta = 2\text{Re}\,\epsilon/(1+\ |\,\epsilon\,|^2) \approx 2\text{Re}\,\epsilon \ . \tag{6}$$

This quantity is independent of phase convention and is seen from Eq. (2) to equal $\langle K_L^0 \mid K_S^0\rangle$. The phase of ϵ is given by

$$\phi(\epsilon) \approx \tan^{-1}\frac{(2\Delta m \tau_s)}{\hbar} = 43.68 \pm 0.14^\circ \tag{7a}$$

while Eq. (5) gives

$$\phi(\epsilon') = \delta_2 - \delta_0 + \frac{\pi}{2} \approx 47 \pm 5^\circ \ . \tag{7b}$$

The approximation in Eq. (7a) depends on the neglect of CP violation in decays other than $K^0 \to 2\pi$ and is known to be good to a few tenths of a degree. Eq. (7a) is evaluated using the values of the $K_L^0 - K_S^0$ mass difference $\Delta m = (0.5351 \pm 0.0024) \times 10^{10}\hbar\text{s}^{-1}$ and the K_S^0 mean life $\tau_s = (0.8922 \pm 0.0020) \times 10^{-10}$s from the current edition. The value of the $\pi\pi$ phase shifts is taken from the fit given by Devlin and Dickey[4]. However, Kleinknecht[1] uses $\phi(\epsilon') = 37 \pm 5^\circ$ and Wahl[5] uses $\phi(\epsilon') = 45^\circ \pm 15^\circ$. The most important point for the analysis is that $\cos[\phi(\epsilon') - \phi(\epsilon)] \simeq 1$. The consequence of this analysis is that only two real quantities need be measured, the magnitude of ϵ and the value of (ϵ'/ϵ) including its sign. The measured quantity $|\eta_{00}/\eta_{+-}|^2$ which is very close to unity, is given to a good approximation by

$$|\eta_{00}/\eta_{+-}|^2 \approx 1 - 6\text{Re}\,(\epsilon'/\epsilon) = 1 - 6(\epsilon'/\epsilon)\cos\left[\phi(\epsilon') - \phi(\epsilon)\right] . \quad (8)$$

Since the cos in Eq. (8) is expected theoretically to be very close to unity it is customary to say that $|\eta_{00}/\eta_{+-}|^2$ determines ϵ'/ϵ.

It is possible to use the values of the ϕ_{+-} and $\phi_{00} - \phi_{+-}$ to set limits on CPT violation. [See Tests of Conservation Laws.]

Models

In the superweak model[6] CP violation is restricted to the mass mixing so that to a high degree of accuracy one expects $\epsilon' = 0$. The phase $\phi(\epsilon)$ is given in this model exactly by Eq. (7a) so that this has sometimes been referred to as the superweak phase; however, as noted above, all CPT invariant models give Eq. (7a) as a very good approximation. In the Standard Model CP violation is entirely due to the phase in the Cabibbo-Kobayashi-Maskawa mixing matrix[7] (q.v.). Since CP violation occurs in first order in decay amplitudes and in second order in mass-matrix mixing, one expects a significant nonzero value of ϵ'. The calculation is uncertain partly because m_t and V_{td} are not well known and primarily because of the difficulty of estimating hadronic matrix elements.[8] The theoretical results for ϵ'/ϵ in the standard model are generally in the range 3×10^{-4} to 5×10^{-3}, but may be even lower for large values of m_t.

Fitting procedures

We list measurements of $|\eta_{+-}|$, $|\eta_{00}|$, and $|\eta_{00}/\eta_{+-}|$. Independent information on $|\eta_{+-}|$ and $|\eta_{00}|$ can be obtained from measurements of the K^0_L and K^0_S lifetimes (τ) and branching ratios (B) to $\pi\pi$, using the relations

$$|\eta_{+-}| = \left[\frac{\text{B}(K^0_L \to \pi^+\pi^-)}{\tau(K^0_L)}\,\frac{\tau(K^0_S)}{\text{B}(K^0_S \to \pi^+\pi^-)}\right]^{1/2} , \quad (9a)$$

$$|\eta_{00}| = \left[\frac{\text{B}(K^0_L \to \pi^0\pi^0)}{\tau(K^0_L)}\,\frac{\tau(K^0_S)}{\text{B}(K^0_S \to \pi^0\pi^0)}\right]^{1/2} . \quad (9b)$$

We approximate a global fit to these independent sources by first performing two independent fits: 1) BRFIT, a fit to the K^0_L branching ratios, rates, and mean life, and 2) ETAFIT, a fit to the $|\eta_{+-}|$, $|\eta_{00}|$, and $|\eta_{+-}/\eta_{00}|$ measurements. The results from fit 1, along with the K^0_S values from this edition are used to compute values of $|\eta_{+-}|$ and $|\eta_{00}|$ which are included as measurements in the $|\eta_{00}|$ and $|\eta_{+-}|$ sections with a document ID of BRFIT 92. Thus the fit values of $|\eta_{+-}|$ and $|\eta_{00}|$ given in this edition include both the direct measurements and the results from the branching ratio fit.

The process is reversed in order to include the direct $|\eta|$ measurements in the branching ratio fit. The results from fit 2 above (before including BRFIT 92 values) are used along with the K^0_L and K^0_S mean lives and the $K^0_S \to \pi\pi$ branching fractions to compute the K^0_L branching ratios $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma(\text{total})$ and $\Gamma(K^0_L \to \pi^0\pi^0)/\Gamma(K^0_L \to \pi^+\pi^-)$. These branching ratio values are included as measurements in the branching ratio section with a document ID of ETAFIT 92. Thus the K^0_L branching ratio fit values in this edition include the results of direct measurements of $|\eta_{+-}|$, $|\eta_{00}|$, and $|\eta_{00}/\eta_{+-}|$. Details of these fits are given in the 1990 edition of this *Review*.[9]

The resulting value $\epsilon'/\epsilon = (2.1 \pm 1.2) \times 10^{-3}(\text{S}^* = 1.4)$ is unchanged since the 1990 edition of the *Review* because more recent results have not yet been published so that they are not included in our fits.

New results were presented at the International Lepton-Photon Symposium and Conference on High Energy Physics, Geneva, 1991: $\epsilon'/\epsilon = (2.3 \pm 0.7) \times 10^{-3}$ (BARR 91B, CERN NA31, Preliminary) and $\epsilon'/\epsilon = (0.60 \pm 0.69) \times 10^{-3}$ (WINSTEIN 91, Fermilab E731, Preliminary).

The disagreement noted in earlier results persists. The CERN NA31 result continues to indicate the presence of direct CP violation with a result which is more than three σ above zero while the Fermilab E731 result is consistent with zero. A more thorough review of these new results is given in Ref. 10.

A separate constrained fit is done to combine measurements of the phases ϕ_{+-} and ϕ_{00}, and their difference $\phi_{00} - \phi_{+-}$. The phase difference is now rather precisely determined by the CERN NA31 (CAROSI 90) and Fermilab E731 (KARLSSON 90). It is consistent with zero as expected from CPT conservation.

Footnotes and References

* The S values in parentheses are scale factors by which the errors have been increased to account for discrepancies in the data.

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CP-VIOLATION PARAMETERS IN K^0_L DECAYS

CHARGE ASYMMETRY IN LEPTONIC DECAYS

Such asymmetry violates CP. It is related to Re(ϵ).

$\delta(\mu) = [\Gamma(\pi^-\mu^+\nu_\mu) - \Gamma(\pi^+\mu^-\overline{\nu}_\mu)]/[\Gamma(\pi^-\mu^+\nu_\mu) + \Gamma(\pi^+\mu^-\overline{\nu}_\mu)]$ $(\Gamma_4-\Gamma_5)/(\Gamma_4+\Gamma_5)$

Only the combined value below is put into the Meson Summary Table.

VALUE (%)	EVTS	DOCUMENT ID		TECN
0.304±0.025 OUR AVERAGE				
0.313±0.029	15M	GEWENIGER	74	ASPK
0.278±0.051	7.7M	PICCIONI	72	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.60 ±0.14	4.1M	MCCARTHY	73	CNTR
0.57 ±0.17	1M	[78] PACIOTTI	69	OSPK
0.403±0.134	1M	[78] DORFAN	67	OSPK

[78] PACIOTTI 69 is a reanalysis of DORFAN 67 and is corrected for $\mu^+\mu^-$ range difference in MCCARTHY 72.

$\delta(e) = [\Gamma(\pi^-e^+\nu_e) - \Gamma(\pi^+e^-\overline{\nu}_e)]/[\Gamma(\pi^-e^+\nu_e) + \Gamma(\pi^+e^-\overline{\nu}_e)]$ $(\Gamma_7-\Gamma_8)/(\Gamma_7+\Gamma_8)$

Only the combined value below is put into the Meson Summary Table.

VALUE (%)	EVTS	DOCUMENT ID		TECN
0.333±0.014 OUR AVERAGE				
0.341±0.018	34M	GEWENIGER	74	ASPK
0.318±0.038	40M	FITCH	73	ASPK
0.346±0.033	10M	MARX	70	CNTR
0.246±0.059	10M	[79] SAAL	69	CNTR
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.36 ±0.18	600k	ASHFORD	72	ASPK
0.224±0.036	10M	[79] BENNETT	67	CNTR

[79] SAAL 69 is a reanalysis of BENNETT 67.

δ = weighted average of $\delta(\mu)$ and $\delta(e)$

(Combination of the above two sections.)

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.327±0.012 OUR AVERAGE					
0.313±0.029	15M	GEWENIGER	74	ASPK	$K_{\mu3}$
0.341±0.018	34M	GEWENIGER	74	ASPK	K_{e3}
0.318±0.038	40M	FITCH	73	ASPK	K_{e3}
0.333±0.050	33M	WILLIAMS	73	ASPK	$K_{\mu3}$ + K_{e3}
0.278±0.051	7.7M	PICCIONI	72	ASPK	$K_{\mu3}$
0.346±0.033	10M	MARX	70	CNTR	K_{e3}
0.246±0.059	10M	SAAL	69	CNTR	K_{e3}
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.60 ±0.14	4.1M	MCCARTHY	73	CNTR	$K_{\mu3}$
0.36 ±0.18	600k	ASHFORD	72	ASPK	K_{e3}
0.57 ±0.17	1M	PACIOTTI	69	OSPK	$K_{\mu3}$

PARAMETERS FOR $K^0_L \to 2\pi$ DECAY

$\eta_{+-} = A(K^0_L \to \pi^+\pi^-) \;/\; A(K^0_S \to \pi^+\pi^-)$
$\eta_{00} = A(K^0_L \to \pi^0\pi^0) \;/\; A(K^0_S \to \pi^0\pi^0)$

The fitted values of $|\eta_{+-}|$ and $|\eta_{00}|$ given below are the results of a fit to $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{00}/\eta_{+-}|$, and Re(ϵ'/ϵ). Independent information on $|\eta_{+-}|$ and $|\eta_{00}|$ can be obtained from the fitted values of the $K^0_L \to \pi\pi$ and $K^0_S \to \pi\pi$ branching ratios and the K^0_L and K^0_S lifetimes. This information is included as data in the $|\eta_{+-}|$ and $|\eta_{00}|$ sections with a Document ID "BRFIT." See the "Note on CP Violation in K^0_L Decay" above for details.

$|\eta_{00}| = |A(K^0_L \to 2\pi^0) \;/\; A(K^0_S \to 2\pi^0)|$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.253±0.024 OUR FIT Error includes scale factor of 1.1.					
2.12 ±0.09 OUR AVERAGE Error includes scale factor of 1.2.					
2.084±0.080		[80] BRFIT	92		
2.33 ±0.18		CHRISTENS...	79	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.71 ±0.37	56	[81] WOLFF	71	OSPK	Cu reg., 4γ's
2.95 ±0.63		[81] CHOLLET	70	OSPK	Cu reg., 4γ's

[80] This BRFIT value is computed from fitted values of the K^0_L and K^0_S lifetimes and branching fractions to $\pi\pi$. See the discussion in the "Note on CP violation in K^0_L decay."

[81] CHOLLET 70 gives $|\eta_{00}|$ = (1.23 ± 0.24) × (regeneration amplitude, 2 GeV/c Cu)/10000mb. WOLFF 71 gives $|\eta_{00}|$ = (1.13 ± 0.12) × (regeneration amplitude, 2 GeV/c Cu)/10000mb. We compute both $|\eta_{00}|$ values for (regeneration amplitude, 2 GeV/c Cu) = 24 ± 2mb. This regeneration amplitude results from averaging over FAISSNER 69, extrapolated using optical-model calculations of Bohm et al., Physics Letters **27B** 594 (1968) and the data of BALATS 71. (From H. Faissner, private communication).

$|\eta_{+-}| = |A(K^0_L \to \pi^+\pi^-) \;/\; A(K^0_S \to \pi^+\pi^-)|$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.268±0.023 OUR FIT Error includes scale factor of 1.1.					
2.279±0.022 OUR AVERAGE					
2.265±0.030		[82] BRFIT	92		
2.27 ±0.12		CHRISTENS...	79B	ASPK	
2.30 ±0.035		GEWENIGER	74B	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.28 ±0.06	1687	[83] COUPAL	85	SPEC	P(K)=70 GeV/c
2.09 ±0.02		[84] ARONSON	82B	SPEC	E=30–110 GeV

[82] This BRFIT value is computed from fitted values of the K^0_L and K^0_S lifetimes and branching fractions to $\pi\pi$. See the discussion in the "Note on CP violation in K^0_L decay."

[83] COUPAL 85 concludes: no energy dependence of $|\eta_{+-}|$, because their value is consistent with above values which occur at lower energies. Not independent of COUPAL 85 $\Gamma(\pi^+\pi^-)/\Gamma(\pi\ell\nu)$ measurement. Enters $|\eta_{+-}|$ via BRFIT value. In editions prior to 1990, this measurement was erroneously also included in our $|\eta_{+-}|$ average and fit. We thank H. Wahl (WAHL 89) for informing us.

[84] ARONSON 82B find that $|\eta_{+-}|$ may depend on the kaon energy.

$|\eta_{00}/\eta_{+-}|$

VALUE	EVTS	DOCUMENT ID		TECN
0.9935±0.0032 OUR FIT Error includes scale factor of 1.3.				
0.9907±0.0030 OUR AVERAGE				
0.9899±0.0020±0.0025		[85] BURKHARDT	88	NA31
0.9904±0.0084±0.0036		[86] WOODS	88	F731
1.014 ±0.016 ±0.007	3152	BERNSTEIN	85B	SPEC
0.995 ±0.025	1122	BLACK	85	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.00 ±0.09		[87] CHRISTENS...	79	ASPK
1.03 ±0.07	124	BANNER	72	OSPK
1.00 ±0.06	167	HOLDER	72	ASPK

[85] This is the square root of the ratio R given by BURKHARDT 88.

[86] We calculate $|\eta_{00}/\eta_{+-}| = 1-3(\epsilon'/\epsilon)$ from WOODS 88 (ϵ'/ϵ) value.

[87] Not independent of $|\eta_{+-}|$ and $|\eta_{00}|$ values which are included in fit.

ϵ'/ϵ

$\epsilon'/\epsilon \approx$ Re(ϵ'/ϵ) = $(1-|\eta_{00}/\eta_{+-}|)/3$. See "Note on CP violation in K^0_L decay."

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
2.2 ±1.1 OUR FIT Error includes scale factor of 1.3.				
−0.4 ±1.4 ±0.6	PATTERSON	90	F731	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.3 ±0.7	[88] BARR	91B	NA31	Preliminary
0.60±0.58±0.37	[89] WINSTEIN	91	F731	Preliminary
3.3 ±1.1	[90] BURKHARDT	88	NA31	
3.2 ±2.8 ±1.2	[90] WOODS	88	F731	

[88] BARR 91B is a preliminary result which includes the NA31 runs from 1986 (BURKHARDT 88), 1988 [$\epsilon'/\epsilon = (1.7\pm1.0)10^{-3}$], and 1989 [$\epsilon'/\epsilon = (2.1\pm0.9)10^{-3}$].

[89] WINSTEIN 91 is a preliminary result which includes PATTERSON 90. The second error includes the systematic error 0.32×10^{-3} and Monte Carlo error 0.18×10^{-3} combined in quadrature.

[90] These values are derived from $|\eta_{00}/\eta_{+-}|$ measurements and enter the fit via the $|\eta_{00}/\eta_{+-}|$ section.

ϕ_{+-}, PHASE of η_{+-}

The dependence of the phase on the $K^0_L - K^0_S$ mass difference is given for each experiment in the comments below, where DM is (mass difference/$\hbar$) in units 10^{10} s^{-1}. We have evaluated these mass dependences using our April 1990 value, DM = 0.5351 ± 0.0024 to obtain the values and average quoted below. We also give the regeneration phase ϕ_f in the comments below.

VALUE (°)	DOCUMENT ID		TECN	COMMENT
46.6± 1.2 OUR FIT				
46.5± 1.2 OUR AVERAGE				
46.9± 1.4±1.7	[91] CAROSI	90	NA31	
45.6± 2.9	[92] CARITHERS	75	SPEC	C regenerator
46.6± 1.7	[93] GEWENIGER	74B	ASPK	Vacuum regen.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
47.7± 2.0±0.9	[94] KARLSSON	90	F731	
35.3± 3.9	[95] ARONSON	82B	SPEC	E=30–110 GeV
41.7± 3.5	CHRISTENS...	79B	ASPK	
36.2± 6.1	[96] CARNEGIE	72	ASPK	Cu regenerator
37.2±12.0	[97] BALATS	71	OSPK	Cu regenerator
40.7± 4.2	[98] JENSEN	70	ASPK	Vacuum regen.
34.2±10.0	[99] BENNETT	69	CNTR	Cu regenerator
45.4±12.0	[100] BOHM	69B	OSPK	Vacuum regen.
45.2± 7.4	[101] FAISSNER	69	ASPK	Cu regenerator
51.0±11.0	[102] BENNETT	68B	CNTR	Cu reg. uses
70.0±21.0	[103] BOTT-...	67B	OSPK	C regenerator
25.0±35.0	[103] MISCHKE	67	OSPK	Cu regenerator
30.0±45.0	[103] FIRESTONE	66	HBC	
45.0±50.0	[103] FITCH	65	OSPK	Be regenerator

[91] Systematic error is quadratic sum of experimental systematic errors (±0.7°) and the systematic errors due to the current uncertainties in τ_S (±0.6°) and Δm (±1.4°).

[92] CARITHERS 75 $\phi_{+-} = (45.5 \pm 2.8)+224[\Delta(m)-0.5348]°$. $\phi_f = -40.9 \pm 2.6°$.
[93] GEWENIGER 74B $\phi_{+-} = (49.4 \pm 1.0)+565[\Delta(m)-0.540]°$.
[94] KARLSSON 90 systematic error does not include regeneration phase uncertainty.
[95] ARONSON 82 find that ϕ_{+-} may depend on the kaon energy.
[96] CARNEGIE 72 ϕ_{+-} is insensitive to $\Delta(m)$. $\phi_f = -56.2 \pm 5.2°$.
[97] BALATS 71 $\phi_{+-} = (39.0 \pm 12.0)+198[\Delta(m)-0.544]°$. $\phi_f = -43.0 \pm 4.0°$.
[98] JENSEN 70 $\phi_{+-} = (42.4 \pm 4.0)+576[\Delta(m)-0.538]°$.
[99] BENNETT 69 uses measurement of $(\phi_{+-})-(\phi_f)$ of ALFF-STEINBERGER 66B. BENNETT 69 $\phi_{+-} = (34.9 \pm 10.0)+69[\Delta(m)-0.545]°$. $\phi_f = -49.9 \pm 5.4°$.
[100] BOHM 69B $\phi_{+-} = (41.0 \pm 12.0)+479(\Delta(m)-0.526)°$.
[101] FAISSNER 69 error enlarged to include error in regenerator phase. FAISSNER 69 $\phi_{+-} = (49.3 \pm 7.4)+205[\Delta(m)-0.555]°$. $\phi_f = -42.7 \pm 5.0°$.
[102] BENNETT 69 is a re-evaluation of BENNETT 68B.
[103] Old experiments with large errors not included in average.

ϕ_{00}, PHASE OF η_{00}

VALUE (°)	EVTS	DOCUMENT ID		TECN	COMMENT
46.6± 2.0 OUR FIT					
47.1± 2.1±1.8		[105] CAROSI	90	NA31	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
47.4± 1.4±0.9		[106] KARLSSON	90	F731	
55.7± 5.8		CHRISTENS...	79	ASPK	
38.0±25.0	56	[107] WOLFF	71	OSPK	Cu reg., 4γ's
51.0±30.0		[108] CHOLLET	70	OSPK	Cu reg., 4γ's
first quadrant preferred		GOBBI	69B	OSPK	

[105] Systematic error is quadratic sum of experimental systematic errors (±1.0°) and the systematic errors due to the current uncertainties in τ_S (±0.5°) and Δm (±1.4°).
[106] KARLSSON 90 systematic error does not include regeneration phase uncertainty.
[107] WOLFF 71 uses regenerator phase $\phi_f = -48.2 \pm 3.5°$.
[108] CHOLLET 70 uses regenerator phase $\phi_f = -46.5 \pm 4.4°$.

PHASE DIFFERENCE $\phi_{00} - \phi_{+-}$

Test of *CPT*.

VALUE (°)	DOCUMENT ID		TECN	COMMENT
0.1± 1.9 OUR FIT				
− 0.1± 2.0 OUR AVERAGE				
0.2± 2.6±1.2	[109] CAROSI	90	NA31	
− 0.3± 2.4±1.2	KARLSSON	90	F731	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
− 0.6± 1.4±0.8	[110] WINSTEIN	91	F731	Preliminary
12.6± 6.2	[109] CHRISTENS...	79	ASPK	
7.6±18.0	[111] BARBIELLINI	73	ASPK	

[109] Not independent of ϕ_{+-} and ϕ_{00} values. This is taken into account in our fitting procedure.
[110] WINSTEIN 91 is a preliminary result which includes KARLSSON 90.
[111] Independent of regenerator mechanism, $\Delta(m)$, and lifetimes.

CHARGE ASYMMETRY IN $\pi^+\pi^-\pi^0$ DECAYS

CP-VIOLATION COEFFICIENT *j* FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$

Defined at beginning of section "LINEAR COEFFICIENT *g* FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$ above. See also note on Daltitz plot parameters in $K^\pm$ section and note on *CP* violation in K^0_L decay above.

VALUE	EVTS	DOCUMENT ID		TECN
0.0011±0.0008 OUR AVERAGE				
0.001 ±0.011	6499	CHO	77	
−0.001 ±0.003	4709	PEACH	77	
0.0013±0.0009	3M	SCRIBANO	70	
0.0 ±0.017	4400	SMITH	70	OSPK
0.001 ±0.004	238k	BLANPIED	68	

NOTE ON $\Delta S = \Delta Q$ IN K^0 DECAYS

The relative amount of $\Delta S \neq \Delta Q$ component present is measured by the parameter x, defined as

$$x = A(\overline{K}^0 \rightarrow \pi^-\ell^+\nu)/A(K^0 \rightarrow \pi^-\ell^+\nu)\ .$$

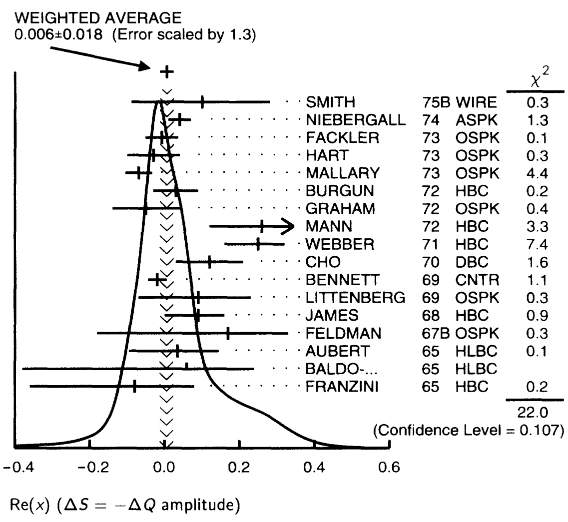
We list $\text{Re}\{x\}$ and $\text{Im}\{x\}$ for K_{e3} and $K_{\mu3}$ combined.

$x = (\Delta S = -\Delta Q \text{ AMPLITUDE}) / (\Delta S = +\Delta Q \text{ AMPLITUDE})$

REAL PART OF x

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.006±0.018 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.			
$0.10\ ^{+0.18}_{-0.19}$	79	SMITH	75B	WIRE	$\pi^- p \rightarrow K^0\Lambda$
0.04 ±0.03	4724	NIEBERGALL	74	ASPK	$K^+ p \rightarrow K^0 p\pi^+$
−0.008±0.044	1757	FACKLER	73	OSPK	K_{e3} from K^0
−0.03 ±0.07	1367	HART	73	OSPK	K_{e3} from $K^0\Lambda$
−0.070±0.036	1079	MALLARY	73	OSPK	K_{e3} from $K^0\Lambda X$
0.03 ±0.06	410	[112] BURGUN	72	HBC	$K^+ p \rightarrow K^0 p\pi^+$
−0.05 ±0.09	442	[113] GRAHAM	72	OSPK	$\pi^- p \rightarrow K^0\Lambda$
$0.26\ ^{+0.10}_{-0.14}$	126	MANN	72	HBC	$K^- p \rightarrow n\overline{K}^0$
$0.25\ ^{+0.07}_{-0.09}$	252	WEBBER	71	HBC	$K^- p \rightarrow n\overline{K}^0$
0.12 ±0.09	215	[114] CHO	70	DBC	$K^+ d \rightarrow K^0 pp$
−0.020±0.025		[115] BENNETT	69	CNTR	Charge asym+ Cu regen.
$0.09\ ^{+0.14}_{-0.16}$	686	LITTENBERG	69	OSPK	$K^+ n \rightarrow K^0 p$
$0.09\ ^{+0.07}_{-0.09}$	121	JAMES	68	HBC	$\overline{p}p$
$0.17\ ^{+0.16}_{-0.35}$	116	FELDMAN	67B	OSPK	$\pi^- p \rightarrow K^0\Lambda$
$0.035\ ^{+0.11}_{-0.13}$	196	AUBERT	65	HLBC	K^+ charge exchange
$0.06\ ^{+0.18}_{-0.44}$	152	[116] BALDO-...	65	HLBC	K^+ charge exchange
$-0.08\ ^{+0.16}_{-0.28}$	109	[117] FRANZINI	65	HBC	$\overline{p}p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.04\ ^{+0.10}_{-0.13}$	100	[113] GRAHAM	72	OSPK	$K_{\mu3}$ from $K^0\Lambda$
−0.13 ±0.11	342	[113] MANTSCH	72	OSPK	K_{e3} from $K^0\Lambda$
$0.04\ ^{+0.07}_{-0.08}$	222	[112] BURGUN	71	HBC	$K^+ p \rightarrow K^0 p\pi^+$
0.03 ±0.03		[115] BENNETT	68	CNTR	
0.17 ±0.10	335	[114] HILL	67	DBC	$K^+ d \rightarrow K^0 pp$

[112] BURGUN 72 is a final result which includes BURGUN 71.
[113] First GRAHAM 72 value is second GRAHAM 72 value combined with MANTSCH 72.
[114] CHO 70 is analysis of unambiguous events in new data and HILL 67.
[115] BENNETT 69 is a reanalysis of BENNETT 68.
[116] BALDO-CEOLIN 65 gives x and θ converted by us to Re(x) and Im(x).
[117] FRANZINI 65 gives x and θ for Re(x) and Im(x). See SCHMIDT 67.



IMAGINARY PART OF x

Assumes $m(K^0_L) - m(K^0_S)$ positive. See Listings above.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.003±0.026 OUR AVERAGE		Error includes scale factor of 1.2.			
$-0.10\ ^{+0.16}_{-0.19}$	79	SMITH	75B	WIRE	$\pi^- p \rightarrow K^0\Lambda$
−0.06 ±0.05	4724	NIEBERGALL	74	ASPK	$K^+ p \rightarrow K^0 p\pi^+$
−0.017±0.060	1757	FACKLER	73	OSPK	K_{e3} from K^0
0.09 ±0.07	1367	HART	73	OSPK	K_{e3} from $K^0\Lambda$
$0.107\ ^{+0.092}_{-0.074}$	1079	MALLARY	73	OSPK	K_{e3} from $K^0\Lambda X$
$0.07\ ^{+0.06}_{-0.07}$	410	[118] BURGUN	72	HBC	$K^+ p \rightarrow K^0 p\pi^+$
0.05 ±0.13	442	[119] GRAHAM	72	OSPK	$\pi^- p \rightarrow K^0\Lambda$
$0.21\ ^{+0.15}_{-0.12}$	126	MANN	72	HBC	$K^- p \rightarrow n\overline{K}^0$

0.0	±0.08	252	WEBBER	71 HBC	$K^- p \to n\overline{K}^0$
−0.08	±0.07	215	[120] CHO	70 DBC	$K^+ d \to K^0 pp$
−0.11	$^{+0.10}_{-0.11}$	686	LITTENBERG	69 OSPK	$K^+ n \to K^0 p$
+0.22	$^{+0.37}_{-0.29}$	121	JAMES	68 HBC	$\overline{p}p$
0.0	±0.25	116	FELDMAN	67B OSPK	$\pi^- p \to K^0 \Lambda$
−0.21	$^{+0.11}_{-0.15}$	196	AUBERT	65 HLBC	K^+ charge exchange
−0.44	$^{+0.32}_{-0.19}$	152	[121] BALDO-...	65 HLBC	K^+ charge exchange
+0.24	$^{+0.40}_{-0.30}$	109	[122] FRANZINI	65 HBC	$\overline{p}p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.12	$^{+0.17}_{-0.16}$	100	[119] GRAHAM	72 OSPK	$K_{\mu 3}$ from $K^0 \Lambda$
−0.04	±0.16	342	[119] MANTSCH	72 OSPK	K_{e3} from $K^0 \Lambda$
0.12	$^{+0.08}_{-0.09}$	222	[118] BURGUN	71 HBC	$K^+ p \to K^0 p \pi^+$
−0.20	±0.10	335	[120] HILL	67 DBC	$K^+ d \to K^0 pp$

[118] BURGUN 72 is a final result which includes BURGUN 71.
[119] First GRAHAM 72 value is second GRAHAM 72 value combined with MANTSCH 72.
[120] Footnote 10 of HILL 67 should read +0.58, not −0.58 (private communication) CHO 70 is analysis of unambiguous events in new data and HILL 67.
[121] BALDO-CEOLIN 65 gives x and θ converted by us to Re(x) and Im(x).
[122] FRANZINI 65 gives x and θ for Re(x) and Im(x). See SCHMIDT 67.

K^0_L REFERENCES

BRFIT	92	RPP		
ETAFIT	92	RPP		
MORSE	92	PR D45 36	+Leipuner, Larsen, Jastrzembski+	(BNL, YALE, VASS)
AKAGI	91	PRL 67 2614	+Fukuhisa, Hemmi+	(TOHO, TOKY, KYOT, KEK)
AKAGI	91B	PRL 67 2618	+Fukuhisa, Hemmi+	(TOHO, TOKY, KYOT, KEK)
BARR	91	PL B259 389	+Carosi+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
BARR	91B	Lep. Phot. Sym.	+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
		Proc. Intl. Lepton Photon Symp. and Conf. on HEP, Geneva, 1991.		
HEINSON	91	PR D44 R1	+	(UCI, UCLA, LANL, PENN, STAN, TEMP, TEXA+)
PAPADIMITR...	91	PR D44 R573	Papadimitriou, Barker, Briere+	(FNAL-731 Collab.)
WINSTEIN	91	Lep. Phot. Sym.		(EFI)
		Proc. Intl. Lepton Photon Symp. and Conf. on HEP, Geneva, 1991.		
BARKER	90	PR D41 3546	+Briere, Gibbons, Makoff+	(FNAL-731 Collab.)
Also	88	PRL 61 2661	Gibbons, Papadimitriou+	(FNAL-731 Collab.)
BARR	90B	PL B240 283	+Carosi+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
BARR	90C	PL B242 523	+Carosi+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
CAROSI	90	PL B237 303	+Clarke+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
KARLSSON	90	PRL 64 2976	+Gollin, Okamitsu, Tschirhart, Barker+	(FNAL-731 Collab.)
OHL	90	PRL 64 2755	+Adair, Greenlee, Kasha, Mannelli+	(BNL-845 Collab.)
OHL	90B	PRL 65 1407	+Adair, Greenlee, Kasha, Mannelli+	(BNL-845 Collab.)
PATTERSON	90	PRL 64 1491	+Barker+	(FNAL-731 Collab.)
INAGAKI	89	PR D40 1712	+Kobayashi, Sato, Shinkawa+	(KEK, TOKY, KYOT)
LITTENBERG	89	PR D39 3322		(BNL)
MATHIAZHA...	89	PRL 63 2181	Mathiazhagan+	(UCI, UCLA, LANL, PENN, STAN+)
MATHIAZHA...	89B	PRL 63 2185	Mathiazhagan+	(UCI, UCLA, LANL, PENN, STAN+)
PAPADIMITR...	89	PRL 63 28	Papadimitriou, Gibbons, Patterson+	(FNAL-731 Collab.)
SCHAFFNER	89	PR D39 990	+Greenlee, Kasha, Mannelli, Ohl+	(YALE, BNL)
WAHL	89	CERN-EP/89-86, H. Wahl — Rare Decay Symposium, Vancouver		(CERN)
BARR	88	PL B214 303	+Clarke+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
BURKHARDT	88	PL B206 169	+Clarke+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
COUSINS	88	PR D38 2914	+Konigsberg+	(UCLA, LASL, PENN, STAN, TEMP, WILL)
GREENLEE	88	PRL 60 893	+Kasha, Mannelli, Mannelli+	(YALE, BNL)
JASTRZEM...	88	PRL 61 2300	Jastrzembski, Larsen, Leipuner, Morse+	(BNL, YALE)
WOODS	88	PRL 60 1695	+Nishikawa, Patterson, Wah, Winstein+	(FNAL-731 Collab.)
BURKHARDT	87	PL B199 139	+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
ARONSON	86	PR D33 3180	+Bernstein, Bock+	(BNL, CHIC, STAN, WISC)
Also	82	PRL 48 1078	Aronson, Bernstein+	(BNL, CHIC, STAN, WISC)
PDG	86C	PL 170B 132	Aguilar-Benitez, Porter+	(CERN, CIT+)
BERNSTEIN	85B	PRL 54 1631	+Bock, Carlsmith, Coupal+	(CHIC, SACL)
BLACK	85	PRL 54 1628	+Blatt, Campbell, Kasha, Mannelli+	(BNL, YALE)
COUPAL	85	PRL 55 566	+Bernstein, Bock, Carlsmith+	(CHIC, SACL)
BALATS	83	SJNP 38 556	+Berezin, Bogdanov, Vishnevsky+	(ITEP)
		Translated from YAF 38 927.		
BERGSTROM	83	PL 131B 229	+Masso, Singer	(CERN)
ARONSON	82	PRL 48 1078	+Bernstein+	(BNL, CHIC, STAN, WISC)
ARONSON	82B	PRL 48 1306	+Bock, Cheng, Fischbach	(BNL, CHIC, PURD)
Also	82B	PL 116B 73	Fischbach, Cheng+	(PURD, BNL, CHIC)
Also	83	PR D28 476	Aronson, Bock, Cheng+	(BNL, CHIC, PURD)
Also	83B	PR D28 495	Aronson, Bock, Cheng+	(BNL, CHIC, PURD)
PDG	82B	PL 111B 70	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
BIRULEV	81	NP B182 1	+Dzhordzhadze, Genchev, Grigalashvili+	(JINR)
Also	80	SJNP 31 622	Birulev, Vestergombi, Genchev+	(JINR)
		Translated from YAF 31 1204.		
CARROLL	80B	PRL 44 529	+Chiang, Kycia, Li, Littenberg, Marx+	(BNL, ROCH)
CARROLL	80C	PL 96B 407	+Chiang, Kycia, Li, Littenberg, Marx+	(BNL, ROCH)
CARROLL	80D	PRL 44 525	+Chiang, Kycia, Li, Littenberg, Marx+	(BNL, ROCH)
CHO	80	PR D22 2688	+Derrick, Miller, Schlereth, Engler+	(ANL, CMU)
MORSE	80	PR D21 1750	+Leipuner, Larsen, Schmidt, Blatt+	(BNL, YALE)
BIRULEV	79	SJNP 29 778	+Vestergombi, Gvakhariya, Genchev+	(JINR)
		Translated from YAF 29 1516.		
CHRISTENS...	79	PRL 43 1209	Christenson, Goldman, Hummel, Roth+	(NYU)
CHRISTENS...	79B	PRL 43 1212	Christenson, Goldman, Hummel, Roth+	(NYU)
HILL	79	NP B153 39	+Sakitt, Snape, Stevens+	(BNL, SLAC, SBER)
SCHMIDT	79	PRL 43 556	+Blatt, Campbell, Grannan+	(YALE, BNL)
SHOCHET	79	PR D19 1965	+Linsay, Grosso-Pilcher, Frisch+	(EFI, ANL)
Also	77	PRL 39 59	Shochet, Linsay, Grosso-Pilcher+	(EFI, ANL)
ENGLER	78B	PR D18 623	+Keyes, Kraemer, Tanaka, Cho+	(CMU, ANL)
HILL	78	PL 73B 483	+Sakitt, Snape, Stevens+	(BNL, SLAC, SBER)
CHO	77	PR D15 587	+Derrick, Lissauer, Miller, Engler+	(ANL, CMU)
CLARK	77	PR D15 553	+Field, Holley, Johnson, Kerth, Sah, Shen	(LBL)
Also	75	LBL-4275 Thesis	Shen	(LBL)
DEVOE	77	PR D16 565	+Cronin, Frisch, Grosso-Pilcher+	(EFI, ANL)
DZHORD...	77	SJNP 26 478	Dzhordzhadze, Kekelidze, Krivokhizhin+	(JINR)
		Translated from YAF 26 910.		
PEACH	77	NP B127 399	+Cameron+	(BGNA, EDIN, GLAS, PISA, RHEL)
BIRULEV	76	SJNP 24 178	+Vestergombi, Vovenko, Votruba+	(JINR)
		Translated from YAF 24 340.		
COOMBES	76	PRL 37 249	+Flexer, Hall, Kennelly, Kirkby+	(STAN, NYU)
DONALDSON	76	PR D14 2839	+Hitlin, Kennelly, Kirkby, Liu+	(SLAC)
Also	74	SLAC-184 Thesis	Donaldson	(SLAC)
FUKUSHIMA	76	PRL 36 348	+Jensen, Surko, Thaler+	(PRIN, MASA)
GJESDAL	76	NP B109 118	+Kamae, Presser, Steffen+	(CERN, HEID)
REY	76	PR D13 1161	+Cence, Jones, Parker+	(NDAM, HAWA, LBL)
Also	69	PRL 22 1210	Cence, Jones, Peterson, Stenger+	(HAWA, LRL)
BALDO-...	75	NC 25A 688	Baldo-Ceolin, Bobisut, Calimani+	(PADO, WISC)
BLUMENTHAL	75	PRL 34 164	+Frankel, Nagy+	(PENN, CHIC, TEMP)
BUCHANAN	75	PR D11 457	+Drickey, Pepper, Rudnick+	(UCLA, SLAC, JHU)
CARITHERS	75	PRL 34 1244	+Modis, Nygren, Pun+	(COLU, NYU)
SMITH	75B	UCSD Thesis unpub.		(UCSD)
ALBRECHT	74	PL 48B 393		(JINR, BERL, BUDA, PRAG, SERP, SOFI)
BISI	74	PL 50B 504	+Ferrero	(TORI)
BOBISUT	74	LNC 11 646	+Huzita, Mattioli, Puglierin	(PADO)
DONALDSON	74	SLAC-184 Thesis		(SLAC)
Also	76	PR D14 2839	Donaldson, Hitlin, Kennelly, Kirkby, Liu+	(SLAC)
DONALDSON	74B	PR D9 2960	+Fryberger, Hitlin, Liu+	(SLAC, UCSC)
Also	73B	PRL 31 337	Donaldson, Fryberger, Hitlin, Liu+	(SLAC, UCSC)
DONALDSON	74C	PRL 33 554	+Hitlin, Kennelly, Kirkby+	(SLAC)
Also	74	SLAC-184 Thesis	Donaldson	(SLAC)
Also	76	PR D14 2839	Donaldson, Hitlin, Kennelly, Kirkby, Liu+	(SLAC)
FIELD	74	SLAC-PUB-1498 unpub.		(SLAC)
GEWENIGER	74	PL 48B 483	+Gjesdal, Kamae, Presser+	(CERN, HEID)
Also	74	CERN Int. 74-4 Thesis	Luth	(HEID)
GEWENIGER	74B	PL 48B 487	+Gjesdal, Presser+	(CERN, HEID)
Also	74B	PL 52B 119	Gjesdal, Presser, Steffen+	(CERN, HEID)
GEWENIGER	74C	PL 52B 108	+Gjesdal, Presser+	(CERN, HEID)
GJESDAL	74	PL 52B 113	+Presser, Kamae, Steffen+	(CERN, HEID)
MESSNER	74	PRL 33 1458	+Franklin, Morse+	(COLO, SLAC, UCSC)
NIEBERGALL	74	PL 49B 103	+Regler, Stier+	(CERN, ORSA, VIEN)
WANG	74	PR D9 540	+Smith, Whatley, Zorn, Hornbostel	(UMD, BNL)
WILLIAMS	74	PRL 33 240	+Larsen, Leipuner, Sapp, Sessoms+	(BNL, YALE)
WOO	74	LNC 10 38	+Buchanan, Pepper	(UCLA)
ALBROW	73	NP B58 22	+Aston, Barber, Bird, Ellison+	(MCHS, DARE)
ALEXANDER	73B	NP B65 301	+Benary, Borowitz, Lande+	(TELA, HEID)
ANIKINA	73	JINR P1 7539	+Balashov, Bannik+	(JINR)
BARBIELLINI	73	PL 43B 529	+Darriulat, Fainberg+	(CERN)
BRANDENB...	73	PR D8 1978	Brandenburg, Johnson, Leith, Loos+	(SLAC)
CARITHERS	73	PRL 31 1025	+Nygren, Gordon+	(COLU, BNL, CERN)
Also	73B	PRL 30 1336	Carithers, Modis, Nygren+	(COLU, CERN, NYU)
EVANS	73	PR D7 36	+Muir, Peach, Budagov+	(EDIN, CERN)
Also	69	PRL 23 427	Evans, Golden, Muir, Peach+	(EDIN, CERN)
FACKLER	73	PRL 31 847	+Frisch, Martin, Smoot, Sompayrac	(MIT)
FITCH	73	PRL 31 1524	+Hepp, Jensen, Strovink, Webb	(PRIN)
Also	72	COO-3072-13 Thesis	Webb	(PRIN)
GINSBERG	73	PR D8 3887	+Smith	(MIT, STON)
HART	73	NP B66 317	+Hutton, Field, Sharp, Blackmore+	(CAVE, RHEL)
MALLARY	73	PR D7 1953	+Binnie, Gallivan, Gomez, Peck, Sciulli+	(CIT)
Also	70	PRL 25 1214	Sciulli, Gallivan, Binnie, Gomez+	(CIT)
MCCARTHY	73	PR D7 687	+Brewer, Budnitz, Entis, Graven, Miller+	(LBL)
Also	72	PL 42B 291	McCarthy, Brewer, Budnitz, Entis, Graven+	(LBL)
Also	71	LBL-550 Thesis	McCarthy	(LBL)
MESSNER	73	PRL 30 876	+Morse, Nauenberg, Hitlin+	(COLO, SLAC, UCSC)
PEACH	73	PL 43B 441	+Evans, Muir, Hopkins, Krenz	(EDIN, CERN, AACH)
SANDWEISS	73	PRL 30 1002	+Sunderland, Turner, Willis, Keller	(YALE, ANL)
WILLIAMS	73	PRL 31 1521	+Larsen, Leipuner, Sapp, Sessoms+	(BNL, YALE)
ALBROW	72	NP B44 1	+Aston, Barber, Bird, Ellison+	(MCHS, DARE)
ASHFORD	72	PL 38B 47	+Brown, Masek, Maung, Miller, Ruderman+	(UCSD)
BANNER	72	PRL 28 1597	+Cronin, Hoffman, Knapp, Shochet	(PRIN)
BANNER	72B	PRL 29 237	+Cronin, Hoffman, Knapp, Shochet	(PRIN)
BARMIN	72	SJNP 15 636	+Davidenko, Demidov, Dolgolenko+	(ITEP)
		Translated from YAF 15 1149.		
BARMIN	72B	SJNP 15 638	+Barylov, Davidenko, Demidov+	(ITEP)
		Translated from YAF 15 1152.		
BURGUN	72	NP B50 194	+Lesquoy, Muller, Pauli+	(SACL, CERN, OSLO)
CARNEGIE	72	PR D6 2335	+Cester, Fitch, Strovink, Sulak	(PRIN)
DALLY	72	PL 41B 647	+Innocenti, Seppi+	(SLAC, JHU, UCLA)
Also	70	PL 33B 627	Chien, Cox, Ettlinger+	(JHU, SLAC, UCLA)
Also	71	PL 35B 261	Chien, Cox, Ettlinger+	(JHU, SLAC, UCLA)
GRAHAM	72	NC 9A 166	+Abashian, Jones, Mantsch, Orr+	(ILL, NEAS)
HOLDER	72	PL 40B 141	+Radermacher, Staude+	(AACH, CERN, TORI)
JAMES	72	NP B49 1	+Montanet, Paul, Saetre+	(CERN, SACL, OSLO)
KRENZ	72	LNC 4 213	+Hopkins, Evans, Muir, Peach	(AACH, CERN, EDIN)
MANN	72	PR D6 137	+Kofler, Meisner, Hertzbach+	(MASA, BNL, YALE)
MANTSCH	72	NC 9A 160	+Abashian, Graham, Jones, Orr+	(ILL, NEAS)
MCCARTHY	72	PL 42B 291	+Brewer, Budnitz, Entis, Graven+	(LBL)
METCALF	72	PL 40B 703	+Neuhofer, Niebergall+	(CERN, IPN, WIEN)
NEUHOFER	72	PL 41B 642	+Niebergall, Regler, Stier+	(CERN, ORSA, VIEN)
PICCIONI	72	PRL 29 1412	+Coombes, Donaldson, Dorfan, Fryberger+	(SLAC)
Also	74	PR D9 2939	Piccioni, Donaldson+	(SLAC, UCSC, COLO)
VOSBURGH	72	PR D6 1834	+Devlin, Esterling, Goz, Bryman+	(RUTG, MASA)
Also	71	PRL 26 866	Vosburgh, Devlin, Esterling, Goz+	(RUTG, MASA)
BALATS	71	SJNP 13 53	+Berezin, Vishnevsky, Galanina+	(ITEP)
		Translated from YAF 13 93.		
BARMIN	71	PL 35B 604	+Barylov, Veselovsky, Davidenko+	(ITEP)
BISI	71	PL 36B 533	+Darriulat, Ferrero, Rubbia+	(AACH, CERN, TORI)
BURGUN	71	LNC 2 1169	+Lesquoy, Muller, Pauli+	(SACL, CERN, OSLO)
CARNEGIE	71	PR D4 1	+Cester, Fitch, Strovink, Sulak	(PRIN)
CHAN	71	LBL-350 Thesis		(LBL)
CHIEN	71	PL 35B 261	+Cox, Ettlinger+	(JHU, SLAC, UCLA)
Also	72	PL 41B 647	Dally, Innocenti, Seppi+	(SLAC, JHU, UCLA)
CHO	71	PR D3 1557	+Dralle, Canter, Engler, Fisk+	(CMU, BNL, CASE)
CLARK	71	PRL 26 1667	+Elioff, Field, Frisch, Johnson, Kerth+	(LRL)
Also	70	UCRL 19709 Thesis	Johnson	(LRL)
Also	71	UCRL 20264 Thesis	Frisch	(LRL)
Also	74	SLAC-PUB-1498 unpub.	Field	(SLAC)
ENSTROM	71	PR D4 2629	+Akavia, Coombes, Dorfan+	(SLAC, STAN)
Also	70	SLAC-125 Thesis	Enstrom	(STAN)
JAMES	71	PL 35B 265	+Montanet, Paul, Pauli+	(CERN, SACL, OSLO)
MEISNER	71	PR D3 59	+Mann, Hertzbach, Kofler+	(MASA, BNL, YALE)
PEACH	71	PL 35B 351	+Evans, Muir, Budagov, Hopkins+	(EDIN, CERN)
REPELLIN	71	PL 36B 603	+Wolff, Chollet, Gaillard, Jane+	(ORSA, CERN)
WEBBER	71	PR D3 64	+Solmitz, Crawford, Alston-Garnjost	(LRL)
Also	68	PRL 21 498	Webber, Solmitz, Crawford, Alston-Garnjost	(LRL)
Also	69	UCRL 19226 Thesis	Webber	(LRL)
WOLFF	71	PL 36B 517	+Chollet, Repellin, Gaillard+	(ORSA, CERN)
ALBROW	70	PL 33B 516	+Aston, Barber, Bird, Ellison+	(MCHS, DARE)
ARONSON	70	PRL 25 1057	+Ehrlich, Hofer, Jensen+	(EFI, ILLC, SLAC)
BARMIN	70	PL 33B 377	+Barylov, Borisov, Bysheva+	(ITEP, JINR)
BASILE	70	PR D2 78	+Cronin, Thevent, Turlay, Zylberajch+	(SACL)
BECHERRAWY	70	PR D1 1452		(ROCH)
BUCHANAN	70	PL 33B 623	+Drickey, Rudnick, Shepard+	(SLAC, JHU, UCLA)
Also	71	Private Comm.	Cox	
BUDAGOV	70	PR D2 815	+Cundy, Myatt, Nezrick+	(CERN, ORSA, EPOL)
Also	68B	PL 28B 215	Budagov, Cundy, Myatt+	(CERN, ORSA, EPOL)
CHIEN	70	PL 33B 627	+Cox, Ettlinger+	(JHU, SLAC, UCLA)
Also	71	Private Comm.	Cox	
CHO	70	PR D1 3031	+Dralle, Canter, Engler, Fisk+	(CMU, BNL, CASE)
Also	67	PRL 19 668	Hill, Luers, Robinson, Sakitt+	(BNL, CMU)

CHOLLET	70	PL 31B 658	+Gaillard, Jane, Ratcliffe, Repellin+	(CERN)
CULLEN	70	PL 32B 523	+Darriulat, Deutsch, Foeth+	(AACH, CERN, TORI)
DARRIULAT	70	PL 33B 249	+Ferrero, Grosso, Holder+	(AACH, CERN, TORI)
FAISSNER	70	NC 70A 57	+Reithler, Thome, Gaillard+	(AACH, CERN, RHEL)
GINSBERG	70	PR D1 229		(HAIF)
JENSEN	70	Thesis		(EFI)
Also	69	PRL 23 615	Jensen, Aronson, Ehrlich, Fryberger+	(EFI, ILL)
MARX	70	PL 32B 219	+Nygren, Peoples+	(COLU, HARV, CERN)
Also	70B	Nevis 179 Thesis	Marx	(COLU)
SCRIBANO	70	PL 32B 224	+Mannelli, Pierazzini, Marx+	(PISA, COLU, HARV)
SMITH	70	PL 32B 133	+Wang, Whatley, Zorn, Hornbostel	(UMD, BNL)
WEBBER	70	PR D1 1967	+Solmitz, Crawford, Alston-Garnjost	(LRL)
Also	69	UCRL 19226 Thesis	Webber	(LRL)
BANNER	69	PR 188 2033	+Cronin, Liu, Pilcher	(PRIN)
Also	68	PRL 21 1103	Banner, Cronin, Liu, Pilcher	(PRIN)
Also	68	PRL 21 1107	Cronin, Liu, Pilcher	(PRIN)
BEILLIERE	69	PL 30B 202	+Boutang, Limon	(EPOL)
BENNETT	69	PL 29B 317	+Nygren, Saal, Steinberger+	(COLU, BNL)
BOHM	69B	NP B9 605	+Darriulat, Grosso, Kaftanov+	(CERN)
Also	68	PL 27B 321	Bohm, Darriulat, Grosso, Kaftanov	(CERN)
CENCE	69	PRL 22 1210	+Jones, Peterson, Stenger+	(HAWA, LRL)
EVANS	69	PRL 23 427	+Golden, Muir, Peach+	(EDIN, CERN)
FAISSNER	69	PL 30B 204	+Foeth, Staude, Tittel+	(AACH, CERN, TORI)
FOETH	69	PL 30B 282	+Holder, Radermacher+	(AACH, CERN, TORI)
GAILLARD	69	NC 59A 453	+Galbraith, Hussri, Jane+	(CERN, RHEL, AACH)
Also	67	PRL 18 20	Gaillard, Krienen, Galbraith+	(CERN, RHEL, AACH)
GOBBI	69B	PRL 22 685	+Green, Hakel, Moffett, Rosen, Goz+	(ROCH, RUTG)
LITTENBERG	69	PRL 22 654	+Field, Piccioni, Mehlhop+	(UCSD)
LONGO	69	PR 181 1808	+Young, Helland	(MICH, UCLA)
PACIOTTI	69	UCRL 19446 Thesis		(LRL)
SAAL	69	Thesis		(COLU)
ABRAMS	68B	PR 176 1603	+Abashian, Mischke, Nefkens, Smith+	(ILL)
ARNOLD	68B	PL 28B 56	+Budagov, Cundy, Aubert+	(CERN, ORSA)
ARONSON	68	PRL 20 287	+Chen	(PRIN)
Also	69	PR 175 1708	Aronson, Chen	(PRIN)
BARTLETT	68	PRL 21 558	+Carnegie, Fitch+	(PRIN)
BASILE	68	PL 26B 542	+Cronin, Thevenet, Turlay+	(SACL)
BASILE	68B	PL 28B 58	+Cronin, Thevenet, Turlay, Zylberajch+	(SACL)
BENNETT	68	PL 27B 244	+Nygren, Steinberger+	(COLU, CERN)
BENNETT	68B	PL 27B 248	+Nygren, Steinberger+	(COLU, CERN)
BLANPIED	68	PRL 21 1650	+Levit, Engels+	(CASE, HARV, MCGI)
BOHM	68B	PL 27B 594	+	
BUDAGOV	68	NC 57A 182	+Burmeister, Cundy+	(CERN, ORSA, IPNP)
Also	68B	PL 28B 215	Budagov, Cundy, Myatt+	(CERN, ORSA, EPOL)
JAMES	68	NP B8 365	+Briand	(IPNP, CERN)
Also	68	PRL 21 257	Helland, Longo, Young	(UCLA, MICH)
KULYUKINA	68	JETP 26 20 Translated from ZETF 53 29.	+Mestvirishvili, Nyagu+	(JINR)
KUNZ	68	PU 46 Thesis		(PRIN)
THATCHER	68	PR 174 1674	+Abashian, Abrams, Carpenter+	(ILL)
BENNETT	67	PRL 19 993	+Nygren, Saal, Steinberger+	(COLU)
BOTT-...	67	PL 24B 194	Bott-Bodenhausen, DeBouard, Cassel+	(CERN)
BOTT-...	67B	PL 24B 438	Bott-Bodenhausen, Debouard, Dekkers+	(CERN)
Also	66B	PL 20 212	Bott-Bodenhausen, Debouard, Cassel+	(CERN)
Also	66	PL 23 277	Bott-Bodenhausen, DeBouard, Cassel+	(CERN)
CRONIN	67	PRL 18 25	+Kunz, Risk, Wheeler	(PRIN)
Also	68	Thesis (unpub.)	Wheeler	(PRIN)
CRONIN	67B	Princeton 11/67	+Kunz, Risk, Wheeler	(PRIN)
DEBOUARD	67	NC 52A 662	+Dekkers, Jordan, Mermod+	(CERN)
Also	65	PL 15 58	DeBouard, Dekkers, Scharff+	(CERN, ORSA, MPIM)
DEVLIN	67	PRL 18 54	+Solomon, Shepard, Beall+	(PRIN, UMD)
Also	68	PR 169 1045	Sayer, Beall, Devlin, Shephard+	(UMD, PPA, PRIN)
DORFAN	67	PRL 19 987	+Enstrom, Raymond, Schwartz+	(SLAC, LRL)
FELDMAN	67B	PR 155 1611	+Frankel, Highland, Sloan	(PENN)
FIRESTONE	67	PRL 18 176	+Kim, Lach, Sandweiss+	(YALE, BNL)
FITCH	67	PR 164 1711	+Roth, Russ, Vernon	(PRIN)
GINSBERG	67	PR 162 1570		(MASB)
HAWKINS	67	PR 156 1444		(YALE)
HILL	67	PRL 19 668	+Luers, Robinson, Sakitt+	(BNL, CMU)
HOPKINS	67	PRL 19 185	+Bacon, Eisler	(BNL)
KADYK	67	PRL 19 597	+Chan, Drijard, Oren, Sheldon	(LRL)
KULYUKINA	67	Preprint	+Mestvirishvili, Nyagu+	(JINR)
LOWYS	67	PL 24B 75	+Aubert, Chounet, Pascaud+	(EPOL, ORSA)
MISCHKE	67	PRL 18 138	+Abashian, Abrams+	(ILL)
NEFKENS	67	PR 157 1233	+Abashian, Abrams, Carpenter, Fisher+	(ILL)
SCHMIDT	67	Nevis 160 Thesis		(COLU)
TODOROFF	67	Thesis		(ILL)
ALFF-...	66B	PL 21 595	Alff-Steinberger, Heuer, Kleinknecht+	(CERN)
ANIKINA	66	SJNP 2 339 Translated from YAF 2 471.	+Vardenga, Zhuravleva+	(JINR)
AUERBACH	66B	PRL 17 980	+Mann, McFarlane, Sciulli	(PENN)
BASILE	66	Balaton Conf.	+Cronin, Thevenet+	(SACL)
BEHR	66	PL 22 540	+Brisson, Petiau+	(EPOL, MILA, PADO, ORSA)
BELLOTTI	66	NC 45A 737	+Pullia, Baldo-Ceolin+	(MILA, PADO)
BOTT-...	66	PL 23 277	Bott-Bodenhausen, DeBouard, Cassel+	(CERN)
CARPENTER	66	PR 142 871	+Abashian, Abrams, Fisher	(ILL)
CRIEGEE	66	PRL 17 150	+Fox, Frauenfelder, Hanson, Moscat+	(ILL)
FIRESTONE	66	PRL 16 556	+Kim, Lach, Sandweiss+	(YALE, BNL)
HAWKINS	66	PL 21 238		(YALE)
Also	67	PR 156 1444	Hawkins	(YALE)
NEFKENS	66	PL 19 706	+Abashian, Abrams, Carpenter+	(ILL)
ANDERSON	65	PRL 14 475	+Crawford, Golden, Stern, Binford+	(LRL, WISC)
ANIKINA	65	JINR P 2488	+Vardenga, Zhuravleva, Kotlya+	(JINR)
ASTBURY	65	PL 16 80	+Finocchiaro, Beusch+	(CERN, ZURI)
Also	65	HPA 39 523	Pepin	
ASTBURY	65B	PL 18 175	+Michelini, Beusch+	(CERN, ZURI)
ASTBURY	65C	PL 18 178	+Michelini, Beusch+	(CERN, ZURI)
AUBERT	65	PL 17 59	+Behr, Canavan, Chounet+	(EPOL, ORSA)
Also	67	PL 24B 75	Lowys, Aubert, Chounet, Pascaud+	(EPOL, ORSA)
BALDO-...	65	NC 38 684	Baldo-Ceolin, Calimani, Ciampolillo+	(PADO)
FISHER	65	ANL 7130 83	+Abashian, Abrams, Carpenter+	(ILL)
FITCH	65	PRL 15 73	+Roth, Russ, Vernon	(PRIN)
FRANZINI	65	PR 140B 127	+Kirsch, Plano+	(COLU, RUTG)
GALBRAITH	65	PRL 14 383	+Manning, Jones+	(AERE, BRIS, RHEL)
GUIDONI	65	Argonne Conf. 49	+Barnes, Foelsche, Ferbel, Firestone+	(BNL, YALE)
HOPKINS	65	Argonne Conf. 67	+Bacon, Eisler	(VAND, RUTG)
ADAIR	64	PL 12 67	+Leipuner	(YALE, BNL)
ALEKSANYAN	64B	Dubna Conf. 2 102	+Alikhanyan, Vartazaryan+	(YERE)
Also	64	JETP 19 1019 Translated from ZETF 46 1504.	Aleksanyan+	(LEBD, MPEI, YERE)
ANIKINA	64	JETP 19 42 Translated from ZETF 46 59.	+Zhuravleva+	(GEOR, JINR)
CHRISTENS...	64	PRL 13 138	Christenson, Cronin, Fitch, Turlay	(PRIN)
FUJII	64	Dubna Conf. 2 146	+Jovanovich, Turkot+	(BNL, UMD, MIT)
LUERS	64	PR 133B 1276	+Mittra, Willis, Yamamoto	(BNL)
DARMON	62	PL 3 57	+Rousset, Six	(EPOL)
ASTIER	61	Aix Conf. 1 227	+Blaskovic, Rivet, Siaud+	(EPOL)
FITCH	61	NC 22 1160	+Piroue, Perkins	(PRIN, LASL)
GOOD	61	PR 124 1223	+Matsen, Muller, Piccioni+	(LRL)
NYAGU	61	PRL 6 552	+Okonov, Petrov, Rosanova, Rusakov	(JINR)
Also	61B	JETP 13 1138 Translated from ZETF 40 1618.	Nyagu, Okonov, Petrov, Rozanova+	(JINR)
BARDON	58	ANP 5 156	+Lande, Lederman	(COLU, BNL)

OTHER RELATED PAPERS

KLEINKNECHT	91	CNPP (to be pub.) MZ-ETAP/91-02		(MANZ)
KLEINKNECHT	90	ZPHY C46 S57		(MANZ)
PEACH	90	JP G16 131		(EDIN)
BRYMAN	89	IJMP A4 79 "Rare Kaon Decays"		(TRIU)
KLEINKNECHT	76	ARNS 26 1		(DORT)
GINSBERG	73	PR D8 3887	+Smith	(MIT, STON)
GINSBERG	70	PR D1 229		(HAIF)
HEUSSE	70	LNC 3 449	+Aubert, Pascaud, Vialle	(ORSA)
CRONIN	68C	Vienna Conf. 281		(PRIN)
RUBBIA	67	PL 24B 531	+Steinberger	(CERN, COLU)
Also	66C	PL 23 167	Rubbia, Steinberger	(CERN, COLU)
Also	66C	PL 20 207	Alff-Steinberger, Heuer, Kleinknecht+	(CERN)
Also	66B	PL 21 595	Alff-Steinberger, Heuer, Kleinknecht+	(CERN)
AUERBACH	66	PR 149 1052	+Dobbs, Lande, Mann, Sciulli+	(PENN)
Also	65	PRL 14 192	Auerbach, Lande, Mann, Sciulli, Uto+	(PENN)
FIRESTONE	66B	PRL 17 116	+Kim, Lach, Sandweiss+	(YALE, BNL)
BEHR	65	Argonne Conf. 59	+Brisson, Bellotti+	(EPOL, MILA, PADO)
MESTVIRISH...	65	JINR P 2449	Mestvirishvili, Nyagu, Petrov, Rusakov+	(JINR)
TRILLING	65B	UCRL 16473 Updated from 1965 Argonne Conference, page 115.		(LRL)
JOVANOV...	63	BNL Conf. 42	Jovanovich, Fischer, Burris+	(BNL, UMD)

$K^*(892)$

$I(J^P) = \frac{1}{2}(1^-)$

$K^*(892)$ MASS

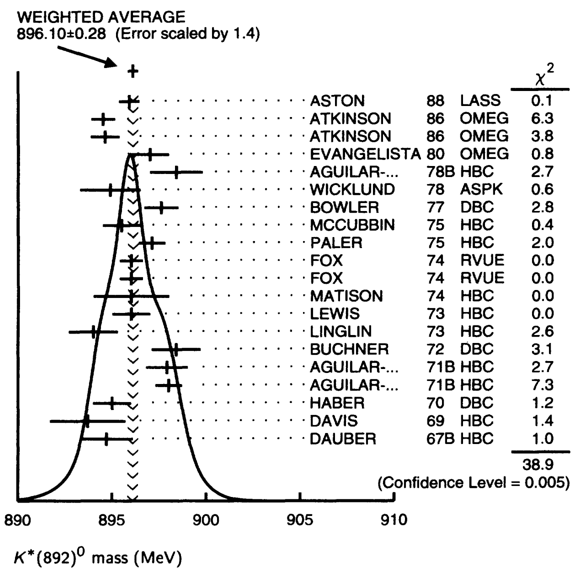
CHARGED ONLY

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
891.59±0.24 OUR AVERAGE		Error includes scale factor of 1.1.			
890.4 ±0.2 ±0.5	79709±801	[1] BIRD 89	LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
892.6 ±0.5	5840	BAUBILLIER 84B	HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
888.0 ±3.0		NAPIER 84	SPEC	+	200 $\pi^- p \to 2K^0_S X$
891.0 ±1.0		NAPIER 84	SPEC	−	200 $\pi^- p \to 2K^0_S X$
891.7 ±2.1	3700	BARTH 83	HBC	+	70 $K^+ p \to K^0 \pi^+ X$
891.0 ±1.0	4100	TOAFF 81	HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
892.8 ±1.6		AJINENKO 80	HBC	+	32 $K^+ p \to K^0 \pi^+ X$
890.7 ±0.9	1800	AGUILAR-... 78B	HBC	±	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
886.6 ±2.4	1225	BALAND 78	HBC	±	12 $\overline{p} p \to (K\pi)^\pm X$
891.7 ±0.6	6706	COOPER 78	HBC	±	0.76 $\overline{p} p \to (K\pi)^\pm X$
891.9 ±0.7	9000	[2] PALER 75	HBC	−	14.3 $K^- p \to (K\pi)^- X$
892.2 ±1.5	4404	AGUILAR-... 71B	HBC	−	3.9,4.6 $K^- p \to (K\pi)^- p$
891.0 ±2.0	1000	CRENNELL 69D	DBC	−	3.9 $K^- N \to K^0 \pi^- X$
894 ±1.0	2886	[3] FRIEDMAN 69	HBC	−	2.1 $K^- p \to \overline{K}^0 \pi^- p$
892 ±2	728	FRIEDMAN 69	HBC	−	2.45 $K^- p \to \overline{K}^0 \pi^- p$
892 ±1.0	3229	FRIEDMAN 69	HBC	−	2.6 $K^- p \to \overline{K}^0 \pi^- p$
892 ±1.6	1027	FRIEDMAN 69	HBC	−	2.7 $K^- p \to \overline{K}^0 \pi^- p$
890 ±3.0	720	BARLOW 67	HBC	±	1.2 $\overline{p} p \to (K^0 \pi)^\pm K^\mp$
889 ±3.0	600	BARLOW 67	HBC	±	1.2 $\overline{p} p \to (K^0 \pi)^\pm K\pi$
891 ±2.3	620	[3] DEBAERE 67B	HBC	+	3.5 $K^+ p \to K^0 \pi^+ p$
891.0 ±1.2	1700	[4] WOJCICKI 64	HBC	−	1.7 $K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
890.0 ±2.3	800	[3,4] CLELAND 82	SPEC	+	30 $K^+ p \to K^0_S \pi^+ p$
896.0 ±1.1	3200	[3,4] CLELAND 82	SPEC	+	50 $K^+ p \to K^0_S \pi^+ p$
893.0 ±1.0	3600	[3,4] CLELAND 82	SPEC	−	50 $K^+ p \to K^0_S \pi^- p$
896.0 ±1.9	380	DELFOSSE 81	SPEC	+	50 $K^\pm p \to K^\pm \pi^0 p$
886.0 ±2.3	187	DELFOSSE 81	SPEC	−	50 $K^\pm p \to K^\pm \pi^0 p$
894.2 ±2.0	765	[3] CLARK 73	HBC	−	3.13 $K^- p \to \overline{K}^0 \pi^- p$
894.3 ±1.5	1150	[3,4] CLARK 73	HBC	−	3.3 $K^- p \to \overline{K}^0 \pi^- p$
888 ±2.5	540	[3] DEWIT 68	HBC	−	3 $K^- n \to \overline{K}^0 \pi^- n$
892.0 ±2.6	341	[3] SCHWEING... 68	HBC	−	5.5 $K^- p \to \overline{K}^0 \pi^- p$

NEUTRAL ONLY

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
896.10±0.28 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.			
895.9 ±0.5 ±0.2		ASTON 88	LASS	0	11 $K^- p \to K^- \pi^+ n$
894.52±0.63	25k	[2] ATKINSON 86	OMEG		20–70 γp
894.63±0.76	20k	[2] ATKINSON 86	OMEG		20–70 γp
897 ±1	28k	EVANGELISTA 80	OMEG	0	10 $\pi^- p \to K^+ \pi^- (\Lambda,\Sigma)$
898.4 ±1.4	1180	AGUILAR-... 78B	HBC	0	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
894.9 ±1.6		WICKLUND 78	ASPK	0	3,4,6 $K^\pm N \to (K\pi)^0 N$
897.6 ±0.9		BOWLER 77	DBC	0	5.4 $K^+ d \to K^+ \pi^- p p$
895.5 ±1.0	3600	MCCUBBIN 75	HBC	0	3.6 $K^- p \to K^- \pi^+ n$
897.1 ±0.7	22k	[2] PALER 75	HBC	0	14.3 $K^- p \to (K\pi)^0 X$
896.0 ±0.6	10k	FOX 74	RVUE	0	2 $K^- p \to K^- \pi^+ n$

896.0 ±0.6		FOX	74	RVUE	0	$2\ K^+ n \to K^+ \pi^- p$
896 ±2		[5] MATISON	74	HBC	0	$12\ K^+ p \to K^+ \pi^- \Delta$
896.0 ±1.0	3186	LEWIS	73	HBC	0	$2.1–2.7\ K^+ p \to K \pi \pi p$
894.0 ±1.3		[5] LINGLIN	73	HBC	0	$2–13\ K^+ p \to K^+ \pi^- \pi^+ p$
898.4 ±1.3	1700	[3] BUCHNER	72	DBC	0	$4.6\ K^+ n \to K^+ \pi^- p$
897.9 ±1.1	2934	[3] AGUILAR-...	71B	HBC	0	$3.9,4.6\ K^- p \to K^- \pi^+ n$
898.0 ±0.7	5362	[3] AGUILAR-...	71B	HBC	0	$3.9,4.6\ K^- p \to K^- \pi^+ \pi^- p$
895.0 ±1.0	4300	[4] HABER	70	DBC	0	$3\ K^- N \to K^- \pi^+ X$
893.7 ±2.0	10k	DAVIS	69	HBC	0	$12\ K^+ p \to K^+ \pi^- \pi^+ p$
894.7 ±1.4	1040	[3] DAUBER	67B	HBC	0	$2.0\ K^- p \to K^- \pi^+ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
900.7 ±1.1	5900	BARTH	83	HBC	0	$70\ K^+ p \to K^+ \pi^- X$



[1] From a partial wave amplitude analysis.
[2] Inclusive reaction. Complicated background and phase-space effects.
[3] Mass errors enlarged by us to $\Gamma/\sqrt{N}$. See note.
[4] Number of events in peak reevaluated by us.
[5] From pole extrapolation.

NOTE ON $K^*(892)$ MASSES AND MASS DIFFERENCES

Unrealistically small errors are reported by some experiments. We use simple "realistic" tests for the minimum errors on the determination of mass and width from a sample of N events:

$$\delta_{\min}(m) = \frac{\Gamma}{\sqrt{N}}, \quad \delta_{\min}(\Gamma) = 4\frac{\Gamma}{\sqrt{N}} \ .$$

(For a detailed discussion, see the 1971 edition of this note.) We consistently increase unrealistic errors before averaging.

$K^*(892)^0 - K^*(892)^\pm$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
6.7±1.2 OUR AVERAGE						
7.7±1.7	2980	AGUILAR-...	78B	HBC	±0	$0.76\ \bar{p} p \to K^\mp K^0_S \pi^\pm$
5.7±1.7	7338	AGUILAR-...	71B	HBC	−0	$3.9,4.6\ K^- p$
6.3±4.1	283	[6] BARASH	67B	HBC		$0.0\ \bar{p} p$

[6] Number of events in peak reevaluated by us.

$K^*(892)$ RANGE PARAMETER

All from partial wave amplitude analyses.

VALUE (GeV^{-1})	DOCUMENT ID		TECN	CHG	COMMENT
12.1±3.2±3.0	BIRD	89	LASS	−	$11\ K^- p \to \overline{K}^0 \pi^- p$
3.4±0.7	ASTON	88	LASS	0	$11\ K^- p \to K^- \pi^+ n$

$K^*(892)$ WIDTH

CHARGED ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
49.8±0.8 OUR FIT						
49.8±0.8 OUR AVERAGE						
45.2±1 ±2	79709±801	[7] BIRD	89	LASS	−	$11\ K^- p \to \overline{K}^0 \pi^- p$
49.0±2.0	5840	BAUBILLIER	84B	HBC	−	$8.25\ K^- p \to \overline{K}^0 \pi^- p$
56.0±4.0		NAPIER	84	SPEC	−	$200\ \pi^- p \to 2K^0_S X$
51.0±2.0	4100	TOAFF	81	HBC	−	$6.5\ K^- p \to \overline{K}^0 \pi^- p$
50.5±5.6		AJINENKO	80	HBC	+	$32\ K^+ p \to K^0 \pi^+ X$
45.8±3.6	1800	AGUILAR-...	78B	HBC	±	$0.76\ \bar{p} p \to K^\mp K^0_S \pi^\pm$
52.0±2.5	6706	[8] COOPER	78	HBC	±	$0.76\ \bar{p} p \to (K\pi)^\pm X$
52.1±2.2	9000	[9] PALER	75	HBC	−	$14.3\ K^- p \to (K\pi)^- X$
46.3±6.7	765	[8] CLARK	73	HBC	−	$3.13\ K^- p \to \overline{K}^0 \pi^- p$
48.2±5.7	1150	[8,10] CLARK	73	HBC	−	$3.3\ K^- p \to \overline{K}^0 \pi^- p$
54.3±3.3	4404	[8] AGUILAR-...	71B	HBC	−	$3.9,4.6\ K^- p \to (K\pi)^- p$
53 ±4.0	2886	[8] FRIEDMAN	69	HBC	−	$2.1\ K^- p \to \overline{K}^0 \pi^- p$
49 ±7.3	728	[8] FRIEDMAN	69	HBC	−	$2.45\ K^- p \to \overline{K}^0 \pi^- p$
46 ±3.2	3229	[8] FRIEDMAN	69	HBC	−	$2.6\ K^- p \to \overline{K}^0 \pi^- p$
49 ±6.1	1027	[8] FRIEDMAN	69	HBC	−	$2.7\ K^- p \to \overline{K}^0 \pi^- p$
46.0±5.0	1700	[8,10] WOJCICKI	64	HBC	−	$1.7\ K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
42.8±7.1	3700	BARTH	83	HBC	+	$70\ K^+ p \to K^0 \pi^+ X$
64.0±9.2	800	[8,10] CLELAND	82	SPEC	+	$30\ K^+ p \to K^0_S \pi^+ p$
62.0±4.4	3200	[8,10] CLELAND	82	SPEC	+	$50\ K^+ p \to K^0_S \pi^+ p$
55.0±4.0	3600	[8,10] CLELAND	82	SPEC	−	$50\ K^+ p \to K^0_S \pi^- p$
62.6±3.8	380	DELFOSSE	81	SPEC	+	$50\ K^\pm p \to K^\pm \pi^0 p$
50.5±3.9	187	DELFOSSE	81	SPEC	−	$50\ K^\pm p \to K^\pm \pi^0 p$

NEUTRAL ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
50.5±0.6 OUR FIT Error includes scale factor of 1.1.						
50.5±0.6 OUR AVERAGE Error includes scale factor of 1.1.						
50.8±0.8±0.9		ASTON	88	LASS	0	$11\ K^- p \to K^- \pi^+ n$
46.5±4.3	5900	BARTH	83	HBC	0	$70\ K^+ p \to K^+ \pi^- X$
54 ±2	28k	EVANGELISTA	80	OMEG	0	$10\ \pi^- p \to K^+ \pi^- (\Lambda,\Sigma)$
45.9±4.8	1180	AGUILAR-...	78B	HBC	0	$0.76\ \bar{p} p \to K^\mp K^0_S \pi^\pm$
51.2±1.7		WICKLUND	78	ASPK	0	$3,4,6\ K^\pm N \to (K\pi)^0 N$
48.9±2.5		BOWLER	77	DBC	0	$5.4\ K^+ d \to K^+ \pi^- pp$
$48\ ^{+3}_{-2}$	3600	MCCUBBIN	75	HBC	0	$3.6\ K^- p \to K^- \pi^+ n$
50.6±2.5	22k	[9] PALER	75	HBC	0	$14.3\ K^- p \to (K\pi)^0 X$
47 ±2	10k	FOX	74	RVUE	0	$2\ K^- p \to K^- \pi^+ n$
51 ±2		FOX	74	RVUE	0	$2\ K^+ n \to K^+ \pi^- p$
46.0±3.3	3186	[8] LEWIS	73	HBC	0	$2.1–2.7\ K^+ p \to K \pi \pi p$
51.4±5.0	1700	[8] BUCHNER	72	DBC	0	$4.6\ K^+ n \to K^+ \pi^- p$
$55.8^{+4.2}_{-3.4}$	2934	[8] AGUILAR-...	71B	HBC	0	$3.9,4.6\ K^- p \to K^- \pi^+ n$
48.5±2.7	5362	AGUILAR-...	71B	HBC	0	$3.9,4.6\ K^- p \to K^- \pi^+ \pi^- p$
54.0±3.3	4300	[8,10] HABER	70	DBC	0	$3\ K^- N \to K^- \pi^+ X$
53.2±2.1	10k	[8] DAVIS	69	HBC	0	$12\ K^+ p \to K^+ \pi^- \pi^+ p$
44 ±5.5	1040	[8] DAUBER	67B	HBC	0	$2.0\ K^- p \to K^- \pi^+ \pi^- p$

[7] From a partial wave amplitude analysis.
[8] Width errors enlarged by us to $4 \times \Gamma/\sqrt{N}$; see note.
[9] Inclusive reaction. Complicated background and phase-space effects.
[10] Number of events in peak reevaluated by us.

$K^*(892)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$K\pi$	~ 100 %	
Γ_2	$(K\pi)^{\pm}$	(99.899±0.009) %	
Γ_3	$(K\pi)^0$	(99.770±0.020) %	
Γ_4	$K^0\gamma$	(2.30 ±0.20) × 10^{-3}	
Γ_5	$K^{\pm}\gamma$	(1.01 ±0.09) × 10^{-3}	
Γ_6	$K\pi\pi$	< 7 × 10^{-4}	95%

CONSTRAINED FIT INFORMATION

An overall fit to the total width and a partial width uses 18 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 = 15.2$ for 16 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_5	−100	
Γ	17	−17
	x_2	x_5

	Mode	Rate (MeV)
Γ_2	$(K\pi)^{\pm}$	49.8 ±0.8
Γ_5	$K^{\pm}\gamma$	0.050±0.005

CONSTRAINED FIT INFORMATION

An overall fit to the total width and a partial width uses 18 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 = 18.4$ for 16 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_4	−100	
Γ	14	−14
	x_3	x_4

	Mode	Rate (MeV)	Scale factor
Γ_3	$(K\pi)^0$	50.4 ±0.6	1.1
Γ_4	$K^0\gamma$	0.117±0.010	

$K^*(892)$ PARTIAL WIDTHS

$\Gamma(K^0\gamma)$ Γ_4

VALUE (keV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
117 ±10 OUR FIT						
116.5± 9.9	584	CARLSMITH	86	SPEC	0	$K^0_L A \to K^0_S \pi^0 A$

$\Gamma(K^{\pm}\gamma)$ Γ_5

VALUE (keV)	DOCUMENT ID		TECN	CHG	COMMENT
50 ± 5 OUR FIT					
50 ± 5 OUR AVERAGE					
48.0±11.0	BERG	83	SPEC	−	156 $K^- A \to \overline{K}\pi A$
51.0± 5.0	CHANDLEE	83	SPEC	+	200 $K^+ A \to K\pi A$

$K^*(892)$ BRANCHING RATIOS

$\Gamma(K^0\gamma)/\Gamma_{total}$ Γ_4/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	CHG	COMMENT
2.30±0.20 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.5 ±0.7	CARITHERS	75B	CNTR	0	8–16 $\overline{K}^0 A$

$\Gamma(K^{\pm}\gamma)/\Gamma_{total}$ Γ_5/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
1.01±0.09 OUR FIT						
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.6	95	BEMPORAD	73	CNTR	+	10–16 $K^+ A$

$\Gamma(K\pi\pi)/\Gamma((K\pi)^{\pm})$ Γ_6/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.0007	95	JONGEJANS	78	HBC		4 $K^- p \to p\overline{K}^0 2\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.002		WOJCICKI	64	HBC	−	1.7 $K^- p \to \overline{K}^0 \pi^- p$

$K^*(892)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, TOKY)
ATKINSON	86	ZPHY C30 521	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP+)
CARLSMITH	86	PRL 56 18	+Bernstein, Peyaud, Turlay	(EFI, SACL)
BAUBILLIER	84B	ZPHY C26 37	+	(BIRM, CERN, GLAS, MICH, LPNP)
NAPIER	84	PL 149B 514	+Chen+	(TUFT, ARIZ, FNAL, FLOR, NDAM+)
BARTH	83	NP B223 296	+Drevermann+	(BRUX, CERN, GENO, MONS+)
BERG	83	Thesis		(ROCH)
CHANDLEE	83	PRL 51 168	+Berg, Cihangir, Collick+	(ROCH, FNAL, MINN)
CLELAND	82	NP B208 189	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
DELFOSSE	81	NP B183 349	+Guisan, Martin, Muhlemann, Weill+	(GEVA, LAUS)
TOAFF	81	PR D23 1500	+Musgrave, Ammar, Davis, Ecklund+	(ANL, KANS)
AJINENKO	80	ZPHY 5 177	+Barth, Dujardin+	(SERP, LIBH, MONS, SACL)
EVANGELISTA	80	NP B165 383	+	(BARI, BONN, CERN, DARE, GLAS, LIVP+)
AGUILAR-...	78B	NP B141 101	Aguilar-Benitez+	(MADR, TATA, CERN+)
BALAND	78	NP B140 220	+Grard+	(MONS, BELG, CERN, LOIC, LALO)
COOPER	78	NP B136 365	+Gurtu+	(TATA, CERN, CDEF+)
JONGEJANS	78	NP B139 383	+Cerrada+	(ZEEM, CERN, NIJM, OXF)
WICKLUND	78	PR D17 1197	+Ayres, Diebold, Greene, Kramer, Pawlicki	(ANL)
BOWLER	77	NP B126 31	+Dainton, Drake, Williams	(OXF)
CARITHERS	75B	PRL 35 349	+Muhlemann, Underwood+	(ROCH, MCGI)
MCCUBBIN	75	NP B86 13	+Lyons	(OXF)
PALER	75	NP B96 1	+Tovey, Shah, Spiro+	(RHEL, SACL, EPOL)
FOX	74	NP B80 403	+Griss	(CIT)
MATISON	74	PR D9 1872	+Galtieri, Alston-Garnjost, Flatte, Friedman+	(LBL)
BEMPORAD	73	NP B51 1	+Beusch, Freudenreich+	(CERN, ETH, LOIC)
CLARK	73	NP B54 432	+Lyons, Radojicic	(OXF)
LEWIS	73	NP B60 283	+Allen, Jacobs+	(LOWC, LOIC, CDEF)
LINGLIN	73	NP B55 408		(CERN)
BUCHNER	72	NP B45 333	+Dehm, Charriere, Cornet+	(MPIM, CERN, BRUX)
AGUILAR-...	71B	PR D4 2583	Aguilar-Benitez, Eisner, Kinson	(BNL)
HABER	70	NP B17 289	+Shapira, Alexander+	(REHO, SACL, BGNA, EPOL)
CRENNELL	69D	PRL 22 487	+Karshon, Lai, O'Neall, Scarr	(BNL)
DAVIS	69	PRL 23 1071	+Derenzo, Flatte, Garnjost, Lynch, Solmitz	(LRL)
FRIEDMAN	69	UCRL 18860 Thesis		(LRL)
DEWIT	68	Thesis		(ANIK)
SCHWEING...	68	PR 166 1317	Schweingruber, Derrick, Fields+	(ANL, NWES)
BARASH	67B	PR 156 1399	+Kirsch, Miller, Tan	(COLU)
BARLOW	67	NC 50A 701	+Lillestol, Montanet+	(CERN, CDEF, IRAD, LIVP)
DAUBER	67B	PR 153 1403	+Schlein, Slater, Ticho	(UCLA)
DEBAERE	67B	NC 51A 401	+Goldschmidt-Clermont, Henri+	(BRUX, CERN)
WOJCICKI	64	PR 135B 484		(LRL)

OTHER RELATED PAPERS

NAPIER	84	PL 149B 514	+Chen+	(TUFT, ARIZ, FNAL, FLOR, NDAM+)
CLELAND	82	NP B208 189	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
ALEXANDER	62	PRL 8 447	+Kalbfleisch, Miller, Smith	(LRL)
ALSTON	62B	CERN Conf. 291	+Ticho, Wojcicki+	(LRL)
ARMENTEROS	62C	CERN Conf. 295	+Astrer, Montanet+	(CERN, CDEF)
COLLEY	62B	CERN Conf. 315	+Gelfand+	(COLU, RUTG)
ALSTON	61	PRL 6 300	+Alvarez, Eberhard, Good+	(LRL)

$K_1(1270)$ was $Q(1280)$

$I(J^P) = \frac{1}{2}(1^+)$

Our latest mini-review on this particle can be found in the 1984 edition.

$K_1(1270)$ MASS

VALUE (MeV)	DOCUMENT ID
1270±10 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

PRODUCED BY BEAMS OTHER THAN K MESONS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
$1242.0^{+9.0}_{-10.0}$		[1] ASTIER	69	HBC	0	$\overline{p}p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1294 ±10	310	RODEBACK	81	HBC		4 $\pi^- p \to \Lambda K 2\pi$
1300	40	CRENNELL	72	HBC	0	4.5 $\pi^- p \to \Lambda K 2\pi$
1300	45	CRENNELL	67	HBC	0	6 $\pi^- p \to \Lambda K 2\pi$

[1] This was called the C meson.

PRODUCED BY K^-, BACKWARD SCATTERING, HYPERON EXCHANGE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1275.0±10.0	700	GAVILLET	78	HBC	+	4.2 $K^- p \to \Xi^- (K\pi\pi)^+$

PRODUCED BY K BEAMS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1270 ±10	DAUM	81C	CNTR	−	63 $K^- p \to \overline{K} 2\pi p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

~ 1276.0	[2] TORNQVIST	82B	RVUE		
~ 1300.0	VERGEEST	79	HBC	−	4.2 $K^- p \to (\overline{K}\pi\pi)^- p$
1289.0±25.0	[3] CARNEGIE	77	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$
~ 1300	BRANDENB...	76	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$
~ 1270.0	OTTER	76	HBC	−	10,14,16 $K^- p \to (\overline{K}\pi\pi)^- p$
1260	DAVIS	72	HBC	+	12 $K^+ p$
1234 ±12	FIRESTONE	72B	DBC	+	12 $K^+ d$

[2] From a unitarized quark-model calculation.
[3] From a model-dependent fit with Gaussian background to BRANDENBURG 76 data.

$K_1(1270)$ WIDTH

VALUE (MeV)	DOCUMENT ID
90±20 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

PRODUCED BY BEAMS OTHER THAN K MESONS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
$127.0^{+7.0}_{-25.0}$		ASTIER 69	HBC	0	$\overline{p}p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
66 ±15	310	RODEBACK 81	HBC		4 $\pi^- p \to \Lambda K 2\pi$
60	40	CRENNELL 72	HBC	0	4.5 $\pi^- p \to \Lambda K 2\pi$
60	45	CRENNELL 67	HBC	0	6 $\pi^- p \to \Lambda K 2\pi$

PRODUCED BY K^-, BACKWARD SCATTERING, HYPERON EXCHANGE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
75.0±15.0	700	GAVILLET 78	HBC	+	4.2 $K^- p \to \Xi^- K\pi\pi$

PRODUCED BY K BEAMS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
90 ± 8	DAUM	81C	CNTR	−	63 $K^- p \to \overline{K} 2\pi p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 150.0	VERGEEST	79	HBC	−	4.2 $K^- p \to (\overline{K}\pi\pi)^- p$
150.00±71.0	[4] CARNEGIE	77	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$
~ 200	BRANDENB...	76	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$
120	DAVIS	72	HBC	+	12 $K^+ p$
188 ±21	FIRESTONE	72B	DBC	+	12 $K^+ d$

[4] From a model-dependent fit with Gaussian background to BRANDENBURG 76 data.

$K_1(1270)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\rho$	(42 ±6) %
Γ_2	$K_0^*(1430)\pi$	(28 ±4) %
Γ_3	$K^*(892)\pi$	(16 ±5) %
Γ_4	$K\omega$	(11.0±2.0) %
Γ_5	$K f_0(1400)$	(3.0±2.0) %

$K_1(1270)$ PARTIAL WIDTHS

$\Gamma(K\rho)$ — Γ_1

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
57.0±5.0	MAZZUCATO	79	HBC	+	4.2 $K^- p \to \Xi^-(K\pi\pi)^+$
75.0±6.0	CARNEGIE	77B	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$

$\Gamma(K_0^*(1430)\pi)$ — Γ_2

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
26.0±6.0	CARNEGIE	77B	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$

$\Gamma(K^*(892)\pi)$ — Γ_3

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
14.0±11.0	MAZZUCATO	79	HBC	+	4.2 $K^- p \to \Xi^-(K\pi\pi)^+$
2.0± 2.0	CARNEGIE	77B	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$

$\Gamma(K\omega)$ — Γ_4

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.0±4.00	MAZZUCATO	79	HBC	+	4.2 $K^- p \to \Xi^-(K\pi\pi)^+$
24.0±3.0	CARNEGIE	77B	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$

$\Gamma(K f_0(1400))$ — Γ_5

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
22.0±5.0	CARNEGIE	77B	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$

$K_1(1270)$ BRANCHING RATIOS

$\Gamma(K\rho)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.42±0.06	[5] DAUM	81C	CNTR	63 $K^- p \to \overline{K} 2\pi p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
dominant	RODEBACK	81	HBC	4 $\pi^- p \to \Lambda K 2\pi$

$\Gamma(K_0^*(1430)\pi)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.28±0.04	[5] DAUM	81C	CNTR	63 $K^- p \to \overline{K} 2\pi p$

$\Gamma(K^*(892)\pi)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.16±0.05	[5] DAUM	81C	CNTR	63 $K^- p \to \overline{K} 2\pi p$

$\Gamma(K\omega)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.11 ±0.02	[5] DAUM	81C	CNTR	63 $K^- p \to \overline{K} 2\pi p$

$\Gamma(K\omega)/\Gamma(K\rho)$ — Γ_4/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.30	95	RODEBACK	81	HBC	4 $\pi^- p \to \Lambda K 2\pi$

$\Gamma(K f_0(1400))/\Gamma_{total}$ — Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.03 ±0.02	[5] DAUM	81C	CNTR	63 $K^- p \to \overline{K} 2\pi p$

D-wave/S-wave RATIO FOR $K_1(1270) \to K^*(892)\pi$

VALUE	DOCUMENT ID		TECN	COMMENT
1.0±0.7	[5] DAUM	81C	CNTR	63 $K^- p \to \overline{K} 2\pi p$

[5] Average from low and high t data.

$K_1(1270)$ REFERENCES

TORNQVIST	82B	NP B203 268		(HELS)
DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
RODEBACK	81	ZPHY C9 9	+Sjogren+	(CERN, CDEF, MADR, STOH)
MAZZUCATO	79	NP B156 532	+Pennington+	(CERN, ZEEM, NIJM, OXF)
VERGEEST	79	NP B158 265	+Jongejans, Dionisi+	(NIJM, AMST, CERN, OXF)
GAVILLET	78	PL 76B 517	+Diaz, Dionisi+	(AMST, CERN, NIJM, OXF) JP
CARNEGIE	77	NP B127 509	+Cashmore, Davier, Dunwoodie, Lasinski+	(SLAC)
CARNEGIE	77B	PL 68B 287	+Cashmore, Dunwoodie, Lasinski+	(SLAC)
BRANDENB...	76	PRL 26 703	Brandenburg, Carnegie, Cashmore+	(SLAC) JP
OTTER	76	NP B106 77	+	(AACH, BERL, CERN, LOIC, VIEN, LPNP+) JP
CRENNELL	72	PR D6 1220	+Gordon, Lai, Scarr	(BNL)
DAVIS	72	PR D5 2688	+Alston-Garnjost, Barbaro, Flatte, Friedman, Lynch+	(LBL)
FIRESTONE	72B	PR D5 505	+Goldhaber, Lissauer, Trilling	(LBL)
ASTIER	69	NP B10 65	+Marechal, Montanet+	(CDEF, CERN, IPNP, LIVP) IJP
CRENNELL	67	PRL 19 44	+Kalbfleisch, Lai, Scarr, Schumann	(BNL) I

OTHER RELATED PAPERS

BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, LPNP)
FERNANDEZ	82	ZPHY C16 95	+Aguilar-Benitez+	(MADR, CERN, CDEF, STOH) JP
GAVILLET	82	ZPHY C16 119	+Armenteros+	(CERN, CDEF, PADO, ROMA)
SHEN	66	PRL 17 726	+Butterworth, Fu, Goldhaber, Trilling	(LRL)
Also	66	Private Comm.	Goldhaber	(LRL)
ALMEIDA	65	PL 16 184	+Atherton, Byer, Dornan, Forson+	(CAVE)
ARMENTEROS	64	PL 9 207	+Edwards, D'Andlau+	(CERN, CDEF)
Also	66	PR 145 1095	Barash, Kirsch, Miller, Tan	(COLU)
ARMENTEROS	64B	Dubna Conf. 1 577	+Edwards, D'Andlau+	(CERN, CDEF)
Also	64C	Dubna Conf. 1 617	Armenteros	

$K_1(1400)$

was $Q(1400)$

$I(J^P) = \frac{1}{2}(1^+)$

$K_1(1400)$ MASS

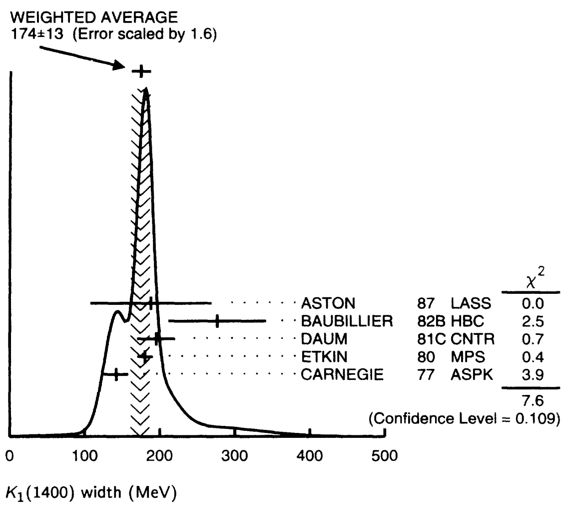
VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1402 ± 7 OUR AVERAGE					
1373 ±14 ±18	[1] ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1392 ±18	BAUBILLIER	82B	HBC	0	8.25 $K^- p \to K_S^0 \pi^+ \pi^- n$
1410 ±25	DAUM	81C	CNTR	−	63 $K^- p \to \overline{K} 2\pi p$
1415 ±15	ETKIN	80	MPS	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1404.0±10.0	[2] CARNEGIE	77	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1350	[3] TORNQVIST	82B	RVUE		
~ 1400.0	VERGEEST	79	HBC	−	4.2 $K^- p \to (\overline{K}\pi\pi)^- p$
~ 1400	BRANDENB...	76	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$
1420	DAVIS	72	HBC	+	12 $K^+ p$
1368 ±18	FIRESTONE	72B	DBC	+	12 $K^+ d$

[1] From partial-wave analysis of $K^0 \pi^+ \pi^-$ system.
[2] From a model-dependent fit with Gaussian background to BRANDENBURG 76 data.
[3] From a unitarized quark-model calculation.

$K_1(1400)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
174 ±13 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.				
188 ±54 ±60	[4] ASTON	87	LASS	0	$11\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$
276 ±65	BAUBILLIER	82B	HBC	0	$8.25\ K^- p \to K^0_S \pi^+ \pi^- n$
195 ±25	DAUM	81C	CNTR	−	$63\ K^- p \to \overline{K} 2\pi p$
180 ±10	ETKIN	80	MPS	0	$6\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$
142.0±16.0	[5] CARNEGIE	77	ASPK	±	$13\ K^\pm p \to (K\pi\pi)^\pm p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 200.0	VERGEEST	79	HBC	−	$4.2\ K^- p \to (\overline{K}\pi\pi)^- p$
~ 160	BRANDENB...	76	ASPK	±	$13\ K^\pm p \to (K\pi\pi)^\pm p$
80	DAVIS	72	HBC	+	$12\ K^+ p$
241 ±30	FIRESTONE	72B	DBC	+	$12\ K^+ d$

[4] From partial-wave analysis of $K^0 \pi^+ \pi^-$ system.
[5] From a model-dependent fit with Gaussian background to BRANDENBURG 76 data.



$K_1(1400)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K^*(892)\pi$	(94 ±6) %
Γ_2	$K\rho$	(3.0±3.0) %
Γ_3	$K f_0(1400)$	(2.0±2.0) %
Γ_4	$K\omega$	(1.0±1.0) %
Γ_5	$K^*_0(1430)\pi$	

$K_1(1400)$ PARTIAL WIDTHS

$\Gamma(K^*(892)\pi)$ Γ_1

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
117.0±10.0	CARNEGIE	77	ASPK	±	$13\ K^\pm p \to (K\pi\pi)^\pm p$

$\Gamma(K\rho)$ Γ_2

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2.0±1.0	CARNEGIE	77	ASPK	±	$13\ K^\pm p \to (K\pi\pi)^\pm p$

$\Gamma(K\omega)$ Γ_4

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
23.0±12.0	CARNEGIE	77	ASPK	±	$13\ K^\pm p \to (K\pi\pi)^\pm p$

$K_1(1400)$ BRANCHING RATIOS

$\Gamma(K^*(892)\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.94±0.06	[6] DAUM	81C	CNTR	$63\ K^- p \to \overline{K} 2\pi p$

$\Gamma(K\rho)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.03 ±0.03	[6] DAUM	81C	CNTR	$63\ K^- p \to \overline{K} 2\pi p$

$\Gamma(K f_0(1400))/\Gamma_{total}$ Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.02 ±0.02	[6] DAUM	81C	CNTR	$63\ K^- p \to \overline{K} 2\pi p$

$\Gamma(K\omega)/\Gamma_{total}$ Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.01 ±0.01	[6] DAUM	81C	CNTR	$63\ K^- p \to \overline{K} 2\pi p$

$\Gamma(K^*_0(1430)\pi)/\Gamma_{total}$ Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 0.00	[6] DAUM	81C	CNTR	$63\ K^- p \to \overline{K} 2\pi p$

D-wave/S-wave RATIO FOR $K_1(1400) \to K^*(892)\pi$

VALUE	DOCUMENT ID		TECN	COMMENT
0.04 ±0.01	[6] DAUM	81C	CNTR	$63\ K^- p \to \overline{K} 2\pi p$

[6] Average from low and high t data.

$K_1(1400)$ REFERENCES

ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, TOKY)
BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, LPNP)
TORNQVIST	82B	NP B203 268		(HELS)
DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY) JP
VERGEEST	79	NP B158 265	+Jongejans, Dionisi+	(NIJM, AMST, CERN, OXF)
CARNEGIE	77	NP B127 509	+Cashmore, Davier, Dunwoodie, Lasinski+	(SLAC)
BRANDENB...	76	PRL 26 703	Brandenburg, Carnegie, Cashmore+	(SLAC) JP
DAVIS	72	PR D5 2688	+Alston-Garnjost, Barbaro, Flatte, Friedman, Lynch+	(LBL)
FIRESTONE	72B	PR D5 505	+Goldhaber, Lissauer, Trilling	(LBL)

OTHER RELATED PAPERS

FERNANDEZ	82	ZPHY C16 95	+Aguilar-Benitez+	(MADR, CERN, CDEF, STOH)
SHEN	66	PRL 17 726	+Butterworth, Fu, Goldhaber, Trilling	(LRL)
Also	66	Private Comm.	Goldhaber	(LRL)
ALMEIDA	65	PL 16 184	+Atherton, Byer, Dornan, Forson+	(CAVE)
ARMENTEROS	64	PL 9 207	+Edwards, D'Andlau+	(CERN, CDEF)
Also	66	PR 145 1095	Barash, Kirsch, Miller, Tan	(COLU)
ARMENTEROS	64B	Dubna Conf. 1 577	+Edwards, D'Andlau+	(CERN, CDEF)
Also	64C	Dubna Conf. 1 617	Armenteros	

$K^*(1410)$

$I(J^P) = \frac{1}{2}(1^-)$

$K^*(1410)$ MASS

All from partial wave amplitude analyses.

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1412±12 OUR AVERAGE	Error includes scale factor of 1.1.				
1367±54	BIRD	89	LASS	−	$11\ K^- p \to \overline{K}^0 \pi^- p$
1380±21±19	ASTON	88	LASS	0	$11\ K^- p \to K^- \pi^+ n$
1420± 7±10	ASTON	87	LASS	0	$11\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1474±25	BAUBILLIER	82B	HBC	0	$8.25\ K^- p \to \overline{K}^0 2\pi n$
1500±30	ETKIN	80	MPS	0	$6\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$

$K^*(1410)$ WIDTH

All from partial wave amplitude analyses.

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
227± 22 OUR AVERAGE	Error includes scale factor of 1.1.				
114±101	BIRD	89	LASS	−	$11\ K^- p \to \overline{K}^0 \pi^- p$
176± 52±22	ASTON	88	LASS	0	$11\ K^- p \to K^- \pi^+ n$
240± 18±12	ASTON	87	LASS	0	$11\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
275± 65	BAUBILLIER	82B	HBC	0	$8.25\ K^- p \to \overline{K}^0 2\pi n$
500±100	ETKIN	80	MPS	0	$6\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$

$K^*(1410)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$K^*(892)\pi$	> 40 %	95%
Γ_2	$K\pi$	(6.6±1.3) %	
Γ_3	$K\rho$	< 7 %	95%

$K^*(1410)$ BRANCHING RATIOS

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.17	95	ASTON	84	LASS	0	$11\ K^- p \to \overline{K}^0 2\pi n$

$\Gamma(K\pi)/\Gamma(K^*(892)\pi)$ Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.16	95	ASTON	84	LASS	0	$11\ K^- p \to \overline{K}^0 2\pi n$

$\Gamma(K\pi)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.066±0.010±0.008	ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$

$K^*(1410)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, TOKY)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, TOKY)
ASTON	84	PL 149B 258	+Carnegie, Dunwoodie+	(SLAC, CARL, OTTA) JP
BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, LPNP)
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY) JP

$K_0^*(1430)$
was $K_0^*(1350)$
was $\kappa(1350)$

$I(J^P) = \frac{1}{2}(0^+)$

Our latest mini-review on this particle can be found in the 1984 edition.

$K_0^*(1430)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1429 ±4±5	ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1430	BAUBILLIER	84B	HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
~ 1425	[1,2] ESTABROOKS	78	ASPK		13 $K^\pm p \to K^\pm \pi^\pm (n,\Delta)$
~ 1450.0	MARTIN	78	SPEC		10 $K^\pm p \to K_S^0 \pi p$

[1] Mass defined by pole position.
[2] From elastic $K\pi$ partial-wave analysis.

$K_0^*(1430)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
287±10±21	ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 200	BAUBILLIER	84B	HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
200 to 300	[3] ESTABROOKS	78	ASPK		13 $K^\pm p \to K^\pm \pi^\pm (n,\Delta)$

[3] From elastic $K\pi$ partial-wave analysis.

$K_0^*(1430)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(93±10) %

$K_0^*(1430)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.93±0.04±0.09	ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$

$K_0^*(1430)$ REFERENCES

ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, TOKY)
BAUBILLIER	84B	ZPHY C26 37	+	(BIRM, CERN, GLAS, MICH, LPNP)
ESTABROOKS	78	NP B133 490	+Carnegie+	(MONT, CARL, DURH, SLAC)
MARTIN	78	NP B134 392	+Shimada, Baldi, Bohringer+	(DURH, GEVA)

OTHER RELATED PAPERS

TORNQVIST	82	PRL 49 624		(HELS)
GOLDBERG	69	PL 30B 434	+Huffer, Laloum+	(SABRE Collab.)
SCHLEIN	69	Argonne Conf. 446		(UCLA)
TRIPPE	68	PL 28B 203	+Chien, Malamud, Mellema, Schlein+	(UCLA)

$K_2^*(1430)$
was $K^*(1430)$

$I(J^P) = \frac{1}{2}(2^+)$

We consider that phase-shift analyses provide more reliable determinations of the mass and width.

$K_2^*(1430)$ MASS

CHARGED ONLY, WITH FINAL STATE $K\pi$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1425.4± 1.3 OUR AVERAGE		Error includes scale factor of 1.1.				
1423.4± 2 ±3	24809± 820	[1] BIRD	89	LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
1420 ± 4	1587	BAUBILLIER	84B	HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
1436 ± 5.5	400	[2,3] CLELAND	82	SPEC	+	30 $K^+ p \to K_S^0 \pi^+ p$
1430 ± 3.2	1500	[2,3] CLELAND	82	SPEC	+	50 $K^+ p \to K_S^0 \pi^+ p$
1430 ± 3.2	1200	[2,3] CLELAND	82	SPEC	−	50 $K^+ p \to K_S^0 \pi^- p$
1423.0± 5.0	935	TOAFF	81	HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
1428.0± 4.6		[4] MARTIN	78	SPEC	+	10 $K^\pm p \to K_S^0 \pi p$
1423.8± 4.6		[4] MARTIN	78	SPEC	−	10 $K^\pm p \to K_S^0 \pi p$
1420.0± 3.1	1400	AGUILAR-...	71B	HBC	−	3.9,4.6 $K^- p$
1425 ± 8.0	225	[2,3] BARNHAM	71C	HBC	+	$K^+ p \to K^0 \pi^+ p$
1416.0±10.0	220	CRENNELL	69D	DBC	−	3.9 $K^- N \to \overline{K}^0 \pi^- N$
1414 ±13.0	60	[2] LIND	69	HBC	+	9 $K^+ p \to K^0 \pi^+ p$
1427.0±12.0	63	[2] SCHWEING...	68	HBC	−	5.5 $K^- p \to \overline{K} \pi N$
1423 ±11.0	39	[2] BASSANO	67	HBC	−	4.6–5.0 $K^- p \to \overline{K}^0 \pi^- p$

NEUTRAL ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1432.4± 1.3 OUR AVERAGE						
1431.2± 1.8± 0.7		[5] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
1434 ± 4 ± 6		[5] ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1433 ± 6 ±10		[5] ASTON	84B	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$
1471 ±12		[5] BAUBILLIER	82B	HBC	0	8.25 $K^- p \to N K_S^0 \pi\pi$
1428 ± 3		[5] ASTON	81C	LASS	0	11 $K^- p \to K^- \pi^+ n$
1434.0± 2.0		[5] ESTABROOKS	78	ASPK	0	13 $K^\pm p \to p K\pi$
1440.0±10.0		[5] BOWLER	77	DBC	0	5.5 $K^+ d \to K\pi pp$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1420.0± 7.0	300	HENDRICK	76	DBC		8.25 $K^+ N \to K^+ \pi N$
1421.6± 4.2	800	MCCUBBIN	75	HBC	0	3.6 $K^- p \to K^- \pi^+ n$
1420.1± 4.3		[6] LINGLIN	73	HBC	0	2–13 $K^+ p \to K^+ \pi^- X$
1419.1± 3.7	1800	AGUILAR-...	71B	HBC	0	3.9,4.6 $K^- p$
1416 ± 6	600	CORDS	71	DBC	0	9 $K^+ n \to K^+ \pi^- p$
1421.1± 2.6	2200	DAVIS	69	HBC	0	12 $K^+ p \to K^+ \pi^- X$

[1] From a partial wave amplitude analysis.
[2] Errors enlarged by us to $\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[3] Number of events in peak re-evaluated by us.
[4] Systematic error added by us.
[5] From phase shift or partial-wave analysis.
[6] From pole extrapolation, using world $K^+ p$ data summary tape.

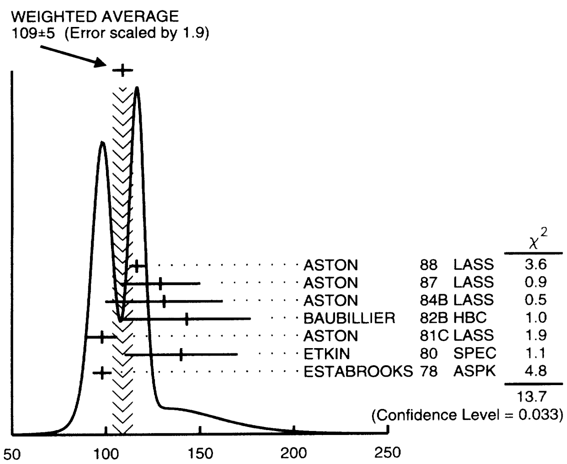
$K_2^*(1430)$ WIDTH

CHARGED ONLY, WITH FINAL STATE $K\pi$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
98.4± 2.3 OUR FIT						
98.4± 2.4 OUR AVERAGE						
98 ± 4 ±4	24809± 820	[7] BIRD	89	LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
109 ±22	400	[8,9] CLELAND	82	SPEC	+	30 $K^+ p \to K_S^0 \pi^+ p$
124 ±12.8	1500	[8,9] CLELAND	82	SPEC	+	50 $K^+ p \to K_S^0 \pi^+ p$
113 ±12.8	1200	[8,9] CLELAND	82	SPEC	−	50 $K^+ p \to K_S^0 \pi^- p$
85.0±16.0	935	TOAFF	81	HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
96.5± 3.8		MARTIN	78	SPEC	+	10 $K^\pm p \to K_S^0 \pi p$
97.7± 4.0		MARTIN	78	SPEC	−	10 $K^\pm p \to K_S^0 \pi p$
$94.7^{+15.1}_{-12.5}$	1400	AGUILAR-...	71B	HBC	−	3.9,4.6 $K^- p$

NEUTRAL ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
109 ± 5 OUR AVERAGE		Error includes scale factor of 1.9. See the ideogram below.				
116.5 ± 3.6 ± 1.7		[10] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
129 ±15 ±15		[10] ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
131 ±24 ±20		[10] ASTON	84B	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$
143 ±34		[10] BAUBILLIER	82B	HBC	0	8.25 $K^- p \to N K_S^0 \pi \pi$
98 ± 8		[10] ASTON	81C	LASS	0	11 $K^- p \to K^- \pi^+ n$
140 ±30		[10] ETKIN	80	SPEC	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
98.0 ± 5.0		[10] ESTABROOKS	78	ASPK	0	13 $K^\pm p \to p K \pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
125.0 ± 29.0	300	[8] HENDRICK	76	DBC		8.25 $K^+ N \to K^+ \pi N$
116 ±18	800	MCCUBBIN	75	HBC	0	3.6 $K^- p \to K^- \pi^+ n$
61.0 ± 14.0		[11] LINGLIN	73	HBC	0	2–13 $K^+ p \to K^+ \pi^- X$
$116.6^{+10.3}_{-15.5}$	1800	AGUILAR-...	71B	HBC	0	3.9,4.6 $K^- p$
144 ±24.0	600	[8] CORDS	71	DBC	0	9 $K^+ n \to K^+ \pi^- p$
101 ±10	2200	DAVIS	69	HBC	0	12 $K^+ p \to K^+ \pi^- \pi^+ p$



$K_2^*(1430)^0$ width (MeV)

[7] From a partial wave amplitude analysis.
[8] Errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[9] Number of events in peak re-evaluated by us.
[10] From phase shift or partial-wave analysis.
[11] From pole extrapolation, using world $K^+ p$ data summary tape.

$K_2^*(1430)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$K\pi$	(49.7±1.2) %	
Γ_2	$K^*(892)\pi$	(25.2±1.7) %	
Γ_3	$K^*(892)\pi\pi$	(13.0±2.3) %	
Γ_4	$K\rho$	(8.8±0.8) %	S=1.2
Γ_5	$K\omega$	(2.9±0.8) %	
Γ_6	$K^+\gamma$	(2.4±0.5) × 10^{-3}	
Γ_7	$K\eta$	($1.4^{+2.8}_{-0.9}$) × 10^{-3}	S=1.1
Γ_8	$K\omega\pi$	< 7.2 × 10^{-4}	CL=95%
Γ_9	$K^0\gamma$	< 9 × 10^{-4}	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to the total width, a partial width, and 10 branching ratios uses 28 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 19.5$ for 21 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−16						
x_3	−33	−75					
x_4	−12	39	−54				
x_5	−11	−3	−25	−8			
x_6	−1	−1	−1	−1	0		
x_7	−3	−6	−4	−4	−2	0	
Γ	0	0	0	0	0	−13	0
	x_1	x_2	x_3	x_4	x_5	x_6	x_7

	Mode	Rate (MeV)	Scale factor
Γ_1	$K\pi$	48.9 ±1.7	
Γ_2	$K^*(892)\pi$	24.8 ±1.7	
Γ_3	$K^*(892)\pi\pi$	12.8 ±2.3	
Γ_4	$K\rho$	8.7 ±0.8	1.2
Γ_5	$K\omega$	2.9 ±0.8	
Γ_6	$K^+\gamma$	0.24±0.04	
Γ_7	$K\eta$	$0.14^{+0.28}_{-0.09}$	1.1

$K_2^*(1430)$ PARTIAL WIDTHS

$\Gamma(K^+\gamma)$ — Γ_6

VALUE (keV)	DOCUMENT ID		TECN	CHG	COMMENT
240±40 OUR FIT					
240±45	CIHANGIR	82	SPEC	+	200 $K^+ Z \to Z K^+ \pi^0$, $Z K_S^0 \pi^+$

$\Gamma(K^0\gamma)$ — Γ_9

VALUE (keV)	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<84	90	CARLSMITH	87	SPEC	0	60–200 $K_L^0 A \to K_S^0 \pi^0 A$

$K_2^*(1430)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.497±0.012 OUR FIT					
0.488±0.014 OUR AVERAGE					
0.485±0.006±0.020	[12] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
0.49 ±0.02	[12] ESTABROOKS	78	ASPK	±	13 $K^\pm p \to p K \pi$

$\Gamma(K^*(892)\pi)/\Gamma(K\pi)$ — $\Gamma_2/(\Gamma_1+\Gamma_2+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.47±0.10	BASSANO	67	HBC	−0	4.6,5.0 $K^- p$
0.45±0.13	[13] BADIER	65C	HBC	−	3 $K^- p$

$\Gamma(K\rho)/\Gamma(K\pi)$ — $\Gamma_4/(\Gamma_1+\Gamma_2+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.14±0.10	BASSANO	67	HBC	−0	4.6,5.0 $K^- p$
0.14±0.07	[13] BADIER	65C	HBC	−	3 $K^- p$

$\Gamma(K^*(892)\pi)/\Gamma(K\pi)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.51±0.04 OUR FIT					
0.48±0.05 OUR AVERAGE					
0.44±0.09	ASTON	84B	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$
0.62±0.19	LAUSCHER	75	HBC	0	10,16 $K^- p \to K^- \pi^+ n$
0.54±0.16	DEHM	74	DBC	0	4.6 $K^+ N$
0.47±0.08	AGUILAR-...	71B	HBC		3.9,4.6 $K^- p$

$\Gamma(K\omega)/\Gamma(K\pi)$ — Γ_5/Γ_1

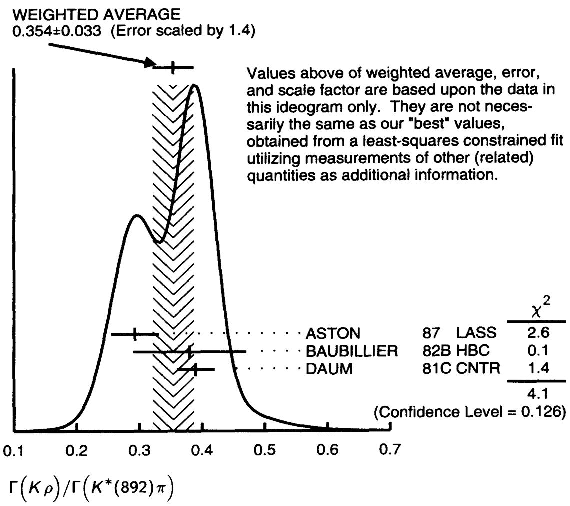
VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.059±0.017 OUR FIT					
0.070±0.035 OUR AVERAGE					
0.05 ±0.04	AGUILAR-...	71B	HBC		3.9,4.6 $K^- p$
0.13 ±0.07	BASSOMPIE...	69	HBC	0	5 $K^+ p$

$\Gamma(K\rho)/\Gamma(K\pi)$ — Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.178±0.018 OUR FIT	Error includes scale factor of 1.2.				
$0.153^{+0.034}_{-0.018}$ OUR AVERAGE					
0.18 ±0.05	ASTON	84B	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$
$0.02^{+0.10}_{-0.02}$	DEHM	74	DBC	0	4.6 $K^+ N$
0.16 ±0.05	AGUILAR-...	71B	HBC		3.9,4.6 $K^- p$

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ — Γ_4/Γ_2

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.351±0.032 OUR FIT Error includes scale factor of 1.5.				
0.354±0.033 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.				
0.293±0.032±0.020	ASTON 87	LASS	0	$11\ K^-p \to \overline{K}^0\pi^+\pi^-n$
0.38 ±0.09	BAUBILLIER 82B	HBC	0	$8.25\ K^-p \to NK_S^0\pi\pi$
0.39 ±0.03	DAUM 81C	CNTR		$63\ K^-p \to \overline{K}2\pi p$



$\Gamma(K\omega)/\Gamma(K^*(892)\pi)$ — Γ_5/Γ_2

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.116±0.034 OUR FIT				
0.10 ±0.04	FIELD 67	HBC	−	$3.8\ K^-p$

$\Gamma(K\eta)/\Gamma(K^*(892)\pi)$ — Γ_7/Γ_2

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
$0.006^{+0.011}_{-0.004}$ OUR FIT				
0.07 ±0.04	FIELD 67	HBC	−	$3.8\ K^-p$

$\Gamma(K\eta)/\Gamma(K\pi)$ — Γ_7/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
$0.0028^{+0.0057}_{-0.0019}$ OUR FIT Error includes scale factor of 1.1.					
0 ±0.0056		[14] ASTON 88B	LASS	−	$11\ K^-p \to K^-\eta p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.04	95	AGUILAR-... 71B	HBC		$3.9,4.6\ K^-p$
<0.065		[13] BASSOMPIE... 69	HBC		$5.0\ K^+p$
<0.02		BISHOP 69	HBC		$3.5\ K^+p$

$\Gamma(K^*(892)\pi\pi)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.130±0.023 OUR FIT				
0.12 ±0.04	[15] GOLDBERG 76	HBC	−	$3\ K^-p \to p\overline{K}^0\pi\pi\pi$

$\Gamma(K^*(892)\pi\pi)/\Gamma(K\pi)$ — Γ_3/Γ_1

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.26±0.05 OUR FIT				
0.21±0.08	[13,15] JONGEJANS 78	HBC	−	$4\ K^-p \to p\overline{K}^0\pi\pi\pi$

$\Gamma(K\omega\pi)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.72	95	0	JONGEJANS 78	HBC	$4\ K^-p \to p\overline{K}^0 4\pi$

[12] From phase shift analysis.
[13] Restated by us.
[14] ASTON 88B quote < 0.0092 at CL=95%. We convert this to a central value and 1 sigma error in order to be abe to use it in our constrained fit.
[15] Assuming $\pi\pi$ system has isospin 1, which is supported by the data.

$K_2^*(1430)$ REFERENCES

BIRD 89 SLAC-332 (SLAC)
ASTON 88 NP B296 493 +Awaji, Bienz, Bird+ (SLAC, NAGO, CINC, TOKY)
ASTON 88B PL B201 169 +Awaji, Bienz+ (SLAC, NAGO, CINC, TOKY)
ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, TOKY)
CARLSMITH 87 PR D36 3502 +Bernstein, Bock, Coupal, Peyaud, Turlay+ (EFI, SACL)
ASTON 84B NP B247 261 +Carnegie, Dunwoodie+ (SLAC, CARL, OTTA)
BAUBILLIER 84B ZPHY C26 37 + (BIRM, CERN, GLAS, MICH, LPNP)
BAUBILLIER 82B NP B202 21 + (BIRM, CERN, GLAS, MSU, LPNP)
CIHANGIR 82 PL 117B 123 +Berg, Biel, Chandlee+ (FNAL, MINN, ROCH)
CLELAND 82 NP B208 189 +Delfosse, Dorsaz, Gloor (DURH, GEVA, LAUS, PITT)
ASTON 81C PL 106B 235 +Carnegie, Dunwoodie+ (SLAC, CARL, OTTA) JP
DAUM 81C NP B187 1 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)
TOAFF 81 PR D23 1500 +Musgrave, Ammar, Davis, Ecklund+ (ANL, KANS)
ETKIN 80 PR D22 42 +Foley, Lindenbaum, Kramer+ (BNL, CUNY) JP
ESTABROOKS 78 NP B133 490 +Carnegie+ (MONT, CARL, DURH, SLAC)
Also 78B PR D17 658 Estabrooks, Carnegie+ (MONT, CARL, DURH+)
JONGEJANS 78 NP B139 383 +Cerrada+ (ZEEM, CERN, NIJM, OXF)
MARTIN 78 NP B134 392 +Shimada, Baldi, Bohringer+ (DURH, GEVA)
BOWLER 77 NP B126 31 +Dainton, Drake, Williams (OXF)
GOLDBERG 76 LNC 17 253 (HAIF)
HENDRICK 76 NP B112 189 +Vignaud, Burlaud+ (MONS, SACL, LPNP, BELG)
LAUSCHER 75 NP B86 189 +Otter, Wieczorek+ (ABCLV Collab.) JP
MCCUBBIN 75 NP B86 13 +Lyons (OXF)
DEHM 74 NP B75 47 +Goebel, Wittek+ (MPIM, BRUX, MONS, CERN)
LINGLIN 73 NP B55 408 (CERN)
AGUILAR-... 71B PR D4 2583 Aguilar-Benitez, Eisner, Kinson (BNL)
BARNHAM 71C NP B28 171 +Colley, Jobes, Griffiths, Hughes+ (BIRM, GLAS)
CORDS 71 PR D4 1974 +Carmony, Erwin, Meiere+ (PURD, UCD, IUPU)
BASSOMPIE... 69 NP B13 189 Bassompierre+ (CERN, BRUX) JP
BISHOP 69 NP B9 403 +Goshaw, Erwin, Walker (WISC)
CRENNELL 69D PRL 22 487 +Karshon, Lai, O'Neall, Scarr (BNL)
DAVIS 69 PRL 23 1071 +Derenzo, Flatte, Garnjost, Lynch, Solmitz (LRL)
LIND 69 NP B14 1 +Alexander, Firestone, Fu, Goldhaber (LRL) JP
SCHWEING... 68 PR 166 1317 Schweingruber, Derrick, Fields+ (ANL, NWES)
Also 67 Thesis Schweingruber (NWES, NWES)
BASSANO 67 PRL 19 968 +Goldberg, Goz, Barnes, Leitner+ (BNL, SYRA)
FIELD 67 PL 24B 638 +Hendricks, Piccioni, Yager (UCSD)
BADIER 65C PL 19 612 +Demoulin, Goldberg+ (EPOL, SACL, AMST)

OTHER RELATED PAPERS

ATKINSON 86 ZPHY C30 521 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
BAUBILLIER 82B NP B202 21 + (BIRM, CERN, GLAS, MSU, LPNP)
CHUNG 65 PRL 15 325 +Dahl, Hardy, Hess, Jacobs, Kirz (LRL)
FOCARDI 65 PL 16 351 +Ranzi, Serra+ (BGNA, SACL)
HAQUE 65 PL 14 338 Hague+
HARDY 65 PRL 14 401 +Chung, Dahl, Hess, Kirz, Miller (LRL)

$K(1460)$
was $K(1400)$

$I(J^P) = \frac{1}{2}(0^-)$

OMITTED FROM SUMMARY TABLE

Observed in $K\pi\pi$ partial-wave analysis. Not seen by VERGEEST 79. Wait confirmation.

$K(1460)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
≈ 1460 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 1460	DAUM 81C	CNTR	−	$63\ K^-p \to \overline{K}2\pi p$
~ 1400	[1] BRANDENB... 76B	ASPK	±	$13\ K^{\pm}p \to K\pi\pi N$

[1] Coupled mainly to $Kf_0(1400)$. Decay into $K^*(892)\pi$ seen.

$K(1460)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 260	DAUM 81C	CNTR	−	$63\ K^-p \to \overline{K}2\pi p$
~ 250	[2] BRANDENB... 76B	ASPK	±	$13\ K^{\pm}p \to K\pi\pi N$

[2] Coupled mainly to $Kf_0(1400)$. Decay into $K^*(892)\pi$ seen.

$K(1460)$ DECAY MODES

	Mode
Γ_1	$K^*(892)\pi$
Γ_2	$K\rho$
Γ_3	$K_0^*(1430)\pi$

$K(1460)$ PARTIAL WIDTHS

$\Gamma(K^*(892)\pi)$ — Γ_1

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 109	DAUM 81C	CNTR	$63\ K^-p \to \overline{K}2\pi p$

$\Gamma(K\rho)$ Γ_2

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 34	DAUM 81C	CNTR	63 $K^- p \to \overline{K} 2\pi p$

$\Gamma(K_0^*(1430)\pi)$ Γ_3

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 117	DAUM 81C	CNTR	63 $K^- p \to \overline{K} 2\pi p$

K(1460) REFERENCES

DAUM 81C NP B187 1 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)
VERGEEST 79 NP B158 265 +Jongejans, Dionisi+ (NIJM, AMST, CERN, OXF)
BRANDENB... 76B PRL 36 1239 Brandenburg, Carnegie, Cashmore+ (SLAC) JP

OTHER RELATED PAPERS

BARNES 82 PL 116B 365 +Close (RHEL)
TANIMOTO 82 PL 116B 198 (BIEL)
VERGEEST 79 NP B158 265 +Jongejans, Dionisi+ (NIJM, AMST, CERN, OXF)

$K_2(1580)$ was $L(1580)$

$I(J^P) = \frac{1}{2}(2^-)$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the $K^-\pi^+\pi^-$ system. Needs confirmation.

$K_2(1580)$ MASS

VALUE (MeV)	DOCUMENT ID	CHG	COMMENT
≈ 1580 OUR ESTIMATE			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 1580	OTTER 79	−	10,14,16 $K^- p$

$K_2(1580)$ WIDTH

VALUE (MeV)	DOCUMENT ID	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 110	OTTER 79	−	10,14,16 $K^- p$

$K_2(1580)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K^*(892)\pi$	seen
Γ_2	$K_2^*(1430)\pi$	possibly seen

$K_2(1580)$ BRANCHING RATIOS

$\Gamma(K^*(892)\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
seen	OTTER 79	HBC	−	10,14,16 $K^- p$

$\Gamma(K_2^*(1430)\pi)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
possibly seen	OTTER 79	HBC	−	10,14,16 $K^- p$

$K_2(1580)$ REFERENCES

OTTER 79 NP B147 1 +Rudolph+ (AACH, BERL, CERN, LOIC, WIEN) JP

$K_1(1650)$

$I(J^P) = \frac{1}{2}(1^+)$

OMITTED FROM SUMMARY TABLE

This entry contains various peaks in strange meson systems ($K^+\phi$, $K\pi\pi$) reported in partial-wave analysis in the 1600–1900 mass region.

$K_1(1650)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1650±50	FRAME 86	OMEG	+	13 $K^+ p \to \phi K^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 1840	ARMSTRONG 83	OMEG	−	18.5 $K^- p \to 3K p$
~ 1800	DAUM 81C	CNTR	−	63 $K^- p \to \overline{K} 2\pi p$

$K_1(1650)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
150±50	FRAME 86	OMEG	+	13 $K^+ p \to \phi K^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 250	DAUM 81C	CNTR	−	63 $K^- p \to \overline{K} 2\pi p$

$K_1(1650)$ DECAY MODES

	Mode
Γ_1	$K\pi\pi$
Γ_2	$K\phi$

$K_1(1650)$ REFERENCES

FRAME 86 NP B276 667 +Hughes, Lynch, Minto, McFadzean+ (GLAS)
ARMSTRONG 83 NP B221 1 + (BARI, BIRM, CERN, MILA, LPNP, PAVI)
DAUM 81C NP B187 1 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)

$K^*(1680)$ was $K^*(1790)$

$I(J^P) = \frac{1}{2}(1^-)$

$K^*(1680)$ MASS

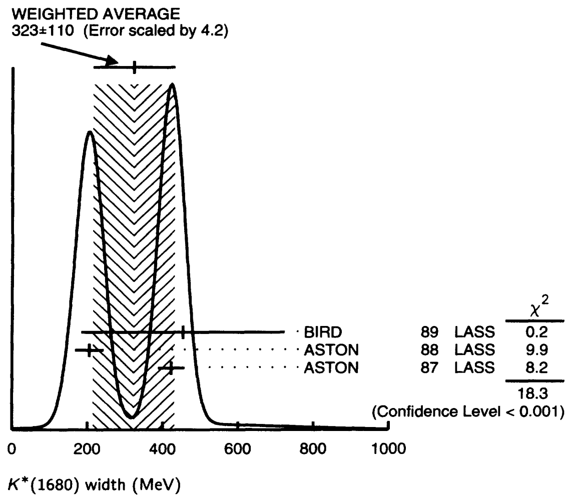
All from partial wave amplitude analyses.

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1714±20 OUR AVERAGE Error includes scale factor of 1.1.				
1678±64	BIRD 89	LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
1677±10±32	ASTON 88	LASS	0	11 $K^- p \to K^- \pi^+ n$
1735±10±20	ASTON 87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1800±70	ETKIN 80	MPS	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
~ 1650	ESTABROOKS 78	ASPK	0	13 $K^\pm p \to K^\pm \pi^\pm n$

$K^*(1680)$ WIDTH

All from partial wave amplitude analyses.

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
323±110 OUR AVERAGE Error includes scale factor of 4.2. See the ideogram below.				
454±270	BIRD 89	LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
205± 16±34	ASTON 88	LASS	0	11 $K^- p \to K^- \pi^+ n$
423± 18±30	ASTON 87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
170± 30	ETKIN 80	MPS	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
250 to 300	ESTABROOKS 78	ASPK	0	13 $K^\pm p \to K^\pm \pi^\pm n$



$K^*(1680)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(38.7 ± 2.5) %
Γ_2	$K\rho$	$(31.4^{+4.7}_{-2.1})$ %
Γ_3	$K^*(892)\pi$	$(29.9^{+2.2}_{-4.7})$ %

CONSTRAINED FIT INFORMATION

An overall fit to 4 branching ratios uses 4 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 2.9 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i \delta x_j\right\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−36	
x_3	−39	−72
	x_1	x_2

$K^*(1680)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.387±0.026 OUR FIT					
0.388±0.014±0.022	ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$

$\Gamma(K\pi)/\Gamma(K^*(892)\pi)$ — Γ_1/Γ_3

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
$\mathbf{1.30^{+0.23}_{-0.14}}$ **OUR FIT**					
2.8 ±1.1	ASTON	84	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$

$\Gamma(K\rho)/\Gamma(K\pi)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
$\mathbf{0.81^{+0.14}_{-0.09}}$ **OUR FIT**					
1.2 ±0.4	ASTON	84	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ — Γ_2/Γ_3

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
$\mathbf{1.05^{+0.27}_{-0.11}}$ **OUR FIT**					
$\mathbf{0.97\pm0.09^{+0.30}_{-0.10}}$	ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$

$K^*(1680)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, TOKY)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, TOKY)
ASTON	84	PL 149B 258	+Carnegie, Dunwoodie+	(SLAC, CARL, OTTA) JP
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY) JP
ESTABROOKS	78	NP B133 490	+Carnegie+	(MONT, CARL, DURH, SLAC) JP

$K_2(1770)$
was $L(1770)$

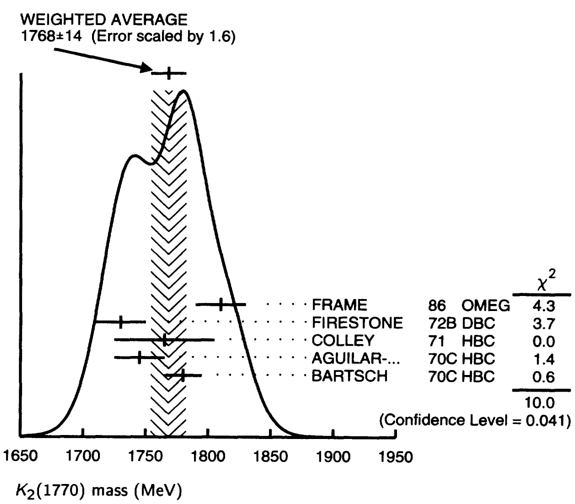
$I(J^P) = \frac{1}{2}(2^-)$

Our latest mini-review on this particle can be found in the 1984 edition.

$K_2(1770)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1768 ±14	**OUR AVERAGE**	Error includes scale factor of 1.6. See the ideogram below.				
1810 ±20		FRAME	86	OMEG	+	13 $K^+ p \to \phi K^+ p$
1730 ±20	306	[1] FIRESTONE	72B	DBC	+	12 $K^+ d$
1765.0±40.0		[2] COLLEY	71	HBC	+	10 $K^+ p \to K 2\pi N$
1745.0±20.0		AGUILAR-...	70C	HBC	−	4.6 $K^- p$
1780.0±15.0		BARTSCH	70C	HBC	−	10.1 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
~ 1730		ARMSTRONG	83	OMEG	−	18.5 $K^- p \to 3K p$
~ 1820		DAUM	81C	CNTR	−	63 $K^- p \to \overline{K} 2\pi p$
1710 ±15	60	CHUNG	74	HBC	−	7.3 $K^- p \to K^- \omega p$
1767 ± 6		BLIEDEN	72	MMS	−	11–16 $K^- p$
1740.0		DENEGRI	71	DBC	−	12.6 $K^- d \to \overline{K} 2\pi d$
1760.0±15.0		LUDLAM	70	HBC	−	12.6 $K^- p$

[1] Produced in conjunction with excited deuteron.
[2] Systematic errors added correspond to spread of different fits.



$K_2(1770)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
136 ±18	**OUR AVERAGE**	Error includes scale factor of 1.2.				
140 ±40		FRAME	86	OMEG	+	13 $K^+ p \to \phi K^+ p$
110 ±50	60	CHUNG	74	HBC	−	7.3 $K^- p \to K^- \omega p$
100 ±26		BLIEDEN	72	MMS	−	11–16 $K^- p$
210 ±30	306	[3] FIRESTONE	72B	DBC	+	12 $K^+ d$
90 ±70		[4] COLLEY	71	HBC	+	10 $K^+ p \to K 2\pi N$
100.0±50.0		AGUILAR-...	70C	HBC	−	4.6 $K^- p$
138.0±40.0		BARTSCH	70C	HBC	−	10.1 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
~ 220		ARMSTRONG	83	OMEG	−	18.5 $K^- p \to 3K p$
~ 200		DAUM	81C	CNTR	−	63 $K^- p \to \overline{K} 2\pi p$
130.0		DENEGRI	71	DBC	−	12.6 $K^- d \to \overline{K} 2\pi d$
$50.0^{+40.0}_{-20.0}$		LUDLAM	70	HBC	−	12.6 $K^- p$

[3] Produced in conjunction with excited deuteron.
[4] Systematic errors added correspond to spread of different fits.

$K_2(1770)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K_2^*(1430)\pi$	dominant
Γ_2	$K^*(892)\pi$	seen
Γ_3	$K f_2(1270)$	seen
Γ_4	$K\phi$	seen
Γ_5	$K\pi\pi$	
Γ_6	$K\omega$	seen

$K_2(1770)$ BRANCHING RATIOS

For discussion of the experimental evidence on other decay modes, see HUGHES 71, SLATTERY 71, EISNER 74.

$\Gamma(K_2^*(1430)\pi)/\Gamma(K\pi\pi)$ — Γ_1/Γ_5

$(K_2^*(1430) \to K\pi)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.2 ±0.2	AGUILAR-...	70C	HBC	−	4.6 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 0.6	DAUM	81C	CNTR		63 $K^- p \to \overline{K} 2\pi p$
~ 1.0	[5] FIRESTONE	72B	DBC	+	12 $K^+ d$
<1.0	COLLEY	71	HBC		10 $K^+ p$
<1.0	BARTSCH	70C	HBC	−	10.1 $K^- p$
1.0	BARBARO-...	69	HBC	+	12.0 $K^+ p$

[5] Produced in conjunction with excited deuteron.

$\Gamma(K^*(892)\pi)/\Gamma(K\pi\pi)$ — Γ_2/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 0.24	DAUM	81C	CNTR	63 $K^- p \to \overline{K} 2\pi p$

$\Gamma(K f_2(1270))/\Gamma(K\pi\pi)$ — Γ_3/Γ_5

$(f_2(1270) \to \pi\pi)$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 0.16	DAUM	81C	CNTR	63 $K^- p \to \overline{K} 2\pi p$

$\Gamma(K\phi)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	ARMSTRONG	83	OMEG	−	18.5 $K^- p \to K^- \phi N$

$\Gamma(K\omega)/\Gamma_{total}$ — Γ_6/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	OTTER	81	HBC	±	8.25,10,16 $K^\pm p$
seen	CHUNG	74	HBC	−	7.3 $K^- p \to K^- \omega p$

$K_2(1770)$ REFERENCES

FRAME 86 NP B276 667 +Hughes, Lynch, Minto, McFadzean+ (GLAS)
ARMSTRONG 83 NP B221 1 + (BARI, BIRM, CERN, MILA, LPNP, PAVI)
DAUM 81C NP B187 1 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)
OTTER 81 NP B181 1 (AACH, BERL, LOIC, VIEN, BIRM, BELG, CERN+)
CHUNG 74 PL 51B 413 +Eisner, Protopopescu, Samios, Strand (BNL)
EISNER 74 Boston Conf. 140 (BNL)
BLIEDEN 72 PL 39B 668 +Finocchiaro, Bowen, Earles+ (STON, NEAS)
FIRESTONE 72B PR D5 505 +Goldhaber, Lissauer, Trilling (LBL)
COLLEY 71 NP B26 71 +Jobes, Kenyon, Pathak, Hughes+ (BIRM, GLAS)
DENEGRI 71 NP B28 13 +Antich, Callahan, Carson, Chien, Cox+ (JHU) JP
HUGHES 71 Bologna Conf. 293 (GLAS)
SLATTERY 71 UR-875-332 (ROCH)
AGUILAR-... 70C PRL 25 54 Aguilar-Benitez, Barnes, Bassano, Chung+ (BNL)
BARTSCH 70C PL 33B 186 +Deutschmann+ (AACH, BERL, CERN, LOIC, VIEN)
LUDLAM 70 PR D2 1234 +Sandweiss, Slaughter (YALE)
BARBARO-... 69 PRL 22 1207 Barbaro-Galtieri, Davis, Flatte+ (LRL)

OTHER RELATED PAPERS

BERLINGHIERI 67 PRL 18 1087 +Farber, Ferbel, Forman (ROCH) I
CARMONY 67 PRL 18 615 +Hendricks, Lander (UCSD)
JOBES 67 PL 26B 49 +Bassompierre, DeBaere+ (BIRM, CERN, BRUX)
BARTSCH 66 PL 22 357 +Deutschmann+ (AACH, BERL, CERN+)

$K_3^*(1780)$

was $K^*(1780)$

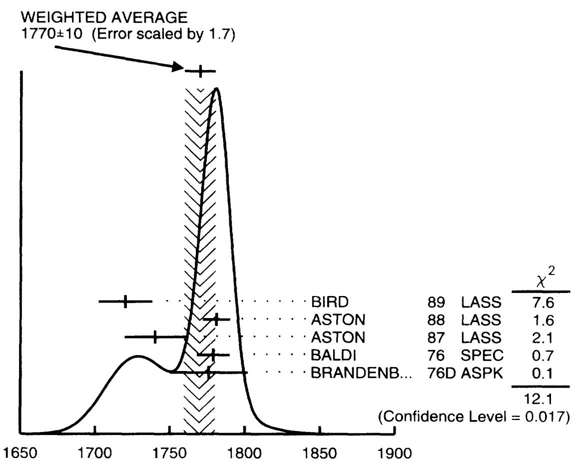
$I(J^P) = \frac{1}{2}(3^-)$

Our latest mini-review on this particle can be found in the 1984 edition.

$K_3^*(1780)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1770 ±10	**OUR AVERAGE**	Error includes scale factor of 1.7. See the ideogram below.				
1720 ±10 ±15	6111±780	[1] BIRD	89	LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
1781 ± 8 ± 4		[2] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
1740 ±14 ±15		[2] ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1779.0±11.0		[3] BALDI	76	SPEC	+	10 $K^+ p \to K^0 \pi^+ p$
1776 ±26		[4] BRANDENB...	76D	ASPK	0	13 $K^\pm p \to K^\pm \pi^\mp N$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1749 ±10		ASTON	88B	LASS	−	11 $K^- p \to K^- \eta p$
1780.0± 9.0	300	BAUBILLIER	84B	HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
1790.0±15.0		BAUBILLIER	82B	HBC	0	8.25 $K^- p \to K_S^0 2\pi N$
1784.0± 9.0	2060	CLELAND	82	SPEC	±	50 $K^+ p \to K_S^0 \pi^\pm p$
1786 ±15		[5] ASTON	81D	LASS	0	11 $K^- p \to K^- \pi^+ n$
1762.0± 9.0	190	TOAFF	81	HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
1850 ±50		ETKIN	80	MPS	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^-$
1812.0±28.0		BEUSCH	78	OMEG		10 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1786.0± 8.0		CHUNG	78	MPS	0	6 $K^- p \to K^- \pi^+ n$

[1] From a partial wave amplitude analysis.
[2] From energy-independent partial-wave analysis.
[3] From a fit to Y_6^2 moment. $J^P = 3^-$ found.
[4] Confirmed by phase shift analysis of ESTABROOKS 78, yields $J^P = 3^-$.
[5] From a fit to the Y_6^0 moment.



$K_3^*(1780)$ mass (MeV)

$K_3^*(1780)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
164 ±17	**OUR AVERAGE**	Error includes scale factor of 1.1.				
187 ±31 ±20	6111±780	[6] BIRD	89	LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
203 ±30 ± 8		[7] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
171 ±42 ±20		[7] ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
135.0±22.0		[8] BALDI	76	SPEC	+	10 $K^+ p \to K^0 \pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
193 $^{+51}_{-37}$		ASTON	88B	LASS	−	11 $K^- p \to K^- \eta p$
99.0±30.0	300	BAUBILLIER	84B	HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
~ 130.0		BAUBILLIER	82B	HBC	0	8.25 $K^- p \to K_S^0 2\pi N$
191.0±24.0	2060	CLELAND	82	SPEC	±	50 $K^+ p \to K_S^0 \pi^\pm p$
225 ±60		[9] ASTON	81D	LASS	0	11 $K^- p \to K^- \pi^+ n$
~ 80	190	TOAFF	81	HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
240 ±50		ETKIN	80	MPS	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^-$
181.0±44.0		[10] BEUSCH	78	OMEG		10 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
96.0±31.0		CHUNG	78	MPS	0	6 $K^- p \to K^- \pi^+ n$
270 ±70		[11] BRANDENB...	76D	ASPK	0	13 $K^\pm p \to K^\pm \pi^\mp N$

[6] From a partial wave amplitude analysis.
[7] From energy-independent partial-wave analysis.
[8] From a fit to Y_6^2 moment. $J^P = 3^-$ found.
[9] From a fit to Y_6^0 moment.
[10] Errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[11] ESTABROOKS 78 find that BRANDENBURG 76D data are consistent with 175 MeV width. Not averaged.

$K_3^*(1780)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$K\rho$	(45 ±4) %	S=1.4
Γ_2	$K^*(892)\pi$	(27.3±3.2) %	S=1.5
Γ_3	$K\pi$	(19.3±1.0) %	
Γ_4	$K\eta$	(8.0±1.5) %	S=1.4
Γ_5	$K_2^*(1430)\pi$	< 21 %	CL=95%

CONSTRAINED FIT INFORMATION

An overall fit to 4 branching ratios uses 5 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 2.2 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−84		
x_3	−33	−4	
x_4	−35	−14	26
	x_1	x_2	x_3

$K_3^*(1780)$ BRANCHING RATIOS

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ — Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
1.66±0.31 OUR FIT	Error includes scale factor of 1.5.				
1.52±0.21±0.10	ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$

$\Gamma(K^*(892)\pi)/\Gamma(K\pi)$ — Γ_2/Γ_3

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
1.42±0.19 OUR FIT	Error includes scale factor of 1.4.				
1.09±0.26	ASTON	84B	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$

$\Gamma(K\pi)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.193±0.010 OUR FIT					
0.188±0.010 OUR AVERAGE					
0.187±0.008±0.008	ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
0.19 ±0.02	ESTABROOKS	78	ASPK	0	13 $K^\pm p \to K\pi N$

$\Gamma(K\eta)/\Gamma(K\pi)$ — Γ_4/Γ_3

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.41±0.07 OUR FIT	Error includes scale factor of 1.5.				
0.41±0.050	[12] BIRD	89	LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.50±0.18	ASTON	88B	LASS	−	11 $K^- p \to K^- \eta p$

[12] This result supersedes ASTON 88B.

$\Gamma(K_2^*(1430)\pi)/\Gamma(K^*(892)\pi)$ — Γ_5/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.78	95	ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$

$K_3^*(1780)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, TOKY)
ASTON	88B	PL B201 169	+Awaji, Bienz+	(SLAC, NAGO, CINC, TOKY) JP
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, TOKY)
ASTON	84B	NP B247 261	+Carnegie, Dunwoodie+	(SLAC, CARL, OTTA)
BAUBILLIER	84B	ZPHY C26 37	+	(BIRM, CERN, GLAS, MICH, LPNP)
BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, LPNP)
CLELAND	82	NP B208 189	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
ASTON	81D	PL 99B 502	+Dunwoodie, Durkin, Fieguth+	(SLAC, CARL, OTTA) JP
TOAFF	81	PR D23 1500	+Musgrave, Ammar, Davis, Ecklund+	(ANL, KANS)
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY) JP
BEUSCH	78	PL 74B 282	+Birman, Konigs, Otter+	(CERN, AACH, ETH) JP
CHUNG	78	PRL 40 355	+Etkin+	(BNL, BRAN, CUNY, MASA, PENN) JP
ESTABROOKS	78	NP B133 490	+Carnegie+	(MONT, CARL, DURH, SLAC) JP
Also	78B	PR D17 658	Estabrooks, Carnegie+	(MONT, CARL, DURH+)
BALDI	76	PL 63B 344	+Boehringer, Dorsaz, Hungerbuhler+	(GEVA) JP
BRANDENB...	76D	PL 60B 478	Brandenburg, Carnegie, Cashmore+	(SLAC) JP

OTHER RELATED PAPERS

AGUILAR-...	73	PRL 30 672	Aguilar-Benitez, Chung, Eisner+	(BNL)
WALUCH	73	PR D8 2837	+Flatte, Friedman	(LBL)
CARMONY	71	PRL 27 1160	+Cords, Clopp, Erwin, Meiere+	(PURD, UCD, IUPU)
FIRESTONE	71	PL 36B 513	+Goldhaber, Lissauer, Trilling	(LBL)

$K(1830)$

$I(J^P) = \frac{1}{2}(0^-)$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of $K^- \phi$ system. Needs confirmation.

$K(1830)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
≈ 1830 OUR ESTIMATE					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1830.0	ARMSTRONG	83	OMEG	−	18.5 $K^- p \to 3K p$

$K(1830)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250.0	ARMSTRONG	83	OMEG	−	18.5 $K^- p \to 3K p$

$K(1830)$ DECAY MODES

	Mode
Γ_1	$K\phi$

$K(1830)$ REFERENCES

ARMSTRONG	83	NP B221 1	+	(BARI, BIRM, CERN, MILA, LPNP, PAVI) JP

$K_0^*(1950)$

$I(J^P) = \frac{1}{2}(0^+)$

OMITTED FROM SUMMARY TABLE

$K_0^*(1950)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1945±10±20	[1] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$

[1] We take the central value of the two solutions and the larger error given.

$K_0^*(1950)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
201±34±79	[2] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$

[2] We take the central value of the two solutions and the larger error given.

$K_0^*(1950)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(52±14) %

$K_0^*(1950)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.52±0.08±0.12	[3] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$

[3] We take the central value of the two solutions and the larger error given.

$K_0^*(1950)$ REFERENCES

ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, TOKY)

$K_2^*(1980)$

$I(J^P) = \frac{1}{2}(2^+)$

OMITTED FROM SUMMARY TABLE

$K_2^*(1980)$ MASS

All from partial wave amplitude analyses.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1975±22 OUR AVERAGE						
1978±40	241±47	BIRD	89	LASS	−	$11\ K^- p \to \overline{K}^0 \pi^- p$
1973± 8±25		ASTON	87	LASS	0	$11\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$

$K_2^*(1980)$ WIDTH

All from partial wave amplitude analyses.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
390±40 OUR AVERAGE						
398±47	241±47	BIRD	89	LASS	−	$11\ K^- p \to \overline{K}^0 \pi^- p$
373±33±60		ASTON	87	LASS	0	$11\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$

$K_2^*(1980)$ DECAY MODES

	Mode
Γ_1	$K^*(892)\pi$
Γ_2	$K\rho$

$K_2^*(1980)$ BRANCHING RATIOS

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
1.49±0.24±0.09	ASTON	87	LASS	0	$11\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$

$K_2^*(1980)$ REFERENCES

BIRD 89 SLAC-332 (SLAC)
ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, TOKY)

$K_4^*(2045)$

was $K^*(2060)$

$I(J^P) = \frac{1}{2}(4^+)$

$K_4^*(2045)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2045± 9 OUR AVERAGE	Error includes scale factor of 1.1.					
2062± 14±13		[1] ASTON	86	LASS	0	$11\ K^- p \to K^- \pi^+ n$
2039± 10	400	[2,3] CLELAND	82	SPEC	±	$50\ K^+ p \to K^0_S \pi^\pm p$
2070^{+100}_{-40}		[4] ASTON	81C	LASS	0	$11\ K^- p \to K^- \pi^+ n$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2079± 7	431	TORRES	86	MPSF		$400\ pA \to 4K\ X$
2088± 20	650	BAUBILLIER	82	HBC	−	$8.25\ K^- p \to K^0_S \pi^- p$
2115± 46	488	CARMONY	77	HBC	0	$9\ K^+ d \to K^+ \pi$'s X

[1] From a fit to all moments.
[2] From a fit to 8 moments.
[3] Number of events evaluated by us.
[4] From energy-independent partial-wave analysis.

$K_4^*(2045)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
198± 30 OUR AVERAGE						
221± 48±27		[5] ASTON	86	LASS	0	$11\ K^- p \to K^- \pi^+ n$
189± 35	400	[6,7] CLELAND	82	SPEC	±	$50\ K^+ p \to K^0_S \pi^\pm p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
61± 58	431	TORRES	86	MPSF		$400\ pA \to 4K\ X$
170^{+100}_{-50}	650	BAUBILLIER	82	HBC	−	$8.25\ K^- p \to K^0_S \pi^- p$
240^{+500}_{-100}		[8] ASTON	81C	LASS	0	$11\ K^- p \to K^- \pi^+ n$
300±200		CARMONY	77	HBC	0	$9\ K^+ d \to K^+ \pi$'s X

[5] From a fit to all moments.
[6] From a fit to 8 moments.
[7] Number of events evaluated by us.
[8] From energy-independent partial-wave analysis.

$K_4^*(2045)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(9.9±1.2) %
Γ_2	$K^*(892)\pi\pi$	(9 ±5) %
Γ_3	$K^*(892)\pi\pi\pi$	(7 ±5) %
Γ_4	$\rho K\pi$	(5.7±3.2) %
Γ_5	$\omega K\pi$	(4.9±3.0) %
Γ_6	$\phi K\pi$	(2.8±1.4) %
Γ_7	$\phi K^*(892)$	(1.4±0.7) %

$K_4^*(2045)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.099±0.012	ASTON	88	LASS	0	$11\ K^- p \to K^- \pi^+ n$

$\Gamma(K^*(892)\pi\pi)/\Gamma(K\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.89±0.53	BAUBILLIER	82	HBC	−	$8.25\ K^- p \to pK^0_S 3\pi$

$\Gamma(K^*(892)\pi\pi\pi)/\Gamma(K\pi)$ Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.75±0.49	BAUBILLIER	82	HBC	−	$8.25\ K^- p \to pK^0_S 3\pi$

$\Gamma(\rho K\pi)/\Gamma(K\pi)$ Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.58±0.32	BAUBILLIER	82	HBC	−	$8.25\ K^- p \to pK^0_S 3\pi$

$\Gamma(\omega K\pi)/\Gamma(K\pi)$ Γ_5/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.50±0.30	BAUBILLIER	82	HBC	−	$8.25\ K^- p \to pK^0_S 3\pi$

$\Gamma(\phi K\pi)/\Gamma_{total}$ Γ_6/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.028±0.014	[9] TORRES	86	MPSF	$400\ pA \to 4K\ X$

[9] Error determination is model dependent.

$\Gamma(\phi K^*(892))/\Gamma_{total}$ Γ_7/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.014±0.007	[10] TORRES	86	MPSF	$400\ pA \to 4K\ X$

[10] Error determination is model dependent.

$K_4^*(2045)$ REFERENCES

ASTON 88 NP B296 493 +Awaji, Bienz, Bird+ (SLAC, NAGO, CINC, TOKY)
ASTON 86 PL B180 308 +Awaji, D'Amore+ (SLAC, NAGO, CINC, TOKY)
TORRES 86 PR 34 707 +Lai+ (VPI, ARIZ, FNAL, FSU, NDAM, TUFT+)
BAUBILLIER 82 PL 118B 447 +Burns+ (BIRM, CERN, GLAS, MSU, LPNP)
CLELAND 82 NP B208 189 +Delfosse, Dorsaz, Gloor (DURH, GEVA, LAUS, PITT)
ASTON 81C PL 106B 235 +Carnegie, Dunwoodie+ (SLAC, CARL, OTTA) JP
CARMONY 77 PR D16 1251 +Clopp, Lander, Meiere, Yen+ (PURD, UCD, IUPU)

OTHER RELATED PAPERS

ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, TOKY)
BROMBERG 80 PR D22 1513 +Haggerty, Abrams, Dzierba (CIT, FNAL, ILLC, IND)
CARMONY 71 PRL 27 1160 +Cords, Clopp, Erwin, Meiere+ (PURD, UCD, IUPU)

$K_2(2250)$ was $K(2250)$

$I(J^P) = \frac{1}{2}(2^-)$

OMITTED FROM SUMMARY TABLE

This entry contains various peaks in strange meson systems reported in the 2100–2300 MeV region, as well as enhancements seen in the antihyperon-nucleon system, either in the mass spectra or in the $J^P = 2^-$ wave.

$K_2(2250)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2247 ±17 OUR AVERAGE						
2200.0±40.0		[1] ARMSTRONG	83C	OMEG	−	18 $K^- p \to \Lambda \bar{p} X$
2235 ±50		[1] BAUBILLIER	81	HBC	−	8 $K^- p \to \Lambda \bar{p} X$
2260 ±20		[1] CLELAND	81	SPEC	±	50 $K^+ p \to \Lambda \bar{p} X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2147 ± 4	37	CHLIAPNIK...	79	HBC	+	32 $K^+ p \to \bar{\Lambda} p X$
2240 ±20	20	LISSAUER	70	HBC		9 $K^+ p$

[1] $J^P = 2^-$ from moments analysis.

$K_2(2250)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
180 ±30 OUR AVERAGE Error includes scale factor of 1.4.						
150.0±30.0		[2] ARMSTRONG	83C	OMEG	−	18 $K^- p \to \Lambda \bar{p} X$
210 ±30		[2] CLELAND	81	SPEC	±	50 $K^+ p \to \Lambda \bar{p} X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
~ 200		[2] BAUBILLIER	81	HBC	−	8 $K^- p \to \Lambda \bar{p} X$
~ 40	37	CHLIAPNIK...	79	HBC	+	32 $K^+ p \to \bar{\Lambda} p X$
80 ±20	20	LISSAUER	70	HBC		9 $K^+ p$

[2] $J^P = 2^-$ from moments analysis.

$K_2(2250)$ DECAY MODES

	Mode
Γ_1	$K \pi \pi$
Γ_2	$\Lambda \bar{p}$

$K_2(2250)$ REFERENCES

ARMSTRONG 83C NP B227 365 + (BARI, BIRM, CERN, MILA, LPNP, PAVI)
BAUBILLIER 81 NP B183 1 + (BIRM, CERN, GLAS, MSU, LPNP) JP
CLELAND 81 NP B184 1 +Nef, Martin+ (PITT, GEVA, LAUS, DURH) JP
CHLIAPNIK... 79 NP B158 253 Chliapnikov, Gerdyukov+ (CERN, BELG, MONS)
LISSAUER 70 NP B18 491 +Alexander, Firestone, Goldhaber (LBL)

OTHER RELATED PAPERS

ALEXANDER 68B PRL 20 755 +Firestone, Goldhaber, Shen (LRL)

$K_3(2320)$ was $K(2320)$

$I(J^P) = \frac{1}{2}(3^+)$

OMITTED FROM SUMMARY TABLE

This entry contains enhancements seen in the $J^P = 3^+$ wave of the antihyperon-nucleon system.

$K_3(2320)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2324 ±24 OUR AVERAGE					
2330.0±40.0	[1] ARMSTRONG	83C	OMEG	−	18 $K^- p \to \Lambda \bar{p} X$
2320.0±30.0	[1] CLELAND	81	SPEC	±	50 $K^+ p \to \Lambda \bar{p} X$

[1] $J^P = 3^+$ from moments analysis.

$K_3(2320)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
150.0±30.0	[2] ARMSTRONG	83C	OMEG	−	18 $K^- p \to \Lambda \bar{p} X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250.0	[2] CLELAND	81	SPEC	±	50 $K^+ p \to \Lambda \bar{p} X$

[2] $J^P = 3^+$ from moments analysis.

$K_3(2320)$ DECAY MODES

	Mode
Γ_1	$\Lambda \bar{p}$

$K_3(2320)$ REFERENCES

ARMSTRONG 83C NP B227 365 + (BARI, BIRM, CERN, MILA, LPNP, PAVI)
CLELAND 81 NP B184 1 +Nef, Martin+ (PITT, GEVA, LAUS, DURH)

$K_5^*(2380)$

$I(J^P) = \frac{1}{2}(5^-)$

OMITTED FROM SUMMARY TABLE

Seen in partial wave analysis of the $K^- \pi^+$ system. Needs confirmation.

$K_5^*(2380)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2382±14±19	[1] ASTON	86	LASS	0	11 $K^- p \to K^- \pi^+ n$

[1] From a fit to all the moments.

$K_5^*(2380)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
178±37±32	[2] ASTON	86	LASS	0	11 $K^- p \to K^- \pi^+ n$

[2] From a fit to all the moments.

$K_5^*(2380)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K \pi$	(6.1±1.2) %

$K_5^*(2380)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.061±0.012	ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$

$K_5^*(2380)$ REFERENCES

ASTON 88 NP B296 493 +Awaji, Bienz, Bird+ (SLAC, NAGO, CINC, TOKY)
ASTON 86 PL B180 308 +Awaji, D'Amore+ (SLAC, NAGO, CINC, TOKY)

$K_4(2500)$ was $K(2500)$

$I(J^P) = \frac{1}{2}(4^-)$

OMITTED FROM SUMMARY TABLE

This entry contains enhancements seen in the $J^P = 4^-$ wave of the antihyperon-nucleon system.

$K_4(2500)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2490.0±20.0	[1] CLELAND	81	SPEC	±	50 $K^+ p \to \Lambda \bar{p}$

[1] $J^P = 4^-$ from moments analysis.

$K_4(2500)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250.0	[2] CLELAND	81	SPEC	±	50 $K^+ p \to \Lambda \bar{p}$

[2] $J^P = 4^-$ from moments analysis.

$K_4(2500)$ DECAY MODES

	Mode
Γ_1	$\Lambda \bar{p}$

$K_4(2500)$ REFERENCES

CLELAND 81 NP B184 1 +Nef, Martin+ (PITT, GEVA, LAUS, DURH)

CHARMED MESONS
($C = \pm1$)

$D^+ = c\overline{d}$, $D^0 = c\overline{u}$, $\overline{D}^0 = \overline{c}\,u$, $D^- = \overline{c}\,d$, similarly for D^*'s

$D^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

$D^{\pm}$ MASS

The fit includes the $D^{\pm}$, D^0, $D_s^{\pm}$, and $D_s^{*\pm}$ masses and the $D^0 - D^{\pm}$, $D_s^{\pm} - D^{\pm}$, and $D_s^{*\pm} - D_s^{\pm}$ mass differences.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1869.3± 0.5 OUR FIT						
1869.4± 0.5 OUR AVERAGE						
1870.0± 0.5±1.0	317	BARLAG	90C	ACCM		π^- Cu 230 GeV
1875 ±10	9	ADAMOVICH	87	EMUL		Photoproduction
1863 ± 4		DERRICK	84	HRS		e^+e^- 29 GeV
1869.4± 0.6		[1] TRILLING	81	RVUE	±	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1860 ±16	6	ADAMOVICH	84	EMUL		Photoproduction
1868.4± 0.5		[1] SCHINDLER	81	MRK2	±	e^+e^- 3.77 GeV
1874 ± 5		GOLDHABER	77	MRK1	±	D^0, D^+ recoil spectra
1868.3± 0.9		[1] PERUZZI	77	MRK1	±	e^+e^- 3.77 GeV
1874 ±11		PICCOLO	77	MRK1	±	e^+e^- 4.03, 4.41 GeV
1876 ±15	50	PERUZZI	76	MRK1	±	$K^{\mp}\pi^{\pm}\pi^{\pm}$

[1] PERUZZI 77 and SCHINDLER 81 errors do not include the 0.13% uncertainty in the absolute SPEAR energy calibration. TRILLING 81 uses the high precision $J/\psi(1S)$ and $\psi(2S)$ measurements of ZHOLENTZ 80 to determine this uncertainty and combines the PERUZZI 77 and SCHINDLER 81 results to obtain the value quoted.

$D^{\pm}$ MEAN LIFE

Measurements with an error $> 2.0 \times 10^{-13}$ s have been omitted.

VALUE (10^{-13} s)	EVTS	DOCUMENT ID		TECN	COMMENT
10.66±0.23 OUR AVERAGE					
10.75±0.40±0.18	2455	FRABETTI	91	SILI	γ Be, $D^+ \to K^-\pi^+\pi^+$
10.3 ±0.8 ±0.6	200	ALVAREZ	90	NA14	γ, $D^+ \to K^-\pi^+\pi^+$
$10.5\ ^{+0.77}_{-0.72}$	317	[2] BARLAG	90C	ACCM	π^- Cu 230 GeV
$9.2\ ^{+1.7}_{-1.3}\ \pm1.6$	155	AVERILL	89	HRS	e^+e^- 29 GeV
10.5 ±0.8 ±0.7	363	ALBRECHT	88I	ARG	e^+e^- 10 GeV
10.90±0.30±0.25	2992	RAAB	88	SILI	Photoproduction
$5.0\ ^{+1.5}_{-1.0}\ \pm1.9$	27	ADAMOVICH	87	EMUL	Photoproduction
$11.2\ ^{+1.4}_{-1.1}$	149	AGUILAR-...	87D	HYBR	$\pi^- p$ and pp
$10.9\ ^{+1.9}_{-1.5}$	59	BARLAG	87B	ACCM	K^- and π^- 200 GeV
11.4 ±1.6 ±0.7	247	CSORNA	87	CLEO	e^+e^- 10 GeV
10.9 ±1.4	74	[3] PALKA	87B	SILI	π Be 200 GeV
$8.6\ \pm1.3\ ^{+0.7}_{-0.3}$	48	ABE	86	HYBR	γp 20 GeV

[2] BARLAG 90C estimates the systematic error to be negligible.
[3] PALKA 87B observes this in $D^+ \to \overline{K}^*(892)e\nu$.

D^+ DECAY MODES

D^- modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Inclusive modes		
Γ_1	e^+ anything	(17.2 ±1.9) %	
Γ_2	K^- anything	(20.8 ±2.8) %	S=1.3
Γ_3	K^+ anything	(5.8 ±1.4) %	
Γ_4	K^0 anything + $\overline{K}^0$ anything	(59 ±7) %	
Γ_5	η anything	[a] < 13 %	CL=90%
Γ_6	μ^+ anything		
Γ_7	$\mu^+\mu^-$ anything		
	Semileptonic modes		
Γ_8	$\mu^+\nu_\mu$	< 7.2 $\times 10^{-4}$	CL=90%
Γ_9	$\overline{K}^0 e^+\nu_e$	($5.5\ ^{+1.2}_{-1.1}$) %	
Γ_{10}	$\overline{K}^0\mu^+\nu_\mu$	($7.0\ ^{+3.0}_{-2.0}$) %	
Γ_{11}	$K^-\pi^+e^+\nu_e$	($3.8\ ^{+0.9}_{-0.7}$) %	
Γ_{12}	$\overline{K}^*(892)^0 e^+\nu_e$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	(2.7 ±0.4) %	
Γ_{13}	$K^-\pi^+e^+\nu_e$ nonresonant	< 7 $\times 10^{-3}$	CL=90%
Γ_{14}	$\overline{K}^0\pi^+\pi^-e^+\nu_e$		
Γ_{15}	$K^-\pi^+\pi^0 e^+\nu_e$		
Γ_{16}	$(\overline{K}^*(892)\pi)^0 e^+\nu_e$	< 1.2 %	CL=90%
Γ_{17}	$(\overline{K}\pi\pi)^0 e^+\nu_e$ non-$\overline{K}^*(892)$	< 9 $\times 10^{-3}$	CL=90%
Γ_{18}	$\pi^+\pi^-e^+\nu_e$	< 5.7 %	CL=90%
Γ_{19}	$\rho^0 e^+\nu_e$	< 3.7 $\times 10^{-3}$	CL=90%
	Fractions of some of the following modes have already appeared above.		
Γ_{20}	$\overline{K}^*(892)^0 e^+\nu_e$	(4.1 ±0.6) %	S=1.1
Γ_{21}	$\rho^0 e^+\nu_e$	< 3.7 $\times 10^{-3}$	CL=90%
Γ_{22}	$\phi e^+\nu_e$	< 2.09 %	CL=90%
Γ_{23}	$\phi\mu^+\nu_\mu$	< 3.72 %	CL=90%
	Hadronic modes with one or three K's		
Γ_{24}	$\overline{K}^0\pi^+$	(2.6 ±0.4) %	S=1.2
Γ_{25}	$K^-\pi^+\pi^+$	($8.0\ ^{+0.8}_{-0.7}$) %	S=1.2
	In the fit as $\frac{2}{3}\Gamma_{50} + \Gamma_{27}$, where $\frac{2}{3}\Gamma_{50} = \Gamma_{26}$.		
Γ_{26}	$\overline{K}^*(892)^0\pi^+$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	(1.3 ±0.5) %	
Γ_{27}	$K^-\pi^+\pi^+$ nonresonant	(6.7 ±0.8) %	S=1.1
Γ_{28}	$\overline{K}^0\pi^+\pi^0$	(8.4 ±1.8) %	
	In the fit as $\frac{1}{3}\Gamma_{50} + \Gamma_{30} + \Gamma_{31}$, where $\frac{1}{3}\Gamma_{50} = \Gamma_{29}$.		
Γ_{29}	$\overline{K}^*(892)^0\pi^+$ $\times$ B($\overline{K}^{*0} \to \overline{K}^0\pi^0$)	(0.6 ±0.2) %	
Γ_{30}	$\overline{K}^0\rho^+$	(6.6 ±1.7) %	
Γ_{31}	$\overline{K}^0\pi^+\pi^0$ nonresonant	($1.2\ ^{+1.0}_{-0.7}$) %	
Γ_{32}	$K^-\pi^+\pi^+\pi^0$	[b] ($4.9\ ^{+1.4}_{-0.8}$) %	S=1.1
Γ_{33}	$\overline{K}^*(892)^0\rho^+$ S-wave $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	($2.7\ ^{+1.0}_{-0.8}$) %	
Γ_{34}	$\overline{K}_1(1400)^0\pi^+$ $\times$ B($\overline{K}_1(1400)^0 \to K^-\pi^+\pi^0$)	(2.0 ±0.5) %	
Γ_{35}	$K^-\rho^+\pi^+$ 3-body	(8 ±5) $\times 10^{-3}$	
Γ_{36}	$K^-\pi^+\pi^+\pi^0$ nonresonant	(9 ±5) $\times 10^{-3}$	
Γ_{37}	$\overline{K}^0\pi^+\pi^+\pi^-$	(6.9 ±1.1) %	
Γ_{38}	$\overline{K}^0 a_1(1260)^+$ $\times$ B($a_1(1260)^+ \to \pi^+\pi^+\pi^-$)	(3.8 ±0.9) %	
Γ_{39}	$\overline{K}_1(1400)^0\pi^+$ $\times$ B($\overline{K}_1(1400)^0 \to \overline{K}^0\pi^+\pi^-$)	(2.0 ±0.5) %	
Γ_{40}	$\overline{K}^0\pi^+\pi^+\pi^-$ nonresonant	(1.2 ±0.8) %	
Γ_{41}	$K^-\pi^+\pi^+\pi^+\pi^-$	(6.1 ±1.5) $\times 10^{-3}$	S=1.6
Γ_{42}	$\overline{K}^*(892)^0\pi^+\pi^+\pi^-$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	(5.1 ±1.7) $\times 10^{-3}$	
Γ_{43}	$\overline{K}^*(892)^0\rho^0\pi^+$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	(3.8 ±1.8) $\times 10^{-3}$	
Γ_{44}	$K^-\pi^+\pi^+\pi^0\pi^0$	($2.2\ ^{+5.0}_{-0.9}$) %	
Γ_{45}	$\overline{K}^0\pi^+\pi^+\pi^-\pi^0$	($8.7\ ^{+3.5}_{-1.6}$) %	S=1.2
Γ_{46}	$\overline{K}^0\pi^+\pi^+\pi^+\pi^-\pi^-$	(1.0 ±1.0) $\times 10^{-3}$	
Γ_{47}	$K^-\pi^+\pi^+\pi^+\pi^-\pi^0$	($1.9\ ^{+2.6}_{-1.3}$) $\times 10^{-3}$	
Γ_{48}	$\overline{K}^0\overline{K}^0K^+$	(2.7 ±0.6) %	
	Fractions of some of the following modes (those with values rather than limits) have already appeared above.		
Γ_{49}	$\overline{K}^0\rho^+$	(6.6 ±1.7) %	
Γ_{50}	$\overline{K}^*(892)^0\pi^+$	(1.9 ±0.7) %	S=1.1
Γ_{51}	$\overline{K}^*(892)^0\rho^+$ S-wave	($4.1\ ^{+1.5}_{-1.2}$) %	
Γ_{52}	$\overline{K}^*(892)^0\rho^+$ P-wave	< 5 $\times 10^{-3}$	CL=90%
Γ_{53}	$\overline{K}^*(892)^0\rho^+$ D-wave longitudinal	< 7 $\times 10^{-3}$	CL=90%
Γ_{54}	$\overline{K}^0 a_1(1260)^+$	(7.5 ±1.7) %	
Γ_{55}	$\overline{K}^0 a_2(1320)^+$	< 8 $\times 10^{-3}$	CL=90%
Γ_{56}	$\overline{K}_1(1270)^0\pi^+$	< 1.1 %	CL=90%

Γ_{57}	$\overline{K}_1(1400)^0\pi^+$	(4.4 ± 1.2) %		
Γ_{58}	$\overline{K}^*(1410)^0\pi^+$	< 7	$\times 10^{-3}$	CL=90%
Γ_{59}	$K^*(892)^-\pi^+\pi^+$ 3-body	< 1.3	%	CL=90%
Γ_{60}	$\overline{K}^*(892)^0\pi^+\pi^0$ 3-body	< 8	$\times 10^{-3}$	CL=90%
Γ_{61}	$K^-\rho^+\pi^+$ 3-body	$(8 \pm 5) \times 10^{-3}$		
Γ_{62}	$\overline{K}^0\rho^0\pi^+$ 3-body	< 4	$\times 10^{-3}$	CL=90%
Γ_{63}	$\overline{K}^*(892)^0\pi^+\pi^+\pi^-$	$(7.6 \pm 2.5) \times 10^{-3}$		
Γ_{64}	$\overline{K}^*(892)^0\rho^0\pi^+$	$(5.7 \pm 2.7) \times 10^{-3}$		

Pionic modes

Γ_{65}	$\pi^+\pi^0$	< 5.3	$\times 10^{-3}$	CL=90%
Γ_{66}	$\pi^+\pi^+\pi^-$	$(2.8 \pm 0.6) \times 10^{-3}$		
Γ_{67}	$\rho^0\pi^+$	< 1.2	$\times 10^{-3}$	CL=90%
Γ_{68}	$\pi^+\pi^+\pi^-$ nonresonant	$(2.2 \pm 0.6) \times 10^{-3}$		
Γ_{69}	$\pi^+\pi^+\pi^-\pi^0$	$(2.3\ ^{+2.0}_{-1.3})$ %		
Γ_{70}	$\eta\pi^+ \times B(\eta \to \pi^+\pi^-\pi^0)$	$(1.6 \pm 0.5) \times 10^{-3}$		
Γ_{71}	$\omega\pi^+ \times B(\omega \to \pi^+\pi^-\pi^0)$	< 5	$\times 10^{-3}$	CL=90%
Γ_{72}	$\pi^+\pi^+\pi^+\pi^-\pi^-$	$(1.5 \pm 1.1) \times 10^{-3}$		
Γ_{73}	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$	$(2.8\ ^{+3.8}_{-2.0}) \times 10^{-3}$		
Γ_{74}	$\eta'(958)\pi^+ \times B(\eta' \to \eta\pi^+\pi^-) \times B(\eta \to \pi^+\pi^-\pi^0)$	< 8	$\times 10^{-4}$	CL=90%

Fractions of most of the following modes have already appeared above.

Γ_{75}	$\rho^0\pi^+$	< 1.2	$\times 10^{-3}$	CL=90%
Γ_{76}	$\eta\pi^+$	$(6.6 \pm 2.2) \times 10^{-3}$		
Γ_{77}	$\omega\pi^+$	< 6	$\times 10^{-3}$	CL=90%
Γ_{78}	$\eta\rho^+$	< 1.0	%	CL=90%
Γ_{79}	$\eta'(958)\pi^+$	< 8	$\times 10^{-3}$	CL=90%
Γ_{80}	$\eta'(958)\rho^+$	< 1.4	%	CL=90%

Hadronic modes with two K's

Γ_{81}	$\overline{K}^0K^+$	$(7.3 \pm 1.8) \times 10^{-3}$		
Γ_{82}	$K^+K^-\pi^+$	(1.01 ± 0.13) %		S=1.1
	In the fit as $\frac{1}{2}\Gamma_{97} + \frac{2}{3}\Gamma_{98} + \Gamma_{85}$, where $\frac{1}{2}\Gamma_{97} = \Gamma_{83}$ and $\frac{2}{3}\Gamma_{98} = \Gamma_{84}$.			
Γ_{83}	$\phi\pi^+ \times B(\phi \to K^+K^-)$	$(3.0 \pm 0.4) \times 10^{-3}$		
Γ_{84}	$\overline{K}^*(892)^0K^+ \times B(\overline{K}^{*0} \to K^-\pi^+)$	$(3.1 \pm 0.6) \times 10^{-3}$		
Γ_{85}	$K^+K^-\pi^+$ nonresonant	$(4.0 \pm 0.8) \times 10^{-3}$		
Γ_{86}	$K^+K^-\pi^+\pi^0$			
Γ_{87}	$\phi\pi^+\pi^0 \times B(\phi \to K^+K^-)$	$(1.2\ ^{+0.6}_{-0.5})$ %		
Γ_{88}	$\phi\rho^+ \times B(\phi \to K^+K^-)$	< 7	$\times 10^{-3}$	CL=90%
Γ_{89}	$K^+K^-\pi^+\pi^0$ non-ϕ	$(1.5\ ^{+0.7}_{-0.5})$ %		
Γ_{90}	$K^+\overline{K}^0\pi^+\pi^-$	< 2	%	CL=90%
Γ_{91}	$K^0K^-\pi^+\pi^+$	$(10 \pm 5) \times 10^{-3}$		
Γ_{92}	$K^*(892)^+\overline{K}^*(892)^0 \times B^2(K^* \to K\pi^+)$	(1.2 ± 0.5) %		
Γ_{93}	$K^0K^-\pi^+\pi^+$ non-$K^{*+}\overline{K}^{*0}$	< 7.9	$\times 10^{-3}$	CL=90%
Γ_{94}	$K^+K^-\pi^+\pi^+\pi^-$			
Γ_{95}	$\phi\pi^+\pi^+\pi^- \times B(\phi \to K^+K^-)$	< 1	$\times 10^{-3}$	CL=90%
Γ_{96}	$K^+K^-\pi^+\pi^+\pi^-$ nonresonant	< 3	%	CL=90%

Fractions of the following modes have already appeared above.

Γ_{97}	$\phi\pi^+$	$(6.0 \pm 0.8) \times 10^{-3}$		S=1.1
Γ_{98}	$\overline{K}^*(892)^0K^+$	$(4.7 \pm 0.9) \times 10^{-3}$		
Γ_{99}	$\phi\pi^+\pi^0$	$(2.4\ ^{+1.1}_{-0.9})$ %		
Γ_{100}	$\phi\rho^+$	< 1.3	%	CL=90%
Γ_{101}	$K^*(892)^+\overline{K}^*(892)^0$	(2.6 ± 1.1) %		
Γ_{102}	$\phi\pi^+\pi^+\pi^-$	< 2	$\times 10^{-3}$	CL=90%

Flavor-Changing neutral current (*FC*), Lepton number (*L*) violating, Lepton Family number (*LF*) violating, or Doubly Cabibbo suppressed (*DC*) modes

Γ_{103}	$\pi^+e^+e^-$	*FC*	< 2.5	$\times 10^{-3}$	CL=90%
Γ_{104}	$\pi^+\mu^+\mu^-$	*FC*	< 2.9	$\times 10^{-3}$	CL=90%
Γ_{105}	$\pi^+e^{\pm}\mu^{\mp}$	*LF*	< 3.8	$\times 10^{-3}$	CL=90%
Γ_{106}	$\pi^+e^+\mu^-$	*LF*	< 3.3	$\times 10^{-3}$	CL=90%
Γ_{107}	$\pi^+e^-\mu^+$	*LF*	< 3.3	$\times 10^{-3}$	CL=90%
Γ_{108}	$K^+e^+e^-$		< 4.8	$\times 10^{-3}$	CL=90%
Γ_{109}	$K^+\mu^+\mu^-$		< 9.2	$\times 10^{-3}$	CL=90%
Γ_{110}	$K^+e^+\mu^-$	*LF*	< 3.4	$\times 10^{-3}$	CL=90%
Γ_{111}	$K^+e^-\mu^+$	*LF*	< 3.4	$\times 10^{-3}$	CL=90%
Γ_{112}	$\pi^-e^+e^+$	*L*	< 4.8	$\times 10^{-3}$	CL=90%
Γ_{113}	$\pi^-\mu^+\mu^+$	*L*	< 6.8	$\times 10^{-3}$	CL=90%
Γ_{114}	$\pi^-e^+\mu^+$	*L*	< 3.7	$\times 10^{-3}$	CL=90%
Γ_{115}	$K^-e^+e^+$	*L*	< 9.1	$\times 10^{-3}$	CL=90%
Γ_{116}	$K^-\mu^+\mu^+$	*L*	< 4.3	$\times 10^{-3}$	CL=90%
Γ_{117}	$K^-e^+\mu^+$	*L*	< 4.0	$\times 10^{-3}$	CL=90%
Γ_{118}	$K^+\pi^+\pi^-$	*DC*	< 4	$\times 10^{-3}$	CL=90%

Mode needed for fitting purposes

Γ_{119}	Modes not in the fit.	$(49\ ^{+5}_{-6})$ %	S=1.1

[*a*] This is a weighted average of $D^{\pm}$ (44%) and D^0 (56%) branching fractions. See the $D^{\pm}$ Listing for $D^{\pm}$ and $D^0 \to \eta X$.

[*b*] The whole differs from the sum of the parts due to interference effects; see COFFMAN 92B.

CONSTRAINED FIT INFORMATION

An overall fit to 9 products of a cross section and a partial width, a cross section, and 24 branching ratios uses 52 measurements and one constraint to determine 18 parameters. The overall fit has a $\chi^2 = 23.2$ for 35 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i\delta p_j\rangle/(\delta p_i\cdot\delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

	x_9	x_{11}	x_{20}	x_{24}	x_{27}	x_{30}	x_{31}	x_{32}	x_{37}	x_{41}
x_{11}	7									
x_{20}	21	33								
x_{24}	21	15	44							
x_{27}	26	18	55	55						
x_{30}	10	7	22	29	30					
x_{31}	3	2	7	9	10	−19				
x_{32}	14	10	31	36	39	19	6			
x_{37}	13	10	29	37	36	20	6	33		
x_{41}	8	5	16	16	20	8	2	11	11	
x_{50}	7	5	16	16	−34	3	0	11	10	6
x_{57}	9	7	20	24	25	13	4	44	44	7
x_{66}	13	9	28	27	34	14	4	19	18	10
x_{85}	13	9	29	29	36	14	4	20	19	10
x_{97}	22	16	47	47	59	24	7	33	31	17
x_{98}	15	11	32	32	41	16	5	23	21	12
x_{119}	−43	−34	−61	−63	−64	−53	−20	−63	−63	−22
σ	−26	−18	−56	−74	−70	−40	−12	−47	−50	−20

	x_{50}	x_{57}	x_{66}	x_{85}	x_{97}	x_{98}	x_{119}
x_{57}	7						
x_{66}	10	12					
x_{85}	10	13	18				
x_{97}	17	21	29	31			
x_{98}	12	15	20	21	35		
x_{119}	−21	−58	−33	−35	−57	−40	
σ	−20	−33	−35	−36	−60	−41	78

NOTE ON CHARMED MESON BRANCHING FRACTIONS AND NEW RESULTS IN CHARM MESON DECAY

(by R.H. Schindler, SLAC)

In a previous edition of this *Review*, we restructured the Listings to both clarify and reduce the uncertainty in the normalization of the D^0 and D^+ mesons. For consistency in the Listings, we now enter only the experimentally measured quantities and not derived quantities. Topological normalizations (*e.g.*, AGUILAR-BENITEZ 84) have been retained, as have other so-called "double tagging" techniques (*e.g.*, BARLAG 90D) from hadro- and electro-produced charm experiments. Thus, all experiments measuring relative branching ratios are included in our calculations. The experiments measuring production cross section σ times branching fractions B_i at the $\psi(3770)$ have been listed separately as $\sigma \cdot B_i$. In the overall fit, we include the average cross section at the $\psi(3770)$ resonance obtained by the direct method of BALTRUSAITUS 86 and subsequently updated in ADLER 88C. A separate heading labeled CHARM PRODUCTION CROSS SECTIONS is now included at the end of the D^0 and the D^+ Listings. We no longer use the cross sections derived by the resonance scan technique, which may suffer systematically from the presence of non-$D^0\overline{D}^0$ or non-D^+D^- production at the $\psi(3770)$ since the magnitude of charmonium decays of the $\psi(3770)$ are not yet well-established.[1]

The most recent measurement of an absolute D^0 branching fraction comes from ALEPH (DECAMP 91J), where the technique pioneered by HRS (ABACHI 88) is applied to $D^*(2010)$ from Z decays. A value of $3.62 \pm 0.34 \pm 0.44\%$ is obtained for $\Gamma(K^-\pi^+)/\Gamma_{\rm total}$, in agreement with earlier results. This technique compares the total rate for $Z \to D^*(2010)^+ + X$, followed by $D^*(2010)^+ \to D^0\pi^+$, measured by observing only the soft low Q value π^+, with the total rate for $Z \to D^*(2010)^+ + X$, followed by $D^*(2010)^+ \to D^0\pi^+$ and then $D^0 \to K^-\pi^+$. The technique relies strongly, however, on detailed understanding of the background under the daughter pion in the $D^*(2010)$ decays, which introduces model-dependent uncertainties.

The MARK III Collaboration has published (COFFMAN 91) a new high statistics measurement at the $\psi(3770)$ of D^0, D^+, and D_s^+ charged and neutral particle multiplicities and strange particle fractions obtained by the direct tagging technique. The D^0 and D^+ multiplicities agree well with previous measurements. The strange particle content of D^+ decays, which were previously poorly measured, agree now with what was anticipated from conventional theoretical models of charm decay, assuming the leading processes. The most interesting result, however, comes from the first D_s^+ inclusive measurements, which are discussed in the "Note on the D_s^+."

New measurements of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ relative to $D^0 \to K^-\pi^+$ have been made by CLEO, ARGUS, and NA14/2. While the K^+K^- rate is similar to previous measurements (MARK II and Mark III), the $\pi^+\pi^-$ rate is about $1.5\,\sigma$ higher. This reduces the difference which must be theoretically understood on the basis of SU(3) breaking and final-state interactions. A number of other multi-kaon channels have been observed.

The MARK III experiment in COFFMAN 92B has published the first comprehensive study of the resonance structure in four-body D^0 and D^+ decays. This follows their initial results on $D^0 \to K^-\pi^+\pi^+\pi^-$ in ADLER 90. COFFMAN 92B presents evidence for the dominance of two-body substructure in the four-body decays, isolating large pseudoscalar-axial vector (PA) and vector-vector (VV) contributions, and making an isospin decomposition of a number of these PA and VV decays. These decays are shown to follow the trend observed first in pseudoscalar-pseudoscalar (PP) and pseudoscalar-vector (PV) decays, namely a ratio of isospin-1/2 to isospin-3/2 amplitudes of about 3 to 1, and large phase shifts between the amplitudes. Two-body decays can now account for about 60% of all D^0 and D^+ hadronic decays. The ratio of D^+ to D^0 two-body decay widths strongly infers their importance in setting the lifetime ratio of the two mesons.

A new set of measurements on semileptonic decays is emerging. Results from Mark III (ADLER 89, BAI 91), E691 (ANJOS 89B, ANJOS 90E, ANJOS 91C), ARGUS (ALBRECHT 91), and E653 (KODAMA 91) agree well (where measured) on the magnitude of the $D_{\ell 3}$ decays, and on the form factor $f_+(0)$ for both D^0 and D^+ decays. MARK III (ADLER 89) has previously reported direct evidence for the $D_{\ell 3}$ Cabibbo-suppressed decay $D^0 \to \pi^- e^+ \nu$. The $D_{\ell 4}$ decays still have experimental and theoretical problems. All experiments (including older fixed-target experiments) find that a dominant fraction (typically 80% or greater) of the $D \to K\pi\ell\nu$ decays are $\overline{K}^*(892)\ell\nu$. The values of the branching ratios relative to the $D_{\ell 3}$ decays are in reasonable agreement with each other, but in only modest agreement with theory, as are the values of the $K^*(892)$ polarizations obtained in some of the most recent experiments. The only detailed attempt at a measurement of the form factors (at $t = 0$) in the $D_{\ell 4}$ decay (the vector $V(0)$ and two axial vector $A_1(0)$ and $A_2(0)$) yields the theoretically surprising result that $A_2(0) \sim 0$. As the simpler $D_{\ell 3}$ decays appear to follow theory well both in magnitude and in dynamics, the discrepancies are likely to lie in the $D_{\ell 4}$ decays. At present, any final conclusions must await more definitive measurements.

We mention here one other paper: Fisher[2] has surveyed plots of the $\phi\pi^+$ mass spectrum from a number of experiments in which D mesons decaying to this final state are seen. Persistent evidence is found for a small, narrow bump at about 1800 MeV. In a similar survey of $K^-\pi^+$ mass spectra from such experiments, Fisher finds evidence for an enhancement at about 1785 MeV. We await further evidence before making entries in the Listings for these possible states.

Reference

1. R.H. Schindler *et al.*, *Proceedings of the XXIV International Conference on High Energy Physics*, Munich Germany (August 1988), Ed. R. Kotthaus, J.H. Kuhn, p. 484.
2. J.C. Fisher, Phys. Rev. **D44**, 1491 (1991).

D^+ BRANCHING RATIOS

$\Gamma(e^+ \text{ anything})/\Gamma_{\rm total}$ $\qquad \Gamma_1/\Gamma$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.172±0.019 OUR AVERAGE					
$0.20\ ^{+0.09}_{-0.07}$		AGUILAR-...	87E	HYBR	πp, $p p$ 360, 400 GeV
0.170±0.019±0.007	158	BALTRUSAIT...	85B	MRK3	$e^+ e^-$ 3.77 GeV
0.168±0.064	23	SCHINDLER	81	MRK2	$e^+ e^-$ 3.771 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.220^{+0.044}_{-0.022}$		BACINO	80	DLCO	$e^+ e^-$ 3.77 GeV

D^+ and $D^0 \to$ (e^+ anything) / (total D^+ and D^0)

If measured at the $\psi(3770)$, this quantity is a weighted average of D^+ (44%) and D^0 (56%) branching fractions. Only experiments at E_{cm} = 3.77 GeV are included in the average here.

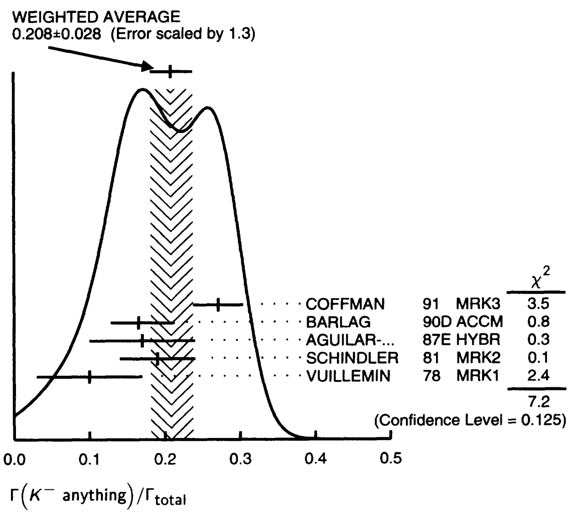
VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.110±0.011 OUR AVERAGE		Error includes scale factor of 1.1.			
0.117±0.011	295	BALTRUSAIT...	85B	MRK3	e^+e^- 3.77 GeV
0.10 ±0.032		[4] SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.072±0.028		FELLER	78	MRK1	e^+e^- 3.772 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.096±0.007±0.015		[5] ONG	88	MRK2	e^+e^- 29 GeV
$0.116^{+0.011}_{-0.009}$		[5] PAL	86	DLCO	e^+e^- 29 GeV
0.091±0.009±0.013		[5] AIHARA	85	TPC	e^+e^- 29 GeV
0.092±0.046		[5] ALTHOFF	84J	TASS	e^+e^- 34.6 GeV
0.091±0.013		[5] KOOP	84	DLCO	See PAL 86
0.08 ±0.015		[6] BACINO	79	DLCO	e^+e^- 3.772 GeV

[4] Isolates D^+ and $D^0 \to e^+$ X and weights for relative production (44%–56%).
[5] Average BR for charm $\to e^+$ X. Unlike at E_{cm} = 3.77 GeV, the admixture of charmed mesons is unknown.
[6] Not independent of BACINO 80 measurements of $\Gamma(e^+ \text{ anything})/\Gamma_{total}$ for the D^+ and D^0 separately.

$\Gamma(K^- \text{ anything})/\Gamma_{total}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.208±0.028 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.			
0.271±0.023±0.024		COFFMAN	91	MRK3	e^+e^- 3.77 GeV
$0.165^{+0.048}_{-0.037}$		[7] BARLAG	90D	ACCM	π^- Cu 230 GeV
0.17 ±0.07		AGUILAR-...	87E	HYBR	πp, pp 360, 400 GeV
0.19 ±0.05	26	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.10 ±0.07	3	VUILLEMIN	78	MRK1	e^+e^- 3.772 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.16\ ^{+0.08}_{-0.07}$		AGUILAR-...	86B	HYBR	See AGUILAR-BENITEZ 87E

[7] BARLAG 90D computes the branching fraction using topological normalization.



$\Gamma(K^+ \text{ anything})/\Gamma_{total}$ Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.058±0.014 OUR AVERAGE					
0.055±0.013±0.009		COFFMAN	91	MRK3	e^+e^- 3.77 GeV
$0.08\ ^{+0.06}_{-0.05}$		AGUILAR-...	87E	HYBR	πp, pp 360, 400 GeV
0.06 ±0.04	12	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.06 ±0.06	2	VUILLEMIN	78	MRK1	e^+e^- 3.772 GeV

$[\Gamma(K^0 \text{ anything}) + \Gamma(\overline{K}^0 \text{ anything})]/\Gamma_{total}$ Γ_4/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.59 ±0.07 OUR AVERAGE					
0.612±0.065±0.043		COFFMAN	91	MRK3	e^+e^- 3.77 GeV
0.52 ±0.18	15	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.39 ±0.29	3	VUILLEMIN	78	MRK1	e^+e^- 3.772 GeV

D^+ and $D^0 \to$ (η anything) / (total D^+ and D^0)

If measured at the $\psi(3770)$, this quantity is a weighted average of D^+ (44%) and D^0 (56%) branching fractions. Only the experiment at E_{cm} = 3.77 GeV is used.

VALUE	DOCUMENT ID		TECN	COMMENT
<0.13	PARTRIDGE	81	CBAL	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.02	[8] BRANDELIK	79	DASP	e^+e^- 4.03 GeV

[8] The BRANDELIK 79 result is based on the absence of an η signal at E_{cm} = 4.03 GeV. PARTRIDGE 81 observes a substantially higher η cross section at 4.03 GeV.

$\Gamma(c/\overline{c} \to \mu^+ \text{ anything})/\Gamma(c/\overline{c} \to \text{anything})$

This is the average branching ratio for charm $\to \mu^+$ X. The mixture of charmed particles is unknown and may actually contain states other than D mesons.

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.079^{+0.011}_{-0.010}}$ **OUR AVERAGE**				
0.078±0.009±0.012	ONG	88	MRK2	e^+e^- 29 GeV
0.078±0.015±0.02	BARTEL	87	JADE	e^+e^- 34.6 GeV
$0.082^{+0.023}_{-0.016}$	ALTHOFF	84G	TASS	e^+e^- 34.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.089±0.018±0.025	BARTEL	85J	JADE	See BARTEL 87

$\Gamma(c/\overline{c} \to e^+e^- \text{ anything})/\Gamma(c/\overline{c} \to \text{anything})$

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<2.2 \times 10^{-3}$	90	0.1	[9] HAAS	88	CLEO	e^+e^- 10 GeV

[9] The normalization uses a continuum charm production estimate.

$\Gamma(c/\overline{c} \to e^+\mu^- \text{ anything})/\Gamma(c/\overline{c} \to \text{anything})$

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<3.7 \times 10^{-3}$	90	0.2	[10] HAAS	88	CLEO	e^+e^- 10 GeV

[10] The normalization uses a continuum charm production estimate.

$\Gamma(c/\overline{c} \to \mu^+\mu^- \text{ anything})/\Gamma(c/\overline{c} \to \text{anything})$

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.018	90	0.3	[11] HAAS	88	CLEO	e^+e^- 10 GeV
<0.007	95		[12] ALTHOFF	84G	TASS	e^+e^- 34.5 GeV

[11] The normalization uses a continuum charm production estimate.
[12] Average BR for charm $\to \mu^+\mu^-$ X. The mixture of charmed particles is unknown and may actually contain states other than D mesons.

$\Gamma(\mu^+\nu_\mu)/\Gamma_{total}$ Γ_8/Γ

See the "Note on Pseudoscalar Meson Decay Constants" in the $\pi^{\pm}$ Listings for the limit inferred on the D^+ decay constant from the limit on $\Gamma(\mu^+\nu_\mu)/\Gamma_{total}$.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.00072	90		ADLER	88B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.02	90	0	[13] AUBERT	83	SPEC	μ^+Fe, 250 GeV

[13] AUBERT 83 obtains an upper limit 0.014 assuming the final state contains equal amounts of (D^+,D^-), $(D^+,\overline{D}^0)$, (D^-,D^0), and $(D^0,\overline{D}^0)$. We quote the limit they get under more general assumptions.

$\Gamma(\overline{K}^0 e^+\nu_e)/\Gamma_{total}$ Γ_9/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.055^{+0.012}_{-0.011}}$ **OUR FIT**					
$\mathbf{0.06\ ^{+0.022}_{-0.013}\pm0.007}$	13	BAI	91	MRK3	$e^+e^- \approx$ 3.77 GeV

$\Gamma(\overline{K}^0 e^+\nu_e)/\Gamma(K^-\pi^+\pi^+)$ $\Gamma_9/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

VALUE	DOCUMENT ID		TECN	COMMENT
0.69±0.14 OUR FIT				
0.66±0.09±0.14	ANJOS	91C	E691	γ Be 80–240 GeV

$\Gamma(\overline{K}^0 \mu^+\nu_\mu)/\Gamma_{total}$ Γ_{10}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.07\ ^{+0.028}_{-0.016}\pm0.012}$	14	BAI	91	MRK3	$e^+e^- \approx$ 3.77 GeV

$\Gamma(\overline{K}^0 \mu^+\nu_\mu)/\Gamma(\mu^+ \text{ anything})$ Γ_{10}/Γ_6

VALUE	EVTS	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.76±0.06	84	[14] AOKI	88	π^- emulsion

[14] From topological branching ratios in emulsion with an identified muon.

$\Gamma(K^-\pi^+e^+\nu_e)/\Gamma_{total}$ Γ_{11}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.038^{+0.009}_{-0.007}}$ **OUR FIT**						
$\mathbf{0.035^{+0.012}_{-0.007}\pm0.004}$		14	[15] BAI	91	MRK3	$e^+e^- \approx$ 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.057	90		[16] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[15] BAI 91 finds that a fraction $0.79^{+0.15}_{-0.17}{}^{+0.09}_{-0.03}$ of combined D^+ and D^0 decays to $\overline{K}\pi e^+\nu_e$ (24 events) are $\overline{K}^*(892)e^+\nu_e$.
[16] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization.

$\Gamma(\overline{K}^*(892)^0 e^+ \nu_e)/\Gamma(K^- \pi^+ e^+ \nu_e)$ Γ_{20}/Γ_{11}

Includes a factor 3/2 to take into account $\overline{K}^*(892)^0 \to \overline{K}^0 \pi^0$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$1.08^{+0.21}_{-0.24}$ OUR FIT					
1.0 ±0.3	35	ADAMOVICH	91	OMEG	π^- 340 GeV

$\Gamma(\overline{K}^*(892)^0 e^+ \nu_e)/\Gamma(K^- \pi^+ \pi^+)$ $\Gamma_{20}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

Includes a factor 3/2 to take into account $\overline{K}^*(892)^0 \to \overline{K}^0 \pi^0$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.51±0.05 OUR FIT					
0.51±0.05 OUR AVERAGE					
0.62±0.15±0.09	35	ADAMOVICH	91	OMEG	π^- 340 GeV
0.55±0.08±0.10	880	ALBRECHT	91	ARG	$e^+e^- \approx$ 10.4 GeV
0.49±0.04±0.05		[17] ANJOS	89B	E691	Photoproduction

[17] For measurements of the form factors for this mode, and of the ratio of longitudinal to transverse polarization of the $\overline{K}^*(892)$, see ANJOS 90E.

$\Gamma(K^- \pi^+ e^+ \nu_e$ nonresonant$)/\Gamma_{total}$ Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.007	90	[18] ANJOS	89B	E691	Photoproduction

[18] ANJOS 89B have assumed a $B(D^+ \to K^- \pi^+ \pi^+) = 9.1 \pm 1.3 \pm 0.4\%$.

$\Gamma(\overline{K}^0 \pi^+ \pi^- e^+ \nu_e)/\Gamma_{total}$ Γ_{14}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.022^{+0.047}_{-0.006}\pm0.004$	1	[19] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[19] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization.

$\Gamma(K^- \pi^+ \pi^0 e^+ \nu_e)/\Gamma_{total}$ Γ_{15}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.044^{+0.052}_{-0.013}\pm0.007$	2	[20] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[20] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization.

$\Gamma((\overline{K}^*(892)\pi)^0 e^+ \nu_e)/\Gamma_{total}$ Γ_{16}/Γ

Unseen decay modes of the $\overline{K}^*(892)$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.012	90	ANJOS	92	E691	Photoproduction

$\Gamma((\overline{K}\pi\pi)^0 e^+ \nu_e$ non-$\overline{K}^*(892))/\Gamma_{total}$ Γ_{17}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.009	90	ANJOS	92	E691	Photoproduction

$\Gamma(\pi^+ \pi^- e^+ \nu_e)/\Gamma_{total}$ Γ_{18}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.057	90	[21] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[21] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization.

$\Gamma(\rho^0 e^+ \nu_e)/\Gamma_{total}$ Γ_{19}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0037	90	BAI	91	MRK3	$e^+e^- \approx$ 3.77 GeV

$\Gamma(\phi e^+ \nu_e)/\Gamma_{total}$ Γ_{22}/Γ

Unseen decay modes of the ϕ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0209	90	BAI	91	MRK3	$e^+e^- \approx$ 3.77 GeV

$\Gamma(\phi \mu^+ \nu_\mu)/\Gamma_{total}$ Γ_{23}/Γ

Unseen decay modes of the ϕ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0372	90	BAI	91	MRK3	$e^+e^- \approx$ 3.77 GeV

$\Gamma(\overline{K}^0 \pi^+)/\Gamma(K^- \pi^+ \pi^+)$ $\Gamma_{24}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.324±0.034 OUR FIT	Error includes scale factor of 1.2.				
0.274±0.030±0.031	264	ANJOS	90C	E691	Photoproduction

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^0 \pi^+)/\Gamma_{total}$ $\sigma \times \Gamma_{24}/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID		TECN	COMMENT
0.124±0.012 OUR FIT	Error includes scale factor of 1.1.				
0.136±0.013 OUR AVERAGE					
0.135±0.012±0.010	161	BALTRUSAIT...	86E	MRK3	e^+e^- 3.77 GeV
0.14 ±0.03	36	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.14 ±0.05	17	PERUZZI	77	MRK1	e^+e^- 3.77 GeV

$\Gamma(K^- \pi^+ \pi^+)/\Gamma_{total}$ $(\Gamma_{27}+\frac{2}{3}\Gamma_{50})/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.080^{+0.008}_{-0.007}$ OUR FIT	Error includes scale factor of 1.2.				
$0.076^{+0.013}_{-0.011}$ OUR AVERAGE					
0.080±0.014		[22] BARLAG	90D	ACCM	π^- Cu 230 GeV
$0.063^{+0.028}_{-0.014}\pm0.011$	8	[22] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[22] AGUILAR-BENITEZ 87F and BARLAG 90D computed the branching fraction by topological normalization.

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K^- \pi^+ \pi^+)/\Gamma_{total}$ $\sigma \times (\Gamma_{27}+\frac{2}{3}\Gamma_{50})/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID		TECN	COMMENT
0.383±0.022 OUR FIT	Error includes scale factor of 1.1.				
0.381±0.024 OUR AVERAGE					
0.388±0.013±0.029	1164	BALTRUSAIT...	86E	MRK3	e^+e^- 3.77 GeV
0.38 ±0.05	239	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.36 ±0.06	85	PERUZZI	77	MRK1	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0 \pi^+)/\Gamma(K^- \pi^+ \pi^+)$ $\Gamma_{50}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

Includes a factor 3/2 to take into account $\overline{K}^*(892)^0 \to \overline{K}^0 \pi^0$.

VALUE	DOCUMENT ID		TECN	COMMENT
0.24±0.08 OUR FIT	Error includes scale factor of 1.1.			
0.21±0.06±0.06	ALVAREZ	91B	NA14	Photoproduction

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^*(892)^0 \pi^+)/\Gamma_{total}$ $\sigma \times \Gamma_{50}/\Gamma$

Includes a factor 3/2 to take into account $\overline{K}^*(892)^0 \to \overline{K}^0 \pi^0$.

VALUE (nanobarns)	CL%	DOCUMENT ID		TECN	COMMENT
0.093±0.033 OUR FIT					
0.24 ±0.07 ±0.10		ADLER	87	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.27	90	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K^- \pi^+ \pi^+$ nonresonant$)/\Gamma_{total}$ $\sigma \times \Gamma_{27}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID		TECN	COMMENT
0.321±0.029 OUR FIT	Error includes scale factor of 1.1.			
0.31 ±0.03 ±0.10	ADLER	87	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0 \pi^+ \pi^0)/\Gamma_{total}$ $(\Gamma_{30}+\Gamma_{31}+\frac{1}{3}\Gamma_{50})/\Gamma$

VALUE	DOCUMENT ID
0.084±0.018 OUR FIT	

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^0 \pi^+ \pi^0)/\Gamma_{total}$ $\sigma \times (\Gamma_{30}+\Gamma_{31}+\frac{1}{3}\Gamma_{50})/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID		TECN	COMMENT
0.40 ±0.08 OUR FIT					
0.44 ±0.11 OUR AVERAGE					
0.417±0.081±0.075	159	BALTRUSAIT...	86E	MRK3	e^+e^- 3.77 GeV
0.78 ±0.48	10	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^0 \rho^+)/\Gamma_{total}$ $\sigma \times \Gamma_{30}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID		TECN	COMMENT
0.32±0.07 OUR FIT				
0.29±0.03±0.09	ADLER	87	MRK3	e^+e^- 3.77 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^0 \pi^+ \pi^0$ nonresonant$)/\Gamma_{total}$ $\sigma \times \Gamma_{31}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID		TECN	COMMENT
$0.057^{+0.047}_{-0.034}$ OUR FIT				
0.05 ±0.03 ±0.04	ADLER	87	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^- \pi^+ \pi^+ \pi^0)/\Gamma_{total}$ Γ_{32}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.049^{+0.014}_{-0.008}$ OUR FIT	Error includes scale factor of 1.1.				
$0.023^{+0.032}_{-0.007}$ OUR AVERAGE					
0.032±0.024±0.036		[23] BARLAG	90D	ACCM	π^- Cu 230 GeV
$0.022^{+0.047}_{-0.006}\pm0.004$	1	[23] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[23] AGUILAR-BENITEZ 87F and BARLAG 90D computed the branching fraction by topological normalization.

$\Gamma(K^- \pi^+ \pi^+ \pi^0)/\Gamma(K^- \pi^+ \pi^+)$ $\Gamma_{32}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.61^{+0.15}_{-0.10}$ OUR FIT	Error includes scale factor of 1.1.				
$0.66^{+0.18}_{-0.13}$ OUR AVERAGE					
0.69±0.10±0.16		ANJOS	89E	E691	Photoproduction
$0.57^{+0.65}_{-0.17}$	1	AGUILAR-...	83B	HYBR	$\pi^- p$, 360 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K^-\pi^+\pi^+\pi^0)/\Gamma_{total}$ — $\sigma \times \Gamma_{32}/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID		TECN	COMMENT
0.23 $^{+0.06}_{-0.04}$ **OUR FIT** Error includes scale factor of 1.1.					
0.248±0.035±0.053	142	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.18 ±0.04 ±0.04	175	BALTRUSAIT...	86E	MRK3	See COFFMAN 92B

$\Gamma(\overline{K}^*(892)^0\rho^+$ S-wave$)/\Gamma(K^-\pi^+\pi^+\pi^0)$ — Γ_{51}/Γ_{32}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.833±0.116±0.165	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\rho^+$ P-wave$)/\Gamma_{total}$ — Γ_{52}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.005	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\rho^+$ D-wave longitudinal$)/\Gamma_{total}$ — Γ_{53}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.007	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}_1(1400)^0\pi^+)/\Gamma(K^-\pi^+\pi^+\pi^0)$ — Γ_{57}/Γ_{32}

Unseen decay modes of the $\overline{K}_1(1400)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.90 ±0.22 OUR FIT				
0.907±0.218±0.180	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\rho^+\pi^+$ 3-body$)/\Gamma(K^-\pi^+\pi^+\pi^0)$ — Γ_{61}/Γ_{32}

VALUE	DOCUMENT ID		TECN	COMMENT
0.159±0.065±0.060	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^0$ 3-body$)/\Gamma_{total}$ — Γ_{60}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.008	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^+\pi^0$ nonresonant$)/\Gamma(K^-\pi^+\pi^+\pi^0)$ — Γ_{36}/Γ_{32}

VALUE	DOCUMENT ID		TECN	COMMENT
0.184±0.070±0.050	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{37}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.069±0.011 OUR FIT					
0.09 ±0.06 OUR AVERAGE Error includes scale factor of 2.9.					
0.061 $^{+0.023}_{-0.022}$		24 BARLAG	90D	ACCM	π^- Cu 230 GeV
0.243 $^{+0.064}_{-0.041}$ ±0.041	11	24 AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[24] AGUILAR-BENITEZ 87F and BARLAG 90D compute the branching fraction by topological normalization.

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^0\pi^+\pi^+\pi^-)/\Gamma_{total}$ — $\sigma \times \Gamma_{37}/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID		TECN	COMMENT
0.33 ±0.05 OUR FIT					
0.31 ±0.06 OUR AVERAGE Error includes scale factor of 1.2.					
0.291±0.047±0.029	168	ADLER	88C	MRK3	e^+e^- 3.77 GeV
0.51 ±0.18	21	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV

$\Gamma(\overline{K}^0 a_1(1260)^+)/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ — Γ_{54}/Γ_{37}

Unseen decay modes of the $a_1(1260)^+$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
1.078±0.114±0.140	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}_1(1400)^0\pi^+)/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ — Γ_{57}/Γ_{37}

Unseen decay modes of the $\overline{K}_1(1400)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.63 ±0.17 OUR FIT				
0.623±0.106±0.180	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0 a_2(1320)^+)/\Gamma_{total}$ — Γ_{55}/Γ

Unseen decay modes of the $a_2(1320)^+$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.008	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}_1(1270)^0\pi^+)/\Gamma_{total}$ — Γ_{56}/Γ

Unseen decay modes of the $\overline{K}_1(1270)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.011	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(1410)^0\pi^+)/\Gamma_{total}$ — Γ_{58}/Γ

Unseen decay modes of the $\overline{K}^*(1410)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.007	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^*(892)^-\pi^+\pi^+$ 3-body$)/\Gamma_{total}$ — Γ_{59}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.013	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\rho^0\pi^+$ 3-body$)/\Gamma_{total}$ — Γ_{62}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.004	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-$ nonresonant$)/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ — Γ_{40}/Γ_{37}

VALUE	DOCUMENT ID		TECN	COMMENT
0.17±0.056±0.100	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{41}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0061±0.0015 OUR FIT Error includes scale factor of 1.6.				
0.0041 $^{+0.0015}_{-0.0014}$	25 BARLAG	90D	ACCM	π^- Cu 230 GeV

[25] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(K^-\pi^+\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{41}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.076±0.019 OUR FIT Error includes scale factor of 1.7.					
0.09 ±0.01 ±0.01	113	ANJOS	90D	E691	Photoproduction

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K^-\pi^+\pi^+\pi^+\pi^-)/\Gamma_{total}$ — $\sigma \times \Gamma_{41}/\Gamma$

VALUE (nanobarns)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.23	90	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^+\pi^-)$ — Γ_{63}/Γ_{41}

Includes a factor 3/2 to take into account $\overline{K}^*(892)^0 \to \overline{K}^0\pi^0$.

VALUE	DOCUMENT ID		TECN	COMMENT
1.25±0.12±0.23	ANJOS	90D	E691	Photoproduction

$\Gamma(\overline{K}^*(892)^0\rho^0\pi^+)/\Gamma(\overline{K}^*(892)^0\pi^+\pi^+\pi^-)$ — Γ_{64}/Γ_{63}

VALUE	DOCUMENT ID		TECN	COMMENT
0.75±0.17±0.19	ANJOS	90D	E691	Photoproduction

$\Gamma(K^-\pi^+\pi^+\pi^0\pi^0)/\Gamma_{total}$ — Γ_{44}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.022 $^{+0.047}_{-0.008}$ **±0.004**	1	26 AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.015		26 BARLAG	90D	ACCM	π^- Cu 230 GeV

[26] AGUILAR-BENITEZ 87F and BARLAG 90D computed the branching fraction by topological normalization.

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{45}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.087 $^{+0.035}_{-0.016}$ **OUR AVERAGE** Error includes scale factor of 1.2.					
0.113±0.024±0.028		27 BARLAG	90D	ACCM	π^- Cu 230 GeV
0.044 $^{+0.052}_{-0.013}$ ±0.007	2	27 AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[27] AGUILAR-BENITEZ 87F and BARLAG 90D computed the branching fraction by topological normalization.

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma_{total}$ — Γ_{46}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0010±0.0010	28 BARLAG	90D	ACCM	π^- Cu 230 GeV

[28] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(K^-\pi^+\pi^+\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{47}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0019 $^{+0.0026}_{-0.0013}$	29 BARLAG	90D	ACCM	π^- Cu 230 GeV

[29] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(\overline{K}^0\overline{K}^0K^+)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{48}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.34±0.07	70	AMMAR	91	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(\pi^+\pi^0)/\Gamma_{total}$ — Γ_{65}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.0053	90	1	BALTRUSAIT...	85E	MRK3	e^+e^- 3.77 GeV

$\Gamma(\pi^+\pi^0)/\Gamma(\overline{K}^0\pi^+)$ — Γ_{65}/Γ_{24}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.30	90	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV

$\Gamma(\pi^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{66}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0028±0.0006 OUR FIT				
$0.0024^{+0.0014}_{-0.0013}$	[30] BARLAG	90D	ACCM	π^- Cu 230 GeV

[30] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{66}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.035±0.007 OUR FIT					
0.036±0.007 OUR AVERAGE					
0.035±0.007±0.003		ANJOS	89	E691	Photoproduction
0.042±0.016±0.010	57	BALTRUSAIT...	85E	MRK3	e^+e^- 3.77 GeV

$\Gamma(\rho^0\pi^+)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{67}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.015	90	ANJOS	89	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^-$ nonresonant$)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{68}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

VALUE	DOCUMENT ID		TECN	COMMENT
0.027±0.007±0.002	ANJOS	89	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{69}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.023^{+0.020}_{-0.013}$	[31] BARLAG	90D	ACCM	π^- Cu 230 GeV

[31] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(\pi^+\pi^+\pi^-\pi^0)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{69}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.4	90	ANJOS	89E	E691	Photoproduction

$\Gamma(\eta\pi^+)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{76}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

Unseen decay modes of the η are included.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.083±0.023±0.014		99	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.12	90		ANJOS	89E	E691	Photoproduction

$\Gamma(\omega\pi^+)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{77}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

Unseen decay modes of the ω are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.08	90	ANJOS	89E	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma_{total}$ — Γ_{72}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0015±0.0011	[32] BARLAG	90D	ACCM	π^- Cu 230 GeV

[32] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{72}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.019	90	ANJOS	89	E691	Photoproduction

$\Gamma(\eta\rho^+)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{78}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

Unseen decay modes of the η are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.13	90	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{total}$ — Γ_{73}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.0028^{+0.0038}_{-0.0020}$	[33] BARLAG	90D	ACCM	π^- Cu 230 GeV

[33] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(\eta'(958)\pi^+)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{79}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

Unseen decay modes of the $\eta'(958)$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.1	90	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV
<0.1	90	ALVAREZ	91	NA14	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.13	90	ANJOS	91B	E691	γBe, $\overline{E}_\gamma \approx$ 145 GeV

$\Gamma(\eta'(958)\rho^+)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{80}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

Unseen decay modes of the $\eta'(958)$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.17	90	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(\overline{K}^0K^+)/\Gamma(\overline{K}^0\pi^+)$ — Γ_{81}/Γ_{24}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.28 ±0.06 OUR AVERAGE					
0.271±0.065±0.039	69	ANJOS	90C	E691	γBe
0.317±0.086±0.048	31	BALTRUSAIT...	85E	MRK3	e^+e^- 3.77 GeV
0.25 ±0.15	6	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV

$\Gamma(K^+K^-\pi^+)/\Gamma_{total}$ — $(\Gamma_{85}+\frac{1}{2}\Gamma_{97}+\frac{2}{3}\Gamma_{98})/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0101±0.0013 OUR FIT Error includes scale factor of 1.1.					
$0.008\ ^{+0.017}_{-0.002}$ ±0.001	1	[34] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[34] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization.

$\Gamma(\phi\pi^+)/\Gamma_{total}$ — Γ_{97}/Γ

Unseen decay modes of the ϕ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.0060±0.0008 OUR FIT Error includes scale factor of 1.1.				
$0.0058^{+0.0028}_{-0.0026}$	[35] BARLAG	90D	ACCM	π^- Cu 230 GeV

[35] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(\phi\pi^+)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{97}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

Unseen decay modes of the ϕ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.075±0.007 OUR FIT					
0.076±0.007 OUR AVERAGE					
0.077±0.011±0.005	128	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV
0.098±0.032±0.014	12	ALVAREZ	90C	NA14	Photoproduction
0.071±0.008±0.007	84	ANJOS	88	E691	Photoproduction
0.084±0.021±0.011	21	BALTRUSAIT...	85E	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0K^+)/\Gamma_{total}$ — Γ_{98}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.0047±0.0009 OUR FIT				
$0.0064^{+0.0026}_{-0.0023}$	[36] BARLAG	90D	ACCM	π^- Cu 230 GeV

[36] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(\overline{K}^*(892)^0K^+)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{98}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

Includes a factor 3/2 to take into account $\overline{K}^*(892)^0 \to \overline{K}^0\pi^0$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.058±0.009 OUR FIT					
0.056±0.010 OUR AVERAGE					
0.058±0.009±0.006	73	ANJOS	88	E691	Photoproduction
0.048±0.021±0.011	14	BALTRUSAIT...	85E	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^+K^-\pi^+$ nonresonant$)/\Gamma_{total}$ — Γ_{85}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0040±0.0008 OUR FIT				
0.0039±0.0016	[37] BARLAG	90D	ACCM	π^- Cu 230 GeV

[37] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(K^+K^-\pi^+$ nonresonant$)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{85}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.050±0.009 OUR FIT					
0.050±0.009 OUR AVERAGE					
0.049±0.008±0.006	95	ANJOS	88	E691	Photoproduction
0.059±0.026±0.009	37	BALTRUSAIT...	85E	MRK3	e^+e^- 3.77 GeV

$\Gamma(\phi\pi^+\pi^0)/\Gamma_{total}$ — Γ_{99}/Γ

Unseen decay modes of the ϕ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
$0.0238^{+0.0111}_{-0.0085}$	[38] BARLAG	90D	ACCM	π^- Cu 230 GeV

[38] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(\phi\pi^+\pi^0)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{99}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

Unseen decay modes of the ϕ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.58	90	ALVAREZ	90C	NA14	Photoproduction
<0.28	90	ANJOS	89E	E691	Photoproduction

$\Gamma(\phi\rho^+)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{100}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

Unseen decay modes of the ϕ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.16	90	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(K^+K^-\pi^+\pi^0$ non-$\phi)/\Gamma_{total}$ — Γ_{89}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.0152^{+0.0065}_{-0.0051}$	[39] BARLAG	90D	ACCM	π^- Cu 230 GeV

[39] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(K^+K^-\pi^+\pi^0$ non-$\phi)/\Gamma(K^-\pi^+\pi^+)$ — $\Gamma_{89}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.25	90	ANJOS	89E	E691	Photoproduction

$\Gamma(K^+\overline{K}^0\pi^+\pi^-)/\Gamma_{total}$ — Γ_{90}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	ALBRECHT	92B	ARG	$e^+e^- \sim$ 10.4 GeV

$\Gamma(K^0 K^- \pi^+ \pi^+)/\Gamma_{total}$ — Γ_{91}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.010±0.005 OUR AVERAGE				
0.01 ±0.005±0.003	ALBRECHT	92B	ARG	$e^+e^- \sim$ 10.4 GeV
$0.009^{+0.011}_{-0.008}$	[40] BARLAG	90D	ACCM	π^- Cu 230 GeV

[40] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(K^*(892)^+ \overline{K}^*(892)^0)/\Gamma_{total}$ — Γ_{101}/Γ

Unseen decay modes of the $\overline{K}^*(892)$'s are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.026±0.008±0.007	ALBRECHT	92B	ARG	$e^+e^- \sim$ 10.4 GeV

$\Gamma(K^0 K^- \pi^+ \pi^+ \text{ non-}K^{*+}\overline{K}^{*0})/\Gamma_{total}$ — Γ_{93}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0079	90	ALBRECHT	92B	ARG	$e^+e^- \sim$ 10.4 GeV

$\Gamma(\phi \pi^+ \pi^+ \pi^-)/\Gamma_{total}$ — Γ_{102}/Γ

Unseen decay modes of the ϕ are included.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.002	90	0	ANJOS	88	E691	Photoproduction

$\Gamma(\phi \pi^+ \pi^+ \pi^-)/\Gamma(K^- \pi^+ \pi^+)$ — $\Gamma_{102}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

Unseen decay modes of the ϕ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.031	90	ALVAREZ	90C	NA14	Photoproduction

$\Gamma(K^+ K^- \pi^+ \pi^+ \pi^- \text{ nonresonant})/\Gamma_{total}$ — Γ_{96}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.03	90	12	ANJOS	88	E691	Photoproduction

$\Gamma(\pi^+ e^+ e^-)/\Gamma_{total}$ — Γ_{103}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<2.5 \times 10^{-3}$	90		WEIR	90B	MRK2	e^+e^- 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<2.6 \times 10^{-3}$	90	39	[41] HAAS	88	CLEO	e^+e^- 10 GeV

[41] The branching ratios are normalized to $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D^{*+} \to D^0\pi^+$ using ADLER 88C.

$\Gamma(\pi^+ \mu^+ \mu^-)/\Gamma_{total}$ — Γ_{104}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<2.9 \times 10^{-3}$	90	36	[42] HAAS	88	CLEO	e^+e^- 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<5.9 \times 10^{-3}$	90		WEIR	90B	MRK2	e^+e^- 29 GeV

[42] The branching ratios are normalized to $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D^{*+} \to D^0\pi^+$ using ADLER 88C.

$\Gamma(\pi^+ e^\pm \mu^\mp)/\Gamma_{total}$ — Γ_{105}/Γ

A test of lepton-family-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<3.8 \times 10^{-3}$	90	58	[43] HAAS	88	CLEO	e^+e^- 10 GeV

[43] The branching ratios are normalized to $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D^{*+} \to D^0\pi^+$ using ADLER 88C.

$\Gamma(\pi^+ e^+ \mu^-)/\Gamma_{total}$ — Γ_{106}/Γ

A test of lepton-family-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.3 \times 10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(\pi^+ e^- \mu^+)/\Gamma_{total}$ — Γ_{107}/Γ

A test of lepton-family-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.3 \times 10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(K^+ e^+ e^-)/\Gamma_{total}$ — Γ_{108}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.8 \times 10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(K^+ \mu^+ \mu^-)/\Gamma_{total}$ — Γ_{109}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<9.2 \times 10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(K^+ e^+ \mu^-)/\Gamma_{total}$ — Γ_{110}/Γ

A test of lepton-family-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.4 \times 10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(K^+ e^- \mu^+)/\Gamma_{total}$ — Γ_{111}/Γ

A test of lepton-family-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.4 \times 10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(\pi^- e^+ e^+)/\Gamma_{total}$ — Γ_{112}/Γ

A test of lepton-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.8 \times 10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(\pi^- \mu^+ \mu^+)/\Gamma_{total}$ — Γ_{113}/Γ

A test of lepton-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<6.8 \times 10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(\pi^- e^+ \mu^+)/\Gamma_{total}$ — Γ_{114}/Γ

A test of lepton-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.7 \times 10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(K^- e^+ e^+)/\Gamma_{total}$ — Γ_{115}/Γ

A test of lepton-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<9.1 \times 10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(K^- \mu^+ \mu^+)/\Gamma_{total}$ — Γ_{116}/Γ

A test of lepton-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.3 \times 10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(K^- e^+ \mu^+)/\Gamma_{total}$ — Γ_{117}/Γ

A test of lepton-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.0 \times 10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(K^+ \pi^+ \pi^-)/\Gamma(K^- \pi^+ \pi^+)$ — $\Gamma_{118}/(\Gamma_{27}+\frac{2}{3}\Gamma_{50})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	90	[44] PICCOLO	77	MRK1	e^+e^- 4.03 GeV

[44] Obtained from $\sigma \times$ BR values of table I.

$D^{\pm}$ PRODUCTION CROSS SECTION AT $\psi(3770)$

A compilation of the cross sections for the direct production of $D^{\pm}$ mesons at or near the $\psi(3770)$ peak in e^+e^- production. We use the absolute cross-section measurement of the Mark III experiment in preference to the $\psi(3770)$ resonance-scan measurements of the other experiments.

VALUE (nanobarns)	DOCUMENT ID		TECN	COMMENT
4.8 ±0.5 OUR FIT Error includes scale factor of 1.2.				
4.2 ±0.6 ±0.3	[45] ADLER	88C	MRK3	e^+e^- 3.768 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
5.5 ±1.0	[46] PARTRIDGE	84	CBAL	e^+e^- 3.771 GeV
6.00±0.72±1.02	[47] SCHINDLER	80	MRK2	e^+e^- 3.771 GeV
9.1 ±2.0	[48] PERUZZI	77	MRK1	e^+e^- 3.774 GeV

[45] This measurement compares events with one detected D to those with two detected D mesons, to determine the the absolute cross section. ADLER 88C measure the ratio of cross sections (neutral to charged) to be 1.36 ± 0.23 ± 0.14. This measurement does not include the decays of the $\psi(3770)$ not associated with charmed particle production.

[46] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. PARTRIDGE 84 measures 6.4 ± 1.15 nb for the cross section. We take the phase space division of neutral and charged D mesons in $\psi(3770)$ decay to be 1.33, and we assume that the $\psi(3770)$ is an isosinglet to evaluate the cross sections. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction.

[47] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. SCHINDLER 80 assume the phase space division of neutral and charged D mesons in $\psi(3770)$ decay to be 1.33, and that the $\psi(3770)$ is an isosinglet. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction.

[48] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. The phase space division of neutral and charged D mesons in $\psi(3770)$ decay is taken to be 1.33, and $\psi(3770)$ is assumed to be an isosinglet. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction. We exclude this measurement from the average because of uncertainties in the contamination from τ lepton pairs. Also see RAPIDIS 77.

$D^{\pm}$ REFERENCES

ALBRECHT 92B ZPHY C53 361 +Ehrlichmann, Hamacher, Krueger+ (ARGUS Collab.)
ANJOS 92 PR D45 R2177 +Appel, Bean, Bracker+ (FNAL E691 Collab.)
COFFMAN 92B PR D45 2196 +DeJongh, Dubois, Eigen+ (Mark III Collab.)
DAOUDI 92 PR D (submitted) +Ford, Johnson, Lingel+ (CLEO Collab.)
ADAMOVICH 91 PL B268 142 +Alexandrov, Antinori, Barberis+ (WA82 Collab.)
ALBRECHT 91 PL B255 634 +Ehrlichmann, Hamacher, Krueger+ (ARGUS Collab.)
ALVAREZ 91 PL B255 639 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
ALVAREZ 91B ZPHY C50 11 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
AMMAR 91 PR D44 3383 +Baringer, Coppage, Davis+ (CLEO Collab.)
ANJOS 91B PR D43 R2063 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
ANJOS 91C PRL 67 1507 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
BAI 91 PRL 66 1011 +Bolton, Brown, Bunnell+ (Mark III Collab.)
COFFMAN 91 PL B263 135 +DeJongh, Dubois, Eigen, Hitlin+ (Mark III Collab.)
FRABETTI 91 PL B263 584 +Bogart, Cheung, Culy+ (FNAL-E687 Collab.)
ALVAREZ 90 ZPHY C47 539 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
ALVAREZ 90C PL B246 261 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
ANJOS 90C PR D41 2705 +Appel, Bean+ (FNAL-TPS Collab.)
ANJOS 90D PR D42 2414 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
ANJOS 90E PRL 65 2630 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
BARLAG 90C ZPHY C46 563 +Becker, Boehringer, Bosman+ (ACCMOR Collab.)
BARLAG 90D ZPHY C48 29 +Becker, Boehringer, Bosman+ (ACCMOR Collab.)
WEIR 90B PR D41 1384 +Klein, Abrams, Adolphsen, Akerlof+ (Mark II Collab.)
ANJOS 89 PRL 62 125 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
ANJOS 89B PRL 62 722 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
ANJOS 89E PL B223 267 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
AVERILL 89 PR D39 123 +Blockus, Brabson+ (HRS Collab.)
ADLER 88B PRL 60 1375 +Becker, Blaylock+ (Mark III Collab.)
ADLER 88C PRL 60 89 +Becker, Blaylock+ (Mark III Collab.)
ALBRECHT 88I PL B210 267 +Boeckmann, Glaeser+ (ARGUS Collab.)
ANJOS 88 PRL 60 897 +Appel+ (FNAL-TPS Collab.)
AOKI 88 PL B209 113 +Arnold, Baroni+ (WA75 Collab.)
HAAS 88 PRL 60 1614 +Hempstead, Jensen+ (CLEO Collab.)
ONG 88 PRL 60 2587 +Weir, Abrams, Amidei+ (Mark II Collab.)
RAAB 88 PR D37 2391 +Anjos, Appel, Bracker+ (FNAL-TPS Collab.)
ADAMOVICH 87 EPL 4 887 +Alexandrov, Bolta+ (Photon Emulsion Collab.)
ADLER 87 PL B196 107 +Becker, Blaylock, Bolton+ (Mark III Collab.)
AGUILAR-... 87D PL B193 140 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
Also 88B ZPHY C40 321 Aguilar-Benitez, Allison, Bailly+ (LEBC-EHS Collab.)
AGUILAR-... 87E ZPHY C36 551 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
Also 88B ZPHY C40 321 Aguilar-Benitez, Allison, Bailly+ (LEBC-EHS Collab.)
AGUILAR-... 87F ZPHY C36 559 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
Also 88 ZPHY C38 520 erratum
BARLAG 87B ZPHY C37 17 +Becker, Boehringer, Bosman+ (ACCMOR Collab.)
BARTEL 87 ZPHY C33 339 +Becker, Felst, Haidt+ (JADE Collab.)
CSORNA 87 PL B191 318 +Mestayer, Panvini, Word+ (CLEO Collab.)
PALKA 87B ZPHY C35 151 +Bailey, Becker+ (ACCMOR Collab.)
ABE 86 PR D33 1 + (SLAC Hybrid Facility Photon Collab.)
AGUILAR-... 86B ZPHY C31 491 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
BALTRUSAIT... 86E PRL 56 2140 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
PAL 86 PR D33 2708 +Atwood, Barish, Bonneaud+ (DELCO Collab.)
AIHARA 85 ZPHY C27 39 +Alston-Garnjost, Badtke, Bakken+ (TPC Collab.)
BALTRUSAIT... 85B PRL 54 1976 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BALTRUSAIT... 85E PRL 55 150 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BARTEL 85J PL 163B 277 +Becker, Cords, Felst+ (JADE Collab.)
ADAMOVICH 84 PL 140B 119 +Alexandrov, Bolta, Bravo+ (WA58 Collab.)
ALTHOFF 84G ZPHY C22 219 +Braunschweig, Kirschfink+ (TASSO Collab.)
ALTHOFF 84J PL 146B 443 +Branschweig, Kirschfink+ (TASSO Collab.)
DERRICK 84 PRL 53 1971 +Fernandez, Fries, Hyman+ (HRS Collab.)
KOOP 84 PRL 52 970 +Sakuda, Atwood, Baillon+ (DELCO Collab.)
PARTRIDGE 84 Cal Tech 1984 Thesis (Crystal Ball Collab.)
AGUILAR-... 83B PL 123B 98 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
AUBERT 83 NP B213 31 +Bassompierre, Becks, Best+ (EMC Collab.)
PARTRIDGE 81 PRL 47 760 +Peck, Porter, Gu+ (Crystal Ball Collab.)
SCHINDLER 81 PR D24 78 +Alam, Boyarski, Breidenbach+ (Mark II Collab.)
TRILLING 81 PRPL 75 57 (LBL, UCB) J
BACINO 80 PRL 45 329 +Ferguson+ (UCLA, SLAC, STAN, UCI, STON)
SCHINDLER 80 PR D21 2716 +Siegrist, Alam, Boyarski+ (Mark II Collab.)
ZHOLENTZ 80 PL 96B 214 +Kurdadze, Lelchuk, Mishnev+ (NOVO)
Also 81 SJNP 34 814 Zholentz, Kurdadze, Lelchuk+ (NOVO)
Translated from YAF 34 1471.
BACINO 79 PRL 43 1073 +Ferguson, Nodulman+ (DELCO Collab.)
BRANDELIK 79 PL 80B 412 +Braunschweig, Martyn, Sander+ (DASP Collab.)
FELLER 78 PRL 40 274 +Litke, Madaras, Ronan+ (LBL, SLAC, NWES, HAWA)
VUILLEMIN 78 PRL 41 1149 +Feldman, Feller+ (LBL, SLAC, NWES, HAWA)
GOLDHABER 77 PL 69B 503 +Wiss, Abrams, Alam+ (LBL, SLAC)
PERUZZI 77 PRL 39 1301 +Piccolo, Feldman+ (SLAC, LBL, NWES, HAWA)
PICCOLO 77 PL 70B 260 +Peruzzi, Luth, Nguyen, Wiss, Abrams+ (SLAC, LBL)
RAPIDIS 77 PRL 39 526 +Gobbi, Luke, Barbaro-Galtieri+ (Mark I Collab.)
PERUZZI 76 PRL 37 569 +Piccolo, Feldman, Nguyen, Wiss+ (SLAC, LBL)

OTHER RELATED PAPERS

MORRISON 89 ARNPS 39 183 +Witherell (UCSB)
SCHINDLER 88 High Energy Electron-Positron Physics 234 (SLAC)
Editors: A. Ali and P. Soeding, World Scientific, Singapore
GRAB 87 SLAC-PUB-4372 (SLAC)
EPS Conference – Uppsala
SCHUBERT 87 IHEP-HD/87-7 (HEID)
EPS Conference – Uppsala, Proc., Vol. 2, p. 791
SNYDER 87 IUHEE-87-11 (IND)
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SCHINDLER 86 SLAC-PUB-4136 (SLAC)
World Press International
SCHINDLER 86B SLAC-PUB-4248 (SLAC)
SLAC Summer Institute

D^0

$I(J^P) = \frac{1}{2}(0^-)$

D^0 MASS

The fit includes the $D^{\pm}$, D^0, $D_s^{\pm}$, and $D_s^{*\pm}$ masses and the $D^0 - D^{\pm}$, $D_s^{\pm} - D^{\pm}$, and $D_s^{*\pm} - D_s^{\pm}$ mass differences.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1864.5± 0.5 OUR FIT					
1864.1± 1.0 OUR AVERAGE					
1864.6± 0.3±1.0	641	BARLAG	90C	ACCM	π^- Cu 230 GeV
1852 ± 7	16	ADAMOVICH	87	EMUL	Photoproduction
1861 ± 4		DERRICK	84	HRS	e^+e^- 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1856 ±36	22	ADAMOVICH	84B	EMUL	Photoproduction
1847 ± 7	1	FIORINO	81	EMUL	$\gamma N \to \overline{D}^0 +$
1863.8± 0.5		[1] SCHINDLER	81	MRK2	e^+e^- 3.77 GeV
1864.7± 0.6		[1] TRILLING	81	RVUE	e^+e^- 3.77 GeV
1863.0± 2.5	238	ASTON	80E	OMEG	$\gamma p \to \overline{D}^0$
1860 ± 2	143	[2] AVERY	80	SPEC	$\gamma N \to D^{*+}$
1869 ± 4	35	[2] AVERY	80	SPEC	$\gamma N \to D^{*+}$
1854 ± 6	94	[2] ATIYA	79	SPEC	$\gamma N \to D^0\overline{D}^0$
1850 ±15	64	BALTAY	78C	HBC	$\nu N \to K^0\pi\pi$
1863 ± 3		GOLDHABER	77	MRK1	D^0, D^+ recoil spectra
1863.3± 0.9		[1] PERUZZI	77	MRK1	e^+e^- 3.77 GeV
1868 ±11		PICCOLO	77	MRK1	e^+e^- 4.03, 4.41 GeV
1865 ±15	234	GOLDHABER	76	MRK1	$K\pi$ and $K3\pi$

[1] PERUZZI 77 and SCHINDLER 81 errors do not include the 0.13% uncertainty in the absolute SPEAR energy calibration. TRILLING 81 uses the high precision $J/\psi(1S)$ and $\psi(2S)$ measurements of ZHOLENTZ 80 to determine this uncertainty and combines the PERUZZI 77 and SCHINDLER 81 results to obtain the value quoted. TRILLING 81 enters the fit in the $D^{\pm}$ mass, and PERUZZI 77 and SCHINDLER 81 enter in the $D^{\pm}-D^0$ mass difference, below.

[2] Error does not include possible systematic mass scale shift, estimated to be less than 5 MeV.

$|m_{D_1^0} - m_{D_2^0}|$, MASS DIFFERENCE

The D_1^0 and D_2^0 are the mass eigenstates of the D^0 meson.

VALUE (10^{-4} eV)	CL%	DOCUMENT ID		TECN	COMMENT
<1.3	90	[3,4] ANJOS	88C	E691	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.6	90	[3] ALBRECHT	87K	ARG	e^+e^- 10 GeV
<1.6	90	[5] LOUIS	86	SPEC	π^- W 225 GeV
<7	90	[3,6] YAMAMOTO	85	DLCO	e^+e^- 29 GeV
<6.5	90	[5] BODEK	82	SPEC	π^-, pFe $\to D^0$

[3] Limit inferred from D^0-$\overline{D}^0$ mixing ratio $\Gamma(K^+\pi^-$ (via $\overline{D}^0))/\Gamma(K^-\pi^+)$ below.

[4] Calculated by us using $\Delta m = (2r/(1-r))^{1/2}\hbar/4.21 \times 10^{-13}$ s, where r is the D^0-$\overline{D}^0$ mixing ratio. See the data on $r \equiv \Gamma(K^+\pi^-$ (via $\overline{D}^0))/\Gamma(K^-\pi^+)$ near the end of the D^0 Listings.

[5] Limit inferred from the D^0-$\overline{D}^0$ mixing ratio $\Gamma(\mu^-$ anything (via $\overline{D}^0))/\Gamma(\mu^+$ anything) near the end of the D^0 Listings.

[6] YAMAMOTO 85 gives $\Delta m/\Gamma < 0.44$. We use $\Gamma = \hbar/4.3 \times 10^{-13}$ s.

$D^{\pm} - D^0$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4.77±0.27 OUR FIT				
4.74±0.28 OUR AVERAGE				
4.7 ±0.3	[7] SCHINDLER	81	MRK2	e^+e^- 3.77 GeV
5.0 ±0.8	[7] PERUZZI	77	MRK1	e^+e^- 3.77 GeV

[7] See the footnote on TRILLING 81 in the D^0 and $D^{\pm}$ sections on the mass.

D^0 MEAN LIFE

Measurements with an error $> 0.5 \times 10^{-13}$ s are omitted from the average, and those with an error $> 1.0 \times 10^{-13}$ s or that have been superseded by later results have been removed from the Listings.

VALUE (10^{-13} s)	EVTS	DOCUMENT ID		TECN	COMMENT
4.20±0.08 OUR AVERAGE					
4.24±0.11±0.07	5118	FRABETTI	91	SILI	γ Be, $D^0 \to K^-\pi^+$, $K^-3\pi$
4.17±0.18±0.15	890	ALVAREZ	90	NA14	$D^0 \to K^-\pi^+$, $K^-3\pi$
$3.88^{+0.23}_{-0.21}$	641	[8] BARLAG	90C	ACCM	π^- Cu 230 GeV
4.8 ±0.4 ±0.3	776	ALBRECHT	88I	ARG	e^+e^- 10 GeV
4.22±0.08±0.10	4212	RAAB	88	SILI	Photoproduction
4.2 ±0.5	90	BARLAG	87B	ACCM	K^- and π^- 200 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

$3.4\ ^{+0.6}_{-0.5}\ \pm0.3$	58	AMENDOLIA	88	SPEC	Photoproduction
$4.6\ ^{+0.6}_{-0.5}$	145	AGUILAR-...	87D	HYBR	$\pi^- p$ and pp
$5.0\ \pm0.7\ \pm0.4$	317	CSORNA	87	CLEO	e^+e^- 10 GeV
$6.1\ \pm0.9\ \pm0.3$	50	ABE	86	HYBR	γp 20 GeV
$4.7\ ^{+0.9}_{-0.8}\ \pm0.5$	74	GLADNEY	86	MRK2	e^+e^- 29 GeV
$4.3\ ^{+0.7}_{-0.5}\ ^{+0.1}_{-0.2}$	58	USHIDA	86B	EMUL	ν wideband
$3.7\ ^{+1.0}_{-0.7}$	26	BAILEY	85	SILI	π^- Be 200 GeV

[8] BARLAG 90C estimate systematic error to be negligible.

$|\tau_{D_1^0} - \tau_{D_2^0}|/\tau_{D^0}$, MEAN LIFE DIFFERENCE/AVERAGE

The D_1^0 and D_2^0 are the mass eigenstates of the D^0 meson.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.17	90	[9,10] ANJOS	88C	E691	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.21	90	[11] LOUIS	86	SPEC	π^- W 225 GeV
<0.8	90	[9] YAMAMOTO	85	DLCO	e^+e^- 29 GeV
<0.55	90	[11] BODEK	82	SPEC	π^-, pFe $\rightarrow D^0$

[9] Limit inferred from the D^0–$\overline{D}^0$ mixing ratio $\Gamma(K^+\pi^-$ (via $\overline{D}^0))/\Gamma(K^-\pi^+)$ near the end of the D^0 Listings.

[10] Calculated by us using $\Delta\Gamma = (8r/(1+r))^{1/2}\hbar/4.21 \times 10^{-13}$ s, where r is the D^0–$\overline{D}^0$ mixing ratio. See the data on $r \equiv \Gamma(K^+\pi^-$ (via $\overline{D}^0))/\Gamma(K^-\pi^+)$ near the end of the D^0 Listings.

[11] Limit inferred from the D^0–$\overline{D}^0$ mixing ratio $\Gamma(\mu^-$ anything (via $\overline{D}^0))/\Gamma(\mu^+$ anything) near the end of the D^0 Listings.

D^0 DECAY MODES

$\overline{D}^0$ modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Inclusive modes			
Γ_1	e^+ anything		(7.7 ± 1.2) %	S=1.1
Γ_2	μ^+ anything		(8.8 ± 2.5) %	
Γ_3	K^- anything		(46 ± 4) %	S=1.5
Γ_4	K^+ anything		$(3.4\ ^{+0.6}_{-0.5})$ %	
Γ_5	K^0 anything + $\overline{K}^0$ anything		(42 ± 5) %	
Γ_6	η anything	[a]	< 13 %	CL=90%
	Semileptonic modes			
Γ_7	$K^-e^+\nu_e$		(3.31 ± 0.29) %	
Γ_8	$K^-\mu^+\nu_\mu$		(2.9 ± 0.5) %	
Γ_9	$K^-\pi^0 e^+\nu_e$	[b]	$(1.6\ ^{+1.3}_{-0.5})$ %	
Γ_{10}	$\overline{K}^0\pi^- e^+\nu_e$	[b]	$(2.8\ ^{+1.7}_{-0.9})$ %	
Γ_{11}	$\overline{K}^*(892)^- e^+\nu_e$ × B($\overline{K}^{*0} \rightarrow K^-\pi^+$)		(1.1 ± 0.4) %	
Γ_{12}	$K^*(892)^-\ell^+\nu_\ell$			
Γ_{13}	$K^-\pi^0(\pi^0)e^+\nu_e$			
Γ_{14}	$\overline{K}^0\pi^-(\pi^0)e^+\nu_e$			
Γ_{15}	$\overline{K}^*(892)^0\pi^- e^+\nu_e$		< 1.1 %	CL=90%
Γ_{16}	$\pi^- e^+\nu_e$		$(3.9\ ^{+2.3}_{-1.2}) \times 10^{-3}$	
	A fraction of the following mode has already appeared above.			
Γ_{17}	$K^*(892)^- e^+\nu_e$		(1.7 ± 0.6) %	
	Hadronic modes with one or three K's			
Γ_{18}	$\overline{K}^0\pi^0$		(2.1 ± 0.5) %	
Γ_{19}	$K^-\pi^+$		(3.65 ± 0.21) %	S=1.1
Γ_{20}	$\overline{K}^0\pi^+\pi^-$		(5.4 ± 0.5) %	S=1.1
	In the fit as $\Gamma_{21} + \frac{2}{3}\Gamma_{60} + \Gamma_{23}$, where $\frac{2}{3}\Gamma_{60} = \Gamma_{22}$.			
Γ_{21}	$\overline{K}^0\rho^0$		$(6.1 \pm 3.0) \times 10^{-3}$	
Γ_{22}	$K^*(892)^-\pi^+$ × B($K^{*-} \rightarrow \overline{K}^0\pi^-$)		(3.0 ± 0.4) %	
Γ_{23}	$\overline{K}^0\pi^+\pi^-$ nonresonant		(1.8 ± 0.5) %	
Γ_{24}	$K^-\pi^+\pi^0$		(11.3 ± 1.1) %	S=1.2
	In the fit as $\Gamma_{25}+\frac{1}{3}\Gamma_{60}+\frac{2}{3}\Gamma_{61}+\Gamma_{28}$, where $\frac{1}{3}\Gamma_{60}=\Gamma_{26}$ and $\frac{2}{3}\Gamma_{61}=\Gamma_{27}$.			
Γ_{25}	$K^-\rho^+$		(7.3 ± 1.1) %	S=1.3
Γ_{26}	$K^*(892)^-\pi^+$ × B($\overline{K}^{*-} \rightarrow K^-\pi^0$)		(1.5 ± 0.2) %	
Γ_{27}	$\overline{K}^*(892)^0\pi^0$ × B($\overline{K}^{*0} \rightarrow K^-\pi^+$)		(1.4 ± 0.7) %	
Γ_{28}	$K^-\pi^+\pi^0$ nonresonant		$(1.1\ ^{+0.8}_{-0.6})$ %	S=1.6
Γ_{29}	$K^-\pi^+\pi^+\pi^-$	[c]	(7.5 ± 0.5) %	S=1.1
Γ_{30}	$K^-\pi^+\rho^0$		(6.4 ± 0.5) %	
Γ_{31}	$K^-\pi^+\rho^0$ 3-body		$(6.3 \pm 3.4) \times 10^{-3}$	
Γ_{32}	$\overline{K}^*(892)^0\rho^0$ × B($\overline{K}^{*0} \rightarrow K^-\pi^+$)		(1.0 ± 0.4) %	
Γ_{33}	$K^-a_1(1260)^+$ × B($a_1(1260)^+ \rightarrow \pi^+\pi^+\pi^-$)		(3.7 ± 0.7) %	
Γ_{34}	$K_1(1270)^-\pi^+$ × B($K_1(1270)^- \rightarrow K^-\pi^+\pi^-$)		$(3.7 \pm 1.1) \times 10^{-3}$	
Γ_{35}	$\overline{K}^*(892)^0\pi^+\pi^-$ 3-body × B($\overline{K}^{*0} \rightarrow K^-\pi^+$)		(1.1 ± 0.3) %	
Γ_{36}	$K^-\pi^+\pi^+\pi^-$ nonresonant		(1.8 ± 0.5) %	
Γ_{37}	$\overline{K}^0\pi^+\pi^-\pi^0$		(10.3 ± 1.7) %	
Γ_{38}	$\overline{K}^0\omega$ × B($\omega \rightarrow \pi^+\pi^-\pi^0$)		(2.2 ± 0.4) %	
Γ_{39}	$K^*(892)^-\rho^+$ × B($K^{*-} \rightarrow \overline{K}^0\pi^-$)		(4.1 ± 1.7) %	
Γ_{40}	$\overline{K}^*(892)^0\rho^0$ × B($\overline{K}^{*0} \rightarrow \overline{K}^0\pi^0$)		$(5.0 \pm 2.0) \times 10^{-3}$	
Γ_{41}	$K_1(1270)^-\pi^+$ × B($K_1(1270)^- \rightarrow \overline{K}^0\pi^-\pi^0$)		$(5.2 \pm 1.6) \times 10^{-3}$	
Γ_{42}	$\overline{K}^*(892)^0\pi^+\pi^-$ 3-body × B($\overline{K}^{*0} \rightarrow \overline{K}^0\pi^0$)		$(5.3 \pm 1.7) \times 10^{-3}$	
Γ_{43}	$\overline{K}^0\pi^+\pi^-\pi^0$ nonresonant		(2.2 ± 2.2) %	
Γ_{44}	$K^-\pi^+\pi^0\pi^0$		(15 ± 5) %	
Γ_{45}	$K^-\pi^+\pi^+\pi^-\pi^0$		(3.5 ± 0.6) %	S=1.6
Γ_{46}	$\overline{K}^*(892)^0\pi^+\pi^-\pi^0$ × B($\overline{K}^{*0} \rightarrow K^-\pi^+$)		(1.1 ± 0.5) %	
Γ_{47}	$\overline{K}^*(892)^0\eta$ × B($\overline{K}^{*0} \rightarrow K^-\pi^+$) × B($\eta \rightarrow \pi^+\pi^-\pi^0$)		$(3.3 \pm 1.9) \times 10^{-3}$	
Γ_{48}	$\overline{K}^0\pi^+\pi^+\pi^-\pi^-$		$(8.5 \pm 1.4) \times 10^{-3}$	
Γ_{49}	$\overline{K}^0\pi^+\pi^-\pi^0\pi^0(\pi^0)$		$(12.7\ ^{+3.5}_{-2.4})$ %	
Γ_{50}	$\overline{K}^0K^+K^-$			
	In the fit as $\frac{1}{2}\Gamma_{59} + \Gamma_{52}$, where $\frac{1}{2}\Gamma_{59} = \Gamma_{51}$.			
Γ_{51}	$\overline{K}^0\phi$ × B($\phi \rightarrow K^+K^-$)		$(4.4 \pm 0.6) \times 10^{-3}$	
Γ_{52}	$\overline{K}^0K^+K^-$ non-ϕ		$(5.2 \pm 0.9) \times 10^{-3}$	S=1.1
Γ_{53}	$K_S^0K_S^0K_S^0$		$(8.9 \pm 2.5) \times 10^{-4}$	
Γ_{54}	$K^+K^-\overline{K}^0\pi^0$		$(9\ ^{+6}_{-4}) \times 10^{-3}$	
	Fractions of many of the following modes have already appeared above. (Modes for which there are only upper limits and $\overline{K}^*(892)\rho$ submodes only appear below.)			
Γ_{55}	$\overline{K}^0\eta$		< 2.3 %	CL=90%
Γ_{56}	$\overline{K}^0\rho^0$		$(6.1 \pm 3.0) \times 10^{-3}$	
Γ_{57}	$K^-\rho^+$		(7.3 ± 1.1) %	S=1.2
Γ_{58}	$\overline{K}^0\omega$		(2.5 ± 0.5) %	
Γ_{59}	$\overline{K}^0\phi$		$(8.8 \pm 1.2) \times 10^{-3}$	S=1.1
Γ_{60}	$K^*(892)^-\pi^+$		(4.5 ± 0.6) %	
Γ_{61}	$\overline{K}^*(892)^0\pi^0$		(2.1 ± 1.0) %	S=1.5
Γ_{62}	$\overline{K}^*(892)^0\pi^+\pi^-$ 3-body		(1.6 ± 0.5) %	
Γ_{63}	$\overline{K}^*(892)^0\rho^0$		(1.5 ± 0.6) %	
Γ_{64}	$\overline{K}^*(892)^0\rho^0$ transverse		(1.5 ± 0.5) %	
Γ_{65}	$\overline{K}^*(892)^0\rho^0$ S-wave longitudinal		< 3 $\times 10^{-3}$	CL=90%
Γ_{66}	$\overline{K}^*(892)^0\rho^0$ P-wave		< 3 $\times 10^{-3}$	CL=90%
Γ_{67}	$\overline{K}^*(892)^-\rho^+$		(6.2 ± 2.5) %	
Γ_{68}	$\overline{K}^*(892)^-\rho^+$ longitudinal		(3.0 ± 1.2) %	
Γ_{69}	$\overline{K}^*(892)^-\rho^+$ transverse		(3.3 ± 1.9) %	
Γ_{70}	$\overline{K}^*(892)^-\rho^+$ P-wave		< 1.5 %	CL=90%
Γ_{71}	$K^-a_1(1260)^+$		(7.4 ± 1.3) %	
Γ_{72}	$\overline{K}^0a_1(1260)^0$		< 1.9 %	CL=90%
Γ_{73}	$K^-a_2(1320)^+$		< 6 $\times 10^{-3}$	CL=90%
Γ_{74}	$K_1(1270)^-\pi^+$		(1.09 ± 0.33) %	
Γ_{75}	$K_1(1400)^-\pi^+$		< 1.2 %	CL=90%
Γ_{76}	$\overline{K}_1(1400)^0\pi^0$		< 3.7 %	CL=90%
Γ_{77}	$K^*(1410)^-\pi^+$		< 1.2 %	CL=90%
Γ_{78}	$\overline{K}^*(892)^0\pi^+\pi^-\pi^0$		(1.6 ± 0.8) %	
Γ_{79}	$\overline{K}^*(892)^0\eta$	[d]	(2.1 ± 1.2) %	
Γ_{80}	$\overline{K}^*(892)^0\omega$		< 1.5 %	CL=90%

Pionic modes

	Mode	Fraction	Scale factor / Confidence level
Γ_{81}	$\pi^+\pi^-$	$(1.63 \pm 0.19) \times 10^{-3}$	
Γ_{82}	$\pi^0\pi^0$	$< 4.6 \times 10^{-3}$	CL=90%
Γ_{83}	$\pi^+\pi^-\pi^0$	(1.5 ± 1.0) %	S=2.5
Γ_{84}	$\pi^+\pi^+\pi^-\pi^-$	$(7.5 \pm 0.9) \times 10^{-3}$	
Γ_{85}	$\pi^+\pi^+\pi^-\pi^-\pi^0$	(1.7 ± 0.5) %	
Γ_{86}	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$	$(4.0 \pm 3.0) \times 10^{-4}$	

Hadronic modes with two K's

	Mode	Fraction	Scale factor / Confidence level
Γ_{87}	K^+K^-	$(4.1 \pm 0.4) \times 10^{-3}$	S=1.1
Γ_{88}	$K^0\overline{K}^0$	$(1.1 \pm 0.4) \times 10^{-3}$	
Γ_{89}	$K^0K^-\pi^+$	$(6.4 \pm 1.1) \times 10^{-3}$	S=1.1
Γ_{90}	$\overline{K}^*(892)^0 K^0 \times B(\overline{K}^{*0} \to K^-\pi^+)$	$< 1.1 \times 10^{-3}$	CL=90%
Γ_{91}	$K^*(892)^+ K^- \times B(K^{*+} \to K^0\pi^+)$	$(2.3 \pm 0.5) \times 10^{-3}$	
Γ_{92}	$K^0K^-\pi^+$ nonresonant	$(2.2 \pm 2.2) \times 10^{-3}$	
Γ_{93}	$\overline{K}^0K^+\pi^-$	$(4.9 \pm 1.0) \times 10^{-3}$	
Γ_{94}	$K^*(892)^0\overline{K}^0 \times B(K^{*0} \to K^+\pi^-)$	$< 5 \times 10^{-4}$	CL=90%
Γ_{95}	$K^*(892)^- K^+ \times B(K^{*-} \to \overline{K}^0\pi^-)$	$(1.3 \pm 0.7) \times 10^{-3}$	
Γ_{96}	$\overline{K}^0K^+\pi^-$ nonresonant	$(3.7 {}^{+2.2}_{-1.8}) \times 10^{-3}$	
Γ_{97}	$K^+K^-\pi^+\pi^-$	$(2.4 \pm 0.4) \times 10^{-3}$	
Γ_{98}	$\phi\pi^+\pi^- \times B(\phi \to K^+K^-)$	$(1.2 \pm 0.4) \times 10^{-3}$	
Γ_{99}	$\phi\rho^0 \times B(\phi \to K^+K^-)$	$(9.0 \pm 2.5) \times 10^{-4}$	
Γ_{100}	$K^*(892)^0K^-\pi^+$ + cc $\times$ $B(K^{*0} \to K^-\pi^+)$	$(5 {}^{+8}_{-5}) \times 10^{-4}$	
Γ_{101}	$K^*(892)^0\overline{K}^*(892)^0 \times B^2(K^{*0} \to K^-\pi^+)$	$(1.2 {}^{+0.7}_{-0.5}) \times 10^{-3}$	
Γ_{102}	$K^+K^-\pi^+\pi^-$ nonresonant	$(7 {}^{+80}_{-8}) \times 10^{-5}$	
Γ_{103}	$K^+K^-\pi^0\pi^0$	seen	
Γ_{104}	$K^0K^-\pi^+\pi^0$	seen	
Γ_{105}	$K^+K^-\pi^+\pi^-\pi^0$	$(2.8 {}^{+2.5}_{-1.5}) \times 10^{-3}$	

Fractions of the following modes have already appeared above.

	Mode	Fraction	Confidence level
Γ_{106}	$\overline{K}^*(892)^0K^0$	$< 1.6 \times 10^{-3}$	CL=90%
Γ_{107}	$K^*(892)^+K^-$	$(3.5 \pm 0.8) \times 10^{-3}$	
Γ_{108}	$K^*(892)^0\overline{K}^0$	$< 8 \times 10^{-4}$	CL=90%
Γ_{109}	$K^*(892)^-K^+$	$(2.0 \pm 1.0) \times 10^{-3}$	
Γ_{110}	$\phi\pi^+\pi^-$	$(2.4 \pm 0.8) \times 10^{-3}$	
Γ_{111}	$\phi\rho^0$	$(1.8 \pm 0.5) \times 10^{-3}$	
Γ_{112}	$K^*(892)^0K^-\pi^+$ +c.c.	$(7 {}^{+12}_{-8}) \times 10^{-4}$	
Γ_{113}	$K^*(892)^0\overline{K}^*(892)^0$	$(2.7 {}^{+1.5}_{-1.2}) \times 10^{-3}$	

Lepton Family number (*LF*) violating, Flavor-Changing neutral current (*FC*), decay via Mixing (*MX*), or Doubly Cabibbo suppressed (*DC*) modes

	Mode		Fraction	Confidence level
Γ_{114}	e^+e^-	*FC*	$< 1.3 \times 10^{-4}$	CL=90%
Γ_{115}	$\mu^+\mu^-$	*FC*	$< 1.1 \times 10^{-5}$	CL=90%
Γ_{116}	$\mu^\pm e^\mp$	*LF*	[e] $< 1.0 \times 10^{-4}$	CL=90%
Γ_{117}	$\overline{K}^0e^+e^-$	*FC*	$< 1.7 \times 10^{-3}$	CL=90%
Γ_{118}	$\rho^0e^+e^-$	*FC*	$< 4.5 \times 10^{-4}$	CL=90%
Γ_{119}	$\rho^0\mu^+\mu^-$	*FC*	$< 8.1 \times 10^{-4}$	CL=90%
Γ_{120}	μ^- anything (via $\overline{D}^0$)	*MX*	$< 5 \times 10^{-4}$	CL=90%
Γ_{121}	$K^+\pi^-$	*DC*	$< 4 \times 10^{-4}$	CL=90%
Γ_{122}	$K^+\pi^-$ (via $\overline{D}^0$)	*MX*	$< 1.4 \times 10^{-4}$	CL=90%
Γ_{123}	$K^+\pi^+\pi^-\pi^-$	*DC*	$< 1.3 \times 10^{-3}$	CL=90%

Mode needed for fitting purposes

	Mode	Fraction	Scale factor
Γ_{124}	Modes not in the fit.	(41 ± 4) %	S=1.1

[*a*] This is a weighted average of $D^\pm$ (44%) and D^0 (56%) branching fractions. See the $D^\pm$ Listing for $D^\pm$ and $D^0 \to \eta X$.

[*b*] It is generally agreed that the $\overline{K}\pi e^+\nu_e$ decays of the D^+ and D^0 are dominantly $\overline{K}^*(892)e^+\nu_e$. In that case, these $\overline{K}\pi e^+\nu_e$ branching fractions are too large to agree with the $K^*(892)^- e^+\nu_e$ branching fraction in the Table. Our guess is that the fault lies with these $\overline{K}\pi e^+\nu_e$ branching fractions. What is lacking in order to include these results in a fit and at least get a consistent set of branching fractions is a measurement of the ratio $\Gamma(K^*(892)^- e^+\nu_e)/\Gamma(\overline{K}\pi e^+\nu_e)$ for the D^0 alone.

[*c*] The whole differs from the sum of the parts due to interference effects; see COFFMAN 92B.

[*d*] This value is, however, in some conflict with an upper limit of 0.9% (90% CL); see the Full Listings.

[*e*] The value is for the sum of the charge states indicated.

CONSTRAINED FIT INFORMATION

An overall fit to 15 products of a cross section and a partial width, a cross section, and 43 branching ratios uses 98 measurements and one constraint to determine 28 parameters. The overall fit has a $\chi^2 = 43.2$ for 71 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_{18}	10									
x_{19}	55	19								
x_{21}	4	7	8							
x_{23}	8	17	15	−33						
x_{25}	19	9	33	5	11					
x_{28}	2	0	3	1	2	−35				
x_{29}	32	13	58	5	10	22	2			
x_{37}	15	15	27	8	18	13	0	21		
x_{45}	10	4	18	2	3	7	0	31	6	
x_{48}	12	17	23	10	23	11	0	16	19	5
x_{52}	14	17	25	10	23	12	0	17	20	5
x_{58}	11	11	20	6	13	10	0	15	59	5
x_{59}	17	23	31	13	32	15	0	21	26	6
x_{60}	18	16	32	−12	−35	10	−3	22	20	7
x_{61}	4	2	8	1	3	−25	−16	5	3	2
x_{62}	7	4	13	2	4	5	0	20	14	6
x_{64}	6	3	11	2	3	4	0	16	13	5
x_{74}	8	7	14	4	9	7	0	12	47	4
x_{87}	36	12	65	5	10	22	2	38	18	12
x_{88}	7	6	13	4	8	5	0	8	8	2
x_{89}	15	17	27	10	23	12	0	18	20	6
x_{93}	13	13	23	7	17	10	0	15	15	5
x_{97}	8	3	15	1	3	6	0	25	5	8
x_{107}	10	13	19	8	18	9	0	13	15	4
x_{109}	4	6	8	3	8	4	0	5	6	2
x_{124}	−39	−35	−62	−13	−27	−36	−6	−54	−76	−30
σ	−41	−24	−75	−10	−18	−41	−1	−52	−34	−16
	x_7	x_{18}	x_{19}	x_{21}	x_{23}	x_{25}	x_{28}	x_{29}	x_{37}	x_{45}

x_{52}	23									
x_{58}	14	15								
x_{59}	31	14	19							
x_{60}	20	21	14	28						
x_{61}	2	2	2	3	0					
x_{62}	5	5	9	6	6	1				
x_{64}	4	4	8	6	5	1	4			
x_{74}	9	10	28	13	10	1	7	6		
x_{87}	15	16	13	20	21	5	9	7	9	
x_{88}	8	9	6	12	8	1	2	2	4	13
x_{89}	23	23	14	31	21	3	5	4	10	18
x_{93}	17	18	11	24	16	2	4	4	7	15
x_{97}	4	4	4	5	6	1	5	4	3	10
x_{107}	17	18	11	24	16	2	4	3	7	12
x_{109}	8	8	5	10	7	1	2	1	3	5
x_{124}	−35	−35	−56	−45	−36	−19	−28	−28	−43	−41
σ	−28	−31	−24	−39	−41	−9	−13	−10	−17	−49
	x_{48}	x_{52}	x_{58}	x_{59}	x_{60}	x_{61}	x_{62}	x_{64}	x_{74}	x_{87}

x_{89}	9						
x_{93}	7	18					
x_{97}	2	5	4				
x_{107}	7	18	13	3			
x_{109}	3	8	6	1	6		
x_{124}	−15	−36	−28	−14	−27	−13	
σ	−13	−31	−25	−13	−23	−10	66
	x_{88}	x_{89}	x_{93}	x_{97}	x_{107}	x_{109}	x_{124}

D^0 BRANCHING RATIOS

See the note in the $D^{\pm}$ Listing on new measurements of D^+ and D^0 decays. Some older, now obsolete results have been omitted from these Listings. They may be found in our 1990 edition (Phys. Lett. **B239**).

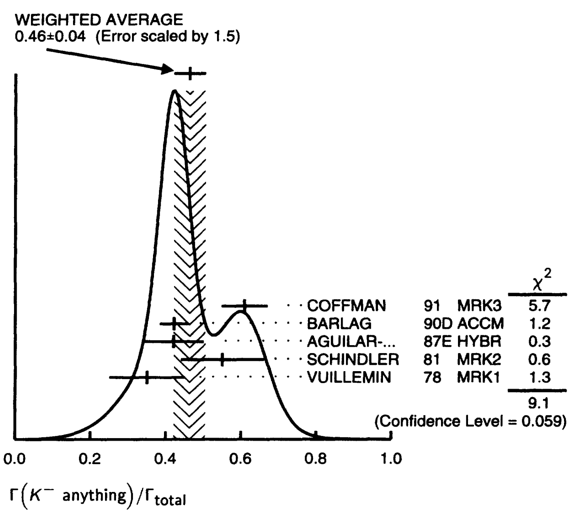
$\Gamma(e^+ \text{ anything})/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.077±0.012 OUR AVERAGE	Error includes scale factor of 1.1.				
0.15 ±0.05		AGUILAR-...	87E	HYBR	πp, pp 360, 400 GeV
0.075±0.011±0.004	137	BALTRUSAIT...	85B	MRK3	e^+e^- 3.77 GeV
0.055±0.037	12	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV

$\Gamma(K^- \text{ anything})/\Gamma_{total}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.46 ±0.04 OUR AVERAGE	Error includes scale factor of 1.5. See the ideogram below.				
0.609±0.032±0.052		COFFMAN	91	MRK3	e^+e^- 3.77 GeV
0.422±0.038		[12] BARLAG	90D	ACCM	π^- Cu 230 GeV
0.42 ±0.08		AGUILAR-...	87E	HYBR	πp, pp 360, 400 GeV
0.55 ±0.11	121	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.35 ±0.10	19	VUILLEMIN	78	MRK1	e^+e^- 3.772 GeV

[12] BARLAG 90D computes the branching fraction using topological normalization.



$\Gamma(K^+ \text{ anything})/\Gamma_{total}$ — Γ_4/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.034^{+0.006}_{-0.005}$ OUR AVERAGE					
0.028±0.009±0.004		COFFMAN	91	MRK3	e^+e^- 3.77 GeV
$0.034^{+0.008}_{-0.007}$		[13] BARLAG	90D	ACCM	π^- Cu 230 GeV
$0.03\ ^{+0.05}_{-0.02}$		AGUILAR-...	87E	HYBR	πp, pp 360, 400 GeV
0.08 ±0.03	25	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV

[13] BARLAG 90D computes the branching fraction using topological normalization.

$[\Gamma(K^0 \text{ anything}) + \Gamma(\overline{K}^0 \text{ anything})]/\Gamma_{total}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.42 ±0.05 OUR AVERAGE					
0.455±0.050±0.032		COFFMAN	91	MRK3	e^+e^- 3.77 GeV
0.29 ±0.11	13	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.57 ±0.26	6	VUILLEMIN	78	MRK1	e^+e^- 3.772 GeV

$\Gamma(K^- e^+ \nu_e)/\Gamma_{total}$ — Γ_7/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0331±0.0029 OUR FIT					
0.034 ±0.005 ±0.004	55	[14] ADLER	89	MRK3	e^+e^- 3.77 GeV

[14] Experiment gives $|V_{cd}/V_{cs}|^2 = 0.057^{+0.038}_{-0.015} \pm 0.005$.

$\Gamma(K^- e^+ \nu_e)/\Gamma(K^- \pi^+)$ — Γ_7/Γ_{19}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.91±0.07 OUR FIT					
0.90±0.07 OUR AVERAGE					
0.90±0.06±0.06	584	CRAWFORD	91B	CLEO	$e^+e^- \approx$ 10.5 GeV
0.91±0.07±0.11		ANJOS	89F	E691	Photoproduction

$\Gamma(K^- \mu^+ \nu_\mu)/\Gamma(K^- \pi^+)$ — Γ_8/Γ_{19}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.79±0.08±0.09	231	CRAWFORD	91B	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(K^- \mu^+ \nu_\mu)/\Gamma(\mu^+ \text{ anything})$ — Γ_8/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.32±0.05±0.05	124	KODAMA	91	EMUL	pA 800 GeV

$\Gamma(K^- \pi^0 e^+ \nu_e)/\Gamma_{total}$ — Γ_9/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.016^{+0.013}_{-0.005}$±0.002	4	[15] BAI	91	MRK3	$e^+e^- \approx$ 3.77 GeV

[15] BAI 91 finds that a fraction $0.79^{+0.15}_{-0.17}{}^{+0.09}_{-0.03}$ of combined D^+ and D^0 decays to $\overline{K}\pi e^+ \nu_e$ (24 events) are $\overline{K}^*(892) e^+ \nu_e$.

$\Gamma(\overline{K}^0 \pi^- e^+ \nu_e)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.028^{+0.017}_{-0.008}$±0.003	6	[16] BAI	91	MRK3	$e^+e^- \approx$ 3.77 GeV

[16] BAI 91 finds that a fraction $0.79^{+0.15}_{-0.17}{}^{+0.09}_{-0.03}$ of combined D^+ and D^0 decays to $\overline{K}\pi e^+ \nu_e$ (24 events) are $\overline{K}^*(892) e^+ \nu_e$.

$\Gamma(K^*(892)^- e^+ \nu_e)/\Gamma(K^- e^+ \nu_e)$ — Γ_{17}/Γ_7

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.51±0.18±0.06	CRAWFORD	91B	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(\overline{K}^*(892)^0 \pi^- e^+ \nu_e)/\Gamma(K^*(892)^- e^+ \nu_e)$ — Γ_{15}/Γ_{17}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.64	90	CRAWFORD	91B	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(K^*(892)^- \ell^+ \nu_\ell)/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ — $\Gamma_{12}/(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})$

This an average of the $K^*(892)^- e^+ \nu_e$ and $K^*(892)^- \mu^+ \nu_\mu$ ratios. Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.24±0.07±0.06	137	[17] ALEXANDER	90B	CLEO	e^+e^- 10.5–11 GeV

[17] ALEXANDER 90B cannot exclude extra π^0's in the final state. See nearby data blocks for more detailed results.

$\Gamma(K^- \pi^0 (\pi^0) e^+ \nu_e)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.023^{+0.050}_{-0.006}$±0.001	1	[18] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[18] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization. Does not distinguish presence of a second π^0.

$\Gamma(\overline{K}^0 \pi^- (\pi^0) e^+ \nu_e)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.079^{+0.069}_{-0.023}$±0.005	3	[19] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[19] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization. Does not distinguish presence of a second π^0.

$\Gamma(\pi^- e^+ \nu_e)/\Gamma_{total}$ — Γ_{16}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.0039^{+0.0023}_{-0.0011}$±0.0004	7	[20] ADLER	89	MRK3	e^+e^- 3.77 GeV

[20] Experiment gives $|V_{cd}/V_{cs}|^2 = 0.057^{+0.038}_{-0.015} \pm 0.005$.

$\Gamma(\overline{K}^0 \pi^0)/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ — $\Gamma_{18}/(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.38±0.08 OUR FIT					
0.36±0.04±0.08	104	KINOSHITA	91	CLEO	$e^+e^- \sim$ 10.7 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^0 \pi^0)/\Gamma_{total}$ — $\sigma \times \Gamma_{18}/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID		TECN	COMMENT
0.139±0.031 OUR FIT					
0.18 ±0.08	8	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV

$\Gamma(K^-\pi^+)/\Gamma_{total}$ Γ_{19}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0365±0.0021 OUR FIT Error includes scale factor of 1.1.				
0.0380±0.0031 OUR AVERAGE				
0.0362±0.0034±0.0044		[21] DECAMP 91J	ALEP	From Z decays
$0.0375^{+0.0044}_{-0.0041}$		[22] BARLAG 90D	ACCM	π^- Cu 230 GeV
0.045 ±0.008 ±0.005	56	[23] ABACHI 88	HRS	e^+e^- 29 GeV
$0.040\ ^{+0.021}_{-0.010}$ ±0.002	7	[22] AGUILAR-... 87F	HYBR	πp, pp 360, 400 GeV

[21] DECAMP 91J uses the technique developed by ABACHI 88. The excess of low p_t pions to the jet axis measures the $D^*(2010)^+$ fraction decaying via a slow pion to the D^0. A separate measurement of $D^*(2010)^+ \rightarrow (K^-\pi^+)\pi^+$ determines the D^0 branching fraction.
[22] AGUILAR-BENITEZ 87F and BARLAG 90D compute the branching fraction using topological normalization.
[23] ABACHI 88 branching fraction computed by tagging $D^*(2010)^+ \rightarrow D^0\pi^+$ through excess low momentum π^+ over background.

$\sigma(e^+e^- \rightarrow \psi(3770)) \times \Gamma(K^-\pi^+)/\Gamma_{total}$ $\sigma \times \Gamma_{19}/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID	TECN	COMMENT
0.246±0.011 OUR FIT Error includes scale factor of 1.1.				
0.245±0.012 OUR AVERAGE				
0.248±0.009±0.014	930	BALTRUSAIT...86E	MRK3	e^+e^- 3.77 GeV
0.24 ±0.02	263	SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
0.25 ±0.05	130	PERUZZI 77	MRK1	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\pi^+\pi^-)/\Gamma_{total}$ $(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.054 ±0.005 OUR FIT Error includes scale factor of 1.1.				
$0.042\ ^{+0.011}_{-0.008}$ OUR AVERAGE				
$0.0411^{+0.0109}_{-0.0105}$		[24] BARLAG 90D	ACCM	π^- Cu 230 GeV
$0.045\ ^{+0.059}_{-0.014}$ ±0.003	2	[24] AGUILAR-... 87F	HYBR	πp, pp 360, 400 GeV

[24] AGUILAR-BENITEZ 87F and BARLAG 90D compute the branching fraction using topological normalization.

$\Gamma(\overline{K}^0\pi^+\pi^-)/\Gamma(K^-\pi^+)$ $(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})/\Gamma_{19}$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.49±0.12 OUR FIT Error includes scale factor of 1.1.				
2.1 ±0.6 OUR AVERAGE				
1.7 ±0.8	35	AVERY 80	SPEC	$\gamma N \rightarrow D^{*+}$
2.8 ±1.0	116	PICCOLO 77	MRK1	e^+e^- 4.03, 4.41 GeV

$\sigma(e^+e^- \rightarrow \psi(3770)) \times \Gamma(\overline{K}^0\pi^+\pi^-)/\Gamma_{total}$ $\sigma \times (\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID	TECN	COMMENT
0.366±0.026 OUR FIT Error includes scale factor of 1.1.				
0.36 ±0.04 OUR AVERAGE				
0.37 ±0.03 ±0.03		ADLER 87	MRK3	e^+e^- 3.77 GeV
0.30 ±0.08	32	SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
0.46 ±0.12	28	PERUZZI 77	MRK1	e^+e^- 3.77 GeV

$\sigma(e^+e^- \rightarrow \psi(3770)) \times \Gamma(\overline{K}^0\rho^0)/\Gamma_{total}$ $\sigma \times \Gamma_{21}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID	TECN	COMMENT
0.041±0.020 OUR FIT			
0.04 ±0.01 ±0.02	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\sigma(e^+e^- \rightarrow \psi(3770)) \times \Gamma(K^*(892)^-\pi^+)/\Gamma_{total}$ $\sigma \times \Gamma_{60}/\Gamma$

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE (nanobarns)	EVTS	DOCUMENT ID	TECN	COMMENT
0.30±0.04 OUR FIT				
0.30±0.04 OUR AVERAGE				
0.28±0.04±0.08		ADLER 87	MRK3	Using $K^{*-} \rightarrow K^-\pi^0$
0.31±0.02±0.05		ADLER 87	MRK3	Using $K^{*-} \rightarrow \overline{K}^0\pi^-$
$0.31^{+0.11}_{-0.12}$	25	SCHINDLER 81	MRK2	e^+e^- 3.771 GeV

$\sigma(e^+e^- \rightarrow \psi(3770)) \times \Gamma(\overline{K}^0\pi^+\pi^-$ nonresonant$)/\Gamma_{total}$ $\sigma \times \Gamma_{23}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID	TECN	COMMENT
0.124±0.032 OUR FIT			
0.12 ±0.02 ±0.04	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^0)/\Gamma_{total}$ $(\Gamma_{25}+\Gamma_{28}+\frac{1}{3}\Gamma_{60}+\frac{2}{3}\Gamma_{61})/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.113 ±0.011 OUR FIT Error includes scale factor of 1.2.				
$0.092\ ^{+0.019}_{-0.016}$ OUR AVERAGE				
$0.0867^{+0.0200}_{-0.0196}$		[25] BARLAG 90D	ACCM	π^- Cu 230 GeV
$0.106\ ^{+0.061}_{-0.028}$ ±0.006	5	[25] AGUILAR-... 87F	HYBR	πp, pp 360, 400 GeV

[25] AGUILAR-BENITEZ 87F and BARLAG 90D compute the branching fraction using topological normalization.

$\Gamma(K^-\pi^+\pi^0)/\Gamma(K^-\pi^+)$ $(\Gamma_{25}+\Gamma_{28}+\frac{1}{3}\Gamma_{60}+\frac{2}{3}\Gamma_{61})/\Gamma_{19}$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
3.10±0.26 OUR FIT Error includes scale factor of 1.2.				
3.1 ±0.5 OUR AVERAGE				
4.0 ±0.9 ±1.0	69	ALVAREZ 91B	NA14	Photoproduction
2.8 ±0.14±0.52	1050	KINOSHITA 91	CLEO	$e^+e^- \sim 10.7$ GeV
4.2 ±1.4	41	SUMMERS 84	E691	Photoproduction

$\sigma(e^+e^- \rightarrow \psi(3770)) \times \Gamma(K^-\pi^+\pi^0)/\Gamma_{total}$ $\sigma \times (\Gamma_{25}+\Gamma_{28}+\frac{1}{3}\Gamma_{60}+\frac{2}{3}\Gamma_{61})/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID	TECN	COMMENT
0.76 ±0.06 OUR FIT Error includes scale factor of 1.2.				
0.75 ±0.09 OUR AVERAGE				
0.759±0.044±0.083	931	BALTRUSAIT...86E	MRK3	e^+e^- 3.77 GeV
0.68 ±0.23	37	SCHINDLER 81	MRK2	e^+e^- 3.771 GeV

$\Gamma(K^-\rho^+)/\Gamma(K^-\pi^+\pi^0)$ $\Gamma_{25}/(\Gamma_{25}+\Gamma_{28}+\frac{1}{3}\Gamma_{60}+\frac{2}{3}\Gamma_{61})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.64±0.08 OUR FIT Error includes scale factor of 1.4.				
$0.31^{+0.20}_{-0.14}$	13	SUMMERS 84	E691	Photoproduction

$\sigma(e^+e^- \rightarrow \psi(3770)) \times \Gamma(K^-\rho^+)/\Gamma_{total}$ $\sigma \times \Gamma_{25}/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID	TECN	COMMENT
0.49±0.07 OUR FIT Error includes scale factor of 1.2.				
0.61±0.09 OUR AVERAGE				
0.62±0.02±0.09		ADLER 87	MRK3	e^+e^- 3.77 GeV
$0.58^{+0.22}_{-0.23}$	31	SCHINDLER 81	MRK2	e^+e^- 3.771 GeV

$\sigma(e^+e^- \rightarrow \psi(3770)) \times \Gamma(\overline{K}^*(892)^0\pi^0)/\Gamma_{total}$ $\sigma \times \Gamma_{61}/\Gamma$

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE (nanobarns)	DOCUMENT ID	TECN	COMMENT
0.14±0.06 OUR FIT Error includes scale factor of 1.5.			
0.15±0.02±0.04	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^0$ nonresonant$)/\Gamma(K^-\pi^+\pi^0)$ $\Gamma_{28}/(\Gamma_{25}+\Gamma_{28}+\frac{1}{3}\Gamma_{60}+\frac{2}{3}\Gamma_{61})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.10^{+0.07}_{-0.06}$ OUR FIT Error includes scale factor of 1.6.				
0.51±0.22	21	SUMMERS 84	E691	Photoproduction

$\sigma(e^+e^- \rightarrow \psi(3770)) \times \Gamma(K^-\pi^+\pi^0$ nonresonant$)/\Gamma_{total}$ $\sigma \times \Gamma_{28}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID	TECN	COMMENT
$0.08^{+0.05}_{-0.04}$ OUR FIT Error includes scale factor of 1.6.			
0.07±0.02±0.03	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^+\pi^-)/\Gamma_{total}$ Γ_{29}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.075 ±0.005 OUR FIT Error includes scale factor of 1.1.				
0.076 ±0.006 OUR AVERAGE				
$0.0772^{+0.0068}_{-0.0065}$		[26] BARLAG 90D	ACCM	π^- Cu 230 GeV
$0.065\ ^{+0.017}_{-0.011}$ ±0.019	13	[26] AGUILAR-... 87F	HYBR	πp, pp 360, 400 GeV

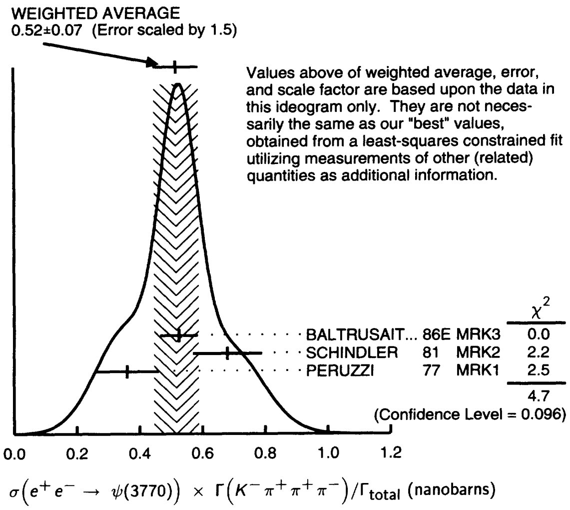
[26] AGUILAR-BENITEZ 87F and BARLAG 90D compute the branching fraction using topological normalization.

$\Gamma(K^-\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+)$ Γ_{29}/Γ_{19}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
2.05±0.11 OUR FIT Error includes scale factor of 1.1.				
2.08±0.14 OUR AVERAGE				
1.90±0.25±0.20	337	ALVAREZ 91B	NA14	Photoproduction
2.12±0.16±0.09		BORTOLETTO88	CLEO	e^+e^- 10.55 GeV
2.0 ±0.9	48	BAILEY 86	SILI	π^- Be fixed target
2.17±0.28±0.23		ALBRECHT 85F	ARG	e^+e^- 10 GeV
2.0 ±1.0	10	BAILEY 83B	SPEC	π^- Be $\rightarrow D^0$
2.2 ±0.8	214	PICCOLO 77	MRK1	e^+e^- 4.03, 4.41 GeV

$\sigma(e^+e^- \rightarrow \psi(3770)) \times \Gamma(K^-\pi^+\pi^+\pi^-)/\Gamma_{total}$ $\sigma \times \Gamma_{29}/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID	TECN	COMMENT
0.504±0.031 OUR FIT Error includes scale factor of 1.1.				
0.52 ±0.07 OUR AVERAGE Error includes scale factor of 1.5. See the ideogram below.				
0.525±0.026±0.054	992	BALTRUSAIT...86E	MRK3	e^+e^- 3.77 GeV
0.68 ±0.11	185	SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
0.36 ±0.10	44	PERUZZI 77	MRK1	e^+e^- 3.77 GeV



$\Gamma(K^-\pi^+\rho^0)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{30}/Γ_{29}

This includes $K^- a_1(1260)^+$, $\overline{K}^*(892)^0\rho^0$, etc. We rely on the MARK III full amplitude analysis of the $K^-\pi^+\pi^+\pi^-$ channel for values of the resonant substructure.

VALUE	DOCUMENT ID		TECN	COMMENT
0.855±0.032±0.030	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.98 ±0.12 ±0.10	ALVAREZ	91B	NA14	Photoproduction

$\Gamma(K^-\pi^+\rho^0\ \text{3-body})/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{31}/Γ_{29}

We rely on the MARK III full amplitude analysis of the $K^-\pi^+\pi^+\pi^-$ channel for values of the resonant substructure.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.084±0.022±0.04		COFFMAN	92B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.77 ±0.06 ±0.06		[27] ALVAREZ	91B	NA14	Photoproduction
0.85 $^{+0.11}_{-0.22}$	180	PICCOLO	77	MRK1	e^+e^- 4.03, 4.41 GeV

[27] This value is for ρ^0 $(K^-\pi^+)$-nonresonant. ALVAREZ 91B are unable to determine what fraction of this is $K^- a_1(1260)^+$.

$\Gamma(\overline{K}^*(892)^0\rho^0)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{63}/Γ_{29}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included. We rely on the MARK III full amplitude analysis of the $K^-\pi^+\pi^+\pi^-$ channel for values of the resonant substructure.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.34±0.09±0.09			ALVAREZ	91B	NA14	Photoproduction
0.75±0.3	90	5	BAILEY	83B	SPEC	π Be → D^0
0.15$^{+0.16}_{-0.15}$		20	PICCOLO	77	MRK1	e^+e^- 4.03, 4.41 GeV

$\Gamma(\overline{K}^*(892)^0\rho^0\ \text{transverse})/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{64}/Γ_{29}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.20 ±0.07 OUR FIT				
0.213±0.024±0.075	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\rho^0\ S\text{-wave longitudinal})/\Gamma_{total}$ — Γ_{65}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.003	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\rho^0\ P\text{-wave})/\Gamma_{total}$ — Γ_{66}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.003	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^- a_1(1260)^+)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{71}/Γ_{29}

VALUE	DOCUMENT ID		TECN	COMMENT
0.984±0.048±0.16	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^- a_2(1320)^+)/\Gamma_{total}$ — Γ_{73}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.006	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K_1(1270)^-\pi^+)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{74}/Γ_{29}

VALUE	DOCUMENT ID		TECN	COMMENT
0.15 ±0.04 OUR FIT				
0.194±0.056±0.088	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K_1(1400)^-\pi^+)/\Gamma_{total}$ — Γ_{75}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.012	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^*(1410)^-\pi^+)/\Gamma_{total}$ — Γ_{77}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.012	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^-\ \text{3-body})/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{62}/Γ_{29}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.22 ±0.06 OUR FIT				
0.210±0.027±0.06	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^+\pi^-\ \text{nonresonant})/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{36}/Γ_{29}

VALUE	DOCUMENT ID		TECN	COMMENT
0.242±0.025±0.06	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — $\Gamma_{37}/(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.89±0.28 OUR FIT					
1.85±0.26±0.30	158	KINOSHITA	91	CLEO	e^+e^- ~ 10.7 GeV

$\sigma(e^+e^-\to\psi(3770))\times\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)/\Gamma_{total}$ — $\sigma\times\Gamma_{37}/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID		TECN	COMMENT
0.69 ±0.10 OUR FIT					
0.586±0.117±0.147	140	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\eta)/\Gamma(K^-\pi^+)$ — Γ_{55}/Γ_{19}

Unseen decay modes of the η are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.64	90	ALBRECHT	89D	ARG	e^+e^- 10 GeV

$\Gamma(\overline{K}^0\omega)/\Gamma(K^-\pi^+)$ — Γ_{58}/Γ_{19}

Unseen decay modes of the ω are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.68±0.15 OUR FIT				
1.00±0.36±0.20	ALBRECHT	89D	ARG	e^+e^- 10 GeV

$\Gamma(\overline{K}^0\omega)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — $\Gamma_{58}/(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})$

Unseen decay modes of the ω are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.46±0.10 OUR FIT					
0.54±0.14±0.16	40	KINOSHITA	91	CLEO	e^+e^- ~ 10.7 GeV

$\Gamma(\overline{K}^0\omega)/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ — Γ_{58}/Γ_{37}

VALUE	DOCUMENT ID		TECN	COMMENT
0.24 ±0.04 OUR FIT				
0.220±0.048±0.0116	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^-\rho^+)/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ — Γ_{67}/Γ_{37}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.606±0.188±0.126	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^-\rho^+\ \text{longitudinal})/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ — Γ_{68}/Γ_{37}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.290±0.111	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^-\rho^+\ \text{transverse})/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ — Γ_{69}/Γ_{37}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.317±0.180	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^-\rho^+\ P\text{-wave})/\Gamma_{total}$ — Γ_{70}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.015	90	[28] COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

[28] Obtained using other $\overline{K}^*(892)\rho$ P-wave limits and isospin relations.

$\Gamma(\overline{K}^*(892)^0\rho^0\ \text{transverse})/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ — Γ_{64}/Γ_{37}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.15 ±0.06 OUR FIT				
0.126±0.111	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0 a_1(1260)^0)/\Gamma_{total}$ — Γ_{72}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.019	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K_1(1270)^-\pi^+)/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ — Γ_{74}/Γ_{37}

VALUE	DOCUMENT ID		TECN	COMMENT
0.106±0.028 OUR FIT				
0.10 ±0.03	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}_1(1400)^0\pi^0)/\Gamma_{total}$ — Γ_{76}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.037	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^-$ 3-body$)/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ — Γ_{62}/Γ_{37}

VALUE	DOCUMENT ID		TECN	COMMENT
0.16 ±0.05 OUR FIT				
0.191±0.105	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\pi^+\pi^-\pi^0$ nonresonant$)/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ — Γ_{43}/Γ_{37}

VALUE	DOCUMENT ID		TECN	COMMENT
0.210±0.147±0.150	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^0\pi^0)/\Gamma_{total}$ — Γ_{44}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.149±0.037±0.030	24	[29] ADLER	88C	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.161±0.025±0.017		[30] BARLAG	90D	ACCM	π^- Cu 230 GeV
$0.209^{+0.074}_{-0.043}\pm0.012$	9	[30] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[29] ADLER 88C uses an absolute normalization method finding this decay channel opposite a detected $\overline{D}^0 \to K^+\pi^-$ in pure $D\overline{D}$ events.

[30] AGUILAR-BENITEZ 87F and BARLAG 90D compute the branching fraction by topological normalization. They do not distinguish the presence of a third π^0, and thus are not included in the average.

$\Gamma(K^-\pi^+\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{45}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.035 ±0.006 OUR FIT Error includes scale factor of 1.6.				
$\mathbf{0.0256^{+0.0057}_{-0.0055}}$	[31] BARLAG	90D	ACCM	π^- Cu 230 GeV

[31] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(K^-\pi^+\pi^+\pi^-\pi^0)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{45}/Γ_{29}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.47±0.08 OUR FIT Error includes scale factor of 1.5.					
0.56±0.07 OUR AVERAGE					
$0.55\pm0.07^{+0.12}_{-0.09}$	167	KINOSHITA	91	CLEO	e^+e^- ~10.7 GeV
0.57±0.06±0.05	180	ANJOS	90D	E691	Photoproduction

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^-\pi^0)/\Gamma(K^-\pi^+\pi^+\pi^-\pi^0)$ — Γ_{78}/Γ_{45}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.45±0.15±0.15	ANJOS	90D	E691	Photoproduction

$\Gamma(\overline{K}^*(892)^0\eta)/\Gamma(K^-\pi^+)$ — Γ_{79}/Γ_{19}

Unseen decay modes of the $\overline{K}^*(892)^0$ and η are included.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.58\pm0.19^{+0.24}_{-0.28}}$		46	[32] KINOSHITA	91	CLEO	e^+e^- ~10.7 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.70	90		ALBRECHT	89D	ARG	e^+e^- 10 GeV

[32] We use this value for the Summary Table, but it in some conflict with the upper limit in the next entry: see the footnote to the Summary Table.

$\Gamma(\overline{K}^*(892)^0\eta)/\Gamma(K^-\pi^+\pi^+\pi^-\pi^0)$ — Γ_{79}/Γ_{45}

Unseen decay modes of the $\overline{K}^*(892)^0$ and η are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.27	90	[33] ANJOS	90D	E691	Photoproduction

[33] Recovered from the published limit, $\Gamma(\overline{K}^*(892)^0\eta)/\Gamma_{total}$, in order to make our normalization consistent.

$\Gamma(\overline{K}^*(892)^0\omega)/\Gamma(K^-\pi^+\pi^+\pi^-\pi^0)$ — Γ_{80}/Γ_{45}

Unseen decay modes of the $\overline{K}^*(892)^0$ and ω are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.44	90	[34] ANJOS	90D	E691	Photoproduction

[34] Recovered from the published limit, $\Gamma(\overline{K}^*(892)^0\omega)/\Gamma_{total}$, in order to make our normalization consistent.

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-\pi^-)/\Gamma_{total}$ — Γ_{48}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0085±0.0014 OUR FIT				
$\mathbf{0.0102^{+0.0040}_{-0.0039}}$	[35] BARLAG	90D	ACCM	π^- Cu 230 GeV

[35] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-\pi^-)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — $\Gamma_{48}/(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.156±0.023 OUR FIT					
0.152±0.025 OUR AVERAGE					
0.149±0.026	56	AMMAR	91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.18 ±0.07 ±0.04	6	ANJOS	90D	E691	Photoproduction

$\Gamma(\overline{K}^0\pi^+\pi^-\pi^0\pi^0(\pi^0))/\Gamma_{total}$ — Γ_{49}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.127^{+0.035}_{-0.024}}$ **OUR AVERAGE**					
0.140±0.034±0.021		[36] BARLAG	90D	ACCM	π^- Cu 230 GeV
$0.106^{+0.073}_{-0.029}\pm0.006$	4	[36] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[36] AGUILAR-BENITEZ 87F and BARLAG 90D compute the branching fraction by topological normalization. They do not distinguish the presence of a third π^0.

$\Gamma(\overline{K}^0K^+K^-)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — $(\Gamma_{52}+\frac{1}{2}\Gamma_{59})/(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.176±0.015 OUR FIT					
0.176±0.020 OUR AVERAGE					
0.170±0.022	136	AMMAR	91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.24 ±0.08		BEBEK	86	CLEO	e^+e^- near $\Upsilon(4S)$
0.185±0.055	52	ALBRECHT	85B	ARG	e^+e^- 10 GeV

$\Gamma(\overline{K}^0\phi)/\Gamma_{total}$ — Γ_{59}/Γ

Unseen decay modes of the ϕ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.0088±0.0012 OUR FIT Error includes scale factor of 1.1.				
0.0175±0.0058	[37] BARLAG	90D	ACCM	π^- Cu 230 GeV

[37] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(\overline{K}^0\phi)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — $\Gamma_{59}/(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})$

Unseen decay modes of the ϕ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.161±0.017 OUR FIT					
0.158±0.018 OUR AVERAGE					
0.163±0.023	63	AMMAR	91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.155±0.033	56	ALBRECHT	87E	ARG	e^+e^- 10 GeV
0.14 ±0.05	29	BEBEK	86	CLEO	e^+e^- near $\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.186±0.052	26	ALBRECHT	85B	ARG	See ALBRECHT 87E

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^0\phi)/\Gamma_{total}$ — $\sigma \times \Gamma_{59}/\Gamma$

Unseen decay modes of the ϕ are included.

VALUE (nanobarns)	DOCUMENT ID		TECN	COMMENT
0.059±0.007 OUR FIT				
$\mathbf{0.05\ ^{+0.03}_{-0.02}\ ^{+0.02}_{-0.01}}$	BALTRUSAIT...	86C	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0K^+K^-$ non-$\phi)/\Gamma_{total}$ — Γ_{52}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0052±0.0009 OUR FIT Error includes scale factor of 1.1.				
$\mathbf{0.0060^{+0.0037}_{-0.0036}}$	[38] BARLAG	90D	ACCM	π^- Cu 230 GeV

[38] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(\overline{K}^0K^+K^-$ non-$\phi)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — $\Gamma_{52}/(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})$

VALUE	DOCUMENT ID		TECN	COMMENT
0.096±0.014 OUR FIT Error includes scale factor of 1.1.				
0.084±0.020	ALBRECHT	87E	ARG	e^+e^- 10 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^0K^+K^-$ non-$\phi)/\Gamma_{total}$ — $\sigma \times \Gamma_{52}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID		TECN	COMMENT
0.035±0.006 OUR FIT				
$\mathbf{0.05\ ^{+0.02}_{-0.01}\pm0.01}$	BALTRUSAIT...	86C	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^0_SK^0_SK^0_S)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — $\Gamma_{53}/(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.016±0.004 OUR AVERAGE					
0.016±0.005	22	AMMAR	91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.017±0.007±0.005	5	ALBRECHT	90C	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^+K^-\overline{K}^0\pi^0)/\Gamma_{total}$ — Γ_{54}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.0092^{+0.0064}_{-0.0044}}$	[39] BARLAG	90D	ACCM	π^- Cu 230 GeV

[39] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_{81}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
9± 6		[40] BARLAG	90D	ACCM	π^- Cu 230 GeV
$50^{+120}_{-20}\pm40$	1	[40] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[40] AGUILAR-BENITEZ 87F and BARLAG 90D compute the branching fraction using topological normalization.

$\Gamma(\pi^+\pi^-)/\Gamma(K^-\pi^+)$ — Γ_{81}/Γ_{19}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.045±0.005 OUR AVERAGE				
0.055±0.008±0.005	120	ANJOS 91D	E691	Photoproduction
0.040±0.007±0.006	57	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV
0.050±0.007±0.005	110	ALEXANDER 90	CLEO	e^+e^- 10.5–11 GeV
0.033±0.010±0.006	39	BALTRUSAIT...85E	MRK3	e^+e^- 3.77 GeV
0.033±0.015		ABRAMS 79D	MRK2	e^+e^- 3.77 GeV

$\Gamma(\pi^0\pi^0)/\Gamma_{total}$ — Γ_{82}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0046	90	ALEXANDER 90	CLEO	e^+e^- 10.5–11 GeV

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{83}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.015 ±0.010 OUR AVERAGE Error includes scale factor of 2.5.				
0.0408±0.0111		[41] BARLAG 90D	ACCM	π^- Cu 230 GeV
0.011 ±0.004 ±0.002	10	[42] BALTRUSAIT...85E	MRK3	e^+e^- 3.77 GeV

[41] BARLAG 90D computes the branching fraction using topological normalization. Possible contamination by extra π^0's may partly explain the unexpectedly large value.
[42] All events consistent with $\rho^0\pi^0$.

$\Gamma(\pi^+\pi^+\pi^-\pi^-)/\Gamma_{total}$ — Γ_{84}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0025±0.0009		[43] BARLAG 90D	ACCM	π^- Cu 230 GeV
$0.005\ ^{+0.011}_{-0.001}\ \pm0.001$	1	[43] AGUILAR-... 87F	HYBR	πp, pp 360, 400 GeV
0.015 ±0.006 ±0.002	9	BALTRUSAIT...85E	MRK3	e^+e^- 3.77 GeV

[43] AGUILAR-BENITEZ 87F and BARLAG 90D compute the branching fraction using topological normalization.

$\Gamma(\pi^+\pi^+\pi^-\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{84}/Γ_{29}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.100±0.011 OUR AVERAGE				
0.102±0.013	345	[44] AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.096±0.018±0.007	66	ANJOS 91	E691	γ Be 80–240 GeV

[44] AMMAR 91 finds 1.25 ± 0.25 ± 0.25 ρ^0's per $\pi^+\pi^+\pi^-\pi^-$ decay, but can't untangle the resonant substructure ($\rho^0\rho^0$, $a_1^\pm\pi^\mp$, $\rho^0\pi^+\pi^-$).

$\Gamma(\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{total}$ — Γ_{85}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.0172^{+0.0047}_{-0.0046}}$	[45] BARLAG 90D	ACCM	π^- Cu 230 GeV

[45] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-)/\Gamma_{total}$ — Γ_{86}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0004±0.0003	[46] BARLAG 90D	ACCM	π^- Cu 230 GeV

[46] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(K^+K^-)/\Gamma_{total}$ — Γ_{87}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.0047±0.0013	[47] BARLAG 90D	ACCM	π^- Cu 230 GeV

[47] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(K^+K^-)/\Gamma(K^-\pi^+)$ — Γ_{87}/Γ_{19}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.113±0.007 OUR FIT				
0.113±0.007 OUR AVERAGE				
0.16 ±0.05	34	ALVAREZ 91B	NA14	Photoproduction
0.107±0.010±0.009	193	ANJOS 91D	E691	Photoproduction
0.10 ±0.02 ±0.01	131	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV
0.117±0.010±0.007	249	ALEXANDER 90	CLEO	e^+e^- 10.5–11 GeV
0.122±0.018±0.012	118	BALTRUSAIT...85E	MRK3	e^+e^- 3.77 GeV
0.113±0.030		ABRAMS 79D	MRK2	e^+e^- 3.77 GeV

$\Gamma(K^+K^-)/\Gamma(\pi^+\pi^-)$ — Γ_{87}/Γ_{81}

The unused results here are redundant with $\Gamma(K^+K^-)/\Gamma(K^-\pi^+)$ and $\Gamma(\pi^+\pi^-)/\Gamma(K^-\pi^+)$ measurements by the same experiments.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.95±0.34±0.22		ANJOS 91D	E691	Photoproduction
2.5 ±0.7		ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV
2.35±0.37±0.28	110	ALEXANDER 90	CLEO	e^+e^- 10.5–11 GeV

$\Gamma(K^0\overline{K}^0)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — $\Gamma_{88}/(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})$

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.020^{+0.008}_{-0.007}}$ **OUR FIT**					
$\mathbf{0.021^{+0.011}_{-0.008}\pm0.002}$		5	ALEXANDER 90	CLEO	e^+e^- 10.5–11 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.016	90		ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^0\overline{K}^0)/\Gamma(K^+K^-)$ — Γ_{88}/Γ_{87}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.26^{+0.11}_{-0.09}}$ **OUR FIT**				
0.24±0.16	4	[48] CUMALAT 88	SPEC	nN 0–800 GeV

[48] Includes a correction communicated to us by the authors of CUMALAT 88.

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K^0\overline{K}^0)/\Gamma_{total}$ — $\sigma \times \Gamma_{88}/\Gamma$

VALUE (nanobarns)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.025	90	BALTRUSAIT...86C	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^0K^-\pi^+)/\Gamma(K^-\pi^+)$ — Γ_{89}/Γ_{19}

VALUE	DOCUMENT ID	TECN	COMMENT
0.175±0.027 OUR FIT Error includes scale factor of 1.1.			
0.16 ±0.06	[49] ANJOS 91	E691	γ Be 80–240 GeV

[49] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(K^0K^-\pi^+)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — $\Gamma_{89}/(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.118±0.017 OUR FIT Error includes scale factor of 1.1.				
0.119±0.021 OUR AVERAGE Error includes scale factor of 1.3.				
0.108±0.019	61	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.16 ±0.03 ±0.02	39	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(\overline{K}^*(892)^0K^0)/\Gamma(K^-\pi^+)$ — Γ_{106}/Γ_{19}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.00^{+0.03}_{-0.00}$	[50] ANJOS 91	E691	γ Be 80–240 GeV

[50] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(\overline{K}^*(892)^0K^0)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — $\Gamma_{106}/(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})$

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.029	90	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.03	90	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^*(892)^+K^-)/\Gamma(K^-\pi^+)$ — Γ_{107}/Γ_{19}

Unseen decay modes of the $K^*(892)^+$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.097±0.021 OUR FIT			
$\mathbf{0.16\ ^{+0.08}_{-0.06}}$	[51] ANJOS 91	E691	γ Be 80–240 GeV

[51] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(K^*(892)^+K^-)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — $\Gamma_{107}/(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})$

Unseen decay modes of the $K^*(892)^+$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.065±0.014 OUR FIT				
0.058±0.014 OUR AVERAGE				
0.064±0.018	23	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.05 ±0.02 ±0.01	15	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^0K^-\pi^+ \text{ nonresonant})/\Gamma(K^-\pi^+)$ — Γ_{92}/Γ_{19}

VALUE	DOCUMENT ID	TECN	COMMENT
0.06±0.06	[52] ANJOS 91	E691	γ Be 80–240 GeV

[52] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(\overline{K}^0K^+\pi^-)/\Gamma(K^-\pi^+)$ — Γ_{93}/Γ_{19}

VALUE	DOCUMENT ID	TECN	COMMENT
0.134±0.026 OUR FIT			
0.10 ±0.05	[53] ANJOS 91	E691	γ Be 80–240 GeV

[53] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(\overline{K}^0K^+\pi^-)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — $\Gamma_{93}/(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.090±0.017 OUR FIT				
0.098±0.020	55	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(K^*(892)^0\overline{K}^0)/\Gamma(K^-\pi^+)$ — Γ_{108}/Γ_{19}

Unseen decay modes of the $K^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.00^{+0.04}_{-0.00}$	[54] ANJOS 91	E691	γ Be 80–240 GeV

[54] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(K^*(892)^0\overline{K}^0)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — $\Gamma_{108}/(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})$

Unseen decay modes of the $K^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.015	90	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(K^*(892)^- K^+)/\Gamma(K^-\pi^+)$ — Γ_{109}/Γ_{19}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.00^{+0.03}_{-0.00}$	[55] ANJOS	91	E691	γ Be 80–240 GeV

[55] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(K^*(892)^- K^+)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — $\Gamma_{109}/(\Gamma_{21}+\Gamma_{23}+\frac{2}{3}\Gamma_{60})$

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.037±0.018 OUR FIT					
0.034±0.019	12	AMMAR	91	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(\overline{K}^0 K^+\pi^-$ nonresonant$)/\Gamma(K^-\pi^+)$ — Γ_{96}/Γ_{19}

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.10^{+0.06}_{-0.05}}$	[56] ANJOS	91	E691	γ Be 80–240 GeV

[56] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\sigma(e^+e^- \to \psi(3770)) \times [\Gamma(\overline{K}^*(892)^0 K^0) + \Gamma(K^*(892)^0\overline{K}^0)]/\Gamma_{total}$ — $\sigma \times (\Gamma_{106}+\Gamma_{108})/\Gamma$

Unseen decay modes of the $\overline{K}^*(892)^0$ and $K^*(892)^0$ are included.

VALUE (nanobarns)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.036	90	BALTRUSAIT...86C		MRK3	e^+e^- 3.77 GeV

$\sigma(e^+e^- \to \psi(3770)) \times [\Gamma(K^*(892)^+ K^-) + \Gamma(K^*(892)^- K^+)]/\Gamma_{total}$ — $\sigma \times (\Gamma_{107}+\Gamma_{109})/\Gamma$

Unseen decay modes of the $K^*(892)^+$ and $K^*(892)^-$ are included.

VALUE (nanobarns)	DOCUMENT ID		TECN	COMMENT
0.037±0.009 OUR FIT				
0.050±0.023±0.010	BALTRUSAIT...86C		MRK3	e^+e^- 3.77 GeV

$\sigma(e^+e^- \to \psi(3770)) \times [\Gamma(K^0 K^-\pi^+$ nonresonant$) + \Gamma(\overline{K}^0 K^+\pi^-$ nonresonant$)]/\Gamma_{total}$ — $\sigma \times (\Gamma_{92}+\Gamma_{96})/\Gamma$

VALUE (nanobarns)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.079	90	BALTRUSAIT...86C		MRK3	e^+e^- 3.77 GeV

$\Gamma(K^+K^-\pi^+\pi^-)/\Gamma_{total}$ — Γ_{97}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0024±0.0004 OUR FIT				
0.0028±0.0007	[57] BARLAG	90D	ACCM	π^- Cu 230 GeV

[57] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(K^+K^-\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{97}/Γ_{29}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.032 ±0.005 OUR FIT					
0.029 ±0.006 OUR AVERAGE					
0.0314±0.010	89	AMMAR	91	CLEO	$e^+e^- \approx$ 10.5 GeV
$0.028\ ^{+0.008}_{-0.007}$		ANJOS	91	E691	γ Be 80–240 GeV

$\Gamma(\phi\pi^+\pi^-)/\Gamma_{total}$ — Γ_{110}/Γ

Unseen decay modes of the ϕ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.0024±0.0008	[58] BARLAG	90D	ACCM	π^- Cu 230 GeV

[58] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(\phi\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{110}/Γ_{29}

Unseen decay modes of the ϕ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.0076^{+0.0066}_{-0.0049}$	3	[59] ANJOS	91	E691	γ Be 80–240 GeV

[59] This ANJOS 91 result is inconsistent with the higher-statistics result of AMMAR 91 on $\phi\rho^0$.

$\Gamma(\phi\rho^0)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{111}/Γ_{29}

Unseen decay modes of the ϕ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.024±0.006	34	[60] AMMAR	91	CLEO	$e^+e^- \approx$ 10.5 GeV

[60] The AMMAR 91 $\phi\pi^+\pi^-$ events are consistent with being entirely $\phi\rho^0$.

$\Gamma(K^*(892)^0 K^-\pi^+$ +c.c.$)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{112}/Γ_{29}

Unseen decay modes of the $K^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.010^{+0.016}_{-0.010}}$	ANJOS	91	E691	γ Be 80–240 GeV

$\Gamma(K^*(892)^0\overline{K}^*(892)^0)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{113}/Γ_{29}

Unseen decay modes of the $K^*(892)^0$ and $\overline{K}^*(892)^0$ are included.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.036^{+0.020}_{-0.016}}$		11	ANJOS	91	E691	γ Be 80–240 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.033	90		[61] AMMAR	91	CLEO	$e^+e^- \approx$ 10.5 GeV

[61] A corrected value (G. Moneti, private communication).

$\Gamma(K^+K^-\pi^+\pi^-$ nonresonant$)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{102}/Γ_{29}

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.001\ ^{+0.011}_{-0.001}}$	ANJOS	91	E691	γ Be 80–240 GeV

$\Gamma(K^+K^-\pi^0\pi^0)/\Gamma_{total}$ — Γ_{103}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	1	AGUILAR-...	86B	HYBR	$\pi^- p$ 360 GeV

$\Gamma(K^0 K^-\pi^+\pi^0)/\Gamma_{total}$ — Γ_{104}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	1	AGUILAR-...	86B	HYBR	$\pi^- p$ 360 GeV

$\Gamma(K^+K^-\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{105}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.0028^{+0.0025}_{-0.0015}}$	[62] BARLAG	90D	ACCM	π^- Cu 230 GeV

[62] BARLAG 90D computes the branching fraction using topological normalization.

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_{114}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{<1.3\times10^{-4}}$	90		ADLER	88	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<1.7\times10^{-4}$	90	7	[63] ALBRECHT	88G	ARG	e^+e^- 10 GeV
$<2.2\times10^{-4}$	90	8	[64] HAAS	88	CLEO	e^+e^- 10 GeV

[63] The branching ratios are normalized to B($D^0 \to K^-\pi^+$) using ADLER 88C.
[64] The branching ratios are normalized to $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D^{*+} \to D^0\pi^+$ using ADLER 88C.

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ — Γ_{115}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{<1.1\times10^{-5}}$	90		LOUIS	86	SPEC	π^- W 225 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<7.0\times10^{-5}$	90	3	[65] ALBRECHT	88G	ARG	e^+e^- 10 GeV
$<3.4\times10^{-4}$	90		AUBERT	85	EMC	Deep inelast. $\mu^- N$

[65] The branching ratios are normalized to B($D^0 \to K^-\pi^+$), using ADLER 88C.

$\Gamma(\mu^\pm e^\mp)/\Gamma_{total}$ — Γ_{116}/Γ

A test of lepton family number conservation.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{<1.0\times10^{-4}}$	90	4	[66] ALBRECHT	88G	ARG	e^+e^- 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<2.7\times10^{-4}$	90	9	[67] HAAS	88	CLEO	e^+e^- 10 GeV
$<1.2\times10^{-4}$	90		BECKER	87C	MRK3	e^+e^- 3.77 GeV
$<9\times10^{-4}$	90		PALKA	87	SILI	200 GeV πp
$<21\times10^{-4}$	90	0	[68] RILES	87	MRK2	e^+e^- 29 GeV

[66] The branching ratios are normalized to B($D^0 \to K^-\pi^+$) using ADLER 88C.
[67] The branching ratios are normalized to $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D^{*+} \to D^0\pi^+$ using ADLER 88C.
[68] RILES 87 assumes B($D \to K\pi$) = 3.0% and has production model dependency.

$\Gamma(\overline{K}^0 e^+e^-)/\Gamma_{total}$ — Γ_{117}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0017	90	ADLER	89C	MRK3	e^+e^- 3.77 GeV

$\Gamma(\rho^0 e^+e^-)/\Gamma_{total}$ — Γ_{118}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{<4.5\times10^{-4}}$	90	2	[69] HAAS	88	CLEO	e^+e^- 10 GeV

[69] The branching ratios are normalized to $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D^{*+} \to D^0\pi^+$ using ADLER 88C.

$\Gamma(\rho^0\mu^+\mu^-)/\Gamma_{total}$ — Γ_{119}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{<8.1\times10^{-4}}$	90	5	[70] HAAS	88	CLEO	e^+e^- 10 GeV

[70] The branching ratios are normalized to $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D^{*+} \to D^0\pi^+$ using ADLER 88C.

$\Gamma(\mu^-$ anything (via $\overline{D}^0$))/$\Gamma(\mu^+$ anything) — Γ_{120}/Γ_2

This is a D^0-$\overline{D}^0$ mixing limit. See the somewhat better limit below on $D^0 \to K^+\pi^-$ (via $\overline{D}^0$).

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0056	90	LOUIS	86	SPEC	π^- W 225 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.012	90	BENVENUTI	85	CNTR	μC, 200 GeV
<0.044	90	BODEK	82	SPEC	π^-, pFe $\to D^0$

$\Gamma(K^+\pi^-)/\Gamma(K^-\pi^+)$ — Γ_{121}/Γ_{19}

Doubly Cabibbo suppressed.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.011	90		AMMAR	91	CLEO	$e^+e^- \approx$ 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.015	90	2	ANJOS	88C	E691	Photoproduction

$\Gamma(K^+\pi^-$ (via $\overline{D}^0$))/$\Gamma(K^-\pi^+)$ — Γ_{122}/Γ_{19}

This is a D^0-$\overline{D}^0$ mixing limit.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.0037	90	1	[71] ANJOS	88C	E691	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.014	90		ALBRECHT	87K	ARG	e^+e^- 10 GeV
<0.04	90		ABACHI	86D	HRS	e^+e^- 29 GeV
<0.07	90	0	[71] BAILEY	86	SILI	π^- Be fixed target
<0.11	90	2	ALBRECHT	85F	ARG	e^+e^- 10 GeV
<0.081	90		[72] YAMAMOTO	85	DLCO	e^+e^- 29 GeV
<0.23	90		[72] ALTHOFF	84B	TASS	e^+e^- 34.4 GeV
<0.11	90		[72] AVERY	80	SPEC	$\gamma N \to D^{*+}$
<0.16	90		[72] FELDMAN	77B	MRK1	$D^{*+} \to D^0\pi^+$
<0.18	90		[72] GOLDHABER	77	MRK1	

[71] This measurement actually comes from combining results on $K^\pm\pi^\mp\pi^+\pi^-$ and $K^\pm\pi^\mp$ modes. See also the data block on $|m(D_1^0)-m(D_2^0)|$ near the beginning of the D^0 Listings.

[72] Results given as $\Gamma(K^+\pi^-)/[\Gamma(K^-\pi^+)+\Gamma(K^+\pi^-)]$ but do not change significantly for our denominator.

$\Gamma(K^+\pi^+\pi^-\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{123}/Γ_{29}

Doubly Cabibbo suppressed.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.018	90		AMMAR	91	CLEO	$e^+e^- \approx$ 10.5 GeV
<0.018	90	5	ANJOS	88C	E691	Photoproduction

D^0 PRODUCTION CROSS SECTION AT $\psi(3770)$

A compilation of the cross sections for the direct production of D^0 mesons at or near the $\psi(3770)$ peak in e^+e^- production. We use the absolute cross-section measurement of the Mark III experiment in preference to the $\psi(3770)$ resonance-scan measurements of the other experiments.

VALUE (nanobarns)	DOCUMENT ID		TECN	COMMENT
6.7 ±0.4 OUR FIT Error includes scale factor of 1.1.				
5.8 ±0.5 ±0.6	[73] ADLER	88C	MRK3	e^+e^- 3.768 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
7.3 ±1.3	[74] PARTRIDGE	84	CBAL	e^+e^- 3.771 GeV
8.00±0.95±1.21	[75] SCHINDLER	80	MRK2	e^+e^- 3.771 GeV
11.5 ±2.5	[76] PERUZZI	77	MRK1	e^+e^- 3.774 GeV

[73] This measurement compares events with one detected D to those with two detected D mesons, to determine the the absolute cross section. ADLER 88C find the ratio of cross sections (neutral to charged) to be 1.36 ± 0.23 ± 0.14.

[74] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. PARTRIDGE 84 measures 6.4 ± 1.15 nb for the cross section. We take the phase space division of neutral and charged D mesons in $\psi(3770)$ decay to be 1.33, and we assume that the $\psi(3770)$ is an isosinglet to evaluate the cross sections. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction.

[75] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. SCHINDLER 80 assume the phase space division of neutral and charged D mesons in $\psi(3770)$ decay to be 1.33, and that the $\psi(3770)$ is an isosinglet. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction.

[76] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. The phase space division of neutral and charged D mesons in $\psi(3770)$ decay is taken to be 1.33, and $\psi(3770)$ is assumed to be an isosinglet. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction. We exclude this measurement from the average because of uncertainties in the contamination from τ lepton pairs. Also see RAPIDIS 77.

D^0 – $\overline{D}^0$ DECAY ASYMMETRY PARAMETER

$[\Gamma(D^0 \to K^+K^-)-\Gamma(\overline{D}^0 \to K^+K^-)]$/SUM

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.45	90	[77] ANJOS	91D	E691	Photoproduction

[77] ANJOS 91D is a limit on the time-independent asymmetry for direct CP violation.

D^0 REFERENCES

COFFMAN 92B PR D45 2196 +DeJongh, Dubois, Eigen+ (Mark III Collab.)
Also 90 PRL 64 2615 Adler, Blaylock, Bolton+ (Mark III Collab.)
ALVAREZ 91B ZPHY C50 11 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
AMMAR 91 PR D44 3383 +Baringer, Coppage, Davis+ (CLEO Collab.)
ANJOS 91 PR D43 R635 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
ANJOS 91D PR D44 R3371 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
BAI 91 PRL 66 1011 +Bolton, Brown, Bunnell+ (Mark III Collab.)
COFFMAN 91 PL B263 135 +DeJongh, Dubois, Eigen, Hitlin+ (Mark III Collab.)
CRAWFORD 91B PR D44 3394 +Fulton, Gan, Jensen+ (CLEO Collab.)
DECAMP 91J PL B266 218 +Deschizeaux, Goy, Lees+ (ALEPH Collab.)
FRABETTI 91 PL B263 584 +Bogart, Cheung, Culy+ (FNAL-E687 Collab.)
KINOSHITA 91 PR D43 2836 +Pipkin, Procario, Wilson+ (CLEO Collab.)
KODAMA 91 PRL 66 1819 +Ushida, Mokhtarani, Paolone+ (FNAL-E653 Collab.)
ALBRECHT 90C ZPHY C46 9 +Glaeser, Harder, Krueger+ (ARGUS Collab.)
ALEXANDER 90 PRL 65 1184 +Artuso, Bebek, Berkelman+ (CLEO Collab.)
ALEXANDER 90B PRL 65 1531 +Artuso, Bebek, Berkelman+ (CLEO Collab.)
ALVAREZ 90 ZPHY C47 539 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
ANJOS 90D PR D42 2414 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
BARLAG 90C ZPHY C46 563 +Becker, Boehringer, Bosman+ (ACCMOR Collab.)
BARLAG 90D ZPHY C48 29 +Becker, Boehringer, Bosman+ (ACCMOR Collab.)
Also 89B PL B232 561 Barlag, Becker, Boehringer, Bosman+ (ACCMOR Collab.)
ADLER 89 PRL 62 1821 +Becker, Blaylock, Bolton+ (Mark III Collab.)
ADLER 89C PR D40 906 +Bai, Becker, Blaylock, Bolton+ (Mark III Collab.)
ALBRECHT 89D ZPHY C43 181 +Boeckmann, Glaeser, Harder+ (ARGUS Collab.)
ANJOS 89F PRL 62 1587 +Appel, Bean, Bracker, Browder+ (FNAL-TPS Collab.)
ABACHI 88 PL B205 411 +Akerlof, Baringer+ (HRS Collab.)
ADLER 88 PR D37 2023 +Becker, Blaylock+ (Mark III Collab.)
ADLER 88C PRL 60 89 +Becker, Blaylock+ (Mark III Collab.)
ALBRECHT 88G PL B209 380 +Boeckmann, Glaeser+ (ARGUS Collab.)
ALBRECHT 88I PL B210 267 +Boeckmann, Glaeser+ (ARGUS Collab.)
AMENDOLIA 88 EPL 5 407 +Bagliesi, Batignani+ (NA1 Collab.)
ANJOS 88C PRL 60 1239 +Appel+ (FNAL-TPS Collab.)
BORTOLETTO 88 PR D37 1719 +Goldberg, Horwitz, Mestayer, Moneti+ (CLEO Collab.)
Also 89D PR D39 1471 erratum
CUMALAT 88 PL B210 253 +Shipbaugh, Binkley+ (E-400 Collab.)
HAAS 88 PRL 60 1614 +Hempstead, Jensen+ (CLEO Collab.)
RAAB 88 PR D37 2391 +Anjos, Appel, Bracker+ (FNAL-TPS Collab.)
ADAMOVICH 87 EPL 4 887 +Alexandrov, Bolta+ (Photon Emulsion Collab.)
ADLER 87 PL B196 107 +Becker, Blaylock, Bolton+ (Mark III Collab.)
AGUILAR-... 87D PL B193 140 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
Also 88B ZPHY C40 321 Aguilar-Benitez, Allison, Bailly+ (LEBC-EHS Collab.)
AGUILAR-... 87E ZPHY C36 551 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
Also 88B ZPHY C40 321 Aguilar-Benitez, Allison, Bailly+ (LEBC-EHS Collab.)
AGUILAR-... 87F ZPHY C36 559 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
Also 88 ZPHY C38 520 erratum
ALBRECHT 87E ZPHY C33 359 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
ALBRECHT 87K PL B199 447 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
BARLAG 87B ZPHY C37 17 +Becker, Boehringer, Bosman+ (ACCMOR Collab.)
BECKER 87C PL B193 147 +Blaylock, Bolton, Brown+ (Mark III Collab.)
Also 87D PL B198 590 erratum Becker, Blaylock, Bolton+ (Mark III Collab.)
CSORNA 87 PL B191 318 +Mestayer, Panvini, Word+ (CLEO Collab.)
PALKA 87 PL B189 238 +Bailey, Becker, Belau+ (ACCMOR Collab.)
RILES 87 PR D35 2914 +Dorfan, Abrams, Amidei+ (Mark II Collab.)
ABACHI 86D PL B182 101 +Akerlof, Baringer, Ballam+ (HRS Collab.)
ABE 86 PR D33 1 + (SLAC Hybrid Facility Photon Collab.)
AGUILAR-... 86B ZPHY C31 491 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
BAILEY 86 ZPHY C30 51 +Belau, Boehringer, Bosman+ (ACCMOR Collab.)
BALTRUSAIT... 86C PRL 56 2136 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BALTRUSAIT... 86E PRL 56 2140 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BEBEK 86 PRL 56 1893 +Berkelman, Blucher, Cassel+ (CLEO Collab.)
GLADNEY 86 PR D34 2601 +Jaros, Ong, Barklow+ (Mark II Collab.)
LOUIS 86 PRL 56 1027 +Adolphsen, Alexander+ (PRIN, CHIC, ISU)
USHIDA 86B PRL 56 1771 +Kondo+ (AICH, FNAL, KOBE, SEOU, MCGI+)
ALBRECHT 85B PL 158B 525 +Binder, Harder, Philipp+ (ARGUS Collab.)
ALBRECHT 85F PL 150B 235 +Binder, Harder, Philipp+ (ARGUS Collab.)
AUBERT 85 PL 155B 461 +Bassompierre, Becks, Benchouk+ (EMC Collab.)
BAILEY 85 ZPHY C28 357 +Belau, Boehringer, Bosman+ (ABCCMR Collab.)
BALTRUSAIT... 85B PRL 54 1976 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BALTRUSAIT... 85E PRL 55 150 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BENVENUTI 85 PL 158B 531 +Bollini, Bruni, Camporesi+ (BCDMS Collab.)
YAMAMOTO 85 PRL 54 522 +Yamamoto, Atwood, Baillon+ (DELCO Collab.)
ADAMOVICH 84B PL 140B 123 +Alexandrov, Bravo, Cartacci+ (WA58 Collab.)
ALTHOFF 84B PL 138B 317 +Braunschweig, Kirschfink+ (TASSO Collab.)
DERRICK 84 PRL 53 1971 +Fernandez, Fries, Hyman+ (HRS Collab.)
PARTRIDGE 84 Cal Tech 1984 Thesis (Crystal Ball Collab.)
SUMMERS 84 PRL 52 410 + (UCSB, CARL, COLO, FNAL, TNTO, OKLA, CNRC)
BAILEY 83B PL 132B 237 +Bardsley, Becker, Blanar+ (ACCMOR Collab.)
BODEK 82 PL 113B 82 +Breedon+ (ROCH, CIT, CHIC, FNAL, STAN)
FIORINO 81 LNC 30 166 + (Photon-Emulsion and Omega-Photon Collab.)
SCHINDLER 81 PR D24 78 +Alam, Boyarski, Breidenbach+ (Mark II Collab.)
TRILLING 81 PRPL 75 57 (LBL, UCB) J
ASTON 80E PL 94B 113 + (BONN, CERN, EPOL, GLAS, LANC, MCHS+)
AVERY 80 PRL 44 1309 +Wiss, Butler, Gladding+ (ILL, FNAL, COLU)
SCHINDLER 80 PR D21 2716 +Siegrist, Alam, Boyarski+ (Mark II Collab.)
ZHOLENTZ 80 PL 96B 214 +Kurdadze, Lelchuk, Mishnev+ (NOVO)
Also 81 SJNP 34 814 Zholentz, Kurdadze, Lelchuk+ (NOVO)
Translated from YAF 34 1471.
ABRAMS 79D PRL 43 481 +Alam, Blocker, Boyarski+ (SLAC, LBL)
ATIYA 79 PRL 43 414 +Holmes, Knapp, Lee+ (COLU, ILL, FNAL)
BALTAY 78C PRL 41 73 +Caroumbalis, French, Hibbs, Hylton+ (COLU, BNL)
VUILLEMIN 78 PRL 41 1149 +Feldman, Feller+ (LBL, SLAC, NWES, HAWA)
FELDMAN 77B PRL 38 1313 +Peruzzi, Piccolo, Abrams, Alam+ (SLAC, LBL)
GOLDHABER 77 PL 69B 503 +Wiss, Abrams, Alam+ (LBL, SLAC)
PERUZZI 77 PRL 39 1301 +Piccolo, Feldman+ (SLAC, LBL, NWES, HAWA)
PICCOLO 77 PL 70B 260 +Peruzzi, Luth, Nguyen, Wiss, Abrams+ (SLAC, LBL)
RAPIDIS 77 PRL 39 526 +Gobbi, Luke, Barbaro-Galtieri+ (Mark I Collab.)
GOLDHABER 76 PRL 37 255 +Pierre, Abrams, Alam+ (LBL, SLAC)

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SNYDER 87 IUHEEE-87-11 (IND)
Symp. on Prod. and Decay of Heavy Flavors, Stanford
SCHINDLER 86 SLAC-PUB-4136 (SLAC)
World Press International
SCHINDLER 86B SLAC-PUB-4248 (SLAC)
SLAC Summer Institute

$D^*(2010)^{\pm}$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

$D^*(2010)^{\pm}$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2010.1±0.6 OUR EVALUATION From D^0 mass and mass difference below.					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2008 ±3	[1] GOLDHABER	77	MRK1	±	e^+e^-
2008.6±1.0	[2] PERUZZI	77	MRK1	±	e^+e^-

[1] From simultaneous fit to $D^*(2010)^+$, $D^*(2010)^0$, D^+, and D^0; not independent of FELDMAN 77B mass difference below.
[2] PERUZZI 77 mass not independent of FELDMAN 77B mass difference below and PERUZZI 77 D^0 mass value.

$D^*(2010)^+ - D^0$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
145.44±0.06 OUR AVERAGE					
145.40±0.05±0.10		ABACHI	88B	HRS	$D^{*\pm} \to D^0\pi^{\pm}$
145.46±0.07±0.03		ALBRECHT	85F	ARG	$D^{*\pm} \to D^0\pi^+$
145.8 ±1.5	16	AHLEN	83	HRS	$D^{*+} \to D^0\pi^+$
145.1 ±1.8	12	BAILEY	83	SPEC	$D^{*\pm} \to D^0\pi^{\pm}$
145.5 ±0.3	28	BAILEY	83	SPEC	$D^{*\pm} \to D^0\pi^{\pm}$
145.1 ±0.5	14	BAILEY	83	SPEC	$D^{*\pm} \to D^0\pi^{\pm}$
145.5 ±0.5	14	YELTON	82	MRK2	$29\ e^+e^- \to K^-\pi^+$
145.5 ±0.3	60	FITCH	81	SPEC	π^-A
145.2 ±0.6	2	BLIETSCHAU	79	BEBC	νp
145.3 ±0.5	30	FELDMAN	77B	MRK1	$D^{*+} \to D^0\pi^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
145.5 ±0.2	115	[3] ALEXANDER	91B	OPAL	$D^{*\pm} \to D^0\pi^{\pm}$
145.30±0.06		[3] DECAMP	91J	ALEP	$D^{*\pm} \to D^0\pi^{\pm}$
~ 145.5		AVERY	80	SPEC	γA

[3] Systematic error not evaluated.

$D^*(2010)^+ - D^*(2010)^0$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2.9±1.3 OUR EVALUATION From D^{*+}-D^0 and D^{*0}-D^0 mass differences.					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.6±1.8	[4] PERUZZI	77	MRK1	±	e^+e^-

[4] Not independent of FELDMAN 77B mass difference above, PERUZZI 77 D^0 mass, and GOLDHABER 77 $D^*(2010)^0$ mass.

$D^*(2010)^{\pm}$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.1	90		ABACHI	88B	HRS	$D^{*\pm} \to D^0\pi^{\pm}$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2.2			YELTON	82	MRK2	$e^+e^- \to K^-\pi^+\pi^-$
<2.0	90	30	FELDMAN	77B	MRK1	$D^{*+} \to D^0\pi^+$

$D^*(2010)^+$ DECAY MODES

$D^*(2010)^-$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^0\pi^+$	(55 ±4) %
Γ_2	$D^+\pi^0$	(27.2±2.5) %
Γ_3	$D^+\gamma$	(18 ±4) %

CONSTRAINED FIT INFORMATION

An overall fit to 3 branching ratios uses 6 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 2.6 for 4 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−19	
x_3	−82	−41
	x_1	x_2

$D^*(2010)^+$ BRANCHING RATIOS

$\Gamma(D^0\pi^+)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.55±0.04 OUR FIT					
0.54±0.05 OUR AVERAGE					
0.57±0.04±0.04	ADLER	88D	MRK3		e^+e^-
0.44±0.10	COLES	82	MRK2		e^+e^-
0.6 ±0.15	[5] GOLDHABER	77	MRK1	+	e^+e^-

[5] Assuming that isospin is conserved in the decay.

$\Gamma(D^+\pi^0)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.272±0.025 OUR FIT				
0.271±0.028 OUR AVERAGE Error includes scale factor of 1.1.				
0.26 ±0.02 ±0.02	ADLER	88D	MRK3	e^+e^-
0.34 ±0.07	COLES	82	MRK2	e^+e^-

$\Gamma(D^+\gamma)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.18±0.04 OUR FIT				
0.17±0.05±0.05	ADLER	88D	MRK3	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22±0.12	[6] COLES	82	MRK2	e^+e^-

[6] Not independent of $\Gamma(D^0\pi^+)/\Gamma_{total}$ and $\Gamma(D^+\pi^0)/\Gamma_{total}$ measurement.

$D^*(2010)^{\pm}$ REFERENCES

ALEXANDER	91B	PL B262 341	+Allison, Allport, Anderson, Arcelli+	(OPAL Collab.)
DECAMP	91J	PL B266 218	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
ABACHI	88B	PL B212 533	+Akerlof+	(ANL, IND, MICH, PURD, LBL)
ADLER	88D	PL B208 152	+Becker+	(Mark III Collab.)
ALBRECHT	85F	PL 150B 235	+Binder, Harder, Philipp+	(ARGUS Collab.)
AHLEN	83	PRL 51 1147	+Akerlof+	(ANL, IND, LBL, MICH, PURD, SLAC)
BAILEY	83	PL 132B 230	+Bardsley+	(AMST, BRIS, CERN, CRAC, MPIM+)
COLES	82	PR D26 2190	+Abrams, Blocker, Blondel+	(LBL, SLAC)
YELTON	82	PRL 49 430	+Feldman, Goldhaber+	(SLAC, LBL, UCB, HARV)
FITCH	81	PRL 46 761	+Devaux, Cavaglia, May+	(PRIN, SACL, TORI, BNL)
AVERY	80	PRL 44 1309	+Wiss, Butler, Gladding+	(ILL, FNAL, COLU)
BLIETSCHAU	79	PL 86B 108	+	(AACH, BONN, CERN, MPIM, OXF)
FELDMAN	77B	PRL 38 1313	+Peruzzi, Piccolo, Abrams, Alam+	(SLAC, LBL)
GOLDHABER	77	PL 69B 503	+Wiss, Abrams, Alam+	(LBL, SLAC)
PERUZZI	77	PRL 39 1301	+Piccolo, Feldman+	(SLAC, LBL, NWES, HAWA)

OTHER RELATED PAPERS

ALTHOFF	83C	PL 126B 493	+Fischer, Burkhardt+	(TASSO Collab.)
BEBEK	82	PRL 49 610	+	(HARV, OSU, ROCH, RUTG, SYRA, VAND+)
TRILLING	81	PRPL 75 57		(LBL, UCB)
PERUZZI	76	PRL 37 569	+Piccolo, Feldman, Nguyen, Wiss+	(SLAC, LBL)

$D^*(2010)^0$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

J consistent with 1, value 0 ruled out (NGUYEN 77).

$D^*(2010)^0$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2007.1±1.4 OUR EVALUATION From D^0 mass and mass difference below.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2006 ±1.5	[1] GOLDHABER	77	MRK1	e^+e^-

[1] From simultaneous fit to $D^*(2010)^+$, $D^*(2010)^0$, D^+, and D^0.

$D^*(2010)^0 - D^0$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
142.5±1.3 OUR AVERAGE					
142.2±2.0	SADROZINSKI	80	CBAL	0	$D^{*0} \to D^0\pi^0$
142.7±1.7	[2] GOLDHABER	77	MRK1	0	e^+e^-

[2] From simultaneous fit to $D^*(2010)^+$, $D^*(2010)^0$, D^+, and D^0.

$D^*(2010)^0$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
<2.1	90	[3] ABACHI	88B	HRS	$D^{*0} \to D^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<5		GOLDHABER	76B	MRK1	$e^+e^- \to D^*D^*$

[3] Assuming $m(D^{*0}) = 2007.2 \pm 2.1$ MeV/c^2.

$D^*(2010)^0$ DECAY MODES

$\overline{D}{}^*(2010)^0$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^0\pi^0$	(55±6) %
Γ_2	$D^0\gamma$	(45±6) %

CONSTRAINED FIT INFORMATION

An overall fit to a branching ratio uses 5 measurements and one constraint to determine 2 parameters. The overall fit has a $\chi^2 =$ 0.9 for 4 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left<\delta x_i \delta x_j\right>/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−100
	x_1

$D^*(2010)^0$ BRANCHING RATIOS

$\Gamma(D^0\gamma)/[\Gamma(D^0\pi^0) + \Gamma(D^0\gamma)]$ **$\Gamma_2/(\Gamma_1+\Gamma_2)$**

VALUE	DOCUMENT ID		TECN	COMMENT
0.45±0.06 OUR FIT				
0.45±0.06 OUR AVERAGE				
0.37±0.08±0.08	ADLER	88D	MRK3	e^+e^-
0.47±0.23	LOW	87	HRS	29 GeV e^+e^-
0.53±0.13	BARTEL	85G	JADE	e^+e^-, hadrons
0.47±0.12	COLES	82	MRK2	e^+e^-
0.45±0.15	[4] GOLDHABER	77	MRK1	e^+e^-

[4] We quote the normal fit value from table 1. The isospin-constrained fit is now known to give a $D^0\gamma$ fraction which is too large. See details in footnote 21 of FELDMAN 77C review.

$D^*(2010)^0$ REFERENCES

ABACHI 88B PL B212 533 +Akerlof+ (ANL, IND, MICH, PURD, LBL)
ADLER 88D PL B208 152 +Becker+ (Mark III Collab.)
LOW 87 PL B183 232 +Abachi, Akerlof, Baringer+ (HRS Collab.)
BARTEL 85G PL 161B 197 +Dietrich, Ambrus+ (JADE Collab.)
COLES 82 PR D26 2190 +Abrams, Blocker, Blondel+ (LBL, SLAC)
SADROZINSKI 80 Madison Conf. 681 + (PRIN, CIT, HARV, SLAC, STAN)
FELDMAN 77C Banff Sum. Inst. 75 (SLAC)
GOLDHABER 77 PL 69B 503 +Wiss, Abrams, Alam+ (LBL, SLAC)
NGUYEN 77 PRL 39 262 +Wiss, Abrams, Alam, Boyarski+ (LBL, SLAC) J
GOLDHABER 76B SLAC Conf. 379 (LBL, SLAC)
Available as LBL-5534.

OTHER RELATED PAPERS

TRILLING 81 PRPL 75 57 (LBL, UCB)
FELDMAN 77C Banff Sum. Inst. 75 (SLAC)
GOLDHABER 76 PRL 37 255 +Pierre, Abrams, Alam+ (LBL, SLAC)

$D_1(2420)^0$

$I(J^P) = \frac{1}{2}(1^+)$
I, J, P need confirmation.

Seen in $D^*(2010)^+\pi^-$. $J^P = 1^+$ according to ALBRECHT 89B and ALBRECHT 89H. The $D_J(2420)^0$ entry of 1988 is a superposition of $D_1(2420)^0$ and $D_2^*(2460)^0$ according to ALBRECHT 89H and AVERY 90.

$D_1(2420)^0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2424±6 OUR AVERAGE Error includes scale factor of 2.2.					
2428±3±2	279±34	AVERY	90	CLEO	$e^+e^- \rightarrow D^{*+}\pi^- X$
2414±2±5	171±22	ALBRECHT	89H	ARG	$e^+e^- \rightarrow D^{*+}\pi^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2428±8±5	171^{+43}_{-58}	ANJOS	89C	TPS	$\gamma N \rightarrow D^{*+}\pi^- X$
2421±5		[1] PRENTICE	87	ARG	$e^+e^- \rightarrow D^{*+}\pi^- X$

[1] Includes data of ALBRECHT 86E.

$D_1(2420)^0$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{20^{+\ 9}_{-\ 5}}$ **OUR AVERAGE**					
$23^{+\ 8+10}_{-\ 6-\ 3}$	279±34	AVERY	90	CLEO	$e^+e^- \rightarrow D^{*+}\pi^- X$
$13\pm\ 6^{+10}_{-\ 5}$	171±22	ALBRECHT	89H	ARG	$e^+e^- \rightarrow D^{*+}\pi^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
58±14±10	171^{+43}_{-58}	ANJOS	89C	TPS	$\gamma N \rightarrow D^{*+}\pi^- X$
62±14		[2] PRENTICE	87	ARG	$e^+e^- \rightarrow D^{*+}\pi^- X$

[2] Includes data of ALBRECHT 86E.

$D_1(2420)^0$ DECAY MODES

$\overline{D}_1(2420)^0$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^*(2010)^+\pi^-$	seen
Γ_2	$D^+\pi^-$	

$D_1(2420)^0$ BRANCHING RATIOS

$\Gamma(D^*(2010)^+\pi^-)/\Gamma_{total}$ **Γ_1/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
seen	AVERY	90	CLEO	$e^+e^- \rightarrow D^{*+}\pi^- X$
seen	ALBRECHT	89H	ARG	$e^+e^- \rightarrow D^*\pi^- X$
seen	ANJOS	89C	TPS	$\gamma N \rightarrow D^{*+}\pi^- X$

$\Gamma(D^+\pi^-)/\Gamma(D^*(2010)^+\pi^-)$ **Γ_2/Γ_1**

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.24	90	AVERY	90	CLEO	$e^+e^- \rightarrow D^+\pi^- X$

$D_1(2420)^0$ REFERENCES

AVERY 90 PR D41 774 +Besson (CLEO Collab.)
ALBRECHT 89B PL B221 422 +Boeckmann+ (ARGUS Collab.)
ALBRECHT 89H PL 232 398 +Glaser, Harder+ (ARGUS Collab.) JP
ANJOS 89C PRL 62 1717 +Appel+ (FNAL-TPS Collab.)
PRENTICE 87 Uppsala Conf. 910 + (ARGUS Collab.)
ALBRECHT 86E PRL 56 549 +Binder, Harder+ (ARGUS Collab.)

$D_J(2440)^\pm$

$I(J^P) = \frac{1}{2}(?^?)$
I needs confirmation.

OMITTED FROM SUMMARY TABLE

Possibly seen in $D^*(2010)^0\pi^+$. $J^P = 0^+$ ruled out.

$D_J(2440)^\pm$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2443±7±5	190^{+77}_{-44}	ANJOS	89C	TPS	$\gamma N \rightarrow D^0\pi^+ X^0$

$D_J(2440)^\pm$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
41±19±8	190^{+77}_{-44}	ANJOS	89C	TPS	$\gamma N \rightarrow D^0\pi^+ X^0$

$D_J(2440)^\pm$ DECAY MODES

$D_J^*(2440)^-$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^*(2010)^0\pi^+$	seen

$D_J(2440)^\pm$ BRANCHING RATIOS

$\Gamma(D^*(2010)^0\pi^+)/\Gamma_{total}$ **Γ_1/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
seen	ANJOS	89C	TPS	$\gamma N \rightarrow D^0\pi^+ X^0$

$D_J(2440)^\pm$ REFERENCES

ANJOS 89C PRL 62 1717 +Appel+ (FNAL-TPS Collab.)

$D_2^*(2460)^0$

$I(J^P) = \frac{1}{2}(2^+)$
I, J, P need confirmation.

$J^P = 2^+$ assignment strongly favored (ALBRECHT 89B).

$D_2^*(2460)^0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2459.4±2.2 OUR AVERAGE					
2461 ±3 ±1	440±97	AVERY	90	CLEO	$e^+e^- \to D^{*+}\pi^- X$
2455 ±3 ±5	337±100	ALBRECHT	89B	ARG	$e^+e^- \to D^+\pi^- X$
2459 ±3 ±2	153^{+42}_{-37}	ANJOS	89C	TPS	$\gamma N \to D^+\pi^- X$

$D_2^*(2460)^0$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
19± 7 OUR AVERAGE					
$20^{+\ 9+\ 9}_{-12-10}$	440±97	AVERY	90	CLEO	$e^+e^- \to D^{*+}\pi^- X$
$15^{+13+\ 5}_{-10-10}$	337±100	ALBRECHT	89B	ARG	$e^+e^- \to D^+\pi^- X$
20±10± 5	153^{+42}_{-37}	ANJOS	89C	TPS	$\gamma N \to D^+\pi^- X$

$D_2^*(2460)^0$ DECAY MODES

$\overline{D}_2^*(2460)^0$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^+\pi^-$	seen
Γ_2	$D^*(2010)^+\pi^-$	seen

$D_2^*(2460)^0$ BRANCHING RATIOS

$\Gamma(D^+\pi^-)/\Gamma_{total}$ $\qquad \Gamma_1/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	337±100	ALBRECHT	89B	ARG	$e^+e^- \to D^+\pi^- X$
seen		ANJOS	89C	TPS	$\gamma N \to D^+\pi^- X$

$\Gamma(D^*(2010)^+\pi^-)/\Gamma_{total}$ $\qquad \Gamma_2/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
seen	AVERY	90	CLEO	$e^+e^- \to D^{*+}\pi^- X$
seen	ALBRECHT	89H	ARG	$e^+e^- \to D^*\pi^- X$

$\Gamma(D^+\pi^-)/\Gamma(D^*(2010)^+\pi^-)$ $\qquad \Gamma_1/\Gamma_2$

VALUE	DOCUMENT ID		TECN	COMMENT
2.4±0.7 OUR AVERAGE				
2.3±0.8	AVERY	90	CLEO	e^+e^-
3.0±1.1±1.5	ALBRECHT	89H	ARG	$e^+e^- \to D^*\pi^- X$

$D_2^*(2460)^0$ REFERENCES

AVERY	90	PR D41 774	+Besson	(CLEO Collab.)
ALBRECHT	89B	PL B221 422	+Boeckmann+	(ARGUS Collab.) JP
ALBRECHT	89H	PL 232 398	+Glaser, Harder+	(ARGUS Collab.) JP
ANJOS	89C	PRL 62 1717	+Appel+	(FNAL-TPS Collab.)

$D_J^*(2470)^\pm$

$I(J^P) = \frac{1}{2}(?^?)$
I needs confirmation.

OMITTED FROM SUMMARY TABLE

Seen in $D^0\pi^+$.

$D_J^*(2470)^\pm$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2469±4±6	ALBRECHT	89F	ARG	$e^+e^- \to D^0\pi^+ X$

$D_J^*(2470)^\pm - D_2^*(2460)^0$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
14±5±8	ALBRECHT	89F	ARG	$e^+e^- \to D^0\pi^+ X$

$D_J^*(2470)^+$ DECAY MODES

$D_J^*(2470)^-$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^0\pi^+$	seen

$D_J^*(2470)^+$ BRANCHING RATIOS

$\Gamma(D^0\pi^+)/\Gamma_{total}$ $\qquad \Gamma_1/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
seen	ALBRECHT	89F	ARG	$e^+e^- \to D^0\pi^+ X$

$D_J^*(2470)^\pm$ REFERENCES

ALBRECHT 89F PL B231 208 +Glaser+ (ARGUS Collab.)

CHARMED STRANGE MESONS
$(C = S = \pm 1)$

$D_s^+ = c\overline{s}$, $D_s^- = \overline{c}s$, similarly for D_s^*'s

$D_s^\pm$
was $F^\pm$

$I(J^P) = 0(0^-)$

The angular distributions of the decays of the ϕ and $\overline{K}^*(892)^0$ in the $\phi\pi^+$ and $K^+\overline{K}^*(892)^0$ modes strongly indicate that the spin is zero. The parity given is that expected of a $c\overline{s}$ ground state.

NOTE ON THE D_s^+

(by W.H. Toki, SLAC)

Results published since our 1990 edition include lifetime measurements, many good measurements of hadronic branching ratios, and estimates of the $D_s^+ \to \phi\pi^+$ absolute branching fraction using the $D_s^+ \to \phi e^+\nu$ decay mode. In this Note, we discuss briefly recent high-statistics measurements of branching ratios from CLEO-II,[1] the attempts to establish absolute branching fractions, and an estimate of what fraction of D_s^+ decays remain unmeasured.

(1) New results from CLEO—The new hadronic modes from CLEO-II are $\eta\rho^+$ and $\eta'\rho^+$. In addition, CLEO-II has made precise measurements of the problematical $\phi\rho^+$, $\eta\pi^+$, and $\eta'\pi^+$ modes using several η and η' decay modes. (The modes with the ρ meson remain somewhat uncertain, however, due to the difficulty of determining the nonresonant $\pi\pi$ content.)

The $\eta\pi^+$ and $\eta'\pi^+$ branching ratios from CLEO-II are smaller than those obtained previously by MARK-II, ARGUS, and ACCMOR, but are within upper limits from TPS and MARK-III. When MARK-II found large $\eta\pi/\phi\pi$ and $\eta'\pi/\eta\pi$ ratios, Kamal *et al.*[2] pointed out that such large ratios implied severe η-η' mixing problems. The CLEO-II $\eta'\pi/\eta\pi$ ratio is smaller, but still is larger than predicted by models using a $-19°$ η-η' mixing angle.[3] Eventually, perhaps, the η-η' mixing angle can be measured using the theoretically cleaner but experimentally more difficult $D_s \to \eta e\nu$ and $\eta' e\nu$ modes.

Table 1 gives the new CLEO-II branching ratios, relative to the $\phi\pi$ rate. These results signify an increase in D_s partial widths for 2-body vector-pseudoscalar and vector-vector decays relative to pseudoscalar-pseudoscalar decays.

Table 1. New or improved D_s branching ratios from CLEO-II

D_s^+ mode	No. events	B(mode)/B($\phi\pi^+$)
$\eta\pi^+$	165	$0.54 \pm 0.09 \pm 0.06$
$\eta'\pi^+$	281	$1.20 \pm 0.15 \pm 0.11$
$\eta\rho^+$	217	$2.86 \pm 0.38\ ^{+0.36}_{-0.38}$
$\eta'\rho^+$	68	$3.44 \pm 0.62\ ^{+0.44}_{-0.46}$
$\phi\rho^+$	253	$1.86 \pm 0.26\ ^{+0.29}_{-0.40}$

(2) New estimates of B($D_s^+ \to \phi\pi^+$)—The new attempts to estimate absolute branching fractions equate[4] $\Gamma(D^+ \to \overline{K}^*(892)^0 e^+\nu)$ to $\Gamma(D_s^+ \to \phi e^+\nu)$. Using the measured D^+ and D_s^+ lifetimes and the branching fraction $B(D^+ \to \overline{K}^*(892)^0 e^+\nu)$, the branching fraction $B(D_s^+ \to \phi e^+\nu)$ may be predicted. Then by measuring the $\phi e\nu/\phi\pi$ branching ratio, the $D_s^+ \to \phi\pi^+$ branching fraction is obtained. Table 2 lists the recent measurements of the $\phi e\nu/\phi\pi$ ratio. The measurements of ARGUS and CLEO-II lead to estimates of the absolute $\phi\pi$ branching fraction of 2.5–3%. Averaging with the other measurements in our Listings, which are perhaps less reliable and less statistically significant, yields a branching fraction $B(D_s^+ \to \phi\pi^+) = 2.8 \pm 0.5\%$.

Table 2. Measurements of the $D_s \to \phi e\nu/\phi\pi$ ratio

Group	No. events	$B(D_s \to \phi e\nu)/B(D_s \to \phi\pi)$
TPS	none	< 0.45
ARGUS	104	$0.57 \pm 0.15 \pm 0.15$
CLEO-II	54	$0.49 \pm 0.10\ ^{+0.10}_{-0.14}$

(3) What remains to be measured—An important exercise is the estimate[1] of the remaining unmeasured D_s^+ decays. Assuming the semileptonic partial widths of the D_s^+ and D^+ are equal, we estimate that $B(D_s \to e\nu X) = B(D_s \to \mu\nu X) = 8\%$; and taking an estimate for the leptonic decay from $B \to DD_s$ decay rates from Rosner,[5] we use $B(D_s \to \mu\nu + \tau\nu) = 5\%$. Adding up the decays in Table 1 and the rates for $\phi\pi^+$, $K^+\overline{K}^0$, $K^*(892)^+\overline{K}^0$, $K^+\overline{K}^*(892)^0$, nonresonant $K^+K^-\pi^+$, $K^*(892)^+\overline{K}^*(892)^0$, $\phi\pi^+\pi^+\pi^-$, $f^0(975)\pi^+$, and nonresonant $\pi^+\pi^+\pi^-$, we find a total hadronic branching fraction of $18.3 \times B(D_s^+ \to \phi\pi^+)$. Hence,

$$B(\text{seen} + \text{estimated}) \approx 18.3 \times B(D_s^+ \to \phi\pi^+) + 21\% \ .$$

Using $B(D_s^+ \to \phi\pi^+) = 2.8\%$, we get B(seen+estimated) = 72%. We can also turn the prediction around to predict that $B(D_s \to \phi\pi) < 4.3\%$; otherwise B(seen+estimated) exceeds 100%.

The nature of the missing 28% of the D_s^+ decays in unclear. Naively, we would expect decays with $K\overline{K}$ plus many charged and neutral pions, which experimentally are difficult to detect. In a Mark III study of inclusive D_s^+ decays,[6] a large (64±17%) non-$K\overline{K}$ fraction was measured. This is consistent with the observed $K\overline{K} + X$ fraction of D_s^+ decays seen to date, and would imply that most if not all of the remaining D_s^+ decays are non-$K\overline{K}$. These could include η and η' decays with more than two pions. The recent CLEO data indicates an empirical trend of bigger branching fractions with more pions.

In the future, we hope for more precise branching ratios, direct and model-independent measurements of the absolute branching fractions in associated production of $D_s^+ D_s^-$ pairs in e^+e^- collisions, and possibly a measurement of the leptonic modes, $D_s \to \tau\nu$ and $\mu\nu$.

References

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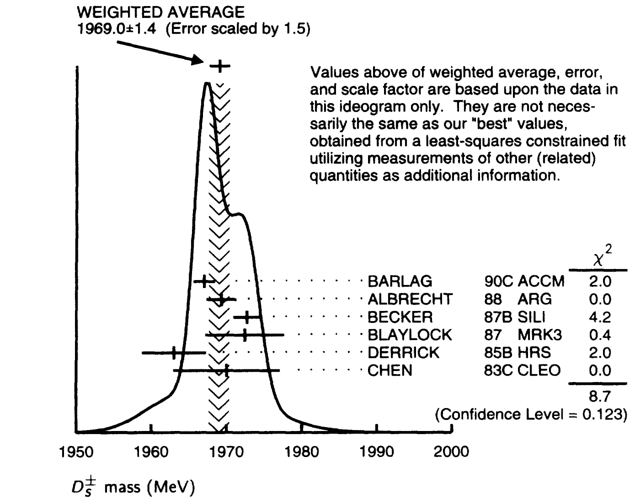
$D_s^{\pm}$ MASS

The fit includes the $D^{\pm}$, D^0, $D_s^{\pm}$, and $D_s^{*\pm}$ masses, and the $D^0 - D^{\pm}$, $D_s^{\pm} - D^{\pm}$, and $D_s^{*\pm} - D_s^{\pm}$ mass differences. Measurements of the $D_s^{\pm}$ mass with an error greater than 10 MeV are omitted from the fit and average. A number of early measurements giving $m > 2000$ MeV have been omitted altogether. They may be found in our 1990 edition (Phys. Lett. **B239**).

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1968.8± 0.7 OUR FIT	Error includes scale factor of 1.1.				
1969.0± 1.4 OUR AVERAGE	Error includes scale factor of 1.5. See the ideogram below.				
1967.0± 1.0± 1.0	54	BARLAG	90C	ACCM	π^- Cu 230 GeV
1969.3± 1.4± 1.4		ALBRECHT	88	ARG	e^+e^- 9.4–10.6 GeV
1972.7± 1.5± 1.0	21	BECKER	87B	SILI	200 GeV π,K,p
1972.4± 3.7± 3.7	27	BLAYLOCK	87	MRK3	e^+e^- 4.14 GeV
1963 ± 3 ± 3	30	DERRICK	85B	HRS	e^+e^- 29 GeV
1970 ± 5 ± 5	104	CHEN	83C	CLEO	e^+e^- 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1968.3± 0.7± 0.7	290	[1] ANJOS	88	E691	Photoproduction
1980 ±15	6	USHIDA	86	EMUL	ν wideband
1973.6± 2.6± 3.0	163	ALBRECHT	85D	ARG	e^+e^- 10 GeV
1948 ±28 ±10	65	AIHARA	84D	TPC	e^+e^- 29 GeV
1975 ± 9 ±10	49	ALTHOFF	84	TASS	e^+e^- 14–25 GeV
1975 ± 4	3	BAILEY	84	SILI	hadron$^+$ Be $\to \phi\pi^+ X$

[1] ANJOS 88 enters the fit via the $D_s^{\pm} - D^{\pm}$ mass difference (see below).



$D_s^{\pm} - D^{\pm}$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
99.5±0.6 OUR FIT Error includes scale factor of 1.1.					
99.5±0.7 OUR AVERAGE					
98.5±1.5	555	CHEN	89	CLEO	e^+e^- 10.5 GeV
99.8±0.8	290	ANJOS	88	E691	Photoproduction

$D_s^{\pm}$ MEAN LIFE

VALUE (10^{-13} s)	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{4.50^{+0.30}_{-0.26}}$ **OUR AVERAGE**					
$3.3\ ^{+1.2}_{-0.8}\ \pm0.3$	15	ALVAREZ	90	NA14	γ, $D_s^+ \rightarrow \phi\pi^+$
$4.69^{+1.02}_{-0.86}$	54	[2] BARLAG	90C	ACCM	π^- Cu 230 GeV
$5.0\ \pm0.6\ \pm0.3$	104	FRABETTI	90	SILI	γBe, $\phi\pi^+$
$3.1\ ^{+2.4}_{-2.0}\ \pm0.5$	18	AVERILL	89	HRS	e^+e^- 29 GeV
$5.6\ ^{+1.3}_{-1.2}\ \pm0.8$	144	ALBRECHT	88I	ARG	e^+e^- 10 GeV
$4.7\ \pm0.4\ \pm0.2$	228	RAAB	88	SILI	Photoproduction
$3.3\ ^{+1.0}_{-0.6}$	21	[3] BECKER	87B	SILI	200 GeV π,K,p
$5.7\ ^{+3.6}_{-2.6}\ \pm0.9$	9	BRAUNSCH...	87	TASS	e^+e^- 35–44 GeV
$4.7\ \pm2.2\ \pm0.5$	141	CSORNA	87	CLEO	e^+e^- 10 GeV
$2.6\ ^{+1.6}_{-0.9}$	6	USHIDA	86	EMUL	ν wideband
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$4.8\ ^{+0.6}_{-0.5}\ \pm0.2$	99	ANJOS	87B	E691	See RAAB 88
$3.5\ ^{+2.4}_{-1.8}\ \pm0.9$	17	JUNG	86	HRS	See AVERILL 89
$3.2\ ^{+3.0}_{-1.3}$	3	BAILEY	84	SILI	hadron$^+$ Be $\rightarrow \phi\pi^+$X
$1.9\ ^{+1.3}_{-0.7}$	4	USHIDA	83	EMUL	See USHIDA 86

[2] BARLAG 90C estimates the systematic error to be negligible.
[3] BECKER 87B estimates the systematic error to be negligible.

D_s^+ DECAY MODES

D_s^- modes are charge conjugates of the modes below.

Nearly all the other modes are measured relative to the $\phi\pi^+$ mode. However, none of the determinations of the $\phi\pi^+$ branching fraction are direct measurements: all rely on calculated relations between D^+ and D_s^+ decay widths or on estimates of D_s^+ cross sections. Thus a better determination of the $\phi\pi^+$ branching fraction could cause the other branching fractions to slide up or down, all together.

	Mode		Fraction (Γ_i/Γ)	Confidence level
	Inclusive modes			
Γ_1	K^- anything		$(13\ ^{+14}_{-12})$ %	
Γ_2	K^+ anything		$(20\ ^{+18}_{-14})$ %	
Γ_3	K^0 anything + $\overline{K}^0$ anything		$(39\ \pm28)$ %	
Γ_4	non-$K\overline{K}$ anything		$(64\ \pm17)$ %	
Γ_5	e^+ anything		< 20 %	90%
	Modes with two K's (including from ϕ's)			
Γ_6	$K^+\overline{K}^0$		(2.8 ± 0.7) %	
Γ_7	$K^+K^-\pi^+$	[a]	(3.9 ± 0.4) %	
Γ_8	$\phi\pi^+$	[b]	(2.8 ± 0.5) %	
Γ_9	$K^+\overline{K}^*(892)^0$	[b]	(2.6 ± 0.5) %	
Γ_{10}	$K^+K^-\pi^+$ nonresonant		$(8.1\pm3.0)\times10^{-3}$	
Γ_{11}	$K^0\overline{K}^0\pi^+$			
Γ_{12}	$K^*(892)^+\overline{K}^0$	[b]	(3.3 ± 0.9) %	
Γ_{13}	$K^+K^-\pi^+\pi^0$			
Γ_{14}	$\phi\pi^+\pi^0$	[b]	(6.7 ± 3.3) %	
Γ_{15}	$\phi\rho^+$	[b]	$(5.2\ ^{+1.4}_{-1.6})$ %	
Γ_{16}	$\phi\pi^+\pi^0$ 3-body	[b]	< 2.0 %	90%
Γ_{17}	$K^+K^-\pi^+\pi^0$ non-ϕ		< 7 %	90%
Γ_{18}	$K^+\overline{K}^0\pi^+\pi^-$		< 2.1 %	90%
Γ_{19}	$K^0K^-\pi^+\pi^+$		(3.3 ± 1.0) %	
Γ_{20}	$K^*(892)^+\overline{K}^*(892)^0$	[b]	(5.0 ± 1.7) %	
Γ_{21}	$K^0K^-\pi^+\pi^+$ non-$K^{*+}\overline{K}^{*0}$		< 2.2 %	90%
Γ_{22}	$K^+K^-\pi^+\pi^+\pi^-$			
Γ_{23}	$\phi\pi^+\pi^+\pi^-$	[b]	(1.2 ± 0.4) %	
Γ_{24}	$K^+K^-\pi^+\pi^+\pi^-$ non-ϕ		$(1.9\pm1.4)\times10^{-3}$	
	Other hadronic modes			
Γ_{25}	$\pi^+\pi^+\pi^-$		(1.2 ± 0.4) %	
Γ_{26}	$\rho^0\pi^+$		< 2.2 $\times10^{-3}$	90%
Γ_{27}	$f_0(975)\pi^+$	[b]	$(7.8\pm3.2)\times10^{-3}$	
Γ_{28}	$\pi^+\pi^+\pi^-$ nonresonant		$(8.0\pm3.0)\times10^{-3}$	
Γ_{29}	$\pi^+\pi^+\pi^-\pi^0$		< 9 %	90%
Γ_{30}	$\eta\pi^+$	[b]	(1.5 ± 0.4) %	
Γ_{31}	$\omega\pi^+$	[b]	< 1.4 %	90%
Γ_{32}	$\pi^+\pi^+\pi^+\pi^-\pi^-$		$(1.9\pm2.0)\times10^{-3}$	
Γ_{33}	$\pi^+\pi^+\pi^-\pi^0\pi^0$			
Γ_{34}	$\eta\rho^+$	[b]	(7.9 ± 2.1) %	
Γ_{35}	$\eta\pi^+\pi^0$ 3-body	[b]	< 2.3 %	90%
Γ_{36}	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$			
Γ_{37}	$\eta\pi^+\pi^+\pi^-$			
Γ_{38}	$\eta'(958)\pi^+$	[b]	(3.7 ± 1.2) %	
Γ_{39}	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$			
Γ_{40}	$\eta'(958)\rho^+$	[b]	(9.5 ± 2.7) %	
Γ_{41}	$\eta'(958)\pi^+\pi^0$ 3-body	[b]	< 2.4 %	90%
Γ_{42}	$K^0\pi^+$		< 6 $\times10^{-3}$	90%
Γ_{43}	$K^+\pi^+\pi^-$		$(1.4\pm2.0)\times10^{-3}$	
	Leptonic and semileptonic modes			
Γ_{44}	$\mu^+\nu$		< 3 %	
Γ_{45}	$\phi e^+\nu$	[b]	(1.6 ± 0.7) %	
Γ_{46}	$\phi\ell^+\nu$	[b,c]	(1.4 ± 0.5) %	

[a] The sum of appropriate fractions of the next three modes.
[b] Includes all the decay modes of the ϕ, $K^*(892)$, η, ω, $\eta'(958)$, or $f_0(975)$.
[c] This is an average of the $\phi e^+\nu_e$ and $\phi\mu^+\nu_\mu$ branching fractions.

D_s^+ BRANCHING RATIOS

A few older, now obsolete results have been omitted. They may be found in our 1990 edition (Phys. Lett. **B239**).

$\Gamma(K^-\text{ anything})/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.13^{+0.14}_{-0.12}\pm0.02}$	COFFMAN	91	MRK3	e^+e^- 4.14 GeV

$\Gamma(K^+\text{ anything})/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.20^{+0.18}_{-0.13}\pm0.04}$	COFFMAN	91	MRK3	e^+e^- 4.14 GeV

$[\Gamma(K^0\text{ anything}) + \Gamma(\overline{K}^0\text{ anything})]/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.39^{+0.28}_{-0.27}\pm0.04}$	COFFMAN	91	MRK3	e^+e^- 4.14 GeV

$\Gamma(\text{non-}K\overline{K}\text{ anything})/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.64±0.17±0.03	[4] COFFMAN	91	MRK3	e^+e^- 4.14 GeV

[4] COFFMAN 91 uses the direct measurements of the kaon content to determine this non-$K\overline{K}$ fraction. This number implies a large fraction of D_s decays involve η, η', and/or non-spectator decays.

$\Gamma(e^+ \text{ anything})/\Gamma_{total}$ — Γ_5/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.20	90	[5] BAI	90	MRK3	e^+e^- 4.14 GeV

[5] Expressed as a value, the BAI 90 result is $\Gamma(e^+ \text{ anything})/\Gamma_{total} = 0.05 \pm 0.05 \pm 0.02$.

$\Gamma(\phi\pi^+)/\Gamma_{total}$ — Γ_8/Γ

Nearly all the other modes are measured relative to this mode, which, however, is an uncertain anchor; see the footnotes to the values and the note at the beginning of the list of decay modes, above.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.028±0.005 OUR AVERAGE						
0.024±0.010			[6] ALBRECHT	91	ARG	$e^+e^- \approx$ 10.4 GeV
$0.031\pm0.006^{+0.011}_{-0.009}$			[6] ALEXANDER	90B	CLEO	e^+e^- 10.5–11 GeV
0.048±0.017±0.019			[7] ALVAREZ	90C	NA14	Photoproduction
0.02 ±0.01		405	[8] CHEN	89	CLEO	e^+e^- 10 GeV
0.033±0.016±0.010		9	[8] BRAUNSCH...	87	TASS	e^+e^- 35–44 GeV
0.033±0.011		30	[8] DERRICK	85B	HRS	e^+e^- 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.041	90	0	[9] ADLER	90B	MRK3	e^+e^- 4.14 GeV
>0.034	90		[6] ANJOS	90B	E691	γBe, $\overline{E}_\gamma \approx$ 145 GeV

[6] ALEXANDER 90B, ANJOS 90B, and ALBRECHT 91 rely on a calculated relation between $\Gamma(D_s^+ \to \phi \ell^+ \nu)$ and $\Gamma(D^+ \to \overline{K}^{*0} \ell^+ \nu)$.

[7] ALVAREZ 90C relies on the Lund model to estimate the ratio of D_s^+ to D^+ cross sections.

[8] Values based on crude estimates of the $D_s^\pm$ production level. DERRICK 85B errors are statistical only.

[9] ADLER 90 uses a technique based on full reconstruction of $D_s^+ D_s^-$ pairs (double tags) to obtain a branching ratio limit without assumptions about $\sigma(D_s^\pm)$.

$\Gamma(K^+\overline{K}^0)/\Gamma(\phi\pi^+)$ — Γ_6/Γ_8

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.01±0.16 OUR AVERAGE					
1.15±0.31±0.19	68	ANJOS	90C	E691	γ Be
0.92±0.32±0.20		ADLER	89B	MRK3	e^+e^- 4.14 GeV
0.99±0.17±0.10		CHEN	89	CLEO	e^+e^- 10 GeV

$\Gamma(K^+\overline{K}^*(892)^0)/\Gamma(\phi\pi^+)$ — Γ_9/Γ_8

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.95±0.10 OUR AVERAGE					
0.85±0.34±0.20	9	ALVAREZ	90C	NA14	Photoproduction
0.94±0.35	20	BARLAG	90D	ACCM	π^- 230 GeV
0.84±0.30±0.22		ADLER	89B	MRK3	e^+e^- 4.14 GeV
1.05±0.17±0.12		CHEN	89	CLEO	e^+e^- 10 GeV
0.87±0.13±0.05	117	ANJOS	88	E691	Photoproduction
1.44±0.37	87	ALBRECHT	87F	ARG	e^+e^- 10 GeV

$\Gamma(K^+K^-\pi^+ \text{ nonresonant})/\Gamma(\phi\pi^+)$ — Γ_{10}/Γ_8

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.29±0.09 OUR AVERAGE Error includes scale factor of 1.2.					
0.51±0.20	18	BARLAG	90D	ACCM	π^- 230 GeV
0.25±0.07±0.05	48	ANJOS	88	E691	Photoproduction

$\Gamma(K^*(892)^+\overline{K}^0)/\Gamma(\phi\pi^+)$ — Γ_{12}/Γ_8

VALUE	DOCUMENT ID		TECN	COMMENT
1.20±0.21±0.13	CHEN	89	CLEO	e^+e^- 10 GeV

$\Gamma(\phi\pi^+\pi^0)/\Gamma(\phi\pi^+)$ — Γ_{14}/Γ_8

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
2.4±1.0±0.5		11	ANJOS	89E	E691	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2.6	90		ALVAREZ	90C	NA14	Photoproduction

$\Gamma(\phi\rho^+)/\Gamma(\phi\pi^+)$ — Γ_{15}/Γ_8

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{1.86\pm0.26^{+0.29}_{-0.40}}$	253	AVERY	92	CLEO	$e^+e^- \sim$ 10.5 GeV

$\Gamma(\phi\pi^+\pi^0 \text{ 3-body})/\Gamma(\phi\pi^+)$ — Γ_{16}/Γ_8

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.71	90	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(K^+K^-\pi^+\pi^0 \text{ non-}\phi)/\Gamma(\phi\pi^+)$ — Γ_{17}/Γ_8

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.4	90	[10] ANJOS	89E	E691	Photoproduction

[10] Total minus ϕ component.

$\Gamma(K^+\overline{K}^0\pi^+\pi^-)/\Gamma(\phi\pi^+)$ — Γ_{18}/Γ_8

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.77	90	ALBRECHT	92B	ARG	$e^+e^- \sim$ 10.4 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.56±0.62		BARLAG	90D	ACCM	π^- 230 GeV

$\Gamma(K^0K^-\pi^+\pi^+)/\Gamma(\phi\pi^+)$ — Γ_{19}/Γ_8

VALUE	DOCUMENT ID		TECN	COMMENT
1.2 ±0.2 ±0.2	ALBRECHT	92B	ARG	$e^+e^- \sim$ 10.4 GeV

$\Gamma(K^*(892)^+\overline{K}^*(892)^0)/\Gamma(\phi\pi^+)$ — Γ_{20}/Γ_8

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.8 ±0.5 OUR AVERAGE					
1.6 ±0.4 ±0.4		ALBRECHT	92B	ARG	$e^+e^- \sim$ 10.4 GeV
2.92±1.37±0.26	7	BARLAG	90D	ACCM	π^- 230 GeV

$\Gamma(K^0K^-\pi^+\pi^+ \text{ non-}K^{*+}\overline{K}^{*0})/\Gamma(\phi\pi^+)$ — Γ_{21}/Γ_8

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.80	90	ALBRECHT	92B	ARG	$e^+e^- \sim$ 10.4 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.32±0.35±0.06		BARLAG	90D	ACCM	π^- 230 GeV

$\Gamma(\phi\pi^+\pi^+\pi^-)/\Gamma(\phi\pi^+)$ — Γ_{23}/Γ_8

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.42±0.12 OUR AVERAGE Error includes scale factor of 1.1.						
0.34±0.16		8	BARLAG	90D	ACCM	π^- 230 GeV
0.42±0.13±0.07		19	ANJOS	88	E691	Photoproduction
1.11±0.37±0.28		62	ALBRECHT	85D	ARG	e^+e^- 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.24	90		ALVAREZ	90C	NA14	Photoproduction

$\Gamma(K^+K^-\pi^+\pi^+\pi^- \text{ non-}\phi)/\Gamma(\phi\pi^+)$ — Γ_{24}/Γ_8

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.07±0.05			BARLAG	90D	ACCM	π^- 230 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.32	90	10	ANJOS	88	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^-)/\Gamma(\phi\pi^+)$ — Γ_{25}/Γ_8

VALUE	DOCUMENT ID		TECN	COMMENT
0.44±0.10±0.04	ANJOS	89	E691	Photoproduction

$\Gamma(\rho^0\pi^+)/\Gamma(\phi\pi^+)$ — Γ_{26}/Γ_8

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.08	90	ANJOS	89	E691	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.22	90	ALBRECHT	87G	ARG	e^+e^- 10 GeV

$\Gamma(f_0(975)\pi^+)/\Gamma(\phi\pi^+)$ — Γ_{27}/Γ_8

VALUE	DOCUMENT ID		TECN	COMMENT
0.28±0.10±0.03	ANJOS	89	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^- \text{ nonresonant})/\Gamma(\phi\pi^+)$ — Γ_{28}/Γ_8

VALUE	DOCUMENT ID		TECN	COMMENT
0.29±0.09±0.03	ANJOS	89	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^-\pi^0)/\Gamma(\phi\pi^+)$ — Γ_{29}/Γ_8

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.3	90	ANJOS	89E	E691	Photoproduction

$\Gamma(\eta\pi^+)/\Gamma(\phi\pi^+)$ — Γ_{30}/Γ_8

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.54±0.09±0.06		165	ALEXANDER	92	CLEO	$\eta \to \gamma\gamma, \pi^+\pi^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.5	90		ANJOS	89E	E691	Photoproduction

$\Gamma(\omega\pi^+)/\Gamma(\phi\pi^+)$ — Γ_{31}/Γ_8

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.5	90	ANJOS	89E	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma(\phi\pi^+)$ — Γ_{32}/Γ_8

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.07±0.07		BARLAG	90D	ACCM	π^- 230 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.29	90	ANJOS	89	E691	Photoproduction

$\Gamma(\eta\rho^+)/\Gamma(\phi\pi^+)$ — Γ_{34}/Γ_8

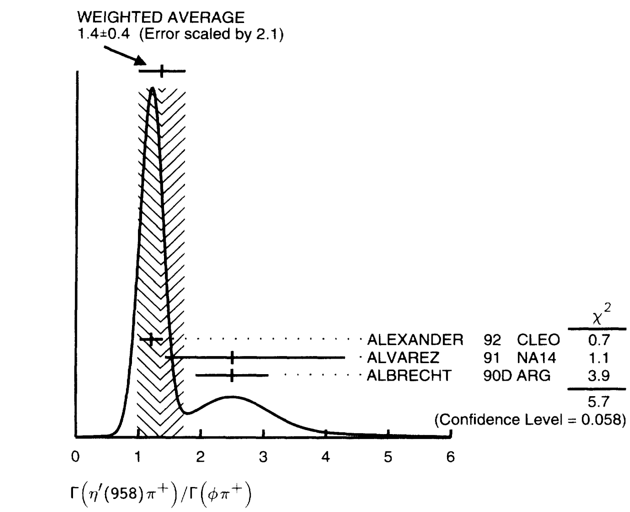
VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{2.86\pm0.38^{+0.36}_{-0.38}}$	217	AVERY	92	CLEO	$\eta \to \gamma\gamma, \pi^+\pi^-\pi^0$

$\Gamma(\eta\pi^+\pi^0 \text{ 3-body})/\Gamma(\phi\pi^+)$ — Γ_{35}/Γ_8

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.82	90	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(\eta'(958)\pi^+)/\Gamma(\phi\pi^+)$ — Γ_{38}/Γ_8

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
1.4 ±0.4 OUR AVERAGE Error includes scale factor of 2.1. See the ideogram below.						
$1.20\pm0.15\pm0.11$		281	ALEXANDER	92	CLEO	$\eta' \to \eta\pi^+\pi^-$, $\rho^0\gamma$
$2.5\ \pm1.0\ ^{+1.5}_{-0.4}$		22	ALVAREZ	91	NA14	Photoproduction
$2.5\ \pm0.5\ \pm0.3$		215	ALBRECHT	90D	ARG	$e^+e^- \approx 10.4$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.3	90		ANJOS	91B	E691	γBe, $\overline{E}_\gamma \approx 145$ GeV



$\Gamma(\eta'(958)\rho^+)/\Gamma(\phi\pi^+)$ — Γ_{40}/Γ_8

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$3.44\pm0.62^{+0.44}_{-0.46}$	68	AVERY	92	CLEO	$\eta' \to \eta\pi^+\pi^-$

$\Gamma(\eta'(958)\pi^+\pi^0$ 3-body$)/\Gamma(\phi\pi^+)$ — Γ_{41}/Γ_8

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.85	90	DAOUDI	92	CLEO	$e^+e^- \approx 10.5$ GeV

$\Gamma(K^0\pi^+)/\Gamma(\phi\pi^+)$ — Γ_{42}/Γ_8

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.21	90	ADLER	89B	MRK3	e^+e^- 4.14 GeV

$\Gamma(K^+\pi^+\pi^-)/\Gamma(\phi\pi^+)$ — Γ_{43}/Γ_8

VALUE	DOCUMENT ID		TECN	COMMENT
0.05±0.07	BARLAG	90D	ACCM	π^- 230 GeV

$\Gamma(\mu^+\nu)/\Gamma_{total}$ — Γ_{44}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
<0.03	0	[11] AUBERT	83	SPEC	μ^+Fe, 250 GeV

[11] AUBERT 83 assume that the $D_s^{\pm}$ production rate is 20% of total charm production rate.

$\Gamma(\phi e^+\nu)/\Gamma(\phi\pi^+)$ — Γ_{45}/Γ_8

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.57±0.15±0.15		104	ALBRECHT	91	ARG	$e^+e^- \approx 10.4$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.45	90		ANJOS	90B	E691	γBe, $\overline{E}_\gamma \approx 145$ GeV

$\Gamma(\phi\ell^+\nu)/\Gamma(\phi\pi^+)$ — Γ_{46}/Γ_8

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.49\pm0.10^{+0.10}_{-0.14}$	54	[12] ALEXANDER	90B	CLEO	e^+e^- 10.5–11 GeV

[12] ALEXANDER 90B is an average of $\phi e^+\nu_e$ and $\phi\mu^+\nu_\mu$ ratios.

$D_s^{\pm}$ REFERENCES

ALBRECHT 92B ZPHY C53 361 +Ehrlichmann, Hamacher, Krueger+ (ARGUS Collab.)
ALEXANDER 92 PRL 68 1275 +Bebek, Berkelman, Besson+ (CLEO Collab.)
AVERY 92 PRL 68 1279 +Freyberger, Rodriguez, Yelton+ (CLEO Collab.)
DAOUDI 92 PR D (submitted) +Ford, Johnson, Lingel+ (CLEO Collab.)
ALBRECHT 91 PL B255 634 +Ehrlichmann, Hamacher, Krueger+ (ARGUS Collab.)
ALVAREZ 91 PL B255 639 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
ANJOS 91B PR D43 R2063 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
COFFMAN 91 PL B263 135 +DeJongh, Dubois, Eigen, Hitlin+ (Mark III Collab.)
ADLER 90 PRL 64 2615 +Blaylock, Bolton+ (Mark III Collab.)
ADLER 90B PRL 64 169 +Bai, Blaylock, Bolton+ (Mark III Collab.)
ALBRECHT 90D PL B245 315 +Ehrlichmann, Glaeser, Harder+ (ARGUS Collab.)
ALEXANDER 90B PRL 65 1531 +Artuso, Bebek, Berkelman+ (CLEO Collab.)
ALVAREZ 90 ZPHY C47 539 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
ALVAREZ 90C PL B246 261 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
ANJOS 90B PRL 64 2885 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
ANJOS 90C PR D41 2705 +Appel, Bean+ (FNAL-TPS Collab.)
BAI 90 PRL 65 686 +Blaylock, Bolton, Brient+ (Mark III Collab.)
BARLAG 90C ZPHY C46 563 +Becker, Boehringer, Bosman+ (ACCMOR Collab.)
BARLAG 90D ZPHY C48 29 +Becker, Boehringer, Bosman+ (ACCMOR Collab.)
FRABETTI 90 PL B251 639 +Bogart, Cheung, Coteus+ (FNAL-E687 Collab.)
ADLER 89B PRL 63 1211 +Bai, Becker, Blaylock, Bolton+ (Mark III Collab.)
Also 89D PRL 63 2858 erratum
ANJOS 89 PRL 62 125 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
ANJOS 89E PL B223 267 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
AVERILL 89 PR D39 123 +Blockus, Brabson+ (HRS Collab.)
CHEN 89 PL B226 192 +McIlwain, Miller, Ng, Shibata+ (CLEO Collab.)
ALBRECHT 88 PL B207 349 +Binder, Boeckmann+ (ARGUS Collab.)
ALBRECHT 88I PL B210 267 +Boeckmann, Glaeser+ (ARGUS Collab.)
ANJOS 88 PRL 60 897 +Appel+ (FNAL-TPS Collab.)
RAAB 88 PR D37 2391 +Anjos, Appel, Bracker+ (FNAL-TPS Collab.)
ALBRECHT 87F PL B179 398 +Binder, Boeckmann, Glaeser+ (ARGUS Collab.)
ALBRECHT 87G PL B195 102 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
ANJOS 87B PRL 58 1818 +Appel, Bracker, Browder+ (FNAL-TPS Collab.)
BECKER 87B PL B184 277 +Boehringer, Bosman+ (NA11 and NA32 Collab.)
BLAYLOCK 87 PRL 58 2171 +Bolton, Brown, Bunnell+ (Mark III Collab.)
BRAUNSCH... 87 ZPHY C35 317 Braunschweig, Gerhards+ (TASSO Collab.)
CSORNA 87 PL B191 318 +Mestayer, Panvini, Word+ (CLEO Collab.)
JUNG 86 PRL 56 1775 +Abachi+ (HRS Collab.)
USHIDA 86 PRL 56 1767 +Kondo+ (AICH, FNAL, GIFU, GYEO, KOBE, SEOU+)
ALBRECHT 85D PL 153B 343 +Drescher, Binder, Drews+ (ARGUS Collab.)
DERRICK 85B PRL 54 2568 +Fernandez, Fries, Hyman+ (HRS Collab.)
AIHARA 84D PRL 53 2465 +Alston-Garnjost, Badtke, Bakken+ (TPC Collab.)
ALTHOFF 84 PL 136B 130 +Braunschweig, Kirschfink+ (TASSO Collab.)
BAILEY 84 PL 139B 320 +Belau, Bohringer, Bosman+ (ACCMOR Collab.)
AUBERT 83 NP B213 31 +Bassompierre, Becks, Best+ (EMC Collab.)
CHEN 83C PRL 51 634 +Alam, Giles, Kagan+ (CLEO Collab.)
USHIDA 83 PRL 51 2362 + (AICH, FNAL, KOBE, SEOU, MCGI, NAGO+)

OTHER RELATED PAPERS

SCHINDLER 88 High Energy Electron-Positron Physics 234 (SLAC)
Editors: A. Ali and P. Soeding, World Scientific, Singapore

$D_s^{*\pm}$
was $F^{*\pm}$

$I(J^P) = ?(?^?)$

$D_s^{*\pm}$ MASS

The fit includes the $D^{\pm}$, D^0, $D_s^{\pm}$, and $D_s^{*\pm}$ masses and the $D^0 - D^{\pm}$, $D_s^{\pm} - D^{\pm}$, and $D_s^{*\pm} - D_s^{\pm}$ mass differences.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2110.3±2.0 OUR FIT Error includes scale factor of 1.3.				
2106.6±2.1±2.7	[1] BLAYLOCK	87	MRK3	$e^+e^- \to D_s^{\pm}\gamma X$

[1] Assuming $D_s^{\pm}$ mass $= 1968.7 \pm 0.9$ MeV.

$D_s^{*\pm} - D_s^{\pm}$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
141.5± 1.9 OUR FIT Error includes scale factor of 1.3.					
142.4± 1.7 OUR AVERAGE					
$142.5\pm\ 0.8\pm1.5$		[2] ALBRECHT	88	ARG	$e^+e^- \to D_s^{\pm}\gamma X$
143.0 ± 18.0	8	ASRATYAN	85	HLBC	FNAL 15-ft, ν-^{2}H
$139.5\pm\ 8.3\pm9.7$	60	AIHARA	84D	TPC	$e^+e^- \to$ hadrons
$110\ \ \pm46$		BRANDELIK	79	DASP	$e^+e^- \to D_s^{\pm}\gamma X$

[2] Result includes data of ALBRECHT 84B

$D_s^{*\pm}$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
< 4.5	90	ALBRECHT	88	ARG	$E^{ee}_{cm} = 10.2$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<22	90	BLAYLOCK	87	MRK3	$e^+e^- \to D_s^{\pm}\gamma X$

D_s^{*+} DECAY MODES

D_s^{*-} modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D_s^+\gamma$	dominant

D_s^{*+} BRANCHING RATIOS

$\Gamma(D_s^+\gamma)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
dominant OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	ASRATYAN	91	HLBC	$\overline{\nu}_\mu$ Ne
seen	ALBRECHT	88	ARG	$e^+e^- \rightarrow D_s^\pm\gamma X$
seen	AIHARA	84D		
seen	ALBRECHT	84B		
seen	BRANDELIK	79		

$D_s^{*\pm}$ REFERENCES

ASRATYAN 91 PL B257 525 +Marage+(ITEP, BELG, SACL, SERP, CRAC, BARI, CERN)
ALBRECHT 88 PL B207 349 +Binder, Boeckmann+ (ARGUS Collab.)
BLAYLOCK 87 PRL 58 2171 +Bolton, Brown, Bunnell+ (Mark III Collab.)
ASRATYAN 85 PL 156B 441 +Fedotov, Ammosov, Burtovoy+ (ITEP, SERP)
AIHARA 84D PRL 53 2465 +Alston-Garnjost, Badtke, Bakken+ (TPC Collab.)
ALBRECHT 84B PL 146B 111 +Drescher, Heller+ (ARGUS Collab.)
BRANDELIK 79 PL 80B 412 +Braunschweig, Martyn, Sander+ (DASP Collab.)

OTHER RELATED PAPERS

BRANDELIK 78C PL 76B 361 +Cords+ (AACH, DESY, HAMB, MPIM, TOKY)
BRANDELIK 77B PL 70B 132 +Braunschweig, Martyn, Sander+ (DASP Collab.)

$D_{s1}(2536)^\pm$

$I(J^P) = 0(1^+)$
I, J, P need confirmation.

Seen in $D^*(2010)^+K^0$. Not seen in D^+K^0. $J^P = 1^+$ assignment strongly favored.

$D_{s1}(2536)^\pm$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2536.5± 0.8 OUR AVERAGE				
2536.6± 0.7±0.4	AVERY	90	CLEO	$e^+e^- \rightarrow D^{*+}K^0 X$
2535.9± 0.9±2.0	ALBRECHT	89E	ARG	$D_{s1}^* \rightarrow D^*(2010)K^0$
2535 ±28	[1] ASRATYAN	88	HLBC	$\nu N \rightarrow D_s\gamma\gamma X$

[1] Not seen in D^*K.

$D_{s1}(2536)^\pm - D_s^*(2111)$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
424±28	ASRATYAN	88	HLBC	$D_s^{*\pm}\gamma$

$D_{s1}(2536)^\pm$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
<5.44	90	AVERY	90	CLEO	$e^+e^- \rightarrow D^{*+}K^0 X$
<4.6	90	ALBRECHT	89E	ARG	$D_{s1}^* \rightarrow D^*(2010)K^0$

$D_{s1}(2536)^+$ DECAY MODES

$D_{s1}(2536)^-$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^*(2010)^+K^0$	seen
Γ_2	D^+K^0	
Γ_3	$D_s^{*+}\gamma$	possibly seen

$D_{s1}(2536)^+$ BRANCHING RATIOS

$\Gamma(D^+K^0)/\Gamma(D^*(2010)^+K^0)$ Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.43	90	ALBRECHT	89E	ARG	$D_{s1}^* \rightarrow D^*(2010)K^0$

$\Gamma(D_s^{*+}\gamma)/\Gamma_{total}$ Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
possibly seen	ASRATYAN	88	HLBC	$\nu N \rightarrow D_s\gamma\gamma X$

$D_{s1}(2536)^\pm$ REFERENCES

AVERY 90 PR D41 774 +Besson (CLEO Collab.)
ALBRECHT 89E PL B230 162 +Glaser, Harder+ (ARGUS Collab.)
ASRATYAN 88 ZPHY C40 483 +Fedotov+ (ITEP, SERP)

$D_{sJ}(2564)^\pm$

$I(J^P) = ?(?^?)$

OMITTED FROM SUMMARY TABLE

$D_{sJ}(2564)^\pm$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2564.3±4.4	ASRATYAN	88	HLBC	D^*K

$D_{sJ}(2564)^\pm$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
<2.5	ASRATYAN	88	HLBC	D^*K

$D_{sJ}(2564)^+$ DECAY MODES

$D_{sJ}(2564)^-$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	D^*K	seen

$D_{sJ}(2564)^+$ BRANCHING RATIOS

$\Gamma(D^*K)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	ASRATYAN	88	HLBC	D^*K

$D_{sJ}(2564)^\pm$ REFERENCES

ASRATYAN 88 ZPHY C40 483 +Fedotov+ (ITEP, SERP)

BOTTOM MESONS
($B = \pm 1$)

$B^+ = u\bar{b}$, $B^0 = d\bar{b}$, $\overline{B}^0 = \bar{d}\,b$, $B^- = \bar{u}\,b$, similarly for B^*'s

HIGHLIGHTS OF B MESON PRODUCTION AND DECAY

(by R.H. Schindler, SLAC)

This edition of the *Review of Particle Properties* contains some of the final results from CLEO-I and ARGUS running on the $\Upsilon(4S)$ resonance.[1] During 1991, CESR with the new CLEO-II detector was commissioned and ran in the Υ resonance region collecting record luminosities of 8–9 pb^{-1}/day for a symmetric e^+e^- collider. While a large data set (>1 fb^{-1}) has now been accumulated with the new CLEO-II detector on the $\Upsilon(4S)$ resonance and in the nearby continuum, few new results are available in the current Listings. The new data sample, however, is already significantly greater than the previous data sample sizes (0.2–0.4 fb^{-1}). We anticipate in the next edition of the *Review of Particle Properties* a major advance in our knowledge of B meson decays from the CESR/CLEO-II Cornell program. This edition's Listings also contain the first measurements of B mesons from Z decays. The addition of silicon vertex devices in many of the LEP detectors, coupled with their average accumulations of 250k Z during 1991 running, implies that we should see some of the first direct B meson results on lifetimes in the near future. This past year has also seen the first reconstruction from a hadron collider experiment (CDF) of exclusive B decays (containing $J/\psi(1S) \to 1^+1^-$). The implementation of silicon vertexing in CDF for the collider run next year should also result in the measurement of B lifetimes from exclusive decays.

In the 1990 edition of the *Review of Particle Properties*, CLEO reported the first evidence[2] for significant non-$b\bar{b}$ decays of the $\Upsilon(4S)$. This was in the form of $J/\psi(1S)$ with momenta outside the kinematic limit for production from B meson decay. The branching ratio for this OZI suppressed process was approximately 0.2%. Subsequent data from CLEO-II has been presented[3] suggesting that these high $\times$ $J/\psi(1S)$ decays can be explained by continuum production.

The mixing of B^0 and $\overline{B}^0$ mesons first suggested by UA1 and subsequently measured by ARGUS, provided the first indirect evidence of a heavy t-quark. Mixing has similarly been observed by L3 and ALEPH with events from the Z resonance.[4] Their results (like UA1) are for an admixture of B_d and B_s mesons. Combined with the precise results from CLEO-I and ARGUS on pure B_d mixing, the L3 result alone suggests, for example, an allowed region for B_s mixing $\chi_s > 0.14$ at 90% CL. Present constraints on the CKM matrix suggest that B_s mixing will be found experimentally to be close to maximal (that is, $\chi_s \approx 0.5$). If χ_s is greater than approximately 0.3–0.4, then experimental sensitivity to the CKM parameters[5] ($|V_{tb}V_{ts}^*|$) through B_s mixing will come about more likely through the direct measurement of the mixing oscillation frequency (the time evolution), rather than through time-averaged quantity such as χ_s. These studies are likely to occur in hadron and electron machines where the B mesons are adequately boosted.

Extensive work on semileptonic B meson decay has been done by CLEO and ARGUS. The semileptonic branching fraction is important for establishing the values of the CKM parameters V_{cb} and V_{ub}. The branching fractions to exclusive states $B \to D\ell\nu$ and $B \to D(2010)^*\ell\nu$ have been measured. In comparison with the inclusive rate for leptons, it appears that these can account for only about 1/2 to 2/3 of the total semileptonic branching fraction. The balance must be a mixture of other channels such as $D^{**}\ell\nu$, $D\pi\ell\nu$, $D(2010)^*\pi\ell\nu$, *etc.* The total semileptonic branching fraction still retains about a 10% uncertainty, owing largely to model dependence of the inclusive spectrum. Improvements can be anticipated from a comparison of single- and double-tagged semileptonic decays, combined with higher statistics measurements of the exclusive charged and neutral $B_{\ell 3}$ channels. The uncertainty in the B semileptonic branching fractions may limit the ultimate precision of LEP and SLC measurements of the partial width for $Z \to b\bar{b}$ unless direct (double-tagged) techniques can be used. The Z experiments must also deal with an admixture of B mesons and baryons as the source of the leptons. Use of vertex detectors to count $Z \to b\bar{b}$ events directly may also ultimately circumvent this limitation.

The $b \to u$ transition in semileptonic decays has been measured by CLEO and ARGUS, inclusively. Some exclusive event candidates have been found by ARGUS. The $b \to u$ transition has not been seen in hadronic decays, with upper limits still significantly higher than the theoretically-anticipated branching fractions. The value of $|V_{ub}/V_{cb}| \approx 0.10$ determined from the lepton spectrum carries as much as a 50% uncertainty from a combination of experimental procedure and model dependence.

The $b \to s\gamma$ and $b \to sg$ transitions would provide evidence for the so-called "penguin-type" diagrams and provide sensitivity to the mass of the t-quark. No penguin decays have yet been observed. Extensive sets of limits in many exclusive channels at few parts in 10^4 branching fraction range have been reported, still somewhat above the level expected by theory (10^{-4}).

No rare decays of B mesons have been observed with flavor-changing neutral current-type decays, or lepton family number violations. The limits are in the 10^{-4} to few parts in 10^{-5} range at present.

The separate lifetimes of B^0 and B^+ mesons have yet to be measured directly. The present data from ARGUS and CLEO using semileptonic decays improves significantly on the previous limits, and suggests that the meson lifetimes are equal to approximately $\pm 25\%$. Theory suggests that the difference from unity may be as small as 5–10%, providing an interesting experimental challenge. Separate B^0 and B^+ lifetimes at this precision will come either from tagging of B mesons at the $\Upsilon(4S)$, with the subsequent measurement of the semileptonic decay of the recoil, from the improved statistics for exclusive

$B_{\ell 3}$ decays, or from the direct measurement of a lifetime of a decay of a distinct B meson species at LEP/SLC or CDF using vertexing techniques. These measurements should appear within the course of about one year.

Over the next few years, a combination of CESR/CLEO-II, ARGUS at the $\Upsilon(4S)$, and the higher energy programs of the LEP/SLC, HERA, and FNAL detectors should provide new insights into all aspects of B_d, B_u, and B_s meson decays. We anticipate that the experimental reach of the present program is adequate to address all the theoretically interesting areas of B physics, except that of CP violation. In the past year, CLEO-II has demonstrated[6] that the cross section for BB^* production is too small in the $\Upsilon(5S)$ region to study CP violation in B decays with the highest luminosity (10^{34} cm^{-2} s^{-1}) symmetric e^+e^- machine considered feasible. Numerous proposals are now under consideration for high luminosity asymmetric e^+e^- machines, believed to be suitable for the study of CP violation in the B system. While no B mesons have yet to be detected in photo- and hadro-production off fixed targets, and only a few dozen events have been reconstructed in hadron colliders, advances in vertexing and particle identification make it likely that future experiments at SSC or LHC will be able to take advantage of the significantly larger B meson production, to also study CP violation in the B system. All such studies, in combination with those existing and future programs to measure CP violation in the kaon and hyperon systems, may ultimately result in our understanding of whether the CP-violation phenomenon has its origin simply in the CKM matrix, or arises from a nonstandard source.

References

1. For excellent recent reviews see: K. Berkelman and S. Stone, "Decays of B Mesons," CLNS 91-1044 (January, 1991), to be published in Annual Review of Nuclear and Particle Science; and S. Stone, "B Decays," Syracuse Preprint HEPSYS 4-91 (October 1991), to be published in World Scientific Press, Singapore.
2. J. Alexander *et al.*, Phys. Rev. Lett. **64**, 2226 (1990).
3. Y. Kubota *et al.*, "ψ Production in the $\Upsilon(4S)$ Region," submitted to the *Lepton Photon Symposium*, Geneva, Switzerland, September, 1991.
4. B. Adeva *et al.*, Phys. Lett. **B252**, 703 (1990); D. Decamp *et al.*, Phys. Lett. **B258**, 236 (1991).
5. See for example, T. Browder *et al.*, in "SLD Physics Studies," SLAC-REPORT-354, p. 291.
6. D.S. Akerib *et al.*, Phys. Rev. Lett. **67**, 1692 (1991).

$B^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

Quantum numbers not measured. Values shown are quark-model predictions.

This section also includes measurements which do not identify the charge state of B.

$B^{\pm}$ MASS

The fit uses the $B^{\pm}$ and B^0 mass and mass difference measurements. These experiments actually measure the difference between half of E_{cm} and the B mass.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
5278.6±2.0 OUR FIT					
5278.6±2.0 OUR AVERAGE					
5278.3±0.4±2.0		[1] BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
5280.5±1.0±2.0		[1,2] ALBRECHT	90J	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
5278.6±0.8±2.0		[1] BEBEK	87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5275.8±1.3±3.0	32	ALBRECHT	87C	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
5278.2±1.8±3.0	12	[3] ALBRECHT	87D	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[1] These experiments all report a common systematic error 2.0 MeV. We have artificially increased the systematic error to allow the experiments to be treated as independent measurements in our average and B^+–B^0 mass fit. See "Treatment of Errors" section of the Introductory Text.

[2] ALBRECHT 90J assumes 10580 for $\Upsilon(4S)$ mass. Supersedes ALBRECHT 87C and ALBRECHT 87D.

[3] Found using fully reconstructed decays with $J/\psi(1S)$. ALBRECHT 87D assume $m(\Upsilon(4S))$ = 10577 MeV.

B MEAN LIFE

Unless stated otherwise, the measurements of the B mean life do not distinguish the charge state ($B^{\pm}$ or B^0) and the lifetime is an average over bottom particles produced, weighted by their semileptonic branching ratios.

VALUE (10^{-13} s)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
12.9±0.5 OUR AVERAGE						
12.8±1.0			[4] ABREU	92	DLPH	E^{ee}_{cm}= 91.31 GeV
13.7±0.7±0.6		1354	[5] ACTON	92	OPAL	E^{ee}_{cm}= 91.31 GeV
13.2±0.8±0.9		1386	[6] ADEVA	91H	L3	E^{ee}_{cm}= 91.31 GeV
$13.2^{+3.1}_{-2.5}\pm1.5$		91	[7] ALEXANDER	91G	OPAL	E^{ee}_{cm}= 91.31 GeV
12.9±0.6±1.0		2973	[8] DECAMP	91C	ALPH	E^{ee}_{cm}= 91.31 GeV
$13.6^{+2.5}_{-2.3}$			[9] HAGEMANN	90	JADE	E^{ee}_{cm}= 35 GeV
$12.0^{+5.2}_{-3.6}{}^{+1.6}_{-1.4}$		15	[10] WAGNER	90	MRK2	B^0, E^{ee}_{cm}= 29 GeV
13.5±1.0±2.4			BRAUNSCH...	89B	TASS	E^{ee}_{cm}= 35 GeV
9.8±1.2±1.3			ONG	89	MRK2	E^{ee}_{cm}= 29 GeV
$11.7^{+2.7}_{-2.2}{}^{+1.7}_{-1.6}$			KLEM	88	DLCO	E^{ee}_{cm}= 29 GeV
12.9±2.0±2.1			[11] ASH	87	MAC	E^{ee}_{cm}= 29 GeV
$10.2^{+4.2}_{-3.9}$		301	[12] BROM	87	HRS	E^{ee}_{cm}= 29 GeV
14.6±2.2±3.4			[13] WU	87	RVUE	JADE result
$18\ ^{+5}_{-4}\ \pm4$		25	BARTEL	86B	JADE	E^{ee}_{cm}= 35 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
11.3±1.5			[14] LYONS	90	RVUE	
$8.2^{+5.7}_{-3.7}\pm2.7$			[15] AVERILL	89	HRS	E^{ee}_{cm}= 29 GeV
		2	[16] ALBANESE	85	HYBR	350 GeV $\pi^- p$ emulsion
$18.3^{+3.8}_{-3.7}{}^{+3.7}_{-3.4}$			ALTHOFF	84H	TASS	E^{ee}_{cm}= 30–46.8 GeV
$11.6^{+3.7}_{-3.4}\pm2.3$		46	KLEM	84	DLCO	Repl. by KLEM 88
18 ±6 ±4			FERNANDEZ	83B	MAC	E^{ee}_{cm}= 29 GeV
$12.0^{+4.5}_{-3.6}\pm3.0$			[17] LOCKYER	83	MRK2	Repl. by ONG 89
<14.	95		BARTEL	82C	JADE	e^+e^-, average E_{cm}= 34 GeV

[4] ABREU 92 is combined result of muon and hadron impact parameter analyses. Hadron tracks gave $(12.7 \pm 0.4 \pm 1.2) \times 10^{-13}$ s for an admixture of B species weighted by production fraction and mean charge multiplicity, while muon tracks gave $(13.0 \pm 1.0 \pm 0.8) \times 10^{-13}$ s for an admixture weighted by production fraction and semileptonic branching fraction.

[5] ACTON 92 is combined result of muon and electron impact parameter analyses. Result is for an admixture of B species weighted by production fraction and semileptonic branching fraction.

[6] Using $Z \rightarrow e^+ X$ or $\mu^+ X$, ADEVA 91H determined the average lifetime for an admixture of B^0 and B^+ from the impact parameter distribution of the lepton.

[7] Using $Z \to J/\psi(1S)$ X, $J/\psi(1S) \to \ell^+\ell^-$, ALEXANDER 91G determined the average lifetime for an admixture of B^0 and B^+ from the decay point of the $J/\psi(1S)$.
[8] Using $Z \to e$ X or μ X, DECAMP 91C determines the average lifetime for an admixture of B hadrons from the signed impact parameter distribution of the lepton.
[9] HAGEMANN 90 uses electrons and muons in an impact parameter analysis.
[10] WAGNER 90 tagged B^0 mesons by their decays into $D^{*-}e^+\nu$ and $D^{*-}\mu^+\nu$ where the D^{*-} is tagged by its decay into $\pi^-\overline{D}^0$.
[11] We have combined an overall scale error of 15% in quadrature with the systematic error of ±0.7 to obtain ±2.1 systematic error.
[12] Statistical and systematic errors were combined by BROM 87.
[13] The errors quoted here came from a private communication from the Jade collaboration. This result will be submitted to Zeit. Phys. in 1990, along with a different technique which yields $13.2^{+2.8}_{-2.5}$.
[14] LYONS 90 combine the results of the B lifetime measuresments of ONG 89, BRAUNSCHWEIG 89B, KLEM 88, and ASH 87, but not WAGNER 90, and replacing the WU 87 and BARTEL 86B data by private communication. They use statistical techniques which include variation of the error with the mean life, and possible correlations between the systematic errors. This result is not independent of the measured results used in our average.
[15] This is an estimate of the B^0 mean lifetime assuming that $B^0 \to D^{*+}$ + X always.
[16] The mean flight time for the one B^0 was 5×10^{-13} s while the one B^- was 0.8×10^{-13} s. Possible evidence for difference in B^0 and $B^{\pm}$ lifetime.
[17] The lifetime is an average over bottom particles produced.

B^+ DECAY MODES

B^- modes are charge conjugates of the modes below.

Only data from $\Upsilon(4S)$ decays are used for branching fractions, with rare exceptions. Each paper makes an estimate of the $\Upsilon(4S) \to B^+B^-$ and $B^0\overline{B}^0$ branching fractions, usually 50:50 in recent papers.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Semileptonic modes			
Γ_1	$B^+ \to \overline{D}^0\ell^+\nu$	[a]	(1.6 ± 0.7) %	
Γ_2	$B^+ \to \overline{D}^*(2010)^0\ell^+\nu$	[a]	(4.6 ± 1.0) %	
Γ_3	$B^+ \to \pi^0 e^+\nu_e$		$< 2.2 \times 10^{-3}$	CL=90%
Γ_4	$B^+ \to \omega\mu^+\nu_\mu$		seen	
	D, D^*, or D_s modes			
Γ_5	$B^+ \to \overline{D}^0\pi^+$		$(3.8 \pm 1.1) \times 10^{-3}$	S=1.7
Γ_6	$B^+ \to \overline{D}^0\rho^+$		(1.3 ± 0.6) %	
Γ_7	$B^+ \to \overline{D}^0\pi^+\pi^+\pi^-$		(1.1 ± 0.4) %	
Γ_8	$B^+ \to \overline{D}^0\pi^+\pi^+\pi^-$ nonresonant		$(5 \pm 4) \times 10^{-3}$	
Γ_9	$B^+ \to \overline{D}^0\pi^+\rho^0$		$(4.2 \pm 3.0) \times 10^{-3}$	
Γ_{10}	$B^+ \to \overline{D}^0 a_1(1260)^+$		$(5 \pm 4) \times 10^{-3}$	
Γ_{11}	$B^+ \to D^*(2010)^-\pi^+\pi^+$		$(2.5 \pm 1.2) \times 10^{-3}$	
Γ_{12}	$B^+ \to D^-\pi^+\pi^+$		$(2.5 ^{+4.8}_{-2.4}) \times 10^{-3}$	
Γ_{13}	$B^+ \to \overline{D}^*(2010)^0\pi^+$		$(5.2 \pm 1.5) \times 10^{-3}$	S=1.1
Γ_{14}	$B^+ \to \overline{D}^*(2010)^0\rho^+$		(1.0 ± 0.7) %	
Γ_{15}	$B^+ \to D^*(2010)^-\pi^+\pi^+\pi^0$		(1.8 ± 0.9) %	
Γ_{16}	$B^+ \to D^*(2010)^-\pi^+\pi^+\pi^+\pi^-$		< 1 %	CL=90%
Γ_{17}	$B^+ \to \overline{D}^0 D_s^+$		(1.9 ± 1.1) %	
	$J/\psi(1S)$ or $\psi(2S)$ modes			
Γ_{18}	$B^+ \to J/\psi(1S)K^+$		$(7.7 \pm 2.0) \times 10^{-4}$	
Γ_{19}	$B^+ \to J/\psi(1S)K^+\pi^+\pi^-$		$(1.1 \pm 0.5) \times 10^{-3}$	
Γ_{20}	$B^+ \to J/\psi(1S)K^*(892)^+$		$(1.4 \pm 0.7) \times 10^{-3}$	
Γ_{21}	$B^+ \to \psi(2S)K^+$		$< 2 \times 10^{-3}$	CL=90%
Γ_{22}	$B^+ \to \psi(2S)K^*(892)^+$		$< 3.5 \times 10^{-3}$	CL=90%
Γ_{23}	$B^+ \to \psi(2S)K^*(892)^+\pi^+\pi^-$		$(1.9 \pm 1.2) \times 10^{-3}$	
	K or K^* modes			
Γ_{24}	$B^+ \to K^0\pi^+$		$< 9 \times 10^{-5}$	CL=90%
Γ_{25}	$B^+ \to K^*(892)^0\pi^+$		$< 1.3 \times 10^{-4}$	CL=90%
Γ_{26}	$B^+ \to K^+\pi^-\pi^+$ (no charm)		$< 1.7 \times 10^{-4}$	CL=90%
Γ_{27}	$B^+ \to K_1(1400)^0\pi^+$		$< 2.6 \times 10^{-3}$	CL=90%
Γ_{28}	$B^+ \to K_2^*(1430)^0\pi^+$		$< 6.8 \times 10^{-4}$	CL=90%
Γ_{29}	$B^+ \to K^+\rho^0$		$< 7 \times 10^{-5}$	CL=90%
Γ_{30}	$B^+ \to K^*(892)^+\pi^+\pi^-$		$< 1.1 \times 10^{-3}$	CL=90%
Γ_{31}	$B^+ \to K^*(892)^+\rho^0$		$< 9.0 \times 10^{-4}$	CL=90%
Γ_{32}	$B^+ \to K_1(1400)^+\rho^0$		$< 7.8 \times 10^{-4}$	CL=90%
Γ_{33}	$B^+ \to K_2^*(1430)^+\rho^0$		$< 1.5 \times 10^{-3}$	CL=90%
Γ_{34}	$B^+ \to K^+K^-K^+$		$< 3.5 \times 10^{-4}$	CL=90%
Γ_{35}	$B^+ \to K^+\phi$		$< 8 \times 10^{-5}$	CL=90%
Γ_{36}	$B^+ \to K^*(892)^+K^+K^-$		$< 1.6 \times 10^{-3}$	CL=90%
Γ_{37}	$B^+ \to K^*(892)^+\phi$		$< 1.3 \times 10^{-3}$	CL=90%
Γ_{38}	$B^+ \to K_1(1400)^+\phi$		$< 1.1 \times 10^{-3}$	CL=90%
Γ_{39}	$B^+ \to K_2^*(1430)^+\phi$		$< 3.4 \times 10^{-3}$	CL=90%
Γ_{40}	$B^+ \to K^+f_0(975)$		$< 7 \times 10^{-5}$	CL=90%
Γ_{41}	$B^+ \to K^*(892)^+\gamma$		$< 5.5 \times 10^{-4}$	CL=90%
Γ_{42}	$B^+ \to K_1(1270)^+\gamma$		$< 6.6 \times 10^{-3}$	CL=90%
Γ_{43}	$B^+ \to K_1(1400)^+\gamma$		$< 2.0 \times 10^{-3}$	CL=90%
Γ_{44}	$B^+ \to K_2^*(1430)^+\gamma$		$< 1.3 \times 10^{-3}$	CL=90%
Γ_{45}	$B^+ \to K^*(1680)^+\gamma$		$< 1.7 \times 10^{-3}$	CL=90%
Γ_{46}	$B^+ \to K_3^*(1780)^+\gamma$		$< 5 \times 10^{-3}$	CL=90%
Γ_{47}	$B^+ \to K_4^*(2045)^+\gamma$		$< 9.0 \times 10^{-3}$	CL=90%
	Light unflavored meson modes			
Γ_{48}	$B^+ \to \pi^+\pi^0$		$< 2.4 \times 10^{-4}$	CL=90%
Γ_{49}	$B^+ \to \pi^+\pi^+\pi^-$		$< 1.7 \times 10^{-4}$	CL=90%
Γ_{50}	$B^+ \to \rho^0\pi^+$		$< 1.5 \times 10^{-4}$	CL=90%
Γ_{51}	$B^+ \to \pi^+f_0(975)$		$< 1.2 \times 10^{-4}$	CL=90%
Γ_{52}	$B^+ \to \pi^+f_2(1270)$		$< 2.1 \times 10^{-4}$	CL=90%
Γ_{53}	$B^+ \to \pi^+\pi^0\pi^0$		$< 8.9 \times 10^{-4}$	CL=90%
Γ_{54}	$B^+ \to \rho^+\pi^0$		$< 5.5 \times 10^{-4}$	CL=90%
Γ_{55}	$B^+ \to \pi^+\pi^-\pi^+\pi^0$		$< 4.0 \times 10^{-3}$	CL=90%
Γ_{56}	$B^+ \to \rho^+\rho^0$		$< 1.0 \times 10^{-3}$	CL=90%
Γ_{57}	$B^+ \to a_1(1260)^+\pi^0$		$< 1.7 \times 10^{-3}$	CL=90%
Γ_{58}	$B^+ \to a_1(1260)^0\pi^+$		$< 9.0 \times 10^{-4}$	CL=90%
Γ_{59}	$B^+ \to \omega\pi^+$		$< 4.0 \times 10^{-4}$	CL=90%
Γ_{60}	$B^+ \to \eta\pi^+$		$< 7.0 \times 10^{-4}$	CL=90%
Γ_{61}	$B^+ \to \pi^+\pi^+\pi^+\pi^-\pi^-$		$< 8.6 \times 10^{-4}$	CL=90%
Γ_{62}	$B^+ \to \rho^0 a_1(1260)^+$		$< 5.4 \times 10^{-4}$	CL=90%
Γ_{63}	$B^+ \to \rho^0 a_2(1320)^+$		$< 6.3 \times 10^{-4}$	CL=90%
Γ_{64}	$B^+ \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$		$< 6.3 \times 10^{-3}$	CL=90%
Γ_{65}	$B^+ \to a_1(1260)^+a_1(1260)^0$		< 1.3 %	CL=90%
	Baryon modes			
Γ_{66}	$B^+ \to p\overline{p}\pi^+$		$< 1.4 \times 10^{-4}$	CL=90%
Γ_{67}	$B^+ \to p\overline{p}\pi^+\pi^+\pi^-$		$< 4.7 \times 10^{-4}$	CL=90%
Γ_{68}	$B^+ \to p\overline{\Lambda}$		$< 5 \times 10^{-5}$	CL=90%
Γ_{69}	$B^+ \to p\overline{\Lambda}\pi^+\pi^-$		$< 1.8 \times 10^{-4}$	CL=90%
Γ_{70}	$B^+ \to \overline{\Delta}^0 p$		$< 3.3 \times 10^{-4}$	CL=90%
Γ_{71}	$B^+ \to \Delta^{++}\overline{p}$		$< 1.3 \times 10^{-4}$	CL=90%
	Lepton number (L) or Lepton Family number (LF) violating modes, or Flavor-Changing neutral current (FC) modes			
Γ_{72}	$B^+ \to K^*(892)^+e^+e^-$	FC	$< 6.3 \times 10^{-4}$	CL=90%
Γ_{73}	$B^+ \to K^*(892)^+\mu^+\mu^-$	FC	$< 1.1 \times 10^{-3}$	CL=90%
Γ_{74}	$B^+ \to \pi^+e^+e^-$	FC	$< 3.9 \times 10^{-3}$	CL=90%
Γ_{75}	$B^+ \to \pi^+\mu^+\mu^-$	FC	$< 9.1 \times 10^{-3}$	CL=90%
Γ_{76}	$B^+ \to K^+e^+e^-$	FC	$< 5 \times 10^{-5}$	CL=90%
Γ_{77}	$B^+ \to K^+\mu^+\mu^-$	FC	$< 1.5 \times 10^{-4}$	CL=90%
Γ_{78}	$B^+ \to \pi^+e^+\mu^-$	LF	$< 6.4 \times 10^{-3}$	CL=90%
Γ_{79}	$B^+ \to \pi^+e^-\mu^+$	LF	$< 6.4 \times 10^{-3}$	CL=90%
Γ_{80}	$B^+ \to K^+e^+\mu^-$	LF	$< 6.4 \times 10^{-3}$	CL=90%
Γ_{81}	$B^+ \to K^+e^-\mu^+$	LF	$< 6.4 \times 10^{-3}$	CL=90%
Γ_{82}	$B^+ \to \pi^-e^+e^+$	L	$< 3.9 \times 10^{-3}$	CL=90%
Γ_{83}	$B^+ \to \pi^-\mu^+\mu^+$	L	$< 9.1 \times 10^{-3}$	CL=90%
Γ_{84}	$B^+ \to \pi^-e^+\mu^+$	L	$< 6.4 \times 10^{-3}$	CL=90%
Γ_{85}	$B^+ \to K^-e^+e^+$	L	$< 3.9 \times 10^{-3}$	CL=90%
Γ_{86}	$B^+ \to K^-e^+\mu^+$	L	$< 6.4 \times 10^{-3}$	CL=90%
Γ_{87}	$B^+ \to K^-\mu^+\mu^+$	L	$< 9.1 \times 10^{-3}$	CL=90%

B DECAY MODES

For the following modes, the charge of B was not determined.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Semileptonic and leptonic modes			
Γ_{88}	$B \to e^{\pm}\nu_e$ hadrons		(10.7 ± 0.5) %	S=1.4
Γ_{89}	$B \to D^*(2010)e\nu_e$		(7.0 ± 2.3) %	
Γ_{90}	$B \to \overline{p}e^+\nu_e$ anything		$< 1.6 \times 10^{-3}$	CL=90%
Γ_{91}	$B \to \mu^{\pm}\nu_\mu$ hadrons		(10.3 ± 0.5) %	
Γ_{92}	$B \to \ell^+$ anything	[a]		
Γ_{93}	$B \to \ell\nu$ hadrons	[a]		
Γ_{94}	$B \to D^{\pm}\ell\nu$ hadrons	[a]		
Γ_{95}	$B \to D^0/\overline{D}^0\ell\nu$ hadrons	[a]		
Γ_{96}	$B \to \ell\nu$ noncharm-hadrons	[a]		
Γ_{97}	$B \to K^+\ell^+$ anything	[a]		
Γ_{98}	$B \to K^-\ell^+$ anything	[a]		
Γ_{99}	$B \to K^0/\overline{K}^0\ell^+$ anything	[a]		

D, D^*, or D_s modes

Γ_{100}	$B \to D^{\pm}$ anything		(22.7 ± 3.3) %	
Γ_{101}	$B \to D^0/\overline{D}^0$ anything		(46 ± 5) %	S=1.2
Γ_{102}	$B \to D^*(2010)^{\pm}$ anything		(26.9 ± 3.5) %	
Γ_{103}	$B \to D_s^{\mp}$ anything		(11.5 ± 2.8) %	
Γ_{104}	$B \to D_s D$, $D_s^* D$, $D_s D^*$, or $D_s^* D^*$	[b]	(6.5 ± 1.9) %	
Γ_{105}	$B \to \overline{D}^0 \pi^+$, $D^- \pi^+$, $\overline{D}^*(2010)^0 \pi^+$, or $D^*(2010)^- \pi^+$	[b]		

$J/\psi(1S)$ or $\psi(2S)$ modes

Γ_{106}	$B \to J/\psi(1S)$ anything		(1.12± 0.16) %	
Γ_{107}	$B \to \psi(2S)$ anything		(4.6 ± 2.0) × 10^{-3}	

K or K^* modes

Γ_{108}	$B \to K^{\pm}$ anything		(85 ±11) %	
Γ_{109}	$B \to K^+$ anything			
Γ_{110}	$B \to K^-$ anything			
Γ_{111}	$B \to K^0/\overline{K}^0$ anything		(63 ± 8) %	
Γ_{112}	$B \to K^*(892)\gamma$		< 2.4 × 10^{-4}	CL=90%
Γ_{113}	$B \to K_1(1400)\gamma$		< 4.1 × 10^{-4}	CL=90%
Γ_{114}	$B \to K_2^*(1430)\gamma$		< 8.3 × 10^{-4}	CL=90%
Γ_{115}	$B \to K_3^*(1780)\gamma$		< 3.0 × 10^{-3}	CL=90%

Light unflavored meson modes

Γ_{116}	$B \to \phi$ anything		(2.3 ± 0.8) %	

Baryon modes

Γ_{117}	$B \to$ charmed-baryon anything		< 11.2 %	CL=90%
Γ_{118}	$B \to p$ anything		($8.2\ ^{+1.4}_{-1.1}$) %	
Γ_{119}	$B \to p$ (direct) anything		(5.5 ± 1.6) %	
Γ_{120}	$B \to \Lambda$ anything		(4.2 ± 0.8) %	
Γ_{121}	$B \to \Xi^-$ anything		(2.8 ± 1.4) × 10^{-3}	
Γ_{122}	$B \to$ baryons anything		(7.6 ± 1.4) %	
Γ_{123}	$B \to p\overline{p}$ anything		(2.50± 0.28) %	
Γ_{124}	$B \to \Lambda\overline{p}$ anything		(2.3 ± 0.5) %	
Γ_{125}	$B \to \Lambda\overline{\Lambda}$ anything		< 8.8 × 10^{-3}	CL=90%

Flavor-Changing neutral current (FC) modes

Γ_{126}	$B \to e^+ e^-$ anything	FC	< 2.4 × 10^{-3}	CL=90%
Γ_{127}	$B \to \mu^+ \mu^-$ anything	FC [c]	< 5.0 × 10^{-5}	CL=90%

[a] ℓ indicates e or μ mode, not sum over modes.

[b] The value is for the sum of the charge states indicated.

[c] B^0, $B^{\pm}$, and B_s^0 not separated.

B^+ BRANCHING RATIOS

$\Gamma(\overline{D}^0 \ell^+ \nu)/\Gamma_{total}$ — Γ_1/Γ

$\ell = e$ or μ, not sum over e and μ modes.

VALUE	DOCUMENT ID		TECN	COMMENT
0.016±0.006±0.003	[18] FULTON	91	CLEO	$e^+e^- \to \Upsilon(4S)$

[18] FULTON 91 assumes equal production of $B^0\overline{B}^0$ and B^+B^- at the $\Upsilon(4S)$.

$\Gamma(\overline{D}^*(2010)^0 \ell^+ \nu)/\Gamma_{total}$ — Γ_2/Γ

$\ell = e$ or μ, not sum over e and μ modes.

VALUE	DOCUMENT ID		TECN	COMMENT
0.046±0.010 OUR AVERAGE				
0.058±0.014±0.013	[19] ALBRECHT	92C	ARG	$e^+e^- \to \Upsilon(4S)$
$0.041\pm0.008^{+0.008}_{-0.009}$	[19] FULTON	91	CLEO	$e^+e^- \to \Upsilon(4S)$

[19] Assumes equal production of $B^0\overline{B}^0$ and B^+B^- at the $\Upsilon(4S)$.

$\Gamma(\pi^0 e^+ \nu_e)/\Gamma_{total}$ — Γ_3/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0022	90	ANTREASYAN	90B	CBAL	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\omega \mu^+ \nu_\mu)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN
seen	[20] ALBRECHT	91C	ARG

[20] In ALBRECHT 91C, one event is fully reconstructed providing evidence for the $b \to u$ transition.

$\Gamma(\overline{D}^0 \pi^+)/\Gamma_{total}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0038±0.0011 OUR AVERAGE	Error includes scale factor of 1.7.				
0.0050±0.0007±0.0006		[21] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0020±0.0008±0.0006	12	ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$
$0.0054^{+0.0018+0.0012}_{-0.0015-0.0009}$	14	[22] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0019±0.0010±0.0006	7	[23] ALBRECHT	88K	ARG	$e^+e^- \to \Upsilon(4S)$

[21] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses the Mark III branching fractions for the D.

[22] BEBEK 87 value has been updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92.

[23] ALBRECHT 88K assumes $B^0\overline{B}^0$:B^+B^- ratio is 45:55. Superseded by ALBRECHT 90J.

$\Gamma(\overline{D}^0 \rho^+)/\Gamma_{total}$ — Γ_6/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.013±0.004±0.004	19	ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.021±0.008±0.009	10	[24] ALBRECHT	88K	ARG	$e^+e^- \to \Upsilon(4S)$

[24] ALBRECHT 88K assumes $B^0\overline{B}^0$:B^+B^- ratio is 45:55.

$\Gamma(\overline{D}^0 \pi^+ \pi^+ \pi^-)/\Gamma_{total}$ — Γ_7/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0115±0.0029±0.0021	[25] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$

[25] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(\overline{D}^0 \pi^+ \pi^+ \pi^-$ nonresonant$)/\Gamma_{total}$ — Γ_8/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0051±0.0034±0.0023	[26] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$

[26] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(\overline{D}^0 \pi^+ \rho^0)/\Gamma_{total}$ — Γ_9/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0042±0.0023±0.0020	[27] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$

[27] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(\overline{D}^0 a_1(1260)^+)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0045±0.0019±0.0031	[28] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$

[28] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(D^*(2010)^- \pi^+ \pi^+)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.0025±0.0012 OUR AVERAGE						
0.0026±0.0014±0.0007		11	ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$
$0.0024^{+0.0017+0.0010}_{-0.0016-0.0006}$		3	[29] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.004	90		[30] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.005 ±0.002 ±0.003		7	[31] ALBRECHT	87C	ARG	$e^+e^- \to \Upsilon(4S)$

[29] BEBEK 87 value has been updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92.

[30] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$. The authors also find the product branching fraction into $D^{**}\pi$ followed by $D^{**} \to D^*(2010)\pi$ to be $0.0014^{+0.0008}_{-0.0006} \pm 0.0003$ where D^{**} represents all orbitally excited D mesons.

[31] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume $B(\Upsilon(4S) \to B^+B^-) = 55\%$ and $B(\Upsilon(4S) \to B^0\overline{B}^0) = 45\%$. Superseded by ALBRECHT 90J.

$\Gamma(D^- \pi^+ \pi^+)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.0025^{+0.0041+0.0024}_{-0.0023-0.0008}}$		1	[32] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.007	90		[33] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$

[32] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. $B(D^- \to K^+\pi^-\pi^-) = (9.1 \pm 1.3 \pm 0.4)\%$ is assumed.

[33] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D. The product branching fraction into $D_0^*(2340)\pi$ followed by $D_0^*(2340) \to D\pi$ is <0.005 at 90%CL and into $D_2^*(2460)$ followed by $D_2^*(2460) \to D\pi$ is <0.004 at 90%CL.

$\Gamma(\overline{D}^*(2010)^0\pi^+)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0052±0.0015 OUR AVERAGE Error includes scale factor of 1.1.				
0.0072±0.0018±0.0016		[34] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0040±0.0014±0.0012	9	ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0027±0.0044		[35] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[34] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.
[35] This is a derived branching ratio, using the inclusive pion spectrum and other two-body B decays. BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\overline{D}^*(2010)^0\rho^+)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.010±0.006±0.004	7	ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(D^*(2010)^-\pi^+\pi^+\pi^0)/\Gamma_{total}$ — Γ_{15}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.018±0.007±0.005	26	ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.043±0.013±0.026	24	[36] ALBRECHT 87C	ARG	$e^+e^- \to \Upsilon(4S)$

[36] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume $B(\Upsilon(4S) \to B^+B^-) = 55\%$ and $B(\Upsilon(4S) \to B^0\overline{B}^0) = 45\%$. Superseded by ALBRECHT 90J.

$\Gamma(D^*(2010)^-\pi^+\pi^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{16}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.01	90	ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\overline{D}^0 D_s^+)/\Gamma_{total}$ — Γ_{17}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.019±0.008±0.007		[37] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.029±0.013	5	[38] BORTOLETTO90	CLEO	$e^+e^- \to \Upsilon(4S)$

[37] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses the Mark III branching fractions for the D. The branching fraction for $D_s \to \phi\pi^+$ is taken as 0.030 ± 0.011. This measurement supersedes BORTOLETTO 90.
[38] BORTOLETTO 90 assume $B(D_s \to \phi\pi^+) = 2\%$.

$\Gamma(J/\psi(1S)K^+)/\Gamma_{total}$ — Γ_{18}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
7.7±2.0 OUR AVERAGE				
8 ±2 ±2		[39] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
7 ±3 ±1	6	ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
10 ±7 ±2	3	[40] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
7 ±4	3	[41] ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$
9 ±5	3	[42] ALAM 86	CLEO	$e^+e^- \to \Upsilon(4S)$

[39] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.
[40] BEBEK 87 value has been updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92.
[41] ALBRECHT 87D assume $B^+B^-/B^0\overline{B}^0$ ratio is 55/45. Superseded by ALBRECHT 90J.
[42] ALAM 86 assumes $B^{\pm}/B^0$ ratio is 60/40.

$\Gamma(J/\psi(1S)K^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{19}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.0011±0.0005 OUR AVERAGE					
0.0012±0.0006±0.0004			[43] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0011±0.0007		6	[44] ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0016	90		ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$

[43] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.
[44] ALBRECHT 87D assume $B^+B^-/B^0\overline{B}^0$ ratio is 55/45. Analysis explicitly removes $B^+ \to \psi(2S)K^+$.

$\Gamma(J/\psi(1S)K^*(892)^+)/\Gamma_{total}$ — Γ_{20}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0014±0.0007 OUR AVERAGE				
0.0013±0.0009±0.0003		[45] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0016±0.0011±0.0003	2	ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$

[45] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(\psi(2S)K^+)/\Gamma_{total}$ — Γ_{21}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.002 (CL = 90%) OUR LIMIT					
<0.0005	90		[46] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0018±0.0008±0.0004		5	ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0022±0.0017		3	[47] ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$

[46] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.
[47] ALBRECHT 87D assume $B^+B^-/B^0\overline{B}^0$ ratio is 55/45. Superseded by ALBRECHT 90J.

$\Gamma(\psi(2S)K^*(892)^+)/\Gamma_{total}$ — Γ_{22}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0035	90	[48] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0049	90	ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$

[48] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(\psi(2S)K^*(892)^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{23}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0019±0.0011±0.0004	3	ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^0\pi^+)/\Gamma_{total}$ — Γ_{24}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<9 × 10^{-5}	90	[49] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.9 × 10^{-4}	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$
<6.8 × 10^{-4}	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[49] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^*(892)^0\pi^+)/\Gamma_{total}$ — Γ_{25}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.3 × 10^{-4}	90	[50] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.7 × 10^{-4}	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$
<2.6 × 10^{-4}	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[50] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^+\pi^-\pi^+ \text{ (no charm)})/\Gamma_{total}$ — Γ_{26}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.7 × 10^{-4}	90	[51] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<3.3 × 10^{-4}	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$

[51] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K_1(1400)^0\pi^+)/\Gamma_{total}$ — Γ_{27}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<2.6 × 10^{-3}	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2^*(1430)^0\pi^+)/\Gamma_{total}$ — Γ_{28}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<6.8 × 10^{-4}	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^+\rho^0)/\Gamma_{total}$ — Γ_{29}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<7 × 10^{-5}	90	[52] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.8 × 10^{-4}	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$
<2.6 × 10^{-4}	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[52] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^*(892)^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{30}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.1 × 10^{-3}	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^+\rho^0)/\Gamma_{total}$ — Γ_{31}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<9.0 × 10^{-4}	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_1(1400)^+\rho^0)/\Gamma_{total}$ — Γ_{32}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<7.8 × 10^{-4}	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2^*(1430)^+\rho^0)/\Gamma_{total}$ — Γ_{33}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.5 × 10^{-3}	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^+K^-K^+)/\Gamma_{total}$ — Γ_{34}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<3.5 × 10^{-4}	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^+\phi)/\Gamma_{total}$ — Γ_{35}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<8 × 10^{-5}	90	[53] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.8 × 10^{-4}	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$
<2.1 × 10^{-4}	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[53] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

See key on page IV.1

$\Gamma(K^*(892)^+ K^+ K^-)/\Gamma_{total}$ Γ_{36}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.6 \times 10^{-3}$	90	ALBRECHT 91E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(K^*(892)^+ \phi)/\Gamma_{total}$ Γ_{37}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.3 \times 10^{-3}$	90	ALBRECHT 91B	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(K_1(1400)^+ \phi)/\Gamma_{total}$ Γ_{38}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.1 \times 10^{-3}$	90	ALBRECHT 91B	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(K_2^*(1430)^+ \phi)/\Gamma_{total}$ Γ_{39}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.4 \times 10^{-3}$	90	ALBRECHT 91B	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(K^+ f_0(975))/\Gamma_{total}$ Γ_{40}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<7 \times 10^{-5}$	90	[54] AVERY 89B	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[54] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^*(892)^+ \gamma)/\Gamma_{total}$ Γ_{41}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.5 \times 10^{-4}$	90	[55] ALBRECHT 89G	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
$<5.5 \times 10^{-4}$	90	[56] AVERY 89B	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.8 \times 10^{-3}$	90	AVERY 87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[55] Assumes the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$.
[56] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K_1(1270)^+ \gamma)/\Gamma_{total}$ Γ_{42}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0066	90	[57] ALBRECHT 89G	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[57] Assumes the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$.

$\Gamma(K_1(1400)^+ \gamma)/\Gamma_{total}$ Γ_{43}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0020	90	[58] ALBRECHT 89G	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[58] Assumes the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$.

$\Gamma(K_2^*(1430)^+ \gamma)/\Gamma_{total}$ Γ_{44}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0013	90	[59] ALBRECHT 89G	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[59] Assumes the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$.

$\Gamma(K^*(1680)^+ \gamma)/\Gamma_{total}$ Γ_{45}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0017	90	[60] ALBRECHT 89G	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[60] Assumes the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$.

$\Gamma(K_3^*(1780)^+ \gamma)/\Gamma_{total}$ Γ_{46}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.005	90	[61] ALBRECHT 89G	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[61] Assumes the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$.

$\Gamma(K_4^*(2045)^+ \gamma)/\Gamma_{total}$ Γ_{47}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0090	90	[61] ALBRECHT 89G	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(\pi^+ \pi^0)/\Gamma_{total}$ Γ_{48}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.4 \times 10^{-4}$	90	[62] ALBRECHT 90B	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.3 \times 10^{-3}$	90	[63] BEBEK 87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[62] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.
[63] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\pi^+ \pi^+ \pi^-)/\Gamma_{total}$ Γ_{49}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.7 \times 10^{-4}$	90	[64] BORTOLETTO 89	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<4.5 \times 10^{-4}$	90	[65] ALBRECHT 90B	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[64] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.
[65] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^0 \pi^+)/\Gamma_{total}$ Γ_{50}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<1.5 \times 10^{-4}$	90		[66] ALBRECHT 90B	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
$<1.5 \times 10^{-4}$	90		[67] BORTOLETTO 89	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2 \times 10^{-4}$	90		[67] BEBEK 87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
$<6 \times 10^{-4}$	90	0	GILES 84	CLEO	Repl. by BEBEK 87

[66] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.
[67] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\pi^+ f_0(975))/\Gamma_{total}$ Γ_{51}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.2 \times 10^{-4}$	90	[68] BORTOLETTO 89	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[68] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\pi^+ f_2(1270))/\Gamma_{total}$ Γ_{52}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.1 \times 10^{-4}$	90	[69] BORTOLETTO 89	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[69] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\pi^+ \pi^0 \pi^0)/\Gamma_{total}$ Γ_{53}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<8.9 \times 10^{-4}$	90	[70] ALBRECHT 90B	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[70] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^+ \pi^0)/\Gamma_{total}$ Γ_{54}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.5 \times 10^{-4}$	90	[71] ALBRECHT 90B	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[71] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\pi^+ \pi^- \pi^+ \pi^0)/\Gamma_{total}$ Γ_{55}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.0 \times 10^{-3}$	90	[72] ALBRECHT 90B	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[72] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^+ \rho^0)/\Gamma_{total}$ Γ_{56}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.0 \times 10^{-3}$	90	[73] ALBRECHT 90B	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[73] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^+ \pi^0)/\Gamma_{total}$ Γ_{57}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.7 \times 10^{-3}$	90	[74] ALBRECHT 90B	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[74] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^0 \pi^+)/\Gamma_{total}$ Γ_{58}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<9.0 \times 10^{-4}$	90	[75] ALBRECHT 90B	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[75] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\omega \pi^+)/\Gamma_{total}$ Γ_{59}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.0 \times 10^{-4}$	90	[76] ALBRECHT 90B	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[76] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\eta \pi^+)/\Gamma_{total}$ Γ_{60}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<7.0 \times 10^{-4}$	90	[77] ALBRECHT 90B	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[77] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\pi^+ \pi^+ \pi^+ \pi^- \pi^-)/\Gamma_{total}$ Γ_{61}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<8.6 \times 10^{-4}$	90	[78] ALBRECHT 90B	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[78] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^0 a_1(1260)^+)/\Gamma_{total}$ Γ_{62}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.4 \times 10^{-4}$	90	[79] BORTOLETTO 89	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<6.0 \times 10^{-4}$	90	[80] ALBRECHT 90B	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
$<3.2 \times 10^{-3}$	90	[79] BEBEK 87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[79] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.
[80] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^0 a_2(1320)^+)/\Gamma_{total}$ Γ_{63}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<6.3 \times 10^{-4}$	90	[81] BORTOLETTO 89	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.3 \times 10^{-3}$	90	[81] BEBEK 87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[81] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{total}$ — Γ_{64}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<6.3 x 10⁻³	90	[82] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[82] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^+ a_1(1260)^0)/\Gamma_{total}$ — Γ_{65}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.3 x 10⁻²	90	[83] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[83] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(p\overline{p}\pi^+)/\Gamma_{total}$ — Γ_{66}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 1.4 x 10⁻⁴	90	BEBEK 89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$(5.2\pm1.4\pm1.9)\times10^{-4}$		ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(p\overline{p}\pi^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{67}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<4.7 x 10⁻⁴	90	ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(p\overline{\Lambda})/\Gamma_{total}$ — Γ_{68}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<5 x 10⁻⁵	90	[84] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<8.5\times10^{-5}$	90	ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$

[84] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(p\overline{\Lambda}\pi^+\pi^-)/\Gamma_{total}$ — Γ_{69}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.8 x 10⁻⁴	90	ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\overline{\Delta}^0 p)/\Gamma_{total}$ — Γ_{70}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<3.3 x 10⁻⁴	90	[85] BORTOLETTO89	CLEO	$e^+e^- \to \Upsilon(4S)$

[85] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\Delta^{++}\overline{p})/\Gamma_{total}$ — Γ_{71}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.3 x 10⁻⁴	90	[86] BORTOLETTO89	CLEO	$e^+e^- \to \Upsilon(4S)$

[86] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^*(892)^+ e^+e^-)/\Gamma_{total}$ — Γ_{72}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<6.3 x 10⁻⁴	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^+ \mu^+\mu^-)/\Gamma_{total}$ — Γ_{73}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.1 x 10⁻³	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\pi^+ e^+e^-)/\Gamma_{total}$ — Γ_{74}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0039	90	[87] WEIR 90B	MRK2	e^+e^- 29 GeV

[87] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(\pi^+\mu^+\mu^-)/\Gamma_{total}$ — Γ_{75}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0091	90	[88] WEIR 90B	MRK2	e^+e^- 29 GeV

[88] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^+ e^+e^-)/\Gamma_{total}$ — Γ_{76}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<5 x 10⁻⁵	90	[89] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<9.0\times10^{-5}$	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$
$<6.8\times10^{-3}$	90	[90] WEIR 90B	MRK2	e^+e^- 29 GeV
$<2.1\times10^{-4}$	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[89] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.
[90] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^+\mu^+\mu^-)/\Gamma_{total}$ — Γ_{77}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.5 x 10⁻⁴	90	[91] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.2\times10^{-4}$	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$
$<6.4\times10^{-3}$	90	[92] WEIR 90B	MRK2	e^+e^- 29 GeV
$<3.2\times10^{-4}$	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[91] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.
[92] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(\pi^+ e^+\mu^-)/\Gamma_{total}$ — Γ_{78}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0064	90	[93] WEIR 90B	MRK2	e^+e^- 29 GeV

[93] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(\pi^+ e^-\mu^+)/\Gamma_{total}$ — Γ_{79}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0064	90	[94] WEIR 90B	MRK2	e^+e^- 29 GeV

[94] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^+ e^+\mu^-)/\Gamma_{total}$ — Γ_{80}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0064	90	[95] WEIR 90B	MRK2	e^+e^- 29 GeV

[95] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^+ e^-\mu^+)/\Gamma_{total}$ — Γ_{81}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0064	90	[96] WEIR 90B	MRK2	e^+e^- 29 GeV

[96] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(\pi^- e^+e^+)/\Gamma_{total}$ — Γ_{82}/Γ

Test of total lepton number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0039	90	[97] WEIR 90B	MRK2	e^+e^- 29 GeV

[97] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(\pi^-\mu^+\mu^+)/\Gamma_{total}$ — Γ_{83}/Γ

Test of total lepton number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0091	90	[98] WEIR 90B	MRK2	e^+e^- 29 GeV

[98] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(\pi^- e^+\mu^+)/\Gamma_{total}$ — Γ_{84}/Γ

Test of total lepton number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0064	90	[99] WEIR 90B	MRK2	e^+e^- 29 GeV

[99] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^- e^+e^+)/\Gamma_{total}$ — Γ_{85}/Γ

Test of total lepton number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0039	90	[100] WEIR 90B	MRK2	e^+e^- 29 GeV

[100] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^- e^+\mu^+)/\Gamma_{total}$ — Γ_{86}/Γ

Test of total lepton number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0064	90	[101] WEIR 90B	MRK2	e^+e^- 29 GeV

[101] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^-\mu^+\mu^+)/\Gamma_{total}$ — Γ_{87}/Γ

Test of total lepton number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0091	90	[102] WEIR 90B	MRK2	e^+e^- 29 GeV

[102] WEIR 90B assumes B^+ production cross section from LUND.

For all of the decays below, the charge of the decaying B was not determined (B^0, $\overline{B}^0$, B^+, or B^-).

$\Gamma(e^{\pm}\nu_e \text{ hadrons})/\Gamma_{total}$ — Γ_{88}/Γ

Only the experiments at the $\Upsilon(4S)$ are used in the average.

VALUE	DOCUMENT ID	TECN	COMMENT
0.107±0.005 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.		
0.100±0.004±0.003	[103] YANAGISAWA 91	CSB2	$e^+e^- \to \Upsilon(4S)$
0.103±0.006±0.002	[104] ALBRECHT 90H	ARG	$e^+e^- \to \Upsilon(4S)$
0.117±0.004±0.010	[105] WACHS 89	CBAL	Direct e at $\Upsilon(4S)$
0.120±0.007±0.005	CHEN 84	CLEO	Direct e at $\Upsilon(4S)$
0.132±0.008±0.014	[106] KLOPFEN... 83B	CUSB	Direct e at $\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.138±0.032±0.008	[107] ADEVA 91C	L3	Z decays
0.111±0.028±0.026	BEHREND 90D	CELL	E_{cm}^{ee}= 43 GeV
0.150±0.011±0.022	BEHREND 90D	CELL	E_{cm}^{ee}= 35 GeV
0.112±0.009±0.011	ONG 88	MRK2	E_{cm}^{ee}= 29 GeV
$0.149^{+0.022}_{-0.019}$	PAL 86	DLCO	E_{cm}^{ee}= 29 GeV
0.110±0.018±0.010	AIHARA 85	TPC	E_{cm}^{ee}= 29 GeV
0.111±0.034±0.040	ALTHOFF 84J	TASS	E_{cm}^{ee}= 34.6 GeV
0.146±0.028	KOOP 84	DLCO	Repl. by PAL 86
0.116±0.021±0.017	NELSON 83	MRK2	E_{cm}^{ee}= 29 GeV

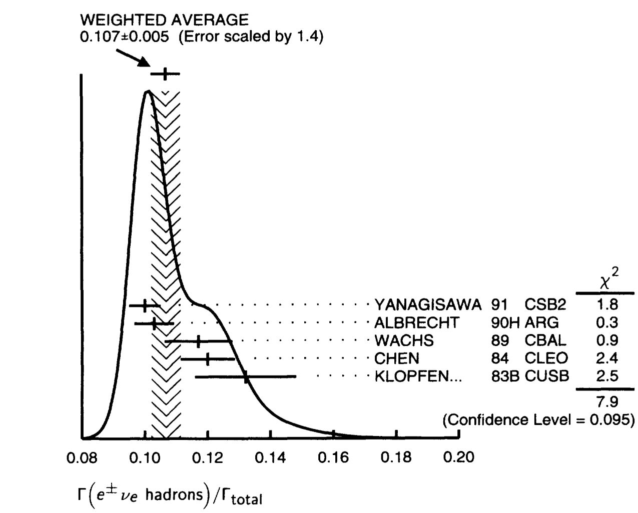
[103] YANAGISAWA 91 also measures an average semileptonic branching ratio at the $\Upsilon(5S)$ of 9.6–10.5% depending on assumptions about the relative production of different B meson species.

[104] ALBRECHT 90H uses the model of ALTARELLI 82 to correct over all lepton momenta. 0.099 ± 0.006 is obtained using ISGUR 89B.

[105] Using data above $p(e)$ = 2.4 GeV, WACHS 89 determine $\sigma(B \to e\nu \text{ up})/\sigma(B \to e\nu \text{ charm}) <$ 0.065 at 90% CL.

[106] Ratio $\sigma(b \to e\nu \text{ up})/\sigma(b \to e\nu \text{ charm})$ <0.055 at CL = 90%.

[107] ADEVA 91C measure the average B($b \to e$ X) branching ratio using single and double tagged b enhanced Z events. Combining e and μ results, they obtain 0.113 ± 0.010 ± 0.006. Constraining the initial number of b quarks by the Standard Model prediction (378 ± 3 MeV) for the decay of the Z into $b\overline{b}$, the electron result gives 0.112 ± 0.004 ± 0.008. They obtain 0.119 ± 0.003 ± 0.006 when e and μ results are combined. Used to measure the $b\overline{b}$ width itself, this electron result gives 370 ± 12 ± 24 MeV and combined with the muon result gives 385 ± 7 ± 22 MeV.



$\Gamma(D^*(2010)e\nu_e)/\Gamma_{total}$ — Γ_{89}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
0.070±0.018±0.014	90	ANTREASYAN 90B	CBAL	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\overline{p}e^+\nu_e \text{ anything})/\Gamma_{total}$ — Γ_{90}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0016	90	ALBRECHT 90H	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\mu^{\pm}\nu_{\mu} \text{ hadrons})/\Gamma_{total}$ — Γ_{91}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.103±0.005 OUR AVERAGE			
0.100±0.006±0.002	[108] ALBRECHT 90H	ARG	$e^+e^- \to \Upsilon(4S)$
0.108±0.006±0.01	CHEN 84	CLEO	Direct μ at $\Upsilon(4S)$
0.112±0.009±0.01	LEVMAN 84	CUSB	Direct μ at $\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.113±0.012±0.006	[109] ADEVA 91C	L3	Z decays
0.104±0.023±0.016	BEHREND 90D	CELL	E_{cm}^{ee}= 43 GeV
0.148±0.010±0.016	BEHREND 90D	CELL	E_{cm}^{ee}= 35 GeV
0.118±0.012±0.010	ONG 88	MRK2	E_{cm}^{ee}= 29 GeV
0.117±0.016±0.015	BARTEL 87	JADE	E_{cm}^{ee}= 34.6 GeV
0.114±0.018±0.025	BARTEL 85J	JADE	Repl. by BARTEL 87
0.117±0.028±0.010	ALTHOFF 84G	TASS	E_{cm}^{ee}= 34.5 GeV
0.105±0.015±0.013	ADEVA 83B	MRKJ	E_{cm}^{ee}= 33–38.5 GeV
$0.155^{+0.054}_{-0.029}$	FERNANDEZ 83D	MAC	E_{cm}^{ee}= 29 GeV

[108] ALBRECHT 90H uses the model of ALTARELLI 82 to correct over all lepton momenta. 0.097 ± 0.006 is obtained using ISGUR 89B.

[109] ADEVA 91C measure the average B($b \to e$ X) branching ratio using single and double tagged b enhanced Z events. Combining e and μ results, they obtain 0.113 ± 0.010 ± 0.006. Constraining the initial number of b quarks by the Standard Model prediction (378±3 MeV) for the decay of the Z into $b\overline{b}$, the muon result gives 0.123±0.003±0.006. They obtain 0.119 ± 0.003 ± 0.006 when e and μ results are combined. Used to measure the $b\overline{b}$ width itself, this muon result gives 394 ± 9 ± 22 MeV and combined with the electron result gives 385 ± 7 ± 22 MeV.

$\Gamma(D^{\pm}\ell\nu \text{ hadrons})/\Gamma(\ell\nu \text{ hadrons})$ — Γ_{94}/Γ_{93}

$\ell = e$ or μ.

VALUE	DOCUMENT ID	TECN	COMMENT
0.26±0.07±0.04	[110] FULTON 91	CLEO	$e^+e^- \to \Upsilon(4S)$

[110] FULTON 91 uses B($D^+ \to K^-\pi^+\pi^+$) = (9.1 ± 1.3 ± 0.4)% as measured by MARK III.

$\Gamma(D^0/\overline{D}^0\ell\nu \text{ hadrons})/\Gamma(\ell\nu \text{ hadrons})$ — Γ_{95}/Γ_{93}

$\ell = e$ or μ.

VALUE	DOCUMENT ID	TECN	COMMENT
0.67±0.09±0.10	[111] FULTON 91	CLEO	$e^+e^- \to \Upsilon(4S)$

[111] FULTON 91 uses B($D^0 \to K^-\pi^+$) = (4.2 ± 0.4 ± 0.4)% as measured by MARK III.

$\Gamma(\ell\nu \text{ noncharm-hadrons})/\Gamma(\ell\nu \text{ hadrons})$ — Γ_{96}/Γ_{93}

ℓ denotes e or μ, not the sum. These experiments measure this ratio in very limited momentum intervals.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
		77	[112] ALBRECHT 91C	ARG	$e^+e^- \to \Upsilon(4S)$
		76	[113] FULTON 90	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		41	[114] ALBRECHT 90	ARG	$e^+e^- \to \Upsilon(4S)$
<0.04	90		[115] BEHRENDS 87	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.04	90		CHEN 84	CLEO	Direct e at $\Upsilon(4S)$
<0.055	90		KLOPFEN... 83B	CUSB	Direct e at $\Upsilon(4S)$

[112] ALBRECHT 91C result supersedes ALBRECHT 90. Two events are fully reconstructed providing evidence for the $b \to u$ transition. Using the model of ALTARELLI 82, they obtain $|V_{bu}/V_{bc}|$ = 0.11 ± 0.012 from 77 leptons in the 2.3–2.6 GeV momentum range.

[113] FULTON 90 observe 76 ± 20 excess e and μ (lepton) events in the momentum interval p = 2.4–2.6 GeV signaling the presence of the $b \to u$ transition. The average branching ratio, (1.8 ± 0.4 ± 0.3) × 10^{-4}, corresponds to a model-dependent measurement of approximately $|V_{bu}/V_{bc}|$ = 0.1 using B($b \to c\ell\nu$) = 10.2 ± 0.2 ± 0.7%.

[114] ALBRECHT 90 observes 41 ± 10 excess e and μ (lepton) events in the momentum interval p = 2.3–2.6 GeV signaling the presence of the $b \to u$ transition. The events correspond to a model-dependent measurement of $|V_{bu}/V_{bc}|$ = 0.10 ± 0.01.

[115] The quoted possible limits range from 0.018 to 0.04 for the ratio, depending on which model or momentum range is chosen. We select the most conservative limit they have calculated. This corresponds to a limit on $|V_{bu}|/|V_{bc}| <$ 0.20. While the endpoint technique employed is more robust than their previous results in CHEN 84, these results do not provide a numerical improvement in the limit.

$\Gamma(K^+\ell^+ \text{ anything})/\Gamma(\ell^+ \text{ anything})$ — Γ_{97}/Γ_{92}

ℓ denotes e or μ, not the sum.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.54±0.07±0.06	[116] ALAM 87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[116] ALAM 87B measurement relies on lepton-kaon correlations. It does not consider the possibility of $B\overline{B}$ mixing. We have thus removed it from the average.

$\Gamma(K^-\ell^+ \text{ anything})/\Gamma(\ell^+ \text{ anything})$ — Γ_{98}/Γ_{92}

ℓ denotes e or μ, not the sum.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.10±0.05±0.02	[117] ALAM 87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[117] ALAM 87B measurement relies on lepton-kaon correlations. It does not consider the possibility of $B\overline{B}$ mixing. We have thus removed it from the average.

$\Gamma(K^0/\overline{K}^0\ell^+ \text{ anything})/\Gamma(\ell^+ \text{ anything})$ — Γ_{99}/Γ_{92}

ℓ denotes e or μ, not the sum. Sum over K^0 and $\overline{K}^0$ states.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.39±0.06±0.04	[118] ALAM 87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[118] ALAM 87B measurement relies on lepton-kaon correlations. It does not consider the possibility of $B\overline{B}$ mixing. We have thus removed it from the average.

$\Gamma(c/\overline{c})/\Gamma_{\text{total}}$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.98\pm0.16\pm0.12$	[119] ALAM	87B	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[119] From the difference between K^- and K^+ widths. ALAM 87B measurement relies on lepton-kaon correlations. It does not consider the possibility of $B\overline{B}$ mixing. We have thus removed it from the average.

$\Gamma(D^{\pm}\text{ anything})/\Gamma_{\text{total}}$ — Γ_{100}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.227±0.033 OUR AVERAGE					
$0.25\pm0.04\pm0.03$		[120] BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
$0.272\pm0.063\pm0.035$		[121] ALBRECHT	91H	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
$0.17\pm0.04\pm0.04$	20k	[122] BORTOLETTO	87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[120] The first error is the combined statistical and systematic error and the second error is due to the uncertainty in the D meson branching ratio. BORTOLETTO 92 measures $B(B \rightarrow D^+\text{ anything}) \times B(D^+ \rightarrow K^-\pi^+\pi^+) = 0.0226 \pm 0.0030 \pm 0.0018$ and has chosen to normalize by the Mark III branching fractions.

[121] ALBRECHT 91H measures $B(B \rightarrow D^{\pm}\text{ anything}) \times B(D^+ \rightarrow K^-\pi^+\pi^+) = 0.0209 \pm 0.0027 \pm 0.0040$. Uses the PDG 90 $B(D^+ \rightarrow K^-\pi^+\pi^+) = 0.077 \pm 0.010$.

[122] BORTOLETTO 87 uses old MARK III (BALTRUSAITIS 86E) branching ratio for $K^-\pi^+\pi^+ = 0.116 \pm 0.014 \pm 0.007$. The product branching ratio for $B(B \rightarrow D^+ X)\ B(D^+ \rightarrow K^-\pi^+\pi^+)$ is $0.019 \pm 0.004 \pm 0.002$.

$\Gamma(D^0/\overline{D}^0\text{ anything})/\Gamma_{\text{total}}$ — Γ_{101}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.46 ±0.05 OUR AVERAGE		Error includes scale factor of 1.2.			
$0.55\pm0.04\pm0.08$		[123] BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
$0.522\pm0.082\pm0.035$		[124] ALBRECHT	91H	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
$0.39\pm0.05\pm0.04$	21k	[125] BORTOLETTO	87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.57\pm0.14\pm0.12$		[126] GREEN	83	CLEO	Repl. by BORTOLETTO 87

[123] The first error is the combined statistical and systematic error and the second error is due to the uncertainty in the D meson branching ratio. BORTOLETTO 92 measures $B(B \rightarrow D^0\text{ anything}) \times B(D^0 \rightarrow K^-\pi^+) = 0.0233 \pm 0.0012 \pm 0.0014$ and has chosen to normalize by the Mark III branching fractions.

[124] ALBRECHT 91H measures $B(B \rightarrow D^0/\overline{D}^0\text{ anything}) \times B(D^0 \rightarrow K^-\pi^+) = 0.0194 \pm 0.0015 \pm 0.0025$. Uses the PDG 90 $B(D^0 \rightarrow K^-\pi^+) = 0.0371 \pm 0.0025$.

[125] BORTOLETTO 87 uses old MARK III (BALTRUSAITIS 86E) branching ratio for $K^-\pi^+ = 0.056 \pm 0.004 \pm 0.003$. The product branching ratio for $B(B \rightarrow D^0 X)\ B(D^0 \rightarrow K^-\pi^+)$ is $0.0210 \pm 0.0015 \pm 0.0021$.

[126] Corrected by us using assumptions $B(D^0 \rightarrow K^-\pi^+) = (0.042 \pm 0.006)$. The product branching ratio is $B(B^0 \rightarrow D^0 X) \cdot B(D^0 \rightarrow K^-\pi^+) = 0.024 \pm 0.006 \pm 0.004$.

$\Gamma(D^*(2010)^{\pm}\text{ anything})/\Gamma_{\text{total}}$ — Γ_{102}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.269±0.035 OUR AVERAGE					
$0.25\pm0.03\pm0.04$		[127] BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
$0.348\pm0.060\pm0.035$		[128] ALBRECHT	91H	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
$0.22\pm0.04\ ^{+0.07}_{-0.04}$	5200	[129] BORTOLETTO	87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.27\pm0.06\ ^{+0.08}_{-0.06}$	510	[130] CSORNA	85	CLEO	Repl. by BORTOLETTO 87

[127] The first error is the combined statistical and systematic error and the second error is due to the uncertainty in the D meson branching ratio. BORTOLETTO 92 measures $B(B \rightarrow D^*(2010)^+\text{ anything}) \times B(D^*(2010)^+ \rightarrow D^0\pi^+) \times B(D^0 \rightarrow K^-\pi^+) = 0.00604 \pm 0.00034 \pm 0.00057$ including an estimated efficiency of 0.92 ± 0.03 due to missing $D^*(2010)$'s at x<0.1. They have chosen to normalize by the Mark III branching fractions.

[128] ALBRECHT 91H measures $B(B \rightarrow D^*(2010)^{\pm}\text{ anything}) \times B(D^*(2010)^+ \rightarrow D^0\pi^+) \times B(D^0 \rightarrow K^-\pi^+) = 0.0071 \pm 0.0006 \pm 0.0012$. Uses the PDG 90 $B(D^*(2010)^+ \rightarrow D^0\pi^+) = 0.55 \pm 0.04$ and $B(D^0 \rightarrow K^-\pi^+) = 0.0371 \pm 0.0025$.

[129] BORTOLETTO 87 uses old MARK III (BALTRUSAITIS 86E) branching ratios $B(D^0 \rightarrow K^-\pi^+) = 0.056 \pm 0.004 \pm 0.003$ and also assumes $B(D^*(2010)^+ \rightarrow D^0\pi^+) = 0.60^{+0.08}_{-0.15}$. The product branching ratio for $B(B \rightarrow D^*(2010)^+)\ B(D^*(2010)^+ \rightarrow D^0\pi^+)$ is $0.13 \pm 0.02 \pm 0.012$.

[130] $V-A$ momentum spectrum used to extrapolate below $p = 1$ GeV. We correct the value assuming $B(D^0 \rightarrow K^-\pi^+) = 0.042 \pm 0.006$ and $B(D^{*+} \rightarrow D^0\pi^+) = 0.6^{+0.08}_{-0.15}$. The product branching fraction is $B(B \rightarrow D^{*+} X) \cdot B(D^{*+} \rightarrow \pi^+ D^0) \cdot B(D^0 \rightarrow K^-\pi^+) = (68 \pm 15 \pm 9) \times 10^{-4}$.

$\Gamma(D_s^{\mp}\text{ anything})/\Gamma_{\text{total}}$ — Γ_{103}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.115±0.028 OUR AVERAGE					
$0.10\pm0.02\pm0.04$		[131] BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
0.13 ± 0.05		[132] ALBRECHT	87H	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
0.12 ± 0.05		[133] HAAS	86	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.153 ± 0.023	257	[134] BORTOLETTO	90	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[131] BORTOLETTO 92 supersedes BORTOLETTO 90. The first error is the combined statistical and systematic error and the second error is due to the uncertainty in the D_s meson branching ratio. Uses $B(D_s^+ \rightarrow \phi\pi^+) = (3.0 \pm 1.1)\%$ based on the average of ARGUS and CLEO using the theoretical relation between $\phi\ell\nu$ and $K^*(892)\ell\nu$.

[132] ALBRECHT 87H measure $B(B \rightarrow D_s^+ X)\ B(D_s^+ \rightarrow \phi\pi^+) = 0.0042 \pm 0.0009 \pm 0.0006$ and we obtain the result shown by dividing by $B(D_s^+ \rightarrow \phi\pi^+) = 0.033 \pm 0.010$. $46 \pm 16\%$ of $B \rightarrow D_s X$ decays are 2-body.

[133] HAAS 86 measure $B(B \rightarrow D_s^+ X) B(D_s^+ \rightarrow \phi\pi^+) = 0.0038 \pm 0.001$ and we obtain the result shown by dividing by $B(D_s^+ \rightarrow \phi\pi^+) = 0.033 \pm 0.010$. $64 \pm 22\%$ decays are 2-body.

[134] BORTOLETTO 90 assume $B(D_s \rightarrow \phi\pi^+) = 2\%$.

$\Gamma(D_s D,\ D_s^* D,\ D_s D^*,\text{ or } D_s^* D^*)/\Gamma(D_s^{\mp}\text{ anything})$ — $\Gamma_{104}/\Gamma_{103}$

Sum over modes.

VALUE	DOCUMENT ID		TECN	COMMENT
0.56±0.10	BORTOLETTO	90	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(\overline{D}^0\pi^+,\ D^-\pi^+,\ \overline{D}^*(2010)^0\pi^+,\text{ or } D^*(2010)^-\pi^+)/\Gamma_{\text{total}}$ — Γ_{105}/Γ

Sum over modes.

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0162 ± 0.0032	[135] BEBEK	87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
$0.020\pm0.006\pm0.005$	[136] GILES	84	CLEO	Repl by BEBEK 87

[135] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. This measurement is independent of D and $D^*(2010)$ meson branching fractions.

[136] No dependence on D used fast-π momentum.

$\Gamma(J/\psi(1S)\text{ anything})/\Gamma_{\text{total}}$ — Γ_{106}/Γ

VALUE (units 10^{-2})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
1.12±0.16 OUR AVERAGE						
$1.12\pm0.33\pm0.25$		27	MASCHMANN	90	CBAL	$e^+e^- \rightarrow \Upsilon(4S)$
$1.07\pm0.16\pm0.22$		120	[137] ALBRECHT	87D	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
$1.09\pm0.16\pm0.21$		52	ALAM	86	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
$1.4\ ^{+0.6}_{-0.5}$		7	[138] ALBRECHT	85H	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$1.1\pm0.21\pm0.23$		46	[139] HAAS	85	CLEO	Repl. by ALAM 86
<4.9	90		MATTEUZZI	83	MRK2	$E_{\text{cm}}^{ee} = 29$ GeV

[137] ALBRECHT 87D find the branching ratio for J/ψ not from $\psi(2S)$ to be 0.0081 ± 0.0023.

[138] Statistical and systematic errors were added in quadrature. ALBRECHT 85H also report a CL = 90% limit of 0.007 for $B \rightarrow J/\psi(1S) + X$ where $m(X)$ <1 GeV.

[139] Dimuon and dielectron events used.

$\Gamma(\psi(2S)\text{ anything})/\Gamma_{\text{total}}$ — Γ_{107}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0046±0.0017±0.0011	8	ALBRECHT	87D	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(K^{\pm}\text{ anything})/\Gamma_{\text{total}}$ — Γ_{108}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.85±0.07±0.09	ALAM	87B	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	[140] BRODY	82	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
seen	[141] GIANNINI	82	CUSB	$e^+e^- \rightarrow \Upsilon(4S)$

[140] Assuming $\Upsilon(4S) \rightarrow B\overline{B}$, a total of $3.38 \pm 0.34 \pm 0.68$ kaons per $\Upsilon(4S)$ decay is found (the second error is systematic). In the context of the standard B-decay model, this leads to a value for (b-quark $\rightarrow$ c-quark)/(b-quark $\rightarrow$ all) of $1.09 \pm 0.33 \pm 0.13$.

[141] GIANNINI 82 at CESR-CUSB observed 1.58 ± 0.35 K^0 per hadronic event much higher than 0.82 ± 0.10 below threshold. Consistent with predominant $b \rightarrow c X$ decay.

$\Gamma(K^+\text{ anything})/\Gamma_{\text{total}}$ — Γ_{109}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.66\pm0.05\pm0.07$	[142] ALAM	87B	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[142] ALAM 87B measurement relies on lepton-kaon correlations. It does not consider the possibility of $B\overline{B}$ mixing. We have thus removed it from the average.

$\Gamma(K^-\text{ anything})/\Gamma_{\text{total}}$ — Γ_{110}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.19\pm0.05\pm0.02$	[143] ALAM	87B	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[143] ALAM 87B measurement relies on lepton-kaon correlations. It does not consider the possibility of $B\overline{B}$ mixing. We have thus removed it from the average.

$\Gamma(K^0/\overline{K}^0\text{ anything})/\Gamma_{\text{total}}$ — Γ_{111}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.63±0.06±0.06	ALAM	87B	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(K^*(892)\gamma)/\Gamma_{\text{total}}$ — Γ_{112}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.4 \times 10^{-4}$	90	ALBRECHT	88H	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(K_1(1400)\gamma)/\Gamma_{\text{total}}$ — Γ_{113}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.1 \times 10^{-4}$	90	ALBRECHT	88H	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(K_2^*(1430)\gamma)/\Gamma_{total}$ — Γ_{114}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<8.3 × 10⁻⁴	90	ALBRECHT 88H	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_3^*(1780)\gamma)/\Gamma_{total}$ — Γ_{115}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.0 \times 10^{-3}$	90	ALBRECHT 88H	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\phi \text{ anything})/\Gamma_{total}$ — Γ_{116}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.023±0.006±0.005	BORTOLETTO 86	CLEO	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\text{charmed-baryon anything})/\Gamma_{total}$ — Γ_{117}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.112	90	[144] ALAM 87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.14 ±0.09		[145] ALBRECHT 88E	ARG	$e^+e^- \to \Upsilon(4S)$

[144] Assuming all baryons result from charmed baryons, ALAM 86 conclude the branching fraction is 7.4 ± 2.9%. The limit given above is model independent.

[145] ALBRECHT 88E measured $B(B \to \Lambda_c^+ X) \cdot B(\Lambda_c^+ \to pK^-\pi^+) = (0.30\pm0.12\pm0.06)\%$ and used $B(\Lambda_c^+ \to pK^-\pi^+) = (2.2\pm1.0)\%$ from ABRAMS 80 to obtain above number.

$\Gamma(p \text{ anything})/\Gamma_{total}$ — Γ_{118}/Γ

Values are for $[B(B \to p X)+B(B \to \overline{p} X)]/2$ and include protons from Λ decay.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.082\pm0.005^{+0.013}_{-0.010}$	2163	[146] ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>0.021		[147] ALAM 83B	CLEO	$e^+e^- \to \Upsilon(4S)$

[146] ALBRECHT 89K include direct and nondirect protons.

[147] ALAM 83B reported their result as > 0.036 ± 0.006 ± 0.009. Data are consistent with equal yields of p and $\overline{p}$. Using assumed yields below cut, $B(B \to p + X) = 0.03$ not including protons from Λ decays.

$\Gamma(p \text{ (direct) anything})/\Gamma_{total}$ — Γ_{119}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.055±0.016	1220	[148] ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

[148] ALBRECHT 89K subtract contribution of Λ decay from the inclusive proton yield.

$\Gamma(\Lambda \text{ anything})/\Gamma_{total}$ — Γ_{120}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.042±0.005±0.006	943	ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>0.011		[149] ALAM 83B	CLEO	$e^+e^- \to \Upsilon(4S)$

[149] ALAM 83B reported their result as > 0.022 ± 0.007 ± 0.004. Values are for $(B(\Lambda X)+B(\overline{\Lambda} X))/2$. Data are consistent with equal yields of p and $\overline{p}$. Using assumed yields below cut, $B(B \to \Lambda X) = 0.03$.

$\Gamma(\Xi^- \text{ anything})/\Gamma_{total}$ — Γ_{121}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0028±0.0014	54	ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\text{baryons anything})/\Gamma_{total}$ — Γ_{122}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.076±0.014	[150] ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

[150] ALBRECHT 89K obtain this result by adding their their measurements (5.5 ± 1.6)% for direct protons and (4.2 ± 0.5 ± 0.6)% for inclusive Λ production. They then assume (5.5 ± 1.6)% for neutron production and add it in also. Since each B decay has two baryons, they divide by 2 to obtain (7.6 ± 1.4)%.

$\Gamma(p\overline{p} \text{ anything})/\Gamma_{total}$ — Γ_{123}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.025 ±0.002 ±0.002	918	ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\Lambda\overline{p} \text{ anything})/\Gamma_{total}$ — Γ_{124}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.023±0.004±0.003	165	ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\Lambda\overline{\Lambda} \text{ anything})/\Gamma_{total}$ — Γ_{125}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.0088	90	12	ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(e^+e^- \text{ anything})/\Gamma_{total}$ — Γ_{126}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0024 OUR LIMIT	Our 90% CL limit, using $[\Gamma(e^+e^- \text{ anything}) + \Gamma(\mu^+\mu^- \text{ anything})]/\Gamma_{total}$ below.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.05	90	BEBEK 81	CLEO	$e^+e^- \to \Upsilon(4S)$

$[\Gamma(e^+e^- \text{ anything}) + \Gamma(\mu^+\mu^- \text{ anything})]/\Gamma_{total}$ — $(\Gamma_{126}+\Gamma_{127})/\Gamma$

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0024	90	[151] BEAN 87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0062	90	[152] AVERY 84	CLEO	Repl. by BEAN 87
<0.008	90	MATTEUZZI 83	MRK2	E_{cm}^{ee}= 29 GeV

[151] BEAN 87 reports $[(\mu^+\mu^-)+(e^+e^-)]/2$ and we converted it.

[152] Determine ratio of B^+ to B^0 semileptonic decays to be in the range 0.25–2.9.

$\Gamma(\mu^+\mu^- \text{ anything})/\Gamma_{total}$ — Γ_{127}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.0 \times 10^{-5}$	90	[153] ALBAJAR 91C	UA1	$E_{cm}^{p\overline{p}}$= 540 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.02	95	ALTHOFF 84G	TASS	E_{cm}^{ee}= 34.5 GeV
<0.007	95	ADEVA 83	MRKJ	E_{cm}^{ee}= 30–38 GeV
<0.007	95	BARTEL 83B	JADE	E_{cm}^{ee}= 33–37 GeV
<0.017	90	CHADWICK 81	CLEO	$e^+e^- \to \Upsilon(4S)$

[153] B^0, $B^{\pm}$, and B_s^0 not separated.

$B^{\pm}$ REFERENCES

ABREU 92 ZPHY C (to be pub.) +Adam, Adami, Adye+ (DELPHI Collab.)
CERN-PPE/91-131
ACTON 92 PL B274 513 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ALBRECHT 92C PL B275 195 +Erlichmann, Hamacher, Krueger, Nau+ (ARGUS Collab.)
BORTOLETTO 92 PR D45 21 +Brown, Dominick, McIlwain, Miller+ (CLEO Collab.)
ADEVA 91C PL B261 177 +Adriani, Aguilar-Benitez, Akbari+ (L3 Collab.)
ADEVA 91H PL B270 111 +Adrani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ALBAJAR 91C PL B262 163 +Albrow, Allkofer, Ankoviak, Apsimon+ (UA1 Collab.)
ALBRECHT 91B PL B254 288 +Glaeser, Harder, Krueger, Nippe+ (ARGUS Collab.)
ALBRECHT 91C PL B255 297 +Ehrlichmann, Glaeser, Harder, Krueger+ (ARGUS Collab.)
ALBRECHT 91E PL B262 148 +Glaeser, Harder, Krueger, Nippe+ (ARGUS Collab.)
ALBRECHT 91H ZPHY C52 353 +Ehrlichmann, Hamacher, Harder, Krueger+(ARGUS Collab.)
ALEXANDER 91G PL B266 485 +Allison, Allport+ (OPAL Collab.)
BERKELMAN 91 ARNPS 41 1 +Stone (CORN, SYRA)
"Decays of B Mesons"
DECAMP 91C PL B257 492 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
FULTON 91 PR D43 651 +Jensen, Johnson, Kagan, Kass+ (CLEO Collab.)
YANAGISAWA 91 PRL 66 2436 +Heintz, Lee-Franzini, Lovelock, Narain+ (CUSB II Collab.)
ALBRECHT 90 PL B234 409 +Glaeser, Harder, Krueger+ (ARGUS Collab.)
ALBRECHT 90B PL B241 278 +Glaeser, Harder, Krueger, Nilsson+ (ARGUS Collab.)
ALBRECHT 90H PL B249 359 +Ehrlichmann, Glaeser, Harder, Krueger+ (Argus Collab.)
ALBRECHT 90J ZPHY C48 543 +Ehrlichmann, Harder, Krueger+ (ARGUS Collab.)
ANTREASYAN 90B ZPHY C48 553 +Bartels, Bieler, Bienlein, Bizzeti+ (Crystal Ball Collab.)
BEHREND 90D ZPHY C47 333 +Criegee, Field, Franke, Jung+ (CELLO Collab.)
BORTOLETTO 90 PRL 64 2117 +Goldberg, Horwitz, Jain, Mestayer+ (CLEO Collab.)
FULTON 90 PRL 64 16 +Hempstead, Jensen, Johnson+ (CLEO Collab.)
HAGEMANN 90 ZPHY C48 401 +Ramcke, Allison, Ambrus, Barlow+ (JADE Collab.)
LYONS 90 PR D41 982 +Martin, Saxon (OXF, BRIS, RAL)
MASCHMANN 90 ZPHY C46 555 +Antreasyan, Bartels, Besset+ (Crystal Ball Collab.)
PDG 90 PL B239 Hernandez, Stone, Porter+ (IFIC, BOST, CIT+)
WAGNER 90 PRL 64 1095 +Hinshaw, Ong, Snyder+ (Mark II Collab.)
WEIR 90B PR D41 1384 +Klein, Abrams, Adolphsen, Akerlof+ (Mark II Collab.)
ALBRECHT 89G PL B229 304 +Glaeser, Harder, Krueger+ (ARGUS Collab.)
ALBRECHT 89K ZPHY C42 519 +Boeckmann, Glaeser, Harder+ (ARGUS Collab.)
AVERILL 89 PR D39 123 +Blockus, Brabson+ (HRS Collab.)
AVERY 89B PL B223 470 +Besson, Garren, Yelton+ (CLEO Collab.)
BEBEK 89 PRL 62 8 +Berkelman, Blucher+ (CLEO Collab.)
BORTOLETTO 89 PRL 62 2436 +Goldberg, Horwitz, Mestayer+ (CLEO Collab.)
BRAUNSCH... 89B ZPHY C44 1 Braunschweig, Gerhards, Kirschfink+ (TASSO Collab.)
ISGUR 89B PR D39 799 +Scora, Grinstein, Wise (TORO, CIT)
ONG 89 PRL 62 1236 +Jaros, Abrams, Amidei, Baden+ (Mark II Collab.)
WACHS 89 ZPHY C42 33 +Antreasyan, Bartels, Bieler+ (Crystal Ball Collab.)
ALBRECHT 88E PL B210 263 +Boeckmann, Glaeser+ (ARGUS Collab.)
ALBRECHT 88F PL B209 119 +Boeckmann, Glaeser+ (ARGUS Collab.)
ALBRECHT 88H PL B210 258 +Boeckmann, Glaeser+ (ARGUS Collab.)
ALBRECHT 88K PL B215 424 +Boeckmann, Glaeser+ (ARGUS Collab.)
KLEM 88 PR D37 41 +Atwood, Barish+ (DELCO Collab.)
ONG 88 PRL 60 2587 +Weir, Abrams, Amidei+ (Mark II Collab.)
ALAM 87 PRL 59 22 +Kitukama, Kim, Li+ (CLEO Collab.)
ALAM 87B PRL 58 1814 +Katayama, Kim, Sun+ (CLEO Collab.)
ALBRECHT 87C PL B185 218 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
ALBRECHT 87D PL B199 451 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
ALBRECHT 87H PL B187 425 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
ASH 87 PRL 58 640 +Band, Bloom, Bosman+ (MAC Collab.)
AVERY 87 PL B183 429 +Besson, Bowcock, Giles+ (CLEO Collab.)
BARTEL 87 ZPHY C33 339 +Becker, Felst, Haidt+ (JADE Collab.)
BEAN 87 PR D35 3533 +Bobbink, Brock, Engler+ (CLEO Collab.)
BEBEK 87 PR D36 1289 +Berkelman, Blucher, Cassel+ (CLEO Collab.)
BEHRENDS 87 PRL 59 407 +Morrow, Guida, Guida+ (CLEO Collab.)
BORTOLETTO 87 PR D35 19 +Chen, Garren, Goldberg+ (CLEO Collab.)
BROM 87 PL B195 301 +Abachi, Akerlof, Baringer+ (HRS Collab.)
WU 87 Lepton-Photon Conf. (WISC, DESY)
DESY 87/164 and CERN-EP/87-235
ALAM 86 PR D34 3279 +Katayama, Kim, Sun+ (CLEO Collab.)
BALTRUSAIT... 86E PRL 56 2140 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BARTEL 86B ZPHY C31 349 +Becker, Cords, Felst, Haidt+ (JADE Collab.)
BORTOLETTO 86 PRL 56 800 +Chen, Garren, Goldberg+ (CLEO Collab.)
HAAS 86 PRL 56 2781 +Hempstead, Jensen, Kagan+ (CLEO Collab.)
PAL 86 PR D33 2708 +Atwood, Barish, Bonneaud+ (DELCO Collab.)
PDG 86 PL 170B Aguilar-Benitez, Porter+ (CERN, CIT+)
AIHARA 85 ZPHY C27 39 +Alston-Garnjost, Badtke, Bakken+ (TPC Collab.)
ALBANESE 85 PL 158B 186 +Alpe, Aoki+ (BARI, CERN, DUUC, LOUC, NAGO+)
WA75 experiment.
ALBRECHT 85H PL 162B 395 +Binder, Harder+ (ARGUS Collab.)
BARTEL 85J PL 163B 277 +Becker, Cords, Felst+ (JADE Collab.)
CSORNA 85 PRL 54 1894 +Garren, Mestayer, Panvini+ (CLEO Collab.)
HAAS 85 PRL 55 1248 +Hempstead, Jensen, Kagan+ (CLEO Collab.)
ALTHOFF 84G ZPHY C22 219 +Braunschweig, Kirschfink+ (TASSO Collab.)
ALTHOFF 84H PL 149B 524 +Braunschweig, Kirschfink+ (TASSO Collab.)
ALTHOFF 84J PL 146B 443 +Branschweig, Kirschfink+ (TASSO Collab.)

AVERY	84	PRL 53 1309	+Bebek, Berkelman, Cassel+	(CLEO Collab.)
CHEN	84	PRL 52 1084	+Goldberg, Horwitz, Jawahery+	(CLEO Collab.)
GILES	84	PR D30 2279	+Hassard, Hempstead, Kinoshita+	(CLEO Collab.)
KLEM	84	PRL 53 1873	+Dubois, Young, Atwood+	(DELCO Collab.)
KOOP	84	PRL 52 970	+Sakuda, Atwood, Baillon+	(DELCO Collab.)
LEVMAN	84	PL 141B 271	+Sreedhar, Han, Imlay+	(CUSB Collab.)
ADEVA	83	PRL 50 799	+Barber, Becker, Berdugo+	(Mark-J Collab.)
ADEVA	83B	PRL 51 443	+Barber, Becker, Berdugo+	(Mark-J Collab.)
ALAM	83B	PRL 51 1143	+Csorna, Garren, Mestayer+	(CLEO Collab.)
BARTEL	83B	PL 132B 241	+Becker, Bowdery, Cords+	(JADE Collab.)
FERNANDEZ	83B	PRL 51 1022	+Ford, Read, Smith+	(MAC Collab.)
FERNANDEZ	83D	PRL 50 2054	+Ford, Read, Smith+	(MAC Collab.)
GREEN	83	PRL 51 347	+Hicks, Sannes, Skubic+	(CLEO Collab.)
KLOPFEN...	83B	PL 130B 444	Klopfenstein, Horstkotte+	(CUSB Collab.)
LOCKYER	83	PRL 51 1316	+Jaros, Nelson, Abrams+	(Mark II Collab.)
MATTEUZZI	83	PL 129B 141	+Abrams, Amidei, Blocker+	(Mark II Collab.)
NELSON	83	PRL 50 1542	+Blondel, Trilling, Abrams+	(Mark II Collab.)
ALTARELLI	82	NP B208 365	+Cabibbo, Corbo, Maini, Martinelli	(ROMA, INFN, FRAS)
BARTEL	82C	PL 114B 71	+Cords, Dittmann, Eichler+	(JADE Collab.)
BRODY	82	PRL 48 1070	+Chen, Goldberg, Horwitz+	(CLEO Collab.)
GIANNINI	82	NP B206 1	+Finocchiaro, Franzini+	(CUSB Collab.)
BEBEK	81	PRL 46 84	+Haggerty, Izen, Longuemare+	(CLEO Collab.)
CHADWICK	81	PRL 46 88	+Ganci, Kagar, Kass+	(CLEO Collab.)
ABRAMS	80	PRL 44 10	+Alam, Blocker, Boyarski+	(SLAC, LBL)

OTHER RELATED PAPERS

BERKELMAN 91 ARNPS 41 1 +Stone (CORN, SYRA)
"Decays of B Mesons"
MILLER 90 MPL A5 2683
"Recent Results in B Physics"
SCHINDLER 88 High Energy Electron-Positron Physics 234 (SLAC)
Editors: A. Ali and P. Soeding, World Scientific, Singapore
SCHUBERT 87 IHEP-HD/87-7 (HEID)
EPS Conference – Uppsala, Proc., Vol. 2, p. 791

B^0

$I(J^P) = \frac{1}{2}(0^-)$

Quantum numbers not measured. Values shown are quark-model predictions.

For measurements of the B mean life and for branching ratios in which the charge of the decaying B is not determined, see the $B^{\pm}$ section.

In this issue we have attempted to bring the oldest measurements of branching ratios up to date wherever possible, and to explicitly state the input assumptions that the author(s) have made. Our own best fits to the D branching fractions now differ somewhat from the ones that have been used to calculate the B branching fractions. Whenever possible, the product branching fractions (the measured quantities) have been given.

See the Note at the beginning of the $B^{\pm}$ section.

B^0 MASS

The fit uses the $B^{\pm}$ and B^0 mass and mass difference measurements. These experiments actually measure the difference between half of E_{cm} and the B mass.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
5278.7±2.1 OUR FIT					
5278.7±2.0 OUR AVERAGE					
5278.0±0.4±2.0		[1] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
5279.6±0.7±2.0	40	[1,2] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$
5280.6±0.8±2.0		[1] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5278.2±1.0±3.0	40	ALBRECHT	87C	ARG	$e^+e^- \to \Upsilon(4S)$
5279.5±1.6±3.0	7	[3] ALBRECHT	87D	ARG	$e^+e^- \to \Upsilon(4S)$

[1] These experiments all report a common systematic error 2.0 MeV. We have artificially increased the systematic error to allow the experiments to be treated as independent measurements in our average and B^+–B^0 mass fit. See "Treatment of Errors" section of the Introductory Text.

[2] ALBRECHT 90J assumes 10580 for $\Upsilon(4S)$ mass. Supersedes ALBRECHT 87C and ALBRECHT 87D.

[3] Found using fully reconstructed decays with J/ψ. ALBRECHT 87D assume $m(\Upsilon(4S))$ = 10577 MeV.

$|m_{B^0_1} - m_{B^0_2}|$, MASS DIFFERENCE

VALUE (10^{-10} MeV)	DOCUMENT ID		TECN	COMMENT
3.6±0.7 OUR AVERAGE				
3.5±1.0	[4] ARTUSO	89	CLEO	$e^+e^- \to \Upsilon(4S)$
3.7±1.0	[4] ALBRECHT	87I	ARG	$e^+e^- \to \Upsilon(4S)$

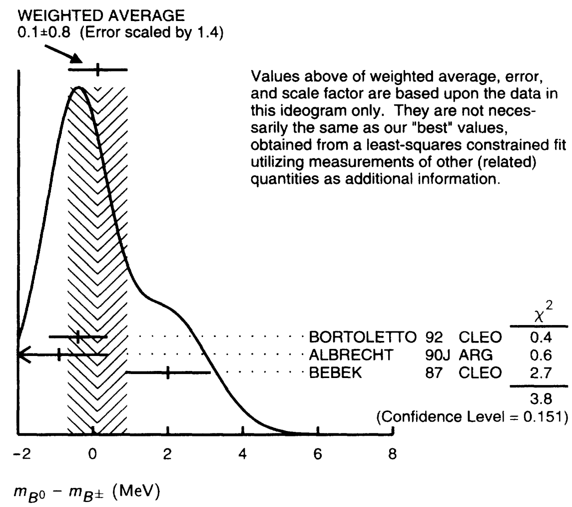
[4] Calculated by us using $\Delta m = (2r/(1-r))^{1/2}\hbar/\tau_{B^0}$ where $\tau_{B^0} = (12.9 \pm 2.0) \times 10^{-13}$s and r is the B^0–$\overline{B}^0$ mixing ratio $\Gamma(B^0 \to \overline{B}^0 \to \mu^- \text{ anything})/\Gamma(B^0 \to \mu^+ \text{ anything})$.

$B^0 - B^+$ MASS DIFFERENCE

The fit uses the $B^{\pm}$ and B^0 mass and mass difference measurements. The mass difference measurements are not independent of the $B^{\pm}$ and B^0 mass measurement by the same experimenters. Our fitting procedures take this into account.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0.1±0.8 OUR FIT Error includes scale factor of 1.3.				
0.1±0.8 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.				
−0.4±0.6±0.5	BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
−0.9±1.2±0.5	ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$
2.0±1.1±0.3	[5] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[5] BEBEK 87 actually measure the difference between half of E_{cm} and the $B^{\pm}$ or B^0 mass, so the $B^0 - B^{\pm}$ mass difference is more accurate. Assume $m(\Upsilon(4S))$ = 10580 MeV.



B MEAN LIFE

This is an average over species of bottom particles. See $B^{\pm}$ Full Listings for data and further details.

VALUE (10^{-13} s)	DOCUMENT ID
12.9±0.5 OUR EVALUATION	

MEAN LIFE RATIO $\tau(B^+)/\tau(B^0)$

These measurements are obtained from semileptonic branching fractions by assuming that the semileptonic decay rates for B^0 and B^+ are equal, as is expected from dominance of the spectator diagram in semileptonic processes. Equal production of B^0 and B^+ is assumed unless otherwise noted. For unequal fractions f_0 and f_+, this measurement can be interpreted as $f_+\tau(B^+)/f_0\tau(B^0)$.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.93±0.16 OUR AVERAGE					
0.91±0.27±0.21		ALBRECHT	92C	ARG	$e^+e^- \to \Upsilon(4S)$
0.89±0.19±0.13		FULTON	91	CLEO	$e^+e^- \to \Upsilon(4S)$
1.00±0.23±0.14		ALBRECHT	89L	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.49 to 2.3	90	[6] BEAN	87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[6] BEAN 87B assume the fraction of $B^0\overline{B}^0$ events at the $\Upsilon(4S)$ is 0.41.

B^0 DECAY MODES

$\overline{B}^0$ modes are charge conjugates of the modes below. Decays in which the charge of the B is not determined are in the $B^{\pm}$ section.

Only data from $\Upsilon(4S)$ decays are used for branching fractions, with rare exceptions. Each paper makes an estimate of the $\Upsilon(4S) \to B^+B^-$ and $B^0\overline{B}^0$ branching fractions, usually 50:50 in recent papers.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

	Mode	Fraction (Γ_i/Γ)	Confidence level
	Semileptonic and leptonic modes		
Γ_1	$D^- \ell^+ \nu$	[a] (1.8 ± 0.5) %	
Γ_2	$D^*(2010)^- \ell^+ \nu$	[a] (4.9 ± 0.8) %	
Γ_3	μ^+ anything		
Γ_4	$\pi^- \mu^+ \nu_\mu$	seen	
	D, D^*, or D_s modes		
Γ_5	$D^- \pi^+$	$(3.2 \pm 0.7) \times 10^{-3}$	
Γ_6	$D^- \rho^+$	$(9 \pm 6) \times 10^{-3}$	
Γ_7	$\overline{D}^0 \pi^+ \pi^-$	$< 7 \times 10^{-3}$	90%
Γ_8	$\overline{D}^0 \rho^0$	$< 6 \times 10^{-4}$	90%
Γ_9	$D^*(2010)^- \pi^+$	$(3.2 \pm 0.7) \times 10^{-3}$	
Γ_{10}	$D^- \pi^+ \pi^+ \pi^-$	$(8.0 \pm 2.5) \times 10^{-3}$	
Γ_{11}	$(D^- \pi^+ \pi^+ \pi^-)$ nonresonant	$(3.9 \pm 1.9) \times 10^{-3}$	
Γ_{12}	$D^- \pi^+ \rho^0$	$(1.1 \pm 1.0) \times 10^{-3}$	
Γ_{13}	$D^- a_1(1260)^+$	$(6.0 \pm 3.3) \times 10^{-3}$	
Γ_{14}	$D^*(2010)^- \pi^+ \pi^0$	(1.8 ± 0.6) %	
Γ_{15}	$D^*(2010)^- \rho^+$	$(8 \pm 4) \times 10^{-3}$	
Γ_{16}	$D^*(2010)^- \pi^+ \pi^+ \pi^-$	(1.41 ± 0.34) %	
Γ_{17}	$(D^*(2010)^- \pi^+ \pi^+ \pi^-)$ nonresonant	$(0.0 \pm 2.5) \times 10^{-3}$	
Γ_{18}	$D^*(2010)^- \pi^+ \rho^0$	$(7 \pm 4) \times 10^{-3}$	
Γ_{19}	$D^*(2010)^- a_1(1260)^+$	(1.8 ± 0.8) %	
Γ_{20}	$D^*(2010)^- \pi^+ \pi^+ \pi^- \pi^0$	(4.1 ± 2.2) %	
Γ_{21}	$D^- D_s^+$	$(8 \pm 5) \times 10^{-3}$	
Γ_{22}	$D^*(2010)^- D_s^+$	(1.6 ± 1.1) %	
Γ_{23}	$D^*(2010)^- D_s^{*+}$		
Γ_{24}	$\pi^- D_s^+$	$< 1.3 \times 10^{-3}$	90%
Γ_{25}	$K^+ D_s^-$	$< 1.3 \times 10^{-3}$	90%
	$J/\psi(1S)$ or $\psi(2S)$ modes		
Γ_{26}	$J/\psi(1S) K^0$	$(6.5 \pm 3.1) \times 10^{-4}$	
Γ_{27}	$J/\psi(1S) K^+ \pi^-$	$(1.0 \pm 0.5) \times 10^{-3}$	
Γ_{28}	$J/\psi(1S) K^*(892)^0$	$(1.3 \pm 0.4) \times 10^{-3}$	
Γ_{29}	$\psi(2S) K^0$	$< 1.5 \times 10^{-3}$	90%
Γ_{30}	$\psi(2S) K^+ \pi^-$	$< 1 \times 10^{-3}$	90%
Γ_{31}	$\psi(2S) K^*(892)^0$	$(1.4 \pm 0.9) \times 10^{-3}$	
	K or K^* modes		
Γ_{32}	$K^+ \pi^-$	$< 9 \times 10^{-5}$	90%
Γ_{33}	$K^0 \pi^+ \pi^-$	$< 4.4 \times 10^{-4}$	90%
Γ_{34}	$K^0 \rho^0$	$< 3.2 \times 10^{-4}$	90%
Γ_{35}	$K^0 f_0(975)$	$< 4.2 \times 10^{-4}$	90%
Γ_{36}	$K^*(892)^+ \pi^-$	$< 4.4 \times 10^{-4}$	90%
Γ_{37}	$K_2^*(1430)^+ \pi^-$	$< 2.6 \times 10^{-3}$	90%
Γ_{38}	$K^0 K^+ K^-$	$< 1.3 \times 10^{-3}$	90%
Γ_{39}	$K^0 \phi$	$< 4.9 \times 10^{-4}$	90%
Γ_{40}	$K^*(892)^0 \pi^+ \pi^-$	$< 1.4 \times 10^{-3}$	90%
Γ_{41}	$K^*(892)^0 \rho^0$	$< 4.6 \times 10^{-4}$	90%
Γ_{42}	$K^*(892)^0 f_0(975)$	$< 2.0 \times 10^{-4}$	90%
Γ_{43}	$K_1(1400)^+ \pi^-$	$< 1.1 \times 10^{-3}$	90%
Γ_{44}	$K^*(892)^0 K^+ K^-$	$< 6.1 \times 10^{-4}$	90%
Γ_{45}	$K^*(892)^0 \phi$	$< 3.2 \times 10^{-4}$	90%
Γ_{46}	$K_1(1400)^0 \rho^0$	$< 3.0 \times 10^{-3}$	90%
Γ_{47}	$K_1(1400)^0 \phi$	$< 5.0 \times 10^{-3}$	90%
Γ_{48}	$K_2^*(1430)^0 \rho^0$	$< 1.1 \times 10^{-3}$	90%
Γ_{49}	$K_2^*(1430)^0 \phi$	$< 1.4 \times 10^{-3}$	90%
Γ_{50}	$K^*(892)^0 \gamma$	$< 2.8 \times 10^{-4}$	90%
Γ_{51}	$K_1(1270)^0 \gamma$	$< 7.8 \times 10^{-3}$	90%
Γ_{52}	$K_1(1400)^0 \gamma$	$< 4.8 \times 10^{-3}$	90%
Γ_{53}	$K_2^*(1430)^0 \gamma$	$< 4.4 \times 10^{-4}$	90%
Γ_{54}	$K^*(1680)^0 \gamma$	$< 2.2 \times 10^{-3}$	90%
Γ_{55}	$K_3^*(1780)^0 \gamma$	< 1.1 %	90%
Γ_{56}	$K_4^*(2045)^0 \gamma$	$< 4.8 \times 10^{-3}$	90%
	Light unflavored meson modes		
Γ_{57}	$\pi^+ \pi^-$	$< 9 \times 10^{-5}$	90%
Γ_{58}	$\pi^+ \pi^- \pi^0$	$< 7.2 \times 10^{-4}$	90%
Γ_{59}	$\rho^0 \pi^0$	$< 4.0 \times 10^{-4}$	90%
Γ_{60}	$\rho^{\mp} \pi^{\pm}$	[b] $< 5.2 \times 10^{-4}$	90%
Γ_{61}	$\pi^+ \pi^- \pi^+ \pi^-$	$< 6.7 \times 10^{-4}$	90%
Γ_{62}	$\rho^0 \rho^0$	$< 2.8 \times 10^{-4}$	90%
Γ_{63}	$a_1(1260)^{\mp} \pi^{\pm}$	[b] $< 5.7 \times 10^{-4}$	90%
Γ_{64}	$a_2(1320)^{\mp} \pi^{\pm}$	[b] $< 3.5 \times 10^{-4}$	90%
Γ_{65}	$\pi^+ \pi^- \pi^0 \pi^0$	$< 3.1 \times 10^{-3}$	90%
Γ_{66}	$\rho^+ \rho^-$	$< 2.2 \times 10^{-3}$	90%
Γ_{67}	$a_1(1260)^0 \pi^0$	$< 1.1 \times 10^{-3}$	90%
Γ_{68}	$\omega \pi^0$	$< 4.6 \times 10^{-4}$	90%
Γ_{69}	$\eta \pi^0$	$< 1.8 \times 10^{-3}$	90%
Γ_{70}	$\pi^+ \pi^+ \pi^- \pi^- \pi^0$	$< 9.0 \times 10^{-3}$	90%
Γ_{71}	$a_1(1260)^+ \rho^-$	$< 3.4 \times 10^{-3}$	90%
Γ_{72}	$a_1(1260)^0 \rho^0$	$< 2.4 \times 10^{-3}$	90%
Γ_{73}	$\pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^-$	$< 3.0 \times 10^{-3}$	90%
Γ_{74}	$a_1(1260)^+ a_1(1260)^-$	$< 3.2 \times 10^{-3}$	90%
Γ_{75}	$\pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^0$	< 1.1 %	90%
	Baryon modes		
Γ_{76}	$p \overline{p}$	$< 4 \times 10^{-5}$	90%
Γ_{77}	$p \overline{p} \pi^+ \pi^-$	$(6.0 \pm 3.0) \times 10^{-4}$	
Γ_{78}	$p \overline{\Lambda} \pi^-$	$< 2.0 \times 10^{-4}$	90%
Γ_{79}	$\Delta^0 \overline{\Delta}^0$	$< 1.8 \times 10^{-3}$	90%
Γ_{80}	$\Delta^{++} \Delta^{--}$	$< 1.3 \times 10^{-4}$	90%
	Lepton Family number (LF) violating, Flavor-Changing neutral current (FC), or decay via Mixing (MX) modes		
Γ_{81}	$e^+ e^-$ FC	$< 3 \times 10^{-5}$	90%
Γ_{82}	$\mu^+ \mu^-$ FC	$< 1.2 \times 10^{-5}$	90%
Γ_{83}	$K^0 e^+ e^-$ FC	$< 3.0 \times 10^{-4}$	90%
Γ_{84}	$K^0 \mu^+ \mu^-$ FC	$< 4.5 \times 10^{-4}$	90%
Γ_{85}	$K^*(892)^0 e^+ e^-$ FC	$< 2.9 \times 10^{-4}$	90%
Γ_{86}	$K^*(892)^0 \mu^+ \mu^-$ FC	$< 2.3 \times 10^{-5}$	90%
Γ_{87}	$e^{\pm} \mu^{\mp}$ LF	[b] $< 4 \times 10^{-5}$	90%
Γ_{88}	μ^- anything (via $\overline{B}^0$) MX		

Measurements which do not identify the charge state of B appear in the $B^{\pm}$ section.

[a] ℓ indicates e or μ mode, not sum over modes.

[b] The value is for the sum of the charge states indicated.

B^0 BRANCHING RATIOS

For branching ratios in which the charge of the decaying B is not determined, see the $B^{\pm}$ section.

$\Gamma(D^- \ell^+ \nu)/\Gamma_{\text{total}}$ Γ_1/Γ

ℓ denotes e or μ, not the sum.

VALUE	DOCUMENT ID		TECN	COMMENT
0.018±0.005 OUR AVERAGE				
0.018±0.006±0.003	[7] FULTON	91	CLEO	$e^+ e^- \to \Upsilon(4S)$
0.018±0.006±0.005	[8] ALBRECHT	89J	ARG	$e^+ e^- \to \Upsilon(4S)$

[7] FULTON 91 assumes equal production of B^0 and B^+ at the $\Upsilon(4S)$.

[8] ALBRECHT 89J assume e-μ universality, $B(D^{*+} \to D^0 \pi^+) = 57 \pm 4 \pm 4\%$, the Mark III D^0 and D^+ branching fractions, and $B(\Upsilon(4S) \to B^0 \overline{B}^0) = 45\%$. The measurement gives $V_{cb} = 0.044 \pm 0.009$ averaging different models.

$[\Gamma(D^*(2010)^- \mu^+ \nu_\mu) + \Gamma(D^*(2010)^- e^+ \nu_e)]/\Gamma_{\text{total}}$ $2\Gamma_2/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.098±0.015 OUR AVERAGE					
0.120±0.020±0.028		[9] ALBRECHT	89J	ARG	$e^+ e^- \to \Upsilon(4S)$
0.092±0.010±0.014		[10] BORTOLETTO	89B	CLEO	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[11] ALBRECHT	89C	ARG	$e^+ e^- \to \Upsilon(4S)$
0.140±0.024±0.038	47	[12] ALBRECHT	87J	ARG	$e^+ e^- \to \Upsilon(4S)$

[9] ALBRECHT 89J is ALBRECHT 87J value rescaled using $B(D^*(2010)^- \to D^0 \pi^-) = 0.57 \pm 0.04 \pm 0.04$.

[10] We have taken 2 times the BORTOLETTO 89B value to get the sum for electrons and muons. The measurement suggests a D^* polarization parameter value $\alpha = 0.65 \pm 0.66 \pm 0.25$. Assumes the $\Upsilon(4S)$ decays 50% to $B^0 \overline{B}^0$, $B(D^0 \to K^- \pi^+) = 4.2 \pm 0.4 \pm 0.4\%$, $B(D^0 \to K^- \pi^+ \pi^- \pi^+) = 9.1 \pm 1.3 \pm 0.4\%$, and $B(D^{*+} \to D^0 \pi^+) = 57 \pm 4 \pm 4\%$.

[11] The measurement of ALBRECHT 89C suggests a D^* polarization γ_L/γ_T of 0.85 ± 0.45. or $\alpha = 0.7 \pm 0.9$.

[12] ALBRECHT 87J assume μ-e universality, the $B(\Upsilon(4S) \to B^0 \overline{B}^0) = 0.45$, the $B(D^0 \to K^- \pi^+) = (0.042 \pm 0.004 \pm 0.004)$, and the $B(D^*(2010)^- \to D^0 \pi^-) = 0.49 \pm 0.08$. Superseded by ALBRECHT 89J.

$\Gamma(\pi^- \mu^+ \nu_\mu)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE	DOCUMENT ID	TECN
seen	[13] ALBRECHT 91C	ARG

[13] In ALBRECHT 91C, one event is fully reconstructed providing evidence for the $b \to u$ transition.

$\Gamma(D^- \pi^+)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0032±0.0007 OUR AVERAGE				
0.0027±0.0006±0.0005		[14] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0048±0.0011±0.0011	22	ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
$0.0051^{+0.0028+0.0013}_{-0.0025-0.0012}$	4	[15] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0031±0.0013±0.0010	7	[16] ALBRECHT 88K	ARG	$e^+e^- \to \Upsilon(4S)$

[14] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.
[15] BEBEK 87 value has been updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92.
[16] ALBRECHT 88K assumes $B^0\overline{B}^0$:B^+B^- production ratio is 45:55. Superseded by ALBRECHT 90J.

$\Gamma(D^- \rho^+)/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.009±0.005±0.003	9	ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.022±0.012±0.009	6	[17] ALBRECHT 88K	ARG	$e^+e^- \to \Upsilon(4S)$

[17] ALBRECHT 88K assumes $B^0\overline{B}^0$:B^+B^- production ratio is 45:55. Superseded by ALBRECHT 90J.

$\Gamma(\overline{D}^0 \pi^+ \pi^-)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.007	90		[18] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.039	90		[19] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$
0.09 ±0.06		5	[20] BEHRENDS 83	CLEO	$e^+e^- \to \Upsilon(4S)$

[18] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D. The product branching fraction into $D_0^*(2340)\pi$ followed by $D_0^*(2340) \to D^0\pi$ is <0.0001 at 90% CL and into $D_2^*(2460)$ followed by $D_2^*(2460) \to D^0\pi$ is < 0.0004 at 90% CL.
[19] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. $B(D^0 \to K^-\pi^+) = (4.2 \pm 0.4 \pm 0.4)\%$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-) = (9.1 \pm 0.8 \pm 0.8)\%$ were used.
[20] Corrected by us using assumptions: $B(D^0 \to K^-\pi^+) = (0.042 \pm 0.006)$ and $B(\Upsilon(4S) \to B^0\overline{B}^0) = 0.40 \pm 0.02$. The product branching ratio is $B(B^0 \to \overline{D}^0\pi^+\pi^-)B(\overline{D}^0 \to K^+\pi^-) = (0.39 \pm 0.26) \times 10^{-2}$

$\Gamma(\overline{D}^0 \rho^0)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.0006	90		[21] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.003	90	4	[22] ALBRECHT 88K	ARG	$e^+e^- \to \Upsilon(4S)$

[21] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.
[22] ALBRECHT 88K assumes $B^0\overline{B}^0$:B^+B^- production ratio is 45:55.

$\Gamma(D^*(2010)^- \pi^+)/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0032±0.0007 OUR AVERAGE				
0.0040±0.0010±0.0007		[23] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0028±0.0009±0.0006	12	[24] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
$0.0028^{+0.0015+0.0010}_{-0.0012-0.0006}$	5	[25] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0027±0.0014±0.0010	5	[26] ALBRECHT 87C	ARG	$e^+e^- \to \Upsilon(4S)$
0.0035±0.002 ±0.002		[27] ALBRECHT 86F	ARG	$e^+e^- \to \Upsilon(4S)$
0.017 ±0.005 ±0.005	41	[28] GILES 84	CLEO	$e^+e^- \to \Upsilon(4S)$

[23] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.
[24] ALBRECHT 90J assume $B(D^*(2010)^+ \to D^0\pi^+) = (57 \pm 6)\%$.
[25] BEBEK 87 value has been updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92.
[26] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume $B(\Upsilon(4S) \to B^+B^-) = 55\%$ and $B(\Upsilon(4S) \to B^0\overline{B}^0) = 45\%$. Superseded by ALBRECHT 90J.
[27] ALBRECHT 86F uses pseudomass that is independent of D^0 and D^+ branching ratios.
[28] Assumes $B(D^*(2010)^+ \to D^0\pi^+) = 0.60^{+0.08}_{-0.15}$. Assumes $B(\Upsilon(4S) \to B^0\overline{B}^0) = 0.40 \pm 0.02$ Does not depend on D branching ratios.

$\Gamma(D^- \pi^+ \pi^+ \pi^-)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0080±0.0021±0.0014	[29] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[29] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma((D^- \pi^+ \pi^+ \pi^-)\ \text{nonresonant})/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0039±0.0014±0.0013	[30] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[30] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(D^- \pi^+ \rho^0)/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0011±0.0009±0.0004	[31] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[31] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(D^- a_1(1260)^+)/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0060±0.0022±0.0024	[32] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[32] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(D^*(2010)^- \pi^+ \pi^0)/\Gamma_{\text{total}}$ — Γ_{14}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.018±0.004±0.005	51	[33] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.015±0.008±0.008	8	[34] ALBRECHT 87C	ARG	$e^+e^- \to \Upsilon(4S)$

[33] ALBRECHT 90J assume $B(D^*(2010)^+ \to D^0\pi^+) = (57 \pm 6)\%$.
[34] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume $B(\Upsilon(4S) \to B^+B^-) = 55\%$ and $B(\Upsilon(4S) \to B^0\overline{B}^0) = 45\%$. Superseded by ALBRECHT 90J.

$\Gamma(D^*(2010)^- \rho^+)/\Gamma_{\text{total}}$ — Γ_{15}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.008±0.004 OUR AVERAGE				
0.019±0.008±0.011		[35] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.007±0.003±0.003	19	[36] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.081\pm0.029^{+0.059}_{-0.024}$	19	[37] CHEN 85	CLEO	$e^+e^- \to \Upsilon(4S)$

[35] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.
[36] ALBRECHT 90J assume $B(D^*(2010)^+ \to D^0\pi^+) = (57 \pm 6)\%$.
[37] Uses $B(D^* \to D^0\pi^+) = 0.6 \pm 0.15$ and $B(\Upsilon(4S) \to B^0\overline{B}^0) = 0.4$. Does not depend on D branching ratios.

$\Gamma(D^*(2010)^- \pi^+ \pi^+ \pi^-)/\Gamma_{\text{total}}$ — Γ_{16}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.0141±0.0034 OUR AVERAGE					
0.0159±0.0028±0.0037			[38] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.012 ±0.003 ±0.004		26	[39] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.033 ±0.009 ±0.016		27	[40] ALBRECHT 87C	ARG	$e^+e^- \to \Upsilon(4S)$
<0.042	90		[41] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[38] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.
[39] ALBRECHT 90J assume $B(D^*(2010)^+ \to D^0\pi^+) = (57 \pm 6)\%$.
[40] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume $B(\Upsilon(4S) \to B^+B^-) = 55\%$ and $B(\Upsilon(4S) \to B^0\overline{B}^0) = 45\%$. Superseded by ALBRECHT 90J.
[41] BEBEK 87 value has been updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92.

$\Gamma((D^*(2010)^- \pi^+ \pi^+ \pi^-)\ \text{nonresonant})/\Gamma_{\text{total}}$ — Γ_{17}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0000±0.0019±0.0016	[42] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[42] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.

$\Gamma(D^*(2010)^- \pi^+ \rho^0)/\Gamma_{\text{total}}$ — Γ_{18}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0068±0.0032±0.0021	[43] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[43] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.

$\Gamma(D^*(2010)^- a_1(1260)^+)/\Gamma_{\text{total}}$ — Γ_{19}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.018±0.006±0.006	[44] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[44] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.

$\Gamma(D^*(2010)^- \pi^+ \pi^+ \pi^- \pi^0)/\Gamma_{\text{total}}$ — Γ_{20}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.041±0.015±0.016	28	[45] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$

[45] ALBRECHT 90J assume $B(D^*(2010)^+ \to D^0\pi^+) = (57 \pm 6)\%$.

$\Gamma(D^- D_s^+)/\Gamma_{total}$ — Γ_{21}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0080±0.0045±0.0030		[46] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.012 ±0.007	3	[47] BORTOLETTO90	CLEO	$e^+e^- \to \Upsilon(4S)$

[46] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D. The branching fraction for $D_s \to \phi\pi^+$ is taken as 0.030 ± 0.011.
[47] BORTOLETTO 90 assume B($D_s \to \phi\pi^+$) = 2%. Superseded by BORTOLETTO 92.

$\Gamma(D^*(2010)^- D_s^+)/\Gamma_{total}$ — Γ_{22}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.016±0.009±0.006		[48] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.024±0.014	3	[49] BORTOLETTO90	CLEO	$e^+e^- \to \Upsilon(4S)$

[48] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$. The branching fraction for $D_s \to \phi\pi^+$ is taken as 0.030 ± 0.011.
[49] BORTOLETTO 90 assume B($D_s \to \phi\pi^+$) = 2%. Superseded by BORTOLETTO 92.

$[\Gamma(D^*(2010)^- D_s^+) + \Gamma(D^*(2010)^- D_s^{*+})]/\Gamma_{total}$ — $(\Gamma_{22}+\Gamma_{23})/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
7.5±2.0	22	[50] BORTOLETTO90	CLEO	$e^+e^- \to \Upsilon(4S)$

[50] BORTOLETTO 90 assume B($D_s \to \phi\pi^+$) = 2%.

$\Gamma(\pi^- D_s^+)/\Gamma_{total}$ — Γ_{24}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0013	90	[51] BORTOLETTO90	CLEO	$e^+e^- \to \Upsilon(4S)$

[51] BORTOLETTO 90 assume B($D_s \to \phi\pi^+$) = 2%.

$\Gamma(K^+ D_s^-)/\Gamma_{total}$ — Γ_{25}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0013	90	[52] BORTOLETTO90	CLEO	$e^+e^- \to \Upsilon(4S)$

[52] BORTOLETTO 90 assume B($D_s \to \phi\pi^+$) = 2%.

$\Gamma(J/\psi(1S) K^0)/\Gamma_{total}$ — Γ_{26}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
(6.5 ±3.1) × 10^{-4} OUR AVERAGE					
0.0006±0.0003±0.0002			[53] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0008±0.0006±0.0002		2	ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.005	90		ALAM 86	CLEO	$e^+e^- \to \Upsilon(4S)$

[53] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(J/\psi(1S) K^+\pi^-)/\Gamma_{total}$ — Γ_{27}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.0010±0.0004±0.0003			[54] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0013	90		[55] ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$
<0.0063	90	2	GILES 84	CLEO	$e^+e^- \to \Upsilon(4S)$

[54] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.
[55] ALBRECHT 87D assume $B^+B^-/B^0\overline{B}^0$ ratio is 55/45. $K\pi$ system is specifically selected as nonresonant.

$\Gamma(J/\psi(1S) K^*(892)^0)/\Gamma_{total}$ — Γ_{28}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0013±0.0004 OUR AVERAGE				
0.0011±0.0005±0.0003		[56] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0040±0.0030		[57] ALBAJAR 91E	UA1	$E_{cm}^{p\overline{p}}$= 630 GeV
0.0011±0.0005±0.0002	6	ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
0.0035±0.0016±0.0003	5	[58] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0033±0.0018	5	[59] ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$
0.0041±0.0018	5	[60] ALAM 86	CLEO	Repl. by BEBEK 87

[56] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.
[57] ALBAJAR 91E assumes B_d^0 production fraction of 36%.
[58] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.
[59] ALBRECHT 87D assume $B^+B^-/B^0\overline{B}^0$ ratio is 55/45. Superseded by ALBRECHT 90J.
[60] ALAM 86 assumes $B^\pm/B^0$ ratio is 60/40. The observation of the decay $B^+ \to J/\psi K^*(892)^+$ (HAAS 85) has been retracted in this paper.

$\Gamma(\psi(2S) K^0)/\Gamma_{total}$ — Γ_{29}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0015	90	[61] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0028	90	ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$

[61] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(\psi(2S) K^+\pi^-)/\Gamma_{total}$ — Γ_{30}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.001	90	ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\psi(2S) K^*(892)^0)/\Gamma_{total}$ — Γ_{31}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
0.0014±0.0008±0.0004		[62] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0023	90	ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$

[62] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(K^+\pi^-)/\Gamma_{total}$ — Γ_{32}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<9 × 10^{-5}	90	[63] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.8 × 10^{-4}	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$
<3.2 × 10^{-4}	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[63] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^0\pi^+\pi^-)/\Gamma_{total}$ — Γ_{33}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<4.4 × 10^{-4}	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^0\rho^0)/\Gamma_{total}$ — Γ_{34}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<3.2 × 10^{-4}	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<5.8 × 10^{-4}	90	[64] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.08	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[64] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^0 K^+ K^-)/\Gamma_{total}$ — Γ_{38}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.3 × 10^{-3}	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^0\phi)/\Gamma_{total}$ — Γ_{39}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<4.9 × 10^{-4}	90	[65] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<7.2 × 10^{-4}	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$
<1.3 × 10^{-3}	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[65] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^0 f_0(975))/\Gamma_{total}$ — Γ_{35}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<4.2 × 10^{-4}	90	[66] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$

[66] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^*(892)^+\pi^-)/\Gamma_{total}$ — Γ_{36}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<4.4 × 10^{-4}	90	[67] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<6.2 × 10^{-4}	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$
<7 × 10^{-4}	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[67] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^*(892)^0\pi^+\pi^-)/\Gamma_{total}$ — Γ_{40}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.4 × 10^{-3}	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^0\rho^0)/\Gamma_{total}$ — Γ_{41}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<4.6 × 10^{-4}	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<6.7 × 10^{-4}	90	[68] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<1.2 × 10^{-3}	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[68] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^*(892)^0 K^+ K^-)/\Gamma_{total}$ — Γ_{44}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<6.1 × 10^{-4}	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^0\phi)/\Gamma_{total}$ — Γ_{45}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<3.2 × 10^{-4}	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<4.4 × 10^{-4}	90	[69] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<4.7 × 10^{-4}	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[69] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

B^0 REFERENCES

ALBRECHT 92C PL B275 195 +Erlichmann, Hamacher, Krueger, Nau+ (ARGUS Collab.)
BORTOLETTO 92 PR D45 21 +Brown, Dominick, McIlwain, Miller+ (CLEO Collab.)
ABE 91G PRL 67 3351 +Amidei, Apollinari, Atac, Auchincloss+ (CDF Collab.)
ALBAJAR 91C PL B262 163 +Albrow, Allkofer, Ankoviak, Apsimon+ (UA1 Collab.)
ALBAJAR 91D PL B262 171 +Albrow, Allkofer, Ankoviak, Apsimon+ (UA1 Collab.)
ALBAJAR 91E PL B273 540 +Albrow, Allkofer, Ankoviak+ (UA1 Collab.)
ALBRECHT 91B PL B254 288 +Glaeser, Harder, Krueger, Nippe+ (ARGUS Collab.)
ALBRECHT 91C PL B255 297 +Ehrlichmann, Glaeser, Harder, Krueger+ (ARGUS Collab.)
ALBRECHT 91E PL B262 148 +Glaeser, Harder, Krueger, Nippe+ (ARGUS Collab.)
BERKELMAN 91 ARNPS 41 1 +Stone (CORN, SYRA)
"Decays of *B* Mesons"
DECAMP 91 PL B258 236 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
FULTON 91 PR D43 651 +Jensen, Johnson, Kagan, Kass+ (CLEO Collab.)
ADEVA 90P PL B252 703 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ALBRECHT 90B PL B241 278 +Glaeser, Harder, Krueger, Nilsson+ (ARGUS Collab.)
ALBRECHT 90J ZPHY C48 543 +Ehrlichmann, Harder, Krueger+ (ARGUS Collab.)
BORTOLETTO 90 PRL 64 2117 +Goldberg, Horwitz, Jain, Mestayer+ (CLEO Collab.)
ELSEN 90 ZPHY C46 349 +Allison, Ambrus, Barlow, Bartel+ (JADE Collab.)
WEIR 90 PL B240 289 +Abrams, Adolphsen, Alexander, Alvarez+ (Mark II Collab.)
ALBRECHT 89C PL B219 121 +Boeckmannn, Glaeser, Harder+ (ARGUS Collab.)
ALBRECHT 89G PL B229 304 +Glaeser, Harder, Krueger+ (ARGUS Collab.)
ALBRECHT 89J PL B229 175 +Glaser, Harder+ (ARGUS Collab.)
ALBRECHT 89L PL B232 554 +Glaeser, Harder, Krueger, Nippe, Oest+ (ARGUS Collab.)
ARTUSO 89 PRL 62 2233 +Bebek, Berkelman, Blucher+ (CLEO Collab.)
AVERY 89B PL B223 470 +Besson, Garren, Yelton+ (CLEO Collab.)
BORTOLETTO 89 PRL 62 2436 +Goldberg, Horwitz, Mestayer+ (CLEO Collab.)
BORTOLETTO 89B PRL 63 1667 +Goldberg, Horwitz, Mestayer+ (CLEO Collab.)
ALBRECHT 88F PL B209 119 +Boeckmann, Glaeser+ (ARGUS Collab.)
ALBRECHT 88K PL B215 424 +Boeckmann, Glaeser+ (ARGUS Collab.)
BAND 88 PL B200 221 +Camporesi, Chadwick+ (MAC Collab.)
ALBAJAR 87C PL B186 247 +Albrow, Allkofer, Arnison+ (UA1 Collab.)
ALBRECHT 87C PL B185 218 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
ALBRECHT 87D PL B199 451 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
ALBRECHT 87I PL B192 245 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
ALBRECHT 87J PL B197 452 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
AVERY 87 PL B183 429 +Besson, Bowcock, Giles+ (CLEO Collab.)
BEAN 87B PRL 58 183 +Bobbink, Brock, Engler+ (CLEO Collab.)
BEBEK 87 PR D36 1289 +Berkelman, Blucher, Cassel+ (CLEO Collab.)
ALAM 86 PR D34 3279 +Katayama, Kim, Sun+ (CLEO Collab.)
ALBRECHT 86F PL B182 95 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
PDG 86 PL 170B Aguilar-Benitez, Porter+ (CERN, CIT+)
CHEN 85 PR D31 2386 +Goldberg, Horwitz, Jawahery+ (CLEO Collab.)
HAAS 85 PRL 55 1248 +Hempstead, Jensen, Kagan+ (CLEO Collab.)
SCHAAD 85 PL 160B 188 +Nelson, Abrams, Amidei+ (Mark II Collab.)
AVERY 84 PRL 53 1309 +Bebek, Berkelman, Cassel+ (CLEO Collab.)
GILES 84 PR D30 2279 +Hassard, Hempstead, Kinoshita+ (CLEO Collab.)
BEHRENDS 83 PRL 50 881 +Chadwick, Chauveau, Ganci+ (CLEO Collab.)

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SCHUBERT 87 IHEP-HD/87-7 (HEID)
EPS Conference – Uppsala, Proc., Vol. 2, p. 791

B^*

$I(J^P) = \frac{1}{2}(1^-)$

I, *J*, *P* need confirmation. Quantum numbers shown are quark-model predictions.

B^* MASS

From mass difference below and the average of our *B* masses $(m(B^{\pm})+m(B^0))/2$.

VALUE (MeV)	DOCUMENT ID
5324.6±2.1 OUR FIT	

$B^* - B$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
46.0±0.6 OUR FIT					
46.0±0.6 OUR AVERAGE					
46.2±0.3±0.8		[1] AKERIB	91	CLE2	$e^+e^- \to \gamma X$
45.4±1.0		[2] LEE-FRANZINI	90	CSB2	$e^+e^- \to \Upsilon(5S)$
52.0±2. ±4.	1400	HAN	85	CUSB	$e^+e^- \to \gamma e X$

[1] Admixture of B^0 and B^+.
[2] This value is for an admixture of B^0 and B^+. LEE-FRANZINI 90 measure 46.7 ± 0.4 ± 0.2 MeV for an admixture of B^0, B^+, and B_s. They use the shape of the photon line to separate the above value.

B^* REFERENCES

AKERIB 91 PRL 67 1692 +Barish, Cown, Eigen, Stroynowski+ (CLEO II Collab.)
LEE-FRANZINI 90 PRL 65 2947 +Heintz, Lovelock, Narain, Schamberger+ (CUSB-II Collab.)
HAN 85 PRL 55 36 +Klopfenstein, Mageras+ (COLU, LSU, MPIM, STON)

B^0_s

$I(J^P) = ?(?^?)$
I, *J*, *P* need confirmation.

OMITTED FROM SUMMARY TABLE

$B^0_s - B$ MASS DIFFERENCE

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
80 to 130	68	LEE-FRANZINI	90	CSB2	$e^+e^- \to \Upsilon(5S)$

B^0_s DECAY MODES

	Mode
Γ_1	μ^+ anything
	Decay via mixing modes (MX)
Γ_2	μ^- anything (via $\overline{B}^0_s$)

B^0_s BRANCHING RATIOS

$\Gamma(\mu^-$ anything (via $\overline{B}^0_s))/\Gamma(\mu^\pm$ anything) $\Gamma_2/(\Gamma_1+\Gamma_2)$

This is χ_S, a measure of B^0_s–$\overline{B}^0_s$ mixing. Violates $\Delta B \neq 2$ rule.

VALUE	DOCUMENT ID		TECN
0.53±0.15	[1] ALBAJAR	91D	RVUE

[1] From combination of UA1 (ALBAJAR 91D), CLEO (BEAN 87B), ARGUS (ALBRECHT 87I), ALEPH (DECAMP 91), and L3 (ADEVA 90P). Corresponding limits are > 0.23 at 95% CL and > 0.27 at 90% CL.

B^0_s REFERENCES

ALBAJAR 91D PL B262 171 +Albrow, Allkofer, Ankoviak, Apsimon+ (UA1 Collab.)
DECAMP 91 PL B258 236 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
ADEVA 90P PL B252 703 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
LEE-FRANZINI 90 PRL 65 2947 +Heintz, Lovelock, Narain, Schamberger+ (CUSB-II Collab.)
ALBRECHT 87I PL B192 245 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
BEAN 87B PRL 58 183 +Bobbink, Brock, Engler+ (CLEO Collab.)

B^*_s

$I(J^P) = ?(?^?)$
I, *J*, *P* need confirmation.

OMITTED FROM SUMMARY TABLE

$B^*_s - B_s$ MASS DIFFERENCE

VALUE	DOCUMENT ID		TECN	COMMENT
47.0±2.6	[1] LEE-FRANZINI	90	CSB2	$e^+e^- \to \Upsilon(5S)$

[1] LEE-FRANZINI 90 measure 46.7 ± 0.4 ± 0.2 MeV for an admixture of B^0, B^+, and B_s. They use the shape of the photon line to separate the above value for B_s.

B^*_s REFERENCES

LEE-FRANZINI 90 PRL 65 2947 +Heintz, Lovelock, Narain, Schamberger+ (CUSB-II Collab.)

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-)/\Gamma_{total}$ — Γ_{73}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<3.0 × 10⁻³	90	[92] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[92] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^+ a_1(1260)^-)/\Gamma_{total}$ — Γ_{74}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<3.2 × 10⁻³	90	[93] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<6.0 × 10⁻³	90	[94] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[93] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.
[94] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0)/\Gamma_{total}$ — Γ_{75}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.1 × 10⁻²	90	[95] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[95] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(p\overline{p})/\Gamma_{total}$ — Γ_{76}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<4 × 10⁻⁵	90	[96] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.3 × 10⁻⁴	90	ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$
<2 × 10⁻⁴	90	[96] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[96] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(p\overline{p}\pi^+\pi^-)/\Gamma_{total}$ — Γ_{77}/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
6.0±2.0±2.2	ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(p\overline{\Lambda}\pi^-)/\Gamma_{total}$ — Γ_{78}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<2.0 × 10⁻⁴	90	ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\Delta^0\overline{\Delta}^0)/\Gamma_{total}$ — Γ_{79}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0018	90	[97] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$

[97] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\Delta^{++}\Delta^{--})/\Gamma_{total}$ — Γ_{80}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.3 × 10⁻⁴	90	[98] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$

[98] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_{81}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<3 × 10⁻⁵	90	[99] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<8.5 × 10⁻⁵	90	ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$
<8 × 10⁻⁵	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$
<3 × 10⁻⁴	90	GILES 84	CLEO	Repl. by AVERY 87

[99] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ — Γ_{82}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.2 × 10⁻⁵	90	[100] ALBAJAR 91C	UA1	$E_{cm}^{p\overline{p}}$= 540 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<8.3 × 10⁻⁶	90	[101] ALBAJAR 91C	UA1	$E_{cm}^{p\overline{p}}$= 540 GeV
<5 × 10⁻⁵	90	[102] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<5 × 10⁻⁵	90	ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$
<9 × 10⁻⁵	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$
<2 × 10⁻⁴	90	GILES 84	CLEO	Repl. by AVERY 87

[100] Obtained from unseparated B^0 and B_s^0 measurement by assuing a B^0:B_s^0 ratio 2:1.
[101] B^0 and B_s^0 are not separated.
[102] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^0e^+e^-)/\Gamma_{total}$ — Γ_{83}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<3.0 × 10⁻⁴	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<6.5 × 10⁻⁴	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^0\mu^+\mu^-)/\Gamma_{total}$ — Γ_{84}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<4.5 × 10⁻⁴	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<5.2 × 10⁻⁴	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^0e^+e^-)/\Gamma_{total}$ — Γ_{85}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<2.9 × 10⁻⁴	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^0\mu^+\mu^-)/\Gamma_{total}$ — Γ_{86}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<2.3 × 10⁻⁵	90	[103] ALBAJAR 91C	UA1	$E_{cm}^{p\overline{p}}$= 540 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<3.4 × 10⁻⁴	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$

[103] ALBAJAR 91C assumes 36% of $\overline{b}$ quarks give B^0 mesons.

$\Gamma(e^\pm\mu^\mp)/\Gamma_{total}$ — Γ_{87}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<4 × 10⁻⁵	90	[104] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<5 × 10⁻⁵	90	ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$
<9 × 10⁻⁵	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$
<3 × 10⁻⁴	90	GILES 84	CLEO	Repl. by AVERY 87

[104] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\mu^-\text{ anything (via }\overline{B}^0))/\Gamma(\mu^\pm\text{ anything})$ — $\Gamma_{88}/(\Gamma_3+\Gamma_{88})$

This is a B^0-$\overline{B}^0$ mixing measurement. Violates $\Delta B \neq 2$ rule. Two different variables, χ and r, are used. We have converted all results to χ.

$$\chi = \Gamma(B \to \mu^- X)/\Gamma(B \to \mu^\pm X)$$
$$= \Gamma(\overline{B} \to \mu^+ X)/\Gamma(\overline{B} \to \mu^\pm X)$$

or $r = \chi/(1-\chi)$.

Note that the experiments other than those at the $\Upsilon(4S)$ have not separated χ_d from χ_s where the subscripts indicate $B^0(\overline{b}d)$ or $B_s^0(\overline{b}s)$, so they are not included in the average.

The experiments at $\Upsilon(4S)$ make an assumption about the $B^0\overline{B}^0$ fraction and about the ratio of the $B^\pm$ and B^0 semileptonic branching ratios (usually that it equals one).

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.16 ±0.04 OUR AVERAGE					
$0.158^{+0.052}_{-0.059}$			[105] ARTUSO 89	CLEO	$e^+e^- \to \Upsilon(4S)$
0.17 ±0.05			[106] ALBRECHT 87I	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.176±0.031±0.032		1112	[107] ABE 91G	CDF	$p\overline{p}$ 1.8 TeV
0.148±0.029±0.017			[108] ALBAJAR 91D	UA1	$p\overline{p}$ 540 GeV
$0.132\pm0.22\ ^{+0.015}_{-0.012}$		823	[109] DECAMP 91	ALPH	e^+e^- 91.31 GeV
$0.178^{+0.049}_{-0.040}\pm0.020$			[110,111] ADEVA 90P	L3	e^+e^- Z peak
0.24 ±0.12			[111] ELSEN 90	JADE	e^+e^- 35–44 GeV
$0.17\ ^{+0.15}_{-0.08}$			[111,112] WEIR 90	MRK2	e^+e^- 29 GeV
$0.21\ ^{+0.29}_{-0.15}$			[111] BAND 88	MAC	E_{cm}^{ee}= 29 GeV
>0.02	90		[111] BAND 88	MAC	E_{cm}^{ee}= 29 GeV
0.121±0.047			[111,113] ALBAJAR 87C	UA1	Repl. by ALBAJAR 91D
<0.19	90		[114] BEAN 87B	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.12	90		[111,115] SCHAAD 85	MRK2	E_{cm}^{ee}= 29 GeV
<0.27	90		[116] AVERY 84	CLEO	$e^+e^- \to \Upsilon(4S)$

[105] χ is calculated as $r/(1+r)$. They also give $\Delta m/\Gamma = 0.69 \pm 0.17$. The authors take the B^+B^- fraction as 55% of the $\Upsilon(4S)$. The measurement is an average of $\mu\mu$, μe, and ee events.
[106] ALBRECHT 87I is inclusive measurement with like-sign dileptons, with tagged B decays plus leptons, and one fully reconstructed event. Measures r=0.21 ± 0.08. We convert to χ for comparison.
[107] ABE 91G value for χ is unknown admixture of B hadrons and is not included in the average. The measurement is done with $e\mu$ and ee events.
[108] ALBAJAR 91D value for χ is unknown admixture of B_d^0 and B_s^0 hadrons and is not included in the average. The measurement is done with dimuons.
[109] DECAMP 91 value for χ is unknown admixture of B_d^0 and B_s^0 hadrons and is not included in the average. The measurement is done with opposite and like-sign dileptons.
[110] ADEVA 90P measurement uses ee, $\mu\mu$, and $e\mu$ events from 118k events at the Z.
[111] These experiments see a combination of B_s and B_d mesons.
[112] The WEIR 90 measurement supersedes the limit obtained in SCHAAD 85. The 90% CL are 0.06 and 0.38.
[113] ALBAJAR 87C measured $\chi = (\overline{B}^0 \to B^0 \to \mu^+ X)$ divided by the average production weighted semileptonic branching fraction for B hadrons at 546 and 630 GeV.
[114] BEAN 87B measured $r <$ 0.24; we converted to χ.
[115] Limit is average probability for hadron containing B quark to produce a positive lepton.
[116] Same-sign dilepton events. Limit assumes semileptonic BR for B^+ and B^0 equal. If $B^0/B^\pm$ ratio <0.58, no limit exists. The limit was corrected in BEAN 87B from $r <$ 0.30 to $r <$ 0.37. We converted this limit to χ.

B^0 REFERENCES

ALBRECHT 92C PL B275 195 +Erlichmann, Hamacher, Krueger, Nau+ (ARGUS Collab.)
BORTOLETTO 92 PR D45 21 +Brown, Dominick, McIlwain, Miller+ (CLEO Collab.)
ABE 91G PRL 67 3351 +Amidei, Apollinari, Atac, Auchincloss+ (CDF Collab.)
ALBAJAR 91C PL B262 163 +Albrow, Allkofer, Ankoviak, Apsimon+ (UA1 Collab.)
ALBAJAR 91D PL B262 171 +Albrow, Allkofer, Ankoviak, Apsimon+ (UA1 Collab.)
ALBAJAR 91E PL B273 540 +Albrow, Allkofer, Ankoviak+ (UA1 Collab.)
ALBRECHT 91B PL B254 288 +Glaeser, Harder, Krueger, Nippe+ (ARGUS Collab.)
ALBRECHT 91C PL B255 297 +Ehrlichmann, Glaeser, Harder, Krueger+ (ARGUS Collab.)
ALBRECHT 91E PL B262 148 +Glaeser, Harder, Krueger, Nippe+ (ARGUS Collab.)
BERKELMAN 91 ARNPS 41 1 +Stone (CORN, SYRA)
"Decays of *B* Mesons"
DECAMP 91 PL B258 236 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
FULTON 91 PR D43 651 +Jensen, Johnson, Kagan, Kass+ (CLEO Collab.)
ADEVA 90P PL B252 703 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ALBRECHT 90B PL B241 278 +Glaeser, Harder, Krueger, Nilsson+ (ARGUS Collab.)
ALBRECHT 90J ZPHY C48 543 +Ehrlichmann, Harder, Krueger+ (ARGUS Collab.)
BORTOLETTO 90 PRL 64 2117 +Goldberg, Horwitz, Jain, Mestayer+ (CLEO Collab.)
ELSEN 90 ZPHY C46 349 +Allison, Ambrus, Barlow, Bartel+ (JADE Collab.)
WEIR 90 PL B240 289 +Abrams, Adolphsen, Alexander, Alvarez+ (Mark II Collab.)
ALBRECHT 89C PL B219 121 +Boeckmannn, Glaeser, Harder+ (ARGUS Collab.)
ALBRECHT 89G PL B229 304 +Glaeser, Harder, Krueger+ (ARGUS Collab.)
ALBRECHT 89J PL B229 175 +Glaser, Harder+ (ARGUS Collab.)
ALBRECHT 89L PL B232 554 +Glaeser, Harder, Krueger, Nippe, Oest+ (ARGUS Collab.)
ARTUSO 89 PRL 62 2233 +Bebek, Berkelman, Blucher+ (CLEO Collab.)
AVERY 89B PL B223 470 +Besson, Garren, Yelton+ (CLEO Collab.)
BORTOLETTO 89 PRL 62 2436 +Goldberg, Horwitz, Mestayer+ (CLEO Collab.)
BORTOLETTO 89B PRL 63 1667 +Goldberg, Horwitz, Mestayer+ (CLEO Collab.)
ALBRECHT 88F PL B209 119 +Boeckmann, Glaeser+ (ARGUS Collab.)
ALBRECHT 88K PL B215 424 +Boeckmann, Glaeser+ (ARGUS Collab.)
BAND 88 PL B200 221 +Camporesi, Chadwick+ (MAC Collab.)
ALBAJAR 87C PL B186 247 +Albrow, Allkofer, Arnison+ (UA1 Collab.)
ALBRECHT 87C PL B185 218 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
ALBRECHT 87D PL B199 451 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
ALBRECHT 87I PL B192 245 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
ALBRECHT 87J PL B197 452 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
AVERY 87 PL B183 429 +Besson, Bowcock, Giles+ (CLEO Collab.)
BEAN 87B PRL 58 183 +Bobbink, Brock, Engler+ (CLEO Collab.)
BEBEK 87 PR D36 1289 +Berkelman, Blucher, Cassel+ (CLEO Collab.)
ALAM 86 PR D34 3279 +Katayama, Kim, Sun+ (CLEO Collab.)
ALBRECHT 86F PL B182 95 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
PDG 86 PL 170B Aguilar-Benitez, Porter+ (CERN, CIT+)
CHEN 85 PR D31 2386 +Goldberg, Horwitz, Jawahery+ (CLEO Collab.)
HAAS 85 PRL 55 1248 +Hempstead, Jensen, Kagan+ (CLEO Collab.)
SCHAAD 85 PL 160B 188 +Nelson, Abrams, Amidei+ (Mark II Collab.)
AVERY 84 PRL 53 1309 +Bebek, Berkelman, Cassel+ (CLEO Collab.)
GILES 84 PR D30 2279 +Hassard, Hempstead, Kinoshita+ (CLEO Collab.)
BEHRENDS 83 PRL 50 881 +Chadwick, Chauveau, Ganci+ (CLEO Collab.)

OTHER RELATED PAPERS

BERKELMAN 91 ARNPS 41 1 +Stone (CORN, SYRA)
"Decays of *B* Mesons"
MILLER 90 MPL A5 2683
"Recent Results in *B* Physics"
SCHINDLER 88 High Energy Electron-Positron Physics 234 (SLAC)
Editors: A. Ali and P. Soeding, World Scientific, Singapore
SCHUBERT 87 IHEP-HD/87-7 (HEID)
EPS Conference – Uppsala, Proc., Vol. 2, p. 791

B^*

$I(J^P) = \frac{1}{2}(1^-)$

I, *J*, *P* need confirmation. Quantum numbers shown are quark-model predictions.

B^* MASS

From mass difference below and the average of our *B* masses $(m(B^{\pm})+m(B^0))/2$.

VALUE (MeV)	DOCUMENT ID
5324.6±2.1 OUR FIT	

B^* – B MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
46.0±0.6 OUR FIT					
46.0±0.6 OUR AVERAGE					
46.2±0.3±0.8		[1] AKERIB	91	CLE2	$e^+e^- \rightarrow \gamma X$
45.4±1.0		[2] LEE-FRANZINI	90	CSB2	$e^+e^- \rightarrow \Upsilon(5S)$
52.0±2. ±4.	1400	HAN	85	CUSB	$e^+e^- \rightarrow \gamma e X$

[1] Admixture of B^0 and B^+.
[2] This value is for an admixture of B^0 and B^+. LEE-FRANZINI 90 measure 46.7 ± 0.4 ± 0.2 MeV for an admixture of B^0, B^+, and B_s. They use the shape of the photon line to separate the above value.

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HAN 85 PRL 55 36 +Klopfenstein, Mageras+ (COLU, LSU, MPIM, STON)

B_s^0

$I(J^P) = ?(?^?)$
I, *J*, *P* need confirmation.

OMITTED FROM SUMMARY TABLE

B_s^0 – B MASS DIFFERENCE

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
80 to 130	68	LEE-FRANZINI 90	CSB2	$e^+e^- \rightarrow \Upsilon(5S)$

B_s^0 DECAY MODES

	Mode
Γ_1	μ^+ anything
	Decay via mixing modes (MX)
Γ_2	μ^- anything (via $\overline{B}_s^0$)

B_s^0 BRANCHING RATIOS

$\Gamma(\mu^-$ anything (via $\overline{B}_s^0))/\Gamma(\mu^{\pm}$ anything) $\Gamma_2/(\Gamma_1+\Gamma_2)$

This is χ_s, a measure of B_s^0–$\overline{B}_s^0$ mixing. Violates $\Delta B \neq 2$ rule.

VALUE	DOCUMENT ID		TECN
0.53±0.15	[1] ALBAJAR	91D	RVUE

[1] From combination of UA1 (ALBAJAR 91D), CLEO (BEAN 87B), ARGUS (ALBRECHT 87I), ALEPH (DECAMP 91), and L3 (ADEVA 90P). Corresponding limits are > 0.23 at 95% CL and > 0.27 at 90% CL.

B_s^0 REFERENCES

ALBAJAR 91D PL B262 171 +Albrow, Allkofer, Ankoviak, Apsimon+ (UA1 Collab.)
DECAMP 91 PL B258 236 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
ADEVA 90P PL B252 703 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
LEE-FRANZINI 90 PRL 65 2947 +Heintz, Lovelock, Narain, Schamberger+ (CUSB-II Collab.)
ALBRECHT 87I PL B192 245 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
BEAN 87B PRL 58 183 +Bobbink, Brock, Engler+ (CLEO Collab.)

B_s^*

$I(J^P) = ?(?^?)$
I, *J*, *P* need confirmation.

OMITTED FROM SUMMARY TABLE

B_s^* – B_s MASS DIFFERENCE

VALUE	DOCUMENT ID	TECN	COMMENT
47.0±2.6	[1] LEE-FRANZINI 90	CSB2	$e^+e^- \rightarrow \Upsilon(5S)$

[1] LEE-FRANZINI 90 measure 46.7 ± 0.4 ± 0.2 MeV for an admixture of B^0, B^+, and B_s. They use the shape of the photon line to separate the above value for B_s.

B_s^* REFERENCES

LEE-FRANZINI 90 PRL 65 2947 +Heintz, Lovelock, Narain, Schamberger+ (CUSB-II Collab.)

HEAVY QUARK SEARCHES

Searches for Top and Fourth Generation Hadrons

MASS LIMITS for Top Hadrons in $p\overline{p}$ Collisions

These experiments are based on the assumption that no nonstandard decay modes such as $t \to bH^+$ are available, except as shown in the comments.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>91	95	[1] ABE 92	CDF	$\ell\ell$, $\ell + b$-jet
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>60	95	[2] ALBAJAR 91B	UA1	$t \to bH^+$; $H^+ \to \tau^+\nu$
		[3] BAER 91B	RVUE	$t \to \tilde{t}_1 \tilde{\chi}_1^0$
>72	95	[4] ABE 90B	CDF	$e + \mu$
>77	95	[5] ABE 90C	CDF	e + jets + missing E_T
>69	95	[6] AKESSON 90	UA2	e + jets + missing E_T
>60	95	ALBAJAR 90B	UA1	e or μ + jets, $\mu\mu$ + jet
		[7] BARGER 90E	RVUE	$t \to bH^+$
>41	95	[8] ALBAJAR 88	UA1	e or μ + jets

[1] ABE 92 search for ee, $e\mu$, $\mu\mu$ dilepton final states and (e or μ) plus a b-quark jet. The b jet is tagged by a soft muon. The 90%CL limit is 95 GeV.
[2] ALBAJAR 91B searched for the decay $t \to H^+ b$ using single muon and dimuon events and assuming B($H^+ \to \tau^+\nu$) $\geq$ 0.95. The limit holds for $m(H^+) \lesssim m(t) - m(b) - (3\text{–}6)$ GeV.
[3] BAER 91B argue that a top quark as light as 60 GeV may have escaped detection at CDF if a supersymmetric decay mode is open.
[4] ABE 90B exclude the region 28–72 GeV.
[5] ABE 90C cannot exclude $m(t) < 40$ GeV, but this region is ruled out by other experiments. They study events with an energetic electron, missing transverse energy and two or more jets. Only the $t\overline{t}$ contribution (not $W \to tb$) is relevant for these masses. See also ABE 91.
[6] AKESSON 90 searched for events having an electron with p_T > 12 GeV, missing momentum > 15 GeV, and a jet with E_T > 10 GeV, $|\eta| < 2.2$, and excluded $m(t)$ between 30 and 69 GeV.
[7] BARGER 90E claim that ABE 90C data exclude most regions of two-Higgs-doublet models with $m(t) < 80$ GeV even if $t \to bH^+$ decay is allowed.
[8] ALBAJAR 88 value quoted here is revised using the full $O(\alpha_s^3)$ cross section of ALTARELLI 88. Superseded by ALBAJAR 90B.

MASS LIMITS for Top Hadrons in e^+e^- Collisions

The last column specifies measured quantities: S = Sphericity, T = Thrust.

For limits prior to 1987, see our 1990 edition, Physics Letters **B239**, p. VII.167 (1990).

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>45.8	95	[9] DECAMP 90F	ALEP	isolated charged particle and aplanarity
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>43	95	[9] ABREU 91F	DLPH	$\Gamma(Z)$
>30.2	95	ABE 90D	VNS	Event shape
>44.5	95	[9] ABREU 90D	DLPH	Event shape
>44.0	95	[9,10] ABREU 90D	DLPH	$t \to bH^+$, $H^+ \to c\overline{s}$, $\tau^+\nu$
>33.5	95	[11] ABREU 90D	DLPH	$\Gamma(Z \to$ hadrons)
>44.5	95	[12] AKRAWY 90B	OPAL	Acoplanarity
>44.3	95	[13] AKRAWY 90B	OPAL	$t \to bH^+$, $H^+ \to c\overline{s}$, $\tau\nu$
>40.7	95	[14] ABRAMS 89C	MRK2	Event shape
>42.5	95	ABRAMS 89C	MRK2	$t \to bH^+$, $H^+ \to c\overline{s}$
>29.9	95	[15] ADACHI 89C	TOPZ	μ
>29.9	95	[16] ENO 89	AMY	μ, e
>25.8	95	[17] ADACHI 88	TOPZ	R, T, Acoplanarity
>25.9	95	[18] IGARASHI 88	AMY	T + (μ,e)
>25.9	95	[19] SAGAWA 88	AMY	R, T
none E_{cm}=50	95	[20] ABE 87	VNS	R, T, Acoplanarity
>25.5	95	[21] YOSHIDA 87	VNS	R, T, Acoplanarity

[9] Search was near the Z peak at LEP.
[10] Assumed $m(H^+) < m(t) - 6$ GeV.
[11] Superseded by ABREU 91F.
[12] AKRAWY 90B search was restricted to data near the Z peak at E_{cm} = 91.26 GeV at LEP. The excluded region is between 23.4 and 44.5 GeV if no H^+ decays exist.
[13] AKRAWY 90B limit applies for any H^+ branching ratio B($c\overline{s}$). Limit increases to 45.2 GeV if B($c\overline{s}$) = 1. The lower end of the excluded region is $m(H^+)$ + 5 GeV.
[14] The ABRAMS 89C limit from an isolated track search is 40.0 GeV.
[15] ADACHI 89C search was at E_{cm} = 56.5–60.8 GeV at TRISTAN using multi-hadron events accompanying muons.
[16] ENO 89 search at E_{cm} = 50–60.8 GeV at TRISTAN.
[17] ADACHI 88 set limit σ(top) < 8.2 pb at CL=95% for top-flavored-hadron production from event shape analyses at E_{cm} = 52 GeV. By using the quark-parton model cross-section formula with first-order QCD corrections near the threshold, the above limit leads to a lower mass limit of 25.8 GeV at 95% confidence level for top quarks.
[18] IGARASHI 88 searches for leptons in low-thrust events and gives $\Delta R(t)$ < 0.15 (95% CL) at E_{cm} = 50–52 GeV.
[19] SAGAWA 88 set limit σ(top) < 6.1 pb at CL=95% for top-flavored hadron production from event shape analyses at E_{cm} = 52 GeV. By using the quark parton model cross-section formula near threshold, the above limit leads to lower mass bounds of 25.9 GeV for charge 2/3 quarks.
[20] ABE 87 set limit σ(top) < 16 pb at CL=95% for top-flavored hadron production, which should be compared with the full top-quark production cross section of 45.9 pb.
[21] YOSHIDA 87 set limit σ(top) < 17 pb at CL=95% for top-flavored hadron production from event shape analyses at E_{cm} = 52 GeV. This limit should be compared with the full top-quark production cross section of 34 pb, which takes into account the effect of weak neutral current but neglects its axial-vector coupling contribution expected to be suppressed near threshold. After considering the radiative effects, top quarks of mass below 25.5 GeV can be excluded by the above limit.

MASS LIMITS for Top Hadrons Independent of Top Decay Mode

These limits are derived from $\Gamma(W)$ values shown in the W width section. Independent of the top decay mode, any W decay to $t\overline{b}$ would increase the total width of the W boson.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>55	95	[22] ALITTI 92	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>53	95	[23] ALITTI 92	UA2	$E_{cm}^{p\overline{p}}$= 630 GeV
>43	95	[24] ABE 91C	CDF	$E_{cm}^{p\overline{p}}$= 1800 GeV
>38	90	[25] ALBAJAR 91	UA1	$E_{cm}^{p\overline{p}}$= 630 GeV
>51	90	[26] ALBAJAR 91	RVUE	$\Gamma(W)$

[22] Limit is from combined data of ALBAJAR 91, ALITTI 92, and ABE 90: $\Gamma(W)$ = 2.15 ± 0.11 GeV.
[23] ALITTI 92 result is derived from $\Gamma(W)$ = 2.10 ± 0.16 GeV.
[24] ABE 91C result is derived from $\Gamma(W)$ = 2.12 ± 0.20 GeV. At 90%CL, the limit is > 48 GeV.
[25] ALBAJAR 91 result is derived from $\Gamma(W) = 2.18^{+0.26}_{-0.24} \pm 0.04$ GeV.
[26] Limit is from combined data of ALBAJAR 91, ALITTI 90C, and ABE 90.

CONSTRAINTS ON m_t, M_H, AND HEAVY PHYSICS FROM PRECISION EXPERIMENTS

(by Paul Langacker, University of Pennsylvania)

A large value of $|m_t - m_b|$ breaks vector SU(2) symmetry and significantly affects many precision electroweak observables. The major sensitivity for processes involving light external fermions is through t- and b-quark loop contributions to the W and Z self-energies.[1] Most of the shift in M_W is absorbed into the measured value of the Fermi constant G_F, while the prediction for M_Z,

$$M_Z = \frac{M_W}{\widehat{\rho}^{1/2} \cos\widehat{\theta}_W} , \tag{1}$$

decreases rapidly for large m_t. In Eq. (1) $\widehat{\rho} \simeq 1 + \rho_t$, where

$$\rho_t = \frac{3 G_F m_t^2}{8\sqrt{2}\pi^2} \sim 0.0031 \left(\frac{m_t}{100 \text{ GeV}}\right)^2 , \tag{2}$$

and $\cos\widehat{\theta}_W$ is the cosine of the weak angle in the $\overline{\text{MS}}$ scheme.[2] In addition to M_Z itself, neutral current amplitudes and the coefficient of $G_F M_Z^3$ in the expression for Γ_Z are multiplied by $\widehat{\rho}$. There is additional logarithmic m_t dependence in these quantities and in M_W. Vertex and box diagrams also introduce large (quadratic) m_t dependence, which is especially important in quantities involving external b quarks (in order to avoid mixing angle suppressions), such as in the $Z \to b\overline{b}$ partial width or in $B - \overline{B}$ mixing. Finally, in the on-shell renormalization scheme, significant but somewhat artificial m_t dependence is introduced into Z vertices through the definition[2] $\sin^2\theta_W \equiv 1 - M_W^2/M_Z^2$.

As discussed in the section on the Standard Model of Electroweak Interactions (see especially Figure 1 of that section) the consistency of the various observables places an upper limit of order 200 GeV on m_t, assuming the exact validity of the

Standard Model. The precise value depends on the mass M_H of the Standard Model Higgs boson, which yields additional logarithmic corrections to $\widehat{\rho}$ and other quantities. A global fit to all data (see Table 2 of the Standard Model section) yields

$$m_t = 150^{+23}_{-26} \pm 16 \text{ GeV} , \qquad (3)$$

where the central value is for M_H= 250 GeV and the second uncertainty is from varying M_H in the range 50 GeV (-) to 1000 GeV (+). One obtains upper limits $m_t < 194(201)$ GeV at 90 (95)% CL for M_H= 1000 GeV, while $m_t < 178(186)$ GeV for M_H= 250 GeV and $m_t < 165(173)$ GeV for M_H= 50 GeV. The general range indicated by Eq. (3) is reliable, but the exact values and limits are somewhat sensitive to the inputs. For example, the forward-backward asymmetry in $Z \to b\bar{b}$ is 1.6σ above the Standard Model expectation[2] and pulls up the m_t prediction and limits by $\sim$ 7 GeV. Similarly, the value of $\alpha_s(M_Z)$= 0.115 ± 0.008 used in the QCD corrections to Γ_Z yields a value for m_t higher by $\sim$ 8 GeV than would $\alpha_s(M_Z)$= 0.12 ±0.02.

Most theoretical uncertainties are included in Eq. (3) and the m_t limits. One exception is the two-loop QCD corrections of order $-\alpha\alpha_s m_t^2/M_Z^2$ to the self-energy diagrams, which are not included in Eq. (3). The perturbative estimate[3] multiplies the expression for ρ_t in Eq. (2) by $1-2\alpha_s(m_t)(\pi^2+3)/9\pi \sim 0.9$, which would raise the value and limits on m_t by 5%, or 8–10 GeV. However, there is uncertainty in both the magnitude and sign of important nonperturbative effects, so it is reasonable to view the $-\alpha\alpha_s m_t^2/M_Z^2$ terms as introducing an uncertainty of $\sim$ 5%.

The upper limit on m_t is unchanged or strengthened in the presence of many types of new physics. For example, nondegenerate multiplets of heavy fermions or scalars break the vector part of weak SU(2) and lead to a decrease in the value of M_Z/M_W. A nondegenerate SU(2) doublet $\binom{f_1}{f_2}$ yields a positive contribution to ρ_t of [1]

$$\frac{CG_F}{8\sqrt{2}\pi^2}\Delta m^2, \qquad (4)$$

where

$$\Delta m^2 \equiv m_1^2 + m_2^2 - \frac{4m_1^2m_2^2}{m_1^2-m_2^2}\ln\frac{m_1}{m_2} \geq (m_1-m_2)^2, \qquad (5)$$

and $C = 1$ (3) for color singlets (triplets). Thus, to a good first approximation (*i.e.*, except for $\Gamma(Z \to b\bar{b})$ and logarithmic effects) the 90% CL upper limit $m_t < 194$ GeV in the Standard Model can be reinterpreted as

$$m_t^2 + \sum_i \frac{C_i}{3}\Delta m_i^2 < (194 \text{ GeV})^2, \qquad (6)$$

where the sum includes fourth-family quark or lepton doublets, $\binom{t'}{b'}$ or $\binom{E^0}{E^-}$, and scalar doublets such as $\binom{\tilde{t}}{\tilde{b}}$ in supersymmetry (in the absence of $L-R$ mixing). Similarly, heavy Z' bosons decrease the prediction for M_Z due to mixing and generally strengthen the m_t limit.[5] Additional Higgs doublets which participate in spontaneous symmetry breaking,[6] heavy lepton doublets involving Majorana neutrinos,[7] and the presence of heavy degenerate chiral multiplets (the S parameter, to be discussed below) can weaken the limits on m_t, though the effect is usually small for reasonable parameter ranges. The only known way to significantly weaken the limits is to allow for the presence of Higgs triplets (or higher-dimensional representations), whose vacuum expectation values can cancel all of the quadratic m_t dependence except for the $b\bar{b}$ vertex. Even in that case one has an upper limit around 330 GeV.[2,8]

The data will not significantly constrain M_H until m_t is known separately. At present the best fit occurs for lower values of M_H, but the change in χ^2 between $M_H = 50$ and 1000 GeV is only $\sim$ 1. If m_t is measured directly to within 5–10 GeV in the future, it may be possible to constrain M_H (assuming the exact validity of the Standard Model), particularly if m_t is in the lower part of the allowed range.

In addition to nondegenerate multiplets, which break the vector part of weak SU(2), heavy degenerate multiplets of chiral fermions break the axial generators. The effects of one degenerate chiral doublet are small, but it has recently been emphasized that in technicolor theories there may be many chiral doublets and therefore significant effects.[9]

A number of authors[9–14] have considered the general effects on neutral current and Z and W-pole observables of types of heavy (*i.e.*, $M > M_Z$) physics which contribute to the W and Z self-energies but do not have any direct coupling to the ordinary fermions. Such effects can be described by just three parameters, S, T, and U. T is proportional to the difference between the W and Z self-energies at $Q^2 = 0$ (*i.e.*, vector SU(2)-breaking), while S $(S+U)$ is associated with the difference between the Z (W) self-energy at $Q^2 = M^2_{Z,W}$ and $Q^2 = 0$ (axial SU(2)-breaking). In the $\overline{\text{MS}}$ scheme[10]

$$\alpha T \equiv \frac{\Pi^{\rm new}_{WW}(0)}{M_W^2} - \frac{\Pi^{\rm new}_{ZZ}(0)}{M_Z^2}$$

$$\frac{\alpha}{4\widehat{s}^2\widehat{c}^2}S \equiv \frac{\Pi^{\rm new}_{ZZ}(M_Z^2) - \Pi^{\rm new}_{ZZ}(0)}{M_Z^2}$$

$$\frac{\alpha}{4\widehat{s}^2}(S+U) \equiv \frac{\Pi^{\rm new}_{WW}(M_W^2) - \Pi^{\rm new}_{WW}(0)}{M_W^2}, \qquad (7)$$

where $\Pi^{\rm new}_{WW}$ and $\Pi^{\rm new}_{ZZ}$ are respectively the contributions of the new physics to the W and Z self-energies, $\widehat{s}^2 = \sin^2\widehat{\theta}_W(M_Z)$, $\widehat{c}^2 = 1 - \widehat{s}^2$, and α is the running coupling evaluated at M_Z. S, T, and U are related to other parameters defined in[10,12] by

$$T = h_V = \epsilon_1/\alpha$$

$$S = h_{AZ} = S_Z = 4\widehat{s}^2\epsilon_3/\alpha$$

$$U = h_{AW} - h_{AZ} = S_W - S_Z = -4\widehat{s}^2\epsilon_2/\alpha. \qquad (8)$$

A heavy nondegenerate multiplet of fermions or scalars contributes to T as

$$\widehat{\rho} = \frac{1}{1-\alpha T} \simeq 1 + \alpha T, \qquad (9)$$

so that $\alpha T \sim \rho_t$. If there are non-doublet Higgs representations, their vacuum expectation values can be expressed in terms of a parameter ρ_0 which is unity in the Standard Model.[2] ρ_0 and T enter all observables in the combination $\rho^{\rm eff} \equiv \rho_0/(1-\alpha T)$, so that ρ_0 cannot be separated from T unless the new physics has other consequences, such as vertex corrections.

A multiplet of heavy degenerate chiral fermions yields

$$S = C \sum_i \left(t_{3L}(i)^2 - t_{3R}(i)^2\right)/3\pi, \quad (10)$$

where $t_{3L,R}(i)$ is the third component of weak isospin of the left- (right-) handed component of fermion i and C is the number of colors. For example, a heavy degenerate family would contribute $2/3\pi$ to S. In technicolor models with QCD-like dynamics, one expects[9] $S \sim 0.45$ for an isodoublet of technifermions, assuming N_{TC} =4 technicolors, while $S \sim 1.62$ for a full technigeneration with N_{TC} =4; T is harder to estimate. These estimates do not apply to models of walking technicolor. In these examples one has $S \geq 0$. However, it is possible to find situations in which $S < 0$.[15] Supersymmetric extensions of the Standard Model generally give very small effects.[16] Most simple types of new physics yield $U = 0$, although there are counter-examples, such as the effects of anomalous triple-gauge vertices.[12]

S, T, and U are defined with a factor of α removed, so that they are expected to be of order unity in the presence of new physics. It is also possible to parametrize the effects of large $m_t > M_Z$ (except for the $b\bar{b}$ vertex) or $M_H > M_Z$ in terms of S, T, and U. If one takes $m_t = M_H = M_Z$ as a reference point, then larger values of m_t and M_H can be expressed as[11]

$$\Delta T = \frac{\rho_t(m_t) - \rho_t(M_Z)}{\alpha} - \frac{3G_F}{4\sqrt{2}\alpha\pi^2}(M_Z^2 - M_W^2)\ln(M_H/M_Z)$$

$$\Delta S = c_S \ln(m_t/M_Z) + \frac{1}{6\pi}\ln(M_H/M_Z)$$

$$\Delta U = c_U \ln(m_t/M_Z), \quad (11)$$

where the coefficients c_S and c_U depend on the renormalization scheme. Various authors use different reference values for m_t and M_H when determining S, T, and U from the data. In the following $m_t = M_H = M_Z$ will be used.

The Standard Model expressions for observables are replaced by

$$M_Z^2 = M_{Z0}^2 \frac{1-\alpha T}{\rho_0} \frac{1}{1 - G_F M_{Z0}^2 S/2\sqrt{2}\pi}$$

$$M_W^2 = M_{W0}^2 \frac{1}{1 - G_F M_{W0}^2 (S+U)/2\sqrt{2}\pi}, \quad (12)$$

where $M_{Z,W0}$ are the Standard Model expressions in terms of $\sin^2\hat{\theta}_W(M_Z)$. Furthermore,

$$\Gamma_Z = \frac{\rho_0}{1-\alpha T} M_Z^3 \beta_Z$$

$$\Gamma_W = M_W^3 \beta_W$$

$$A_i = \frac{\rho_0}{1-\alpha T} A_{i0}, \quad (13)$$

where $\beta_{Z,W}$ is the Standard Model expression for the reduced width $\Gamma_{Z,W0}/M_{Z,W0}^3$, $M_{Z,W}$ is the physical mass, and A_i (A_{i0}) is a neutral current amplitude (in the Standard Model).

The 90% CL allowed regions in S, T, and U from a fit to all data are shown in Figure 1. One obtains

$$S = -0.90 \pm 0.69$$

$$T = -0.11 \pm 0.56$$

$$U = 0.05 \pm 0.98. \quad (14)$$

Also, $S < 0.02(+0.29)$, $T < 0.60(0.81), U < 1.3(1.6)$ at 90 (95)% CL, while $S > -1.8$, $T > -0.83, U > -1.2$ (90%). If one requires that $S \geq 0$ then $S < 0.76(0.94)$. Allowing arbitrary S, only one heavy generation of ordinary fermions is allowed at 95% CL, and the favored value is problematic for technicolor models with many techni-doublets and QCD-like dynamics. If future more precise measurements of atomic parity violation and LEP asymmetries continue to favor $S < 0$, it will be possible to exclude many technicolor models. The simplest origin of $S < 0$ would probably be an additional heavy Z' boson,[5] which could mimic $S < 0$.

The S, T, and U formalism describes many types of heavy physics which affect only the gauge self-energies. New physics which couples directly to ordinary fermions, such as heavy Z' bosons or mixing with exotic fermions cannot be fully parametrized in the S, T, and U framework. An alternate formalism[17] redefines ϵ_1, ϵ_2, and ϵ_3 in terms of the specific observables M_W/M_Z, the leptonic Z width $\Gamma_{\ell\ell}$, and the forward-backward asymmetry[2] at the Z-pole, $A_{FB}(\ell)$. The definitions coincide with (7) and (8) for physics which affects gauge self-energies only, but the redefined ϵ's now parametrize a broader class of types of new physics. However, they are not related to other observables in a model-independent way. Another approach[18] parametrizes new physics in terms of gauge-invariant sets of operators. It is especially powerful in studying the effects of new physics on nonabelian gauge vertices.

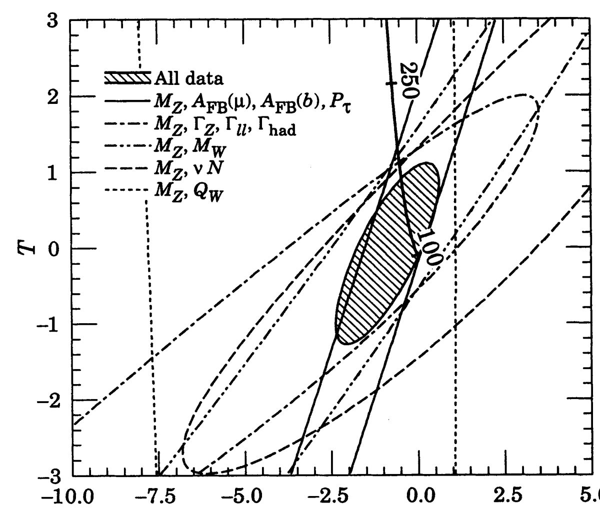

Figure 1. 90% CL limits on S and T from various inputs. One expects $S = T = 0$ for $m_t = M_H = M_Z$. The expected values for various m_t for $M_H = 250$ GeV are also shown (other M_H yield very similar predictions). The fit to M_W and M_Z assumes $U = 0$, while U is arbitrary in the other fits.

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INDIRECT MASS LIMITS for Top Quark

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
<200 (CL = 95%) OUR EVALUATION					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
160^{+50}_{-60}		[27] ALITTI	92B	UA2	$m(W)$, $m(Z)$
170^{+42+21}_{-55-14}		[28,29] DECAMP	92B	ALEP	Z parameters
139^{+30+22}_{-35-15}		[29] DECAMP	92B	RVUE	Electroweak
120^{+27}_{-28}		[30] ELLIS	92	RVUE	Electroweak
$124^{+40}_{-56}\pm 21$		[31] LEP	92	RVUE	Z parameters
132^{+27+18}_{-31-19}		[31] LEP	92	RVUE	Electroweak
$150^{+23}_{-26}\pm 16$		[32] PDG	92	RVUE	Electroweak
<220	95	[33] ABE	91B	RVUE	$m(W)$, $m(Z)$
<215	95	[28] ABREU	91F	DLPH	Z parameters
$193^{+52}_{-69}\pm 16$		[28,34] ADEVA	91E	L3	Z parameters
$164^{+37}_{-44}\pm 16$		[34,35] ADEVA	91E	RVUE	Electroweak
100^{+70+24}_{-52-11}		[36,37] ALEXANDER	91F	OPAL	Z parameters
129^{+42+24}_{-39-16}		[36,38] ALEXANDER	91F	RVUE	Electroweak
		[39] DELAGUILA	91C	RVUE	Z'
119^{+39}_{-45}		[40] GONZALEZ-G..	91	RVUE	Electroweak
134^{+47}_{-48}		[41] HIOKI	91	RVUE	Electroweak
124^{+28+20}_{-34-15}		[42] LANGACKER	91	RVUE	Electroweak
<366	90	[43] ADACHI	90F	RVUE	$\sigma(e^+e^- \rightarrow$ hadrons)
<200	95	[44] ADEVA	90I	RVUE	Electroweak
<200	95	[45] BARGER	90C	RVUE	Electroweak
<240	90	[46] BLONDEL	90	CDHS	$\nu N \rightarrow \nu X$ or $\overline{\nu} N \rightarrow \overline{\nu} X$
$120\pm 40\pm 20$		[47] DECAMP	90P	RVUE	Electroweak
127^{+24}_{-30}		[48] ELLIS	90B	RVUE	Electroweak
<190	95	[49] KENNEDY	90	RVUE	Electroweak
132^{+31}_{-37}		[50] ELLIS	89B	RVUE	Electroweak
140^{+43}_{-52}		[51] LANGACKER	89	RVUE	Electroweak
<168	90	[52] COSTA	88	RVUE	Electroweak
<153	68	[53] ELLIS	88C	RVUE	Electroweak
<291	90	[54] FOGLI	88	RVUE	$\nu N \rightarrow \nu X$
<180	90	[55] AMALDI	87	RVUE	Electroweak

[27] ALITTI 92B assume $m(H)$ = 100 GeV. The 95%CL limit is $m(t) < 250$ GeV for $m(H) < 1$ TeV.
[28] Limit from Z cross sections, leptonic forward-backward asymmetries, τ polarization asymmetry, quark charge asymmetry, and $b\overline{b}$ and $c\overline{c}$ forward-backward asymmetries.
[29] DECAMP 92B uses $\alpha_s = 0.121 \pm 0.008$. The second error is from $m(H^0) = 200^{+800}_{-150}$ GeV. The "Electroweak" value combines ALEPH Z data and $m(W)/m(Z)$ from ALITTI 90B and ABE 90G.
[30] ELLIS 92 is an update of ELLIS 90B to include the latest LEP, UA2, CDF, and CHARM II results presented at the Lepton-Photon and EPS Conference, July 1991. $\alpha_s = 0.115 \pm 0.008$ assumed and $m(H)$ left free. Fit gives 1.3 GeV $< m(H) <$ 160 GeV, CL = 68% for $m(t) = 130$ GeV.
[31] The LEP 92 values are combined results of the four LEP collaborations: ALEPH, DELPHI, L3, and OPAL. The "Electroweak" result includes $m(W)$ and $m(W)/m(Z)$ from ABE 90G and ALITTI 92B, and neutral current data from CDHS and CHARM. Uses $\alpha_s = 0.118 \pm 0.008$. Second error corresponds to $m(H) = 300^{+700}_{-250}$ GeV.
[32] PDG 92 value comes from a fit by P. Langacker to recent data as discussed in the minireview above.
[33] The ABE 91B limit is derived from their $m(W)$ with $m(Z) = 91.161$ GeV. Combining with the $m(W)$ measurement of ALITTI 90B, one obtains $m(t) < 230$ GeV (95%CL).
[34] $\alpha_s = 0.115 \pm 0.009$. The second error is from $m(H^0) = 300^{+700}_{-250}$ GeV.
[35] ADEVA 91E combine Z data from L3 and $\sin^2\theta_W$ from ABE 90G and ALITTI 90B.
[36] ALEXANDER 91F use $\alpha_s = 0.118 \pm 0.008$. The second error comes from $m(H) = 300^{+700}_{-250}$ GeV.
[37] The 95%CL upper limit is 218 GeV.
[38] From OPAL Z data and $m(W)$ from ABE 90G and ALITTI 90B. The 95%CL upper limit is 207 GeV.
[39] DELAGUILA 91C study bound on $m(t)$ in the presence of extra Z' (Z_{LR} and Z_X) from various electroweak data. The upper bound on $m(t)$ is more strict for lower Z' masses. See their Fig. 2.
[40] GONZALEZ-GARCIA 91 result is based on low-energy neutral current data, Z mass and widths, $m(W)$ from ABE 90G. $m(H^0) = 100$ GeV assumed.
[41] HIOKI 91 uses $m(Z)$, $\Gamma_{tot}(Z)$, and $m(W)$. $m(H^0) = 100$ GeV, $\alpha_s = 0.12$ assumed. For $m(H^0) = 1$ TeV, one finds $m(t) = 162^{+43}_{-46}$ GeV.
[42] LANGACKER 91 is a fit to various electroweak data. The second error is from $m(H^0) = 250^{+750}_{-200}$ GeV. $\alpha_s = 0.12 \pm 0.02$ used. The 95%CL upper limit is 182 GeV [for $m(H^0)$ = 1 TeV]. For arbitrary Higgs structure, one obtains $m(t) < 310$ GeV.
[43] ADACHI 90F limit is from R at PEP, PETRA, and TOPAZ at TRISTAN. Top mass dependence enters via radiative correction. Minimal standard model with $m(Z) = 91.1$ GeV, $m(H^0) = 100$ GeV assumed. $\Lambda_{\overline{MS}}$ is varied in the fit.
[44] ADEVA 90I analysis is based on $m(Z)$ measured by L3 and $\sin^2\theta_W = 0.2284 \pm 0.0043$ determined from $m(W)/m(Z)$ and νN scattering data. $40 < m(H) < 1000$ GeV assumed. The 1σ range is $m(t) = 130^{+38}_{-42}$ GeV.
[45] BARGER 90C limit is a fit using only LEP and $m(W)$ data. $m(H^0) = 100$ GeV assumed. The most likely value is $m(t) = 151$ GeV. The limit increases to 225 GeV for $m(H)$ = 1000 GeV.
[46] BLONDEL 90 limit comes from $R_{\overline{\nu}} = \sigma^{NC}(\overline{\nu}N) / \sigma^{CC}(\overline{\nu}N)$ and R_ν. Comparison of R_ν and $m(W)$ (the latter from ALBAJAR 89 and ANSARI 87) gives an independent limit $m(t) < 240$ GeV (90%CL).
[47] DECAMP 90P result is from $m(Z)$, $\Gamma(Z \rightarrow \ell\ell)$, and $m(W)/m(Z)$ from UA2 (ALITTI 90B), $m(W)$ from CDF (APS conf. '90), and νN neutral current data from CDHS and CHARM.
[48] ELLIS 90B limit is a fit to various electroweak data. $m(H^0) = m(Z)$ assumed. $m(c)$ = 1.45 GeV is used for νN data.
[49] KENNEDY 90 limit is a fit to neutral current data, W, Z masses, and Z widths. $m(H)$ = $m(Z)$ assumed. For $m(H)$ = 1 TeV, the limit is 212 GeV. For nonminimal Higgs sector (with $\rho \neq 1$), one obtains $m(t) < 350$ GeV (90%CL).
[50] ELLIS 89B limit is a fit to various electroweak data. $m(H^0) = m(Z)$ assumed. $m(c)$ = 1.45 GeV is used for νN data. Superseded by ELLIS 90B.
[51] LANGACKER 89 limit is a fit to various electroweak data. $m(H^0) = 100$ GeV assumed. The 90%CL upper limit is 190(210) GeV for $m(H^0)$ = 100(1000) GeV.
[52] COSTA 88 limit is a fit to various electroweak data. $m(H^0) = m(Z)$ assumed. $m(c)$ = 1.5 GeV is used for νN data.
[53] ELLIS 88C limit is a fit to neutral current data and W, Z masses. $m(H^0) = m(Z)$ assumed. $m(c) = 1.45$ GeV is used for νN data. Varying $m(c)$ relaxes the limit to 185 GeV. Superseded by ELLIS 89B.
[54] FOGLI 88 limit is a fit to neutrino deep-inelastic scattering data.
[55] AMALDI 87 limit is a fit to various electroweak data. $m(H^0) < 100$ GeV assumed.

MASS LIMITS for b' (Fourth Generation) Hadrons in $p\overline{p}$ Collisions

These experiments assume that no two-body modes such as $b' \rightarrow b\gamma$, $b' \rightarrow bg$, or $b' \rightarrow cH^+$ are available.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>72	95	[56] ABE	90B	CDF	$e + \mu$

• • • We do not use the following data for averages, fits, limits, etc. • • •

>54	95	[57] AKESSON	90	UA2	e + jets + missing E_T
>43	95	[58] ALBAJAR	90B	UA1	μ + jets
>34	95	[59] ALBAJAR	88	UA1	e or μ + jets

[56] ABE 90B exclude the region 28–72 GeV.

[57] AKESSON 90 searched for events having an electron with p_T > 12 GeV, missing momentum > 15 GeV, and a jet with E_T > 10 GeV, $|\eta|$ < 2.2, and excluded $m(b')$ between 30 and 69 GeV.

[58] For the reduction of the limit due to non-charged-current decay modes, see Fig. 19 of ALBAJAR 90B.

[59] ALBAJAR 88 study events at E_{cm} = 546 and 630 GeV with a muon or isolated electron, accompanied by one or more jets and find agreement with Monte Carlo predictions for the production of charm and bottom, without the need for a new quark. The lower mass limit is obtained by using a conservative estimate for the $b'\overline{b}'$ production cross section and by assuming that it cannot be produced in W decays. The value quoted here is revised using the full $O(\alpha_s^3)$ cross section of ALTARELLI 88.

MASS LIMITS for b' (Fourth Generation) Hadrons in e^+e^- Collisions

Search for hadrons containing a fourth-generation −1/3 quark denoted b'.

The last column specifies the assumption for the decay mode (CC denotes the conventional charged-current decay) and the event signature which is looked for.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>46.0	95	[60] DECAMP	90F	ALEP	any decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>45	95	ABREU	91F	DLPH	$\Gamma(Z)$
none 19.4–28.2	95	ABE	90D	VNS	Any decay; event shape
>45.0	95	ABREU	90D	DLPH	B(CC) = 1; event shape
>44.5	95	[61] ABREU	90D	DLPH	$b' \rightarrow cH^-$, $H^- \rightarrow \overline{c}s$, $\tau^-\nu$
>40.5	95	[62] ABREU	90D	DLPH	$\Gamma(Z \rightarrow$ hadrons)
>28.3	95	ADACHI	90	TOPZ	B(FCNC)=100%; isol. γ or 4 jets
>41.4	95	[63] AKRAWY	90B	OPAL	Any decay; acoplanarity
>45.2	95	[63] AKRAWY	90B	OPAL	B(CC) = 1; acoplanarity
>46	95	[64] AKRAWY	90J	OPAL	$b' \rightarrow \gamma$ + any
>27.5	95	[65] ABE	89E	VNS	B(CC) =1; μ, e
none 11.4–27.3	95	[66] ABE	89G	VNS	B($b' \rightarrow b\gamma$) > 10%; isolated γ
>44.7	95	[67] ABRAMS	89C	MRK2	B(CC)= 100%; isol. track
>42.7	95	[67] ABRAMS	89C	MRK2	B(bg)= 100%; event shape
>42.0	95	[67] ABRAMS	89C	MRK2	Any decay; event shape
>28.4	95	[68,69] ADACHI	89C	TOPZ	B(CC) =1; μ
>28.8	95	[70] ENO	89	AMY	B(CC) $\gtrsim$ 90%; μ, e
>27.2	95	[70,71] ENO	89	AMY	any decay; event shape
>29.0	95	[70] ENO	89	AMY	B($b' \rightarrow bg$) $\gtrsim$ 85%; event shape
>24.4	95	[72] IGARASHI	88	AMY	μ,e
>23.8	95	[73] SAGAWA	88	AMY	event shape
>22.7	95	[74] ADEVA	86	MRKJ	μ
>21		[75] ALTHOFF	84C	TASS	R, event shape
>19		[76] ALTHOFF	84I	TASS	Aplanarity

[60] DECAMP 90F looked for isolated charged particles, for isolated photons, and for four-jet final states. The modes $b' \rightarrow bg$ for B($b' \rightarrow bg$) > 65% $b' \rightarrow b\gamma$ for B($b' \rightarrow b\gamma$) > 5% are excluded. Charged Higgs decay were not discussed.

[61] ABREU 90D assumed $m(H^-) < m(b') - 3$ GeV.

[62] Superseded by ABREU 91F.

[63] AKRAWY 90B search was restricted to data near the Z peak at E_{cm} = 91.26 GeV at LEP. The excluded region is between 23.6 and 41.4 GeV if no H^+ decays exist. For charged Higgs decays the excluded regions are between ($m(H^+)$ +1.5 GeV) and 45.5 GeV.

[64] AKRAWY 90J search for isolated photons in hadronic Z decay and derive B($Z \rightarrow b'\overline{b}'$)·B($b' \rightarrow \gamma$ X)/B($Z \rightarrow$ hadrons) < 2.2×10^{-3}. Mass limit assumes B($b' \rightarrow \gamma$ X) > 10%.

[65] ABE 89E search at E_{cm} = 56–57 GeV at TRISTAN for multihadron events with a spherical shape (using thrust and acoplanarity) or containing isolated leptons.

[66] ABE 89G search was at E_{cm} = 55–60.8 GeV at TRISTAN.

[67] If the photonic decay mode is large (B($b' \rightarrow b\gamma$) > 25%), the ABRAMS 89C limit is 45.4 GeV. The limit for for Higgs decay ($b' \rightarrow cH^-$, $H^- \rightarrow \overline{c}s$) is 45.2 GeV.

[68] ADACHI 89C search was at E_{cm} = 56.5–60.8 GeV at TRISTAN using multi-hadron events accompanying muons.

[69] ADACHI 89C also gives limits for any mixture of CC and bg decays.

[70] ENO 89 search at E_{cm} = 50–60.8 at TRISTAN

[71] ENO 89 considers arbitrary mixture of the charged current, bg, and $b\gamma$ decays.

[72] IGARASHI 88 searches for leptons in low-thrust events and gives $\Delta R(b')$ < 0.26 (95% CL) assuming charged current decay, which translates to $m(b')$ > 24.4 GeV.

[73] SAGAWA 88 set limit σ(top) < 6.1 pb at CL=95% for top-flavored hadron production from event shape analyses at E_{cm} = 52 GeV. By using the quark parton model cross-section formula near threshold, the above limit leads to lower mass bounds of 23.8 GeV for charge −1/3 quarks.

[74] ADEVA 86 give 95%CL upper bound on an excess of the normalized cross section, ΔR, as a function of the minimum c.m. energy (see their figure 3). Production of a pair of 1/3 charge quarks is excluded up to E_{cm} = 45.4 GeV.

[75] ALTHOFF 84C narrow state search sets limit $\Gamma(e^+e^-)$B(hadrons) <2.4 keV CL = 95% and heavy charge 1/3 quark pair production m >21 GeV, CL = 95%.

[76] ALTHOFF 84I exclude heavy quark pair production for 7 < m <19 GeV (1/3 charge) using aplanarity distributions (CL = 95%).

REFERENCES FOR Searches for Top and Fourth Generation Hadrons

ABE	92	PRL 68 447	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ALITTI	92	PL B276 365	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92B	PL B276 354	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
DECAMP	92B	ZPHY C53 1	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
ELLIS	92	PL B274 456	+Fogli, Lisi	(CERN, BARI)
LEP	92	PL B276 247	+ALEPH, DELPHI, L3, OPAL	(LEP Collabs.)
PDG	92	PR D45, Part 2	Hikasa, Barnett, Stone+	(KEK, LBL, BOST+)
ABE	91	PR D43 664	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	91B	PR D43 2070	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	91C	PR D44 29	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABREU	91F	NP B367 511	+Adam, Adami, Adye, Akesson, Alekseev+	(DELPHI Collab.)
ADEVA	91E	ZPHY C51 179	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ALBAJAR	91	PL B253 503	+Albrow, Allkofer, Ankoviak, Apsimon+	(UA1 Collab.)
ALBAJAR	91B	PL B257 459	+Albrow, Allkofer, Ankoviak, Apsimon+	(UA1 Collab.)
ALEXANDER	91F	ZPHY C52 175	+Allison, Allport, Anderson, Arcelli+	(OPAL Collab.)
BAER	91B	PR D44 725	+Drees, Godbole+	(FSU, DESY, BOMB, UCD, HAWA)
DELAGUILA	91C	NP B361 45	del Aguila, Moreno, Quiros	(BARC, MADE)
GONZALEZ-G...	91	PL B259 365	Gonzalez-Garcia, Valle	(VALE)
HIOKI	91	MPL A6 2129		(TOKU)
LANGACKER	91	PR D44 817	+Luo	(PENN)
ABE	90	PRL 64 152	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	90B	PRL 64 147	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	90C	PRL 64 142	+Amidei, Apollinari, Atac+	(CDF Collab.)
Also	91	PR D43 664	Abe, Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	90D	PL B234 382	+Amako, Arai, Asano+	(VENUS Collab.)
ABE	90G	PRL 65 2243	+Amidei, Apollinari, Atac+	(CDF Collab.)
ABREU	90D	PL B242 536	+Adam, Adami, Adye, Alekseev, Allaby+	(DELPHI Collab.)
ADACHI	90	PL B234 197	+Aihara, Doser, Enomoto+	(TOPAZ Collab.)
ADACHI	90F	PL B234 525	+Doser, Enomoto, Fujii+	(TOPAZ Collab.)
ADEVA	90I	PL B249 341	+Adriani, Aguilar-Benitez, Akbari, Alcarez+	(L3 Collab.)
AKESSON	90	ZPHY C46 179	+Alitti, Ansari, Ansorge, Bagnaia+	(UA2 Collab.)
AKRAWY	90B	PL B236 364	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
AKRAWY	90J	PL B246 285	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ALBAJAR	90B	ZPHY C48 1	+Albrow, Allkofer, Andrieu, Ankoviak+	(UA1 Collab.)
ALITTI	90B	PL B241 150	+Ansari, Ansorge, Autiero+	(UA2 Collab.)
ALITTI	90C	ZPHY C47 11	+Ansari, Ansorge, Bagnaia+	(UA2 Collab.)
BARGER	90C	PRL 65 1313	+Hewett, Rizzo	(WISC, ISU)
BARGER	90E	PR D41 3421	+Hewett, Phillips	(WISC, RAL)
BLONDEL	90	ZPHY C45 361	+Boeckmann, Burkhardt, Dydak, Grant+	(CDHSW Collab.)
DECAMP	90F	PL B236 511	+Deschizeaux, Lees, Minard+	(ALEPH Collab.)
DECAMP	90P	ZPHY C48 365	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
ELLIS	90B	PL B249 543	+Fogli	(CERN)
KENNEDY	90	PRL 65 2967	+Langacker	(PENN)
ABE	89E	PR D39 3524	+Amako, Arai, Asano, Chiba, Chiba+	(VENUS Collab.)
ABE	89G	PRL 63 1776	+Amako, Arai, Asano, Chiba+	(VENUS Collab.)
ABRAMS	89C	PRL 63 2447	+Adolphsen, Averill, Ballam+	(Mark II Collab.)
ADACHI	89C	PL B229 427	+Aihara, Doser, Enomoto, Fujii+	(TOPAZ Collab.)
ALBAJAR	89	ZPHY C44 15	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
ELLIS	89B	PL B232 139	+Fogli	(CERN, BARI)
ENO	89	PRL 63 1910	+Auchincloss, Blanis, Bodek, Budd+	(AMY Collab.)
LANGACKER	89	PRL 63 1920		(PENN)
ADACHI	88	PRL 60 97	+Aihara, Dijkstra+	(TOPAZ Collab.)
ALBAJAR	88	ZPHY C37 505	+Albrow, Allkofer+	(UA1 Collab.)
ALTARELLI	88	NP B308 724	+Diemoz, Martinelli, Nason	(CERN, ROMA, ETH)
COSTA	88	NP B297 244	+Ellis, Fogli+	(PADO, CERN, BARI, WISC, LBL)
ELLIS	88C	PL B213 526	+Fogli	(CERN, BARI)
FOGLI	88	ZPHY C40 379	+Haidt	(BARI, DESY)
IGARASHI	88	PRL 60 2359	+Myung, Chiba, Hanaoka+	(AMY Collab.)
SAGAWA	88	PRL 60 93	+Mori, Abe+	(AMY Collab.)
ABE	87	JPSJ 56 3763	+Amako, Arai+	(VENUS Collab.)
AMALDI	87	PR D36 1385	+Bohm, Durkin, Langacker+	(CERN, AACH, OSU+)
ANSARI	87	PL B186 440	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
YOSHIDA	87	PL B198 570	+Chiba, Endo+	(VENUS Collab.)
ADEVA	86	PR D34 681	+Ansari, Becker, Becker-Szendy+	(Mark-J Collab.)
ALTHOFF	84C	PL 138B 441	+Braunschweig, Kirschfink+	(TASSO Collab.)
ALTHOFF	84I	ZPHY C22 307	+Braunschweig, Kirschfink+	(TASSO Collab.)

$c\bar{c}$ MESONS

$\eta_c(1S)$ or $\eta_c(2980)$

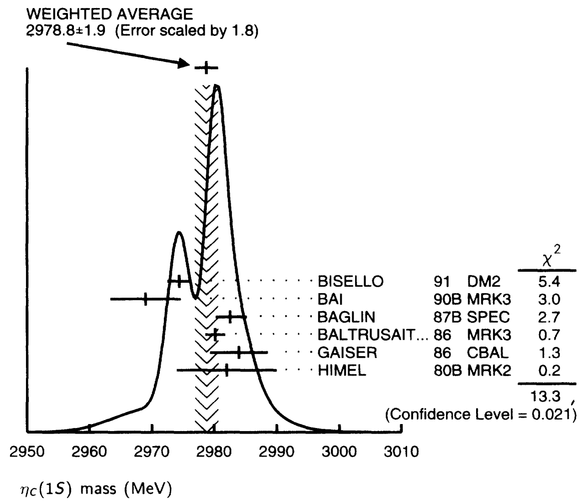
$I^G(J^{PC}) = 0^+(0^{-+})$

Observed in the inclusive γ spectrum generated from $\psi(2S)$ decay, therefore $C = +$. From the 4π decay $G = +$, therefore $I = 0$. From angular distribution in $J/\psi(1S) \rightarrow \eta_c\gamma$, $\eta_c \rightarrow \phi\phi$, $J^P = 0^-$ (BALTRUSAITIS 84).

$\eta_c(1S)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2978.8± 1.9 OUR AVERAGE		Error includes scale factor of 1.8. See the ideogram below.			
2974.4± 1.9		[1] BISELLO	91	DM2	$J/\psi \rightarrow \eta_c\gamma$
2969 ± 4 ± 4	80	BAI	90B	MRK3	$J/\psi \rightarrow \gamma K^+K^-K^+K^-$
$2982.6^{+2.7}_{-2.3}$	12	BAGLIN	87B	SPEC	$\bar{p}p \rightarrow \gamma\gamma$
2980.2± 1.6		[1] BALTRUSAIT...	86	MRK3	$J/\psi \rightarrow \eta_c\gamma$
2984 ± 2.3± 4.0		GAISER	86	CBAL	$J/\psi \rightarrow \gamma X$, $\psi(2S) \rightarrow \gamma X$
2982 ± 8	18	[2] HIMEL	80B	MRK2	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2956 ±12 ±12		BAI	90B	MRK3	$J/\psi \rightarrow \gamma K^+K^-K^0_S K^0_L$
2976 ± 8		[3] BALTRUSAIT...	84	MRK3	$J/\psi \rightarrow 2\phi\gamma$
2980 ± 9		[2] PARTRIDGE	80B	CBAL	e^+e^-

[1] Average of several decay modes.
[2] Mass adjusted by us to correspond to $J/\psi(1S)$ mass = 3097 MeV.
[3] $\eta_c \rightarrow \phi\phi$.

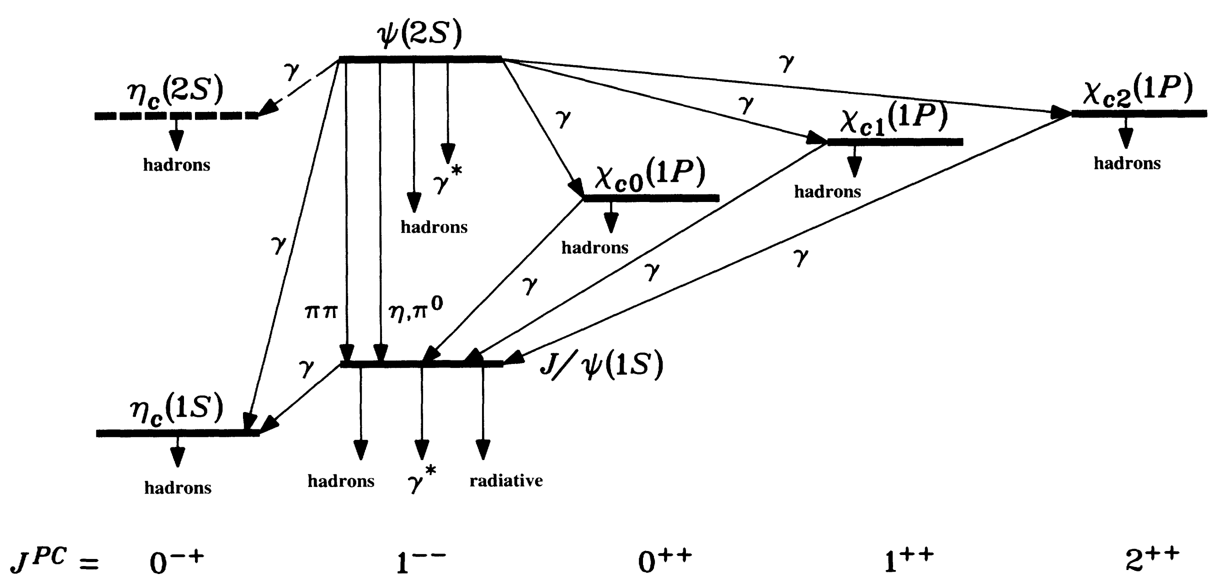


$\eta_c(1S)$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$10.3^{+3.8}_{-3.4}$ OUR AVERAGE						
$7.0^{+7.5}_{-7.0}$		12	BAGLIN	87B	SPEC	$\bar{p}p \rightarrow \gamma\gamma$
$10.1^{+33.0}_{-8.2}$		23 ± 11	[4] BALTRUSAIT...	86	MRK3	$J/\psi \rightarrow \gamma p\bar{p}$
11.5± 4.5			GAISER	86	CBAL	$J/\psi \rightarrow \gamma X$, $\psi(2S) \rightarrow \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<40	90	18	HIMEL	80B	MRK2	e^+e^-
<20	90		PARTRIDGE	80B	CBAL	e^+e^-

[4] Positive and negative errors correspond to 90% confidence level.

THE CHARMONIUM SYSTEM



The current state of knowledge of the charmonium system and transitions, as interpreted by the charmonium model. Uncertain states and transitions are indicated by dashed lines. The notation γ^* refers to decay processes involving intermediate virtual photons, including decays to e^+e^- and $\mu^+\mu^-$.

$\eta_c(1S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
	Decays involving hadronic resonances		
Γ_1	$\eta'(958)\pi\pi$	(4.1 ±1.7) %	
Γ_2	$\rho\rho$	(2.6 ±0.9) %	
Γ_3	$K^*(892)^0 K^- \pi^+$ + c.c.	(2.0 ±0.7) %	
Γ_4	$K^*(892)\overline{K}^*(892)$	(8.5 ±3.1) × 10^{-3}	
Γ_5	$K^*(892)K$ + c.c.	< 1.28 %	90%
Γ_6	$\phi\phi$	(7.1 ±2.8) × 10^{-3}	
Γ_7	$a_0(980)\pi$	< 2 %	90%
Γ_8	$a_2(1320)\pi$	< 2 %	90%
Γ_9	$f_2(1270)\eta$	< 1.1 %	90%
Γ_{10}	$\omega\omega$	< 3.1 × 10^{-3}	90%
	Decays into stable hadrons		
Γ_{11}	$K\overline{K}\pi$	(6.6 ±1.8) %	
Γ_{12}	$\eta\pi\pi$	(4.9 ±1.8) %	
Γ_{13}	$\pi^+\pi^- K^+ K^-$	(2.0 $^{+0.7}_{-0.6}$) %	
Γ_{14}	$2(\pi^+\pi^-)$	(1.2 ±0.4) %	
Γ_{15}	$p\overline{p}$	(1.2 ±0.4) × 10^{-3}	
Γ_{16}	$K\overline{K}\eta$	< 3.1 %	90%
Γ_{17}	$\pi^+\pi^- p\overline{p}$	< 1.2 %	90%
Γ_{18}	$\Lambda\overline{\Lambda}$	< 2 × 10^{-3}	90%
	Radiative decays		
Γ_{19}	$\gamma\gamma$	(6 $^{+6}_{-5}$) × 10^{-4}	

$\eta_c(1S)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ Γ_{19}

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
6.6$^{+2.4}_{-2.1}$ OUR AVERAGE					
5.9$^{+2.1}_{-1.8}$±1.9		CHEN	90B	CLEO	$e^+e^- \to e^+e^-\eta_c$
6.4$^{+5.0}_{-3.4}$		AIHARA	88D	TPC	$e^+e^- \to e^+e^- X$
28 ±15		[5] BERGER	86	PLUT	$\gamma\gamma \to K\overline{K}\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<11	90	BLINOV	86	MD1	$e^+e^- \to e^+e^- X$

[5] Re-evaluated by AIHARA 88D.

$\eta_c(1S)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\Gamma_{11}\Gamma_{19}/\Gamma$

VALUE (keV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
1.2 ±0.4 OUR AVERAGE						
1.06±0.41±0.27		11 ± 4	BRAUNSCH...	89	TASS	$\gamma\gamma \to K\overline{K}\pi$
1.5 $^{+0.60}_{-0.45}$±0.3		7	[6] BERGER	86	PLUT	$\gamma\gamma \to K\overline{K}\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.63	95		[6] BEHREND	89	CELL	$\gamma\gamma \to K^0_S K^\pm \pi^\mp$
<4.4	95		ALTHOFF	85B	TASS	$\gamma\gamma \to K\overline{K}\pi$

[6] $K^\pm K^0_S \pi^\mp$ corrected to $K\overline{K}\pi$ by factor 3.

$\eta_c(1S)$ BRANCHING RATIOS

HADRONIC DECAYS

$\Gamma(\eta'(958)\pi\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.041±0.017	14 ± 4	[7] BALTRUSAIT...	86	MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(\rho\rho)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
26 ± 9 OUR EVALUATION						
25 ± 8 OUR AVERAGE						
26.0± 2.4±8.8		113± 11	[7] BISELLO	91	DM2	$J/\psi \to \gamma\rho^0\rho^0$
23.6±10.6±8.2		32 ± 14	[7] BISELLO	91	DM2	$J/\psi \to \gamma\rho^+\rho^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<140	90		[7] BALTRUSAIT...	86	MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(K^*(892)^0 K^- \pi^+ + \text{c.c.})/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.02 ±0.007	63 ± 10	[7] BALTRUSAIT...	86	MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(K^*(892)\overline{K}^*(892))/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
85±31 OUR AVERAGE					
82±28±27	14 ± 5	[7] BISELLO	91	DM2	$e^+e^- \to \gamma K^+K^-\pi^+\pi^-$
90±50	9 ± 4	[7] BALTRUSAIT...	86	MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(K^*(892)K + \text{c.c.})/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0128	90	BISELLO	91	DM2	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
<0.0132	90	[7] BISELLO	91	DM2	$J/\psi \to \gamma K^+K^-\pi^0$

$\Gamma(\phi\phi)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
71±28 OUR EVALUATION (Treating systematic errors as correlated.)					
71±22 OUR AVERAGE					
74±18±24	80	[7] BAI	90B	MRK3	$J/\psi \to \gamma K^+K^-K^+K^-$
67±21±24		[7] BAI	90B	MRK3	$J/\psi \to \gamma K^+K^-K^0_S K^0_L$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
31± 7±10	19 ± 5	[7] BISELLO	91	DM2	$J/\psi \to \gamma K^+K^-K^+K^-$
30$^{+18}_{-12}$±10	5 ± 3	[7] BISELLO	91	DM2	$J/\psi \to \gamma K^+K^-K^0_S K^0_L$

$\Gamma(a_0(980)\pi)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[7,8] BALTRUSAIT...	86	MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(a_2(1320)\pi)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[7] BALTRUSAIT...	86	MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(f_2(1270)\eta)/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.011	90	[7] BALTRUSAIT...	86	MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(\omega\omega)/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0031	90	[7] BALTRUSAIT...	86	MRK3	$J/\psi \to \eta_c\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0063		[7] BISELLO	91	DM2	$J/\psi \to \gamma\omega\omega$

$\Gamma(K\overline{K}\pi)/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.066 ±0.018 OUR EVALUATION						
0.063 ±0.013 OUR AVERAGE						
0.0690±0.0144±0.0234		33 ± 7	[7] BISELLO	91	DM2	$J/\psi \to \gamma K^+K^-\pi^0$
0.0543±0.0096±0.0180		68 ± 10	[7] BISELLO	91	DM2	$J/\psi \to \gamma K^\pm\pi^\mp K^0_S$
0.061 ±0.022		95 ± 18	[7,9] BALTRUSAIT...	86	MRK3	$J/\psi \to \eta_c\gamma$
0.161 $^{+0.092}_{-0.073}$			[10] HIMEL	80B	MRK2	$\psi(2S) \to \eta_c\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.107	90		[7] PARTRIDGE	80B	CBAL	$J/\psi \to \eta_c\gamma$

$\Gamma(\eta\pi\pi)/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.049±0.018 OUR EVALUATION					
0.047±0.015 OUR AVERAGE					
0.054±0.020	75 ± 11	[7] BALTRUSAIT...	86	MRK3	$J/\psi \to \eta_c\gamma$
0.037±0.013±0.020	18	[7] PARTRIDGE	80B	CBAL	$J/\psi \to \eta\pi^+\pi^-\gamma$

$\Gamma(\pi^+\pi^- K^+ K^-)/\Gamma_{\text{total}}$ Γ_{13}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.020$^{+0.007}_{-0.006}$ OUR AVERAGE					
0.021±0.007	110± 17	[7] BALTRUSAIT...	86	MRK3	$J/\psi \to \eta_c\gamma$
0.014$^{+0.022}_{-0.009}$		[10] HIMEL	80B	MRK2	$\psi(2S) \to \eta_c\gamma$

$\Gamma(2(\pi^+\pi^-))/\Gamma_{\text{total}}$ Γ_{14}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.012 ±0.004 OUR EVALUATION					
0.0120±0.0031 OUR AVERAGE					
0.0105±0.0017±0.0034	137± 23	[7] BISELLO	91	DM2	$J/\psi \to \gamma 2\pi^+ 2\pi^-$
0.013 ±0.006	25 ± 9	[7] BALTRUSAIT...	86	MRK3	$J/\psi \to \eta_c\gamma$
0.020 $^{+0.015}_{-0.010}$		[10] HIMEL	80B	MRK2	$\psi(2S) \to \eta_c\gamma$

$\Gamma(p\overline{p})/\Gamma_{total}$ — Γ_{15}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
12± 4 OUR AVERAGE					
10± 3±4	18 ± 6	[7] BISELLO	91	DM2	$J/\psi \to \gamma p\overline{p}$
11± 6	23 ± 11	[7] BALTRUSAIT...86		MRK3	$J/\psi \to \eta_c\gamma$
29^{+29}_{-15}		[10] HIMEL	80B	MRK2	$\psi(2S) \to \eta_c\gamma$

$\Gamma(K\overline{K}\eta)/\Gamma_{total}$ — Γ_{16}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.031	90	[7] BALTRUSAIT...86		MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(\pi^+\pi^-p\overline{p})/\Gamma_{total}$ — Γ_{17}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.012	90	HIMEL	80B	MRK2	$\psi(2S) \to \eta_c\gamma$

$\Gamma(\Lambda\overline{\Lambda})/\Gamma_{total}$ — Γ_{18}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.002	90	[7] BISELLO	91	DM2	$e^+e^- \to \gamma\Lambda\overline{\Lambda}$

$\Gamma_i\Gamma_f/\Gamma^2_{total}$ in $p\overline{p} \to \eta_c(1S) \to \phi\phi$ — $\Gamma_{15}\Gamma_6/\Gamma^2$

VALUE (units 10^{-5})	DOCUMENT ID		TECN	COMMENT
$\mathbf{4.0^{+3.5}_{-3.2}}$	BAGLIN	89	SPEC	$\overline{p}p \to K^+K^-K^+K^-$

[7] The quoted branching ratios use $B(J/\psi(1S) \to \gamma\eta_c(1S)) = 0.0127 \pm 0.0036$. Where relevant, the error in this branching ratio is treated as a common systematic in computing averages.
[8] We are assuming $B(a_0(980) \to \eta\pi) > 0.5$.
[9] Average from $K^+K^-\pi^0$ and $K^\pm K^0$'s $\pi^\mp$ decay channels.
[10] Estimated using $B(\psi(2S) \to \gamma\eta_c(1S)) = 0.0028 \pm 0.0006$.

RADIATIVE DECAYS

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_{19}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
$\mathbf{6^{+4}_{-3}\pm4}$		BAGLIN	87B	SPEC	$\overline{p}p \to \gamma\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 9	90	[7] BISELLO	91	DM2	$J/\psi \to \gamma\gamma\gamma$
<18	90	[11] BLOOM	83	CBAL	$J/\psi \to \eta_c\gamma$

[11] Using $B(J/\psi(1S) \to \gamma\eta_c(1S)) = 0.0127 \pm 0.0036$.

$\Gamma_i\Gamma_f/\Gamma^2_{total}$ in $p\overline{p} \to \eta_c(1S) \to \gamma\gamma$ — $\Gamma_{15}\Gamma_{19}/\Gamma^2$

VALUE (units 10^{-6})	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.68^{+0.42}_{-0.31}}$	12	BAGLIN	87B	SPEC	$\overline{p}p \to \gamma\gamma$

$\eta_c(1S)$ REFERENCES

BISELLO	91	NP B350 1	+Busetto+	(DM2 Collab.)
BAI	90B	PRL 65 1309	+Blaylock+	(Mark III Collab.)
CHEN	90B	PL B243 169	+McIlwain+	(CLEO Collab.)
BAGLIN	89	PL B231 557	+Baird, Bassompierre	(R704 Collab.)
BEHREND	89	ZPHY C42 367	+Criegee+	(CELLO Collab.)
BRAUNSCH...	89	ZPHY C41 533	Braunschweig, Bock+	(TASSO Collab.)
AIHARA	88D	PRL 60 2355	+Alston-Garnjost+	(TPC Collab.)
BAGLIN	87B	PL B187 191	+Baird, Bassompierre, Borreani+	(R704 Collab.)
BALTRUSAIT...	86	PR D33 629	Baltrusaitis, Coffman, Hauser+	(Mark III Collab.)
BERGER	86	PL 167B 120	+Genzel, Lackas, Pielorz+	(PLUTO Collab.)
BLINOV	86	NOVO 86-107 Translated from IYAF 86-107.	+Blinov, Bondar, Bukin+	(NOVO)
GAISER	86	PR D34 711	+Bloom, Bulos, Godfrey+	(Crystal Ball Collab.)
ALTHOFF	85B	ZPHY C29 189	+Braunschweig, Kirschfink+	(TASSO Collab.)
BALTRUSAIT...	84	PRL 52 2126	Baltrusaitis+	(CIT, UCSC, ILL, SLAC, WASH) JP
BLOOM	83	ARNS 33 143	+Peck	(SLAC, CIT)
HIMEL	80B	PRL 45 1146	+Trilling, Abrams, Alam+	(SLAC, LBL, UCB)
PARTRIDGE	80B	PRL 45 1150	+Peck+	(CIT, HARV, PRIN, STAN, SLAC)

OTHER RELATED PAPERS

ARMSTRONG	89	PL B221 216	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, LPNP)
BLOOM	79	Fermilab Symp. 92		(CIT, HARV, PRIN, SLAC, STAN)

$J/\psi(1S)$ or $J/\psi(3097)$

$I^G(J^{PC}) = 0^-(1^{--})$

$J/\psi(1S)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3096.93±0.09 OUR AVERAGE					
3096.95±0.1 ±0.3	193	BAGLIN	87	SPEC	$\overline{p}p \to e^+e^-X$
3098.4 ±2.0	38k	LEMOIGNE	82	GOLI	190 GeV π^- Be $\to 2\mu$
3096.93±0.09	502	ZHOLENTZ	80	REDE	e^+e^-
3097.0 ±1		[1] BRANDELIK	79C	DASP	e^+e^-

[1] From a simultaneous fit to e^+e^-, $\mu^+\mu^-$ and hadronic channels assuming $\Gamma(e^+e^-) = \Gamma(\mu^+\mu^-)$.

$J/\psi(1S)$ WIDTH

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
$\mathbf{85.5^{+6.1}_{-5.8}}$	[2] HSUEH	92	RVUE	See Υ mini-review

[2] Using data from COFFMAN 92, BALDINI-CELIO 75, BOYARSKI 75, ESPOSITO 75B, BRANDELIK 79C

$J/\psi(1S)$ DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	hadrons		(86.0 ±2.0) %	
Γ_2	virtual $\gamma \to$ hadrons		(17.0 ±2.0) %	
Γ_3	e^+e^-		(6.27±0.20) %	
Γ_4	$\mu^+\mu^-$		(5.97±0.25) %	S=1.1
	Decays involving hadronic resonances			
Γ_5	$\rho\pi$		(1.28±0.10) %	
Γ_6	$\rho^0\pi^0$		(4.2 ±0.5) $\times 10^{-3}$	
Γ_7	$a_2(1320)\rho$		(1.09±0.22) %	
Γ_8	$\omega\pi^+\pi^+\pi^-\pi^-$		(8.5 ±3.4) $\times 10^{-3}$	
Γ_9	$\omega\pi^+\pi^-$		(7.2 ±1.0) $\times 10^{-3}$	
Γ_{10}	$K^*(892)^0\overline{K}^*_2(1430)^0$ + c.c.		(6.7 ±2.6) $\times 10^{-3}$	
Γ_{11}	$\omega K^*(892)\overline{K}$ + c.c.		(5.3 ±2.0) $\times 10^{-3}$	
Γ_{12}	$\omega f_2(1270)$		(4.3 ±0.6) $\times 10^{-3}$	
Γ_{13}	$K^+\overline{K}^*(892)^-$ + c.c.		(5.0 ±0.4) $\times 10^{-3}$	
Γ_{14}	$K^0\overline{K}^*(892)^0$ + c.c.		(4.2 ±0.4) $\times 10^{-3}$	
Γ_{15}	$\omega\pi^0\pi^0$		(3.4 ±0.8) $\times 10^{-3}$	
Γ_{16}	$b_1(1235)^\pm\pi^\mp$	[a]	(3.0 ±0.5) $\times 10^{-3}$	
Γ_{17}	$\omega K^\pm K^0_S\pi^\mp$	[a]	(2.9 ±0.7) $\times 10^{-3}$	
Γ_{18}	$b_1(1235)^0\pi^0$		(2.3 ±0.6) $\times 10^{-3}$	
Γ_{19}	$\phi K^*(892)\overline{K}$ + c.c.		(2.04±0.28) $\times 10^{-3}$	
Γ_{20}	$\omega K\overline{K}$		(1.9 ±0.4) $\times 10^{-3}$	
Γ_{21}	$\omega f_0(1710) \to \omega K\overline{K}$		(4.8 ±1.1) $\times 10^{-4}$	
Γ_{22}	$\phi 2(\pi^+\pi^-)$		(1.60±0.32) $\times 10^{-3}$	
Γ_{23}	$\Delta(1232)^{++}\overline{p}\pi^-$		(1.6 ±0.5) $\times 10^{-3}$	
Γ_{24}	$\omega\eta$		(1.58±0.16) $\times 10^{-3}$	
Γ_{25}	$\phi K\overline{K}$		(1.48±0.22) $\times 10^{-3}$	
Γ_{26}	$\phi f_0(1710) \to \phi K\overline{K}$		(3.6 ±0.6) $\times 10^{-4}$	
Γ_{27}	$p\overline{p}\omega$		(1.30±0.25) $\times 10^{-3}$	S=1.3
Γ_{28}	$\Delta(1232)^{++}\overline{\Delta}(1232)^{--}$		(1.10±0.29) $\times 10^{-3}$	
Γ_{29}	$\Sigma(1385)^-\overline{\Sigma}(1385)^+$ (or c.c.)	[a]	(1.03±0.13) $\times 10^{-3}$	
Γ_{30}	$p\overline{p}\eta'(958)$		(9 ±4) $\times 10^{-4}$	S=1.7
Γ_{31}	$\phi f'_2(1525)$		(8 ±4) $\times 10^{-4}$	S=2.7
Γ_{32}	$\phi\pi^+\pi^-$		(8.0 ±1.2) $\times 10^{-4}$	
Γ_{33}	$\phi K^\pm K^0_S\pi^\mp$	[a]	(7.2 ±0.9) $\times 10^{-4}$	
Γ_{34}	$\omega f_1(1420)$		(6.8 ±2.4) $\times 10^{-4}$	
Γ_{35}	$\phi\eta$		(6.5 ±0.7) $\times 10^{-4}$	
Γ_{36}	$\Xi(1530)^-\overline{\Xi}^+$		(5.9 ±1.5) $\times 10^{-4}$	
Γ_{37}	$pK^-\overline{\Sigma}(1385)^0$		(5.1 ±3.2) $\times 10^{-4}$	
Γ_{38}	$\omega\pi^0$		(4.2 ±0.6) $\times 10^{-4}$	S=1.4
Γ_{39}	$\phi\eta'(958)$		(3.3 ±0.4) $\times 10^{-4}$	
Γ_{40}	$\phi f_0(975)$		(3.2 ±0.9) $\times 10^{-4}$	S=1.9
Γ_{41}	$\Xi(1530)^0\overline{\Xi}^0$		(3.2 ±1.4) $\times 10^{-4}$	
Γ_{42}	$\Sigma(1385)^-\overline{\Sigma}^+$ (or c.c.)	[a]	(3.1 ±0.5) $\times 10^{-4}$	
Γ_{43}	$\phi f_1(1285)$		(2.6 ±0.5) $\times 10^{-4}$	S=1.1

Γ_{44}	$\rho\eta$		$(1.93\pm0.23)\times10^{-4}$	
Γ_{45}	$\omega\eta'(958)$		$(1.67\pm0.25)\times10^{-4}$	
Γ_{46}	$\omega f_0(975)$		$(1.4\pm0.5)\times10^{-4}$	
Γ_{47}	$\rho\eta'(958)$		$(1.05\pm0.18)\times10^{-4}$	
Γ_{48}	$p\overline{p}\phi$		$(4.5\pm1.5)\times10^{-5}$	
Γ_{49}	$a_2(1320)^{\pm}\pi^{\mp}$	[a]	$<4.3\times10^{-3}$	CL=90%
Γ_{50}	$K\overline{K}{}_2^*(1430)$ + c.c.		$<4.0\times10^{-3}$	CL=90%
Γ_{51}	$K_2^*(1430)^0\overline{K}{}_2^*(1430)^0$		$<2.9\times10^{-3}$	CL=90%
Γ_{52}	$K^*(892)^0\overline{K}{}^*(892)^0$		$<5\times10^{-4}$	CL=90%
Γ_{53}	$\phi f_2(1270)$		$<3.7\times10^{-4}$	CL=90%
Γ_{54}	$p\overline{p}\rho$		$<3.1\times10^{-4}$	CL=90%
Γ_{55}	$\phi\eta(1440)\to\phi\eta\pi\pi$		$<2.5\times10^{-4}$	CL=90%
Γ_{56}	$\omega f_2'(1525)$		$<2.2\times10^{-4}$	CL=90%
Γ_{57}	$\Sigma(1385)^0\overline{\Lambda}$		$<2\times10^{-4}$	CL=90%
Γ_{58}	$\Delta(1232)^+\overline{p}$		$<1\times10^{-4}$	CL=90%
Γ_{59}	$\Sigma^0\overline{\Lambda}$		$<9\times10^{-5}$	CL=90%
Γ_{60}	$\phi\pi^0$		$<6.8\times10^{-6}$	CL=90%

Decays into stable hadrons

Γ_{61}	$2(\pi^+\pi^-)\pi^0$		(3.37 ± 0.26) %	
Γ_{62}	$3(\pi^+\pi^-)\pi^0$		(2.9 ± 0.6) %	
Γ_{63}	$\pi^+\pi^-\pi^0$		(1.50 ± 0.15) %	
Γ_{64}	$\pi^+\pi^-\pi^0K^+K^-$		(1.20 ± 0.30) %	
Γ_{65}	$4(\pi^+\pi^-)\pi^0$		$(9.0\pm3.0)\times10^{-3}$	
Γ_{66}	$\pi^+\pi^-K^+K^-$		$(7.2\pm2.3)\times10^{-3}$	
Γ_{67}	$K\overline{K}\pi$		$(6.1\pm1.0)\times10^{-3}$	
Γ_{68}	$p\overline{p}\pi^+\pi^-$		$(6.0\pm0.5)\times10^{-3}$	S=1.3
Γ_{69}	$2(\pi^+\pi^-)$		$(4.0\pm1.0)\times10^{-3}$	
Γ_{70}	$3(\pi^+\pi^-)$		$(4.0\pm2.0)\times10^{-3}$	
Γ_{71}	$n\overline{n}\pi^+\pi^-$		$(4\pm4)\times10^{-3}$	
Γ_{72}	$\Sigma\overline{\Sigma}$		$(3.8\pm0.5)\times10^{-3}$	
Γ_{73}	$2(\pi^+\pi^-)K^+K^-$		$(3.1\pm1.3)\times10^{-3}$	
Γ_{74}	$p\overline{p}\pi^+\pi^-\pi^0$	[b]	$(2.3\pm0.9)\times10^{-3}$	S=1.9
Γ_{75}	$p\overline{p}$		$(2.16\pm0.11)\times10^{-3}$	
Γ_{76}	$p\overline{p}\eta$		$(2.09\pm0.18)\times10^{-3}$	
Γ_{77}	$p\overline{n}\pi^-$		$(2.00\pm0.10)\times10^{-3}$	
Γ_{78}	$\Xi\overline{\Xi}$		$(1.8\pm0.4)\times10^{-3}$	S=1.8
Γ_{79}	$n\overline{n}$		$(1.8\pm0.9)\times10^{-3}$	
Γ_{80}	$\Lambda\overline{\Lambda}$		$(1.35\pm0.14)\times10^{-3}$	S=1.2
Γ_{81}	$p\overline{p}\pi^0$		$(1.09\pm0.09)\times10^{-3}$	
Γ_{82}	$\Lambda\overline{\Sigma}{}^-\pi^+$ (or c.c.)	[a]	$(1.06\pm0.12)\times10^{-3}$	
Γ_{83}	$pK^-\overline{\Lambda}$		$(8.9\pm1.6)\times10^{-4}$	
Γ_{84}	$2(K^+K^-)$		$(7.0\pm3.0)\times10^{-4}$	
Γ_{85}	$pK^-\overline{\Sigma}{}^0$		$(2.9\pm0.8)\times10^{-4}$	
Γ_{86}	K^+K^-		$(2.37\pm0.31)\times10^{-4}$	
Γ_{87}	$\Lambda\overline{\Lambda}\pi^0$		$(2.2\pm0.7)\times10^{-4}$	
Γ_{88}	$\pi^+\pi^-$		$(1.47\pm0.23)\times10^{-4}$	
Γ_{89}	$K_S^0K_L^0$		$(1.08\pm0.14)\times10^{-4}$	
Γ_{90}	$\Lambda\overline{\Sigma}$ + c.c.		$<1.5\times10^{-4}$	CL=90%
Γ_{91}	$K_S^0K_S^0$		$<5.2\times10^{-6}$	CL=90%

Radiative decays

Γ_{92}	$\gamma\eta_c(1S)$		(1.3 ± 0.4) %	
Γ_{93}	$\gamma\pi^+\pi^-2\pi^0$		$(8.3\pm3.1)\times10^{-3}$	
Γ_{94}	$\gamma\eta\pi\pi$		$(6.1\pm1.0)\times10^{-3}$	
Γ_{95}	$\gamma\eta(1440)\to\gamma K\overline{K}\pi$	[c]	$(9.1\pm1.8)\times10^{-4}$	
Γ_{96}	$\gamma\eta(1440)\to\gamma\gamma\rho^0$		$(6.4\pm1.4)\times10^{-5}$	
Γ_{97}	$\gamma\rho\rho$		$(4.5\pm0.8)\times10^{-3}$	
Γ_{98}	$\gamma\eta'(958)$		$(4.34\pm0.34)\times10^{-3}$	
Γ_{99}	$\gamma2\pi^+2\pi^-$		$(2.8\pm0.5)\times10^{-3}$	S=1.9
Γ_{100}	$\gamma f_4(2050)$		$(2.7\pm0.7)\times10^{-3}$	
Γ_{101}	$\gamma\omega\omega$		$(1.59\pm0.33)\times10^{-3}$	
Γ_{102}	$\gamma\eta(1440)\to\gamma\rho^0\rho^0$		$(1.4\pm0.4)\times10^{-3}$	
Γ_{103}	$\gamma f_2(1270)$		$(1.38\pm0.14)\times10^{-3}$	
Γ_{104}	$\gamma f_0(1710)\to\gamma K\overline{K}$		$(9.7\pm1.2)\times10^{-4}$	
Γ_{105}	$\gamma\eta$		$(8.6\pm0.8)\times10^{-4}$	
Γ_{106}	$\gamma f_1(1420)\to\gamma K\overline{K}\pi$		$(8.3\pm1.5)\times10^{-4}$	
Γ_{107}	$\gamma f_1(1285)$		$(7.0\pm1.8)\times10^{-4}$	
Γ_{108}	$\gamma f_2'(1525)$		$(6.3\pm1.0)\times10^{-4}$	
Γ_{109}	$\gamma\phi\phi$		$(4.0\pm1.2)\times10^{-4}$	S=2.1
Γ_{110}	$\gamma p\overline{p}$		$(3.8\pm1.0)\times10^{-4}$	
Γ_{111}	$\gamma\eta(2100)$		$(2.9\pm0.6)\times10^{-4}$	
Γ_{112}	$\gamma\eta(1760)\to\gamma\rho^0\rho^0$		$(1.3\pm0.9)\times10^{-4}$	
Γ_{113}	$\gamma\pi^0$		$(3.9\pm1.3)\times10^{-5}$	
Γ_{114}	$\gamma p\overline{p}\pi^+\pi^-$		$<7.9\times10^{-4}$	CL=90%
Γ_{115}	$\gamma\gamma$		$<5\times10^{-4}$	CL=90%
Γ_{116}	$\gamma\Lambda\overline{\Lambda}$		$<1.3\times10^{-4}$	CL=90%
Γ_{117}	3γ		$<5.5\times10^{-5}$	CL=90%
Γ_{118}	$\gamma X(2200)$			
Γ_{119}	$\gamma f_4(2220)$			
Γ_{120}	$\gamma X(1400)$			

[a] Value is for the sum of the charge states indicated.

[b] Includes $p\overline{p}\pi^+\pi^-\gamma$ and excludes $p\overline{p}\eta$, $p\overline{p}\omega$, $p\overline{p}\eta'$.

[c] See $\eta(1440)$ mini-review.

$J/\psi(1S)$ PARTIAL WIDTHS

Γ(hadrons) — Γ_1

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
59±24	BALDINI-...	75	FRAG	e^+e^-
59±14	BOYARSKI	75	MRK1	e^+e^-
50±25	ESPOSITO	75B	FRAM	e^+e^-

Γ(virtual $\gamma\to$ hadrons) — Γ_2

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
12 ±2	[3] BOYARSKI	75	MRK1	e^+e^-

[3] Included in Γ(hadrons).

$\Gamma(e^+e^-)$ — Γ_3

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
$\mathbf{5.36^{+0.29}_{-0.28}}$	[4] HSUEH	92	RVUE	See Υ mini-review
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.72±0.35	ALEXANDER	89	RVUE	See Υ mini-review
4.4 ±0.6	[5] BRANDELIK	79C	DASP	e^+e^-
4.6 ±0.8	[6] BALDINI-...	75	FRAG	e^+e^-
4.8 ±0.6	BOYARSKI	75	MRK1	e^+e^-
4.6 ±1.0	ESPOSITO	75B	FRAM	e^+e^-

[4] From COFFMAN 92 and data below.
[5] From a simultaneous fit to e^+e^-, $\mu^+\mu^-$, and hadronic channels assuming $\Gamma(e^+e^-) = \Gamma(\mu^+\mu^-)$.
[6] Assuming equal partial widths for e^+e^- and $\mu^+\mu^-$.

$\Gamma(\mu^+\mu^-)$ — Γ_4

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.8±0.6	BOYARSKI	75	MRK1	e^+e^-
5.0±1.0	ESPOSITO	75B	FRAM	e^+e^-

$\Gamma(\gamma\gamma)$ — Γ_{115}

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<5.4	90	BRANDELIK	79C	DASP	e^+e^-

$J/\psi(1S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma$(total)

This combination of a partial width with the partial width into e^+e^- and with the total width is obtained from the integrated cross section into channel$_i$ in the e^+e^- annihilation.

Γ(hadrons) × $\Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4 ±0.8	[7] BALDINI-...	75	FRAG	e^+e^-
3.9±0.8	[7] ESPOSITO	75B	FRAM	e^+e^-

$\Gamma(e^+e^-)$ × $\Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_3\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.35±0.02	BRANDELIK	79C	DASP	e^+e^-
0.32±0.07	[7] BALDINI-...	75	FRAG	e^+e^-
0.34±0.14	BEMPORAD	75	FRAB	e^+e^-
0.34±0.09	[7] ESPOSITO	75B	FRAM	e^+e^-
0.36±0.10	[7] FORD	75	SPEC	e^+e^-

$\Gamma(\mu^+\mu^-) \times \Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_4\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.31±0.09	BEMPORAD	75	FRAB	e^+e^-
0.51±0.09	DASP	75	DASP	e^+e^-
0.38±0.05	[7] ESPOSITO	75B	FRAM	e^+e^-
0.46±0.10	[7] LIBERMAN	75	SPEC	e^+e^-

[7] Data redundant with branching ratios or partial widths above.

$J/\psi(1S)$ BRANCHING RATIOS

For the first four branching ratios, see also the partial widths, and (partial widths) × $\Gamma(e^+e^-)/\Gamma_{total}$ above.

$\Gamma(\text{hadrons})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.86 ±0.02	BOYARSKI	75	MRK1	e^+e^-

$\Gamma(\text{virtual } \gamma \to \text{hadrons})/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.17 ±0.02	[8] BOYARSKI	75	MRK1	e^+e^-

[8] Included in $\Gamma(\text{hadrons})/\Gamma_{total}$.

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.0627^{+0.0020}_{-0.0019}$	[9] HSUEH	92	RVUE	See Υ mini-review
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0592±0.0015±0.0020	COFFMAN	92	MRK3	$\psi(2S) \to J/\psi \pi^+\pi^-$
0.069 ±0.009	BOYARSKI	75	MRK1	e^+e^-

[9] Using COFFMAN 92 and BOYARSKI 75. Not independent of full width and leptonic partial width determinations.

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0597±0.0025 OUR AVERAGE	Error includes scale factor of 1.1.			
0.0590±0.0015±0.0019	COFFMAN	92	MRK3	$\psi(2S) \to J/\psi \pi^+\pi^-$
0.069 ±0.009	BOYARSKI	75	MRK1	e^+e^-

$\Gamma(e^+e^-)/\Gamma(\mu^+\mu^-)$ — Γ_3/Γ_4

VALUE	DOCUMENT ID		TECN	COMMENT
0.98±0.04 OUR AVERAGE				
1.00±0.05	BOYARSKI	75	MRK1	e^+e^-
0.91±0.15	ESPOSITO	75B	FRAM	e^+e^-
0.93±0.10	FORD	75	SPEC	e^+e^-

HADRONIC DECAYS

$\Gamma(\rho\pi)/\Gamma_{total}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0128±0.0010 OUR AVERAGE					
0.0142±0.0001±0.0019		COFFMAN	88	MRK3	e^+e^-
0.013 ±0.003	150	FRANKLIN	83	MRK2	e^+e^-
0.016 ±0.004	183	ALEXANDER	78	PLUT	e^+e^-
0.0133±0.0021		BRANDELIK	78B	DASP	e^+e^-
0.010 ±0.002	543	BARTEL	76	CNTR	e^+e^-
0.013 ±0.003	153	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(\rho^0\pi^0)/\Gamma(\rho\pi)$ — Γ_6/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
0.328±0.005±0.027	COFFMAN	88	MRK3	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.36 ±0.03	SCHARRE	79B	MRK1	e^+e^-
0.35 ±0.08	ALEXANDER	78	PLUT	e^+e^-
0.32 ±0.08	BRANDELIK	78B	DASP	e^+e^-
0.39 ±0.11	BARTEL	76	CNTR	e^+e^-
0.37 ±0.09	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(a_2(1320)\rho)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
10.9±2.2 OUR AVERAGE					
11.7±0.7±2.5	7584	AUGUSTIN	89	DM2	$J/\psi \to \rho^0\rho^\pm\pi^\mp$
8.4±4.5	36	VANNUCCI	77	MRK1	$e^+e^- \to 2(\pi^+\pi^-)\pi^0$

$\Gamma(\omega\pi^+\pi^+\pi^-\pi^-)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
85±34	140	VANNUCCI	77	MRK1	$e^+e^- \to 3(\pi^+\pi^-)\pi^0$

$\Gamma(\omega\pi^+\pi^-)/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
7.2±1.0 OUR AVERAGE					
7.0±1.6	18058	AUGUSTIN	89	DM2	$J/\psi \to 2(\pi^+\pi^-)\pi^0$
7.8±1.6	215	BURMESTER	77D	PLUT	e^+e^-
6.8±1.9	348	VANNUCCI	77	MRK1	$e^+e^- \to 2(\pi^+\pi^-)\pi^0$

$\Gamma(\omega\pi^+\pi^-)/\Gamma(2(\pi^+\pi^-)\pi^0)$ — Γ_9/Γ_{61}

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.3	[10] JEAN-MARIE	76	MRK1	e^+e^-

[10] Final state $(\pi^+\pi^-)\pi^0$ under the assumption that $\pi\pi$ is isospin 0.

$\Gamma(K^*(892)^0\overline{K}{}^*_2(1430)^0 + \text{c.c.})/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
67±26	40	VANNUCCI	77	MRK1	$e^+e^- \to \pi^+\pi^-K^+K^-$

$\Gamma(\omega K^*(892)\overline{K} + \text{c.c.})/\Gamma_{total}$ — Γ_{11}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
53±14±14	530±140	BECKER	87	MRK3	$e^+e^- \to$ hadrons

$\Gamma(\omega f_2(1270))/\Gamma_{total}$ — Γ_{12}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
4.3±0.6 OUR AVERAGE					
4.3±0.2±0.6	5860	AUGUSTIN	89	DM2	e^+e^-
4.0±1.6	70	BURMESTER	77D	PLUT	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.9±0.8	81	VANNUCCI	77	MRK1	$e^+e^- \to 2(\pi^+\pi^-)\pi^0$

$\Gamma(K^+\overline{K}{}^*(892)^- + \text{c.c.})/\Gamma_{total}$ — Γ_{13}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
5.0 ±0.4 OUR AVERAGE					
4.57±0.17±0.70	2285	JOUSSET	90	DM2	$J/\psi \to$ hadrons
5.26±0.13±0.53		COFFMAN	88	MRK3	$J/\psi \to K^\pm K^0_S \pi^\mp$, $K^+K^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.6 ±0.6	24	FRANKLIN	83	MRK2	$J/\psi \to K^+K^-\pi^0$
3.2 ±0.6	48	VANNUCCI	77	MRK1	$J/\psi \to K^\pm K^0_S \pi^\mp$
4.1 ±1.2	39	BRAUNSCH...	76	DASP	$J/\psi \to K^\pm X$

$\Gamma(K^0\overline{K}{}^*(892)^0 + \text{c.c.})/\Gamma_{total}$ — Γ_{14}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
4.2 ±0.4 OUR AVERAGE					
3.96±0.15±0.60	1192	JOUSSET	90	DM2	$J/\psi \to$ hadrons
4.33±0.12±0.45		COFFMAN	88	MRK3	$J/\psi \to K^\pm K^0_S \pi^\mp$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.7 ±0.6	45	VANNUCCI	77	MRK1	$J/\psi \to K^\pm K^0_S \pi^\mp$

$\Gamma(K^0\overline{K}{}^*(892)^0 + \text{c.c.})/\Gamma(K^+\overline{K}{}^*(892)^- + \text{c.c.})$ — Γ_{14}/Γ_{13}

VALUE	DOCUMENT ID		TECN	COMMENT
0.82±0.05±0.09	COFFMAN	88	MRK3	$J/\psi \to K\overline{K}{}^*(892)$ +c.c.

$\Gamma(\omega\pi^0\pi^0)/\Gamma_{total}$ — Γ_{15}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
3.4±0.3±0.7	509	AUGUSTIN	89	DM2	$J/\psi \to \pi^+\pi^-3\pi^0$

$\Gamma(b_1(1235)^\pm\pi^\mp)/\Gamma_{total}$ — Γ_{16}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
30±5 OUR AVERAGE					
31±6	4600	AUGUSTIN	89	DM2	$J/\psi \to 2(\pi^+\pi^-)\pi^0$
29±7	87	BURMESTER	77D	PLUT	e^+e^-

$\Gamma(\omega K^\pm K^0_S \pi^\mp)/\Gamma_{total}$ — Γ_{17}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
29.5±1.4±7.0	879±41	BECKER	87	MRK3	$e^+e^- \to$ hadrons

$\Gamma(b_1(1235)^0\pi^0)/\Gamma_{total}$ — Γ_{18}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
23±3±5	229	AUGUSTIN	89	DM2	e^+e^-

$\Gamma(\phi K^*(892)\overline{K} + \text{c.c.})/\Gamma_{total}$ — Γ_{19}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
20.4±2.8 OUR AVERAGE					
20.7±2.4±3.0		FALVARD	88	DM2	$J/\psi \to$ hadrons
20 ±3 ±3	155±20	BECKER	87	MRK3	$e^+e^- \to$ hadrons

$\Gamma(\omega K\overline{K})/\Gamma_{total}$ — Γ_{20}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
19 ± 4 OUR AVERAGE					
19.8± 2.1±3.9		[11] FALVARD	88	DM2	$J/\psi \to$ hadrons
16 ±10	22	FELDMAN	77	MRK1	e^+e^-

[11] Addition of ωK^+K^- and $\omega K^0\overline{K}{}^0$ branching ratios.

$\Gamma(\omega f_0(1710) \to \omega K\overline{K})/\Gamma_{total}$ — Γ_{21}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
4.8±1.1±0.3	[12,13] FALVARD	88	DM2	$J/\psi \to$ hadrons

[12] Includes unknown branching fraction $f_0(1710) \to K\overline{K}$.
[13] Addition of $f_0(1710) \to K^+K^-$ and $f_0(1710) \to K^0\overline{K}^0$ branching ratios.

$\Gamma(\phi 2(\pi^+\pi^-))/\Gamma_{total}$ — Γ_{22}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
16.0±1.0±3.0	FALVARD	88	DM2	$J/\psi \to$ hadrons

$\Gamma(\Delta(1232)^{++}\overline{p}\pi^-)/\Gamma_{total}$ — Γ_{23}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.58±0.23±0.40	332	EATON	84	MRK2	e^+e^-

$\Gamma(\omega\eta)/\Gamma_{total}$ — Γ_{24}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.58±0.16 OUR AVERAGE					
1.43±0.10±0.21	378	JOUSSET	90	DM2	$J/\psi \to$ hadrons
1.71±0.08±0.20		COFFMAN	88	MRK3	$e^+e^- \to 3\pi\eta$

$\Gamma(\phi K\overline{K})/\Gamma_{total}$ — Γ_{25}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
14.8±2.2 OUR AVERAGE					
14.6±0.8±2.1		[14] FALVARD	88	DM2	$J/\psi \to$ hadrons
18 ±8	14	FELDMAN	77	MRK1	e^+e^-

[14] Addition of ϕK^+K^- and $\phi K^0\overline{K}^0$ branching ratios.

$\Gamma(\phi f_0(1710) \to \phi K\overline{K})/\Gamma_{total}$ — Γ_{26}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
3.6± .2±0.6	[15,16] FALVARD	88	DM2	$J/\psi \to$ hadrons

[15] Including interference with $f_2'(1525)$.
[16] Includes unknown branching fraction $f_0(1710) \to K\overline{K}$.

$\Gamma(p\overline{p}\omega)/\Gamma_{total}$ — Γ_{27}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.30±0.25 OUR AVERAGE Error includes scale factor of 1.3.					
1.10±0.17±0.18	486	EATON	84	MRK2	e^+e^-
1.6 ±0.3	77	PERUZZI	78	MRK1	e^+e^-

$\Gamma(\Delta(1232)^{++}\overline{\Delta}(1232)^{--})/\Gamma_{total}$ — Γ_{28}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.10±0.09±0.28	233	EATON	84	MRK2	e^+e^-

$\Gamma(\Sigma(1385)^-\overline{\Sigma}(1385)^+$ (or c.c.)$)/\Gamma_{total}$ — Γ_{29}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.03±0.13 OUR AVERAGE					
1.00±0.04±0.21	631±25	HENRARD	87	DM2	$e^+e^- \to \Sigma^{*-}$
1.19±0.04±0.25	754±27	HENRARD	87	DM2	$e^+e^- \to \Sigma^{*+}$
0.86±0.18±0.22	56	EATON	84	MRK2	$e^+e^- \to \Sigma^{*-}$
1.03±0.24±0.25	68	EATON	84	MRK2	$e^+e^- \to \Sigma^{*+}$

$\Gamma(p\overline{p}\eta'(958))/\Gamma_{total}$ — Γ_{30}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.9 ±0.4 OUR AVERAGE Error includes scale factor of 1.7.					
0.68±0.23±0.17	19	EATON	84	MRK2	e^+e^-
1.8 ±0.6	19	PERUZZI	78	MRK1	e^+e^-

$\Gamma(\phi f_2'(1525))/\Gamma_{total}$ — Γ_{31}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
8 ±4 OUR AVERAGE Error includes scale factor of 2.7.					
12.3±0.6±2.0		[17,18] FALVARD	88	DM2	$J/\psi \to$ hadrons
4.8±1.8	46	[17] GIDAL	81	MRK2	e^+e^-

[17] Re-evaluated using B($f_2'(1525) \to K\overline{K}$) = 0.713.
[18] Including interference with $f_0(1710)$.

$\Gamma(\phi\pi^+\pi^-)/\Gamma_{total}$ — Γ_{32}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.80±0.12 OUR AVERAGE					
0.78±0.03±0.12		FALVARD	88	DM2	$J/\psi \to$ hadrons
2.1 ±0.9	23	FELDMAN	77	MRK1	e^+e^-

$\Gamma(\phi K^\pm K^0_S\pi^\mp)/\Gamma_{total}$ — Γ_{33}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
7.2±0.9 OUR AVERAGE					
7.4±0.9±1.1		FALVARD	88	DM2	$J/\psi \to$ hadrons
7 ±0.6±1.0	163±15	BECKER	87	MRK3	$e^+e^- \to$ hadrons

$\Gamma(\omega f_1(1420))/\Gamma_{total}$ — Γ_{34}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
$6.8^{+1.9}_{-1.6}$±1.7	111^{+31}_{-26}	BECKER	87	MRK3	$e^+e^- \to$ hadrons

$\Gamma(\phi\eta)/\Gamma_{total}$ — Γ_{35}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.65 ±0.07 OUR AVERAGE					
0.64 ±0.04 ±0.11	346	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.661±0.045±0.078		COFFMAN	88	MRK3	$e^+e^- \to K^+K^-\eta$

$\Gamma(\Xi(1530)^-\overline{\Xi}^+)/\Gamma_{total}$ — Γ_{36}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.59±0.09±0.12	75±11	HENRARD	87	DM2	e^+e^-

$\Gamma(pK^-\overline{\Sigma}(1385)^0)/\Gamma_{total}$ — Γ_{37}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.51±0.26±0.18	89	EATON	84	MRK2	e^+e^-

$\Gamma(\omega\pi^0)/\Gamma_{total}$ — Γ_{38}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.42 ±0.06 OUR AVERAGE Error includes scale factor of 1.4.					
0.360±0.028±0.054	222	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.482±0.019±0.064		COFFMAN	88	MRK3	$e^+e^- \to \pi^0\pi^+\pi^-\pi^0$

$\Gamma(\phi\eta'(958))/\Gamma_{total}$ — Γ_{39}/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.33 ±0.04 OUR AVERAGE						
0.41 ±0.03 ±0.08		167	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.308±0.034±0.036			COFFMAN	88	MRK3	$e^+e^- \to K^+K^-\eta'$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.3	90		VANNUCCI	77	MRK1	e^+e^-

$\Gamma(\phi f_0(975))/\Gamma_{total}$ — Γ_{40}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
3.2±0.9 OUR AVERAGE Error includes scale factor of 1.9.					
4.6±0.4±0.8		[19] FALVARD	88	DM2	$J/\psi \to$ hadrons
2.6±0.6	50	[19] GIDAL	81	MRK2	e^+e^-

[19] Assuming B($f_0(975) \to \pi\pi$) = 0.78.

$\Gamma(\Xi(1530)^0\overline{\Xi}^0)/\Gamma_{total}$ — Γ_{41}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.32±0.12±0.07	24±9	HENRARD	87	DM2	e^+e^-

$\Gamma(\Sigma(1385)^-\overline{\Sigma}^+$ (or c.c.)$)/\Gamma_{total}$ — Γ_{42}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.31±0.05 OUR AVERAGE					
0.30±0.03±0.07	74±8	HENRARD	87	DM2	$e^+e^- \to \Sigma^{*-}$
0.34±0.04±0.07	77±9	HENRARD	87	DM2	$e^+e^- \to \Sigma^{*+}$
0.29±0.11±0.10	26	EATON	84	MRK2	$e^+e^- \to \Sigma^{*-}$
0.31±0.11±0.11	28	EATON	84	MRK2	$e^+e^- \to \Sigma^{*+}$

$\Gamma(\phi f_1(1285))/\Gamma_{total}$ — Γ_{43}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.6±0.5 OUR AVERAGE Error includes scale factor of 1.1.					
3.2±0.6±0.4		JOUSSET	90	DM2	$J/\psi \to \phi 2(\pi^+\pi^-)$
2.1±0.5±0.4	25	[20] JOUSSET	90	DM2	$J/\psi \to \phi\eta\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.6±0.2±0.1	16±6	BECKER	87	MRK3	$J/\psi \to \phi K\overline{K}\pi$

[20] We attrribute to the $f_1(1285)$ the signal observed in the $\pi^+\pi^-\eta$ invariant mass distribution at 1297 Mev.

$\Gamma(\rho\eta)/\Gamma_{total}$ — Γ_{44}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.193±0.023 OUR AVERAGE					
0.194±0.017±0.029	299	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.193±0.013±0.029		COFFMAN	88	MRK3	$e^+e^- \to \pi^+\pi^-\eta$

$\Gamma(\omega\eta'(958))/\Gamma_{total}$ — Γ_{45}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.167±0.025 OUR AVERAGE					
0.18 $^{+0.10}_{-0.08}$ ±0.03	6	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.166±0.017±0.019		COFFMAN	88	MRK3	$e^+e^- \to 3\pi\eta'$

$\Gamma(\omega f_0(975))/\Gamma_{total}$ — Γ_{46}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
1.41±0.27±0.47	[21] AUGUSTIN	89	DM2	$J/\psi \to 2(\pi^+\pi^-)\pi^0$

[21] Assuming B($f_0(975) \to \pi\pi$) = 0.78.

$\Gamma(\rho\eta'(958))/\Gamma_{total}$ — Γ_{47}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.105±0.018 OUR AVERAGE					
0.083±0.030±0.012	19	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.114±0.014±0.016		COFFMAN	88	MRK3	$J/\psi \to \pi^+\pi^-\eta'$

$\Gamma(p\overline{p}\phi)/\Gamma_{total}$ — Γ_{48}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
0.45±0.13±0.07	FALVARD	88	DM2	$J/\psi \to$ hadrons

$\Gamma(a_2(1320)^{\pm}\pi^{\mp})/\Gamma_{total}$ — Γ_{49}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<43	90	BRAUNSCH...	76	DASP	e^+e^-

$\Gamma(K\overline{K}{}^*_2(1430) + \text{c.c.})/\Gamma_{total}$ — Γ_{50}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<40	90	VANNUCCI	77	MRK1	$e^+e^- \to K^0\overline{K}{}^{*0}_2$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<66	90	BRAUNSCH...	76	DASP	$e^+e^- \to K^{\pm}\overline{K}{}^{*\mp}_2$

$\Gamma(K^*_2(1430)^0\overline{K}{}^*_2(1430)^0)/\Gamma_{total}$ — Γ_{51}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<29	90	VANNUCCI	77	MRK1	$e^+e^- \to \pi^+\pi^-K^+K^-$

$\Gamma(K^*(892)^0\overline{K}{}^*(892)^0)/\Gamma_{total}$ — Γ_{52}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<5	90	VANNUCCI	77	MRK1	$e^+e^- \to \pi^+\pi^-K^+K^-$

$\Gamma(\phi f_2(1270))/\Gamma_{total}$ — Γ_{53}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<3.7	90	VANNUCCI	77	MRK1	$e^+e^- \to \pi^+\pi^-K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.5	90	FALVARD	88	DM2	$J/\psi \to$ hadrons

$\Gamma(p\overline{p}\rho)/\Gamma_{total}$ — Γ_{54}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.31	90	EATON	84	MRK2	$e^+e^- \to$ hadrons γ

$\Gamma(\phi\eta(1440) \to \phi\eta\pi\pi)/\Gamma_{total}$ — Γ_{55}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<2.5	90	[22] FALVARD	88	DM2	$J/\psi \to$ hadrons

[22] Includes unknown branching fraction $\eta(1440) \to \eta\pi\pi$.

$\Gamma(\omega f'_2(1525))/\Gamma_{total}$ — Γ_{56}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<2.2	90	[23] VANNUCCI	77	MRK1	$e^+e^- \to \pi^+\pi^-\pi^0K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.8	90	[23] FALVARD	88	DM2	$J/\psi \to$ hadrons

[23] Re-evaluated assuming $B(f'_2(1525) \to K\overline{K}) = 0.713$.

$\Gamma(\Sigma(1385)^0\overline{\Lambda})/\Gamma_{total}$ — Γ_{57}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.2	90	HENRARD	87	DM2	e^+e^-

$\Gamma(\Delta(1232)^+\overline{p})/\Gamma_{total}$ — Γ_{58}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.1	90	HENRARD	87	DM2	e^+e^-

$\Gamma(\Sigma^0\overline{\Lambda})/\Gamma_{total}$ — Γ_{59}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<0.9	90	HENRARD	87	DM2	e^+e^-

$\Gamma(\phi\pi^0)/\Gamma_{total}$ — Γ_{60}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<0.068	90	COFFMAN	88	MRK3	$e^+e^- \to K^+K^-\pi^0$

$\Gamma(2(\pi^+\pi^-)\pi^0)/\Gamma_{total}$ — Γ_{61}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0337±0.0026 OUR AVERAGE					
0.0325±0.0049	46055	AUGUSTIN	89	DM2	$J/\psi \to 2(\pi^+\pi^-)\pi^0$
0.0317±0.0042	147	FRANKLIN	83	MRK2	$e^+e^- \to$ hadrons
0.0364±0.0052	1500	BURMESTER	77D	PLUT	e^+e^-
0.04 ±0.01	675	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(3(\pi^+\pi^-)\pi^0)/\Gamma_{total}$ — Γ_{62}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.029±0.006 OUR AVERAGE					
0.028±0.009	11	FRANKLIN	83	MRK2	$e^+e^- \to$ hadrons
0.029±0.007	181	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{63}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0150±0.0015 OUR AVERAGE					
0.0149±0.0022		EINSWEILER	83	MRK3	e^+e^-
0.015 ±0.002	168	FRANKLIN	83	MRK2	e^+e^-

$\Gamma(\pi^+\pi^-\pi^0K^+K^-)/\Gamma_{total}$ — Γ_{64}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.012 ±0.003	309	VANNUCCI	77	MRK1	e^+e^-

$\Gamma(4(\pi^+\pi^-)\pi^0)/\Gamma_{total}$ — Γ_{65}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
90±30	13	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{total}$ — Γ_{66}/Γ

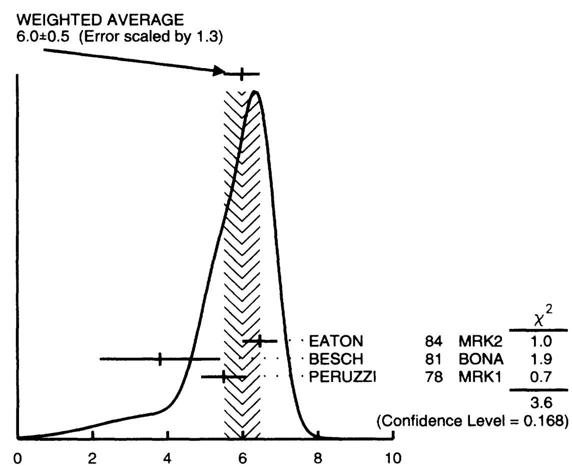
VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
72±23	205	VANNUCCI	77	MRK1	e^+e^-

$\Gamma(K\overline{K}\pi)/\Gamma_{total}$ — Γ_{67}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
61 ±10 OUR AVERAGE					
55.2±12.0	25	FRANKLIN	83	MRK2	$e^+e^- \to K^+K^-\pi^0$
78.0±21.0	126	VANNUCCI	77	MRK1	$e^+e^- \to K^0_S K^{\pm}\pi^{\mp}$

$\Gamma(p\overline{p}\pi^+\pi^-)/\Gamma_{total}$ — Γ_{68}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
6.0 ±0.5 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.					
6.46±0.17±0.43	1435	EATON	84	MRK2	e^+e^-
3.8 ±1.6	48	BESCH	81	BONA	e^+e^-
5.5 ±0.6	533	PERUZZI	78	MRK1	e^+e^-



$\Gamma(p\overline{p}\pi^+\pi^-)/\Gamma_{total}$ (units 10^{-3})

$\Gamma(2(\pi^+\pi^-))/\Gamma_{total}$ — Γ_{69}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.004 ±0.001	76	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(3(\pi^+\pi^-))/\Gamma_{total}$ — Γ_{70}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
40±20	32	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(n\overline{n}\pi^+\pi^-)/\Gamma_{total}$ — Γ_{71}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
3.8±3.6	5	BESCH	81	BONA	e^+e^-

$\Gamma(\Sigma\overline{\Sigma})/\Gamma_{total}$ — Γ_{72}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
3.8 ±0.5 OUR AVERAGE					
3.18±0.12±0.69	884±30	PALLIN	87	DM2	e^+e^-
4.74±0.48±0.75	90	EATON	84	MRK2	$e^+e^- \to \Sigma^0\overline{\Sigma}{}^0$
7.2 ±7.8	3	BESCH	81	BONA	$e^+e^- \to \Sigma^+\overline{\Sigma}{}^-$
3.9 ±1.2	52	PERUZZI	78	MRK1	$e^+e^- \to \Sigma^0\overline{\Sigma}{}^0$

$\Gamma(2(\pi^+\pi^-)K^+K^-)/\Gamma_{total}$ — Γ_{73}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
31±13	30	VANNUCCI	77	MRK1	e^+e^-

$\Gamma(p\overline{p}\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{74}/Γ

Including $p\overline{p}\pi^+\pi^-\gamma$ and excluding ω, η, η'

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.3 ±0.9 OUR AVERAGE Error includes scale factor of 1.9.					
3.36±0.65±0.28	364	EATON	84	MRK2	e^+e^-
1.6 ±0.6	39	PERUZZI	78	MRK1	e^+e^-

$\Gamma(p\overline{p})/\Gamma_{total}$ — Γ_{75}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.16±0.11 OUR AVERAGE					
1.91±0.04±0.30		PALLIN	87	DM2	e^+e^-
2.16±0.07±0.15	1420	EATON	84	MRK2	e^+e^-
2.5 ±0.4	133	BRANDELIK	79C	DASP	e^+e^-
2.0 ±0.5		BESCH	78	BONA	e^+e^-
2.2 ±0.2	331	[24] PERUZZI	78	MRK1	e^+e^-

[24] Assuming angular distribution $(1+\cos^2\theta)$.

$\Gamma(p\overline{p})/\Gamma(\mu^+\mu^-)$ — Γ_{75}/Γ_4

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.051±0.02	20	[25] WIIK	75	PLUT	e^+e^-

[25] Assuming angular distribution $(1+\cos^2\theta)$.

$\Gamma(p\overline{p}\eta)/\Gamma_{total}$ — Γ_{76}/Γ

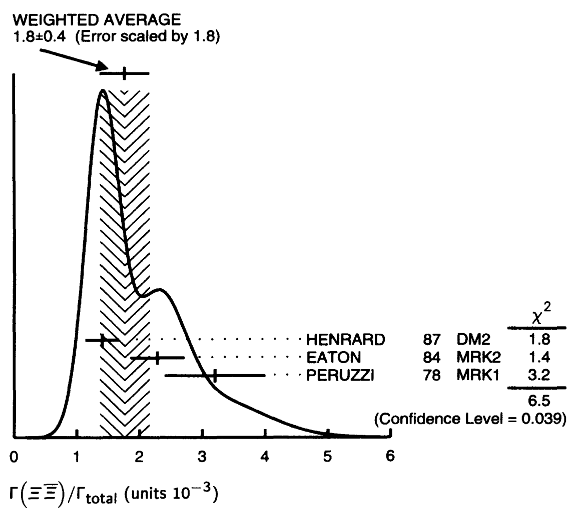
VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.09±0.18 OUR AVERAGE					
2.03±0.13±0.15	826	EATON	84	MRK2	e^+e^-
2.5 ±1.2		BRANDELIK	79C	DASP	e^+e^-
2.3 ±0.4	197	PERUZZI	78	MRK1	e^+e^-

$\Gamma(p\overline{n}\pi^-)/\Gamma_{total}$ — Γ_{77}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.00±0.10 OUR AVERAGE					
2.02±0.07±0.16	1288	EATON	84	MRK2	$e^+e^-\to p\pi^-$
1.93±0.07±0.16	1191	EATON	84	MRK2	$e^+e^-\to \overline{p}\pi^+$
1.7 ±0.7	32	BESCH	81	BONA	$e^+e^-\to p\pi^-$
1.6 ±1.2	5	BESCH	81	BONA	$e^+e^-\to \overline{p}\pi^+$
2.16±0.29	194	PERUZZI	78	MRK1	$e^+e^-\to p\pi^-$
2.04±0.27	204	PERUZZI	78	MRK1	$e^+e^-\to \overline{p}\pi^+$

$\Gamma(\Xi\overline{\Xi})/\Gamma_{total}$ — Γ_{78}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.8 ±0.4 OUR AVERAGE	Error includes scale factor of 1.8. See the ideogram below.				
1.40±0.12±0.24	132±11	HENRARD	87	DM2	$e^+e^-\to \Xi^-\overline{\Xi}^+$
2.28±0.16±0.40	194	EATON	84	MRK2	$e^+e^-\to \Xi^-\overline{\Xi}^+$
3.2 ±0.8	71	PERUZZI	78	MRK1	e^+e^-



$\Gamma(n\overline{n})/\Gamma_{total}$ — Γ_{79}/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
0.18±0.09	BESCH	78	BONA	e^+e^-

$\Gamma(\Lambda\overline{\Lambda})/\Gamma_{total}$ — Γ_{80}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.35±0.14 OUR AVERAGE	Error includes scale factor of 1.2.				
1.38±0.05±0.20	1847	PALLIN	87	DM2	e^+e^-
1.58±0.08±0.19	365	EATON	84	MRK2	e^+e^-
2.6 ±1.6	5	BESCH	81	BONA	e^+e^-
1.1 ±0.2	196	PERUZZI	78	MRK1	e^+e^-

$\Gamma(p\overline{p}\pi^0)/\Gamma_{total}$ — Γ_{81}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.09±0.09 OUR AVERAGE					
1.13±0.09±0.09	685	EATON	84	MRK2	e^+e^-
1.4 ±0.4		BRANDELIK	79C	DASP	e^+e^-
1.00±0.15	109	PERUZZI	78	MRK1	e^+e^-

$\Gamma(\Lambda\overline{\Sigma}^-\pi^+$ (or c.c.)$)/\Gamma_{total}$ — Γ_{82}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.06±0.12 OUR AVERAGE					
0.90±0.06±0.16	225±15	HENRARD	87	DM2	$e^+e^-\to \Lambda\overline{\Sigma}^+\pi^-$
1.11±0.06±0.20	342±18	HENRARD	87	DM2	$e^+e^-\to \Lambda\overline{\Sigma}^-\pi^+$
1.53±0.17±0.38	135	EATON	84	MRK2	$e^+e^-\to \Lambda\overline{\Sigma}^+\pi^-$
1.38±0.21±0.35	118	EATON	84	MRK2	$e^+e^-\to \Lambda\overline{\Sigma}^-\pi^+$

$\Gamma(pK^-\overline{\Lambda})/\Gamma_{total}$ — Γ_{83}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.89±0.07±0.14	307	EATON	84	MRK2	e^+e^-

$\Gamma(2(K^+K^-))/\Gamma_{total}$ — Γ_{84}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
7 ±3	VANNUCCI	77	MRK1	e^+e^-

$\Gamma(pK^-\overline{\Sigma}^0)/\Gamma_{total}$ — Γ_{85}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.29±0.06±0.05	90	EATON	84	MRK2	e^+e^-

$\Gamma(K^+K^-)/\Gamma_{total}$ — Γ_{86}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.37±0.31 OUR AVERAGE					
2.39±0.24±0.22	107	BALTRUSAIT...	85D	MRK3	e^+e^-
2.2 ±0.9	6	BRANDELIK	79C	DASP	e^+e^-

$\Gamma(\Lambda\overline{\Lambda}\pi^0)/\Gamma_{total}$ — Γ_{87}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.22±0.05±0.05	19±4	HENRARD	87	DM2	e^+e^-

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_{88}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.47±0.23 OUR AVERAGE					
1.58±0.20±0.15	84	BALTRUSAIT...	85D	MRK3	e^+e^-
1.0 ±0.5	5	BRANDELIK	78B	DASP	e^+e^-
1.6 ±1.6	1	VANNUCCI	77	MRK1	e^+e^-

$\Gamma(K^0_S K^0_L)/\Gamma_{total}$ — Γ_{89}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.08±0.14 OUR AVERAGE					
1.18±0.12±0.18		JOUSSET	90	DM2	$J/\psi\to$ hadrons
1.01±0.16±0.09	74	BALTRUSAIT...	85D	MRK3	e^+e^-

$\Gamma(\Lambda\overline{\Sigma}$ + c.c.$)/\Gamma_{total}$ — Γ_{90}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.15	90	PERUZZI	78	MRK1	$e^+e^-\to \Lambda X$

$\Gamma(K^0_S K^0_S)/\Gamma_{total}$ — Γ_{91}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<0.052	90	[26] BALTRUSAIT...	85C	MRK3	e^+e^-

[26] Forbidden by *CP*.

RADIATIVE DECAYS

$\Gamma(\gamma\eta_c(1S))/\Gamma_{total}$ — Γ_{92}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0127±0.0036		GAISER	86	CBAL	$J/\psi\to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	16	BALTRUSAIT...	84	MRK3	$J/\psi\to 2\phi\gamma$

$\Gamma(\gamma\pi^+\pi^-2\pi^0)/\Gamma_{total}$ — Γ_{93}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
8.3±0.2±3.1	[27] BALTRUSAIT...	86B	MRK3	$J/\psi\to 4\pi\gamma$

[27] 4π mass less than 2.0 GeV.

$\Gamma(\gamma\eta\pi\pi)/\Gamma_{total}$ — Γ_{94}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
6.1 ±1.0 OUR AVERAGE				
5.85±0.3±1.05	[28] EDWARDS	83B	CBAL	$J/\psi\to \eta\pi^+\pi^-$
7.8 ±1.2±2.4	[28] EDWARDS	83B	CBAL	$J/\psi\to \eta 2\pi^0$

[28] Broad enhancement at 1700 MeV.

$\Gamma(\gamma\eta(1440)\to \gamma K\overline{K}\pi)/\Gamma_{total}$ — Γ_{95}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
0.91±0.18 OUR AVERAGE				
0.83±0.13±0.18	[29,30] AUGUSTIN	91	DM2	$J/\psi\to \gamma K\overline{K}\pi$
$1.03^{+0.21}_{-0.18}{}^{+0.26}_{-0.19}$	[29,31] BAI	90C	MRK3	$J/\psi\to \gamma K^0_S K^\pm\pi^\mp$

• • • We do not use the following data for averages, fits, limits, etc. • • •

$1.78\pm0.21\pm0.33$	[29,32] AUGUSTIN	91	DM2	$J/\psi \to \gamma K \overline{K} \pi$
$3.8\ \pm0.3\ \pm0.6$	[29] AUGUSTIN	90	DM2	$J/\psi \to \gamma K \overline{K} \pi$
$0.66^{+0.17}_{-0.16}{}^{+0.24}_{-0.15}$	[29,33] BAI	90C	MRK3	$J/\psi \to \gamma K^0_S K^{\pm}\pi^{\mp}$
$6.3\ \pm1.4$	[29] WISNIEWSKI	87	MRK3	$J/\psi \to K \overline{K} \pi \gamma$
$4.0\ \pm0.7\ \pm1.0$	[29] EDWARDS	82E	CBAL	$J/\psi \to K^+ K^- \pi^0 \gamma$
$4.3\ \pm1.7$	[29,34] SCHARRE	80	MRK2	$e^+ e^-$

[29] Includes unknown branching fraction $\eta(1440) \to K \overline{K} \pi$.
[30] From fit to the $K^*(892) K$ 0^{-+} partial wave.
[31] From $K^*(890) K$ final state.
[32] From fit to the $a_0(980)\pi$ 0^{-+} partial wave.
[33] From $a_0(980)\pi$ final state.
[34] Corrected for spin-zero hypothesis for $\eta(1440)$.

$\Gamma(\gamma\eta(1440) \to \gamma\gamma\rho^0)/\Gamma_{total}$ — Γ_{96}/Γ

VALUE (units 10^{-5})	DOCUMENT ID		TECN	COMMENT
6.4±1.2±0.7	[35] COFFMAN	90	MRK3	$J/\psi \to \gamma\gamma\pi^+\pi^-$

[35] Includes unknown branching fraction $\eta(1440) \to \gamma \rho^0$.

$\Gamma(\gamma\rho\rho)/\Gamma_{total}$ — Γ_{97}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
4.5 ±0.8 OUR AVERAGE					
$4.7\ \pm0.3\ \pm0.9$		[36] BALTRUSAIT...86B		MRK3	$J/\psi \to 4\pi\gamma$
$3.75\pm1.05\pm1.20$		[37] BURKE	82	MRK2	$J/\psi \to 4\pi\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.09	90	[38] BISELLO	89B		$J/\psi \to 4\pi\gamma$

[36] 4π mass less than 2.0 GeV.
[37] 4π mass less than 2.0 GeV, $2\rho^0$ corrected to 2ρ by factor of 3.
[38] 4π mass in the range 2.0–25 GeV.

$\Gamma(\gamma\eta'(958))/\Gamma_{total}$ — Γ_{98}/Γ

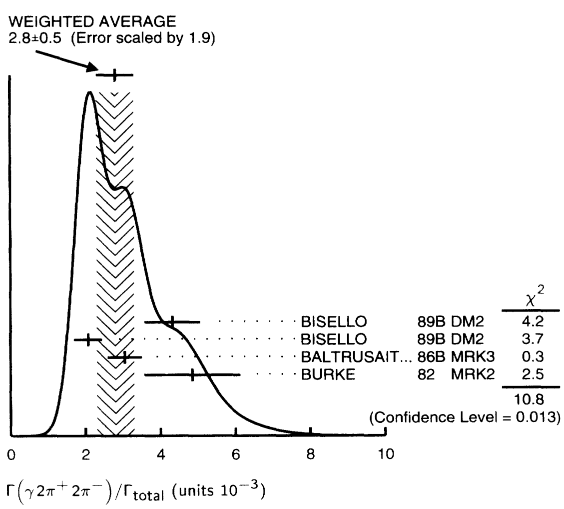
VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
4.34±0.34 OUR AVERAGE					
$4.04\pm0.16\pm0.85$	622	AUGUSTIN	90	DM2	$J/\psi \to \gamma\eta\pi^+\pi^-$
$4.39\pm0.09\pm0.66$	2420	AUGUSTIN	90	DM2	$J/\psi \to \gamma\gamma\pi^+\pi^-$
$4.1\ \pm0.3\ \pm0.6$		BLOOM	83	CBAL	$e^+e^- \to 3\gamma +$ hadrons γ
$4.6\ \pm0.4\ \pm0.65$		EINSWEILER	83	MRK3	$e^+e^- \to \gamma\eta\pi^+\pi^-$
$4.7\ \pm0.3\ \pm0.9$		EINSWEILER	83	MRK3	$e^+e^- \to \gamma\rho^0\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$2.9\ \pm1.1$	6	BRANDELIK	79C	DASP	$e^+e^- \to 3\gamma$
$3.8\ \pm1.3$		[39] SCHARRE	79B	MRK1	$e^+e^- \to \gamma X$
$3.4\ \pm0.7$		SCHARRE	79B	MRK1	$e^+e^- \to 2\pi 2\gamma$
$2.4\ \pm0.7$	57	BARTEL	76	CNTR	$e^+e^- \to 2\gamma\rho$

[39] From the inclusive γ decay spectrum.

$\Gamma(\gamma 2\pi^+ 2\pi^-)/\Gamma_{total}$ — Γ_{99}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
2.8 ±0.5 OUR AVERAGE Error includes scale factor of 1.9. See the ideogram below.				
$4.32\pm0.14\pm0.73$	[40] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$
$2.08\pm0.13\pm0.35$	[41] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$
$3.05\pm0.08\pm0.45$	[41] BALTRUSAIT...86B		MRK3	$J/\psi \to 4\pi\gamma$
$4.85\pm0.45\pm1.20$	[42] BURKE	82	MRK2	e^+e^-

[40] 4π mass less than 3.0 GeV.
[41] 4π mass less than 2.0 GeV.
[42] 4π mass less than 2.5 GeV.



$\Gamma(\gamma 2\pi^+ 2\pi^-)/\Gamma_{total}$ (units 10^{-3})

$\Gamma(\gamma f_4(2050))/\Gamma_{total}$ — Γ_{100}/Γ

VALUE (units 10^{-3})	DOCUMENT ID	TECN	COMMENT
2.7±0.5±0.5	[43] BALTRUSAIT...87	MRK3	$J/\psi \to \gamma\pi^+\pi^-$

[43] Assuming branching fraction $f_4(2050) \to \pi\pi/$ total = 0.167.

$\Gamma(\gamma\omega\omega)/\Gamma_{total}$ — Γ_{101}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.59±0.33 OUR AVERAGE					
$1.41\pm0.2\ \pm0.42$	120 ± 17	BISELLO	87	SPEC	e^+e^-, hadrons γ
$1.76\pm0.09\pm0.45$		BALTRUSAIT...85C		MRK3	$e^+e^- \to$ hadrons γ

$\Gamma(\gamma\eta(1440) \to \gamma\rho^0\rho^0)/\Gamma_{total}$ — Γ_{102}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
1.36±0.38	[44,45] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[44] Estimated by us from various fits.
[45] Includes unknown branching fraction to $\rho^0\rho^0$.

$\Gamma(\gamma f_2(1270))/\Gamma_{total}$ — Γ_{103}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.38±0.14 OUR AVERAGE						
$1.33\pm0.05\pm0.20$		[46] AUGUSTIN	87	DM2		$J/\psi \to \gamma\pi^+\pi^-$
$1.36\pm0.09\pm0.23$		[46] BALTRUSAIT...87		MRK3		$J/\psi \to \gamma\pi^+\pi^-$
$1.48\pm0.25\pm0.30$	178	EDWARDS	82B	CBAL		$e^+e^- \to 2\pi^0\gamma$
$2.0\ \pm0.7$	35	ALEXANDER	78	PLUT	0	e^+e^-
$1.2\ \pm0.6$	30	[47] BRANDELIK	78B	DASP		$e^+e^- \to \pi^+\pi^-\gamma$

[46] Estimated using $B(f_2(1270) \to \pi\pi)=0.843 \pm 0.012$. The errors do not contain the uncertainty in the $f_2(1270)$ decay.
[47] Restated by us to take account of spread of E1, M2, E3 transitions.

$\Gamma(\gamma f_0(1710) \to \gamma K\overline{K})/\Gamma_{total}$ — Γ_{104}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
9.7±1.2 OUR AVERAGE					
$9.2\pm1.4\pm1.4$		[48] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+K^-$
$10.4\pm1.2\pm1.6$		[48] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^0_S K^0_S$
$9.6\pm1.2\pm1.8$		[48] BALTRUSAIT...87		MRK3	$J/\psi \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.8	90	[49] BISELLO	89B		$J/\psi \to 4\pi\gamma$
$1.6\pm0.4\pm0.3$		[50] BALTRUSAIT...87		MRK3	$J/\psi \to \gamma\pi^+\pi^-$
3.8 ± 1.6		[51] EDWARDS	82D	CBAL	$e^+e^- \to \eta\eta\gamma$

[48] Includes unknown branching fraction to K^+K^- or $K^0_S K^0_S$. We have multiplied K^+K^- measurement by 2, and $K^0_S K^0_S$ by 4 to obtain $K\overline{K}$ result.
[49] Includes unknown branching fraction to $\rho^0\rho^0$.
[50] Includes unknown branching fraction to $\pi^+\pi^-$.
[51] Includes unknown branching fraction to $\eta\eta$.

$\Gamma(\gamma\eta)/\Gamma_{total}$ — Γ_{105}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.86±0.08 OUR AVERAGE					
$0.88\pm0.08\pm0.11$		BLOOM	83	CBAL	e^+e^-
0.82 ± 0.10		BRANDELIK	79C	DASP	e^+e^-
$1.3\ \pm0.4$	21	BARTEL	77	CNTR	e^+e^-

$\Gamma(\gamma f_1(1420) \to \gamma K\overline{K}\pi)/\Gamma_{total}$ — Γ_{106}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
0.83±0.15 OUR AVERAGE				
$0.76\pm0.15\pm0.21$	[52,53] AUGUSTIN	91	DM2	$J/\psi \to \gamma K \overline{K}\pi$
$0.87\pm0.14^{+0.14}_{-0.11}$	[52] BAI	90C	MRK3	$J/\psi \to \gamma K^0_S K^{\pm}\pi^{\mp}$

[52] Included unknown branching fraction $f_1(1420) \to K\overline{K}\pi$.
[53] From fit to the $K^*(892) K$ 1^{++} partial wave.

$\Gamma(\gamma f_1(1285))/\Gamma_{total}$ — Γ_{107}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
0.70 ±0.09 ±0.16		[54] BURCHELL	91	MRK3	$J/\psi \to \gamma\eta\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.025\pm0.007\pm0.003$		[55] COFFMAN	90	MRK3	$J/\psi \to \gamma\gamma\pi^+\pi^-$
<6	90	[56] SCHARRE	80	MRK2	$J/\psi \to \gamma K\overline{K}\pi$

[54] Using $B(f_1(1285) \to a_0(980)\pi) = 0.37$, and including unknown branching ratio for $a_0(980) \to \eta\pi$.
[55] Includes unknown branching fraction $f_1(1285) \to \gamma\rho^0$
[56] Using $B(f_1(1285) \to K\overline{K}\pi) = 0.12$.

$\Gamma(\gamma f_2'(1525))/\Gamma_{total}$ — Γ_{108}/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.63±0.10 OUR AVERAGE						
$0.70\pm0.17\pm0.11$			[57] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+K^-$
$0.56\pm0.06\pm0.11$			[57] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^0_S K^0_S$
$0.84\pm0.20\pm0.17$			[57] BALTRUSAIT...87		MRK3	$J/\psi \to \gamma K^+K^-$

• • • We do not use the following data for averages, fits, limits, etc. • • •

0.25±0.14			[57] FRANKLIN	83B	MRK2	$J/\psi \to \gamma K\overline{K}$
<0.34	90	4	[58] BRANDELIK	79C	DASP	$e^+e^- \to \pi^+\pi^-\gamma$
<0.23	90	3	ALEXANDER	78	PLUT	$e^+e^- \to K^+K^-\gamma$

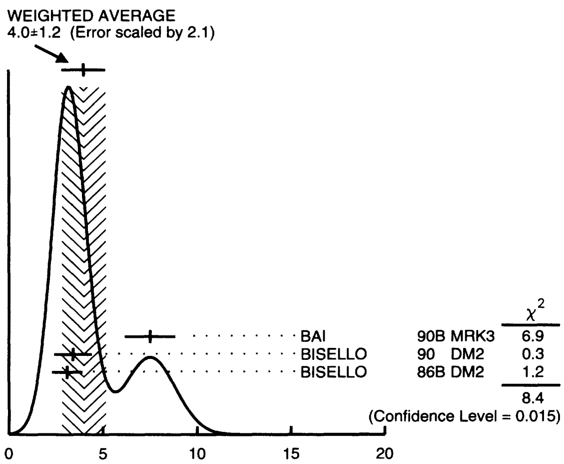
[57] Using $B(f_2'(1525) \to K\overline{K}) = 0.713$.

[58] Assuming isotropic production and decay of the $f_2'(1525)$ and isospin.

$\Gamma(\gamma\phi\phi)/\Gamma_{total}$ — Γ_{109}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
4.0±1.2 OUR AVERAGE	Error includes scale factor of 2.1. See the ideogram below.				
7.5±0.6±1.2	168	BAI	90B	MRK3	$J/\psi \to \gamma 4K$
3.4±0.8±0.6	33 ± 7	[59] BISELLO	90	DM2	$J/\psi \to \gamma K^+K^-K^0_S K^0_L$
3.1±0.7±0.4		[59] BISELLO	86B	DM2	$J/\psi \to \gamma K^+K^-K^+K^-$

[59] $\phi\phi$ mass less than 2.9 GeV, η_c excluded.



$\Gamma(\gamma\phi\phi)/\Gamma_{total}$ (units 10^{-4})

$\Gamma(\gamma p\overline{p})/\Gamma_{total}$ — Γ_{110}/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.38±0.07±0.07		49	EATON	84	MRK2	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.11	90		PERUZZI	78	MRK1	e^+e^-

$\Gamma(\gamma\eta(2100))/\Gamma_{total}$ — Γ_{111}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
0.29±0.06 OUR AVERAGE				
0.33±0.08±0.05	[60] BAI	90B	MRK3	$J/\psi \to \gamma K^+K^-K^+K^-$
0.27±0.06±0.06	[60] BAI	90B	MRK3	$J/\psi \to \gamma K^+K^-K^0_S K^0_L$
$0.24^{+0.15}_{-0.10}$	[61,62] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[60] Includes unknown branching fraction to $\phi\phi$.

[61] Estimated by us from various fits.

[62] Includes unknown branching fraction to $\rho^0\rho^0$.

$\Gamma(\gamma\eta(1760) \to \gamma\rho^0\rho^0)/\Gamma_{total}$ — Γ_{112}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
0.13±0.09	[63,64] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[63] Estimated by us from various fits.

[64] Includes unknown branching fraction to $\rho^0\rho^0$.

$\Gamma(\gamma\pi^0)/\Gamma_{total}$ — Γ_{113}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.039±0.013 OUR AVERAGE					
0.036±0.011±0.007		BLOOM	83	CBAL	e^+e^-
0.073±0.047	10	BRANDELIK	79C	DASP	e^+e^-

$\Gamma(\gamma p\overline{p}\pi^+\pi^-)/\Gamma_{total}$ — Γ_{114}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.79	90	EATON	84	MRK2	e^+e^-

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_{115}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.5	90	BARTEL	77	CNTR	e^+e^-

$\Gamma(\gamma\Lambda\overline{\Lambda})/\Gamma_{total}$ — Γ_{116}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.13	90	HENRARD	87	DM2	e^+e^-

$\Gamma(3\gamma)/\Gamma_{total}$ — Γ_{117}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.055	90	PARTRIDGE	80	CBAL	e^+e^-

$\Gamma(\gamma X(2200))/\Gamma_{total}$ — Γ_{118}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.5	[65] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^0_S K^0_S$

[65] Includes unknown branching fraction to $K^0_S K^0_S$

$\Gamma(\gamma f_4(2220))/\Gamma_{total}$ — Γ_{119}/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 2.3	95	[66] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+K^-$
< 1.6	95	[66] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^0_S K^0_S$
$12.4^{+6.4}_{-5.2}\pm2.8$	23	[66] BALTRUSAIT...	86D	MRK3	$J/\psi \to \gamma K^0_S K^0_S$
$8.4^{+3.4}_{-2.8}\pm1.6$	93	[66] BALTRUSAIT...	86D	MRK3	$J/\psi \to \gamma K^+K^-$

[66] Includes unknown branching fraction to K^+K^- or $K^0_S K^0_S$.

$\Gamma(\gamma X(1400))/\Gamma_{total}$ — Γ_{120}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.83±0.33±0.059		[67] BURCHELL	91	MRK3	$J/\psi \to \gamma\eta\pi^+\pi^-$
7.0 ±0.6 ±1.1	261	[67] AUGUSTIN	90	DM2	$J/\psi \to \gamma\eta\pi^+\pi^-$

[67] Includes unknown branching fraction to $\eta\pi^+\pi^-$.

$J/\psi(1S)$ REFERENCES

COFFMAN	92	PRL 68 282	+DeJongh, Dubois, Hitlin+	(Mark III Collab.)
HSUEH	92	PR D45	+Palestini	(FNAL, TORI)
AUGUSTIN	91	PR D (to be pub.)	+Cosme	(DM2 Collab.)
BURCHELL	91	NP B21 132 (suppl)		(Mark III Collab.)
AUGUSTIN	90	PR D42 10	+Cosme+	(DM2 Collab.)
BAI	90B	PRL 65 1309	+Blaylock+	(Mark III Collab.)
BAI	90C	PRL 65 2507	+Blaylock+	(Mark III Collab.)
BISELLO	90	PL B241 617	+Busetto+	(DM2 Collab.)
COFFMAN	90	PR D41 1410	+De Jongh+	(Mark III Collab.)
JOUSSET	90	PR D41 1389	+Ajaltouni+	(DM2 Collab.)
ALEXANDER	89	NP B320 45	+Bonvicini, Drell, Frey, Luth	(LBL, MICH, SLAC)
AUGUSTIN	89	NP B320 1	+Cosme	(DM2 Collab.)
BISELLO	89B	PR D39 701	Busetto+	(DM2 Collab.)
AUGUSTIN	88	PRL 60 2238	+Calcaterra+	(DM2 Collab.)
COFFMAN	88	PR D38 2695	+Dubois, Eigen, Hauser+	(Mark III Collab.)
FALVARD	88	PR D38 2706	+Ajaltouni+	(CLER, FRAS, LALO, PADO)
AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
BAGLIN	87	NP B286 592	+	(LAPP, CERN, GENO, LYON, OSLO, ROMA+)
BALTRUSAIT...	87	PR D35 2077	Baltrusaitis, Coffman, Dubois+	(Mark III Collab.)
BECKER	87	PRL 59 186	+Blaylock, Bolton, Brown+	(Mark III Collab.)
BISELLO	87	PL B192 239	+Ajaltouni, Baldini+	(PADO, CLER, FRAS, LALO)
HENRARD	87	NP B292 670	+Ajaltouni, et al	(CLER, FRAS, LALO, PADO)
PALLIN	87	NP B292 653	+Ajaltouni+	(CLER, FRAS, LALO, PADO)
WISNIEWSKI	87	Hadron 87 Conf.		(Mark III Collab.)
BALTRUSAIT...	86B	PR D33 1222	Baltrusaitis, Coffman, Hauser+	(Mark III Collab.)
BALTRUSAIT...	86D	PRL 56 107	Baltrusaitis	(CIT, UCSC, ILL, SLAC, WASH)
BISELLO	86B	PL B179 294	+Busetto, Castro, Limentani+	(DM2 Collab.)
GAISER	86	PR D34 711	+Bloom, Bulos, Godfrey+	(Crystal Ball Collab.)
BALTRUSAIT...	85C	PRL 55 1723	Baltrusaitis+	(CIT, UCSC, ILL, SLAC, WASH)
BALTRUSAIT...	85D	PR D32 566	Baltrusaitis, Coffman+	(CIT, UCSC, ILL, SLAC, WASH)
BALTRUSAIT...	84	PRL 52 2126	Baltrusaitis+	(CIT, UCSC, ILL, SLAC, WASH)
EATON	84	PR D29 804	+Goldhaber, Abrams, Alam, Boyarski+	(LBL, SLAC)
BLOOM	83	ARNS 33 143	+Peck	(SLAC, CIT)
EDWARDS	83B	PRL 51 859	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
EINSWEILER	83	Brighton Conf. 348		(Mark III Collab.)
FRANKLIN	83	PRL 51 963	+Franklin, Feldman, Abrams, Alam+	(LBL, SLAC)
FRANKLIN	83B	SLAC-254 Thesis		(STAN)
BURKE	82	PRL 49 632	+Trilling, Abrams, Alam, Blocker+	(LBL, SLAC)
EDWARDS	82B	PR D25 3065	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
EDWARDS	82D	PRL 48 458	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
Also	83	ARNS 33 143	Bloom, Peck	(SLAC, CIT)
EDWARDS	82E	PRL 49 259	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
LEMOIGNE	82	PL 113B 509	+Barate, Astbury+	(SACL, LOIC, SHMP, IND)
BESCH	81	ZPHY C8 1	+Eisermann, Lohr, Kowalski+	(BONN, DESY, MANZ)
GIDAL	81	PL 107B 153	+Goldhaber, Guy, Millikan, Abrams+	(SLAC, LBL)
PARTRIDGE	80	PRL 44 712	+Peck+	(CIT, HARV, PRIN, SLAC, STAN)
SCHARRE	80	PL 97B 329	+Trilling, Abrams, Alam, Blocker+	(SLAC, LBL)
ZHOLENTZ	80	PL 96B 214	+Kurdadze, Lelchuk, Mishnev+	(NOVO)
Also	81	SJNP 34 814 Translated from YAF 34 1471.	Zholentz, Kurdadze, Lelchuk+	(NOVO)

BRANDELIK	79C	ZPHY C1 233	+	(AACH, DESY, HAMB, MPIM, TOKY)
SCHARRE	79B	SLAC-PUB-2321		(SLAC, LBL)
Also	79	LBL-9502	Abrams, Alam, Blocker, Boyarski+	(SLAC, LBL)
ALEXANDER	78	PL 72B 493	+Criegee+	(DESY, HAMB, SIEG, WUPP)
BESCH	78	PL 78B 347	+Eisermann, Kowalski, Eyss+	(BONN, DESY, MANZ)
BRANDELIK	78B	PL 74B 292	+Cords+	(AACH, DESY, HAMB, MPIM, TOKY)
PERUZZI	78	PR D17 2901	+Piccolo, Alam, Boyarski, Goldhaber+	(SLAC, LBL)
BARTEL	77	PL 66B 489	+Duinker, Olsson, Heintze+	(DESY, HEID)
BURMESTER	77D	PL 72B 135	+Criegee+	(DESY, HAMB, SIEG, WUPP)
FELDMAN	77	PL 33C 285	+Perl	(LBL, SLAC)
VANNUCCI	77	PR D15 1814	+Abrams, Alam, Boyarski+	(SLAC, LBL)
BARTEL	76	PL 64B 483	+Duinker, Olsson, Steffen, Heintze+	(DESY, HEID)
BRAUNSCH...	76	PL 63B 487	Braunschweig+	(AACH, DESY, HAMB, MPIM+)
JEAN-MARIE	76	PRL 36 291	+Abrams, Boyarski, Breidenbach+	(SLAC, LBL) IG
BALDINI-...	75	PL 58B 471	Baldini-Celio, Bozzo, Capon+	(FRAS, ROMA)
BEMPORAD	75	Stanford Symp. 113		(PISA, FRAS)
BOYARSKI	75	PRL 34 1357	+Breidenbach, Bulos, Feldman+	(SLAC, LBL) JPC
DASP	75	PL 56B 491	Braunschweig+	(AACH, DESY, MPIM, TOKY)
ESPOSITO	75B	LNC 14 73	+Bartoli, Bisello+	(FRAS, NAPL, PADO, ROMA)
FORD	75	PRL 34 604	+Beron, Hilger, Hofstadter+	(SLAC, PENN)
LIBERMAN	75	Stanford Symp. 55		(STAN)
WIIK	75	Stanford Symp. 69		(DESY)

OTHER RELATED PAPERS

BAGLIN	85	SLAC Summer Inst. 609		(LAPP, CERN, GENO, LYON, OSLO, ROMA+)
LEE	85	SLAC 282		(SLAC)
BARATE	83	PL 121B 449	+Bareyre, Bonamy+	(SACL, LOIC, SHMP, IND)
ABRAMS	74	PRL 33 1453	+Briggs, Augustin, Boyarski+	(LBL, SLAC)
ASH	74	LNC 11 705	+Zorn, Bartoli+	(FRAS, UMD, NAPL, PADO, ROMA)
AUBERT	74	PRL 33 1404	+Becker, Biggs, Burger, Chen, Everhart	(MIT, BNL)
AUGUSTIN	74	PRL 33 1406	+Boyarski, Abrams, Briggs+	(SLAC, LBL)
BACCI	74	PRL 33 1408	+Bartoli, Barbarino, Barbiellini+	(FRAS)
Also	74B	PRL 33 1649	Bacci	
BALDINI-...	74	LNC 11 711	Baldini-Celio, Bacci+	(FRAS, ROMA)
BARBIELLINI	74	LNC 11 718	+Bemporad+	(FRAS, NAPL, PISA, ROMA)
BRAUNSCH...	74	PL 53B 393	Braunschweig+	(AACH, HAMB, MUNI, TOKY)
CHRISTENS...	70	PRL 25 1523	Christenson, Hicks, Lederman+	(COLU, BNL, CERN)

$\chi_{c0}(1P)$
or $\chi_{c0}(3415)$ [was $\chi(3415)$]

$$I^G(J^{PC}) = 0^+(0^{++})$$

Observed in the radiative decay $\psi(2S) \to \chi_{c0}(1P)\gamma$. Therefore $C = +$. The observed decay into $\pi^+\pi^-$ or K^+K^- implies $G = +$, $J^P = 0^+, 2^+, \ldots$ The angular distribution is consistent with $J = 0$. J^P abnormal excluded by $\pi^+\pi^-$ and K^+K^- decays. $J^P = 0^+$ preferred (FELDMAN 77).

$\chi_{c0}(1P)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3415.1± 1.0 OUR AVERAGE					
3417.8± 0.4±4		[1] GAISER	86	CBAL	$\psi(2S) \to \gamma X$
3414.8± 1.1		[2,3] HIMEL	79	MRK2	$e^+e^- \to$ hadrons
3422.0±10.0		[2] BARTEL	78B	CNTR	$e^+e^- \to J/\psi 2\gamma$
3416.0± 3 ±4		[2] TANENBAUM	78	MRK1	e^+e^-
3415.0± 9.0		[2] BIDDICK	77	CNTR	$e^+e^- \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3407.0± 8.0	2	[4] WIIK	75	DASP	$e^+e^- \to J/\psi 2\gamma$

[1] Using mass of $\psi(2S) = 3686.0$ MeV.
[2] Mass value shifted by us by amount appropriate for $\psi(2S)$ mass = 3686 MeV and $J/\psi(1S)$ mass = 3097 MeV.
[3] Systematic error added linearly by us.
[4] Only two events; this mass apparently never published.

$\chi_{c0}(1P)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
13.5±3.3±4.2	GAISER	86	CBAL	$\psi(2S) \to \gamma X$, $\gamma\pi^0\pi^0$

$\chi_{c0}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
	Hadronic decays		
Γ_1	$2(\pi^+\pi^-)$	(3.7 ± 0.7) %	
Γ_2	$\pi^+\pi^-K^+K^-$	(3.0 ± 0.7) %	
Γ_3	$\rho^0\pi^+\pi^-$	(1.6 ± 0.5) %	
Γ_4	$3(\pi^+\pi^-)$	(1.5 ± 0.5) %	
Γ_5	$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	(1.2 ± 0.4) %	
Γ_6	$\pi^+\pi^-$	$(7.5\pm2.1) \times 10^{-3}$	
Γ_7	K^+K^-	$(7.1\pm2.4) \times 10^{-3}$	
Γ_8	$\pi^+\pi^-p\overline{p}$	$(5.0\pm2.0) \times 10^{-3}$	
Γ_9	$\pi^0\pi^0$	$(3.1\pm0.6) \times 10^{-3}$	
Γ_{10}	$\eta\eta$	$(2.5\pm1.1) \times 10^{-3}$	
Γ_{11}	$p\overline{p}$	$< 9.0 \times 10^{-4}$	90%
	Radiative decays		
Γ_{12}	$\gamma J/\psi(1S)$	$(6.6\pm1.8) \times 10^{-3}$	
Γ_{13}	$\gamma\gamma$	$(4.0\pm2.3) \times 10^{-4}$	

$\chi_{c0}(1P)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ — Γ_{13}

VALUE (KeV)	CL%	DOCUMENT ID		TECN	COMMENT
< 6.2	95	CHEN	90B	CLEO	$e^+e^- \to e^+e^-\chi_{c0}$
4.0±2.8		LEE	85	CBAL	$\psi' \to$ photons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<17	95	AIHARA	88D	TPC	$e^+e^- \to e^+e^- X$

$\chi_{c0}(1P)$ BRANCHING RATIOS

HADRONIC DECAYS

$\Gamma(2(\pi^+\pi^-))/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.037±0.007	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.030±0.007	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.016±0.005	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(3(\pi^+\pi^-))/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.015±0.005	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(K^+\overline{K}^*(892)^0\pi^- + \text{c.c.})/\Gamma_{total}$ — Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.012±0.004	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
75±21 OUR AVERAGE				
70±30	[5] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c0}$
80±30	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(K^+K^-)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
71±24 OUR AVERAGE				
60±30	[5] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c0}$
90±40	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\pi^+\pi^-p\overline{p})/\Gamma_{total}$ — Γ_8/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.005 ±0.002	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\pi^0\pi^0)/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
3.1±0.4±0.5	[6] LEE	85	CBAL	$\psi' \to$ photons

$\Gamma(\eta\eta)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
2.5±0.8±0.8	[6] LEE	85	CBAL	$\psi' \to$ photons

$\Gamma(p\overline{p})/\Gamma_{total}$ — Γ_{11}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<9.0	90	[5] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c0}$

[5] Calculated using $B(\psi(2S) \to \gamma\chi_{c0}(1P)) = 0.094$; the errors do not contain the uncertainty in the $\psi(2S)$ decay.
[6] Calculated using $B(\psi(2S) \to \gamma\chi_{c0}(1P)) = 0.093 \pm 0.008$.

RADIATIVE DECAYS

$\Gamma(\gamma J/\psi(1S))/\Gamma_{total}$ — Γ_{12}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
66± 18 OUR AVERAGE				
60± 18	GAISER	86	CBAL	$\psi(2S) \to \gamma\chi_{c0}$
320±210	[7] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c0}$
150±100	[7] BARTEL	78B	CNTR	$\psi(2S) \to \gamma\chi_{c0}$
210±210	[7] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
4.0±2.0±1.1		[6] LEE	85	CBAL	$\psi' \to$ photons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<15	90	[7] YAMADA	77	DASP	$e^+e^- \to 3\gamma$

[7] Calculated using $B(\psi(2S) \to \gamma\chi_{c0}(1P)) = 0.094$; the errors do not contain the uncertainty in the $\psi(2S)$ decay.

$\chi_{c0}(1P)$ REFERENCES

CHEN	90B	PL B243 169	+McIlwain+	(CLEO Collab.)
AIHARA	88D	PRL 60 2355	+Alston-Garnjost+	(TPC Collab.)
GAISER	86	PR D34 711	+Bloom, Bulos, Godfrey+	(Crystal Ball Collab.)
LEE	85	SLAC 282		(SLAC)
BRANDELIK	79B	NP B160 426	+Cords+	(AACH, DESY, HAMB, MPIM, TOKY)
HIMEL	79	SLAC-223 Thesis		(SLAC)
Also	82	Private Comm.	Trilling	(LBL, UCB)
BARTEL	78B	PL 79B 492	+Dittmann, Duinker, Olsson, O'Neill+	(DESY, HEID)
TANENBAUM	78	PR D17 1731	+Alam, Boyarski+	(SLAC, LBL)
Also	82	Private Comm.	Trilling	(LBL, UCB)
BIDDICK	77	PRL 38 1324	+Burnett+	(UCSD, UMD, PAVI, PRIN, SLAC, STAN)
FELDMAN	77	PL 33C 285	+Perl	(LBL, SLAC)
YAMADA	77	Hamburg Conf. 69		(DESY, TOKY)
WIIK	75	Stanford Symp. 69		(DESY)

——— OTHER RELATED PAPERS ———

OREGLIA	82	PR D25 2259	+Partridge+	(SLAC, CIT, HARV, PRIN, STAN)
FELDMAN	75B	PRL 35 821	+Jean-Marie, Sadoulet, Vannucci+	(LBL, SLAC)
Also Erratum.	75C	PRL 35 1189	Feldman	
TANENBAUM	75	PRL 35 1323	+Whitaker, Abrams+	(LBL, SLAC)

$\chi_{c1}(1P)$
or $\chi_{c1}(3510)$ [was $\chi(3510)$]

$I^G(J^{PC}) = 0^+(1^{++})$

Observed in the radiative sequential decay $\psi(2S) \to \chi_{c1}(1P)\gamma$, $\chi_{c1}(1P) \to J/\psi(1S)\gamma$. Therefore, $C = +$. The lack of decays into $\pi^+\pi^-$ or K^+K^- is suggestive of J^P=abnormal. The decays into 4π and 6π imply $G = +$, thus $I = 0$. J=0,2 excluded by angular distribution in the $J/\psi(1S)\gamma$ decay. $J^P = 1^+$ preferred (FELDMAN 77, OREGLIA 82).

$\chi_{c1}(1P)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3510.53± 0.12 OUR AVERAGE					
3510.53± 0.04±0.12	513	ARMSTRONG	92	SPEC	$\bar{p}p \to e^+e^- X$
3511.3 ± 0.4 ±0.4	30	BAGLIN	86B	SPEC	$\bar{p}p \to e^+e^- X$
3512.3 ± 0.3 ±4.0		[1] GAISER	86	CBAL	$\psi(2S) \to \gamma X$
3507.4 ± 1.7	91	[2] LEMOIGNE	82	GOLI	190 GeV π^- Be $\to \gamma 2\mu$
3510.4 ± 0.6		OREGLIA	82	CBAL	$e^+e^- \to J/\psi 2\gamma$
3510.1 ± 1.1	254	[3] HIMEL	80	MRK2	$e^+e^- \to J/\psi 2\gamma$
3509.0 ±11.0	21	BRANDELIK	79B	DASP	$e^+e^- \to J/\psi 2\gamma$
3507.0 ± 3.0		[3] BARTEL	78B	CNTR	$e^+e^- \to J/\psi 2\gamma$
3505.0 ± 4 ±4		[3,4] TANENBAUM	78	MRK1	e^+e^-
3513.0 ± 7.0	367	[3] BIDDICK	77	CNTR	$\psi(2S) \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3510.0 ±20.0		BARTEL	76B	CNTR	$e^+e^- \to J/\psi 2\gamma$
3500 ±10	40	TANENBAUM	75	MRK1	Hadrons γ
3507.0 ± 7.0	7	WIIK	75	DASP	$e^+e^- \to J/\psi 2\gamma$

[1] Using mass of $\psi(2S)$ = 3686.0 MeV.
[2] $J/\psi(1S)$ mass constrained to 3097 MeV.
[3] Mass value shifted by us by amount appropriate for $\psi(2S)$ mass = 3686 MeV and $J/\psi(1S)$ mass = 3097 MeV.
[4] From a simultaneous fit to radiative and hadronic decay channels.

$\chi_{c1}(1P)$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.88±0.11±0.08		513	ARMSTRONG	92	SPEC	$\bar{p}p \to e^+e^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.3	95		BAGLIN	86B	SPEC	$\bar{p}p \to e^+e^- X$
<3.8	90		GAISER	86	CBAL	$\psi(2S) \to \gamma X$

$\chi_{c1}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
	Hadronic decays		
Γ_1	$3(\pi^+\pi^-)$	(2.2±0.8) %	
Γ_2	$2(\pi^+\pi^-)$	(1.6±0.5) %	
Γ_3	$\pi^+\pi^-K^+K^-$	(9 ±4) $\times 10^{-3}$	
Γ_4	$\rho^0\pi^+\pi^-$	(3.9±3.5) $\times 10^{-3}$	
Γ_5	$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	(3.2±2.1) $\times 10^{-3}$	
Γ_6	$\pi^+\pi^-p\bar{p}$	(1.4±0.9) $\times 10^{-3}$	
Γ_7	$p\bar{p}$	(8.6±1.2) $\times 10^{-5}$	
Γ_8	$\pi^+\pi^-$ + K^+K^-	< 2.1 $\times 10^{-3}$	
	Radiative decays		
Γ_9	$\gamma J/\psi(1S)$	(27.3±1.6) %	
Γ_{10}	$\gamma\gamma$	< 1.5 $\times 10^{-3}$	90%

$\chi_{c1}(1P)$ PARTIAL WIDTHS

$\Gamma(p\bar{p})$ — Γ_7

VALUE (eV)	EVTS	DOCUMENT ID		TECN	COMMENT
74± 9 OUR AVERAGE					
76±10±5	513	[5] ARMSTRONG	92	SPEC	$\bar{p}p \to e^+e^- X$
69^{+16}_{-13}±4		[5] BAGLIN	86B	SPEC	$\bar{p}p \to e^+e^- X$

[5] Restated by us using $B(\chi_{c1}(1P) \to J/\psi(1S)\gamma)B(J/\psi(1S) \to e^+e^-) = 0.0171 \pm 0.0011$.

$\chi_{c1}(1P)$ BRANCHING RATIOS

——— HADRONIC DECAYS ———

$\Gamma(3(\pi^+\pi^-))/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.022±0.008	[7] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$

$\Gamma(2(\pi^+\pi^-))/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.016±0.005	[7] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{total}$ — Γ_3/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
90±40	[7] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
39±35	[7] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$

$\Gamma(K^+\overline{K}^*(892)^0\pi^- + c.c.)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
32±21	[7] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$

$\Gamma(\pi^+\pi^-p\bar{p})/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
14±9	[7] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$

$\Gamma(p\bar{p})/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.86±0.12		513	[6] ARMSTRONG	92	SPEC	$\bar{p}p \to e^+e^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 0.54	95		BAGLIN	86B	SPEC	$\bar{p}p \to e^+e^- X$
<12.0	90		[7] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c1}$

[6] Restated by us using $B(\chi_{c1}(1P) \to J/\psi(1S)\gamma)B(J/\psi(1S) \to e^+e^-) = 0.0171 \pm 0.0011$.

$[\Gamma(\pi^+\pi^-) + \Gamma(K^+K^-)]/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<21		[7] FELDMAN	77	MRK1	$\psi(2S) \to \gamma\chi_{c1}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<38	90	[7] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c1}$

[7] Estimated using $B(\psi(2S) \to \gamma\chi_{c1}(1P)) = 0.087$. The errors do not contain the uncertainty in the $\psi(2S)$ decay.

RADIATIVE DECAYS

$\Gamma(\gamma J/\psi(1S))/\Gamma_{total}$ — Γ_9/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.273±0.016 OUR AVERAGE					
0.284±0.021		GAISER	86	CBAL	$\psi(2S) \to \gamma X$
0.274±0.046	943	[8] OREGLIA	82	CBAL	$\psi(2S) \to \gamma\chi_{c1}$
0.28 ±0.07		[8] HIMEL	80	MRK2	$\psi(2S) \to \gamma\chi_{c1}$
0.19 ±0.05		[8] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c1}$
0.29 ±0.05		[8] BARTEL	78B	CNTR	$\psi(2S) \to \gamma\chi_{c1}$
0.28 ±0.09		[8] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.57 ±0.17		[8] BIDDICK	77	CNTR	$\psi(2S) \to \gamma X$

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0015	90	[8] YAMADA	77	DASP	$e^+e^- \to 3\gamma$

[8] Estimated using $B(\psi(2S) \to \gamma\chi_{c1}(1P)) = 0.087$. The errors do not contain the uncertainty in the $\psi(2S)$ decay.

$\chi_{c1}(1P)$ REFERENCES

ARMSTRONG 92 NP B (accepted) +Bettoni+ (FNAL, FERR, GENO, UCI, NWES+)
Also 92B PRL (accepted) Armstrong, Bettoni+(FNAL, FERR, GENO, UCI, NWES+)
BAGLIN 86B PL B172 455 (LAPP, CERN, GENO, LYON, OSLO, ROMA+)
GAISER 86 PR D34 711 +Bloom, Bulos, Godfrey+ (Crystal Ball Collab.)
LEMOIGNE 82 PL 113B 509 +Barate, Astbury+ (SACL, LOIC, SHMP, IND)
OREGLIA 82 PR D25 2259 +Partridge+ (SLAC, CIT, HARV, PRIN, STAN)
Also 82B Private Comm. Oreglia (EFI)
HIMEL 80 PRL 44 920 +Abrams, Alam, Blocker+ (LBL, SLAC)
Also 82 Private Comm. Trilling (LBL, UCB)
BRANDELIK 79B NP B160 426 +Cords+ (AACH, DESY, HAMB, MPIM, TOKY)
BARTEL 78B PL 79B 492 +Dittmann, Duinker, Olsson, O'Neill+ (DESY, HEID)
TANENBAUM 78 PR D17 1731 +Alam, Boyarski+ (SLAC, LBL)
Also 82 Private Comm. Trilling (LBL, UCB)
BIDDICK 77 PRL 38 1324 +Burnett+ (UCSD, UMD, PAVI, PRIN, SLAC, STAN)
FELDMAN 77 PL 33C 285 +Perl (LBL, SLAC)
YAMADA 77 Hamburg Conf. 69 (DESY, TOKY)
BARTEL 76B Tbilisi Conf. N75 +Duinker, Olsson, Heintze+ (DESY, HEID)
TANENBAUM 75 PRL 35 1323 +Whitaker, Abrams+ (LBL, SLAC)
WIIK 75 Stanford Symp. 69 (DESY)

OTHER RELATED PAPERS

BARATE 83 PL 121B 449 +Bareyre, Bonamy+ (SACL, LOIC, SHMP, IND)
BRAUNSCH... 75B PL 57B 407 Braunschweig+ (AACH, DESY, MPIM, TOKY)
FELDMAN 75 Stanford Symp. 39 (SLAC)
HEINTZE 75 Stanford Symp. 97 (HEID)
SIMPSON 75 PRL 35 699 +Beron, Ford, Hilger, Hofstadter+ (STAN, PENN)

$\chi_{c2}(1P)$
or $\chi_{c2}(3555)$ [was $\chi(3555)$]

$I^G(J^{PC}) = 0^+(2^{++})$

Observed in the radiative decay $\psi(2S) \to \chi_{c2}(1P)\gamma$. Therefore $C = +$. The observed decay into 4π and 6π imply $G = +$, thus $I = 0$. $J = 0$ is excluded by the angular distribution in the hadronic decays. J^P abnormal excluded by $\pi^+\pi^-$ and K^+K^- decays. $J^P = 2^+$ preferred (FELDMAN 77, OREGLIA 82).

$\chi_{c2}(1P)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3556.17± 0.13 OUR AVERAGE					
3556.15± 0.07±0.12	585	ARMSTRONG	92	SPEC	$\bar{p}p \to e^+e^- X$
3556.9 ± 0.4 ±0.5	50	BAGLIN	86B	SPEC	$\bar{p}p \to e^+e^- X$
3557.8 ± 0.2 ±4		[1] GAISER	86	CBAL	$\psi(2S) \to \gamma X$
3553.4 ± 2.2	66	[2] LEMOIGNE	82	GOLI	190 GeV π^- Be $\to \gamma 2\mu$
3555.9 ± 0.7		[3] OREGLIA	82	CBAL	$e^+e^- \to J/\psi 2\gamma$
3557 ± 1.5	69	[4] HIMEL	80	MRK2	$e^+e^- \to J/\psi 2\gamma$
3551.0 ±11.0	15	BRANDELIK	79B	DASP	$e^+e^- \to J/\psi 2\gamma$
3553.0 ± 4.0		[4] BARTEL	78B	CNTR	$e^+e^- \to J/\psi 2\gamma$
3553.0 ± 4 ±4		[4,5] TANENBAUM	78	MRK1	e^+e^-
3563.0 ± 7.0	360	[4] BIDDICK	77	CNTR	$e^+e^- \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3550.0 ±10.0		TRILLING	76	MRK1	$e^+e^- \to$ hadrons γ
3543.0 ±10.0	4	WHITAKER	76	MRK1	$e^+e^- \to J/\psi 2\gamma$

[1] Using mass of $\psi(2S) = 3686.0$ MeV.
[2] $J/\psi(1S)$ mass constrained to 3097 MeV.
[3] Assuming $\psi(2S)$ mass = 3686 MeV and $J/\psi(1S)$ mass = 3097 MeV.
[4] Mass value shifted by us by amount appropriate for $\psi(2S)$ mass = 3686 MeV and $J/\psi(1S)$ mass = 3097 MeV.
[5] From a simultaneous fit to radiative and hadronic decay channels.

$\chi_{c2}(1P)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2.00±0.18 OUR AVERAGE					
1.98±0.17±0.07	585	ARMSTRONG	92	SPEC	$\bar{p}p \to e^+e^- X$
$2.6\ ^{+1.4}_{-1.0}$	50	BAGLIN	86B	SPEC	$\bar{p}p \to e^+e^- X$
$2.8\ ^{+2.1}_{-2.0}$		[6] GAISER	86	CBAL	$\psi(2S) \to \gamma X$

[6] Errors correspond to 90% confidence level; authors give only width range.

$\chi_{c2}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
	Hadronic decays		
Γ_1	$2(\pi^+\pi^-)$	(2.2 ±0.5) %	
Γ_2	$\pi^+\pi^-K^+K^-$	(1.9 ±0.5) %	
Γ_3	$3(\pi^+\pi^-)$	(1.2 ±0.8) %	
Γ_4	$\rho^0\pi^+\pi^-$	(7 ±4) $\times 10^{-3}$	
Γ_5	$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	(4.8 ±2.8) $\times 10^{-3}$	
Γ_6	$\pi^+\pi^-p\bar{p}$	(3.3 ±1.3) $\times 10^{-3}$	
Γ_7	$\pi^+\pi^-$	(1.9 ±1.0) $\times 10^{-3}$	
Γ_8	K^+K^-	(1.5 ±1.1) $\times 10^{-3}$	
Γ_9	$p\bar{p}$	(10.0 ±1.0) $\times 10^{-5}$	
Γ_{10}	$\pi^0\pi^0$	(1.10±0.28) $\times 10^{-3}$	
Γ_{11}	$\eta\eta$	(8 ±5) $\times 10^{-4}$	
Γ_{12}	$J/\psi(1S)\pi^+\pi^-\pi^0$	< 1.5 %	90%
	Radiative decays		
Γ_{13}	$\gamma J/\psi(1S)$	(13.5 ±1.1) %	
Γ_{14}	$\gamma\gamma$	< 50 %	95%

$\chi_{c2}(1P)$ PARTIAL WIDTHS

$\Gamma(p\bar{p})$ — Γ_9

VALUE (eV)	EVTS	DOCUMENT ID		TECN	COMMENT
206±22 OUR AVERAGE					
197±18±16	585	[7] ARMSTRONG	92	SPEC	$\bar{p}p \to e^+e^- X$
$252^{+55}_{-48}\pm21$		[7] BAGLIN	86B	SPEC	$\bar{p}p \to e^+e^- X$

[7] Restated by us using $B(\chi_{c2}(1P) \to J/\psi(1S)\gamma)B(J/\psi(1S) \to e^+e^-) = 0.0085 \pm 0.0007$.

$\Gamma(\gamma\gamma)$ — Γ_{14}

VALUE (KeV)	CL%	DOCUMENT ID		TECN	COMMENT
<1.0	95	CHEN	90B	CLEO	$e^+e^- \to e^+e^-\chi_{c2}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.2	95	UEHARA	91	VNS	$e^+e^- \to e^+e^-\chi_{c2}$
<4.2	95	AIHARA	88D	TPC	$e^+e^- \to e^+e^- X$
$2.9^{+1.3}_{-1.0}\pm1.7$		BAGLIN	87B	SPEC	$\bar{p}p \to \gamma\gamma$
2.8±2.0		LEE	85	CBAL	$\psi' \to$ photons
<1.6	90	YAMADA	77	DASP	$e^+e^- \to 3\gamma$

$\chi_{c2}(1P)$ BRANCHING RATIOS

HADRONIC DECAYS

$\Gamma(2(\pi^+\pi^-))/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.022±0.005	[9] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.019±0.005	[9] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(3(\pi^+\pi^-))/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.012±0.008	[9] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
68±40	[9] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(K^+\overline{K}^*(892)^0\pi^-$ + c.c.$)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
48±28	[9] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(\pi^+\pi^-p\bar{p})/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
33±13	[9] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.9±1.0	4	[9] BRANDELIK	79C	DASP	$\psi(2S) \to \gamma\chi_{c2}$

$[\Gamma(\pi^+\pi^-) + \Gamma(K^+K^-)]/\Gamma_{total}$ — $(\Gamma_7+\Gamma_8)/\Gamma$

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
24±10	[9] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(K^+K^-)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.5±1.1	2	[9] BRANDELIK	79C	DASP	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(p\bar{p})/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
1.00±0.10 OUR AVERAGE						
1.00±0.11		585	[8] ARMSTRONG	92	SPEC	$\bar{p}p \to e^+e^- X$
$0.97^{+0.44}_{-0.28}\pm0.08$			BAGLIN	86B	SPEC	$\bar{p}p \to e^+e^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<9.5	90		[9] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c2}$

[8] Restated by us using $B(\chi_{c2}(1P) \to J/\psi(1S)\gamma)B(J/\psi(1S) \to e^+e^-) = 0.0085 \pm 0.0007$.

$\Gamma_i\Gamma_f/\Gamma^2_{total}$ in $p\bar{p} \to \chi_{c2}(1P) \to \gamma\gamma$ — $\Gamma_9\Gamma_{14}/\Gamma^2$

VALUE (units 10^{-7})	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.99^{+0.46}_{-0.35}}$	6	[10] BAGLIN	87B	SPEC	$\bar{p}p \to \gamma\gamma$

$\Gamma(\pi^0\pi^0)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
1.1 ±0.2 ±0.2	[11] LEE	85	CBAL	$\psi' \to$ photons

$\Gamma(\eta\eta)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
7.9±4.1±2.4	[11] LEE	85	CBAL	$\psi' \to$ photons

$\Gamma(J/\psi(1S)\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.015	90	BARATE	81	SPEC	190 GeV π^- Be $\to 2\pi 2\mu$

[9] Estimated using $B(\psi(2S) \to \gamma\chi_{c2}(1P)) = 0.078$; the errors do not contain the uncertainty in the $\psi(2S)$ decay.

[10] Assuming isotropic $\chi_{c2}(1P) \to \gamma\gamma$ distribution.

[11] LEE 85 result is calculated using $B(\psi(2S) \to \gamma\chi_{c2}(1P)) = 0.078 \pm 0.008$.

RADIATIVE DECAYS

$\Gamma(\gamma J/\psi(1S))/\Gamma_{total}$ — Γ_{13}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.135±0.011 OUR AVERAGE					
0.124±0.015		GAISER	86	CBAL	$\psi(2S) \to \gamma X$
0.162±0.028	479	[12] OREGLIA	82	CBAL	$\psi(2S) \to \gamma\chi_{c2}$
0.14 ±0.04		[12] HIMEL	80	MRK2	$\psi(2S) \to \gamma\chi_{c2}$
0.18 ±0.05		[12] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c2}$
0.13 ±0.03		[12] BARTEL	78B	CNTR	$\psi(2S) \to \gamma\chi_{c2}$
$0.11\ ^{+0.13}_{-0.07}$		[12] SPITZER	78	PLUT	$\psi(2S) \to \gamma\chi_{c2}$
0.13 ±0.08		[12] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.28 ±0.13		[12] BIDDICK	77	CNTR	$\psi(2S) \to \gamma X$

[12] Estimated using $B(\psi(2S) \to \gamma\chi_{c2}(1P)) = 0.078$; the errors do not contain the uncertainty in the $\psi(2S)$ decay.

$\chi_{c2}(1P)$ REFERENCES

ARMSTRONG 92 NP B (accepted) +Bettoni+ (FNAL, FERR, GENO, UCI, NWES+)
Also 92B PRL (accepted) Armstrong, Bettoni+(FNAL, FERR, GENO, UCI, NWES+)
UEHARA 91 PL B266 188 +Abe+ (VENUS Collab.)
CHEN 90B PL B243 169 +McIlwain+ (CLEO Collab.)
AIHARA 88D PRL 60 2355 +Alston-Garnjost+ (TPC Collab.)
BAGLIN 87B PL B187 191 +Baird, Bassompierre, Borreani+ (R704 Collab.)
BAGLIN 86B PL B172 455 (LAPP, CERN, GENO, LYON, OSLO, ROMA+)
GAISER 86 PR D34 711 +Bloom, Bulos, Godfrey+ (Crystal Ball Collab.)
LEE 85 SLAC 282 (SLAC)
LEMOIGNE 82 PL 113B 509 +Barate, Astbury+ (SACL, LOIC, SHMP, IND)
OREGLIA 82 PR D25 2259 +Partridge+ (SLAC, CIT, HARV, PRIN, STAN)
Also 82B Private Comm. Oreglia (EFI)
BARATE 81 PR D24 2994 +Astbury+ (SACL, LOIC, SHMP, CERN, IND)
HIMEL 80 PRL 44 920 +Abrams, Alam, Blocker+ (LBL, SLAC)
Also 82 Private Comm. Trilling (LBL, UCB)
BRANDELIK 79B NP B160 426 +Cords+ (AACH, DESY, HAMB, MPIM, TOKY)
BRANDELIK 79C ZPHY C1 233 + (AACH, DESY, HAMB, MPIM, TOKY)
BARTEL 78B PL 79B 492 +Dittmann, Duinker, Olsson, O'Neill+ (DESY, HEID)
SPITZER 78 Kyoto Sum. Inst. 47 (HAMB)
TANENBAUM 78 PR D17 1731 +Alam, Boyarski+ (SLAC, LBL)
Also 82 Private Comm. Trilling (LBL, UCB)
BIDDICK 77 PRL 38 1324 +Burnett+ (UCSD, UMD, PAVI, PRIN, SLAC, STAN)
FELDMAN 77 PL 33C 285 +Perl (LBL, SLAC)
YAMADA 77 Hamburg Conf. 69 (DESY, TOKY)
TRILLING 76 Stanford Symp. 437 (LBL)
WHITAKER 76 PRL 37 1596 +Tanenbaum, Abrams, Alam+ (SLAC, LBL)

OTHER RELATED PAPERS

BARATE 83 PL 121B 449 +Bareyre, Bonamy+ (SACL, LOIC, SHMP, IND)
FELDMAN 75B PRL 35 821 +Jean-Marie, Sadoulet, Vannucci+ (LBL, SLAC)
Also 75C PRL 35 1189 Feldman
Erratum.
TANENBAUM 75 PRL 35 1323 +Whitaker, Abrams+ (LBL, SLAC)

$\eta_c(2S)$ or $\eta_c(3590)$

$I^G(J^{PC}) = ?^?(?^{?+})$

OMITTED FROM SUMMARY TABLE

Our latest mini-review on this particle can be found in the 1984 edition. Needs confirmation.

$\eta_c(2S)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
3594.0±5.0	[1] EDWARDS	82C	CBAL	$e^+e^- \to \gamma X$

[1] Assuming mass of $\psi(2S)$ = 3686 MeV.

$\eta_c(2S)$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<8.0	95	EDWARDS	82C	CBAL	$e^+e^- \to \gamma X$

$\eta_c(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	hadrons	seen
Γ_2	$\gamma\gamma$	

$\eta_c(2S)$ BRANCHING RATIOS

$\Gamma(\text{hadrons})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	EDWARDS	82C	CBAL	$e^+e^- \to \gamma X$

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_2/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.01	90	LEE	85	CBAL	$\psi' \to$ photons

$\eta_c(2S)$ REFERENCES

LEE 85 SLAC 282 (SLAC)
EDWARDS 82C PRL 48 70 +Partridge, Peck+ (CIT, HARV, PRIN, STAN, SLAC)

OTHER RELATED PAPERS

OREGLIA 82 PR D25 2259 +Partridge+ (SLAC, CIT, HARV, PRIN, STAN)
PORTER 81 SLAC Summer Inst. 355+Edwards+ (CIT, HARV, PRIN, STAN, SLAC)
BARTEL 78B PL 79B 492 +Dittmann, Duinker, Olsson, O'Neill+ (DESY, HEID)

$\psi(2S)$ or $\psi(3685)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\psi(2S)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3686.00±0.10	413	ZHOLENTZ	80	OLYA	e^+e^-

$\psi(2S) - J/\psi(1S)$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
589.07±0.13 OUR AVERAGE				
589.7 ±1.2	LEMOIGNE	82	GOLI	190 GeV π^- Be $\rightarrow 2\mu$
589.07±0.13	[1] ZHOLENTZ	80	OLYA	e^+e^-
588.7 ±0.8	LUTH	75	MRK1	

[1] Redundant with data in mass above.

$\psi(2S)$ WIDTH

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT
278±32 OUR AVERAGE Error includes scale factor of 1.1.					
308±36±16	1624	ARMSTRONG	92B	SPEC	$\bar{p}p \rightarrow e^+e^-$
243±43		[2] PDG	92	RVUE	

[2] Uses $\Gamma(ee)$ from ALEXANDER 89 and $B(ee) = (88 \pm 13) \times 10^{-4}$ from FELDMAN 77.

$\psi(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	hadrons	(98.10±0.30) %	
Γ_2	virtual $\gamma \rightarrow$ hadrons	(2.9 ±0.4) %	
Γ_3	e^+e^-	(8.8 ±1.3) × 10^{-3}	
Γ_4	$\mu^+\mu^-$	(7.7 ±1.7) × 10^{-3}	
	Decays into $J/\psi(1S)$ and anything		
Γ_5	$J/\psi(1S)$ anything	(57 ±4) %	
Γ_6	$J/\psi(1S)$ neutrals	(23.2 ±2.6) %	
Γ_7	$J/\psi(1S)\pi^+\pi^-$	(32.4 ±2.6) %	
Γ_8	$J/\psi(1S)\pi^0\pi^0$	(18.4 ±2.7) %	
Γ_9	$J/\psi(1S)\eta$	(2.7 ±0.4) %	S=1.7
Γ_{10}	$J/\psi(1S)\pi^0$	(9.7 ±2.1) × 10^{-4}	
	Hadronic decays		
Γ_{11}	$3(\pi^+\pi^-)\pi^0$	(3.5 ±1.6) × 10^{-3}	
Γ_{12}	$2(\pi^+\pi^-)\pi^0$	(3.1 ±0.7) × 10^{-3}	
Γ_{13}	$\pi^+\pi^-K^+K^-$	(1.6 ±0.4) × 10^{-3}	
Γ_{14}	$\pi^+\pi^-p\bar{p}$	(8.0 ±2.0) × 10^{-4}	
Γ_{15}	$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	(6.7 ±2.5) × 10^{-4}	
Γ_{16}	$2(\pi^+\pi^-)$	(4.5 ±1.0) × 10^{-4}	
Γ_{17}	$\rho^0\pi^+\pi^-$	(4.2 ±1.5) × 10^{-4}	
Γ_{18}	$\bar{p}p$	(1.9 ±0.5) × 10^{-4}	
Γ_{19}	$3(\pi^+\pi^-)$	(1.5 ±1.0) × 10^{-4}	
Γ_{20}	$\bar{p}p\pi^0$	(1.4 ±0.5) × 10^{-4}	
Γ_{21}	K^+K^-	(1.0 ±0.7) × 10^{-4}	
Γ_{22}	$\pi^+\pi^-$	(8 ±5) × 10^{-5}	
Γ_{23}	$\pi^+\pi^-\pi^0$	(8 ±5) × 10^{-5}	
Γ_{24}	$\Lambda\overline{\Lambda}$	< 4 × 10^{-4}	CL=90%
Γ_{25}	$\Xi^-\overline{\Xi}^+$	< 2 × 10^{-4}	CL=90%
Γ_{26}	$\rho\pi$	< 8.3 × 10^{-5}	CL=90%
Γ_{27}	$K^+K^-\pi^0$	< 2.96 × 10^{-5}	CL=90%
Γ_{28}	$K^+\overline{K}^*(892)^-$ + c.c.	< 1.79 × 10^{-5}	CL=90%
	Radiative decays		
Γ_{29}	$\gamma\chi_{c0}(1P)$	(9.3 ±0.8) %	
Γ_{30}	$\gamma\chi_{c1}(1P)$	(8.7 ±0.8) %	
Γ_{31}	$\gamma\chi_{c2}(1P)$	(7.8 ±0.8) %	
Γ_{32}	$\gamma\eta_c(1S)$	(2.8 ±0.6) × 10^{-3}	
Γ_{33}	$\gamma\eta_c(2S)$		
Γ_{34}	$\gamma\pi^0$	< 5.4 × 10^{-3}	CL=95%
Γ_{35}	$\gamma\eta'(958)$	< 1.1 × 10^{-3}	CL=90%
Γ_{36}	$\gamma\eta$	< 2 × 10^{-4}	CL=90%
Γ_{37}	$\gamma\gamma$	< 1.5 × 10^{-4}	CL=90%
Γ_{38}	$\gamma\eta(1440) \rightarrow \gamma K\overline{K}\pi$	[a] < 1.2 × 10^{-4}	CL=90%
	Mode needed for fitting purposes		
Γ_{39}	1. − other fit modes	(30 ±4) %	

[a] See $\eta(1440)$ mini-review.

CONSTRAINED FIT INFORMATION

An overall fit to 7 branching ratios uses 13 measurements and one constraint to determine 6 parameters. The overall fit has a $\chi^2 =$ 6.9 for 8 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_8	35				
x_9	0	−11			
x_{30}	1	−7	0		
x_{31}	0	−3	0	0	
x_{39}	−80	−78	−4	−14	−16
	x_7	x_8	x_9	x_{30}	x_{31}

$\psi(2S)$ PARTIAL WIDTHS

Γ(hadrons) — Γ_1

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
224±56	LUTH	75	MRK1	e^+e^-

$\Gamma(e^+e^-)$ — Γ_3

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
2.14±0.21	ALEXANDER	89	RVUE	See Υ mini-review
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.0 ±0.3	BRANDELIK	79C	DASP	e^+e^-
2.1 ±0.3	[3] LUTH	75	MRK1	e^+e^-

[3] From a simultaneous fit to e^+e^-, $\mu^+\mu^-$, and hadronic channels assuming $\Gamma(e^+e^-) = \Gamma(\mu^+\mu^-)$

$\Gamma(\gamma\gamma)$ — Γ_{37}

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<43	90	BRANDELIK	79C	DASP	e^+e^-

$\psi(2S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

This combination of a partial width with the partial width into e^+e^- and with the total width is obtained from the integrated cross section into channel$_i$ in the e^+e^- annihilation. We list only data that have not been used to determine the partial width $\Gamma(i)$ or the branching ratio $\Gamma(i)$/total.

$\Gamma(\text{hadrons}) \times \Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.2±0.4	ABRAMS	75	MRK1	e^+e^-

$\psi(2S)$ BRANCHING RATIOS

$\Gamma(\text{hadrons})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.981 ±0.003	[4] LUTH	75	MRK1	e^+e^-

$\Gamma(\text{virtual } \gamma \rightarrow \text{hadrons})/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.029±0.004	[5] LUTH	75	MRK1	e^+e^-

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_3/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
88±13	[6] FELDMAN	77	RVUE	e^+e^-

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
77±17	[7] HILGER	75	SPEC	e^+e^-

$\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-)$ — Γ_4/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
0.89±0.16	BOYARSKI	75C	MRK1	e^+e^-

[4] Includes cascade decay into $J/\psi(1S)$.
[5] Included in $\Gamma(\text{hadrons})/\Gamma_{\text{total}}$.
[6] From an overall fit assuming equal partial widths for e^+e^- and $\mu^+\mu^-$. For a measurement of the ratio see the entry $\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-)$ below. Includes LUTH 75, HILGER 75, BURMESTER 77.
[7] Restated by us using $B(\psi(2S) \to J/\psi(1S)\text{ anything}) = 0.55$.

DECAYS INTO $J/\psi(1S)$ AND ANYTHING

$\Gamma(J/\psi(1S)\text{ anything})/\Gamma_{\text{total}}$ — Γ_5/Γ
$(\Gamma_7+\Gamma_8+\Gamma_9+0.273\Gamma_{30}+0.135\Gamma_{31})/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.57±0.04 OUR FIT				
0.55±0.07 OUR AVERAGE				
0.51±0.12	BRANDELIK	79C	DASP	$e^+e^- \to \mu^+\mu^- X$
0.57±0.08	ABRAMS	75B	MRK1	$e^+e^- \to \mu^+\mu^- X$

$\Gamma(J/\psi(1S)\text{ neutrals})/\Gamma_{\text{total}}$ — Γ_6/Γ
$(0.9761\Gamma_8+0.708\Gamma_9+0.273\Gamma_{30}+0.135\Gamma_{31})/\Gamma$

VALUE	DOCUMENT ID
0.232±0.026 OUR FIT	

$\Gamma(J/\psi(1S)\text{ neutrals})/\Gamma(J/\psi(1S)\text{ anything})$ — Γ_6/Γ_5
$(0.9761\Gamma_8+0.708\Gamma_9+0.273\Gamma_{30}+0.135\Gamma_{31})/(\Gamma_7+\Gamma_8+\Gamma_9+0.273\Gamma_{30}+0.135\Gamma_{31})$

VALUE	DOCUMENT ID		TECN	COMMENT
0.409±0.026 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.44 ±0.03	[8] ABRAMS	75B	MRK1	$e^+e^- \to J/\psi$

$\Gamma(J/\psi(1S)\text{ neutrals})/\Gamma(J/\psi(1S)\pi^+\pi^-)$ — Γ_6/Γ_7
$(0.9761\Gamma_8+0.708\Gamma_9+0.273\Gamma_{30}+0.135\Gamma_{31})/\Gamma_7$

VALUE	DOCUMENT ID		TECN	COMMENT
0.72±0.08 OUR FIT				
0.73±0.09	[8] TANENBAUM	76	MRK1	e^+e^-

$\Gamma(J/\psi(1S)\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.324±0.026 OUR FIT				
0.332±0.033 OUR AVERAGE				
0.32 ±0.04	ABRAMS	75B	MRK1	$e^+e^- \to J/\psi\pi^+\pi^-$
0.36 ±0.06	WIIK	75	DASP	$e^+e^- \to J/\psi\pi^+\pi^-$

$\Gamma(J/\psi(1S)\pi^0\pi^0)/\Gamma_{\text{total}}$ — Γ_8/Γ

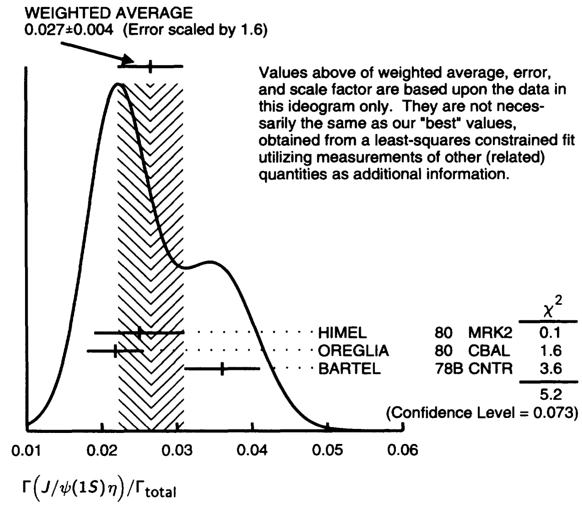
VALUE	DOCUMENT ID		TECN	COMMENT
0.184±0.027 OUR FIT				
0.18 ±0.06	WIIK	75	DASP	$e^+e^- \to J/\psi 2\pi^0$

$\Gamma(J/\psi(1S)\pi^0\pi^0)/\Gamma(J/\psi(1S)\pi^+\pi^-)$ — Γ_8/Γ_7

VALUE	DOCUMENT ID		TECN	COMMENT
0.57±0.08 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.53±0.06	[9] TANENBAUM	76	MRK1	e^+e^-
0.64±0.15	[10] HILGER	75	SPEC	e^+e^-

$\Gamma(J/\psi(1S)\eta)/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.027 ±0.004 OUR FIT Error includes scale factor of 1.7.					
0.027 ±0.004 OUR AVERAGE Error includes scale factor of 1.6. See the ideogram below.					
0.025 ±0.006	166	HIMEL	80	MRK2	e^+e^-
0.0218±0.0014±0.0035	386	OREGLIA	80	CBAL	$e^+e^- \to J/\psi 2\gamma$
0.036 ±0.005	164	BARTEL	78B	CNTR	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.035 ±0.009	17	[11] BRANDELIK	79B	DASP	$e^+e^- \to J/\psi 2\gamma$
0.043 ±0.008	44	[11] TANENBAUM	76	MRK1	e^+e^-



$\Gamma(J/\psi(1S)\eta)/\Gamma_{\text{total}}$

$\Gamma(J/\psi(1S)\pi^0)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
9.7±2.1 OUR AVERAGE					
15 ±6	7	HIMEL	80	MRK2	e^+e^-
9 ±2 ±1	23	OREGLIA	80	CBAL	$\psi(2S) \to J/\psi 2\gamma$

[8] The ABRAMS 75B measurement of Γ_6/Γ_5 and the TANENBAUM 76 result for Γ_6/Γ_7 are not independent. The TANENBAUM 76 result is used in the fit because it includes more accurate corrections for angular distributions.
[9] Not independent of the TANENBAUM 76 result for Γ_6/Γ_7.
[10] Ignoring the $J/\psi(1S)\eta$ and $J/\psi(1S)\gamma\gamma$ decays.
[11] Low statistics data removed from average.

HADRONIC DECAYS

$\Gamma(3(\pi^+\pi^-)\pi^0)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
35±16	6	FRANKLIN	83	MRK2	$e^+e^- \to$ hadrons

$\Gamma(2(\pi^+\pi^-)\pi^0)/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
31± 7 OUR AVERAGE					
30± 8	42	FRANKLIN	83	MRK2	e^+e^-
35±15		ABRAMS	75	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
16±4	[12] TANENBAUM	78	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-p\overline{p})/\Gamma_{\text{total}}$ — Γ_{14}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
8 ±2	[12] TANENBAUM	78	MRK1	e^+e^-

$\Gamma(K^+\overline{K}^*(892)^0\pi^- + \text{c.c.})/\Gamma_{\text{total}}$ — Γ_{15}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
6.7±2.5	TANENBAUM	78	MRK1	e^+e^-

$\Gamma(2(\pi^+\pi^-))/\Gamma_{\text{total}}$ — Γ_{16}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
4.5±1.0	TANENBAUM	78	MRK1	e^+e^-

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{17}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
4.2±1.5	TANENBAUM	78	MRK1	e^+e^-

$\Gamma(\overline{p}p)/\Gamma_{\text{total}}$ — Γ_{18}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.9±0.5 OUR AVERAGE					
1.4±0.8	4	BRANDELIK	79C	DASP	e^+e^-
2.3±0.7		FELDMAN	77	MRK1	e^+e^-

$\Gamma(3(\pi^+\pi^-))/\Gamma_{\text{total}}$ — Γ_{19}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
1.5±1.0	[12] TANENBAUM	78	MRK1	e^+e^-

$\Gamma(\overline{p}p\pi^0)/\Gamma_{\text{total}}$ — Γ_{20}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.4±0.5	9	FRANKLIN	83	MRK2	e^+e^-

$\Gamma(K^+K^-)/\Gamma_{total}$ — Γ_{21}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
1.0±0.7		BRANDELIK	79C	DASP	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.5	90	FELDMAN	77	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_{22}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
0.8±0.5		BRANDELIK	79C	DASP	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.5	90	FELDMAN	77	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{23}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
0.85±0.46	4	FRANKLIN	83	MRK2	$e^+e^- \rightarrow$ hadrons

$\Gamma(\Lambda\overline{\Lambda})/\Gamma_{total}$ — Γ_{24}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<4	90	FELDMAN	77	MRK1	e^+e^-

$\Gamma(\Xi^-\overline{\Xi}^+)/\Gamma_{total}$ — Γ_{25}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<2	90	FELDMAN	77	MRK1	e^+e^-

$\Gamma(\rho\pi)/\Gamma_{total}$ — Γ_{26}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 0.83	90	1	FRANKLIN	83	MRK2	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<10	90		BARTEL	76	CNTR	e^+e^-
<10	90		[13] ABRAMS	75	MRK1	e^+e^-

$\Gamma(K^+K^-\pi^0)/\Gamma_{total}$ — Γ_{27}/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<2.96	90	1	FRANKLIN	83	MRK2	$e^+e^- \rightarrow$ hadrons

$\Gamma(K^+\overline{K}^*(892)^- + c.c.)/\Gamma_{total}$ — Γ_{28}/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.79	90	0	FRANKLIN	83	MRK2	$e^+e^- \rightarrow$ hadrons

[12] Assuming entirely strong decay.
[13] Final state $\rho^0\pi^0$.

RADIATIVE DECAYS

$\Gamma(\gamma\chi_{c0}(1P))/\Gamma_{total}$ — Γ_{29}/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
9.3±0.8 OUR AVERAGE				
9.9±0.5±0.8	[14] GAISER	86	CBAL	$e^+e^- \rightarrow \gamma X$
7.2±2.3	[14] BIDDICK	77	CNTR	$e^+e^- \rightarrow \gamma X$
7.5±2.6	[14] WHITAKER	76	MRK1	e^+e^-

$\Gamma(\gamma\chi_{c1}(1P))/\Gamma_{total}$ — Γ_{30}/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
8.7±0.8 OUR FIT				
8.7±0.8 OUR AVERAGE				
9.0±0.5±0.7	[15] GAISER	86	CBAL	$e^+e^- \rightarrow \gamma X$
7.1±1.9	[16] BIDDICK	77	CNTR	$e^+e^- \rightarrow \gamma X$

$\Gamma(\gamma\chi_{c2}(1P))/\Gamma_{total}$ — Γ_{31}/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
7.8±0.8 OUR FIT				
7.8±0.8 OUR AVERAGE				
8.0±0.5±0.7	[17] GAISER	86	CBAL	$e^+e^- \rightarrow \gamma X$
7.0±2.0	[16] BIDDICK	77	CNTR	$e^+e^- \rightarrow \gamma X$

$\Gamma(\gamma\eta_c(1S))/\Gamma_{total}$ — Γ_{32}/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
0.28±0.06	GAISER	86	CBAL	$e^+e^- \rightarrow \gamma X$

$\Gamma(\gamma\eta_c(2S))/\Gamma_{total}$ — Γ_{33}/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.2 to 1.3	95	EDWARDS	82C	CBAL	$e^+e^- \rightarrow \gamma X$

$\Gamma(\gamma\pi^0)/\Gamma_{total}$ — Γ_{34}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
< 54	95	[18] LIBERMAN	75	SPEC	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<100	90	WIIK	75	DASP	e^+e^-

$\Gamma(\gamma\eta'(958))/\Gamma_{total}$ — Γ_{35}/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID		TECN	COMMENT
<0.11	90	[19] BARTEL	76	CNTR	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.6	90	[20] BRAUNSCH...	77	DASP	e^+e^-

$\Gamma(\gamma\eta)/\Gamma_{total}$ — Γ_{36}/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	YAMADA	77	DASP	$e^+e^- \rightarrow 3\gamma$

$\Gamma(\gamma\eta(1440) \rightarrow \gamma K\overline{K}\pi)/\Gamma_{total}$ — Γ_{38}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.12	90	[21] SCHARRE	80	MRK1	e^+e^-

[14] Angular distribution $(1+\cos^2\theta)$ assumed.
[15] Angular distribution $(1-0.189\cos^2\theta)$ assumed.
[16] Valid for isotropic distribution of the photon.
[17] Angular distribution $(1-0.052\cos^2\theta)$ assumed.
[18] Restated by us using $B(\psi(2S) \rightarrow \mu^+\mu^-) = 0.0077$.
[19] The value is normalized to the branching ratio for $\Gamma(J/\psi(1S)\eta)/\Gamma_{total}$.
[20] Restated by us using total decay width 228 keV.
[21] Includes unknown branching fraction $\eta(1440) \rightarrow K\overline{K}\pi$.

$\psi(2S)$ REFERENCES

ARMSTRONG	92B	PRL (accepted)	+Bettoni+	(FNAL, FERR, GENO, UCI, NWES+)
PDG	92	PR D45, Part 2	Hikasa, Barnett, Stone+	(KEK, LBL, BOST+)
ALEXANDER	89	NP B320 45	+Bonvicini, Drell, Frey, Luth	(LBL, MICH, SLAC)
GAISER	86	PR D34 711	+Bloom, Bulos, Godfrey+	(Crystal Ball Collab.)
FRANKLIN	83	PRL 51 963	+Franklin, Feldman, Abrams, Alam+	(LBL, SLAC)
EDWARDS	82C	PRL 48 70	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
LEMOIGNE	82	PL 113B 509	+Barate, Astbury+	(SACL, LOIC, SHMP, IND)
HIMEL	80	PRL 44 920	+Abrams, Alam, Blocker+	(LBL, SLAC)
OREGLIA	80	PRL 45 959	+Partridge+	(SLAC, CIT, HARV, PRIN, STAN)
SCHARRE	80	PL 97B 329	+Trilling, Abrams, Alam, Blocker+	(SLAC, LBL)
ZHOLENTZ	80	PL 96B 214	+Kurdadze, Lelchuk, Mishnev+	(NOVO)
Also	81	SJNP 34 814	Zholentz, Kurdadze, Lelchuk+	(NOVO)
		Translated from YAF 34 1471.		
BRANDELIK	79B	NP B160 426	+Cords+	(AACH, DESY, HAMB, MPIM, TOKY)
BRANDELIK	79C	ZPHY C1 233	+	(AACH, DESY, HAMB, MPIM, TOKY)
BARTEL	78B	PL 79B 492	+Dittmann, Duinker, Olsson, O'Neill+	(DESY, HEID)
TANENBAUM	78	PR D17 1731	+Alam, Boyarski+	(SLAC, LBL)
BIDDICK	77	PRL 38 1324	+Burnett+	(UCSD, UMD, PAVI, PRIN, SLAC, STAN)
BRAUNSCH...	77	PL 67B 249	Braunschweig+	(AACH, DESY, HAMB, MPIM+)
BURMESTER	77	PL 66B 395	+Criegee+	(DESY, HAMB, SIEG, WUPP)
FELDMAN	77	PL 33C 285	+Perl	(LBL, SLAC)
YAMADA	77	Hamburg Conf. 69		(DESY, TOKY)
BARTEL	76	PL 64B 483	+Duinker, Olsson, Steffen, Heintze+	(DESY, HEID)
TANENBAUM	76	PRL 36 402	+Abrams, Boyarski, Bulos+	(SLAC, LBL) IG
WHITAKER	76	PRL 37 1596	+Tanenbaum, Abrams, Alam+	(SLAC, LBL)
ABRAMS	75	Stanford Symp. 25		(LBL)
ABRAMS	75B	PRL 34 1181	+Briggs, Chinowsky, Friedberg+	(LBL, SLAC)
BOYARSKI	75C	Palermo Conf. 54	+Breidenbach, Bulos, Abrams, Briggs+	(SLAC, LBL)
HILGER	75	PRL 35 625	+Beron, Ford, Hofstadter, Howell+	(STAN, PENN)
LIBERMAN	75	Stanford Symp. 55		(STAN)
LUTH	75	PRL 35 1124	+Boyarski, Lynch, Breidenbach+	(SLAC, LBL) JPC
WIIK	75	Stanford Symp. 69		(DESY)

OTHER RELATED PAPERS

LEE	85	SLAC 282		(SLAC)
BARATE	83	PL 121B 449	+Bareyre, Bonamy+	(SACL, LOIC, SHMP, IND)
FRANKLIN	83B	SLAC-254 Thesis		(STAN)
AUBERT	75B	PRL 33 1624	+Becker, Biggs, Burger, Glenn+	(MIT, BNL)
BRAUNSCH...	75B	PL 57B 407	Braunschweig+	(AACH, DESY, MPIM, TOKY)
CAMERINI	75	PRL 35 483	+Learned, Prepost, Ash, Anderson+	(WISC, SLAC)
FELDMAN	75B	PRL 35 821	+Jean-Marie, Sadoulet, Vannucci+	(LBL, SLAC)
GRECO	75	PL 56B 367	+Pancheri-Srivastava, Srivastava	(FRAS)
JACKSON	75	NIM 128 13	+Scharre	(LBL)
SIMPSON	75	PRL 35 699	+Beron, Ford, Hilger, Hofstadter+	(STAN, PENN)
ABRAMS	74	PRL 33 1453	+Briggs, Augustin, Boyarski+	(LBL, SLAC)

$\psi(3770)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\psi(3770)$ MASS

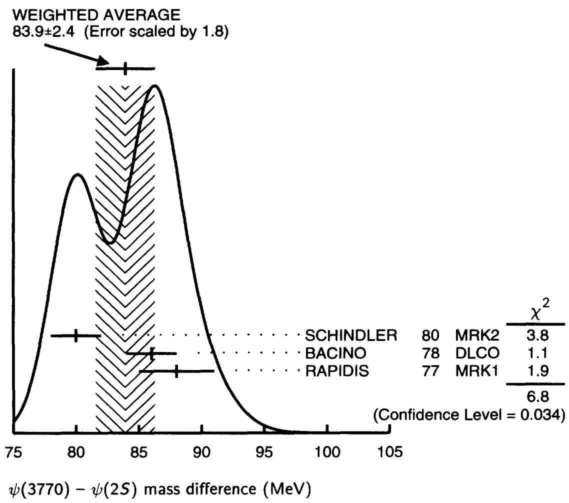
VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
3769.9±2.5 OUR EVALUATION	Error includes scale factor of 1.8. From $\psi(3685)$ mass and mass difference below.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3764.0±5.0	[1] SCHINDLER	80	MRK2	e^+e^-
3770 ±6.0	[1] BACINO	78	DLCO	e^+e^-
3772.0±6.0	[1] RAPIDIS	77	MRK1	e^+e^-

[1] Errors include systematic common to all experiments.

$\psi(3770) - \psi(2S)$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
83.9±2.4 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.			
80.0±2.0	SCHINDLER 80	MRK2	e^+e^-
86.0±2.0	[2] BACINO 78	DLCO	e^+e^-
88.0±3.0	RAPIDIS 77	MRK1	e^+e^-

[2] SPEAR $\psi(2S)$ mass subtracted (see SCHINDLER 80).



$\psi(3770)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
23.6±2.7 OUR FIT Error includes scale factor of 1.1.			
25.3±2.9 OUR AVERAGE			
24.0±5.0	SCHINDLER 80	MRK2	e^+e^-
24.0±5.0	BACINO 78	DLCO	e^+e^-
28.0±5.0	RAPIDIS 77	MRK1	e^+e^-

$\psi(3770)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor
Γ_1	$D\overline{D}$	dominant	
Γ_2	e^+e^-	$(1.12\pm0.17)\times10^{-5}$	1.2

$\psi(3770)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_2

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
0.26 ±0.04 OUR FIT Error includes scale factor of 1.2.			
0.24 ±0.05 OUR AVERAGE Error includes scale factor of 1.2.			
0.276±0.050	SCHINDLER 80	MRK2	e^+e^-
0.18 ±0.06	BACINO 78	DLCO	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.37 ±0.09	[3] RAPIDIS 77	MRK1	e^+e^-

[3] See also $\Gamma(e^+e^-)/\Gamma_{total}$ below.

$\psi(3770)$ BRANCHING RATIOS

$\Gamma(D\overline{D})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
dominant	PERUZZI 77	MRK1	$e^+e^- \to D\overline{D}$

$\Gamma(e^+e^-)/\Gamma_{total}$ Γ_2/Γ

VALUE (units 10^{-5})	DOCUMENT ID	TECN	COMMENT
1.12±0.17 OUR FIT Error includes scale factor of 1.2.			
1.3 ±0.2	RAPIDIS 77	MRK1	e^+e^-

$\psi(3770)$ REFERENCES

SCHINDLER 80 PR D21 2716 +Siegrist, Alam, Boyarski+ (Mark II Collab.)
BACINO 78 PRL 40 671 +Baumgarten, Birkwood+ (SLAC, UCLA, UCI)
PERUZZI 77 PRL 39 1301 +Piccolo, Feldman+ (SLAC, LBL, NWES, HAWA)
RAPIDIS 77 PRL 39 526 +Gobbi, Luke, Barbaro-Galtieri+ (Mark I Collab.)

$\psi(4040)$

$I^G(J^{PC}) = ?^?(1^{--})$

J^{PC} for the $\psi(4040)$ is known by its production in e^+e^- collisions via single-photon annihilation. I^G is not known, and the interpretation of this state as a single resonance is unclear because of the expectation of substantial threshold effects in this energy region.

$\psi(4040)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
4040.0±10.0	BRANDELIK 78C	DASP	e^+e^-

$\psi(4040)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
52.0±10.0	BRANDELIK 78C	DASP	e^+e^-

$\psi(4040)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(1.4\pm0.4)\times10^{-5}$
Γ_2	$D^0\overline{D}^0$	seen
Γ_3	$D^*(2010)^0\overline{D}^0$ + c.c.	seen
Γ_4	$D^*(2010)^0\overline{D}^*(2010)^0$	seen
Γ_5	$J/\psi(1S)$ hadrons	
Γ_6	$\mu^+\mu^-$	

$\psi(4040)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
0.75±0.15	BRANDELIK 78C	DASP	e^+e^-

$\psi(4040)$ BRANCHING RATIOS

$\Gamma(e^+e^-)/\Gamma_{total}$ Γ_1/Γ

VALUE (units 10^{-5})	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~1.0	FELDMAN 77	MRK1	e^+e^-

$\Gamma(D^0\overline{D}^0)/\Gamma(D^*(2010)^0\overline{D}^0$ + c.c.) Γ_2/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
0.05 ±0.03	[1] GOLDHABER 77	MRK1	e^+e^-

[1] Phase-space factor (p^3) explicitly removed.

$\Gamma(D^*(2010)^0\overline{D}^*(2010)^0)/\Gamma(D^*(2010)^0\overline{D}^0$ + c.c.) Γ_4/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
32.0±12.0	[2] GOLDHABER 77	MRK1	e^+e^-

[2] Phase-space factor (p^3) explicitly removed.

$\psi(4040)$ REFERENCES

BRANDELIK 78C PL 76B 361 +Cords+ (AACH, DESY, HAMB, MPIM, TOKY)
Also 79C ZPHY C1 233 Brandelik+ (AACH, DESY, HAMB, MPIM, TOKY)
FELDMAN 77 PL 33C 285 +Perl (LBL, SLAC)
GOLDHABER 77 PL 69B 503 +Wiss, Abrams, Alam+ (LBL, SLAC)

OTHER RELATED PAPERS

HEIKKILA 84 PR D29 110 +Tornqvist, Ono (HELS, TOKY)
ONO 84 ZPHY C26 307 (ORSA)
SIEGRIST 82 PR D26 969 +Schwitters, Alam, Chinowsky+ (SLAC, LBL)
AUGUSTIN 75 PRL 34 764 +Boyarski, Abrams, Briggs+ (SLAC, LBL)
BACCI 75 PL 58B 481 +Bidoli, Penso, Stella+ (ROMA, FRAS)
BOYARSKI 75B PRL 34 762 +Breidenbach, Abrams, Briggs+ (SLAC, LBL)
ESPOSITO 75 PL 58B 478 +Felicetti, Peruzzi+ (FRAS, NAPL, PADO, ROMA)

$\psi(4160)$

$I^G(J^{PC}) = ?^?(1^{--})$

J^{PC} for the $\psi(4160)$ is known by its production in e^+e^- collisions via single-photon annihilation. I^G is not known, and the interpretation of this state as a single resonance is unclear because of the expectation of substantial threshold effects in this energy region.

$\psi(4160)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4159.0±20.0	BRANDELIK	78C	DASP	e^+e^-

$\psi(4160)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
78.0±20.0	BRANDELIK	78C	DASP	e^+e^-

$\psi(4160)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(10\pm4)\times10^{-6}$

$\psi(4160)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.77±0.23	BRANDELIK	78C	DASP	e^+e^-

$\psi(4160)$ REFERENCES

BRANDELIK 78C PL 76B 361 +Cords+ (AACH, DESY, HAMB, MPIM, TOKY)

OTHER RELATED PAPERS

ONO 84 ZPHY C26 307 (ORSA)
KIRKBY 79B Fermilab Symp. 107 (SLAC)
BURMESTER 77 PL 66B 395 +Criegee+ (DESY, HAMB, SIEG, WUPP)

$\psi(4415)$

$I^G(J^{PC}) = ?^?(1^{--})$

J^{PC} for the $\psi(4415)$ is known by its production in e^+e^- collisions via single-photon annihilation. I^G is not known, and the interpretation of this state as a single resonance is unclear because of the expectation of substantial threshold effects in this energy region.

$\psi(4415)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4415 ± 6 OUR AVERAGE				
4417.0±10.0	BRANDELIK	78C	DASP	e^+e^-
4414 ± 7	SIEGRIST	76	MRK1	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 4400	KNIES	77	PLUT	$e^+e^- \to \mu^+\mu^-$

$\psi(4415)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
43 ±15 OUR AVERAGE	Error includes scale factor of 1.8.			
66.0±15.0	BRANDELIK	78C	DASP	e^+e^-
33 ±10	SIEGRIST	76	MRK1	e^+e^-

$\psi(4415)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	hadrons	dominant
Γ_2	e^+e^-	$(1.1\pm0.4)\times10^{-5}$

$\psi(4415)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_2

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.47±0.10 OUR AVERAGE				
0.49±0.13	BRANDELIK	78C	DASP	e^+e^-
0.44±0.14	SIEGRIST	76	MRK1	e^+e^-

$\psi(4415)$ BRANCHING RATIOS

$\Gamma(\text{hadrons})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
dominant	SIEGRIST	76	MRK1	e^+e^-

$\psi(4415)$ REFERENCES

BRANDELIK 78C PL 76B 361 +Cords+ (AACH, DESY, HAMB, MPIM, TOKY)
KNIES 77 Hamburg Symp. 93 (PLUTO Collab.)
SIEGRIST 76 PRL 36 700 +Abrams, Boyarski, Breidenbach+ (LBL, SLAC)

OTHER RELATED PAPERS

BURMESTER 77 PL 66B 395 +Criegee+ (DESY, HAMB, SIEG, WUPP)
LUTH 77 PL 70B 120 +Pierre, Abrams, Alam, Boyarski+ (LBL, SLAC)

$b\bar{b}$ MESONS

NOTE ON WIDTH DETERMINATIONS OF THE Υ STATES

As is the case for $J/\psi(1S)$ and $\psi(2S)$, the full widths of the bound $b\bar{b}$ states $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ are not directly measurable, since they are much smaller than the energy resolution of the e^+e^- storage rings where these states are produced. The common indirect method to determine Γ starts from

$$\Gamma = \Gamma_{\ell\ell}/B_{\ell\ell} \ , \tag{1}$$

where $\Gamma_{\ell\ell}$ is one leptonic partial width and $B_{\ell\ell}$ is the corresponding branching fraction ($\ell = e$, μ, or τ). One then assumes e-μ-τ universality and uses

$$\Gamma_{\ell\ell} = \Gamma_{ee}$$

$$B_{\ell\ell} = \text{average of } B_{ee},\ B_{\mu\mu},\ \text{and } B_{\tau\tau}\ . \tag{2}$$

The electronic partial width Γ_{ee} is also not directly measurable at e^+e^- storage rings, only the combination $\Gamma_{ee}\Gamma_{\rm had}/\Gamma$, where $\Gamma_{\rm had}$ is the hadronic partial width and

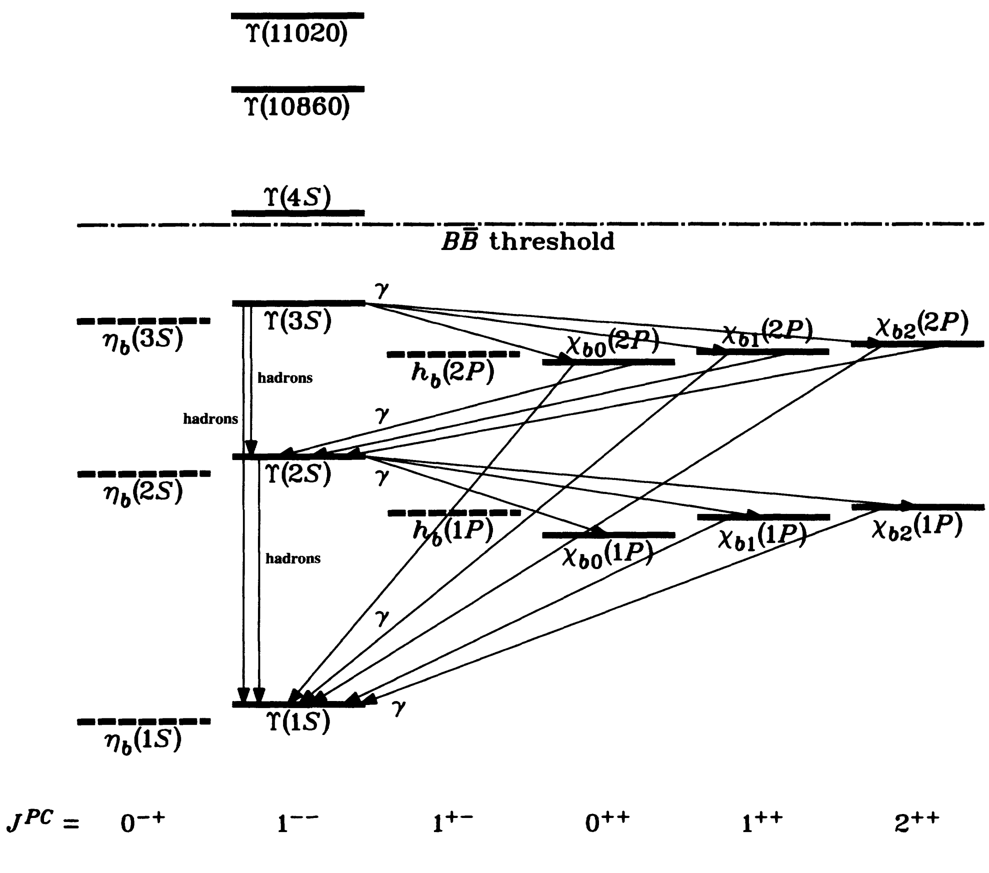
$$\Gamma_{\rm had} + 3\Gamma_{ee} = \Gamma\ . \tag{3}$$

This combination is obtained experimentally from the energy-integrated hadronic cross section

$$\int_{\rm resonance} \sigma(e^+e^- \to \Upsilon \to {\rm hadrons})dE$$

$$= \frac{6\pi}{M^2}\frac{\Gamma_{ee}\Gamma_{\rm had}}{\Gamma}C_r = \frac{6\pi}{M^2}\frac{\Gamma^{(0)}_{ee}\Gamma_{\rm had}}{\Gamma}C_r^{(0)}\ , \tag{4}$$

THE BOTTOMONIUM SYSTEM



The level scheme of the $b\bar{b}$ states showing experimentally established states with solid lines. Singlet states are called η_b and h_b, triplet states Υ and χ_{bJ}. In parentheses it is sufficient to give the radial quantum number and the orbital angular momentum to specify the states with all their quantum numbers. *E.g.*, $h_b(2P)$ means 2^1P_1 with $n = 2$, $L = 1$, $S = 0$, $J = 1$, $PC = +-$. If found, D-wave states would be called $\eta_b(nD)$ and $\Upsilon_J(nD)$, with J = 1,2,3 and $n = 1,2,3,4,\cdots$. For the χ_b states, the spins of only the $\chi_{b2}(1P)$ and $\chi_{b1}(1P)$ have been experimentally established. The spins of the other χ_b are given as the preferred values, based on the quarkonium models. The figure also shows the observed hadronic and radiative transitions.

where M is the Υ mass, and C_r and $C_r^{(0)}$ are radiative correction factors. C_r is used for obtaining Γ_{ee} as defined in Eq. (1) and contains corrections from all orders of QED for describing $(b\bar{b}) \to e^+e^-$. The lowest order QED value $\Gamma_{ee}^{(0)}$, relevant for the comparison with potential-model calculations, is defined by the lowest order QED graph (Born term) alone and is about 7% lower than Γ_{ee}. In the past, this distinction had been overlooked by some authors as pointed out by ALEXANDER 89, BARU 86, COOPER 86, KOENIGSMANN 86, and others.

The Listings give experimental results on B_{ee}, $B_{\mu\mu}$, $B_{\tau\tau}$, and $\Gamma_{ee}\Gamma_{\rm had}/\Gamma$. The entries of the latter quantity have been re-evaluated using consistently the correction procedure of KURAEV 85. The partial width Γ_{ee} is obtained from the average values for $\Gamma_{ee}\Gamma_{\rm had}/\Gamma$ and $B_{\ell\ell}$ using

$$\Gamma_{ee} = \frac{\Gamma_{ee}\Gamma_{\rm had}}{\Gamma(1-3B_{\ell\ell})} \ . \qquad (5)$$

The total width Γ is then obtained from Eq. (1). We do not list Γ_{ee} and Γ values of individual experiments. The Γ_{ee} values in the Meson Summary Table are also those defined in Eq. (1) and no longer the lowest order quantities $\Gamma_{ee}^{(0)}$.

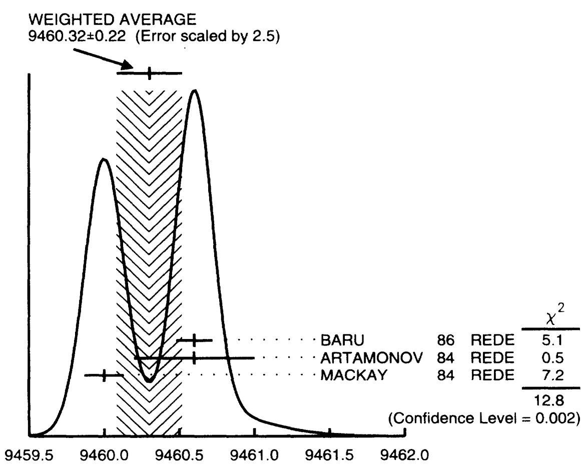
$\Upsilon(1S)$ or $\Upsilon(9460)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(1S)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
9460.32±0.22 OUR AVERAGE	Error includes scale factor of 2.5. See the ideogram below.			
9460.59±0.12	BARU	86	REDE	$e^+e^- \to$ hadrons
9460.6 ±0.4	[1] ARTAMONOV	84	REDE	$e^+e^- \to$ hadrons
9459.97±0.11±0.07	MACKAY	84	REDE	$e^+e^- \to$ hadrons

[1] Value includes data of ARTAMONOV 82.



$\Upsilon(1S)$ mass (MeV)

$\Upsilon(1S)$ WIDTH

VALUE (keV)	DOCUMENT ID
52.1±2.1 OUR EVALUATION	See Υ mini-review.

$\Upsilon(1S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\tau^+\tau^-$	(2.97±0.35) %	
Γ_2	$\mu^+\mu^-$	(2.48±0.06) %	
Γ_3	e^+e^-	(2.52±0.17) %	
	Hadronic decays		
Γ_4	$J/\psi(1S)$ anything	(1.1 ±0.4) × 10^{-3}	
Γ_5	$\rho\pi$	< 2 × 10^{-4}	90%
Γ_6	$\pi^+\pi^-$	< 5 × 10^{-4}	90%
Γ_7	K^+K^-	< 5 × 10^{-4}	90%
Γ_8	$p\bar{p}$	< 9 × 10^{-4}	90%
	Radiative decays		
Γ_9	$\gamma 2\pi^+ 2\pi^-$	(2.5 ±0.9) × 10^{-4}	
Γ_{10}	$\gamma\pi^+\pi^- K^+K^-$	(2.9 ±0.9) × 10^{-4}	
Γ_{11}	$\gamma\pi^+\pi^- p\bar{p}$	(1.5 ±0.6) × 10^{-4}	
Γ_{12}	$\gamma 2K^+ 2K^-$	(2.0 ±2.0) × 10^{-5}	
Γ_{13}	$\gamma 3\pi^+ 3\pi^-$	(2.5 ±1.2) × 10^{-4}	
Γ_{14}	$\gamma 2\pi^+ 2\pi^- K^+K^-$	(2.4 ±1.2) × 10^{-4}	
Γ_{15}	$\gamma 2\pi^+ 2\pi^- p\bar{p}$	(4 ±6) × 10^{-5}	
Γ_{16}	$\gamma 2h^+ 2h^-$	(7.0 ±1.5) × 10^{-4}	
Γ_{17}	$\gamma 3h^+ 3h^-$	(5.4 ±2.0) × 10^{-4}	
Γ_{18}	$\gamma 4h^+ 4h^-$	(7.4 ±3.5) × 10^{-4}	
Γ_{19}	$\gamma\eta'(958)$	< 1.3 × 10^{-3}	90%
Γ_{20}	$\gamma\eta$	< 3.5 × 10^{-4}	90%
Γ_{21}	$\gamma f_2'(1525)$	< 1.4 × 10^{-4}	90%
Γ_{22}	$\gamma f_0(1710) \to \gamma K\bar{K}$	< 6.4 × 10^{-5}	90%
Γ_{23}	$\gamma f_2(1270)$	< 1.3 × 10^{-4}	90%
Γ_{24}	$\gamma f_4(2220) \to \gamma K^+K^-$	< 1.5 × 10^{-5}	90%
Γ_{25}	$\gamma\eta(1440)$	< 8.2 × 10^{-5}	90%

$\Upsilon(1S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(e^+e^-) \times \Gamma(\mu^+\mu^-)/\Gamma_{\rm total}$ $\qquad \Gamma_3\Gamma_2/\Gamma$

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
31.2±1.6±1.7	KOBEL	91	CBAL	$e^+e^- \to \mu^+\mu^-$

$\Gamma(\text{hadrons}) \times \Gamma(e^+e^-)/\Gamma_{\rm total}$ $\qquad \Gamma_0\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
1.24±0.04 OUR AVERAGE				
1.23±0.02±0.05	[2] JAKUBOWSKI	88	CBAL	$e^+e^- \to$ hadrons
1.37±0.06±0.09	[3] GILES	84B	CLEO	$e^+e^- \to$ hadrons
1.17±0.06±0.10	[3] TUTS	83	CUSB	$e^+e^- \to$ hadrons
1.23±0.08±0.04	[3] ALBRECHT	82	DASP	$e^+e^- \to$ hadrons
1.13±0.07±0.11	[3] NICZYPORUK	82	LENA	$e^+e^- \to$ hadrons
1.09±0.25	[3] BOCK	80	CNTR	$e^+e^- \to$ hadrons
1.35±0.14	[4] BERGER	79	PLUT	$e^+e^- \to$ hadrons

[2] Radiative corrections evaluated following KURAEV 85.
[3] Radiative corrections reevaluated by BUCHMUELLER 88 following KURAEV 85.
[4] Radiative corrections reevaluated by ALEXANDER 89 using B($\mu\mu$) = 0.026.

$\Upsilon(1S)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ $\qquad \Gamma_3$

VALUE (keV)	DOCUMENT ID
1.34±0.04 OUR EVALUATION	See Υ mini-review.

$\Upsilon(1S)$ BRANCHING RATIOS

$\Gamma(\tau^+\tau^-)/\Gamma_{\rm total}$ $\qquad \Gamma_1/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.0297±0.0035 OUR AVERAGE				
0.027 ±0.004 ±0.002	[5] ALBRECHT	85C	ARG	$\Upsilon(2S) \to \pi^+\pi^-\tau^+\tau^-$
0.034 ±0.004 ±0.004	GILES	83	CLEO	$e^+e^- \to \tau^+\tau^-$

[5] Using B($\Upsilon(1S) \to ee$) = B($\Upsilon(1S) \to \mu\mu$) = 0.0256; not used for width evaluations.

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0248±0.0006 OUR AVERAGE					
0.0212±0.0020±0.0010		[6] BARU	91	MD1	$e^+e^- \to \mu^+\mu^-$
0.0231±0.0012±0.0010		[6] KOBEL	91	CBAL	$e^+e^- \to \mu^+\mu^-$
0.0252±0.0007±0.0007		CHEN	89B	CLEO	$e^+e^- \to \mu^+\mu^-$
0.0261±0.0009±0.0011		KAARSBERG	89	CSB2	$e^+e^- \to \mu^+\mu^-$
0.0230±0.0025±0.0013	86	ALBRECHT	87	ARG	$\Upsilon(2S) \to \pi^+\pi^-\mu^+\mu^-$
0.029 ±0.003 ±0.002	864	BESSON	84	CLEO	$\Upsilon(2S) \to \pi^+\pi^-\mu^+\mu^-$
0.027 ±0.003 ±0.003		ANDREWS	83	CLEO	$e^+e^- \to \mu^+\mu^-$
0.027 ±0.003 ±0.003		TUTS	83	CUSB	$e^+e^- \to \mu^+\mu^-$
0.032 ±0.013 ±0.003		ALBRECHT	82	DASP	$e^+e^- \to \mu^+\mu^-$
0.038 ±0.015 ±0.002		NICZYPORUK	82	LENA	$e^+e^- \to \mu^+\mu^-$
0.014 $^{+0.034}_{-0.014}$		BOCK	80	CNTR	$e^+e^- \to \mu^+\mu^-$
0.022 ±0.020		BERGER	79	PLUT	$e^+e^- \to \mu^+\mu^-$

[6] Taking into account interference between the resonance and continuum.

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0252±0.0017 OUR AVERAGE					
0.0242±0.0014±0.0014	307	ALBRECHT	87	ARG	$\Upsilon(2S) \to \pi^+\pi^-e^+e^-$
0.028 ±0.003 ±0.002	826	BESSON	84	CLEO	$\Upsilon(2S) \to \pi^+\pi^-e^+e^-$
0.051 ±0.030		BERGER	80C	PLUT	$e^+e^- \to e^+e^-$

$\Gamma(J/\psi(1S)\text{ anything})/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
1.1±0.4±0.2		[7] FULTON	89	CLEO	$e^+e^- \to \mu^+\mu^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 1.7	90	MASCHMANN	90	CBAL	$e^+e^- \to$ hadrons
<20	90	NICZYPORUK	83	LENA	

[7] Using $B((J/\psi) \to \mu^+\mu^-) = (6.9 \pm 0.9)\%$.

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<5	90	BARU	91	MD1	$\Upsilon(1S) \to \pi^+\pi^-$

$\Gamma(K^+K^-)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<5	90	BARU	91	MD1	$\Upsilon(1S) \to K^+K^-$

$\Gamma(p\overline{p})/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<9	90	BARU	91	MD1	$\Upsilon(1S) \to p\overline{p}$

$\Gamma(\gamma 2\pi^+ 2\pi^-)/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.5±0.7±0.5	26 ± 7	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma\pi^+\pi^- K^+K^-)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.9±0.7±0.6	29 ± 8	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma\pi^+\pi^- p\overline{p})/\Gamma_{total}$ — Γ_{11}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.5±0.5±0.3	22 ± 6	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 2K^+ 2K^-)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
0.2 ±0.2	2 ± 2	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 3\pi^+ 3\pi^-)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.5±0.9±0.8	17 ± 5	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 2\pi^+ 2\pi^- K^+K^-)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.4±0.9±0.8	18 ± 7	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 2\pi^+ 2\pi^- p\overline{p})/\Gamma_{total}$ — Γ_{15}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
0.4±0.4±0.4	7 ± 6	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 2h^+ 2h^-)/\Gamma_{total}$ — Γ_{16}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
7.0±1.1±1.0	80 ± 12	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 3h^+ 3h^-)/\Gamma_{total}$ — Γ_{17}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
5.4±1.5±1.3	39 ± 11	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 4h^+ 4h^-)/\Gamma_{total}$ — Γ_{18}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
7.4±2.5±2.5	36 ± 12	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\rho\pi)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
< 2	90	FULTON	90B		$\Upsilon(1S) \to \rho^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<10	90	BLINOV	90	MD1	$\Upsilon(1S) \to \rho^0\pi^0$
<21	90	NICZYPORUK	83	LENA	$\Upsilon(1S) \to \rho^0\pi^0$

$\Gamma(\gamma\eta(1440))/\Gamma_{total}$ — Γ_{25}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<8.2	90	[8] FULTON	90B	CLEO	$\Upsilon(1S) \to \gamma K^+\pi^\mp K^0_S$

[8] Includes unknown branching ratio of $\eta(1440) \to K^\pm\pi^\mp K^0_S$

$\Gamma(\gamma\eta'(958))/\Gamma_{total}$ — Γ_{19}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<1.3	90	SCHMITT	88	CBAL	$\Upsilon(1S) \to \gamma X$

$\Gamma(\gamma\eta)/\Gamma_{total}$ — Γ_{20}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<3.5	90	SCHMITT	88	CBAL	$\Upsilon(1S) \to \gamma X$

$\Gamma(\gamma f'_2(1525))/\Gamma_{total}$ — Γ_{21}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<14	90	[9] FULTON	90B	CLEO	$\Upsilon(1S) \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<19.4	90	[9] ALBRECHT	89	ARG	$\Upsilon(1S) \to \gamma K^+K^-$

[9] Assuming $B(f'_2(1525) \to K\overline{K}) = 0.71$.

$\Gamma(\gamma f_0(1710) \to \gamma K\overline{K})/\Gamma_{total}$ — Γ_{22}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
< 2.6	90	[10] ALBRECHT	89	ARG	$\Upsilon(1S) \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 6.3	90	[10] FULTON	90B	CLEO	$\Upsilon(1S) \to \gamma K^+K^-$
<19	90	[10] FULTON	90B	CLEO	$\Upsilon(1S) \to \gamma K^0_S K^0_S$
< 8	90	[11] ALBRECHT	89	ARG	$\Upsilon(1S) \to \gamma\pi^+\pi^-$
<24	90	[12] SCHMITT	88	CBAL	$\Upsilon(1S) \to \gamma X$

[10] Assuming $B(f_0(1710) \to K\overline{K}) = 0.38$.
[11] Assuming $B(f_0(1710) \to \pi\pi) = 0.04$.
[12] Assuming $B(f_0(1710) \to \eta\eta) = 0.18$.

$\Gamma(\gamma f_2(1270))/\Gamma_{total}$ — Γ_{23}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<13	90	[13] ALBRECHT	89	ARG	$\Upsilon(1S) \to \gamma\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<21	90	[13] FULTON	90B	CLEO	$\Upsilon(1S) \to \gamma\pi^+\pi^-$
<81	90	SCHMITT	88	CBAL	$\Upsilon(1S) \to \gamma X$

[13] Using $B(f_2(1270) \to \pi\pi) = 0.84$.

$\Gamma(\gamma f_4(2220) \to \gamma K^+K^-)/\Gamma_{total}$ — Γ_{24}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
< 1.5	90	[14] FULTON	90B	CLEO	$\Upsilon(1S) \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 2.9	90	[14] ALBRECHT	89	ARG	$\Upsilon(1S) \to \gamma K^+K^-$
<20	90	[14] BARU	89	MD1	$\Upsilon(1S) \to \gamma K^+K^-$

[14] Including unknown branching ratio of $f_4(2220) \to K^+K^-$.

$\Upsilon(1S)$ REFERENCES

BARU	91	INP 91-110 Preprint	+Beilin, Blinov+	(NOVO)
KOBEL	91	DESY 91-089 preprint	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
BLINOV	90	PL B245 311	+Bondar+	(NOVO)
FULTON	90B	PR D41 1401	+Hempstead+	(CLEO Collab.)
MASCHMANN	90	ZPHY C46 555	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
ALBRECHT	89	ZPHY C42 349	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
ALEXANDER	89	NP B320 45	+Bonvicini, Drell, Frey, Luth	(LBL, MICH, SLAC)
BARU	89	ZPHY C42 505	+Beilin, Blinov+	(NOVO)
CHEN	89B	PR D39 3528	+McIlwain, Miller+	(CLEO Collab.)
FULTON	89	PL B224 445	+Haas, Hempstead+	(CLEO Collab.)
KAARSBERG	89	PRL 62 2077	+Heintz+	(CUSB Collab.)
BUCHMUEL...	88	HE e^+e^- Physics 412	Buchmueller, Cooper	(HANN, MIT)
		Editors: A. Ali and P. Soeding, World Scientific, Singapore		
JAKUBOWSKI	88	ZPHY C40 49	+Antreasyan, Bartels+	(Crystal Ball Collab.) IGJPC
SCHMITT	88	ZPHY C40 199	+Antreasyan+	(Crystal Ball Collab.)
ALBRECHT	87	ZPHY C35 283	+Binder, Boeckmann, Glaeser+	(ARGUS Collab.)
BARU	86	ZPHY C30 551	+Blinov, Bondar, Bukin+	(NOVO)
ALBRECHT	85C	PL 154B 452	+Drescher, Heller+	(ARGUS Collab.)
KURAEV	85	SJNP 41 466	+Fadin	(ASCI)
		Translated from YAF 41 733.		
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
BESSON	84	PR D30 1433	+Green, Hicks, Namjoshi, Sannes+	(CLEO Collab.)
GILES	84B	PR D29 1285	+Hassard, Hempstead, Kinoshita+	(CLEO Collab.)
MACKAY	84	PR D29 2483	+Hasard, Giles, Hempstead+	(CUSB Collab.)
ANDREWS	83	PRL 50 807	+Avery, Berkelman, Cassel+	(CLEO Collab.)
GILES	83	PRL 50 877	+	(HARV, OSU, ROCH, RUTG, SYRA, VAND+)
NICZYPORUK	83	ZPHY C17 197	+Jakubowski, Zeludziewicz+	(LENA Collab.)
TUTS	83	Cornell Conf. 284		(CUSB Collab.)
ALBRECHT	82	PL 116B 383	+Hofmann+	(DESY, DORT, HEID, LUND, ITEP)
ARTAMONOV	82	PL 118B 225	+Baru, Blinov, Bondar, Bukin, Groshev+	(NOVO)
NICZYPORUK	82	ZPHY C15 299	+Folger, Bienlein+	(LENA Collab.)
BERGER	80C	PL 93B 497	+Lackas+	(AACH, DESY, HAMB, SIEG, WUPP)
BOCK	80	ZPHY C6 125	+Blanar, Blum+	(HEID, MPIM, DESY, HAMB)
BERGER	79	ZPHY C1 343	+Alexander+	(AACH, DESY, HAMB, SIEG, WUPG)

OTHER RELATED PAPERS

COOPER	86	Berkeley Conf. 67		(MIT)
KOENIGS...	86	DESY 86/136	Koenigsmann	(DESY)
ALBRECHT	84	PL 134B 137	+Drescher, Heller+	(ARGUS Collab.)
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
ARTAMONOV	82	PL 118B 225	+Baru, Blinov, Bondar, Bukin, Groshev+	(NOVO)
BERGER	78	PL 76B 243	+Alexander+	(AACH, DESY, HAMB, SIEG, WUPG)
BIENLEIN	78	PL 78B 360	+Glawe, Bock, Blanar+	(DESY, HAMB, HEID, MPIM)
DARDEN	78	PL 76B 246	+Hofmann, Schubert+	(DESY, DORT, HEID, LUND)
GARELICK	78	PR D18 945	+Gauthier, Hicks, Oliver+	(NEAS, WASH, TUFT)
KAPLAN	78	PRL 40 435	+Appel, Herb, Hom+	(STON, FNAL, COLU)
YOH	78	PRL 41 684	+Herb, Hom, Lederman+	(COLU, FNAL, STON)
COBB	77	PL 72B 273	+Iwata, Fabjan+	(BNL, CERN, SYRA, YALE)
HERB	77	PRL 39 252	+Hom, Lederman, Appel, Ito+	(COLU, FNAL, STON)
INNES	77	PRL 39 1240	+Appel, Brown, Herb, Hom+	(COLU, FNAL, STON)

$\chi_{b0}(1P)$ or $\chi_{b0}(9860)$

$I^G(J^{PC}) = ?^?(0 \text{ preferred}^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(2S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$.

$\chi_{b0}(1P)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
9859.8±1.3 OUR AVERAGE				
9860.0±0.5±1.4	[1] ALBRECHT	85E	ARG	$\Upsilon(2S) \to$ conv. γX
9858.3±1.6±2.7	[1] NERNST	85	CBAL	$\Upsilon(2S) \to \gamma X$
9864.1±7 ±1	[1] HAAS	84	CLEO	$\Upsilon(2S) \to$ conv. γX
• • • We do not use the following data for averages, fits, limits, etc. • • •				
9872.8±0.7±5.0	[1] KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma X$

[1] From γ energy below, assuming $\Upsilon(2S)$ mass = 10023.4 MeV.

γ ENERGY IN $\Upsilon(2S)$ DECAY

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
162.3±1.3 OUR AVERAGE				
162.1±0.5±1.4	ALBRECHT	85E	ARG	$\Upsilon(2S) \to$ conv. γX
163.8±1.6±2.7	NERNST	85	CBAL	$\Upsilon(2S) \to \gamma X$
158.0±7 ±1	HAAS	84	CLEO	$\Upsilon(2S) \to$ conv. γX
• • • We do not use the following data for averages, fits, limits, etc. • • •				
149.4±0.7±5.0	KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma X$

$\chi_{b0}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\gamma\Upsilon(1S)$	<6 %	90%

$\chi_{b0}(1P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{total}$ Γ_1/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.06	90	WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.11	90	PAUSS	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

$\chi_{b0}(1P)$ REFERENCES

WALK	86	PR D34 2611	+Zschorsch+	(Crystal Ball Collab.)
ALBRECHT	85E	PL 160B 331	+Drescher, Heller+	(ARGUS Collab.)
NERNST	85	PRL 54 2195	+Antreasyan, Aschman+	(Crystal Ball Collab.)
HAAS	84	PRL 52 799	+Jensen, Kagan, Kass, Behrends+	(CLEO Collab.)
KLOPFEN...	83	PRL 51 160	Klopfenstein, Horstkotte+	(CUSB Collab.)
PAUSS	83	PL 130B 439	+Dietl, Eigen+	(MPIM, COLU, CORN, LSU, STON)

$\chi_{b1}(1P)$ or $\chi_{b1}(9890)$

$I^G(J^{PC}) = ?^?(1^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(2S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$. $J = 1$ from SKWARNICKI 87.

$\chi_{b1}(1P)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
9891.9±0.7 OUR AVERAGE				
9890.8±0.9±1.3	[1] WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
9890.8±0.3±1.1	[1] ALBRECHT	85E	ARG	$\Upsilon(2S) \to$ conv. γX
9892.0±0.8±2.4	[1] NERNST	85	CBAL	$\Upsilon(2S) \to \gamma X$
9893.6±0.8±1.0	[1] HAAS	84	CLEO	$\Upsilon(2S) \to$ conv. γX
9894.4±0.4±3.0	[1] KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma X$
9892.0±3.0	[1] PAUSS	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

[1] From γ energy below, assuming $\Upsilon(2S)$ mass = 10023.4 MeV.

γ ENERGY IN $\Upsilon(2S)$ DECAY

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
130.6±0.7 OUR AVERAGE				
131.7±0.9±1.3	WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
131.7±0.3±1.1	ALBRECHT	85E	ARG	$\Upsilon(2S) \to$ conv. γX
130.6±0.8±2.4	NERNST	85	CBAL	$\Upsilon(2S) \to \gamma X$
129.0±0.8±1.0	HAAS	84	CLEO	$\Upsilon(2S) \to$ conv. γX
128.1±0.4±3.0	KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma X$
130.6±3.0	PAUSS	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

$\chi_{b1}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\Upsilon(1S)$	(35±8) %

$\chi_{b1}(1P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.35±0.08 OUR AVERAGE				
0.32±0.06±0.07	WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
0.47±0.18	KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

$\chi_{b1}(1P)$ REFERENCES

SKWARNICKI	87	PRL 58 972	+Antreasyan, Besset+	(Crystal Ball Collab.) J
WALK	86	PR D34 2611	+Zschorsch+	(Crystal Ball Collab.)
ALBRECHT	85E	PL 160B 331	+Drescher, Heller+	(ARGUS Collab.)
NERNST	85	PRL 54 2195	+Antreasyan, Aschman+	(Crystal Ball Collab.)
HAAS	84	PRL 52 799	+Jensen, Kagan, Kass, Behrends+	(CLEO Collab.)
KLOPFEN...	83	PRL 51 160	Klopfenstein, Horstkotte+	(CUSB Collab.)
PAUSS	83	PL 130B 439	+Dietl, Eigen+	(MPIM, COLU, CORN, LSU, STON)

$\chi_{b2}(1P)$ or $\chi_{b2}(9915)$

$I^G(J^{PC}) = ?^?(2^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(2S)$, therefore $C=+$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P=+$. $J=2$ from SKWARNICKI 87.

$\chi_{b2}(1P)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
9913.2±0.6 OUR AVERAGE				
9915.8±1.1±1.3	[1] WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
9912.2±0.3±0.9	[1] ALBRECHT	85E	ARG	$\Upsilon(2S) \to$ conv. γ X
9912.4±0.8±2.2	[1] NERNST	85	CBAL	$\Upsilon(2S) \to \gamma$ X
9913.3±0.7±1.0	[1] HAAS	84	CLEO	$\Upsilon(2S) \to$ conv. γ X
9914.6±0.3±2.0	[1] KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma$ X
9914.0±4.0	[1] PAUSS	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

[1] From γ energy below, assuming $\Upsilon(2S)$ mass = 10023.4 MeV.

γ ENERGY IN $\Upsilon(2S)$ DECAY

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
109.6±0.6 OUR AVERAGE				
107.0±1.1±1.3	WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
110.6±0.3±0.9	ALBRECHT	85E	ARG	$\Upsilon(2S) \to$ conv. γ X
110.4±0.8±2.2	NERNST	85	CBAL	$\Upsilon(2S) \to \gamma$ X
109.5±0.7±1.0	HAAS	84	CLEO	$\Upsilon(2S) \to$ conv. γ X
108.2±0.3±2.0	KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma$ X
108.8±4.0	PAUSS	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

$\chi_{b2}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\Upsilon(1S)$	(22±4) %

$\chi_{b2}(1P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.22±0.04 OUR AVERAGE				
0.27±0.06±0.06	WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
0.20±0.05	KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

$\chi_{b2}(1P)$ REFERENCES

SKWARNICKI	87	PRL 58 972	+Antreasyan, Besset+	(Crystal Ball Collab.)	J
WALK	86	PR D34 2611	+Zschorsch+	(Crystal Ball Collab.)	
ALBRECHT	85E	PL 160B 331	+Drescher, Heller+	(ARGUS Collab.)	
NERNST	85	PRL 54 2195	+Antreasyan, Aschman+	(Crystal Ball Collab.)	
HAAS	84	PRL 52 799	+Jensen, Kagan, Kass, Behrends+	(CLEO Collab.)	
KLOPFEN...	83	PRL 51 160	Klopfenstein, Horstkotte+	(CUSB Collab.)	
PAUSS	83	PL 130B 439	+Dietl, Eigen+	(MPIM, COLU, CORN, LSU, STON)	

$\Upsilon(2S)$ or $\Upsilon(10023)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(2S)$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.02330±0.00031 OUR AVERAGE				
10.0236 ±0.0005	[1] BARU	86B	REDE	$e^+e^- \to$ hadrons
10.0231 ±0.0004	BARBER	84	REDE	$e^+e^- \to$ hadrons

[1] Reanalysis of ARTAMONOV 84.

$\Upsilon(2S)$ WIDTH

VALUE (keV)	DOCUMENT ID
43±8 OUR EVALUATION	See Υ mini-review.

$\Upsilon(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)		Confidence level
Γ_1	$\Upsilon(1S)\pi^+\pi^-$	(18.5 ±0.8) %		
Γ_2	$\Upsilon(1S)\pi^0\pi^0$	(8.8 ±1.1) %		
Γ_3	$\tau^+\tau^-$	(1.7 ±1.6) %		
Γ_4	$\mu^+\mu^-$	(1.31±0.21) %		
Γ_5	e^+e^-	seen		
Γ_6	$\Upsilon(1S)\pi^0$	< 8	$\times 10^{-3}$	90%
Γ_7	$\Upsilon(1S)\eta$	< 2	$\times 10^{-3}$	90%
Γ_8	$J/\psi(1S)$ anything	< 6	$\times 10^{-3}$	90%
	Radiative decays			
Γ_9	$\gamma\chi_{b1}(1P)$	(6.7 ±0.9) %		
Γ_{10}	$\gamma\chi_{b2}(1P)$	(6.6 ±0.9) %		
Γ_{11}	$\gamma\chi_{b0}(1P)$	(4.3 ±1.0) %		
Γ_{12}	$\gamma f_0(1710)$	< 5.9	$\times 10^{-4}$	90%
Γ_{13}	$\gamma f_2'(1525)$	< 5.3	$\times 10^{-4}$	90%
Γ_{14}	$\gamma f_2(1270)$	< 2.41	$\times 10^{-4}$	90%
Γ_{15}	$\gamma f_4(2220)$			

$\Upsilon(2S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(e^+e^-) \times \Gamma(\mu^+\mu^-)/\Gamma_{total}$ — $\Gamma_5\Gamma_4/\Gamma$

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
6.5±1.5±1.0	KOBEL	91	CBAL	$e^+e^- \to \mu^+\mu^-$

$\Gamma(\text{hadrons}) \times \Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_0\Gamma_5/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.562±0.027 OUR AVERAGE				
0.54 ±0.04 ±0.02	[2] JAKUBOWSKI	88	CBAL	$e^+e^- \to$ hadrons
0.58 ±0.03 ±0.04	[3] GILES	84B	CLEO	$e^+e^- \to$ hadrons
0.59 ±0.03 ±0.05	[3] TUTS	83	CUSB	$e^+e^- \to$ hadrons
0.60 ±0.12 ±0.07	[3] ALBRECHT	82	DASP	$e^+e^- \to$ hadrons
0.54 ±0.07 $^{+0.09}_{-0.05}$	[3] NICZYPORUK	81C	LENA	$e^+e^- \to$ hadrons
0.41 ±0.18	[3] BOCK	80	CNTR	$e^+e^- \to$ hadrons

[2] Radiative corrections evaluated following KURAEV 85.
[3] Radiative corrections reevaluated by BUCHMUELLER 88 following KURAEV 85.

$\Upsilon(2S)$ BRANCHING RATIOS

$\Gamma(J/\psi(1S)\text{ anything})/\Gamma_{total}$ — Γ_8/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.006	90	MASCHMANN	90	CBAL	$e^+e^- \to$ hadrons

$\Gamma(\Upsilon(1S)\pi^+\pi^-)/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.185±0.008 OUR AVERAGE					
0.181±0.005±0.010	11.6k	ALBRECHT	87	ARG	$e^+e^- \to \pi^+\pi^-$ MM
0.169±0.040		GELPHMAN	85	CBAL	$e^+e^- \to e^+e^-\pi^+\pi^-$
0.191±0.012±0.006		BESSON	84	CLEO	$\pi^+\pi^-$ MM
0.189±0.026		FONSECA	84	CUSB	$e^+e^- \to \ell^+\ell^-\pi^+\pi^-$
0.21 ±0.07	7	NICZYPORUK	81B	LENA	$e^+e^- \to \ell^+\ell^-\pi^+\pi^-$

$\Gamma(\Upsilon(1S)\pi^0\pi^0)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.088±0.011 OUR AVERAGE					
0.095±0.019±0.019	25	ALBRECHT	87	ARG	$e^+e^- \to \pi^0\pi^0\ell^+\ell^-$
0.080±0.015		GELPHMAN	85	CBAL	$e^+e^- \to \ell^+\ell^-\pi^0\pi^0$
0.103±0.023		FONSECA	84	CUSB	$e^+e^- \to \ell^+\ell^-\pi^0\pi^0$

$\Gamma(\tau^+\tau^-)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.017±0.015±0.006	HAAS	84B	CLEO	$e^+e^- \to \tau^+\tau^-$

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ — Γ_4/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.0131±0.0021 OUR AVERAGE					
0.0122±0.0028±0.0019		[4] KOBEL	91	CBAL	$e^+e^- \to \mu^+\mu^-$
0.0138±0.0025±0.0015		KAARSBERG	89	CSB2	$e^+e^- \to \mu^+\mu^-$
0.009 ±0.006 ±0.006		[5] ALBRECHT	85	ARG	$e^+e^- \to \mu^+\mu^-$
0.018 ±0.008 ±0.005		HAAS	84B	CLEO	$e^+e^- \to \mu^+\mu^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.038	90	NICZYPORUK	81C	LENA	$e^+e^- \to \mu^+\mu^-$

[4] Taking into account interference between the resonance and continuum.
[5] Re-evaluated using $B(\Upsilon(1S) \to \mu^+\mu^-)$=0.026

$\Gamma(\Upsilon(1S)\pi^0)/\Gamma_{total}$ — Γ_6/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.008	90	LURZ	87	CBAL	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

$\Gamma(\Upsilon(1S)\eta)/\Gamma_{total}$ — Γ_7/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.002	90	FONSECA	84	CUSB	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.005	90	ALBRECHT	87	ARG	$e^+e^- \to \pi^+\pi^-\ell^+\ell^-$ MM
<0.007	90	LURZ	87	CBAL	$e^+e^- \to \ell^+\ell^-(\gamma\gamma, 3\pi^0)$
<0.010	90	BESSON	84	CLEO	

$\Gamma(\gamma\chi_{b1}(1P))/\Gamma_{total}$ — Γ_9/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.067±0.009 OUR AVERAGE				
0.091±0.018±0.022	ALBRECHT	85E	ARG	$e^+e^- \to \gamma$ conv X
0.065±0.007±0.012	NERNST	85	CBAL	$e^+e^- \to \gamma X$
0.080±0.017±0.016	HAAS	84	CLEO	$e^+e^- \to \gamma$ conv X
0.059±0.014	KLOPFEN...	83	CUSB	$e^+e^- \to \gamma X$

$\Gamma(\gamma\chi_{b2}(1P))/\Gamma_{total}$ — Γ_{10}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.066±0.009 OUR AVERAGE				
0.098±0.021±0.024	ALBRECHT	85E	ARG	$e^+e^- \to \gamma$ conv X
0.058±0.007±0.010	NERNST	85	CBAL	$e^+e^- \to \gamma X$
0.102±0.018±0.021	HAAS	84	CLEO	$e^+e^- \to \gamma$ conv X
0.061±0.014	KLOPFEN...	83	CUSB	$e^+e^- \to \gamma X$

$\Gamma(\gamma\chi_{b0}(1P))/\Gamma_{total}$ — Γ_{11}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.043±0.010 OUR AVERAGE				
0.064±0.014±0.016	ALBRECHT	85E	ARG	$e^+e^- \to \gamma$ conv X
0.036±0.008±0.009	NERNST	85	CBAL	$e^+e^- \to \gamma X$
0.044±0.023±0.009	HAAS	84	CLEO	$e^+e^- \to \gamma$ conv X
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.035±0.014	KLOPFEN...	83	CUSB	$e^+e^- \to \gamma X$

$\Gamma(\gamma f_0(1710))/\Gamma_{total}$ — Γ_{12}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<59	90	[6] ALBRECHT	89	ARG	$\Upsilon(2S) \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 5.9	90	[7] ALBRECHT	89	ARG	$\Upsilon(2S) \to \gamma\pi^+\pi^-$

[6] Re-evaluated assuming $B(f_0(1710) \to K^+K^-) = 0.19$.
[7] Includes unknown branching ratio of $f_0(1710) \to \pi^+\pi^-$.

$\Gamma(\gamma f_2'(1525))/\Gamma_{total}$ — Γ_{13}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<53	90	[8] ALBRECHT	89	ARG	$\Upsilon(2S) \to \gamma K^+K^-$

[8] Re-evaluated assuming $B(f_2'(1525) \to K\overline{K}) = 0.71$.

$\Gamma(\gamma f_2(1270))/\Gamma_{total}$ — Γ_{14}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<24.1	90	[9] ALBRECHT	89	ARG	$\Upsilon(2S) \to \gamma\pi^+\pi^-$

[9] Using $B(f_2(1270) \to \pi\pi)=0.84$

$\Gamma(\gamma f_4(2220))/\Gamma_{total}$ — Γ_{15}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<6.8	90	[10] ALBRECHT	89	ARG	$\Upsilon(2S) \to \gamma K^+K^-$

[10] Includes unknown branching ratio of $f_4(2220) \to K^+K^-$.

$\Upsilon(2S)$ REFERENCES

KOBEL	91	DESY 91-089 preprint	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
MASCHMANN	90	ZPHY C46 555	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
ALBRECHT	89	ZPHY C42 349	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
KAARSBERG	89	PRL 62 2077	+Heintz+	(CUSB Collab.)
BUCHMUEL...	88	HE e^+e^- Physics 412	Buchmueller, Cooper	(HANN, MIT)
		Editors: A. Ali and P. Soeding, World Scientific, Singapore		
JAKUBOWSKI	88	ZPHY C40 49	+Antreasyan, Bartels+	(Crystal Ball Collab.) IGJPC
ALBRECHT	87	ZPHY C35 283	+Binder, Boeckmann, Glaeser+	(ARGUS Collab.)
LURZ	87	ZPHY C36 383	+Antreasyan, Besset+	(Crystal Ball Collab.)
BARU	86B	ZPHY C32 662	+Blinov, Bondar, Bukin+	(NOVO)
ALBRECHT	85	ZPHY C28 45	+Dreschell, Heller+	(ARGUS Collab.)
ALBRECHT	85E	PL 160B 331	+Drescher, Heller+	(ARGUS Collab.)
GELPHMAN	85	PR D11 2893	+Lurz, Antreasyan+	(Crystal Ball Collab.)
KURAEV	85	SJNP 41 466	+Fadin	(ASCI)
		Translated from YAF 41 733.		
NERNST	85	PRL 54 2195	+Antreasyan, Aschman+	(Crystal Ball Collab.)
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
BARBER	84	PL 135B 498	+	(DESY, ARGUS Collab., Crystal Ball Collab.)
BESSON	84	PR D30 1433	+Green, Hicks, Namjoshi, Sannes+	(CLEO Collab.)
FONSECA	84	NP B242 31	+Mageras, Son, Dietl, Eigen+	(CUSB Collab.)
GILES	84B	PR D29 1285	+Hassard, Hempstead, Kinoshita+	(CLEO Collab.)
HAAS	84	PRL 52 799	+Jensen, Kagan, Kass, Behrends+	(CLEO Collab.)
HAAS	84B	PR D30 1996	+Jensen, Kagan, Kass, Behrends+	(CLEO Collab.)
KLOPFEN...	83	PRL 51 160	Klopfenstein, Horstkotte+	(CUSB Collab.)
TUTS	83	Cornell Conf. 284		(CUSB Collab.)
ALBRECHT	82	PL 116B 383	+Hofmann+	(DESY, DORT, HEID, LUND, ITEP)
NICZYPORUK	81B	PL 100B 95	+Chen, Folger, Lurz+	(LENA Collab.)
NICZYPORUK	81C	PL 99B 169	+Chen, Vogel, Wegener+	(LENA Collab.)
BOCK	80	ZPHY C6 125	+Blanar, Blum+	(HEID, MPIM, DESY, HAMB)

OTHER RELATED PAPERS

ALEXANDER	89	NP B320 45	+Bonvicini, Drell, Frey, Luth	(LBL, MICH, SLAC)
COOPER	86	Berkeley Conf. 67		(MIT)
WALK	86	PR D34 2611	+Zschorsch+	(Crystal Ball Collab.)
ALBRECHT	84	PL 134B 137	+Drescher, Heller+	(ARGUS Collab.)
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
ANDREWS	83	PRL 50 807	+Avery, Berkelman, Cassel+	(CLEO Collab.)
GREEN	82	PRL 49 617	+Sannes, Skubic, Snyder+	(CLEO Collab.)
BIENLEIN	78	PL 78B 360	+Glawe, Bock, Blanar+	(DESY, HAMB, HEID, MPIM)
DARDEN	78	PL 76B 246	+Hofmann, Schubert+	(DESY, DORT, HEID, LUND)
KAPLAN	78	PRL 40 435	+Appel, Herb, Hom+	(STON, FNAL, COLU)
YOH	78	PRL 41 684	+Herb, Hom, Lederman+	(COLU, FNAL, STON)
COBB	77	PL 72B 273	+Iwata, Fabjan+	(BNL, CERN, SYRA, YALE)
HERB	77	PRL 39 252	+Hom, Lederman, Appel, Ito+	(COLU, FNAL, STON)
INNES	77	PRL 39 1240	+Appel, Brown, Herb, Hom+	(COLU, FNAL, STON)

$\chi_{b0}(2P)$ or $\chi_{b0}(10235)$

$I^G(J^{PC}) = ?^?(0 \text{ preferred}^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(3S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$.

$\chi_{b0}(2P)$ MASS

VALUE (GeV)	EVTS	DOCUMENT ID		TECN	COMMENT
10.2320±0.0007 OUR EVALUATION					
10.2320±0.0005 OUR AVERAGE					
10.2323±0.0007		[1] MORRISON	91	CLE2	$e^+e^- \to \gamma X$
10.2316±0.0008		[1] NARAIN	91	CUSB	$e^+e^- \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
10.2299±0.0014	21 ± 7	[1] HEINTZ	91	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[1] From γ energy below assuming $\Upsilon(3S)$ mass = 10355.3 ± 0.5 MeV. The error on the $\Upsilon(3S)$ mass is not included in the individual measurements. It is included in the final average.

γ ENERGY IN $\Upsilon(3S)$ DECAY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
122.6±0.5 OUR AVERAGE					
122.3±0.3±0.6	9903 ± 550	MORRISON	91	CLE2	$e^+e^- \to \gamma X$
123.0±0.8	4959 ± 339	NARAIN	91	CUSB	$e^+e^- \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
124.6±1.4	21 ± 7	HEINTZ	91	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

$\chi_{b0}(2P)$ WIDTH

VALUE (KeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
416±135±76	21 ± 7	[3] HEINTZ	91	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
422±137±75	21 ± 7	[4] HEINTZ	91	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[3] Kwong-Rosner model.
[4] Franzini model.

$\chi_{b0}(2P)$ HADRONIC WIDTH

VALUE (KeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
396±135±76	21 ± 7	[5] HEINTZ	91	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
402±137±75	21 ± 7	[6] HEINTZ	91	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[5] Kwong-Rosner model.
[6] Franzini model.

$\chi_{b0}(2P)$ DECAY MODES

	Mode
Γ_1	$\gamma\Upsilon(2S)$
Γ_2	$\gamma\Upsilon(1S)$

$\chi_{b0}(2P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(2S))/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.053\pm0.021\pm0.011$	[7] HEINTZ	91	CUSB	$e^+e^-\to\ell^+\ell^-\gamma\gamma$

[7] Using $B(\Upsilon(3S)\to\chi_{b0}(2P)\gamma)=0.060\pm0.007$. Re-evaluated by us using $B(\Upsilon(2S)\to\mu^+\mu^-)=0.0131\pm0.0021$.

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.009\pm0.006\pm0.001$	[8] HEINTZ	91	CUSB	$e^+e^-\to\ell^+\ell^-\gamma\gamma$

[8] Using $B(\Upsilon(3S)\to\chi_{b0}(2P)\gamma)=0.060\pm0.007$.

$\chi_{b0}(2P)$ REFERENCES

HEINTZ 91 PRL 66 1563 +Kaarsberg+ (CUSB Collab.)
MORRISON 91 PRL 67 1696 +Schmidt+ (CLEO II Collab.)
NARAIN 91 PRL 66 3113 +Lovelock+ (CUSB Collab.)

OTHER RELATED PAPERS

TUTS 83 Cornell Conf. 284 (CUSB Collab.)
EIGEN 82 PRL 49 1616 +Bohringer, Herb+ (CUSB Collab.)
HAN 82 PRL 49 1612 +Horstkotte, Imlay+ (CUSB Collab.)

$\chi_{b1}(2P)$ or $\chi_{b1}(10255)$

$I^G(J^{PC})$ = ?$^?$(1 preferred^{++})
J needs confirmation.

Observed in radiative decay of the $\Upsilon(3S)$, therefore $C=+$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P=+$.

$\chi_{b1}(2P)$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.2549 ±0.0006 OUR EVALUATION				
10.25493±0.00031 OUR AVERAGE				
10.2553 ±0.0005	[1] MORRISON	91	CLE2	$e^+e^-\to\gamma X$
10.2547 ±0.0004	[1] NARAIN	91	CUSB	$e^+e^-\to\gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
10.2546 ±0.0005	[1] HEINTZ	91	CUSB	$e^+e^-\to\ell^+\ell^-\gamma\gamma$

[1] From γ energy below assuming $\Upsilon(3S)$ mass = 10355.3 ± 0.5 MeV. The error on the $\Upsilon(3S)$ mass is not included in the individual measurements. It is included in the final evaluation.

$\chi_{b1}(2P) - \chi_{b0}(2P)$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
22.9±0.6 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$23.2\pm0.7\pm0.7$	[2] NARAIN	91	CUSB	$e^+e^-\to\gamma X$

[2] Data included in our evaluation.

γ ENERGY IN $\Upsilon(3S)$ DECAY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
99.87±0.31 OUR AVERAGE					
99.5 ±0.1 ±0.5	25759±510	MORRISON	91	CLE2	$e^+e^-\to\gamma X$
100.1 ±0.4	11147±462	NARAIN	91	CUSB	$e^+e^-\to\gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
100.2 ±0.5		HEINTZ	91	CUSB	$e^+e^-\to\ell^+\ell^-\gamma\gamma$

$\chi_{b1}(2P)$ WIDTH

VALUE (KeV)	DOCUMENT ID		TECN	COMMENT
89± 7±16	[3] HEINTZ	91	CUSB	$e^+e^-\to\ell^+\ell^-\gamma\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
86± 7±15	[4] HEINTZ	91	CUSB	$e^+e^-\to\ell^+\ell^-\gamma\gamma$

[3] Franzini model.
[4] Kwong-Rosner model.

$\chi_{b1}(2P)$ HADRONIC WIDTH

VALUE (KeV)	DOCUMENT ID		TECN	COMMENT
63± 7±16	[5] HEINTZ	91	CUSB	$e^+e^-\to\ell^+\ell^-\gamma\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
61± 7±15	[6] HEINTZ	91	CUSB	$e^+e^-\to\ell^+\ell^-\gamma\gamma$

[5] Franzini model.
[6] Kwong-Rosner model.

$\chi_{b1}(2P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\Upsilon(2S)$	(22 ±4) %
Γ_2	$\gamma\Upsilon(1S)$	(7.9±1.1) %

$\chi_{b1}(2P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(2S))/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.223\pm0.020\pm0.039$	[7] HEINTZ	91	CUSB	$e^+e^-\to\ell^+\ell^-\gamma\gamma$

[7] Using $B(\Upsilon(3S)\to\chi_{b1}(2P)\gamma)=0.115\pm0.007$. Re-evaluated by us using $B(\Upsilon(2S)\to\mu^+\mu^-)=0.0131\pm0.0021$.

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.079\pm0.009\pm0.006$	[8] HEINTZ	91	CUSB	$e^+e^-\to\ell^+\ell^-\gamma\gamma$

[8] Using $B(\Upsilon(3S)\to\chi_{b1}(2P)\gamma)=0.115\pm0.007$.

$\chi_{b1}(2P)$ REFERENCES

HEINTZ 91 PRL 66 1563 +Kaarsberg+ (CUSB Collab.)
MORRISON 91 PRL 67 1696 +Schmidt+ (CLEO II Collab.)
NARAIN 91 PRL 66 3113 +Lovelock+ (CUSB Collab.)

OTHER RELATED PAPERS

TUTS 83 Cornell Conf. 284 (CUSB Collab.)
EIGEN 82 PRL 49 1616 +Bohringer, Herb+ (CUSB Collab.)
HAN 82 PRL 49 1612 +Horstkotte, Imlay+ (CUSB Collab.)

$\chi_{b2}(2P)$ or $\chi_{b2}(10270)$

$I^G(J^{PC})$ = ?$^?$(2 preferred^{++})
J needs confirmation.

Observed in radiative decay of the $\Upsilon(3S)$, therefore $C=+$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P=+$.

$\chi_{b2}(2P)$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.26835±0.00057 OUR EVALUATION				
10.26835±0.00028 OUR AVERAGE				
10.2685 ±0.0004	[1] MORRISON	91	CLE2	$e^+e^-\to\gamma X$
10.2682 ±0.0004	[1] NARAIN	91	CUSB	$e^+e^-\to\gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
10.2680 ±0.0004	[1] HEINTZ	91	CUSB	$e^+e^-\to\ell^+\ell^-\gamma\gamma$

[1] From γ energy below, assuming $\Upsilon(3S)$ mass = 10355.3 ± 0.5 MeV. The error on the $\Upsilon(3S)$ mass is not included in the individual measurements. It is included in the final average.

$\chi_{b2}(2P) - \chi_{b1}(2P)$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
13.4±0.4 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$13.5\pm0.4\pm0.5$	[2] NARAIN	91	CUSB	$e^+e^-\to\gamma X$

[2] Data included in our evaluation.

$\chi_{b2}(2P) - \chi_{b0}(2P)$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
36.4±0.6 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$36.7\pm0.8\pm0.9$	[3] NARAIN	91	CUSB	$e^+e^-\to\gamma X$

[3] Data included in our evaluation.

γ ENERGY IN $\Upsilon(3S)$ DECAY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
86.55±0.29 OUR AVERAGE					
86.4 ±0.1 ±0.4	30741± 560	MORRISON	91	CLE2	$e^+e^- \to \gamma X$
86.7 ±0.4	10319± 478	NARAIN	91	CUSB	$e^+e^- \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
86.9 ±0.4		HEINTZ	91	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

$\chi_{b2}(2P)$ WIDTH

VALUE (KeV)	DOCUMENT ID		TECN	COMMENT
128±12±15	[4] HEINTZ	91	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
125±12±15	[5] HEINTZ	91	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[4] Franzini model.
[5] Kwong-Rosner Model.

$\chi_{b2}(2P)$ HADRONIC WIDTH

VALUE (KeV)	DOCUMENT ID		TECN	COMMENT
100±12±16	[6] HEINTZ	91	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
97±12±15	[7] HEINTZ	91	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[6] Franzini model.
[7] Kwong-Rosner Model.

$\chi_{b2}(2P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\Upsilon(2S)$	(19 ±4) %
Γ_2	$\gamma\Upsilon(1S)$	(7.0±1.1) %

$\chi_{b2}(2P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(2S))/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.192±0.021±0.033	[8] HEINTZ	91	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[8] Using B($\Upsilon(3S) \to \chi_{b2}(2P)\gamma$)=0.111 ± 0.006 Re-evaluated by us using B($\Upsilon(2S) \to \mu^+\mu^-$) = 0.0131 ± 0.0021.

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.070±0.010±0.005	[9] HEINTZ	91	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[9] Using B($\Upsilon(3S) \to \chi_{b2}(2P)\gamma$)=0.111 ± 0.006

$\chi_{b2}(2P)$ REFERENCES

HEINTZ	91	PRL 66 1563	+Kaarsberg+	(CUSB Collab.)
MORRISON	91	PRL 67 1696	+Schmidt+	(CLEO II Collab.)
NARAIN	91	PRL 66 3113	+Lovelock+	(CUSB Collab.)

OTHER RELATED PAPERS

TUTS	83	Cornell Conf. 284		(CUSB Collab.)
EIGEN	82	PRL 49 1616	+Bohringer, Herb+	(CUSB Collab.)
HAN	82	PRL 49 1612	+Horstkotte, Imlay+	(CUSB Collab.)

$\Upsilon(3S)$ or $\Upsilon(10355)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(3S)$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.3553±0.0005	[1] BARU	86B	REDE	$e^+e^- \to$ hadrons

[1] Reanalysis of ARTAMONOV 84.

$\Upsilon(3S)$ WIDTH

VALUE (keV)	DOCUMENT ID
24.3±2.9 OUR EVALUATION	See Υ mini-review.

$\Upsilon(3S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor
Γ_1	$\Upsilon(2S)$ anything	(10.9 ±1.3) %	
Γ_2	$\Upsilon(2S)\pi^+\pi^-$	(2.1 ±0.4) %	
Γ_3	$\Upsilon(2S)\pi^0\pi^0$	(1.3 ±0.4) %	
Γ_4	$\Upsilon(1S)\pi^+\pi^-$	(4.48±0.29) %	
Γ_5	$\Upsilon(1S)\pi^0\pi^0$	(1.8 ±0.4) %	
Γ_6	$\Upsilon(1S)\eta$		
Γ_7	$\mu^+\mu^-$	(1.81±0.17) %	
Γ_8	e^+e^-	seen	
	Radiative decays		
Γ_9	$\gamma\chi_{b2}(2P)$	(11.4 ±0.8) %	1.3
Γ_{10}	$\gamma\chi_{b1}(2P)$	(11.3 ±0.6) %	
Γ_{11}	$\gamma\chi_{b0}(2P)$	(5.4 ±0.6) %	1.1

$\Upsilon(3S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(total)$

$\Gamma(hadrons) \times \Gamma(e^+e^-)/\Gamma_{total}$ $\Gamma_0\Gamma_8/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.415±0.030 OUR AVERAGE	Error includes scale factor of 1.1.			
0.45 ±0.03 ±0.03	[2] GILES	84B	CLEO	$e^+e^- \to$ hadrons
0.39 ±0.02 ±0.03	[2] TUTS	83	CUSB	$e^+e^- \to$ hadrons

[2] Radiative corrections reevaluated by BUCHMUELLER 88 following KURAEV 85.

$\Upsilon(3S)$ BRANCHING RATIOS

$\Gamma(\Upsilon(2S)\,anything)/\Gamma_{total}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.109±0.013	4891	[3,4,5,6] BROCK	91	CLEO	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.101±0.017	1.6k	[7] BOWCOCK	87	CLEO	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$

$\Gamma(\Upsilon(2S)\pi^+\pi^-)/\Gamma_{total}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.021 ±0.004 OUR AVERAGE					
0.0207±0.0038	974	[3,5] BROCK	91	CLEO	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$
0.031 ±0.020	5	MAGERAS	82	CUSB	$\Upsilon(3S) \to \pi^+\pi^-\ell^+\ell^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.021 ±0.005	314	[7] BOWCOCK	87	CLEO	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$

$\Gamma(\Upsilon(2S)\pi^0\pi^0)/\Gamma_{total}$ Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.013±0.004±0.002	[8] HEINTZ	91	CUSB	$e^+e^- \to \ell^+\ell^-\pi^0\pi^0$

$\Gamma(\Upsilon(1S)\pi^+\pi^-)/\Gamma_{total}$ Γ_4/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0448±0.0029 OUR AVERAGE					
0.0447±0.0031	11221	[3,4] BROCK	91	CLEO	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$
0.049 ±0.010	22	GREEN	82	CLEO	$\Upsilon(3S) \to \pi^+\pi^-\ell^+\ell^-$
0.039 ±0.013	26	MAGERAS	82	CUSB	$\Upsilon(3S) \to \pi^+\pi^-\ell^+\ell^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0347±0.0034	3.9k	[7] BOWCOCK	87	CLEO	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$

$\Gamma(\Upsilon(1S)\pi^0\pi^0)/\Gamma_{total}$ Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.018±0.003±0.002	HEINTZ	91	CUSB	$e^+e^- \to \ell^+\ell^-\pi^0\pi^0$

$\Gamma(\Upsilon(1S)\eta)/\Gamma_{total}$ Γ_6/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0022	90	BROCK	91	CLEO	$e^+e^- \to \pi^+\pi^-\pi^0\ell^+\ell^-$

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ Γ_7/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0181±0.0017 OUR AVERAGE					
0.0202±0.0019±0.0033		CHEN	89B	CLEO	$e^+e^- \to \mu^+\mu^-$
0.0173±0.0015±0.0011		KAARSBERG	89	CSB2	$e^+e^- \to \mu^+\mu^-$
0.033 ±0.013 ±0.007	1096	ANDREWS	83	CLEO	$e^+e^- \to \mu^+\mu^-$

$\Gamma(\gamma\chi_{b2}(2P))/\Gamma_{total}$ Γ_9/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.114±0.008 OUR AVERAGE	Error includes scale factor of 1.3.				
0.135±0.003±0.017	30741±560	MORRISON	91	CLE2	$e^+e^- \to \gamma X$
0.111±0.005±0.004	10319±478	NARAIN	91	CUSB	$e^+e^- \to \gamma X$

$\Gamma(\gamma\chi_{b1}(2P))/\Gamma_{total}$ Γ_{10}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.113±0.006 OUR AVERAGE					
$0.105^{+0.003}_{-0.002}\pm0.013$	25759±510	MORRISON	91	CLE2	$e^+e^- \to \gamma X$
0.115±0.005±0.005	11147±462	NARAIN	91	CUSB	$e^+e^- \to \gamma X$

$\Gamma(\gamma\chi_{b0}(2P))/\Gamma_{total}$ Γ_{11}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.054±0.006 OUR AVERAGE	Error includes scale factor of 1.1.				
$0.049^{+0.003}_{-0.004}\pm0.006$	9903±550	MORRISON	91	CLE2	$e^+e^- \to \gamma X$
0.060±0.004±0.006	4959±339	NARAIN	91	CUSB	$e^+e^- \to \gamma X$

[3] With the assumption of $e\mu$ universality.
[4] Using BR($\Upsilon(1S) \to \mu^+\mu^-$)=(2.57 ± 0.07)%.
[5] Using BR($\Upsilon(2S) \to \mu^+\mu^-$)=(1.37 ± 0.26)%, BR($\Upsilon(2S) \to \gamma\gamma\Upsilon(1S)$) × 2 BR($\Upsilon(1S) \to \mu^+\mu^-$)=(0.195 ± 0.036)%, and BR($\Upsilon(2S) \to \pi^0\pi^0\Upsilon(1S)$) × 2 BR($\Upsilon(1S) \to \mu^+\mu^-$)=(0.452 ± 0.058)%.
[6] Using BR($\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$)=(18.5 ± 0.8)%.
[7] Superseded by BROCK 91.
[8] Using BR($\Upsilon(2S) \to \mu^+\mu^-$)=(1.44 ± 0.10)%. Systematic error probably underestimated.

$\Upsilon(3S)$ REFERENCES

BROCK	91	PR D43 1448	+Ferguson+	(CLEO Collab.)
HEINTZ	91	PRL 66 1563	+Kaarsberg+	(CUSB Collab.)
MORRISON	91	PRL 67 1696	+Schmidt+	(CLEO II Collab.)
NARAIN	91	PRL 66 3113	+Lovelock+	(CUSB Collab.)
CHEN	89B	PR D39 3528	+McIlwain, Miller+	(CLEO Collab.)
KAARSBERG	89	PRL 62 2077	+Heintz+	(CUSB Collab.)
BUCHMUEL...	88	HE e^+e^- Physics 412	Buchmueller, Cooper	(HANN, MIT)
Editors: A. Ali and P. Soeding, World Scientific, Singapore				
BOWCOCK	87	PRL 58 307	+Giles, Hassard, Kinoshita+	(CLEO Collab.)
BARU	86B	ZPHY C32 662	+Blinov, Bondar, Bukin+	(NOVO)
KURAEV	85	SJNP 41 466	+Fadin	(ASCI)
		Translated from YAF 41 733.		
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
GILES	84B	PR D29 1285	+Hassard, Hempstead, Kinoshita+	(CLEO Collab.)
ANDREWS	83	PRL 50 807	+Avery, Berkelman, Cassel+	(CLEO Collab.)
TUTS	83	Cornell Conf. 284		(CUSB Collab.)
GREEN	82	PRL 49 617	+Sannes, Skubic, Snyder+	(CLEO Collab.)
MAGERAS	82	PL 118B 453	+Herb, Imlay+	(COLU, CORN, LSU, MPIM, STON)

OTHER RELATED PAPERS

ALEXANDER	89	NP B320 45	+Bonvicini, Drell, Frey, Luth	(LBL, MICH, SLAC)
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
GILES	84B	PR D29 1285	+Hassard, Hempstead, Kinoshita+	(CLEO Collab.)
HAN	82	PRL 49 1612	+Horstkotte, Imlay+	(CUSB Collab.)
PETERSON	82	PL 114B 277	+Giannini, Lee-Franzini+	(CUSB Collab.)
KAPLAN	78	PRL 40 435	+Appel, Herb, Hom+	(STON, FNAL, COLU)
YOH	78	PRL 41 684	+Herb, Hom, Lederman+	(COLU, FNAL, STON)
COBB	77	PL 72B 273	+Iwata, Fabjan+	(BNL, CERN, SYRA, YALE)
HERB	77	PRL 39 252	+Hom, Lederman, Appel, Ito+	(COLU, FNAL, STON)
INNES	77	PRL 39 1240	+Appel, Brown, Herb, Hom+	(COLU, FNAL, STON)

$\Upsilon(4S)$ or $\Upsilon(10580)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(4S)$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.5800±0.0035	[1] BEBEK	87	CLEO	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
10.5774±0.0010	[2] LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

[1] Reanalysis of BESSON 85.
[2] No systematic error given.

$\Upsilon(4S)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
23.8±2.2 OUR AVERAGE				
20.0±2 ±4	BESSON	85	CLEO	$e^+e^- \to$ hadrons
25 ±2.5	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

$\Upsilon(4S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	e^+e^-	$(1.01\pm0.21)\times10^{-5}$	
Γ_2	D^{*+} anything + c.c.	< 7.4 %	90%
Γ_3	ϕ anything	$< 2.3 \times 10^{-3}$	90%
Γ_4	$\Upsilon(1S)$ anything	$< 4 \times 10^{-3}$	90%

$\Upsilon(4S)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.24 ±0.05 OUR AVERAGE	Error includes scale factor of 1.7.			
0.192±0.007±0.038	BESSON	85	CLEO	$e^+e^- \to$ hadrons
0.283±0.037	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

$\Upsilon(4S)$ BRANCHING RATIOS

$[\Gamma(D^{*+}\text{ anything}) + \Gamma(\text{c.c.})]/\Gamma_{total}$ Γ_2/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.074	90	[3] ALEXANDER	90C	CLEO	e^+e^-

[3] For $x > 0.473$.

$\Gamma(\phi\text{ anything})/\Gamma_{total}$ Γ_3/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0023	90	[4] ALEXANDER	90C	CLEO	e^+e^-

[4] For $x > 0.52$.

$\Gamma(\Upsilon(1S)\text{ anything})/\Gamma_{total}$ Γ_4/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.004	90	ALEXANDER	90C	CLEO	e^+e^-

$\Upsilon(4S)$ REFERENCES

ALEXANDER	90C	PRL 64 2226	+Artuso+	(CLEO Collab.)
BEBEK	87	PR D36 1289	+Berkelman, Blucher, Cassel+	(CLEO Collab.)
BESSON	85	PRL 54 381	+Green, Namjoshi, Sannes+	(CLEO Collab.)
LOVELOCK	85	PRL 54 377	+Horstkotte, Klopfenstein+	(CUSB Collab.)

OTHER RELATED PAPERS

ANDREWS	80B	PRL 45 219	+Berkelman, Cabenda, Cassel+	(CLEO Collab.)
FINOCCHI...	80	PRL 45 222	Finocchiaro, Giannini, Lee-Franzini+	(CUSB Collab.)

$\Upsilon(10860)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(10860)$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.865±0.008 OUR AVERAGE	Error includes scale factor of 1.1.			
10.868±0.006±0.005	BESSON	85	CLEO	$e^+e^- \rightarrow$ hadrons
10.845±0.020	LOVELOCK	85	CUSB	$e^+e^- \rightarrow$ hadrons

$\Upsilon(10860)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
110 ±13 OUR AVERAGE				
112.0±17 ±23	BESSON	85	CLEO	$e^+e^- \rightarrow$ hadrons
110.0±15.0	LOVELOCK	85	CUSB	$e^+e^- \rightarrow$ hadrons

$\Upsilon(10860)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(2.8\pm0.7) \times 10^{-6}$

$\Upsilon(10860)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.31 ±0.07 OUR AVERAGE	Error includes scale factor of 1.3.			
0.22 ±0.05 ±0.07	BESSON	85	CLEO	$e^+e^- \rightarrow$ hadrons
0.365±0.070	LOVELOCK	85	CUSB	$e^+e^- \rightarrow$ hadrons

$\Upsilon(10860)$ REFERENCES

BESSON 85 PRL 54 381 +Green, Namjoshi, Sannes+ (CLEO Collab.)
LOVELOCK 85 PRL 54 377 +Horstkotte, Klopfenstein+ (CUSB Collab.)

$\Upsilon(11020)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(11020)$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
11.019±0.008 OUR AVERAGE				
11.019±0.005±0.007	BESSON	85	CLEO	$e^+e^- \rightarrow$ hadrons
11.020±0.030	LOVELOCK	85	CUSB	$e^+e^- \rightarrow$ hadrons

$\Upsilon(11020)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
79 ±16 OUR AVERAGE				
61.0±13 ±22	BESSON	85	CLEO	$e^+e^- \rightarrow$ hadrons
90.0±20.0	LOVELOCK	85	CUSB	$e^+e^- \rightarrow$ hadrons

$\Upsilon(11020)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(1.6\pm0.5) \times 10^{-6}$

$\Upsilon(11020)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.130±0.030 OUR AVERAGE				
0.095±0.03 ±0.035	BESSON	85	CLEO	$e^+e^- \rightarrow$ hadrons
0.156±0.040	LOVELOCK	85	CUSB	$e^+e^- \rightarrow$ hadrons

$\Upsilon(11020)$ REFERENCES

BESSON 85 PRL 54 381 +Green, Namjoshi, Sannes+ (CLEO Collab.)
LOVELOCK 85 PRL 54 377 +Horstkotte, Klopfenstein+ (CUSB Collab.)

NON-$q\overline{q}$ CANDIDATES

We include here mini-reviews and reference lists on gluonium and other non-$q\overline{q}$ candidates. See also $N\overline{N}$(1100–3600) for possible bound states.

NOTE ON NON-$q\overline{q}$ MESONS

The existence of a gluon self coupling in QCD suggests that, in addition to the conventional $q\overline{q}$ meson states, there may be bound states including gluons: gluonia or glueballs, and hybrids ($q\overline{q}g$). Another example of non-$q\overline{q}$ mesons could be multiquark states. For detailed reviews see, *e.g.*, CLOSE 87, COOPER 86, MESHKOV 86, HEUSCH 86, TOKI 88.

The theoretical guidance on the properties of unusual states is often contradictory, and models that agree in the $q\overline{q}$ sector often differ in their predictions about new states. Among the naively expected signatures for gluonium are:

(i) no place in $q\overline{q}$ nonets,
(ii) flavor-singlet couplings,
(iii) enhanced production in gluon-rich channels such as $J/\psi(1S)$ decay,
(iv) reduced $\gamma\gamma$ coupling,
(v) exotic quantum numbers not allowed for $q\overline{q}$ (in some cases).

However it must be pointed out that mixing effects and other dynamical effects such as form factors will obscure these simple signatures. If the mixing is large, only counting the number of observed states remains a clear signal for non-exotic non-$q\overline{q}$ states. Exotic quantum number states $(0^{--}, 0^{+-}, 1^{-+}, 2^{+-} \cdots)$ would be the best signatures for non-$q\overline{q}$ states.

Points (iii) and (iv) can be summarized by the Chanowitz S parameter (CHANOWITZ 87):

$$S = \frac{\Gamma(J/\psi(1S) \rightarrow \gamma X)}{\mathrm{PS}(J/\psi(1S) \rightarrow \gamma X)} \times \frac{\mathrm{PS}(\gamma\gamma \rightarrow X)}{\Gamma(\gamma\gamma \rightarrow X)} ,$$

where PS stands for phase space. S is expected to be larger for gluonium than for $q\overline{q}$ states.

It should be emphasized that no state has unambiguously been identified as gluonium, or as a multiquark state, or as a hybrid. The candidates we discuss below are chosen because interpreting them as conventional quark-model $q\overline{q}$ states has difficulties.

The scalar-meson sector: The established isoscalars with $J^{PC} = 0^{++}$ are the $f_0(975)$, the $f_0(1400)$, the $f_0(1590)$ and the $f_0(1710)$. In the quark model, one expects two 1^3P_0 states and one 2^3P_0 $(u\overline{u}+d\overline{d})$-like state below 1.8 GeV. Thus, by simple state counting, all well-established scalars cannot find a place in the quark model. From further dynamical arguments related to the production or decay, it is very likely that both the $f_0(1590)$ and the $f_0(1710)$ are non-$q\overline{q}$ resonances.

In an early analysis using a K-matrix coupled-channel formalism including the $\pi\pi$ and $K\overline{K}$ channels (AU 84, 87), three resonance poles were claimed in the 1-GeV mass region [$f_0(975)$]. However a more recent reanalysis using more data shows that this is not conclusive (MORGAN 91, MORGAN 91B). In fact, invoking unitarity and analyticity and only conventional quark model $q\overline{q}$ states (CDD poles), one can describe the data better. In particular this disfavors a $K\overline{K}$ "molecule" interpretation of the $f_0(975)$. In this analysis, the ISR data (AKESSON 86) on central pion production, the DM2 and MARK II results on $J/\psi(1S) \to \phi\pi\pi$, $\phi K\overline{K}$, and the SLAC photoproduction data on $D_s \to \pi\pi\pi$ decay are used.

Note, however, that the interpretation of the $f_0(975)$ as a $K\overline{K}$ molecule (WEINSTEIN 83B, 89) has many supporters, since it [and the $a_0(980)$] lies just below the $K\overline{K}$ threshold. But if the $f_0(975)$ is not the 1^3P_0 $s\overline{s}$ state, the latter should be found near 1500 MeV with decay widths as expected from flavor symmetry. The weak signal at 1515 MeV claimed by LASS does not have the expected large width (TORNQVIST 90).

The $f_0(1400)$ is seen in $\pi\pi$ phase-shift analyses and it is conventionally interpreted as the quark-model 1^3P_0 $(u\overline{u} + d\overline{d})$ state. However, a large gluonium mixing is not excluded, because the $\eta\eta/\pi\pi$ branching ratio is only half of the flavor-symmetry prediction (ALDE 86D).

The $f_0(1590)$, seen in π^-p reactions at 38 GeV/c (BINON 83, BINON 84C, ALDE 87, ALDE 87B) has a peculiar decay pattern for a $q\overline{q}$ state:

$$\pi^0\pi^0 : K\overline{K} : \eta\eta : \eta\eta' : 4\pi^0 = < 0.3 : < 0.6 : 1 : 2.7 : 0.8 \ .$$

GERSHTEIN 84 claims that this could favor a gluonium interpretation. It could possibly be a bag-like 4-quark state $(u\overline{u} + d\overline{d})s\overline{s}$, although this interpretation is disfavored by the $K\overline{K}/\eta\eta$ branching ratio (which naively should be 2), and also by a perturbative QCD calculation of SLAUGHTER 88. Another possibility (TORNQVIST 91) is that it is a large deuteron-like $(\omega\omega - \rho\rho)/\sqrt{2}$ bound state.

The $f_0(1710)$ (with spin previously believed to be 2) has been mainly seen in the "gluon-rich" $J/\psi(1S)$ radiative decay, where it is copiously produced, and in central production by the WA76 experiment (ARMSTRONG 89D) at 300 GeV/c pp interactions.

The $f_0(1710)$ has not been seen in hadronic production $(K^-p \to K\overline{K}\Lambda)$ (ASTON 88D) nor in $\gamma\gamma$ fusion. The ratio of the branching fractions indicates a sizable $s\overline{s}$ component. Its branching ratios are not compatible with being an SU(3) singlet without strong form factor effects. But its S parameter favors a large gluonium component. A multiquark interpretation as a deuteron-like $K^*\overline{K}^*$ state is suggested by TORNQVIST 91.

The pseudoscalar-meson sector: The established isoscalars with $J^{PC} = 0^{-+}$ are the η, $\eta'(958)$, $\eta(1280)$, and $\eta(1440)$ [which is likely split into two pseudoscalar peaks, $\eta(1410)$ and $\eta(1490)$; see the $\eta(1440)$ minireview]. In the $q\overline{q}$ model, we expect two 1^1S_0 and two 2^1S_0 pseudoscalars in the 0.5–1.8 GeV mass range.

Whereas the assignment of the $\eta(1280)$ to the 2^1S_0 $(u\overline{u}+d\overline{d})$ state is natural, it is more problematic to assign one of the two peaks in the $\eta(1440)$ region to the 2^1S_0 $s\overline{s}$ state. The $\eta(1440)$ is observed in $s\overline{s}$-depleted reactions like $\pi^-p \to \eta\pi\pi n$ (ANDO 86) and $\pi^-p \to a_0(980)\pi p$ (CHUNG 85, BIRMAN 88), and is not seen in the $s\overline{s}$-enriched channels like $K^-p \to K^*(892)\overline{K}\Lambda$ (ASTON 87). Moreover, its S parameter is large, compared to the light $q\overline{q}$ states:

$$S[\eta] : S[\eta'] : S[\eta(1440)] = 1 : 4 : > 45 \ .$$

One could possibly understand the small $\gamma\gamma$ coupling and therefore the large S parameter within a $q\overline{q}$ model if the quark structure is $(u\overline{u} + d\overline{d} - 5s\overline{s})$, which decouples from $\gamma\gamma$. The fact that ANDO 86 sees the $\eta(1440)$ bump and the $\eta(1280)$ with similar intensities speaks in favor of these states being of similar nature, *i.e.*, radial excitations of the η and $\eta'(958)$. However, as there are probably two resonances in the $\eta(1440)$ structure, the experimental situation remains confused and the possible gluonium nature of $\eta(1440)$ is far from well established. For arguments in favor of this latter interpretation, see GOUNARIS 88, 90.

The axial-vector meson sector: The $q\overline{q}$ model predicts a nonet that includes two isoscalar 1^3P_1 states with mass below ≈ 1.6 GeV. We know three "good" 1^{++} objects, the $f_1(1285)$, the $f_1(1420)$, and the $f_1(1530)$, — one more than expected. This indicates that one of the three is a non-$q\overline{q}$ meson, and the $f_1(1420)$ is the best non-$q\overline{q}$ candidate [see CALDWELL 89 and the "Note on the $f_1(1420)$"]. Most likely it is a multiquark state in the form of a $K\overline{K}\pi$ bound state ("molecule") as suggested by LONGACRE 90, or a $K\overline{K}^*$ deuteron-like ("deuson") state (TORNQVIST 91).

The tensor-meson sector: The two 1^3P_2 $q\overline{q}$ states are very likely the well-known $f_2(1270)$ and $f_2'(1525)$, although the observation by BREAKSTONE 90 of $f_2(1270)$ production by gluon fusion could indicate that it has a glueball component. At least five more $J^{PC} = 2^{++}$ states have to be considered: the $f_2(1520)$, $f_2(1810)$, $f_2(2010)$, $f_2(2300)$, and $f_2(2340)$. [Note that the spin of the state $f_0(1710)$ was previously believed to be 2, but is now rather convincingly shown to be 0 (CHEN 91)].

Of these, the $f_2(1810)$ is likely to be the 2^3P_2, and the three f_2's above 2 GeV could possibly be the 2^3P_2 $s\overline{s}$, the 1^3F_2 $s\overline{s}$, and the 3^3P_2 $s\overline{s}$, but a gluonium interpretation of one of the three is not excluded. These three f_2 resonances have been observed in an OZI-rule-forbidden process $\pi p \to \phi\phi n$ (ETKIN 88). The OZI suppression has been used as a strong argument for favoring a gluonium interpretation of these states. The argument is, however, not fully compelling, since broad resonances, by unitarity, are expected to mix substantially, and therefore the OZI rule may not apply. Moreover, one of these resonances, the one closest to the $\phi\phi$ threshold, could possibly be interpreted as a $\phi\phi$ molecule (mesonium) candidate. A similar $\phi\phi$ mass spectrum is seen by ARMSTRONG 89B in the Ω spectrometer.

The DM2 and MARK-III collaborations see threshold $\phi\phi$ production but favor $J^P = 0^-$, not 2^+.

The ASTERIX collaboration (MAY 89) finds a 2^{++} resonance in $p\overline{p}$ P-wave annihilation at 1565 MeV in the $\pi^+\pi^-\pi^0$ final state, which is listed as $f_2(1520)$. Its mass is better determined in the $3\pi^0$ mode by the CRYSTAL BARREL (AKER 91) to be 1515 MeV. It has definitely no place in a $q\overline{q}$ scheme, since all nearby $q\overline{q}$ states are already occupied. It is most likely a multiquark state as it has been seen only in the quark-rich $N\overline{N}$. DOVER 86 suggests that it is a "quasinuclear" $N\overline{N}$ bound state, and TORNQVIST 91 suggests it is a deuteron-like $(\omega\omega + \rho\rho)/\sqrt{2}$ "deuson" state.

Finally in $\gamma\gamma \to 4\pi$ near the $\rho\rho$ threshold many groups TASSO (BRANDELIK 80B, ALTHOFF 82), MARK II (BURKE 81), CELLO (BEHREND 84E), PLUTO (BERGER 88B), SLAC TPC (AIHARA 88), and ARGUS (ALBRECHT 91F) observe a resonancelike structure. This is dominated by $\rho^0\rho^0$ and the cross section peaks a little above the $f_2(1520)$ mass. But his threshold behaviour has not been understood using models where conventional resonances dominate.

In particular the fact that $\gamma\gamma \to \rho^+\rho^-$ is relatively small (ALBRECHT 91F quotes 1/4 for the $\rho^+\rho^-/\rho^0\rho^0$ ratio) requires both isospin 0 and 2 for the $\rho\rho$ system. A resonance interpretation in terms of four-quark states thus requires the presence of a flavor exotic I=2 resonance (ACHASOV 82, 87, 90). For this $\rho\rho$ structure the 2^{++} partial wave is found to be dominant (BERGER 88B, ALBRECHT 91F) with some 0^{++} at the low-energy end, while the spin parities 0^- and 2^- contribute very little.

Also in $\gamma\gamma \to \omega\rho$ there is a broad threshold enhancement peaking near 1.6 GeV (BEHREND 91, WEGNER 91) which is probably composed of several spin parities (BEHREND 91).

Other exotic or non-$q\overline{q}$ candidates: An isovector $\phi\pi^0$ resonance at 1480 MeV has been reported by BITYUKOV 87 in $\pi^-p \to \phi\pi^0 n$ [see the $\rho(1450)$]. Preliminary indications favor the nonexotic quantum numbers $J^{PC} = 1^{--}$, but the large OZI-rule-violating branching ratio $\phi\pi : \omega\pi$ seems peculiar for a $(u\overline{u} - d\overline{d})$ $I = 1$ $q\overline{q}$ object. However, ACHASOV 88 shows that the threshold effect from the two-step process $\rho(1600) \to K\overline{K}^* \to \phi K$ can violate the rule, in particular near the threshold. No signal of this candidate is seen in $\pi\omega$ (FUKUI 91). In addition, the small coupling to the photon makes an identification with the $\rho(1450)$ difficult (CLEGG 88).

Another exotic candidate is the $\hat{\rho}(1405)$ (ALDE 88B, IDDIR 88), seen in one experiment under the $a_2(1320)$ in $\pi^-p \to \eta\pi^0 n$ with the exotic quantum numbers $J^{PC} = 1^{-+}$. See, however, TUAN 88 for a critical discussion. For another possible 1^{-+} candidate, see the isosinglet $X(1910)$.

A narrow resonance has been reported at $\approx$ 3100 MeV (BOURQUIN 86, KEKELIDZE 90) in several ($\Lambda\overline{p}$ + pions) and ($\overline{\Lambda}p$ + pions) states. The observation of the doubly charged states ($\Lambda\overline{p}\pi^-$ and $\overline{\Lambda}p\pi^+$) implies $I \geq 3/2$, clearly outside the $q\overline{q}$ system. In addition, a narrow peak is observed at $\approx$ 3250 MeV in the "hidden strangeness" combinations containing a baryon-antibaryon pair (KEKELIDZE 90). However, all these observations need confirmation.

Non-$q\overline{q}$ Candidates

OMITTED FROM SUMMARY TABLE

NON-$q\overline{q}$ CANDIDATES REFERENCES

AKER	91	PL B260 249	+Amsler, Peters+	(CBAR Collab.)
ALBRECHT	91F	ZPHY C50 1	+Appuan, Paulini, Funk+	(ARGUS Collab.)
BEHREND	91	ZPHY C49 401	+Criegee, Field, Franke+	(CELLO Collab.)
BEHREND	91D	PL B257 505	+Bussey, Ahme, Apel+	(CELLO Collab.)
CHEN	91	Hadron 91 Conf.		(Mark III Collab.)
SLAC-PUB-5669				
FUKUI	91	PL B257 241	+Horikawa+	(SUGI, NAGO, KEK, KYOT, MIYA)
MORGAN	91	PL B258 444	+Pennington	(RAL, DURH)
MORGAN	91B	Hadron 91 Conf.	+Pennington	(RHEL)
RAL-91-070				
TORNQVIST	91	PRL 67 556		(HELS)
WEGNER	91	ZPHY C48 393	+Olsson, Allison, Ambrus	(JADE Collab.)
ACHASOV	90	TF 20 (178)	+Shestakov	(NOVO)
BREAKSTONE	90	ZPHY C48 569	+	(ISU, BGNA, CERN, DORT, HEID, WARS)
CALDWELL	90	Hadron 89 Conf. p 127		(UCSB)
GOUNARIS	90	NP B346 84	+Paschalis+	(THES)
KEKELIDZE	90	Hadron 89 Conf. p 551	+Aleev+	(BIS-2 Collab.)
LONGACRE	90	PR D42 874		(BNL)
TORNQVIST	90	NPBPS 21,196		(HELS)
ARMSTRONG	89B	PL B221 221	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, LPNP)
ARMSTRONG	89D	PL B227 186	+Benayoun	(ATHU, BARI, BIRM, CERN, CDEF)
MAY	89	PL B225 450	+Duch, Heel+	(ASTERIX Collab.)
WEINSTEIN	89	UTPT 89 03	+Isgur	(TNTO)
AIHARA	88	PR D37 28	+Alston, Avery, Barbaro-Galtieri+	(TPC-2γ Collab)
ALDE	88B	PL B205 397	+Binon, Boutemeur+	(SERP, BELG, LANL, LAPP)
ASTON	88D	NP B301 525	+Awaji, Bienz+	(SLAC, NAGO, CINC, TOKY)
BERGER	88B	ZPHY C38 521	+Klovning, Burger+	(PLUTO Collab.)
BIRMAN	88	PRL 61 1557	+Chung, Peaslee+	(BNL, FSU, IND, SMAS)
CLEGG	88	ZPHY C40 313	+Donnachie	(MCHS, LANC)
ETKIN	88	PL B201 568	+Foley, Lindenbaum+	(BNL, CUNY)
GOUNARIS	88	PL B213 541	+Neufeld	(CERN)
IDDIR	88	PL B205 564	+Le Yaouanc, Ono+	(LPTP, TOKY)
SHOEMAKER	88	PR D37 1120	+Ko, Michael, Lander, Pellet+	(UCD)
SLAUGHTER	88	MPL A3 1361		(LANL)
TOKI	88	AIP Conf.		(SLAC)
TUAN	88	PL B213 537	+Ferbel, Dalitz	(HAWA, ROCH, OXF)
ACHASOV	87	ZPHY C36 161	+Karnakov, Shestakov	(NOVO)
ALDE	87	PL B198 286	+Binon, Bricman+	(LANL, BRUX, SERP, LAPP)
ALDE	87B	ZPHY C36 603	+Binon, Bricman+	(LANL, BELG, SERP, LAPP)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, TOKY)
AU	87	PR D35 1633	+Morgan, Pennington	(DURH, RAL)
BITYUKOV	87	PL B188 383	+Dzhelyadin, Dorofeev, Golovkin+	(SERP)
CHANOWITZ	87	PL B187 409		(LBL)
CLOSE	87	RPP 51 833		(RHEL)
AKESSON	86	NP B264 154	+Albrow, Almehed+	(Axial Field Spec. Collab.)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN)
ANDO	86	PRL 57 1296	+Imai+	(KEK, KYOT, NIRS, SAGA, TOKY, TSUK+)
BISELLO	86	PL B179 289	+Busetto, Castro, Limentani+	(DM2 Collab.)
BOURQUIN	86	PL B172 113	+Brown+	(GEVA, RAL, HEID, LAUS, BRIS, CERN)
COOPER	86	Berkeley Conf. 67		(MIT)
DOVER	86	PRL 57 1207	+	(BNL)
HEUSCH	86	Seewinkel Symposium on Multiparticle Dynamics		(SLAC)
MESHKOV	86	Aspen Winter Conf.		(NBS)
CHUNG	85	PRL 55 779	+Fernow, Boehnlein+	(BNL, FLOR, IND, SMAS)
AU	84	PL 167B 229	+Morgan, Pennington	(RL)
BEHREND	84E	ZPHY C21 205	+Achenberg, Deboer+	(CELLO Collab.)
BINON	84C	NC 80A 363	+Bricman, Donskov+	(BELG, LAPP, SERP, CERN)
DOVER	84	PL 146B 103		(ORSA)
BINON	83	NC 78A 313	+Donskov, Duteil+	(BELG, LAPP, SERP, CERN)
WEINSTEIN	83B	PR D27 588	+Isgur	(TNTO)
ACHASOV	82	PL B108 134	+Devyanin, Shestakov	(NOVO)
AIHARA	82	PR D37 28	+Alston, Avery, Barbaro-Galtieri+	(TPC Collab.)
ALTHOFF	82	ZPHY C16 13	+Boerner, Burkhardt+	(TASSO Collab.)
BURKE	81	PL B103 153	+Abrams, Alam, BLocher+	(Mark II Collab.)
BRANDELIK	80B	PL B97 448	+Boerner, Burkhard+	(TASSO Collab.)

Searches for Top and Fourth Generation Hadrons

The section on "Searches for Top and Fourth Generation Hadrons" can be found immediately after the Bottom Mesons.

N BARYONS ($S = 0, I = 1/2$)

Δ BARYONS ($S = 0, I = 3/2$)

Z BARYONS ($S = +1$)

Λ BARYONS ($S = -1, I = 0$)

Σ BARYONS ($S = -1, I = 1$)

Ξ BARYONS ($S = -2, I = 1/2$)

Ω BARYONS ($S = -3, I = 0$)

CHARMED BARYONS ($C = +1$)

BOTTOM (BEAUTY) BARYON ($B = -1$)

Notes in the Baryon Listings

N BARYONS
($S = 0$, $I = 1/2$)

p, $N^+ = uud$; n, $N^0 = udd$

p

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

p MASS

The mass is known much more precisely in u (atomic mass units) than in MeV; see the footnote. The conversion from u to MeV, 1 u = 931.49432±0.00028 MeV, involves the relatively poorly known electronic charge.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
938.27231±0.00028	[1] COHEN	87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
938.2796 ±0.0027	COHEN	73	RVUE	1973 CODATA value

[1] The mass is known much more precisely in u: $m = 1.007276470 \pm 0.000000012$ u.

$\overline{p}$ MASS

See, however, the next entry in the Listings, which establishes the $\overline{p}$ mass much more precisely.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
938.22 ±0.04 OUR AVERAGE				
938.30 ±0.13	ROBERTS	78	CNTR	
938.229±0.049	ROBERSON	77	CNTR	
938.179±0.058	HU	75	CNTR	Exotic atoms
938.3 ±0.5	BAMBERGER	70	CNTR	

$\overline{p}/p$ MASS RATIO, $m(\overline{p})/m(p)$

A test of CPT invariance. GABRIELSE 90 below measures the ratio of *inertial* masses. For a discussion of what may be inferred about the ratio of $\overline{p}$ and p *gravitational* masses, see ERICSON 90; they obtain an upper bound of 10^{-6}–10^{-7} for violation of the equivalence principle for $\overline{p}$'s.

VALUE	DOCUMENT ID		TECN	COMMENT
0.999999977±0.000000042	[2] GABRIELSE	90	TRAP	Penning trap

[2] GABRIELSE 90 also measures $m(\overline{p})/m(e^-) = 1836.152660 \pm 0.000083$ and $m(p)/m(e^-) = 1836.152680 \pm 0.000088$. Both are completely consistent with the 1986 CODATA (COHEN 87) value for $m(p)/m(e^-)$ of 1836.152701 ± 0.000037. We use the CODATA values of the proton and electron masses—they come from an overall fit to a variety of data on the fundamental constants—and don't try to take into account more recent measurements involving the masses.

p MAGNETIC MOMENT

See the Note on Baryon Magnetic Moments in the Λ Listings.

VALUE (μ_N)	DOCUMENT ID		TECN	COMMENT
2.792847386±0.000000063	COHEN	87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.7928456 ±0.0000011	COHEN	73	RVUE	1973 CODATA value

$\overline{p}$ MAGNETIC MOMENT

A few early results have been omitted.

VALUE (μ_N)	DOCUMENT ID		TECN	COMMENT
−2.800 ±0.008 OUR AVERAGE				
−2.8005±0.0090	KREISSL	88	CNTR	$\overline{p}$ ^{208}Pb 11→ 10 X-ray
−2.817 ±0.048	ROBERTS	78	CNTR	
−2.791 ±0.021	HU	75	CNTR	Exotic atoms

p ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance.

VALUE (10^{-23} e-cm)	EVTS	DOCUMENT ID		TECN	COMMENT
− 3.7± 6.3		CHO	89	NMR	Tl F molecules
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 400		DZUBA	85	THEO	Uses ^{129}Xe moment
130 ± 200		[3] WILKENING	84		
900 ±1400		[4] WILKENING	84		
700 ± 900	1G	HARRISON	69	MBR	Molecular beam

[3] This WILKENING 84 value includes a finite-size effect and a magnetic effect.
[4] This WILKENING 84 value is more cautious than the other and excludes the finite-size effect, which relies on uncertain nuclear integrals.

p ELECTRIC POLARIZABILITY α_p

Following is the (static) electric polarizability α_p defined in terms of the induced electric dipole moment by $\mathbf{D} = 4\pi\epsilon_0\alpha_p\mathbf{E}$.

VALUE (10^{-3} fm^3)	DOCUMENT ID		TECN	COMMENT
0.7 ±0.22±0.13	[5] FEDERSPIEL	91	CNTR	γp Compton scattering

[5] FEDERSPIEL 91 obtains for the dynamic (or Compton) electric and magnetic polarizabilites, which combine static polarizabilities with retardation corrections, the values $\overline{\alpha} = (1.09 \pm 0.22 \pm 0.13) \times 10^{-3}$ and $\overline{\beta} = (0.33 \pm 0.22 \pm 0.13) \times 10^{-3}$ fm^3.

$|q_p + q_e|$ CHARGE MAGNITUDE DIFFERENCE

See DYLLA 73 for a summary of experiments on the neutrality of matter. See also "n CHARGE" in the neutron Listings.

VALUE (10^{-21} e)	DOCUMENT ID		COMMENT
<1.0	[6] DYLLA	73	Neutrality of SF$_6$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.8	MARINELLI	84	Magnetic levitation

[6] Assumes that $q_n = q_p + q_e$.

NOTE ON NUCLEON DECAY

(by K. Nakamura, Institute for Cosmic Ray Research, University of Tokyo)

Although there was a rather long pre-GUT history in the search for nucleon decay,[1] modern nucleon-decay experiments have been motivated by the SU(5) Grand Unified Theory of Georgi and Glashow.[2] GUTs provide a simple and elegant framework for the unification of strong, weak, and electromagnetic forces, a natural understanding of the Weinberg angle, an explanation of electric-charge quantization, and, above all, a prediction that the nucleon lifetime is finite.

In the minimal SU(5) GUT, nucleon decay is mediated by a supermassive gauge boson, and the dominant decay mode is $p \to e^+\pi^0$. The partial lifetime τ to this mode with branching fraction B is predicted[3] to be $\tau/B = 4.5 \times 10^{29\pm1.7}$ yr. To test this clear and striking prediction, modern nucleon-decay experiments have needed the following: a large mass in order to explore the domain of $\tau/B \gtrsim 10^{30}$ yr, a tracking capability for charged particles, a way to measure visible energy, and particle identification—at least the ability to discriminate between showering (e,γ) and non-showering $(\mu,\pi^\pm)$ particles.

There are two main techniques. One uses tracking calorimetry with iron plates interleaved by tracking planes; the other uses a water Čerenkov detector. Figure 1 compares the total and fiducial masses of various nucleon-decay detectors. The Soudan-2 detector is partly operating, with completion expected in 1993. The 5-year construction schedule of the 50,000-ton water-Čerenkov detector Superkamiokande began in 1991.

Candidate nucleon-decay events are those contained in the detector. Background comes from atmospheric neutrino interactions and has a rate of about 100 kton^{-1}yr^{-1}. The kinematical difference between nucleon decay and atmospheric neutrino interactions provides background rejection. The amount of background contamination depends upon the tightness of the kinematical cuts, which are different for the different decay modes, as well as on detector capabilities such as resolutions of energy and vertex position.

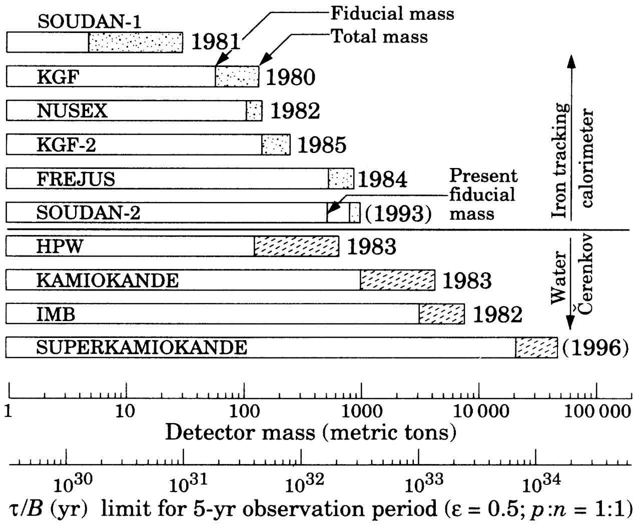


Fig. 1. Nucleon decay experiments. The open bars represent the fiducial masses, while the shaded extensions indicate the total masses. Turn-on dates are at the right. The bottom scale shows the observation limit for the partial lifetime with the assumptions of no background, 50% detection efficiency, and equal numbers of protons and neutrons in the detector material.

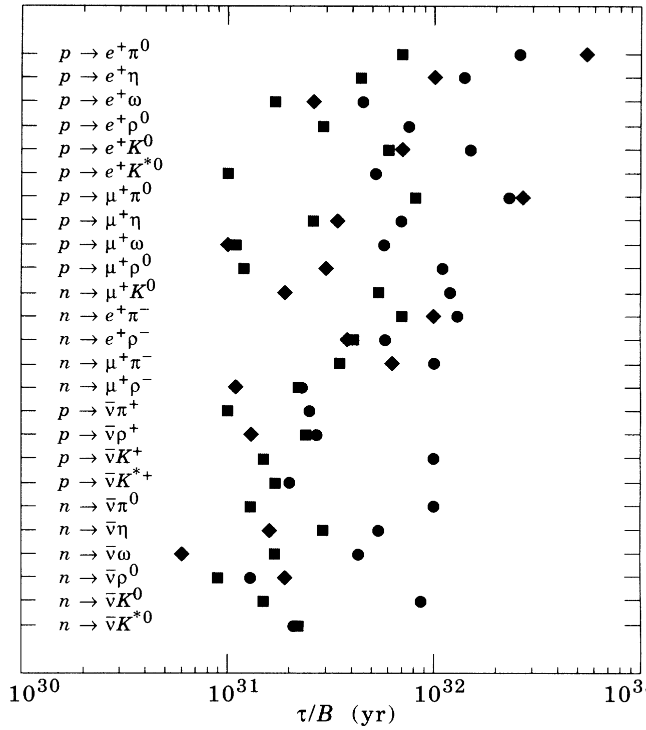


Fig. 2. The 90% confidence-level lower limits of the nucleon partial lifetime for various nucleon decay modes into lepton + meson, obtained by the IMB (diamonds), Kamiokande (circles), and Fréjus (squares) experiments.

Among the most favorable decay modes to detect is $p \to e^+\pi^0$, because all the final-state particles shower and their energies are well measured. No background contamination is as yet expected for this mode in the current experiments. In the absence of background, the τ/B limit is directly proportional to the detector exposure.

On the other hand, the mode $p \to K^+\overline{\nu}$ is only poorly constrained kinematically. This mode, which unfortunately is the most important one in supersymmetric (SUSY) GUTs, is thus dominated by the atmospheric-neutrino background. In such a background-dominated case, the τ/B limit only improves as the square root of the exposure time.

Figure 2 summarizes the present limits from the three major detectors (IMB, Kamiokande, and Fréjus) for nucleon partial lifetimes in various modes involving a lepton and a meson. (For limits on other modes, see the Listings.) There is as yet no compelling experimental evidence for nucleon decay, despite the predictions. The observed number of candidate events in each mode is roughly consistent with the atmospheric-neutrino background. For the $p \to e^+\pi^0$ mode, there are no candidate events in the three experiments, and therefore the τ/B limits from these experiments simply add to give the world limit of $\tau/B(p \to e^+\pi^0) > 9 \times 10^{32}$ yr (90% confidence level). Clearly, the minimal SU(5) GUT has already been ruled out. The best background-subtracted limit for the $p \to K^+\overline{\nu}$ mode has been reported by Kamiokande: it is $\tau/B(p \to K^+\overline{\nu}) > 10^{32}$ yr (90% confidence level).

References

1. See, for example, D.H. Perkins, Ann. Rev. Nucl. and Part. Sci. **34**, 1 (1984).
2. H. Georgi and S.L. Glashow, Phys. Rev. Lett. **32**, 438 (1974).
3. W.J. Marciano, in *Proceedings of the 8th Workshop on Grand Unification*, Syracuse, 1987, ed. K.C. Wali (World Scientific, Singapore, 1988), p. 185.

p MEAN LIFE

Test of baryon conservation. See proton partial mean lives section for limits which depend on decay modes. p = proton, n = bound neutron.

LIMIT (years)	PARTICLE	DOCUMENT ID		TECN
>1.6 × 10^{25}	***p, n***	[7,8] EVANS	77	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>3 × 10^{23}	*p*	[8] DIX	70	CNTR
>3 × 10^{23}	*p, n*	[8,9] FLEROV	58	

[7] Mean lifetime of nucleons in ^{130}Te nuclei.
[8] Converted to mean life by dividing half-life by ln(2) = 0.693.
[9] Mean lifetime of nucleons in ^{232}Th nuclei.

$\overline{p}$ MEAN LIFE

The best limit by far, that of GOLDEN 79, relies, however, on a number of astrophysical assumptions. The other limits come from direct observations of stored antiprotons.

LIMIT (years)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.28			GABRIELSE	90	TRAP	Penning trap
>0.08	90	1	BELL	79	CNTR	Storage ring
>1 × 10^{7}			GOLDEN	79	SPEC	$\overline{p}/p$, cosmic rays
>3.7 × 10^{-3}			BREGMAN	78	CNTR	Storage ring

p DECAY MODES

For N decays, p and n distinguish proton and neutron partial lifetimes.

	Mode	Partial mean life (10^{30} years)	Confidence level
	Antilepton + meson		
τ_1	$N \to e^+\pi$	>130 (n), >550 (p)	90%
τ_2	$N \to \mu^+\pi$	>100 (n), >270 (p)	90%
τ_3	$N \to \nu\pi$	>100 (n), >25 (p)	90%
τ_4	$p \to e^+\eta$	>140	90%
τ_5	$p \to \mu^+\eta$	>69	90%
τ_6	$n \to \nu\eta$	>54	90%
τ_7	$N \to e^+\rho$	>58 (n), >75 (p)	90%
τ_8	$N \to \mu^+\rho$	>23 (n), >110 (p)	90%
τ_9	$N \to \nu\rho$	>19 (n), >27 (p)	90%
τ_{10}	$p \to e^+\omega$	>45	90%
τ_{11}	$p \to \mu^+\omega$	>57	90%
τ_{12}	$n \to \nu\omega$	>43	90%
τ_{13}	$N \to e^+K$	>1.3 (n), >150 (p)	90%
τ_{14}	$p \to e^+K^0_S$	>76	90%
τ_{15}	$p \to e^+K^0_L$	>44	90%
τ_{16}	$N \to \mu^+K$	>1.1 (n), >120 (p)	90%
τ_{17}	$p \to \mu^+K^0_S$	>64	90%
τ_{18}	$p \to \mu^+K^0_L$	>44	90%
τ_{19}	$N \to \nu K$	>86 (n), >100 (p)	90%
τ_{20}	$p \to e^+K^*(892)^0$	>52	90%
τ_{21}	$N \to \nu K^*(892)$	>22 (n), >20 (p)	90%
	Antilepton + mesons		
τ_{22}	$p \to e^+\pi^+\pi^-$	>21	90%
τ_{23}	$p \to e^+\pi^0\pi^0$	>38	90%
τ_{24}	$n \to e^+\pi^-\pi^0$	>32	90%
τ_{25}	$p \to \mu^+\pi^+\pi^-$	>17	90%
τ_{26}	$p \to \mu^+\pi^0\pi^0$	>33	90%
τ_{27}	$n \to \mu^+\pi^-\pi^0$	>33	90%
τ_{28}	$n \to e^+K^0\pi^-$	>18	90%
	Lepton + meson		
τ_{29}	$n \to e^-\pi^+$	>65	90%
τ_{30}	$n \to \mu^-\pi^+$	>49	90%
τ_{31}	$n \to e^-\rho^+$	>62	90%
τ_{32}	$n \to \mu^-\rho^+$	>7	90%
τ_{33}	$n \to e^-K^+$	>32	90%
τ_{34}	$n \to \mu^-K^+$	>57	90%
	Lepton + mesons		
τ_{35}	$p \to e^-\pi^+\pi^+$	>30	90%
τ_{36}	$n \to e^-\pi^+\pi^0$	>29	90%
τ_{37}	$p \to \mu^-\pi^+\pi^+$	>17	90%
τ_{38}	$n \to \mu^-\pi^+\pi^0$	>34	90%
τ_{39}	$p \to e^-\pi^+K^+$	>20	90%
τ_{40}	$p \to \mu^-\pi^+K^+$	>5	90%
	Antilepton + photon(s)		
τ_{41}	$p \to e^+\gamma$	>460	90%
τ_{42}	$p \to \mu^+\gamma$	>380	90%
τ_{43}	$n \to \nu\gamma$	>24	90%
τ_{44}	$p \to e^+\gamma\gamma$	>100	90%
	Three leptons		
τ_{45}	$p \to e^+e^+e^-$	>510	90%
τ_{46}	$p \to e^+\mu^+\mu^-$	>81	90%
τ_{47}	$p \to e^+\nu\nu$	>11	90%
τ_{48}	$n \to e^+e^-\nu$	>74	90%
τ_{49}	$n \to \mu^+e^-\nu$	>47	90%
τ_{50}	$n \to \mu^+\mu^-\nu$	>42	90%
τ_{51}	$p \to \mu^+e^+e^-$	>91	90%
τ_{52}	$p \to \mu^+\mu^+\mu^-$	>190	90%
τ_{53}	$p \to \mu^+\nu\nu$	>21	90%
τ_{54}	$p \to e^-\mu^+\mu^+$	>6.0	90%
τ_{55}	$n \to 3\nu$	>0.0005	90%
	Inclusive modes		
τ_{56}	$N \to e^+$ anything	>0.6 (n, p)	90%
τ_{57}	$N \to \mu^+$ anything	>12 (n, p)	90%
τ_{58}	$N \to \nu$ anything		
τ_{59}	$N \to e^+\pi^0$ anything	>0.6 (n, p)	90%
τ_{60}	$N \to$ 2 bodies, ν-free		

$\Delta B = 2$ dinucleon modes

The following are lifetime limits per iron nucleus.

	Mode	Limit	CL
τ_{61}	$pp \to \pi^+\pi^+$	>0.7	90%
τ_{62}	$pn \to \pi^+\pi^0$	>2.0	90%
τ_{63}	$nn \to \pi^+\pi^-$	>0.7	90%
τ_{64}	$nn \to \pi^0\pi^0$	>3.4	90%
τ_{65}	$pp \to e^+e^+$	>5.8	90%
τ_{66}	$pp \to e^+\mu^+$	>3.6	90%
τ_{67}	$pp \to \mu^+\mu^+$	>1.7	90%
τ_{68}	$pn \to e^+\overline{\nu}$	>2.8	90%
τ_{69}	$pn \to \mu^+\overline{\nu}$	>1.6	90%
τ_{70}	$nn \to \nu_e\overline{\nu}_e$	>0.000012	90%
τ_{71}	$nn \to \nu_\mu\overline{\nu}_\mu$	>0.000006	90%

p PARTIAL MEAN LIVES

Tabulated is the mean life divided by the branching fraction.

Decaying particle: p = proton, n = bound neutron. The same event may appear under more than one partial decay mode. Background estimates may be accurate to a factor of two.

$\tau(N \to e^+\pi)$ — τ_1

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>550	***p***	**90**	**0**	**0.7**	[10] BECKER-SZ...	90	IMB3
>130	***n***	**90**	**0**	**<0.2**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 70	p	90	0	0.5	BERGER	91	FREJ
> 70	n	90	0	≤ 0.1	BERGER	91	FREJ
>260	p	90	0	<0.04	HIRATA	89C	KAMI
>310	p	90	0	0.6	SEIDEL	88	IMB
>100	n	90	0	1.6	SEIDEL	88	IMB
> 1.3	n	90	0		BARTELT	87	SOUD
> 1.3	p	90	0		BARTELT	87	SOUD
>250	p	90	0	0.3	HAINES	86	IMB
> 31	n	90	8	9	HAINES	86	IMB
> 64	p	90	0	<0.4	ARISAKA	85	KAMI
> 26	n	90	0	<0.7	ARISAKA	85	KAMI
> 82	p (free)	90	0	0.2	BLEWITT	85	IMB
>250	p	90	0	0.2	BLEWITT	85	IMB
> 25	n	90	4	4	PARK	85	IMB
> 15	p, n	90	0		BATTISTONI	84	NUSX
> 0.5	p	90	1	0.3	[11] BARTELT	83	SOUD
> 0.5	n	90	1	0.3	[11] BARTELT	83	SOUD
> 5.8	p	90	2		[12] KRISHNA...	82	KOLR
> 5.8	n	90	2		[12] KRISHNA...	82	KOLR
> 0.1	n	90			[13] GURR	67	CNTR

[10] This BECKER-SZENDY 90 result includes data from SEIDEL 88.
[11] Limit based on zero events.
[12] We have calculated 90% CL limit from 1 confined event.
[13] We have converted half-life to 90% CL mean life.

$\tau(N \to \mu^+\pi)$ — τ_2

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>100	***n***	**90**	**0**	**<0.2**	HIRATA	89C	KAMI
>270	***p***	**90**	**0**	**0.5**	SEIDEL	88	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 81	p	90	0	0.2	BERGER	91	FREJ
> 35	n	90	1	1.0	BERGER	91	FREJ
>230	p	90	0	<0.07	HIRATA	89C	KAMI
> 63	n	90	0	0.5	SEIDEL	88	IMB
> 76	p	90	2	1	HAINES	86	IMB
> 23	n	90	8	7	HAINES	86	IMB
> 46	p	90	0	<0.7	ARISAKA	85	KAMI
> 20	n	90	0	<0.4	ARISAKA	85	KAMI
> 59	p (free)	90	0	0.2	BLEWITT	85	IMB
>100	p	90	1	0.4	BLEWITT	85	IMB
> 38	n	90	1	4	PARK	85	IMB
> 10	p, n	90	0		BATTISTONI	84	NUSX
> 1.3	p, n	90	0		ALEKSEEV	81	BAKS

$\tau(N \to \nu\pi)$ — τ_3

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
> 25	***p***	**90**	**32**	**32.8**	HIRATA	89C	KAMI
>100	***n***	**90**	**1**	**3**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
> 13	*n*	90	1	1.2	BERGER	89	FREJ
> 10	*p*	90	11	14	BERGER	89	FREJ
> 6	*n*	90	73	60	HAINES	86	IMB
> 2	*p*	90	16	13	KAJITA	86	KAMI
> 40	*n*	90	0	1	KAJITA	86	KAMI
> 7	*n*	90	28	19	PARK	85	IMB
> 7	*n*	90	0		BATTISTONI	84	NUSX
> 2	*p*	90	≤ 3		BATTISTONI	84	NUSX
> 5.8	*p*	90	1		[14] KRISHNA...	82	KOLR
> 0.3	*p*	90	2		[15] CHERRY	81	HOME
> 0.1	*p*	90			[16] GURR	67	CNTR

[14] We have calculated 90% CL limit from 1 confined event.
[15] We have converted 2 possible events to 90% CL limit.
[16] We have converted half-life to 90% CL mean life.

$\tau(p \to e^+\eta)$ — τ_4

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>140	***p***	**90**	**0**	**<0.04**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 44	*p*	90	0	0.1	BERGER	91	FREJ
>100	*p*	90	0	0.6	SEIDEL	88	IMB
>200	*p*	90	5	3.3	HAINES	86	IMB
> 64	*p*	90	0	<0.8	ARISAKA	85	KAMI
> 64	*p* (free)	90	5	6.5	BLEWITT	85	IMB
>200	*p*	90	5	4.7	BLEWITT	85	IMB
> 1.2	*p*	90	2		[17] CHERRY	81	HOME

[17] We have converted 2 possible events to 90% CL limit.

$\tau(p \to \mu^+\eta)$ — τ_5

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>69	***p***	**90**	**1**	**<0.08**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>26	*p*	90	1	0.8	BERGER	91	FREJ
> 1.3	*p*	90	0	0.7	PHILLIPS	89	HPW
>34	*p*	90	1	1.5	SEIDEL	88	IMB
>46	*p*	90	7	6	HAINES	86	IMB
>26	*p*	90	1	<0.8	ARISAKA	85	KAMI
>17	*p* (free)	90	6	6	BLEWITT	85	IMB
>46	*p*	90	7	8	BLEWITT	85	IMB

$\tau(n \to \nu\eta)$ — τ_6

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>54	***n***	**90**	**2**	**0.9**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>29	*n*	90	0	0.9	BERGER	89	FREJ
>16	*n*	90	3	2.1	SEIDEL	88	IMB
>25	*n*	90	7	6	HAINES	86	IMB
>30	*n*	90	0	0.4	KAJITA	86	KAMI
>18	*n*	90	4	3	PARK	85	IMB
> 0.6	*n*	90	2		[18] CHERRY	81	HOME

[18] We have converted 2 possible events to 90% CL limit.

$\tau(N \to e^+\rho)$ — τ_7

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>75	***p***	**90**	**2**	**2.7**	HIRATA	89C	KAMI
>58	***n***	**90**	**0**	**1.9**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>29	*p*	90	0	2.2	BERGER	91	FREJ
>41	*n*	90	0	1.4	BERGER	91	FREJ
>38	*n*	90	2	4.1	SEIDEL	88	IMB
> 1.2	*p*	90	0		BARTELT	87	SOUD
> 1.5	*n*	90	0		BARTELT	87	SOUD
>17	*p*	90	7	7	HAINES	86	IMB
>14	*n*	90	9	4	HAINES	86	IMB
>12	*p*	90	0	<1.2	ARISAKA	85	KAMI
> 6	*n*	90	2	<1	ARISAKA	85	KAMI
> 6.7	*p* (free)	90	6	6	BLEWITT	85	IMB
>17	*p*	90	7	7	BLEWITT	85	IMB
>12	*n*	90	4	2	PARK	85	IMB
> 0.6	*n*	90	1	0.3	[19] BARTELT	83	SOUD
> 0.5	*p*	90	1	0.3	[19] BARTELT	83	SOUD
> 9.8	*p*	90	1		[20] KRISHNA...	82	KOLR
> 0.8	*p*	90	2		[21] CHERRY	81	HOME

[19] Limit based on zero events.
[20] We have calculated 90% CL limit from 0 confined events.
[21] We have converted 2 possible events to 90% CL limit.

$\tau(N \to \mu^+\rho)$ — τ_8

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>110	***p***	**90**	**0**	**1.7**	HIRATA	89C	KAMI
> 23	***n***	**90**	**1**	**1.8**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 12	*p*	90	0	0.5	BERGER	91	FREJ
> 22	*n*	90	0	1.1	BERGER	91	FREJ
> 4.3	*p*	90	0	0.7	PHILLIPS	89	HPW
> 30	*p*	90	0	0.5	SEIDEL	88	IMB
> 11	*n*	90	1	1.1	SEIDEL	88	IMB
> 16	*p*	90	4	4.5	HAINES	86	IMB
> 7	*n*	90	6	5	HAINES	86	IMB
> 12	*p*	90	0	<0.7	ARISAKA	85	KAMI
> 5	*n*	90	1	<1.2	ARISAKA	85	KAMI
> 5.5	*p* (free)	90	4	5	BLEWITT	85	IMB
> 16	*p*	90	4	5	BLEWITT	85	IMB
> 9	*n*	90	1	2	PARK	85	IMB

$\tau(N \to \nu\rho)$ — τ_9

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>27	***p***	**90**	**5**	**1.5**	HIRATA	89C	KAMI
>19	***n***	**90**	**0**	**0.5**	SEIDEL	88	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 9	*n*	90	4	2.4	BERGER	89	FREJ
>24	*p*	90	0	0.9	BERGER	89	FREJ
>13	*n*	90	4	3.6	HIRATA	89C	KAMI
>13	*p*	90	1	1.1	SEIDEL	88	IMB
> 8	*p*	90	6	5	HAINES	86	IMB
> 2	*n*	90	15	10	HAINES	86	IMB
>11	*p*	90	2	1	KAJITA	86	KAMI
> 4	*n*	90	2	2	KAJITA	86	KAMI
> 4.1	*p* (free)	90	6	7	BLEWITT	85	IMB
> 8.4	*p*	90	6	5	BLEWITT	85	IMB
> 2	*n*	90	7	3	PARK	85	IMB
> 0.9	*p*	90	2		[22] CHERRY	81	HOME
> 0.6	*n*	90	2		[22] CHERRY	81	HOME

[22] We have converted 2 possible events to 90% CL limit.

$\tau(p \to e^+\omega)$ — τ_{10}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>45	***p***	**90**	**2**	**1.45**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>17	*p*	90	0	1.1	BERGER	91	FREJ
>26	*p*	90	1	1.0	SEIDEL	88	IMB
> 1.5	*p*	90	0		BARTELT	87	SOUD
>37	*p*	90	6	5.3	HAINES	86	IMB
>25	*p*	90	1	<1.4	ARISAKA	85	KAMI
>12	*p* (free)	90	6	7.5	BLEWITT	85	IMB
>37	*p*	90	6	5.7	BLEWITT	85	IMB
> 0.6	*p*	90	1	0.3	[23] BARTELT	83	SOUD
> 9.8	*p*	90	1		[24] KRISHNA...	82	KOLR
> 2.8	*p*	90	2		[25] CHERRY	81	HOME

[23] Limit based on zero events.
[24] We have calculated 90% CL limit from 0 confined events.
[25] We have converted 2 possible events to 90% CL limit.

$\tau(p \to \mu^+\omega)$ — τ_{11}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>57	***p***	**90**	**2**	**1.9**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>11	*p*	90	0	1.0	BERGER	91	FREJ
> 4.4	*p*	90	0	0.7	PHILLIPS	89	HPW
>10	*p*	90	2	1.3	SEIDEL	88	IMB
>23	*p*	90	2	1	HAINES	86	IMB
> 6.5	*p* (free)	90	9	8.7	BLEWITT	85	IMB
>23	*p*	90	8	7	BLEWITT	85	IMB

$\tau(n \to \nu\omega)$ — τ_{12}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>43	***n***	**90**	**3**	**2.7**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>17	*n*	90	1	0.7	BERGER	89	FREJ
> 6	*n*	90	2	1.3	SEIDEL	88	IMB
>12	*n*	90	6	6	HAINES	86	IMB
>18	*n*	90	2	2	KAJITA	86	KAMI
>16	*n*	90	1	2	PARK	85	IMB
> 2.0	*n*	90	2		[26] CHERRY	81	HOME

[26] We have converted 2 possible events to 90% CL limit.

$\tau(N \rightarrow e^+ K)$ τ_{13}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>150	***p***	**90**	**0**	**<0.27**	HIRATA 89C	KAMI
> 1.3	***n***	**90**	**0**		ALEKSEEV 81	BAKS
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 60	*p*	90	0		BERGER 91	FREJ
> 70	*p*	90	0	1.8	SEIDEL 88	IMB
> 77	*p*	90	5	4.5	HAINES 86	IMB
> 38	*p*	90	0	<0.8	ARISAKA 85	KAMI
> 24	*p* (free)	90	7	8.5	BLEWITT 85	IMB
> 77	*p*	90	5	4	BLEWITT 85	IMB
> 1.3	*p*	90	0		ALEKSEEV 81	BAKS

$\tau(p \rightarrow e^+ K^0_S)$ τ_{14}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>76	***p***	**90**	**0**	**0.5**	BERGER 91	FREJ

$\tau(p \rightarrow e^+ K^0_L)$ τ_{15}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>44	***p***	**90**	**0**	**≤ 0.1**	BERGER 91	FREJ

$\tau(N \rightarrow \mu^+ K)$ τ_{16}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>120	***p***	**90**	**1**	**0.4**	HIRATA 89C	KAMI
> 1.1	***n***	**90**	**0**		BARTELT 87	SOUD
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 54	*p*	90	0		BERGER 91	FREJ
> 3.0	*p*	90	0	0.7	PHILLIPS 89	HPW
> 19	*p*	90	3	2.5	SEIDEL 88	IMB
> 1.5	*p*	90	0		[27] BARTELT 87	SOUD
> 40	*p*	90	7	6	HAINES 86	IMB
> 19	*p*	90	1	<1.1	ARISAKA 85	KAMI
> 6.7	*p* (free)	90	11	13	BLEWITT 85	IMB
> 40	*p*	90	7	8	BLEWITT 85	IMB
> 6	*p*	90	1		BATTISTONI 84	NUSX
> 0.6	*p*	90	0		[28] BARTELT 83	SOUD
> 0.4	*n*	90	0		[28] BARTELT 83	SOUD
> 5.8	*p*	90	2		[29] KRISHNA... 82	KOLR
> 2.0	*p*	90	0		CHERRY 81	HOME
> 0.2	*n*	90			[30] GURR 67	CNTR

[27] BARTELT 87 limit applies to $p \rightarrow \mu^+ K^0_S$.
[28] Limit based on zero events.
[29] We have calculated 90% CL limit from 1 confined event.
[30] We have converted half-life to 90% CL mean life.

$\tau(p \rightarrow \mu^+ K^0_S)$ τ_{17}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>64	***p***	**90**	**0**	**1.2**	BERGER 91	FREJ

$\tau(p \rightarrow \mu^+ K^0_L)$ τ_{18}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>44	***p***	**90**	**0**	**≤ 0.1**	BERGER 91	FREJ

$\tau(N \rightarrow \nu K)$ τ_{19}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>100	***p***	**90**	**9**	**7.3**	HIRATA 89C	KAMI
> 86	***n***	**90**	**0**	**2.4**	HIRATA 89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 15	*n*	90	1	1.8	BERGER 89	FREJ
> 15	*p*	90	1	1.8	BERGER 89	FREJ
> 0.28	*p*	90	0	0.7	PHILLIPS 89	HPW
> 0.3	*p*	90	0		BARTELT 87	SOUD
> 0.75	*n*	90	0		[31] BARTELT 87	SOUD
> 10	*p*	90	6	5	HAINES 86	IMB
> 15	*n*	90	3	5	HAINES 86	IMB
> 28	*p*	90	3	3	KAJITA 86	KAMI
> 32	*n*	90	0	1.4	KAJITA 86	KAMI
> 1.8	*p* (free)	90	6	11	BLEWITT 85	IMB
> 9.6	*p*	90	6	5	BLEWITT 85	IMB
> 10	*n*	90	2	2	PARK 85	IMB
> 5	*n*	90	0		BATTISTONI 84	NUSX
> 2	*p*	90	0		BATTISTONI 84	NUSX
> 0.3	*n*	90	0		[32] BARTELT 83	SOUD
> 0.1	*p*	90	0		[32] BARTELT 83	SOUD
> 5.8	*p*	90	1		[33] KRISHNA... 82	KOLR
> 0.3	*n*	90	2		[34] CHERRY 81	HOME

[31] BARTELT 87 limit applies to $n \rightarrow \nu K^0_S$.
[32] Limit based on zero events.
[33] We have calculated 90% CL limit from 1 confined event.
[34] We have converted 2 possible events to 90% CL limit.

$\tau(p \rightarrow e^+ K^*(892)^0)$ τ_{20}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>52	***p***	**90**	**2**	**1.55**	HIRATA 89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>10	*p*	90	0	0.8	BERGER 91	FREJ
>10	*p*	90	1	<1	ARISAKA 85	KAMI

$\tau(N \rightarrow \nu K^*(892))$ τ_{21}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>22	***n***	**90**	**0**	**2.1**	BERGER 89	FREJ
>20	***p***	**90**	**5**	**2.1**	HIRATA 89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>17	*p*	90	0	2.4	BERGER 89	FREJ
>21	*n*	90	4	2.4	HIRATA 89C	KAMI
>10	*p*	90	7	6	HAINES 86	IMB
> 5	*n*	90	8	7	HAINES 86	IMB
> 8	*p*	90	3	2	KAJITA 86	KAMI
> 6	*n*	90	2	1.6	KAJITA 86	KAMI
> 5.8	*p* (free)	90	10	16	BLEWITT 85	IMB
> 9.6	*p*	90	7	6	BLEWITT 85	IMB
> 7	*n*	90	1	4	PARK 85	IMB
> 2.1	*p*	90	1		[35] BATTISTONI 82	NUSX

[35] We have converted 1 possible event to 90% CL limit.

$\tau(p \rightarrow e^+ \pi^+ \pi^-)$ τ_{22}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>21	***p***	**90**	**0**	**2.2**	BERGER 91	FREJ

$\tau(p \rightarrow e^+ \pi^0 \pi^0)$ τ_{23}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>38	***p***	**90**	**1**	**0.5**	BERGER 91	FREJ

$\tau(n \rightarrow e^+ \pi^- \pi^0)$ τ_{24}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>32	***n***	**90**	**1**	**0.8**	BERGER 91	FREJ

$\tau(p \rightarrow \mu^+ \pi^+ \pi^-)$ τ_{25}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>17	***p***	**90**	**1**	**2.6**	BERGER 91	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 3.3	*p*	90	0	0.7	PHILLIPS 89	HPW

$\tau(p \rightarrow \mu^+ \pi^0 \pi^0)$ τ_{26}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>33	***p***	**90**	**1**	**0.9**	BERGER 91	FREJ

$\tau(n \rightarrow \mu^+ \pi^- \pi^0)$ τ_{27}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>33	***n***	**90**	**0**	**1.1**	BERGER 91	FREJ

$\tau(n \rightarrow e^+ K^0 \pi^-)$ τ_{28}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>18	***n***	**90**	**1**	**0.2**	BERGER 91	FREJ

$\tau(n \rightarrow e^- \pi^+)$ τ_{29}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>65	***n***	**90**	**0**	**1.6**	SEIDEL 88	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>55	*n*	90	0	1.09	BERGER 91B	FREJ
>16	*n*	90	9	7	HAINES 86	IMB
>25	*n*	90	2	4	PARK 85	IMB

$\tau(n \rightarrow \mu^- \pi^+)$ τ_{30}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>49	***n***	**90**	**0**	**0.5**	SEIDEL 88	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>33	*n*	90	0	1.40	BERGER 91B	FREJ
> 2.7	*n*	90	0	0.7	PHILLIPS 89	HPW
>25	*n*	90	7	6	HAINES 86	IMB
>27	*n*	90	2	3	PARK 85	IMB

$\tau(n \rightarrow e^- \rho^+)$ τ_{31}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>62	***n***	**90**	**2**	**4.1**	SEIDEL 88	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>12	*n*	90	13	6	HAINES 86	IMB
>12	*n*	90	5	3	PARK 85	IMB

$\tau(n \to \mu^- \rho^+)$ — τ_{32}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>7	***n***	**90**	**1**	**1.1**	SEIDEL	88	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>2.6	*n*	90	0	0.7	PHILLIPS	89	HPW
>9	*n*	90	7	5	HAINES	86	IMB
>9	*n*	90	2	2	PARK	85	IMB

$\tau(n \to e^- K^+)$ — τ_{33}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>32	***n***	**90**	**3**	**2.96**	BERGER	91B	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 0.23	*n*	90	0	0.7	PHILLIPS	89	HPW

$\tau(n \to \mu^- K^+)$ — τ_{34}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>57	***n***	**90**	**0**	**2.18**	BERGER	91B	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 4.7	*n*	90	0	0.7	PHILLIPS	89	HPW

$\tau(p \to e^- \pi^+ \pi^+)$ — τ_{35}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>30	***p***	**90**	**1**	**2.50**	BERGER	91B	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 2.0	*p*	90	0	0.7	PHILLIPS	89	HPW

$\tau(n \to e^- \pi^+ \pi^0)$ — τ_{36}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>29	***n***	**90**	**1**	**0.78**	BERGER	91B	FREJ

$\tau(p \to \mu^- \pi^+ \pi^+)$ — τ_{37}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>17	***p***	**90**	**1**	**1.72**	BERGER	91B	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 7.8	*p*	90	0	0.7	PHILLIPS	89	HPW

$\tau(n \to \mu^- \pi^+ \pi^0)$ — τ_{38}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>34	***n***	**90**	**0**	**0.78**	BERGER	91B	FREJ

$\tau(p \to e^- \pi^+ K^+)$ — τ_{39}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>20	***p***	**90**	**3**	**2.50**	BERGER	91B	FREJ

$\tau(p \to \mu^- \pi^+ K^+)$ — τ_{40}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>5	***p***	**90**	**2**	**0.78**	BERGER	91B	FREJ

$\tau(p \to e^+ \gamma)$ — τ_{41}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>460	***p***	**90**	**0**	**0.6**	SEIDEL	88	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>133	*p*	90	0	0.3	BERGER	91	FREJ
>360	*p*	90	0	0.3	HAINES	86	IMB
> 87	*p* (free)	90	0	0.2	BLEWITT	85	IMB
>360	*p*	90	0	0.2	BLEWITT	85	IMB
> 0.1	*p*	90			[36] GURR	67	CNTR

[36] We have converted half-life to 90% CL mean life.

$\tau(p \to \mu^+ \gamma)$ — τ_{42}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>380	***p***	**90**	**0**	**0.5**	SEIDEL	88	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>155	*p*	90	0	0.1	BERGER	91	FREJ
> 97	*p*	90	3	2	HAINES	86	IMB
> 61	*p* (free)	90	0	0.2	BLEWITT	85	IMB
>280	*p*	90	0	0.6	BLEWITT	85	IMB
> 0.3	*p*	90			[37] GURR	67	CNTR

[37] We have converted half-life to 90% CL mean life.

$\tau(n \to \nu \gamma)$ — τ_{43}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>24	***n***	**90**	**10**	**6.86**	BERGER	91B	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 9	*n*	90	73	60	HAINES	86	IMB
>11	*n*	90	28	19	PARK	85	IMB

$\tau(p \to e^+ \gamma \gamma)$ — τ_{44}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>100	***p***	**90**	**1**	**0.8**	BERGER	91	FREJ

$\tau(p \to e^+ e^+ e^-)$ — τ_{45}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>510	***p***	**90**	**0**	**0.3**	HAINES	86	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>147	*p*	90	0	0.1	BERGER	91	FREJ
> 89	*p* (free)	90	0	0.5	BLEWITT	85	IMB
>510	*p*	90	0	0.7	BLEWITT	85	IMB

$\tau(p \to e^+ \mu^+ \mu^-)$ — τ_{46}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>81	***p***	**90**	**0**	**0.16**	BERGER	91	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 5.0	*p*	90	0	0.7	PHILLIPS	89	HPW

$\tau(p \to e^+ \nu \nu)$ — τ_{47}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>11	***p***	**90**	**11**	**6.08**	BERGER	91B	FREJ

$\tau(n \to e^+ e^- \nu)$ — τ_{48}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>74	***n***	**90**	**0**	**<0.1**	BERGER	91B	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>45	*n*	90	5	5	HAINES	86	IMB
>26	*n*	90	4	3	PARK	85	IMB

$\tau(n \to \mu^+ e^- \nu)$ — τ_{49}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>47	***n***	**90**	**0**	**<0.1**	BERGER	91B	FREJ

$\tau(n \to \mu^+ \mu^- \nu)$ — τ_{50}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>42	***n***	**90**	**0**	**1.4**	BERGER	91B	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 5.1	*n*	90	0	0.7	PHILLIPS	89	HPW
>16	*n*	90	14	7	HAINES	86	IMB
>19	*n*	90	4	7	PARK	85	IMB

$\tau(p \to \mu^+ e^+ e^-)$ — τ_{51}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>91	***p***	**90**	**0**	**≤ 0.1**	BERGER	91	FREJ

$\tau(p \to \mu^+ \mu^+ \mu^-)$ — τ_{52}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>190	***p***	**90**	**1**	**0.1**	HAINES	86	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>119	*p*	90	0	0.2	BERGER	91	FREJ
> 10.5	*p*	90	0	0.7	PHILLIPS	89	HPW
> 44	*p* (free)	90	1	0.7	BLEWITT	85	IMB
>190	*p*	90	1	0.9	BLEWITT	85	IMB
> 2.1	*p*	90	1		[38] BATTISTONI	82	NUSX

[38] We have converted 1 possible event to 90% CL limit.

$\tau(p \to \mu^+ \nu \nu)$ — τ_{53}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>21	***p***	**90**	**7**	**11.23**	BERGER	91B	FREJ

$\tau(p \to e^- \mu^+ \mu^+)$ — τ_{54}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>6.0	***p***	**90**	**0**	**0.7**	PHILLIPS	89	HPW

$\tau(n \to 3\nu)$ — τ_{55}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>0.0005	***n***	**90**	**0**		LEARNED	79	RVUE
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>0.00003	*n*	90	11	6.1	[39] BERGER	91B	FREJ
>0.00012	*n*	90	7	11.2	[39] BERGER	91B	FREJ

[39] The first BERGER 91B limit is for $n \to \nu_e \nu_e \overline{\nu}_e$, the second is for $n \to \nu_\mu \nu_\mu \overline{\nu}_\mu$.

$\tau(N \to e^+ \text{ anything})$ — τ_{56}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>0.6	***p, n***	**90**			[40] LEARNED	79	RVUE

[40] The electron may be primary or secondary.

$\tau(N \to \mu^+ \text{ anything})$ — τ_{57}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>12	***p, n***	**90**	**2**		[41,42] CHERRY	81	HOME
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 1.8	*p, n*	90			[42] COWSIK	80	CNTR
> 6	*p, n*	90			[42] LEARNED	79	RVUE

[41] We have converted 2 possible events to 90% CL limit.
[42] The muon may be primary or secondary.

$\tau(N \to \nu \text{ anything})$ — τ_{58}

Anything = π, ρ, K, etc.

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>0.0002	*p, n*	90	0		LEARNED	79	RVUE

$\tau(N \to e^+ \pi^0 \text{ anything})$ — τ_{59}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>0.6	***p, n***	**90**	**0**		LEARNED	79	RVUE

$\tau(N \to 2 \text{ bodies}, \nu\text{-free})$ — τ_{60}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>1.3	*p, n*	90	0		ALEKSEEV	81	BAKS

$\tau(pp \to \pi^+\pi^+)$ — τ_{61}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN	COMMENT
>0.7	**90**	**4**	**2.34**	BERGER	91B	FREJ	τ per iron nucleus

$\tau(pn \to \pi^+\pi^0)$ — τ_{62}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN	COMMENT
>2.0	**90**	**0**	**0.31**	BERGER	91B	FREJ	τ per iron nucleus

$\tau(nn \to \pi^+\pi^-)$ — τ_{63}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN	COMMENT
>0.7	**90**	**4**	**2.18**	BERGER	91B	FREJ	τ per iron nucleus

$\tau(nn \to \pi^0\pi^0)$ — τ_{64}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN	COMMENT
>3.4	**90**	**0**	**0.78**	BERGER	91B	FREJ	τ per iron nucleus

$\tau(pp \to e^+e^+)$ — τ_{65}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN	COMMENT
>5.8	**90**	**0**	**<0.1**	BERGER	91B	FREJ	τ per iron nucleus

$\tau(pp \to e^+\mu^+)$ — τ_{66}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN	COMMENT
>3.6	**90**	**0**	**<0.1**	BERGER	91B	FREJ	τ per iron nucleus

$\tau(pp \to \mu^+\mu^+)$ — τ_{67}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN	COMMENT
>1.7	**90**	**0**	**0.62**	BERGER	91B	FREJ	τ per iron nucleus

$\tau(pn \to e^+\overline{\nu})$ — τ_{68}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN	COMMENT
>2.8	**90**	**5**	**9.67**	BERGER	91B	FREJ	τ per iron nucleus

$\tau(pn \to \mu^+\overline{\nu})$ — τ_{69}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN	COMMENT
>1.6	**90**	**4**	**4.37**	BERGER	91B	FREJ	τ per iron nucleus

$\tau(nn \to \nu_e\overline{\nu}_e)$ — τ_{70}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN	COMMENT
>0.000012	**90**	**5**	**9.7**	BERGER	91B	FREJ	τ per iron nucleus

$\tau(nn \to \nu_\mu\overline{\nu}_\mu)$ — τ_{71}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN	COMMENT
>0.000006	**90**	**4**	**4.4**	BERGER	91B	FREJ	τ per iron nucleus

REFERENCES FOR *p*

BERGER	91	ZPHY C50 385	+Froehlich, Moench, Nisius+	(FREJUS Collab.)
BERGER	91B	PL B269 227	+Froehlich, Moench, Nisius+	(FREJUS Collab.)
FEDERSPIEL	91	PRL 67 1511	+Eisenstein, Lucas, MacGibbon+	(ILL)
BECKER-SZ...	90	PR D42 2974	Becker-Szendy, Bratton, Cady, Casper+	(IMB-3 Collab.)
ERICSON	90	EPL 11 295	+Richter	(CERN, DARM)
GABRIELSE	90	PRL 65 1317	+Fei, Orozco, Tjoelker+	(HARV, MANZ, WASH, IBS)
BERGER	89	NP B313 509	+Froehlich, Moench+	(FREJUS Collab.)
CHO	89	PRL 63 2559	+Sangster, Hinds	(YALE)
HIRATA	89C	PL B220 308	+Kajita, Kifune, Kihara+	(Kamiokande Collab.)
PHILLIPS	89	PL B224 348	+Matthews, Aprile, Cline+	(HPW Collab.)
KREISSL	88	ZPHY C37 557	+	(KARL, BASL, STOC, STRB, THES, MUNI, MISS)
SEIDEL	88	PRL 61 2522	+Bionta, Blewitt, Bratton+	(IMB Collab.)
BARTELT	87	PR D36 1990	+Courant, Heller+	(Soudan Collab.)
Also	89	PR D40 1701 erratum	Bartelt, Courant, Heller+	(Soudan Collab.)
COHEN	87	RMP 59 1121	+Taylor	(RISC, NBS)
HAINES	86	PRL 57 1986	+Bionta, Blewitt, Bratton, Casper+	(IMB Collab.)
KAJITA	86	JPSJ 55 711	+Arisaka, Koshiba, Nakahata+	(Kamiokande Collab.)
ARISAKA	85	JPSJ 54 3213	+Kajita, Koshiba, Nakahata+	(Kamiokande Collab.)
BLEWITT	85	PRL 55 2114	+LoSecco, Bionta, Bratton+	(IMB Collab.)
DZUBA	85	PL 154B 93	+Flambaum, Silvestrov	(NOVO)
PARK	85	PRL 54 22	+Blewitt, Cortez, Foster+	(IMB Collab.)
BATTISTONI	84	PL 133B 454	+Bellotti, Bologna, Campana+	(NUSEX Collab.)
MARINELLI	84	PL 137B 439	+Morpurgo	(GENO)
WILKENING	84	PR A29 425	+Ramsey, Larson	(HARV, VIRG)
BARTELT	83	PRL 50 651	+Courant, Heller, Joyce, Marshak+	(MINN, ANL)
BATTISTONI	82	PL 118B 461	+Bellotti, Bologna, Campana+	(NUSEX Collab.)
KRISHNA...	82	PL 115B 349	Krishnaswamy, Menon+	(TATA, OSKC, TOKY)
ALEKSEEV	81	JETPL 33 651 Translated from ZETFP 33 664.	+Bakatanov, Butkevich, Voevodskii+	(LENI)
CHERRY	81	PRL 47 1507	+Deakyne, Lande, Lee, Steinberg+	(PENN, BNL)
COWSIK	80	PR D22 2204	+Narasimhan	(TATA)
BELL	79	PL 86B 215	+Calvetti, Carron, Chaney, Cittolin+	(CERN)
GOLDEN	79	PRL 43 1196	+Horan, Mauger, Badhwar, Lacy+	(NASA, PSLL)
LEARNED	79	PRL 43 907	+Reines, Soni	(UCI)
BREGMAN	78	PL 78B 174	+Calvetti, Carron, Cittolin, Hauer, Herr+	(CERN)
ROBERTS	78	PR D17 358		(WILL, RHEL)
EVANS	77	Science 197 989	+Steinberg	(BNL, PENN)
ROBERSON	77	PR C16 1945	+King, Kunselman+	(WYOM, CIT, CMU, VPI, WILL)
HU	75	NP A254 403	+Asano, Chen, Cheng, Dugan+	(COLU, YALE)
COHEN	73	JPCRD 2 663	+Taylor	(RISC, NBS)
DYLLA	73	PR A7 1224	+King	(MIT)
BAMBERGER	70	PL 33B 233	+Lynen, Piekarz+	(MPIH, CERN, KARL)
DIX	70	Case Thesis		(CASE)
HARRISON	69	PRL 22 1263	+Sandars, Wright	(OXF)
GURR	67	PR 158 1321	+Kropp, Reines, Meyer	(CASE, WITW)
FLEROV	58	DOKL 3 79	+Klochkov, Skobkin, Terentev	(ASCI)

OTHER RELATED PAPERS

MAMYRIN	83	JETP 57 1152 Translated from ZETF 84 1980.	+Aruev, Alekseenko	(IOFF)
FRANKLIN	77	PR D16 910		(HAIF) P
KALOGERO...	76	PRL 37 1037	Kalogeropoulos, Chiu, Sudarshan	(SYRA, TEXA) P

n

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1986 edition (Physics Letters **170B** (1986)) or in earlier editions.

n MASS

The mass is known much more precisely in u (atomic mass units) than in MeV; see the footnotes. The conversion from u to MeV, 1 u = 931.49432±0.00028 MeV, involves the relatively poorly known electronic charge.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
939.56563±0.00028	[1] COHEN	87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
939.56564±0.00028	[2,3] GREENE	86	SPEC	$np \to d\gamma$
939.5731 ±0.0027	[3] COHEN	73	RVUE	1973 CODATA value

[1] The mass is known much more precisely in u: m = 1.008664904 ± 0.000000014 u.
[2] The mass is known much more precisely in u: m = 1.008664919 ± 0.000000014 u.
[3] These determinations are not independent of the $n - p$ mass difference measurements below.

$\overline{n}$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
939.485±0.051	59	[4] CRESTI	86	HBC	$\overline{p}p \to \overline{n}n$

[4] This is a corrected result (see the erratum). The error is statistical. The maximum systematic error is 0.029 MeV.

$n - p$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1.293318 ±0.000009	[5] COHEN	87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.2933328±0.0000072	GREENE	86	SPEC	$np \to d\gamma$
1.293429 ±0.000036	COHEN	73	RVUE	1973 CODATA value

[5] Calculated by us from the COHEN 87 ratio $m(n)/m(p)$ = 1.001378404 ± 0.000000009. In u, $m(n) - m(p)$ = 0.001388434 ± 0.000000009 u.

n MEAN LIFE

We now compile only direct measurements of the lifetime, not those inferred from decay correlation measurements. (Limits on lifetimes for *bound* neutrons are given in the section "*p* PARTIAL MEAN LIVES.")

For a review, see EROZOLIMSKII 89 and papers that follow it in an issue of NIM devoted to the "Proceedings of the International Workshop on Fundamental Physics with Slow Neutrons" (Grenoble 1989). Also, for commentary, see FREEDMAN 90 and SCHRECKENBACH 92.

VALUE (s)	DOCUMENT ID		TECN	COMMENT
889.1± 2.1 OUR AVERAGE	Error includes scale factor of 1.2.			
888.4± 2.9	ALFIMENKOV	90	CNTR	Ultracold neutrons
893.6± 3.8± 3.7	BYRNE	90	CNTR	Penning trap
878 ±27 ±14	KOSSAKOW...	89	TPC	Pulsed beam
887.6± 3.0	MAMPE	89	CNTR	Ultracold neutrons
877 ±10	PAUL	89	CNTR	Ultracold neutrons
876 ±10 ±19	LAST	88	SPEC	Pulsed beam
891 ± 9	SPIVAK	88	CNTR	Thermal neutrons
903 ±13	KOSVINTSEV	86	CNTR	Ultracold neutrons
918 ±14	CHRISTENSEN	72	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
937 ±18	[6] BYRNE	80	CNTR	
875 ±95	KOSVINTSEV	80	CNTR	
881 ± 8	BONDAREN...	78	CNTR	See SPIVAK 88

[6] This measurement has been withdrawn (J. Byrne, private communication, 1990).

n MAGNETIC MOMENT

VALUE (μ_N)	DOCUMENT ID		TECN	COMMENT
−1.91304275±0.00000045	COHEN	87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−1.91304277±0.00000048	[7] GREENE	82	MRS	

[7] GREENE 82 measures the moment to be $(1.04187564 \pm 0.00000026) \times 10^{-3}$ Bohr magnetons. The value above is obtained by multiplying this by $m(p)/m(e) = 1836.152701 \pm 0.000037$ (the 1986 CODATA value from COHEN 87).

n ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance. A number of early results have been omitted. See RAMSEY 90 for a review.

VALUE (10^{-26} e-cm)	CL%	DOCUMENT ID		TECN	COMMENT
< 12	95	SMITH	90	MRS	$d = (-3 \pm 5) \times 10^{-26}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 26	95	ALTAREV	86	MRS	$d = (-14 \pm 6) \times 10^{-26}$
3±48		PENDLEBURY	84	MRS	Ultracold neutrons
< 60	90	ALTAREV	81	MRS	$d = (21 \pm 24) \times 10^{-26}$
<160	90	ALTAREV	79	MRS	$d = (40 \pm 75) \times 10^{-26}$

n ELECTRIC POLARIZABILITY α_n

Following is the electric polarizability α_n defined in terms of the induced electric dipole moment by $\mathbf{D} = 4\pi\epsilon_0\alpha_n\mathbf{E}$. For a review, see SCHMIEDMAYER 89.

VALUE (10^{-3} fm^3)	DOCUMENT ID		TECN	COMMENT
$1.16^{+0.19}_{-0.23}$ OUR AVERAGE				
1.20±0.15±0.20	SCHMIEDM...	91	CNTR	*n* Pb transmission
$1.07^{+0.33}_{-1.07}$	ROSE	90B	CNTR	$\gamma d \to \gamma n p$
0.8 ±1.0	KOESTER	88	CNTR	*n* Pb, *n* Bi transmission
1.2 ±1.0	SCHMIEDM...	88	CNTR	*n* Pb, *n* C transmission
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.17^{+0.43}_{-1.17}$	ROSE	90	CNTR	See ROSE 90B

n CHARGE

See also "$|q_p + q_e|$ CHARGE MAGNITUDE DIFFERENCE" in the proton Listings.

VALUE (10^{-21} e)	DOCUMENT ID		TECN	COMMENT
− 0.4± 1.1	[8] BAUMANN	88		Cold *n* deflection
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−15 ±22	[9] GAEHLER	82	CNTR	Reactor neutrons

[8] The BAUMANN 88 error ±1.1 gives the 68% CL limits about the the value −0.4.
[9] The GAEHLER 82 error ±22 gives the 90% CL limits about the the value −15.

LIMIT ON $n\overline{n}$ OSCILLATIONS

Mean Time for $n\overline{n}$ Transition in Vacuum

A test of baryon conservation. MOHAPATRA 80 and MOHAPATRA 89 discuss the theoretical motivations for looking for $n\overline{n}$ oscillations. DOVER 83 and DOVER 85 give phenomenological analyses. The best limits come from looking for the decay of neutrons bound in nuclei. However, these analyses require model-dependent corrections for nuclear effects. See KABIR 83, DOVER 89, and ALBERICO 91 for discussions. Direct searches for $n \to \overline{n}$ transitions using reactor neutrons are cleaner but give poorer limits.

VALUE (s)	CL%	DOCUMENT ID		TECN	COMMENT
>1.2 × 10^8	90	BERGER	90	FREJ	*n* bound in iron
>1.2 × 10^8	90	TAKITA	86	CNTR	Kamiokande
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>1 × 10^7	90	BALDO-...	90	CNTR	Reactor neutrons
>4.9 × 10^5	90	BRESSI	90	CNTR	Reactor neutrons
>4.7 × 10^5	90	BRESSI	89	CNTR	See BRESSI 90
>1 × 10^6	90	FIDECARO	85	CNTR	Reactor neutrons
>8.8 × 10^7	90	PARK	85B	CNTR	
>3 × 10^7		BATTISTONI	84	NUSX	
> 2.7 × 10^7–1.1 × 10^8		JONES	84	CNTR	
>2 × 10^7		CHERRY	83	CNTR	
>3 × 10^7		ALBERICO	82	THEO	
>1 × 10^8		CHETYRKIN	81	THEO	
>5 × 10^7	90	COWSIK	81	THEO	

n DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$p e^- \overline{\nu}_e$	100 %	
Γ_2	hydrogen-atom $\overline{\nu}_e$	< 3 %	95%
	Charge conservation (*Q*) violating mode		
Γ_3	$p \nu_e \overline{\nu}_e$	*Q* < 9×10^{-24}	90%

n BRANCHING RATIOS

Γ(hydrogen-atom $\overline{\nu}_e$)/Γ$_{total}$ — Γ_2/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID		TECN
<3	95	[10] GREEN	90	RVUE

[10] GREEN 90 infers that τ(hydrogen-atom $\overline{\nu}_e$) > 3×10^4 s by comparing neutron lifetime measurements made in storage experiments with those made in β-decay experiments.

Γ($p \nu_e \overline{\nu}_e$)/Γ$_{total}$ — Γ_3/Γ

Forbidden by charge conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<9 × 10^{-24}	90	BARABANOV	80	CNTR	^{71}Ga → ^{71}Ge X
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<9.7 × 10^{-18}	90	ROY	83	CNTR	^{113}Cd → ^{113m}In neut.
<7.9 × 10^{-21}		VAIDYA	83	CNTR	^{87}Rb → ^{87m}Sr neut.
<3 × 10^{-19}		NORMAN	79	CNTR	^{87}Rb → ^{87m}Sr neut.

NOTE ON BARYON DECAY PARAMETERS

(by E.D. Commins, University of California, Berkeley)

Baryon semileptonic decays

The typical baryon semileptonic decay is described by a matrix element, the hadronic part of which may be written as:

$$\overline{B}_f \left[f_1(q^2)\gamma_\lambda + i\, f_2(q^2)\sigma_{\lambda\mu}q^\mu + g_1(q^2)\gamma_\lambda\gamma_5 + g_3(q^2)\gamma_5 q_\lambda \right] B_i \,.$$

Here B_i and $\overline{B}_f$ are spinors describing the initial and final baryons and $q = p_i - p_f$, while the terms in f_1, f_2, g_1, and g_3 account for vector, induced tensor ("weak magnetism"), axial vector, and induced pseudoscalar contributions.[1] Second-class current contributions are ignored here. In the limit of zero momentum transfer, f_1 reduces to the vector coupling constant g_V, and g_1 reduces to the axial-vector coupling constant g_A. The latter coefficients are related by Cabibbo's theory,[2] generalized to six quarks (and three mixing angles) by Kobayashi and Maskawa.[3] The g_3 term is negligible for transitions in which an $e^\pm$ is emitted, and gives a very small correction, which can be estimated by PCAC,[4] for $\mu^\pm$ modes. Recoil effects include weak magnetism, and are taken into account adequately by considering terms of first order in

$$\delta = (m_i - m_f)/(m_i + m_f) \ ,$$

where m_i and m_f are the masses of the initial and final baryons.

The experimental quantities of interest are the total decay rate, the lepton-neutrino angular correlation, the asymmetry coefficients in the decay of a polarized initial baryon, and the polarization of the decay baryon in its own rest frame for an unpolarized initial baryon. Formulae for these quantities are derived by standard means[5] and are analogous to similar formulae for beta decay.[6] For comparison with high-precision experiments, it is necessary to modify the form factors at $q^2 = 0$ by a "dipole" q^2 dependence, and also to apply appropriate radiative corrections.[7]

The ratio g_A/g_V may be written as

$$g_A/g_V = |\, g_A/g_V \,| \, e^{i\phi_{AV}} \ .$$

The presence of a "triple correlation" term in the transition probability, proportional to $\mathrm{Im}(g_A/g_V)$ and of the form

$$\boldsymbol{\sigma}_i \cdot (\mathbf{p}_\ell \times \mathbf{p}_\nu)$$

for initial baryon polarization or

$$\boldsymbol{\sigma}_f \cdot (\mathbf{p}_\ell \times \mathbf{p}_\nu)$$

for final baryon polarization, would indicate failure of time-reversal invariance. The phase angle ϕ has been measured precisely only in neutron decay (and in ^{19}Ne nuclear beta decay), and the results are consistent with T invariance.

Hyperon nonleptonic decays

The most general decay amplitude for $J^P = 1/2^+$ hyperons may be written in the form

$$M = G_F \, m_\pi^2 \cdot \overline{B}_f \, (A - B\gamma_5) \, B_i \ ,$$

where A and B are constants.[1] Then the transition rate is proportional to

$$R = 1 + \gamma \ \widehat{\boldsymbol{\omega}}_f \cdot \widehat{\boldsymbol{\omega}}_i + (1-\gamma)(\widehat{\boldsymbol{\omega}}_f \cdot \widehat{\mathbf{n}})(\widehat{\boldsymbol{\omega}}_i \cdot \widehat{\mathbf{n}}) + \alpha(\widehat{\boldsymbol{\omega}}_f \cdot \widehat{\mathbf{n}} + \widehat{\boldsymbol{\omega}}_i \cdot \widehat{\mathbf{n}}) + \beta \, \widehat{\mathbf{n}} \cdot (\widehat{\boldsymbol{\omega}}_f \times \widehat{\boldsymbol{\omega}}_i) \ ,$$

where $\widehat{\mathbf{n}}$ is a unit vector in the direction of the final baryon momentum, and $\widehat{\boldsymbol{\omega}}_i$ and $\widehat{\boldsymbol{\omega}}_f$ are unit vectors in the directions of the initial and final baryon spins. Also,

$$\alpha = 2\,\mathrm{Re}(s^* p)/(|\,s\,|^2 + |\,p\,|^2) \ ,$$

$$\beta = 2\,\mathrm{Im}(s^* p)/(|\,s\,|^2 + |\,p\,|^2) \ ,$$

and

$$\gamma = (|\,s\,|^2 - |\,p\,|^2)/(|\,s\,|^2 + |\,p\,|^2) \ ,$$

where $s = A$ and $p = |\,\mathbf{p}_f\,| B/(E_f + m_f)$; here E_f and $\mathbf{p}_f$ are the energy and momentum of the final baryon. The parameters α, β, and γ satisfy

$$\alpha^2 + \beta^2 + \gamma^2 = 1 \ .$$

If the hyperon polarization is $\mathbf{P}_Y$, the polarization $\mathbf{P}_B$ of the decay baryons is

$$\mathbf{P}_B = \frac{(\alpha + \mathbf{P}_Y \cdot \widehat{\mathbf{n}})\widehat{\mathbf{n}} + \beta(\mathbf{P}_Y \times \widehat{\mathbf{n}}) + \gamma \widehat{\mathbf{n}} \times (\mathbf{P}_Y \times \widehat{\mathbf{n}})}{1 + \alpha \mathbf{P}_Y \cdot \widehat{\mathbf{n}}} \ .$$

Here $\mathbf{P}_B$ is defined in the rest system of the baryon, obtained by a Lorentz transformation along $\widehat{\mathbf{n}}$ from the hyperon rest frame, in which $\widehat{\mathbf{n}}$ and $\mathbf{P}_Y$ are defined.

An additional useful parameter ϕ is defined by

$$\beta = (1 - \alpha^2)^{1/2} \sin\phi \ .$$

In the Listings, we compile α and ϕ for each decay, since these quantities are most closely related to experiment and are essentially uncorrelated. When necessary, we have changed the signs of reported values to agree with our sign conventions. In the Baryon Summary Table, we give α, ϕ, and Δ (defined below) with errors, and also give the value of γ without error.

Time-reversal invariance requires, in the absence of final-state interactions, that s and p be relatively real, and therefore that $\beta = 0$. However, for the decays discussed here, the final-state interaction is strong. Thus

$$s = |\,s\,| \, e^{i\delta_s} \text{ and } p = |\,p\,| \, e^{i\delta_p} \ ,$$

where δ_s and δ_p are the pion-baryon s- and p-wave strong interaction phase shifts. We then have

$$\beta = \frac{-2\,|\,s\,|\,|\,p\,|}{|\,s\,|^2 + |\,p\,|^2} \sin(\delta_s - \delta_p) \ .$$

One also defines $\Delta = -\tan^{-1}(\beta/\alpha)$. If T invariance holds, $\Delta = \delta_s - \delta_p$. For $\Lambda \to p\pi^-$ decay, the value of Δ may be compared with the s- and p-wave phase shifts in low-energy $\pi^- p$ scattering, and the results are consistent with T invariance.

References

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2. N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963).
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$n \to p e^- \nu$ DECAY PARAMETERS

See the above Note on Baryon Decay Parameters. For discussions of recent results, see the references cited at the beginning of the section on the neutron mean life. For discussions of the values of the weak coupling constants g_A and g_V obtained using the neutron and asymmetry parameter A, comparisons with other methods of obtaining these constants, and implications for particle and astrophysics, see DUBBERS 91 and WOOLCOCK 91. For tests of the $V{-}A$ theory of neutron decay, see EROZOLIMSKII 91B.

g_A / g_V

VALUE	DOCUMENT ID		TECN	COMMENT
−1.2573±0.0028 OUR AVERAGE				
−1.2544±0.0036	EROZOLIM...	91	CNTR	*e* mom-*n* spin corr.
−1.262 ±0.005	BOPP	86	SPEC	*e* mom-*n* spin corr.
−1.261 ±0.012	[11] EROZOLIM...	79	CNTR	*e* mom-*n* spin corr.
−1.259 ±0.017	[11] STRATOWA	78	CNTR	proton recoil spectrum
−1.258 ±0.015	[12] KROHN	75	CNTR	*e* mom-*n* spin corr.

• • • We do not use the following data for averages, fits, limits, etc. • • •

−1.226 ±0.042	MOSTOVOY	83	RVUE	
−1.263 ±0.015	EROZOLIM...	77	CNTR	See EROZOLIMSKII 79
−1.250 ±0.036	[11] DOBROZE...	75	CNTR	See STRATOWA 78
−1.263 ±0.016	[13] KROPF	74	RVUE	*n* decay alone
−1.250 ±0.009	[13] KROPF	74	RVUE	*n* decay + nuclear ft

[11] These experiments measure the absolute value of g_A/g_V only.
[12] KROHN 75 includes events of CHRISTENSEN 70.
[13] KROPF 74 reviews all data through 1972.

β ASYMMETRY PARAMETER *A*

This is the neutron-spin electron-momentum correlation coefficient. Unless otherwise noted, the values are corrected for radiative effects and weak magnetism.

VALUE	DOCUMENT ID		TECN
−0.1127±0.0011 OUR AVERAGE			
−0.1116±0.0014	EROZOLIM...	91	CNTR
−0.1146±0.0019	BOPP	86	SPEC
−0.114 ±0.005	[14] EROZOLIM...	79	CNTR
−0.113 ±0.006	[14] KROHN	75	CNTR

[14] These results are not corrected for radiative effects and weak magnetism, but the corrections are small compared to the errors.

$\bar{\nu}$ ASYMMETRY PARAMETER *B*

This is the neutron-spin antineutrino-momentum correlation coefficient.

VALUE	DOCUMENT ID		TECN
0.997±0.028 OUR AVERAGE			
0.995±0.034	CHRISTENSEN	70	CNTR
1.00 ±0.05	EROZOLIM...	70C	CNTR

e-$\bar{\nu}$ ANGULAR CORRELATION COEFFICIENT *a*

VALUE	DOCUMENT ID		TECN	COMMENT
−0.102 ±0.005 OUR AVERAGE				
−0.1017±0.0051	STRATOWA	78	CNTR	Proton recoil spectrum
−0.091 ±0.039	GRIGOREV	68	SPEC	Proton recoil spectrum

ϕ_{AV}, PHASE ANGLE OF g_A RELATIVE TO g_V

Time reversal invariance requires this to be 0 or 180°.

VALUE (°)	DOCUMENT ID		TECN	COMMENT
180.07±0.18 OUR EVALUATION	Using the average value for quantity *D* given in the next data block and $\lambda \equiv g_A/g_V$ in $\sin\phi_{AV} = D(1+3\lambda^2)/2\lambda$.			
180.09±0.18 OUR AVERAGE				
179.71±0.39	EROZOLIM...	78	CNTR	Polarized neutrons
180.35±0.43	EROZOLIM...	74	CNTR	Polarized neutrons
180.14±0.22	STEINBERG	74	CNTR	Polarized neutrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
181.1 ±1.3	[15] KROPF	74	RVUE	*n* decay

[15] KROPF 74 reviews all data through 1972.

TRIPLE CORRELATION COEFFICIENT *D*

These are measurements of the component of *n* spin perpendicular to the decay plane in *β* decay. Should be zero if *T* invariance is not violated.

VALUE	DOCUMENT ID		TECN	COMMENT
(−0.5 ±1.4) × 10^{-3} OUR AVERAGE				
+ 0.0022±0.0030	EROZOLIM...	78	CNTR	Polarized neutrons
− 0.0027±0.0050	[16] EROZOLIM...	74	CNTR	Polarized neutrons
− 0.0011±0.0017	STEINBERG	74	CNTR	Polarized neutrons

[16] EROZOLIMSKII 78 says asymmetric proton losses and nonuniform beam polarization may give a systematic error up to 0.003, thus increasing the EROZOLIMSKII 74 error to 0.005. STEINBERG 74 and STEINBERG 76 estimate these systematic errors to be insignificant in their experiment.

REFERENCES FOR *n*

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1986 edition (Physics Letters **170B** (1986)) or in earlier editions.

SCHRECK... 92 JP G18 1 Schreckenbach, Mampe (ILLG)
ALBERICO 91 NP A523 488 +de Pace, Pignone (TORI)
DUBBERS 91 NP A527 239c (ILLG)
Also 90 EPL 11 195 Dubbers, Mampe, Doehner (ILLG, HEID)
EROZOLIM... 91 PL B263 33 Erozolimskii, Kuznetsov, Stepanenko, Kuida+ (LENI, KIAE)
Also 90 SJNP 52 999 Erozolimskii, Kuznetsov, Stepanenko, Kuida+ (LENI, KIAE)
Translated from YAF 52 1583.
EROZOLIM... 91B SJNP 53 260 Erozolimskii, Mostovoi (KIAE)
Translated from YAF 53 418.
SCHMIEDM... 91 PRL 66 1015 Schmiedmayer, Riehs, Harvey, Hill (TUW, ORNL)
WOOLCOCK 91 MPL A6 2579 (CANB)
ALFIMENKOV 90 JETPL 52 373 +Varlamov, Vasil'ev, Gudkov+ (LENI, JINR)
Translated from ZETFP 52 984.
BALDO-... 90 PL B236 95 Baldo-Ceolin, Benetti, Bitter+ (PADO, PAVI, HEID, ILLG)
BERGER 90 PL B240 237 +Froehlich, Moench, Nisius+ (FREJUS Collab.)
BRESSI 90 NC 103A 731 +Calligarich, Cambiaghi+ (PAVI, ROMA, MILA)
BYRNE 90 PRL 65 289 +Dawber, Spain, Williams+ (SUSS, NBS, SCOT, CBNM)
FREEDMAN 90 CNPP 19 209 (ANL)
GREEN 90 JP G16 L75 +Thompson (RAL)
RAMSEY 90 ARNPS 40 1 (HARV)
ROSE 90 PL B234 460 +Zurmuehl, Rullhusen, Ludwig+ (GOET, MPCM, MANZ)
ROSE 90B NP A514 621 +Zurmuehl, Rullhusen, Ludwig+ (GOET, MPCM)
SMITH 90 PL B234 191 +Crampin+ (SUSS, RAL, HARV, WASH, ILLG, MUNT)
BRESSI 89 ZPHY C43 175 +Calligarich, Cambiaghi+ (INFN, MILA, PAVI, ROMA)
DOVER 89 NIM A284 13 +Gal, Richard (BNL, HEBR, ISNG)
EROZOLIM... 89 NIM A284 89 Erozolimskii (LENI)
KOSSAKOW... 89 NP A503 473 Kossakowski, Grivot+ (LAPP, SAVO, ISNG, ILLG)
MAMPE 89 PRL 63 593 +Ageron, Bates, Pendlebury, Steyerl (ILLG, RISL, SUSS, URI)
MOHAPATRA 89 NIM A284 1 (UMD)
PAUL 89 ZPHY C45 25 +Anton, Paul, Paul, Mampe (BONN, WUPP, MPIH, ILLG)
SCHMIEDM... 89 NIM A284 137 Schmiedmayer, Rauch, Riehs (WIEN)
BAUMANN 88 PR D37 3107 +Gaehler, Kalus, Mampe (BAYR, MUNI, ILLG)
KOESTER 88 ZPHY A329 229 +Waschkowski, Meier (MUNI, MUNT)
LAST 88 PRL 60 995 +Arnold, Doehner, Dubbers+ (HEID, ILLG, ANL)
SCHMIEDM... 88 PRL 61 1065 Schmiedmayer, Rauch, Riehs (TUW)
Also 88B PRL 61 2509 erratum Schmiedmayer, Rauch, Riehs (TUW)
SPIVAK 88 JETP 67 1735 (KIAE)
Translated from ZETF 94 1.
COHEN 87 RMP 59 1121 +Taylor (RISC, NBS)
ALTAREV 86 JETPL 44 460 +Borisov, Borovikova, Brandin, Egorov+ (LENI)
Translated from ZETFP 44 360.
BOPP 86 PRL 56 919 +Dubbers, Hornig, Klemt, Last+ (HEID, ANL, ILLG)
Also 88 ZPHY C37 179 Klemt, Bopp, Hornig, Last+ (HEID, ANL, ILLG)
CRESTI 86 PL B177 206 +Pasquali, Peruzzo, Pinori, Sartori (PADO)
Also 88 PL B200 587 errat. Cresti, Pasquali, Peruzzo, Pinori, Sartori (PADO)
GREENE 86 PRL 56 819 +Kessler, Deslattes, Boerner (NBS, ILLG)
KOSVINTSEV 86 JETPL 44 571 +Morozov, Terekhov (KIAE)
Translated from ZETFP 44 444.
PDG 86 PL 170B Aguilar-Benitez, Porter+ (CERN, CIT+)
TAKITA 86 PR D34 902 +Arisaka, Kajita, Kifune, Koshiba+ (KEK, TOKY)
DOVER 85 PR C31 1423 +Gal, Richard (BNL)
FIDECARO 85 PL 156B 122 +Lanceri+ (CERN, ILLG, PADO, RAL, SUSS)
PARK 85B NP B252 261 +Blewitt, Cortez, Foster+ (IMB Collab.)
BATTISTONI 84 PL 133B 454 +Bellotti, Bologna, Campana+ (NUSEX Collab.)
JONES 84 PRL 52 720 +Bionta, Blewitt, Bratton+ (IMB Collab.)
PENDLEBURY 84 PL 136B 327 +Smith, Golub, Byrne+ (SUSS, HARV, RAL, ILLG)
CHERRY 83 PRL 50 1354 +Lande, Lee, Steinberg, Cleveland (PENN, BNL)
DOVER 83 PR D27 1090 +Gal, Richards (BNL)
KABIR 83 PRL 51 231 (HARV)
MOSTOVOY 83 JETPL 37 196 (KIAE)
Translated from ZETFP 37 162.
ROY 83 PR D28 1770 +Vaidya, Ephraim, Datar, Bhatki+ (TATA)
VAIDYA 83 PR D27 486 +Roy, Ephraim, Datar, Bhattacherjee (TATA)
ALBERICO 82 PL 114B 266 +Bottino, Molinari (CERN, TORI)
GAEHLER 82 PR D25 2887 +Kalus, Mampe (BAYR, ILLG)
GREENE 82 Metrologia 18 93 + (YALE, HARV, ILLG, SUSS, ORNL, CENG)
ALTAREV 81 PL 102B 13 +Borisov, Borovikova, Brandin, Egorov+ (LENI)
CHETYRKIN 81 PL 99B 358 +Kazarnovsky, Kuzmin+ (INRM)
COWSIK 81 PL 101B 237 +Nussinov (UMD)
BARABANOV 80 JETPL 32 359 +Veretenkin, Gavrin+ (LENI)
Translated from ZETFP 32 384.
BYRNE 80 PL 92B 274 +Morse, Smith, Shaikh, Green, Greene (SUSS, RL)
KOSVINTSEV 80 JETPL 31 236 +Kushnir, Morozov, Terekhov (JINR)
Translated from ZETFP 31 257.
MOHAPATRA 80 PRL 44 1316 +Marshak (CUNY, VPI)
ALTAREV 79 JETPL 29 730 +Borisov, Brandin, Egorov, Ezhov, Ivanov+ (LENI)
Translated from ZETFP 29 794.
EROZOLIM... 79 SJNP 30 356 Erozolimskii, Frank, Mostovoy+ (KIAE)
Translated from YAF 30 692.
NORMAN 79 PRL 43 1226 +Seamster (WASH)
BONDAREN... 78 JETPL 28 303 Bondarenko, Kurguzov, Prokofev+ (KIAE)
Translated from ZETFP 28 328.
Also 82 Smolenice Conf. Bondarenko (KIAE)
EROZOLIM... 78 SJNP 28 48 Erozolimskii, Mostovoy, Fedunin, Frank+ (KIAE)
Translated from YAF 28 98.
STRATOWA 78 PR D18 3970 +Dobrozemsky, Weinzierl (SEIB)
EROZOLIM... 77 JETPL 23 663 Erozolimskii, Frank, Mostovoy+ (KIAE)
Translated from ZETFP 23 720.
STEINBERG 76 PR D13 2469 +Liaud, Vignon, Hughes (YALE, ISNG)
DOBROZE... 75 PR D11 510 Dobrozemsky, Kerschbaum, Moraw, Paul+ (SEIB)
KROHN 75 PL 55B 175 +Ringo (ANL)
EROZOLIM... 74 JETPL 20 345 Erozolimskii, Mostovoy, Fedunin, Frank+
Translated from ZETFP 20 745.
KROPF 74 ZPHY 267 129 +Paul (LINZ)
Also 70 NP A154 160 Paul (VIEN)
STEINBERG 74 PRL 33 41 +Liaud, Vignon, Hughes (YALE, ISNG)
COHEN 73 JPCRD 2 663 +Taylor (RISC, NBS)
CHRISTENSEN 72 PR D5 1628 +Nielson, Bahnsen, Brown+ (RISO)
CHRISTENSEN 70 PR C1 1693 +Krohn, Ringo (ANL)
EROZOLIM... 70C PL 33B 351 Erozolimskii, Bondarenko, Mostovoy, Obinyakov+ (KIAE)
GRIGOREV 68 SJNP 6 239 Grigor'ev, Grishin, Vladimirsky, Nikolaevskii+ (ITEP)
Translated from YAF 6 329.

NOTE ON *N* AND *Δ* RESONANCES

I. Introduction

(by R.E. Cutkosky, Carnegie-Mellon University and G. Höhler, University of Karlsruhe)

The excited states of the nucleon have been studied in a large number of formation and production experiments. The masses, widths, and elasticities of the N and Δ resonances in the Baryon Summary Table come almost entirely from partial-wave analyses of πN total, elastic, and charge-exchange scattering data (see Sec. II). Partial-wave analyses have also been made of much smaller sets of data to get $N\eta$, ΛK, and ΣK branching fractions. Other branching fractions come from isobar-model analyses of $\pi N \rightarrow N\pi\pi$ data (Sec. III).

Finally, some $N\gamma$ branching fractions have been determined from photoproduction experiments (Sec. IV).

Table 1 lists all the N and Δ entries in the Baryon Listings and gives our evaluation of the status of each, both overall and channel by channel. Only the "established" resonances (overall status 3 or 4 stars) appear in the Baryon Summary Table. We consider a resonance to be established only if it has been seen in at least two independent analyses and the relevant partial-wave amplitudes do not behave erratically or have large errors. The $J^P = 3/2^+$ $\Delta(1600)$, given two stars on the basis of the Karlsruhe-Helsinki (KH)[1] and Carnegie-Mellon/Berkeley (CMB)[2] analyses, has now also been reported by the VPI[3] and Kent State (KSU)[4] analyses. Although the resonance parameters are still not well determined, we have given it a third star and promoted it to the Summary Table. Three one-star resonances listed in our 1990 edition have been dropped from the current Listings because they were not seen in any of these four analyses, and one new one-star resonance has been added.

The Baryon Listings give, in addition to the usual Breit-Wigner parameters, the positions and residues of the poles of the resonant partial waves on the second sheet of the complex energy plane. These come from $\pi N \to \pi N$ partial-wave analysis and from $\pi N \to N\pi\pi$ isobar-model analysis.

Many theorists disregard the fact that the Breit-Wigner resonance parameters we give are different from the quantities they calculate in their models. In quark shell models, for example, the authors usually calculate energies of stable excited states and ignore the mass shifts expected from the strong coupling to the decay channels. It is essential to estimate these mass shifts before making detailed comparisons between the theoretical results and the experimentally determined resonance parameters. Skyrmion or similar models that predict scattering amplitudes are not subject to this difficulty, although at present such models are only able to give qualitative results.

In order to form an independent opinion of the reliability of resonance information, it is necessary to examine the energy dependence of the individual partial-wave amplitudes. Plots of these amplitudes have been omitted from this edition, but they may be found in any of our last few editions. Copies of these plots may also be obtained from the Particle Data Group upon request. Additional discussion of N and Δ resonances may be found in this Note in our 1990 edition,[5] as well as in two earlier extensive reviews,[6,7] and in the proceedings of several recent conferences and workshops on πN physics.[8–12]

New Data: New $\pi^- p$ elastic differential-cross-section and asymmetry measurements from 900 to 2000 MeV/c have recently been reported by two groups at ITEP in Moscow.[13,14] Some preliminary spin-rotation measurements up to 700 MeV/c have been reported from LNPI[15] and LAMPF.[16] These results have been compared with predictions from the CMB and KH analyses, but do not distinguish strongly between them. They have not yet been included in new analyses.

Table 1. The status of the N and Δ resonances. Only those with an overall status of *** or **** are included in the main Baryon Summary Table.

			Status as seen in —						
Particle	$L_{2I\cdot 2J}$	Overall status	$N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$N(939)$	P_{11}	****							
$N(1440)$	P_{11}	****	****	*			***	*	***
$N(1520)$	D_{13}	****	****	*			****	****	****
$N(1535)$	S_{11}	****	****	****			*	**	***
$N(1650)$	S_{11}	****	****	*	***	**	***	**	***
$N(1675)$	D_{15}	****	****	*	*		****	*	***
$N(1680)$	F_{15}	****	****				****	****	****
$N(1700)$	D_{13}	***	***	*	**	*	**	*	**
$N(1710)$	P_{11}	***	***	**	**	*	**	*	***
$N(1720)$	P_{13}	****	****	*	**	*	*	**	*
$N(1900)$	P_{13}	*	*					*	
$N(1990)$	F_{17}	**	**	*	*	*			*
$N(2000)$	F_{15}	**	**	*	*	*	*	**	
$N(2080)$	D_{13}	**	**	*	*				*
$N(2090)$	S_{11}	*	*						
$N(2100)$	P_{11}	*	*						
$N(2190)$	G_{17}	****	****	*	*	*		*	*
$N(2200)$	D_{15}	**	**	*	*				
$N(2220)$	H_{19}	****	****	*					
$N(2250)$	G_{19}	****	****	*					
$N(2600)$	$I_{1\,11}$	***	***						
$N(2700)$	$K_{1\,13}$	**	**						
$\Delta(1232)$	P_{33}	****	****	F					****
$\Delta(1600)$	P_{33}	***	***	o			***	*	**
$\Delta(1620)$	S_{31}	****	****	r			****	****	***
$\Delta(1700)$	D_{33}	****	****	b		*	***	**	***
$\Delta(1900)$	S_{31}	***	***	i		*	*	**	*
$\Delta(1905)$	F_{35}	****	****	d		*	**	**	***
$\Delta(1910)$	P_{31}	****	****	d		*	*	*	*
$\Delta(1920)$	P_{33}	***	***	e		*	**		*
$\Delta(1930)$	D_{35}	***	***	n		*			*
$\Delta(1940)$	D_{33}	*	*	F					
$\Delta(1950)$	F_{37}	****	****	o		*	****	*	***
$\Delta(2000)$	F_{35}	**		r				**	
$\Delta(2150)$	S_{31}	*	*	b					
$\Delta(2200)$	G_{37}	*	*	i					
$\Delta(2300)$	H_{39}	**	**	d					
$\Delta(2350)$	D_{35}	*	*	d					
$\Delta(2390)$	F_{37}	*	*	e					
$\Delta(2400)$	G_{39}	**	**	n					
$\Delta(2420)$	$H_{3\,11}$	****	****						*
$\Delta(2750)$	$I_{3\,13}$	**	**						
$\Delta(2950)$	$K_{3\,15}$	**	**						

**** Existence is certain, and properties are at least fairly well explored.

*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.

** Evidence of existence is only fair.

* Evidence of existence is poor.

In addition, there have been many new experiments at low energies. These are important for the study of threshold and below-threshold amplitudes (as in the σ term) and for the low side of the $\Delta(1232)$, as well as for the dispersion-theory constraints used in analysis at higher energies. Unfortunately, these new experiments are not completely consistent, but show significant discrepancies. Other recent data are discussed in our 1990 edition.[5]

New Analyses: Results of a new πN partial-wave analysis up to 2.2 GeV/c were recently published by the VPI group,[3] with new determinations of resonance parameters. Resonance parameters have also been determined at KSU,[4] by combining results from the analysis of inelastic data with the KH and CMB elastic amplitudes. In the low-energy region, a new partial-wave analysis has been carried out by Bugg.[18]

(References for this Section are at the end of Section II.)

II. Two-body partial-wave analyses and determination of resonance parameters

(by R.E. Cutkosky, Carnegie-Mellon University and G. Höhler, University of Karlsruhe)

πN partial-wave analysis: Even if all measurable πp scattering data were known with high accuracy, it would not be possible to obtain a unique set of partial waves from the data alone, since there is a phase common to the invariant amplitudes at each energy and angle that is not determined. It is essential to add the theoretical constraints of unitarity, isospin invariance, and analyticity. The unitarity constraint along with continuity in energy can sometimes give unique partial waves when the tail of high partial waves is cut off sharply. However, equally good fits can usually be obtained with changes of the small tail coupled with substantial changes in low partial waves.

All analyses use dispersion relation constraints at $\theta = 0$, and the KH[1] and CMB[2] analyses also used dispersion relations for $\theta = \pi$. In addition, KH used fixed-t dispersion relations to help determine the near-forward amplitudes, along with dispersion relations at several fixed c.m. angles, while CMB used dispersion relations along a set of hyperbolic curves in the Mandelstam variables. The VPI[3] group enforces smoothness in energy, but not consistency with nonforward dispersion relations.

In practice, there are always a few high partial waves that are too large to be neglected but too small to be determined accurately from the data. The omission of high partial waves that are "not required" by tests of their statistical significance can often lead to a significant bias, because these waves are associated with meson and baryon exchange processes that add up coherently in forward and backward directions. Calculations of peripheral waves based on Mandelstam analyticity have been made by Koch[19] and used by the KH group. The CMB group also included exchange terms, and used functional-analysis methods to include collective aspects of the peripheral waves and to estimate uncertainties arising from residual model dependence. Other analyses, for example that of the VPI group, have not made use of two-variable analyticity properties, but instead have used simple parametrizations for the energy dependence and generally include fewer partial waves.

The long-range electromagnetic interactions between the pions and nucleons are taken into account explicitly in a partial-wave analysis, and the interference between electromagnetic scattering and the residual strong interaction gives useful phase information at small angles. Analyses that treat kinematic and electromagnetic corrections by the dispersion-relation method of Tromborg *et al.*[20] are the most reliable. These include the KH and CMB analyses, and in part the most recent VPI analysis. The residual interactions do not conserve isospin exactly because the masses of the up and down quarks are not identical and because they interact electromagnetically. These effects are responsible for mass splittings in the baryon octet. However, the only confirmed isospin violation seen directly in quantities observable in scattering experiments occurs in the $\Delta(1232)$ region, where the total cross sections show slightly different masses and widths for the Δ^{++} and Δ^0. This indicates that careful treatment of the scattering amplitudes will be needed in order to search for additional isospin-breaking effects.

In the region above 800 MeV/c, there are sizeable differences between the KH, CMB, and VPI analyses, but there has been very little new experimentation. Recently, however, some accurate new data on $\pi^- p$ scattering from Moscow have been compared with the KH and CMB fits.[13,14] At some energies and angles these agree better with KH, and at others with CMB. It is not yet known how much change in the amplitudes will be needed to accomodate these data.

Further discussion of the problems of partial-wave analysis and additional references can be found in this Note in our 1990 edition,[5] and in the review by G. Höhler at Bad Honnef.[21]

Determination of resonance parameters: In all existing analyses, the N and Δ resonance parameters have been determined through a two-step process: first, a partial-wave analysis is made of the experimental data, and then resonance parameters are determined from the energy dependence of the amplitudes. Usually, generalized Breit-Wigner formulas are fitted to the amplitudes. In addition to statistical errors, there are systematic errors that depend on the assumptions that go into the parametrization of background terms and the energy dependence of partial widths.

Plots of the energy dependence of the amplitudes show that the resonances are almost never symmetrical. The reason is that angular-momentum barrier-penetration factors and phase-space factors usually increase rapidly with energy. This is taken into account by using Breit-Wigner formulas with energy-dependent widths, $\Gamma(E)$. The quantity we cite as the "width" Γ is the value of $\Gamma(E)$ at the resonance energy $E = M$; it depends on the model used for the energy dependence and on the definition of M. The tabulated elasticities and partial widths have similar meanings. This model dependence is the primary reason for the differences in the parameters quoted by different groups. In our estimates of resonance parameters, we have tried to include in the uncertainties an estimate of these systematic errors.

To determine resonance parameters, the CMB[2] group used a relatively complicated multichannel coupled-resonance scheme and included data on inelastic channels. Their fits to partial-wave amplitudes covered an extended energy range which included all the resonances. The KH group[1] did not include inelastic data, and confined their fitting to the immediate vicinity of a given resonance. The recent KSU resonance study[4] used a scheme that fit the entire energy region, and also used results from a more recent fit to inelastic data by Manley *et al.*[22] for the elastic amplitudes, an average of the KH and CMB values was used. However, the KSU parametrization approximated the analyticity structure. The VPI group[3] used a coupled-channel K-matrix formalism, and did not attempt to build in the desired global analyticity properties. With a few exceptions, these different analyses agree on the existence of N and Δ resonances with specific values of J^P in a given energy region, but they often disagree on the masses, widths, and elasticities. There are also uncertainties about the existence of resonances with low angular momenta at the higher energies. The $1/2^+ N(1710)$ was not seen in earlier work by VPI, but has shown up weakly in their most recent study. In the KSU analysis, several new resonances were proposed. Two of these have lower energies than previously-established prominent resonances in the same partial waves. To decide whether these are real or artifacts, further study will be needed.

Resonance poles: In Table 2, positions and residues are given for the poles of partial-wave amplitudes corresponding to prominent resonances. In general, these are somewhat less model dependent than other resonance parameters; see for example the recent discussion by Sirlin of the Z^0 resonance.[23] It is generally considered, however, even in the case of the Z^0, that appropriately defined conventional parameters are easier to understand and to compare with model calculations. The energy dependence of the width displaces the real part of the pole position from the nominal resonance energy M, and the imaginary part is different from $-i\Gamma/2$. However, there is no simple unique way to compensate for these effects in relating M and Γ to the pole. For a very narrow resonance, the modulus of the residue gives the elastic partial width: $|r| = \frac{1}{2}x\Gamma$, where x is the elasticity, but this is only an approximation for actual N and Δ resonances. The phase of r is given by the background amplitude, and describes the orientation of the resonance loop in the Argand diagram.

A special situation arises when a resonance is located near the threshold of an inelastic channel that is strongly coupled to the πN system. For example, the $\Delta\pi$ threshold is near the $1/2^+ N(1440)$, and the $N\eta$ threshold is near the $1/2^- N(1535)$. In these cases, a resonance is usually associated with poles on more than one sheet of the Riemann surface. We have listed only the pole nearest the first sheet, which contains the physical region. This is the one that can be determined most reliably

Table 2. Determinations of pole parameters of 3- and 4-star N and Δ resonances for the pole reached most directly from the physical region.

	Pole position (MeV)		Residue		
Resonance	ReW	$-2\times$ImW	$\|r\|$ (MeV)	θ (°)	Ref.†
$N(1440)P_{11}$	1375 ± 30	180 ± 40	52 ± 5	-100 ± 35	C
	1360	252	109	-93	A
$N(1520)D_{13}$	1510 ± 5	114 ± 10	35 ± 2	-12 ± 5	C
	1511	108	33	-10	A
$N(1535)S_{11}$	1510 ± 50	260 ± 80	120 ± 40	$+15 \pm 45$	C
	1499	110	23	-13	A
$N(1650)S_{11}$	1640 ± 20	150 ± 30	60 ± 10	-75 ± 25	C
	1657	160	54	-38	A
$N(1675)D_{15}$	1660 ± 10	140 ± 10	31 ± 5	-30 ± 10	C
	1655	124	28	-17	A
$N(1680)F_{15}$	1667 ± 5	110 ± 10	34 ± 2	-25 ± 5	C
	1670	116	37	-14	A
$N(1700)D_{13}$	1660 ± 30	90 ± 40	6 ± 3	0 ± 50	C
	(pole not seen)				A
$N(1710)P_{11}$	1690 ± 20	80 ± 20	8 ± 2	$+175 \pm 35$	C
	1636	542	149	$+149$	A
$N(1720)P_{13}$	1680 ± 30	120 ± 40	8 ± 2	-160 ± 30	C
	1675	114	11	-130	A
$N(2190)G_{17}$	2100 ± 50	400 ± 160	25 ± 10	-30 ± 50	C
	2060	464	54	-44	A
$N(2220)H_{19}$	2160 ± 80	480 ± 100	45 ± 20	-45 ± 25	C
	2253	640	85	-62	A
$N(2250)G_{19}$	2150 ± 50	360 ± 100	20 ± 6	-50 ± 20	C
	2243	650	47	-37	A
$\Delta(1232)P_{33}$	1210 ± 1	100 ± 2	53 ± 2	-47 ± 1	C
	1210	100	52	-31	A
$\Delta(1600)P_{33}$	1550 ± 40	200 ± 60	17 ± 4	—	C
	1612	230	16	-73	A
$\Delta(1620)S_{31}$	1600 ± 15	120 ± 20	15 ± 2	-110 ± 20	C
	1587	120	15	-125	A
$\Delta(1700)D_{33}$	1675 ± 25	220 ± 40	13 ± 3	-20 ± 25	C
	1646	208	13	-22	A
$\Delta(1900)S_{31}$	1870 ± 40	180 ± 50	10 ± 3	$+20 \pm 40$	C
	(pole not seen)				A
$\Delta(1905)F_{35}$	1830 ± 40	280 ± 60	25 ± 8	-50 ± 20	C
	1794	230	14	-40	A
$\Delta(1910)P_{31}$	1880 ± 30	200 ± 40	20 ± 4	-90 ± 30	C
	1950	398	37	-91	A
$\Delta(1920)P_{33}$	1900 ± 80	300 ± 100	24 ± 4	-150 ± 30	C
	(pole not seen)				A
$\Delta(1930)D_{35}$	1890 ± 50	260 ± 60	18 ± 6	-20 ± 40	C
	2018	398	15	-24	A
$\Delta(1950)F_{37}$	1890 ± 15	260 ± 40	50 ± 7	-33 ± 8	C
	1884	238	61	-23	A
$\Delta(2420)H_{3\,11}$	2360 ± 100	420 ± 100	18 ± 6	-30 ± 40	C

† C = Cutkosky *et al.*,[2] A = Arndt *et al.* (solution SM90).[3]

from the data, although the others can be of interest for dynamical models of the resonance. A detailed comparison of the poles of the CMB and VPI amplitudes for the P_{11} partial wave was recently made by Cutkosky and Wang.[24]

Remarkably, there exist families of resonances in which the pole positions are the same within errors. For example, there are six isospin-1/2 resonances with a pole near $\sqrt{s}$ = (1665–60i) MeV, and also six isospin-3/2 resonances with a pole near (1880–120i) MeV. If this is not just an artifact of the analyses, it may arise from the fact that these energies also correspond to clusterings of the branch points associated with openings of two-body and quasi-two-body inelastic channels.

Inelastic two-body reactions: Analyses of the reactions $\pi N \rightarrow N\eta$, $\pi N \rightarrow \Lambda K$, and $\pi N \rightarrow \Sigma K$ are similar to analyses of the elastic channel. However, the data are far less complete and accurate, and special energy-dependent parametrizations must be used.

The best results, giving resonance masses and widths as well as couplings, follow from the $\pi^- p \rightarrow \Lambda K^0$ data of the Rutherford group, using models for the nonresonant and high partial waves.[25,26] In general, agreement with the $\pi N \rightarrow \pi N$ analyses was good, but there were differences in the $5/2^- N(1675)$ and $1/2^+ N(1710)$ widths and the $5/2^- N(2200)$ mass. In an analysis of $\pi^- p \rightarrow n\eta$ data, partial waves were parametrized as Breit-Wigner resonances without background.[27] The resonance spectrum was taken from the $\pi N \rightarrow \pi N$ analyses, and the data were used to determine the $n\eta$ couplings. A similar analysis of data on $\pi^+ p \rightarrow \Sigma^+ K^+$ saw all the resonances with two or more stars, but did not support any of the one-star states.[28] However, recent new data on $\pi^+ p \rightarrow \Sigma^+ K^+$ polarization parameters[29] from 1.49 to 2.069 GeV/c and spin-rotation parameters[30] at 1.69 and 1.88 GeV/c showed some disagreements with the predictions of this analysis.

Low energy parameters: From partial-wave analyses, it is also possible to learn about other quantities that are of fundamental importance for the structure of nucleons. Gasser *et al.*[31] have evaluated the πN amplitude at the Cheng-Dashen point $t = 2m_\pi^2$ and obtained $\Sigma = 60 \pm 7$ MeV. This agrees with earlier work, for example that of Koch.[32] They also showed that this value is consistent with their value σ = 45 MeV for the σ commutator at $t = 0$ and a small $s\bar{s}$ content in the nucleon. The reason is that the scalar form factor of the nucleon has a strong t-dependence. This structure has been confirmed by Pearce *et al.*[33]

There has recently been much renewed interest in the value of the pion-nucleon coupling constant. Koch and Pietarinen[34] determined the value $f_\pm^2 = 0.079 \pm 0.001$ using πN dispersion relations and amplitudes from the KH partial-wave analysis. More recently, Arndt *et al.*[35] obtained $f_\pm^2 = 0.0735 \pm 0.0015$ using the VPI amplitudes. These results have been reexamined critically by Höhler,[36] who concluded that both error estimates were too small. In particular, there are inconsistencies in the extrapolation to the nucleon pole by Arndt *et al.*, as noted also by Stahov *et al.*[37] It should be noted that the value 0.079 had been used by both CMB and KH in their dispersion-relation constraints.

By analysis of low-energy pp scattering, Bergervoet *et al.*[38] obtained $f_{0p}^2 = 0.0749 \pm 0.0007$, and by analysis of $p\bar{p}$ scattering, Timmermans *et al.*[39] obtained $f_\pm^2 = 0.0751 \pm 0.0017$. The error estimates have been questioned by Holinde and Thomas,[40] because the scattering data exist for $t < 0$ and the method of extrapolation to $t = m_\pi^2$ is not clearly defined. Additional independent work on this question would be useful.

We suggest that at this time f^2 is known with an accuracy of about 3%, and that at this level there is no evidence for isospin splitting or for inconsistency between the pole terms in the πN and NN amplitudes. With further effort, it should be possible to attain an accuracy of 1%.

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III. The $\pi N \rightarrow N\pi\pi$ reaction

(by D.M. Manley, Kent State University)

Partial-wave amplitudes for quasi-2-body scattering reactions, such as $\pi N \rightarrow \Delta\pi$ and $\pi N \rightarrow N\rho$. are extracted by using isobar models to analyze data for the $\pi N \rightarrow N\pi\pi$ reaction. The Listings include results from several analyses, summarized below. There are several new results on quasi-2-body branching fractions for this edition.

The first major isobar-model analysis was performed by a Berkeley-SLAC collaboration and included 170,000 events in the center-of-mass (c.m.) energy range 1300 to 1990 MeV.[1] Resonant amplitudes were initially estimated from eyeball fits of circles to the Argand amplitudes.[2] The next major independent isobar-model analysis was performed at Saclay and included 91,000 events in the c.m. energy range 1360 to 1760 MeV.[3] Resonance parameters were estimated from a T matrix, which was derived from a unitary, multichannel K-matrix parametrization of the amplitudes.[4] Resonance parameters were later estimated from the Berkeley-SLAC amplitudes[1] using basically the same procedure.[5] A third major analysis was performed at Imperial College and included 44,000 π^+p events between 1400 and 1700 MeV.[6] Resonant amplitudes for Δ resonances were estimated using the method described in Ref. 2. The most recent major isobar-model analysis was performed at VPI&SU and included 241,000 events between 1320 and 1930 MeV.[7] Further details of these analyses can be found in our previous editions.

Since the last edition, new multichannel fits of the P_{11} amplitudes were performed by Cutkosky and Wang.[8] Their work addressed a controversial feature of the 1985 VPI partial-wave analysis,[9] which found two nearly degenerate poles in the vicinity of the established Roper resonance. Cutkosky and Wang found two resonances, near 1470 and 1700 MeV, and concluded that the double pole found by the VPI group was essentially an artifact of the parametrization used. The resonance structure in this wave near 1700 MeV has also been a subject of recent controversy.[10,11]

In 1991, a new multichannel, multiresonance analysis[10] of the VPI isobar-model amplitudes[7] was completed at Kent State University (KSU). The main purpose of this analysis was to extract new information on inelastic couplings. Conventional resonance parameters were determined by using a unitary, time-reversal-invariant parametrization of the S matrix. The masses and total widths generally agree very well with the results of the earlier Carnegie Mellon-Berkeley analysis.[12] When compared with results of previous inelastic analyses,[4–6] there is generally good agreement for the signs and magnitudes of $\Delta\pi$ couplings but poor agreement for the smaller $N\rho$ couplings. The KSU analysis found some evidence for new resonances, including a P_{13} state at 1879 ± 17 MeV, a P_{31} state at 1744 ± 36 MeV, and an F_{35} state at 1752 ± 32 MeV. Only weak evidence was found for the rather inelastic established D_{13}, P_{11}, and P_{13} resonances with masses near 1700 MeV. There is especially good agreement among all analyses for the masses, widths, and inelastic couplings of the $D_{13}(1520)$, $D_{15}(1675)$, $F_{15}(1680)$, and $F_{37}(1950)$. Results of the new KSU analysis are included in the Listings.

It is worth noting that several new measurements on the $\pi N \rightarrow N\pi\pi$ reaction have been performed in recent years.[13] These measurements were performed near threshold for the purpose of studying chiral-symmetry-breaking terms in the low-energy $\pi\pi$ and πN systems; consequently, they do not contribute directly to our understanding of the resonance structure of the πN system. Burkhardt and Lowe recently performed a new global analysis of all available $\pi N \rightarrow N\pi\pi$ data near threshold.[14]

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IV. Electromagnetic interactions

(by R.L. Crawford, University of Glasgow)

Nearly all the entries in the Listings relating to electromagnetic properties of the N and Δ resonances are couplings for decay to $N\gamma$. These have been obtained mainly from partial-wave analyses of pion photoproduction, but there are also results from analyses of proton Compton scattering and of $\gamma p \to \Lambda K$.

Pion photoproduction: The $N\gamma$ couplings of the N and Δ resonances have been obtained in a large number of partial-wave analyses of single-pion photoproduction, $\gamma N \to \pi N$, on protons and neutrons. The couplings, $A_{1/2}$ and $A_{3/2}$, are related to the helicity amplitudes of the process, $A_{\ell\pm}$ and $B_{\ell\pm}$, by

$$A_{\ell\pm} = \mp\alpha\, C_{N\pi}\, A_{1/2}$$
$$B_{\ell\pm} = \pm 4\alpha[(2J-1)(2J+3)]^{-1/2}\, C_{N\pi}\, A_{3/2}\ ,$$

where

$$\alpha \equiv \left[\frac{1}{\pi}\frac{k}{q}\frac{1}{(2J+1)}\frac{M_N}{M_R}\frac{\Gamma_\pi}{\Gamma^2}\right]^{1/2} .$$

Here k and q are the photon and pion c.m. momenta; J is the angular momentum, M_R the mass, Γ the full width, and Γ_π the $N\pi$ partial width of the resonance; M_N is the nucleon mass; and $C_{N\pi}$ is the Clebsch-Gordan coefficient for the decay of the resonance into the relevant $N\pi$ charge state.

The large amount of pion photoproduction data, including many measurements from single and double polarization experiments, has permitted an accurate evaluation of the couplings for many of the resonances with masses below 2 GeV, and has given at least qualitative information about most of the others. However, most photoproduction analyses rely heavily upon $\pi N \to \pi N$ analyses for information on the existence, masses, and widths of the resonances. The only photoproduction analyses that give masses and widths as well as couplings are BERENDS 75, BERENDS 77, BARBOUR 78, and CRAWFORD 80. These results are of interest since they concern the charge +1 states of the resonances. In particular, the mass of the $\Delta(1232)^+$ seems to be as well determined as are the masses of the Δ^{++} and Δ^0, obtained from $\pi^+ p$ and $\pi^- p$ scattering.

There are several distinct methods of analysis which contribute to the Listings:

(a) Energy-dependent partial-wave analyses (DPWA)— The simplest version of this form of analysis is the isobar model, in which the partial waves are parametrized as Breit-Wigner resonances plus smooth background. In the Listings, FELLER 76, TAKEDA 80, and BRATASHEVSKIJ 80 are of this type.

The most recent addition to the DPWA is ARNDT 90B, which analyzes data from $\gamma p \to n\pi^+$, $\gamma p \to p\pi^0$, $\gamma n \to p\pi^-$, $\gamma n \to n\pi^0$, and $\pi^- p \to n\gamma$. Some of these data had not been included in earlier analyses. The parametrization incorporates the elastic πN scattering amplitudes in a form that gives the correct complex phase as required by Watson's theorem if the inelasticity of the πN partial wave is small.

(b) Fixed-t dispersion relations (FTDR)—These analyses parametrize only the imaginary parts of the partial waves, and use fixed-t dispersion relations to obtain the real parts. The Listings contain the results from the FTDR analyses of BARBOUR 80, ARAI 80, FUJII 81, and AWAJI 81.

(c) Energy-independent partial wave analyses (IPWA) — These fit experimental data at a set of single energies. The Listings now contain the results of BERENDS 77, CRAWFORD 83, and ARNDT 90B. Only the first is completely independent of other analyses. CRAWFORD 83 and ARNDT 90, respectively, use the partial waves from the FTDR of CRAWFORD 80 and from the DPWA of ARNDT 90B in order to get unique solutions. Their results are therefore not entirely independent of energy-dependent analyses.

(d) Other analyses—NOELLE 78 is a hybrid analysis, which uses FTDR in a coupled-channel calculation.

A more detailed description of these methods may be found in our 1982 edition.[1]

Compton scattering: Two analyses, ISHII 80 and WADA 84, contribute measurements of the couplings obtained from Compton scattering on protons. Both are isobar analyses. In general, there is good agreement with results from photoproduction. The differences should not be taken seriously since the quality and quantity of the photoproduction data are much better and constrain the values of the couplings more strongly than do the Compton scattering data.

Resonance couplings in the Listings: The Listings omit a number of analyses that are now obsolete. Most of the older results may be found in our 1982 edition.[1]

The errors quoted for the couplings in the Listings are calculated in different ways in different analyses and therefore should be used with care. In general, it is likely that the systematic differences between the analyses caused by using different parametrization schemes are more indicative of the true uncertainties than are the quoted errors.

Probably the most reliable analyses are those from Glasgow (BARBOUR 78, CRAWFORD 80, and CRAWFORD 83) those based on the Tokyo analysis (ARAI 80, FUJII 81, and AWAJI 81), and the recent VPI analyses (ARNDT 90B).

Table 3 gives a compilation of the couplings extracted from the values quoted in these analyses. The errors given are a combination of the statistical errors quoted in these analyses and of the systematic differences between them.

Two values are quoted for the $A_{1/2}$ coupling of the $\Delta(1620)\,S_{31}$ to take account of the surprisingly large spread in values obtained for it. The reason for this seems to be the different treatments of the imaginary background in this partial wave. The second value given uses only the Glasgow analyses. These have significant amounts of nonresonant imaginary background but have always succeeded in getting stable and acceptable values for the resonance mass and width from the photoproduction data. This suggests that the resonance is being fitted by the analyses and, therefore, that the couplings obtained are reliable.

$N\gamma$ branching fractions: The Baryon Summary Table gives $N\gamma$ branching fractions for those resonances whose couplings are considered to have an unambiguous sign. The $N\gamma$ partial width Γ_γ is given by

$$\Gamma_\gamma = \frac{k^2}{\pi}\frac{2M_N}{(2J+1)M_R}\left[\,|A_{1/2}|^2 + |A_{3/2}|^2\right] ,$$

where M_N and M_R are the masses of the nucleon and the resonance, J is the resonance spin, and k is the photon c.m. decay momentum. The couplings $A_{1/2}$ and $A_{3/2}$ are taken from Table 3.

The E2/M1 ratio for the $\Delta(1232)$: The Listings contain a new result for the E2/M1 ratio for the $\Delta(1232)\,P_{33}$ resonance: DAVIDSON 90 extracts the K-matrix residues for the M_{1+} and E_{1+} partial waves using data from several energy-independent analyses[2−7] of photoproduction in the first resonance region. The value quoted in the Listings is their average over the various fits. TANABE 85 and DAVIDSON 86 are also the results of fits to energy-independent analyses. PDG 86 uses the ratio (Im E_{1+})/(Im M_{1+}) averaged over the values given by the energy-dependent analyses in the Listings.

Table 3. A compilation of measured $N\gamma$ decay couplings. Sources are given in the text.

(a) Proton-target couplings

Resonance	Helicity	Couplings ($\text{GeV}^{-1/2} \times 10^{-3}$)	Status
$N(1440)P_{11}$	1/2	-68 ± 5	good
$N(1520)D_{13}$	1/2	-23 ± 9	good
	3/2	$+163 \pm 8$	good
$N(1535)S_{11}$	1/2	$+74 \pm 11$	good
$N(1650)S_{11}$	1/2	$+48 \pm 16$	good
$N(1675)D_{15}$	1/2	$+19 \pm 12$	good, nonzero
	3/2	$+19 \pm 12$	good, nonzero
$N(1680)F_{15}$	1/2	-17 ± 10	good, nonzero
	3/2	$+127 \pm 12$	good
$N(1700)D_{13}$	1/2	-22 ± 13	good, small
	3/2	0 ± 19	fair, small
$N(1710)P_{11}$	1/2	$+5 \pm 16$	fair, small
$N(1720)P_{13}$	1/2	$+52 \pm 39$	poor
	3/2	-35 ± 24	fair
$N(1990)F_{17}$	1/2	$+24 \pm 30$	poor
	3/2	$+31 \pm 55$	bad
$\Delta(1232)P_{33}$	1/2	-141 ± 5	very good
	3/2	-258 ± 12	very good
$\Delta(1600)P_{33}$	1/2	-20 ± 29	poor, small
	3/2	$+1 \pm 22$	fair, small
$\Delta(1620)S_{31}$	1/2	$+19 \pm 16$	fair
	(1/2	$+30 \pm 10$	good — see text)
$\Delta(1700)D_{33}$	1/2	$+116 \pm 17$	good
	3/2	$+77 \pm 28$	fair
$\Delta(1900)S_{31}$	1/2	$+10 \pm ?$	?
$\Delta(1905)F_{35}$	1/2	$+27 \pm 13$	good
	3/2	-47 ± 19	fair
$\Delta(1910)P_{31}$	1/2	-12 ± 30	poor
$\Delta(1920)P_{33}$	1/2	$+40 \pm ?$	?
	3/2	$+23 \pm ?$	?
$\Delta(1930)D_{35}$	1/2	-30 ± 40	poor
	3/2	-10 ± 35	poor
$\Delta(1950)F_{37}$	1/2	-73 ± 14	good
	3/2	-90 ± 13	good

(continued)

(b) Neutron-target couplings

Resonance	Helicity	Couplings ($GeV^{-1/2} \times 10^{-3}$)	Status
$N(1440)P_{11}$	1/2	$+39 \pm 15$	fair
$N(1520)D_{13}$	1/2	-64 ± 8	good
	3/2	-141 ± 11	good
$N(1535)S_{11}$	1/2	-72 ± 25	fair
$N(1650)S_{11}$	1/2	-17 ± 37	poor
$N(1675)D_{15}$	1/2	-47 ± 23	fair
	3/2	-69 ± 19	fair
$N(1680)F_{15}$	1/2	$+31 \pm 13$	good
	3/2	-30 ± 14	good
$N(1700)D_{13}$	1/2	0 ± 56	bad
	3/2	-2 ± 44	bad
$N(1710)P_{11}$	1/2	-5 ± 23	fair, small
$N(1720)P_{13}$	1/2	-2 ± 26	fair, small
	3/2	-43 ± 94	very bad
$N(1990)F_{17}$	1/2	-49 ± 45	poor
	3/2	-122 ± 55	poor

***KΛ* photoproduction:** The Listings give the results from TANABE 89, an isobar analysis of $\gamma p \to \Lambda K^+$. It includes resonances that have a non-negligible branching ratio to ΛK^+. The isobar contributions to the electric and magnetic multipoles are parametrized in the form

$$M_{\ell\pm} = \left\{ \frac{1}{k_R\, q_R\, \ell(\ell+1)} \frac{v_\ell(qR)}{v_\ell(q_R R)} \right\}^{1/2} \times \frac{M_R\, \Gamma\, \sqrt{X_P X_K}\, \exp(i\theta)}{(M_R^2 - s - iM_R\Gamma)}$$

$$E_{\ell\pm} = \left\{ \frac{1}{k_R\, q_R\, (\ell \pm 1)(\ell \pm 1 + 1)} \frac{v_\ell(qR)}{v_\ell(q_R R)} \right\}^{1/2} \times \frac{M_R\, \Gamma\, \sqrt{X_P X_K}\, \exp(i\theta)}{(M_R^2 - s - iM_R\Gamma)} .$$

Here k and q are the photon and kaon momenta, X_P and X_K are the branching ratios to γp and ΛK^+, $v_\ell(qR)$ is a barrier penetration factor, and θ is a phase angle. The Listings give $\sqrt{X_P X_K}$ and the phase angle θ.

***Magnetic moment of the Δ(1232) P_{33}*:** The Listings now contain several measurements of the magnetic moment μ_Δ of the $\Delta(1232)^{++}$ from analyses of pion bremsstrahlung, $\pi^+ p \to \gamma \pi^+ p$. NEFKENS 78 is an analysis of UCLA data for pion bremsstrahlung that uses the soft pion model of Pascual and Tarrach.[8] HELLER 87 is a fit to the same data using a nonrelativistic dynamical model that measures the magnetic moment of the "bare" $\Delta(1232)^{++}$. LIN 91B fits the data of NEFKENS 87 and from SIN[9] with an amplitude that includes the anomalous magnetic moment of the $\Delta(1232)$ and is relativistic, gauge invariant, and consistent with the soft photon theorem. The quantity measured is not identical to the "bare" magnetic moment since it does not take into account the effect of loop contributions. BOSSHARD 91 measured the polarized target asymmetry in pion-proton bremsstrahlung and fit it using the model of HELLER 87. The geometry of the experiment was chosen to maximize the sensitivity to μ_Δ.

The experimental values for μ_Δ may be compared with the prediction of SU(6), $\mu_\Delta = 2\mu_p = 5.58\,\mu_N$; with a modified SU(6) model with mass corrections,[10] $\mu_\Delta = (m_p/M_\Delta)\mu_p = 4.25\,\mu_N$; and with bag model corrections to the quark model,[11] $\mu_\Delta = 4.41$ to $4.89\,\mu_N$.

Electroproduction: The Listings contain no results from meson electroproduction. This is because the main subject of interest there is the behavior of the couplings of the virtual photon and nucleon to N and Δ resonances as the negative $(\text{mass})^2$ of the virtual photon moves from the photoproduction limit of $Q^2 = 0$. Quantitative results, when they exist, are at a wide range of values of Q^2, and it is difficult to incorporate these into the format of the Listings.

An extensive review of electroproduction was given in our 1982 edition.[1] The reader is also referred to the extensive review by Foster and Hughes.[12] Results have been obtained from π^+ electroproduction for the excitation of the $\Delta(1232)\,P_{33}$, for the $[70, 1^-]$ multiplet resonances $N(1520)\,D_{13}$, $N(1535)\,S_{11}$, $N(1650)\,S_{11}$, and $\Delta(1700)\,D_{33}$, and for the $[56, 2^+]$ multiplet resonance, $N(1680)\,F_{15}$. Results for the $N(1520)\,D_{13}$ and $N(1535)\,S_{11}$ have also been obtained from η electroproduction. The most significant results may be found in tables in our 1982 edition.[1] There has been little activity since then, and most more recent results[13,14] have simply confirmed already well-established features of the electroproduction amplitudes.

However, recently Warren and Carlson[15] have analyzed the highest Q^2 data (3.1 GeV^2) for π^0 electroproduction at the $\Delta(1232)$ and claim that, while the data are consistent with the previously accepted result that the M_{1+} multipole is dominant, with $E_{1+}/M_{1+} = 0.05 \pm 0.05$, it is also possible by assuming dominance of the A_{1+} helicity amplitude $(3E_{1+} + M_{1+})/2$, to have another interpretation of the data. They obtain $E_{1+}/M_{1+} = 0.70 \pm 0.09$ with this assumption.

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$N(1440)$ P_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

N(1440) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1430 to 1470 (≈ 1440) OUR ESTIMATE				
1462±10	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1440±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1410±12	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1411	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1472	[1] BAKER	79	DPWA	$\pi^- p \to n\eta$
1417	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1460	BERENDS	77	IPWA	$\gamma N \to \pi N$
1380	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1390	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1440) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
250 to 450 (≈ 350) OUR ESTIMATE				
391±34	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
340±70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
135±10	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
334	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
113	[1] BAKER	79	DPWA	$\pi^- p \to n\eta$
331	BARBOUR	78	DPWA	$\gamma N \to \pi N$
279	BERENDS	77	IPWA	$\gamma N \to \pi N$
200	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
200	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1440) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1360	[4] ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1375±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1359	ARNDT	85	DPWA	See ARNDT 91
1381 or 1379	[5] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1360 or 1333	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
252	[4] ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
180±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
200	ARNDT	85	DPWA	See ARNDT 91
209 or 210	[5] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
167 or 234	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

N(1440) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−6	[4] ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
−9±31	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−109	[4] ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
− 51±7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

N(1440) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	60–70 %
Γ_2	$N\eta$	
Γ_3	$N\pi\pi$	30–40 %
Γ_4	$\Delta\pi$	20–30 %
Γ_5	$\Delta(1232)\pi$, P-wave	
Γ_6	$N\rho$	<10 %
Γ_7	$N\rho$, S=1/2, P-wave	
Γ_8	$N\rho$, S=3/2, P-wave	
Γ_9	$N\ (\pi\pi)^{I=0}_{S\text{-wave}}$	5–15 %
Γ_{10}	$p\gamma$	0.08–0.10 %
Γ_{11}	$p\gamma$, helicity=1/2	
Γ_{12}	$n\gamma$	0.01–0.06 %
Γ_{13}	$n\gamma$, helicity=1/2	

N(1440) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.6 to 0.7 OUR ESTIMATE				
0.69±0.03	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.68±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.51±0.05	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1440) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
seen	[1] BAKER	79	DPWA	$\pi^- p \to n\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.328	[6] FELTESSE	75	DPWA	1488–1745 MeV

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1440) \to \Delta(1232)\pi$, P-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.39±0.02	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
+0.41	[2,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.37	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1440) \to N\rho$, S=1/2, P-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.11	[2,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.23	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1440) \to N\rho$, S=3/2, P-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.18	[2,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1440) \to N\ (\pi\pi)^{I=0}_{S\text{-wave}}$ — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.24±0.03	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
−0.18	[2,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.23	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1440) PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$N(1440) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.066 ±0.017	ARNDT	90B	IPWA	$\gamma N \to \pi N$
−0.069 ±0.018	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.063 ±0.008	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.069 ±0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.066 ±0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.079 ±0.009	BRATASHEV...	80	DPWA	$\gamma N \to \pi N$
−0.068 ±0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.0584±0.0148	ISHII	80	DPWA	Compton scattering
−0.075 ±0.015	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.087 ±0.006	FELLER	76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.064	ARNDT	90B	DPWA	$\gamma N \to \pi N$
−0.129	[8] WADA	84	DPWA	Compton scattering
−0.125	[9] NOELLE	78		$\gamma N \to \pi N$
−0.076	BERENDS	77	IPWA	$\gamma N \to \pi N$

$N(1440) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.050±0.019	ARNDT	90B	IPWA	$\gamma N \to \pi N$
0.037±0.010	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.030±0.003	FUJII	81	DPWA	$\gamma N \to \pi N$
0.023±0.009	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.019±0.012	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.056±0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.029±0.035	TAKEDA	80	DPWA	$\gamma N \to \pi N$
+0.059±0.016	BARBOUR	78	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.045	ARNDT	90B	DPWA	$\gamma N \to \pi N$
0.062	[9] NOELLE	78		$\gamma N \to \pi N$

$N(1440)$ FOOTNOTES

[1] BAKER 79 finds a coupling of the $N(1440)$ to the $N\eta$ channel near (but slightly below) threshold.
[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.
[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.
[4] ARNDT 91 (Soln SM90) also finds a second-sheet pole with real part = 1413 MeV, $-2\times$ imaginary part = 256 MeV, and residue = $(78-153i)$ MeV.
[5] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.
[6] An alternative which cannot be distinguished from this is to have a P_{13} resonance with M = 1530 MeV, Γ = 79 MeV, and elasticity = +0.271.
[7] LONGACRE 77 considers this coupling to be well determined.
[8] WADA 84 is inconsistent with other analyses; see the Note on N and Δ Resonances.
[9] Converted to our conventions using M = 1486 MeV, Γ = 613 MeV from NOELLE 78.

$N(1440)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
ARNDT	90B	PR C42 1864	+Workman, Li, Roper	(VPI)
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(TOKY)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
BRATASHEV...	80	NP B166 525	Bratashevskij, Gorbenko, Derebchinskij+	(KHAR)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
ISHII	80	NP B165 189	+Egawa, Kato, Miyachi+	(KYOT, TOKY)
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOELLE	78	PTP 60 778		(NAGO)
BERENDS	77	NP B136 317	+Donnachie	(LEID, MCHS) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1520)$ D_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(1520)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1515 to 1530 (≈ 1520) OUR ESTIMATE				
1524± 4	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1525±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1519± 4	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1504	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1503	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1510	BERENDS	77	IPWA	$\gamma N \to \pi N$
1510	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1520	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1520)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
110 to 135 (≈ 120) OUR ESTIMATE				
124± 8	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
120±15	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
114± 7	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
124	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
183	BAKER	79	DPWA	$\pi^- p \to n\eta$
135	BARBOUR	78	DPWA	$\gamma N \to \pi N$
105	BERENDS	77	IPWA	$\gamma N \to \pi N$
110	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
150	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1520)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1511	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1510±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1510	ARNDT	85	DPWA	See ARNDT 91
1514 or 1511	[3] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1508 or 1505	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
108	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
114±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
122	ARNDT	85	DPWA	See ARNDT 91
146 or 137	[3] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
109 or 107	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$N(1520)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
32	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
34±2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−6	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
−7±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(1520)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	50–60 %
Γ_2	$N\eta$	≈ 0.1 %
Γ_3	$N\pi\pi$	40–50 %
Γ_4	$\Delta\pi$	15–30 %
Γ_5	$\Delta(1232)\pi$, S-wave	
Γ_6	$\Delta(1232)\pi$, D-wave	
Γ_7	$N\rho$	10–25 %
Γ_8	$N\rho$, S=1/2, D-wave	
Γ_9	$N\rho$, S=3/2, S-wave	
Γ_{10}	$N\rho$, S=3/2, D-wave	
Γ_{11}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<10 %
Γ_{12}	$p\gamma$	0.43–0.57 %
Γ_{13}	$p\gamma$, helicity=1/2	
Γ_{14}	$p\gamma$, helicity=3/2	
Γ_{15}	$n\gamma$	0.34–0.51 %
Γ_{16}	$n\gamma$, helicity=1/2	
Γ_{17}	$n\gamma$, helicity=3/2	

$N(1520)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.5 to 0.6 OUR ESTIMATE				
0.59±0.03	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.58±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.54±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(1520) \rightarrow N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.02	BAKER	79	DPWA	$\pi^- p \rightarrow n\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.011	FELTESSE	75	DPWA	Soln A; see BAKER 79

Note: Signs of couplings from $\pi N \rightarrow N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(1520) \rightarrow \Delta(1232)\pi$, S-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.18 ± 0.05	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
-0.26	[1,4] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
-0.24	[2] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(1520) \rightarrow \Delta(1232)\pi$, D-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.29 ± 0.03	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
-0.21	[1,4] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
-0.30	[2] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(1520) \rightarrow N\rho$, S=3/2, S-wave — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.35 ± 0.03	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
-0.35	[1,4] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
-0.24	[2] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(1520) \rightarrow N(\pi\pi)^{I=0}_{S\text{-wave}}$ — $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.13	[1,4] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
-0.17	[2] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

N(1520) PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$N(1520) \rightarrow p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
$-0.025\ \pm0.009$	ARNDT	90B	IPWA	$\gamma N \rightarrow \pi N$
$-0.028\ \pm0.014$	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
$-0.007\ \pm0.004$	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
$-0.032\ \pm0.005$	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
$-0.032\ \pm0.004$	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
$-0.031\ \pm0.009$	BRATASHEV...	80	DPWA	$\gamma N \rightarrow \pi N$
$-0.019\ \pm0.007$	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
-0.0430 ± 0.0063	ISHII	80	DPWA	Compton scattering
$-0.016\ \pm0.008$	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
$-0.005\ \pm0.005$	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.023	ARNDT	90B	DPWA	$\gamma N \rightarrow \pi N$
-0.012	WADA	84	DPWA	Compton scattering
-0.008	[5] NOELLE	78		$\gamma N \rightarrow \pi N$
-0.021	BERENDS	77	IPWA	$\gamma N \rightarrow \pi N$

$N(1520) \rightarrow p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
$0.155\ \pm0.006$	ARNDT	90B	IPWA	$\gamma N \rightarrow \pi N$
$0.156\ \pm0.022$	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
$0.168\ \pm0.013$	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
$0.178\ \pm0.003$	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
$0.162\ \pm0.003$	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
$0.166\ \pm0.005$	BRATASHEV...	80	DPWA	$\gamma N \rightarrow \pi N$
$0.167\ \pm0.010$	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
0.1695 ± 0.0014	ISHII	80	DPWA	Compton scattering
$+0.157\ \pm0.007$	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
$+0.164\ \pm0.008$	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.167	ARNDT	90B	DPWA	$\gamma N \rightarrow \pi N$
0.168	WADA	84	DPWA	Compton scattering
0.206	[5] NOELLE	78		$\gamma N \rightarrow \pi N$
$+0.075$	BERENDS	77	IPWA	$\gamma N \rightarrow \pi N$

$N(1520) \rightarrow n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.059 ± 0.014	ARNDT	90B	IPWA	$\gamma N \rightarrow \pi N$
-0.066 ± 0.013	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
-0.067 ± 0.004	FUJII	81	DPWA	$\gamma N \rightarrow \pi N$
-0.076 ± 0.006	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
-0.071 ± 0.011	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
-0.056 ± 0.011	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
-0.050 ± 0.014	TAKEDA	80	DPWA	$\gamma N \rightarrow \pi N$
-0.055 ± 0.014	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.063	ARNDT	90B	DPWA	$\gamma N \rightarrow \pi N$
-0.060	[5] NOELLE	78		$\gamma N \rightarrow \pi N$

$N(1520) \rightarrow n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.126 ± 0.015	ARNDT	90B	IPWA	$\gamma N \rightarrow \pi N$
-0.124 ± 0.009	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
-0.158 ± 0.003	FUJII	81	DPWA	$\gamma N \rightarrow \pi N$
-0.147 ± 0.008	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
-0.148 ± 0.009	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
-0.144 ± 0.015	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
-0.118 ± 0.011	TAKEDA	80	DPWA	$\gamma N \rightarrow \pi N$
-0.141 ± 0.015	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.135	ARNDT	90B	DPWA	$\gamma N \rightarrow \pi N$
-0.127	[5] NOELLE	78		$\gamma N \rightarrow \pi N$

N(1520) FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.
[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.
[3] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.
[4] LONGACRE 77 considers this coupling to be well determined.
[5] Converted to our conventions using $M = 1528$ M , $\Gamma = 187$ MeV from NOELLE 78.

N(1520) REFERENCES

For early references, see Physics Letters **111B** 70 (1982). For very early references, see Reviews of Modern Physics **37** 633 (1965).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
ARNDT	90B	PR C42 1864	+Workman, Li, Roper	(VPI)
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(TOKY)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
BRATASHEV...	80	NP B166 525	Bratashevskij, Gorbenko, Derebchinskij+	(KHAR)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
ISHII	80	NP B165 189	+Egawa, Kato, Miyachi+	(KYOT, TOKY)
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOELLE	78	PTP 60 778		(NAGO)
BERENDS	77	NP B136 317	+Donnachie	(LEID, MCHS) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1535)$ S_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(1535)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1520 to 1555 (≈ 1535) OUR ESTIMATE				
1534± 7	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
1550±40	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
1526± 7	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1513	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
1511	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
1500	BERENDS	77	IPWA	$\gamma N \rightarrow \pi N$
1547± 6	BHANDARI	77	DPWA	Uses $N\eta$ cusp
1520	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
1510	[2] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1535)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
100 to 250 (≈ 150) OUR ESTIMATE				
151±27	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
240±80	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
120±20	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
136	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
180	BAKER	79	DPWA	$\pi^- p \rightarrow n\eta$
132	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
57	BERENDS	77	IPWA	$\gamma N \rightarrow \pi N$
139±33	BHANDARI	77	DPWA	Uses $N\eta$ cusp
135	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
100	[2] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1535)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1499	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
1510±50	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1461	ARNDT	85	DPWA	See ARNDT 91
1496 or 1499	[3] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
1519± 4	BHANDARI	77	DPWA	Uses $N\eta$ cusp
1525 or 1527	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
110	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
260±80	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
140	ARNDT	85	DPWA	See ARNDT 91
103 or 105	[3] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
140±32	BHANDARI	77	DPWA	Uses $N\eta$ cusp
135 or 123	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1535)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
22	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
116±46	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
20±21	BHANDARI	77	DPWA	Uses $N\eta$ cusp

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
− 5	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
31±92	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
13± 8	BHANDARI	77	DPWA	Uses $N\eta$ cusp

$N(1535)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	35–55 %
Γ_2	$N\eta$	30–50 %
Γ_3	$N\pi\pi$	5–20 %
Γ_4	$\Delta\pi$	<10 %
Γ_5	$\Delta(1232)\pi$, D-wave	
Γ_6	$N\rho$	<10 %
Γ_7	$N\rho$, S=1/2, S-wave	
Γ_8	$N\rho$, S=3/2, D-wave	
Γ_9	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<10 %
Γ_{10}	$N(1440)\pi$	<10 %
Γ_{11}	$p\gamma$	0.1–0.2 %
Γ_{12}	$p\gamma$, helicity=1/2	
Γ_{13}	$n\gamma$	0.15–0.35 %
Γ_{14}	$n\gamma$, helicity=1/2	

$N(1535)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ **Γ_1/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
0.35 to 0.55 OUR ESTIMATE				
0.51 ±0.05	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
0.50 ±0.10	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
0.38 ±0.04	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.297±0.026	BHANDARI	77	DPWA	Uses $N\eta$ cusp

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(1535) \rightarrow N\eta$ **$(\Gamma_1\Gamma_2)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
+0.47±0.02	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
+0.33	BAKER	79	DPWA	$\pi^- p \rightarrow n\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.48	FELTESSE	75	DPWA	1488–1745 MeV

Note: Signs of couplings from $\pi N \rightarrow N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(1535) \rightarrow \Delta(1232)\pi$, D-wave **$(\Gamma_1\Gamma_5)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
+0.00±0.04	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
0.00	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
+0.06	[2] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(1535) \rightarrow N\rho$, S=1/2, S-wave **$(\Gamma_1\Gamma_7)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
−0.10±0.03	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
−0.10	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
−0.09	[2] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(1535) \rightarrow N(\pi\pi)^{I=0}_{S\text{-wave}}$ **$(\Gamma_1\Gamma_9)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
+0.07±0.04	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
+0.08	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
+0.09	[2] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(1535) \rightarrow N(1440)\pi$ **$(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
+0.10±0.05	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1535)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$N(1535) \rightarrow p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.095 ±0.011	[4] BENMERROU..	91		$\gamma p \rightarrow p\eta$
0.053 ±0.015	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
0.077 ±0.021	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
0.083 ±0.007	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.080 ±0.007	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.029 ±0.007	BRATASHEV...	80	DPWA	$\gamma N \rightarrow \pi N$
0.065 ±0.016	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
0.0704±0.0091	ISHII	80	DPWA	Compton scattering
+0.082 ±0.019	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
+0.070 ±0.004	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.078	ARNDT	90B	IPWA	$\gamma N \rightarrow \pi N$
0.050	ARNDT	90B	DPWA	$\gamma N \rightarrow \pi N$
0.055	WADA	84	DPWA	Compton scattering
0.046	[5] NOELLE	78		$\gamma N \rightarrow \pi N$
+0.034	BERENDS	77	IPWA	$\gamma N \rightarrow \pi N$

$N(1535) \rightarrow n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.035±0.014	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
−0.062±0.003	FUJII	81	DPWA	$\gamma N \rightarrow \pi N$
−0.075±0.019	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
−0.075±0.018	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
−0.098±0.026	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
−0.011±0.017	TAKEDA	80	DPWA	$\gamma N \rightarrow \pi N$
−0.112±0.034	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.050	ARNDT	90B	IPWA	$\gamma N \rightarrow \pi N$
−0.037	ARNDT	90B	DPWA	$\gamma N \rightarrow \pi N$
−0.048	[5] NOELLE	78		$\gamma N \rightarrow \pi N$

N(1535) FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[4] BENMERROUCHE 91 uses an effective Lagrangian approach to analyze η photoproduction data.

[5] Converted to our conventions using $M = 1548$ MeV, $\Gamma = 73$ MeV from NOELLE 78.

N(1535) REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BENMERROU...	91	PRL 67 1070	Benmerrouche, Mukhopadhyay	(RPI)
ARNDT	90B	PR C42 1864	+Workman, Li, Roper	(VPI)
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(TOKY)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
BRATASHEV...	80	NP B166 525	Bratashevskij, Gorbenko, Derebchinskij+	(KHAR)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
ISHII	80	NP B165 189	+Egawa, Kato, Miyachi+	(KYOT, TOKY)
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOELLE	78	PTP 60 778		(NAGO)
BERENDS	77	NP B136 317	+Donnachie	(LEID, MCHS) IJP
BHANDARI	77	PR D15 192	+Chao	(CMU) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

OTHER RELATED PAPERS

DAVIES	67B	NC 52A 1112	+Moorhouse	(GLAS, RHEL)

$N(1650)$ S_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

N(1650) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1640 to 1680 (≈ 1650) OUR ESTIMATE				
1659± 9	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
1650±30	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
1670± 8	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1688	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
1672	MUSETTE	80	IPWA	$\pi^- p \rightarrow \Lambda K^0$
1680	SAXON	80	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1680	BAKER	78	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1694	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
1700± 5	[1] BAKER	77	IPWA	$\pi^- p \rightarrow \Lambda K^0$
1680	[1] BAKER	77	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1700	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
1675	KNASEL	75	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1660	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

N(1650) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
145 to 190 (≈ 150) OUR ESTIMATE				
173±12	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
150±40	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
180±20	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
183	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
179	MUSETTE	80	IPWA	$\pi^- p \rightarrow \Lambda K^0$
120	SAXON	80	DPWA	$\pi^- p \rightarrow \Lambda K^0$
90	BAKER	78	DPWA	$\pi^- p \rightarrow \Lambda K^0$
193	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
130±10	[1] BAKER	77	IPWA	$\pi^- p \rightarrow \Lambda K^0$
90	[1] BAKER	77	DPWA	$\pi^- p \rightarrow \Lambda K^0$
170	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
170	KNASEL	75	DPWA	$\pi^- p \rightarrow \Lambda K^0$
130	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

N(1650) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1657	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
1640±20	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1660	ARNDT	85	DPWA	See ARNDT 91
1648 or 1651	[4] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
1699 or 1698	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
160	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
150±30	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
122	ARNDT	85	DPWA	See ARNDT 91
117 or 119	[4] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
174 or 173	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

N(1650) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
43	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
16±25	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−33	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
−58±12	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

$N(1650)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	60–80 %
Γ_2	$N\eta$	≈ 1 %
Γ_3	ΛK	≈ 7 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	5–20 %
Γ_6	$\Delta\pi$	<10 %
Γ_7	$\Delta(1232)\pi$, D-wave	
Γ_8	$N\rho$	<15 %
Γ_9	$N\rho$, S=1/2, S-wave	
Γ_{10}	$N\rho$, S=3/2, D-wave	
Γ_{11}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<5 %
Γ_{12}	$N(1440)\pi$	<5 %
Γ_{13}	$p\gamma$	0.04–0.16 %
Γ_{14}	$p\gamma$, helicity=1/2	
Γ_{15}	$n\gamma$	0–0.17 %
Γ_{16}	$n\gamma$, helicity=1/2	

$N(1650)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.6 to 0.8 OUR ESTIMATE				
0.89 ± 0.07	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.65 ± 0.10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.61 ± 0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1650) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.09	[5] BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1650) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.22	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
-0.22	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.25	[6] BAKER	78	DPWA	See SAXON 80
-0.23 ± 0.01	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
-0.25	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
0.12	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1650) \to \Sigma K$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.254	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.066 to 0.137	[7] DEANS	75	DPWA	$\pi N \to \Sigma K$
0.20	KNASEL	75	DPWA	

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1650) \to \Delta(1232)\pi$, D-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.12\pm0.04$	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
$+0.29$	[2,8] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
$+0.15$	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1650) \to N\rho$, S=1/2, S-wave — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.01 ± 0.09	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
$+0.17$	[2,8] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
-0.16	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1650) \to N\rho$, S=3/2, D-wave — $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.16\pm0.06$	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
$+0.29$	[2,8] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1650) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ — $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.12\pm0.08$	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.00	[2,8] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
$+0.25$	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1650) \to N(1440)\pi$ — $(\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.11\pm0.06$	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$N(1650)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$N(1650) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.033 ± 0.015	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.050 ± 0.010	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.065 ± 0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.061 ± 0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.031 ± 0.017	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
$+0.048\pm0.017$	BARBOUR	78	DPWA	$\gamma N \to \pi N$
$+0.068\pm0.009$	FELLER	76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.091	WADA	84	DPWA	Compton scattering

$N(1650) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.008 ± 0.004	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.004 ± 0.004	FUJII	81	DPWA	$\gamma N \to \pi N$
0.010 ± 0.020	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.008 ± 0.019	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
-0.068 ± 0.040	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
-0.011 ± 0.011	TAKEDA	80	DPWA	$\gamma N \to \pi N$
-0.045 ± 0.024	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1650)$ $\gamma p \to \Lambda K^+$ AMPLITUDES

For definitions, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(1650) \to \Lambda K^+$ — (E_{0+} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
8.13	TANABE	89	DPWA

$p\gamma \to N(1650) \to \Lambda K^+$ phase angle θ — (E_{0+} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
-107.8	TANABE	89	DPWA

$N(1650)$ FOOTNOTES

[1] The two BAKER 77 entries are from an IPWA using the Barrelet-zero method and from a conventional energy-dependent analysis.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] BAKER 79 fixed this coupling during fitting, but the negative sign relative to the $N(1535)$ is well determined.

[6] The overall phase of BAKER 78 couplings has been changed to agree with previous conventions. Superseded by SAXON 80.

[7] The range given for DEANS 75 is from the four best solutions.

[8] LONGACRE 77 considers this coupling to be well determined.

$N(1650)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(TOKY)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP

MUSETTE	80	NC 57A 37		(BRUX) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BAKER	78	NP B141 29	+Blissett, Bloodworth, Broome+	(RL, CAMB) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
KNASEL	75	PR D11 1	+Lindquist, Nelson+	(CHIC, WUSL, OSU, ANL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1675)\ D_{15}$

$I(J^P) = \frac{1}{2}(\frac{5}{2}^-)$ Status: ****

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

N(1675) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1670 to 1685 (≈ 1675) OUR ESTIMATE				
1676± 2	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1675±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1679± 8	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1685	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1670	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
1680	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1650	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1660	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1675) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
140 to 180 (≈ 150) OUR ESTIMATE				
159± 7	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
160±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
120±15	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
191	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
40	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
88	BAKER	79	DPWA	$\pi^- p \to n\eta$
192	BARBOUR	78	DPWA	$\gamma N \to \pi N$
130	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
150	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1675) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1655	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1660±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1661	ARNDT	85	DPWA	See ARNDT 91
1663 or 1668	[3] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1649 or 1650	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
124	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
140±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
142	ARNDT	85	DPWA	See ARNDT 91
146 or 171	[3] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
127 or 127	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

N(1675) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
27	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
27±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
− 8	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
−16±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

N(1675) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	40–50 %
Γ_2	$N\eta$	≈ 1 %
Γ_3	ΛK	≈ 0.1 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	50–60 %
Γ_6	$\Delta\pi$	50–60 %
Γ_7	$\Delta(1232)\pi$, D-wave	
Γ_8	$\Delta(1232)\pi$, G-wave	
Γ_9	$N\rho$	<10 %
Γ_{10}	$N\rho$, S=1/2, D-wave	
Γ_{11}	$N\rho$, S=3/2, D-wave	
Γ_{12}	$N\rho$, S=3/2, G-wave	
Γ_{13}	$N\ (\pi\pi)^{I=0}_{S\text{-wave}}$	<1 %
Γ_{14}	$p\gamma$	∼ 0.01 %
Γ_{15}	$p\gamma$, helicity=1/2	
Γ_{16}	$p\gamma$, helicity=3/2	
Γ_{17}	$n\gamma$	0.07–0.12 %
Γ_{18}	$n\gamma$, helicity=1/2	
Γ_{19}	$n\gamma$, helicity=3/2	

N(1675) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.4 to 0.5 OUR ESTIMATE				
0.47±0.02	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.38±0.05	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.38±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1675) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.07	BAKER	79	DPWA	$\pi^- p \to n\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.009	FELTESSE	75	DPWA	Soln A; see BAKER 79

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1675) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.01	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
+0.036	[4] SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.034±0.006	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1675) \to \Sigma K$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.003	[5] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)\ S_{31}$ coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1675) \to \Delta(1232)\pi$, D-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.496±0.003	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
+0.46	[1,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.50	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.5	[7] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1675) \to N\rho$, S=1/2, D-wave — $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.04±0.02	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1675) \to N\rho$, S=3/2, D-wave — $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.03±0.02	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
−0.15	[1,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1675) \to N\ (\pi\pi)^{I=0}_{S\text{-wave}}$ — $(\Gamma_1\Gamma_{13})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.03	[1,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$N(1675)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$N(1675) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.021±0.011	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.034±0.005	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.006±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.006±0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.023±0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.022±0.010	BARBOUR	78	DPWA	$\gamma N \to \pi N$
+0.034±0.004	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1675) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.015±0.009	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.024±0.008	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.030±0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.029±0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.003±0.012	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.015±0.006	BARBOUR	78	DPWA	$\gamma N \to \pi N$
+0.019±0.009	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1675) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.057±0.024	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.033±0.004	FUJII	81	DPWA	$\gamma N \to \pi N$
−0.039±0.017	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.025±0.027	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.059±0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.021±0.011	TAKEDA	80	DPWA	$\gamma N \to \pi N$
−0.066±0.020	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1675) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.077±0.018	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.069±0.004	FUJII	81	DPWA	$\gamma N \to \pi N$
−0.066±0.026	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.071±0.022	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.059±0.020	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.030±0.012	TAKEDA	80	DPWA	$\gamma N \to \pi N$
−0.073±0.014	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1675)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[4] SAXON 80 finds the coupling phase is near 90°.

[5] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[6] LONGACRE 77 considers this coupling to be well determined.

[7] A Breit-Wigner fit to the HERNDON 75 IPWA.

$N(1675)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(TOKY)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOVOSELLER	78	NP B137 509		(CIT) IJP
Also	78B	NP B137 445	Novoseller	(CIT) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)

$N(1680)$ F_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(1680)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1675 to 1690 (≈ 1680) OUR ESTIMATE				
1684± 4	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1680±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1684± 3	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1682	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1680	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1660	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1685	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
1670	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1680)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
120 to 140 (≈ 130) OUR ESTIMATE				
139± 8	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
120±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
128± 8	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
121	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
119	BARBOUR	78	DPWA	$\gamma N \to \pi N$
150	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
155	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
130	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1680)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1670	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1667±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1680	ARNDT	85	DPWA	See ARNDT 91
1668 or 1674	[3] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1656 or 1653	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
116	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
110±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
120	ARNDT	85	DPWA	See ARNDT 91
132 or 137	[3] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
145 or 143	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$N(1680)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
36	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
31±2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−9	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
−14±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(1680)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	60–70 %
Γ_2	$N\eta$	not seen
Γ_3	ΛK	not seen
Γ_4	ΣK	
Γ_5	$N\pi\pi$	30–40 %
Γ_6	$\Delta\pi$	5–15 %
Γ_7	$\Delta(1232)\pi$, P-wave	
Γ_8	$\Delta(1232)\pi$, F-wave	
Γ_9	$N\rho$	5–15 %
Γ_{10}	$N\rho$, S=1/2, F-wave	
Γ_{11}	$N\rho$, S=3/2, P-wave	
Γ_{12}	$N\rho$, S=3/2, F-wave	
Γ_{13}	$N\,(\pi\pi)^{I=0}_{S\text{-wave}}$	5–20 %
Γ_{14}	$p\gamma$	0.21–0.30 %
Γ_{15}	$p\gamma$, helicity=1/2	
Γ_{16}	$p\gamma$, helicity=3/2	
Γ_{17}	$n\gamma$	0.02–0.05 %
Γ_{18}	$n\gamma$, helicity=1/2	
Γ_{19}	$n\gamma$, helicity=3/2	

$N(1680)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.6 to 0.7 OUR ESTIMATE				
0.70±0.03	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.62±0.05	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.65±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1680) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	BAKER	79	DPWA	$\pi^- p \to n\eta$

$\Gamma(N\eta)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0005 or 0.001	[4] CARRERAS	70	MPWA	t pole + resonance
0.0004	[4] BOTKE	69	MPWA	t pole + resonance
0.003 ±0.002	[4] DEANS	69	MPWA	t pole + resonance

$\Gamma(N\eta)/\Gamma(N\pi)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.027	HEUSCH	66	RVUE	π^0, η photoproduction

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1680) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

Coupling to ΛK not required in the analyses of BAKER 77, SAXON 80, or BELL 83.

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.01	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
−0.009±0.009	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1680) \to \Sigma K$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.001	[5] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)\,S_{31}$ coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1680) \to \Delta(1232)\pi$, P-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.26±0.04	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
−0.27	[1,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.25	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.38	[7] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1680) \to \Delta(1232)\pi$, F-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.07±0.03	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
+0.07	[1,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.08	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.05	[7] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1680) \to N\rho$, S=3/2, P-wave — $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.20±0.05	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
−0.23	[1,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.30	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.34	[7] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1680) \to N\rho$, S=3/2, F-wave — $(\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.13±0.03	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
−0.15	[1,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1680) \to N\,(\pi\pi)^{I=0}_{S\text{-wave}}$ — $(\Gamma_1\Gamma_{13})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.29±0.04	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
+0.31	[1,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.30	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.42	[7] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$N(1680)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)\,P_{11}$ Listings.

$N(1680) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.017±0.018	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.009±0.006	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.028±0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.026±0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.018±0.014	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.005±0.015	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.009±0.002	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1680) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.132±0.010	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.115±0.008	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.115±0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.122±0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.141±0.014	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.138±0.021	BARBOUR	78	DPWA	$\gamma N \to \pi N$
+0.121±0.010	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1680) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.017±0.014	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.032±0.003	FUJII	81	DPWA	$\gamma N \to \pi N$
0.026±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.028±0.014	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.044±0.012	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
0.025±0.010	TAKEDA	80	DPWA	$\gamma N \to \pi N$
+0.037±0.010	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1680) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.033±0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.023±0.005	FUJII	81	DPWA	$\gamma N \to \pi N$
−0.024±0.009	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.029±0.017	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.033±0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.035±0.012	TAKEDA	80	DPWA	$\gamma N \to \pi N$
−0.038±0.018	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1680)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[4] The parametrization used may be double counting.

[5] The range given is from 3 of 4 best solutions; not present in solution 1. DEANS 75 disagrees with $\pi^+ p \rightarrow \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[6] LONGACRE 77 considers this coupling to be well determined.

[7] A Breit-Wigner fit to the HERNDON 75 IPWA.

$N(1680)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982). For very early references, see Reviews of Modern Physics **37** 633 (1965).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(TOKY)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOVOSELLER	78	NP B137 509		(CIT) IJP
Also	78B	NP B137 445	Novoseller	(CIT) IJP
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)
KNASEL	75	PR D11 1	+Lindquist, Nelson+	(CHIC, WUSL, OSU, ANL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
CARRERAS	70	NP B16 35	+Donnachie	(DARE, MCHS)
BOTKE	69	PR 180 1417		(UCSB)
DEANS	69	PR 185 1797	+Wooten	(SFLA)
HEUSCH	66	PRL 17 1019	+Prescott, Dashen	(CIT)

$N(1700)$ D_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

The various partial-wave analyses do not agree very well.

$N(1700)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1650 to 1750 (≈ 1700) OUR ESTIMATE				
1737±44	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
1675±25	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
1731±15	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1709	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
1650	SAXON	80	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1690 to 1710	BAKER	78	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1719	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
1670±10	[1] BAKER	77	IPWA	$\pi^- p \rightarrow \Lambda K^0$
1690	[1] BAKER	77	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1660	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
1710	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1700)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50 to 150 (≈ 100) OUR ESTIMATE				
250±220	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
90± 40	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
110± 30	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
166	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
70	SAXON	80	DPWA	$\pi^- p \rightarrow \Lambda K^0$
70 to 100	BAKER	78	DPWA	$\pi^- p \rightarrow \Lambda K^0$
126	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
90± 25	[1] BAKER	77	IPWA	$\pi^- p \rightarrow \Lambda K^0$
100	[1] BAKER	77	DPWA	$\pi^- p \rightarrow \Lambda K^0$
600	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
300	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1700)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1660±30	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
1670	ARNDT	85	DPWA	See ARNDT 91
1710 or 1678	[4] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
1616 or 1613	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
90±40	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
80	ARNDT	85	DPWA	See ARNDT 91
607 or 567	[4] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
577 or 575	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1700)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
6±3	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0±5	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

$N(1700)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	$N\eta$	
Γ_3	ΛK	0.1–0.3 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	85–95 %
Γ_6	$\Delta\pi$	5–70 %
Γ_7	$\Delta(1232)\pi$, S-wave	
Γ_8	$\Delta(1232)\pi$, D-wave	
Γ_9	$N\rho$	<15 %
Γ_{10}	$N\rho$, S=1/2, D-wave	
Γ_{11}	$N\rho$, S=3/2, S-wave	
Γ_{12}	$N\rho$, S=3/2, D-wave	
Γ_{13}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<60 %
Γ_{14}	$p\gamma$	~ 0.01 %
Γ_{15}	$p\gamma$, helicity=1/2	
Γ_{16}	$p\gamma$, helicity=3/2	
Γ_{17}	$n\gamma$	
Γ_{18}	$n\gamma$, helicity=1/2	
Γ_{19}	$n\gamma$, helicity=3/2	

$N(1700)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE				
0.01±0.02	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
0.11±0.05	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
0.08±0.03	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1700) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.012	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
−0.012	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.04	[5] BAKER	78	DPWA	See SAXON 80
−0.03 ±0.004	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
−0.03	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
+0.026±0.019	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1700) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
<0.017	[6] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1700) \to \Delta(1232)\pi$, *S*-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.02±0.03	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.00	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.16	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1700) \to \Delta(1232)\pi$, *D*-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.10±0.09	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
−0.12	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.14	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1700) \to N\rho$, S=3/2, *S*-wave $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.04±0.06	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
−0.07	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.07	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1700) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_{13})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.02±0.02	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.00	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.2	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1700)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$N(1700) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.016±0.014	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.002±0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.028±0.007	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.029±0.006	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.024±0.019	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.033±0.021	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.014±0.025	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1700) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.009±0.012	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.029±0.014	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.002±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.014±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.017±0.014	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.014±0.025	BARBOUR	78	DPWA	$\gamma N \to \pi N$
0.0 ±0.014	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1700) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.006±0.024	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.002±0.013	FUJII	81	DPWA	$\gamma N \to \pi N$
−0.052±0.030	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.055±0.030	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.052±0.035	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.050±0.042	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1700) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.033±0.017	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.018±0.018	FUJII	81	DPWA	$\gamma N \to \pi N$
−0.037±0.036	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.035±0.024	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.041±0.030	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.035±0.030	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1700)$ $\gamma p \to \Lambda K^+$ AMPLITUDES

For definitions, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(1700) \to \Lambda K^+$ (E_{2-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
4.09	TANABE	89	DPWA

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(1700) \to \Lambda K^+$ (M_{2-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−7.09	TANABE	89	DPWA

$p\gamma \to N(1700) \to \Lambda K^+$ phase angle θ (E_{2-} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−35.9	TANABE	89	DPWA

$N(1700)$ FOOTNOTES

[1] The two BAKER 77 entries are from an IPWA using the Barrelet-zero method and from a conventional energy-dependent analysis.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] The overall phase of BAKER 78 couplings has been changed to agree with previous conventions.

[6] The range given is from the four best solutions.

$N(1700)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(TOKY)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BAKER	78	NP B141 29	+Blissett, Bloodworth, Broome+	(RL, CAMB) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)

$N(1710)\ P_{11}$

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

The various partial-wave analyses do not agree very well.

N(1710) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1680 to 1740 (≈ 1710) OUR ESTIMATE				
1717±28	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1700±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1723± 9	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1692	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1730	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
1690	BAKER	79	DPWA	$\pi^- p \to n\eta$
1650 to 1680	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
1721	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1625±10	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
1650	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
1720	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1670	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
1710	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1710) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50 to 250 (≈ 100) OUR ESTIMATE				
480±230	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
90± 30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
120± 15	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
540	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
200	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
550	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
97	BAKER	79	DPWA	$\pi^- p \to n\eta$
90 to 150	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
167	BARBOUR	78	DPWA	$\gamma N \to \pi N$
160± 6	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
95	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
120	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
174	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
75	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1710) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1636	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1690±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1708 or 1712	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1720 or 1711	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
544	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
80±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
17 or 22	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
123 or 115	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

N(1710) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−128	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
− 8±2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
77	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

N(1710) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	$N\eta$	20–40 %
Γ_3	ΛK	5–25 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	20–50 %
Γ_6	$\Delta\pi$	10–25 %
Γ_7	$\Delta(1232)\pi$, P-wave	
Γ_8	$N\rho$	5–20 %
Γ_9	$N\rho$, S=1/2, P-wave	
Γ_{10}	$N\rho$, S=3/2, P-wave	
Γ_{11}	$N\ (\pi\pi)^{I=0}_{S\text{-wave}}$	<25 %
Γ_{12}	$p\gamma$, helicity=1/2	
Γ_{13}	$n\gamma$, helicity=1/2	

N(1710) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10 to 0.20 OUR ESTIMATE				
0.09±0.04	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.20±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.12±0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1710) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.22	BAKER	79	DPWA	$\pi^- p \to n\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.383	FELTESSE	75	DPWA	Soln A; see BAKER 79

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1710) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.16	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
+0.14	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.12	[5] BAKER	78	DPWA	See SAXON 80
−0.05±0.03	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
−0.10	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
0.10	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1710) \to \Sigma K$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.034	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.075 to 0.203	[6] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)\ S_{31}$ coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1710) \to \Delta(1232)\pi$, P-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.21±0.04	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
−0.17	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.20	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1710) \to N\rho$, S=1/2, P-wave — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.05±0.06	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
+0.19	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.20	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1710) \to N\rho$, S=3/2, P-wave — $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.31	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1710) \to N\ (\pi\pi)^{I=0}_{S\text{-wave}}$ — $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.04±0.05	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
−0.26	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.28	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1710) PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$N(1710) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.006 ± 0.018	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.028 ± 0.009	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.009 ± 0.006	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
-0.012 ± 0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.015 ± 0.025	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
$+0.001 \pm 0.039$	BARBOUR	78	DPWA	$\gamma N \to \pi N$
$+0.053 \pm 0.019$	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1710) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.000 ± 0.018	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.001 ± 0.003	FUJII	81	DPWA	$\gamma N \to \pi N$
0.005 ± 0.013	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.011 ± 0.021	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
-0.017 ± 0.020	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
-0.028 ± 0.045	BARBOUR	78	DPWA	$\gamma N \to \pi N$

N(1710) $\gamma p \to \Lambda K^+$ AMPLITUDES

For definitions, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$.

$(\Gamma_i \Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(1710) \to \Lambda K^+$ (M_{1-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
-7.21	TANABE	89	DPWA

$p\gamma \to N(1710) \to \Lambda K^+$ phase angle θ (M_{1-} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
176.3	TANABE	89	DPWA

N(1710) FOOTNOTES

[1] The two BAKER 77 entries are from an IPWA using the Barrelet-zero method and from a conventional energy-dependent analysis.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] The overall phase of BAKER 78 couplings has been changed to agree with previous conventions.

[6] The range given for DEANS 75 is from the four best solutions.

N(1710) REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(TOKY)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BAKER	78	NP B141 29	+Blissett, Bloodworth, Broome+	(RL, CAMB) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
KNASEL	75	PR D11 1	+Lindquist, Nelson+	(CHIC, WUSL, OSU, ANL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1720)$ P_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

N(1720) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1650 to 1750 (≈ 1720) OUR ESTIMATE				
1717 ± 31	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1700 ± 50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1710 ± 20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1785	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1690	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
1710 to 1790	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
1809	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1640 ± 10	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
1710	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
1750	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1850	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
1720	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1720) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
100 to 200 (≈ 150) OUR ESTIMATE				
380 ± 180	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
125 ± 70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
190 ± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
308	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
120	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
447	BAKER	79	DPWA	$\pi^- p \to n\eta$
300 to 400	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
285	BARBOUR	78	DPWA	$\gamma N \to \pi N$
200 ± 50	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
500	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
130	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
327	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
150	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1720) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1675	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1680 ± 30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1705	ARNDT	85	DPWA	See ARNDT 91
1716 or 1716	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1745 or 1748	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
114	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
120 ± 40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
80	ARNDT	85	DPWA	See ARNDT 91
124 or 126	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
135 or 123	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

N(1720) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
-7	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
-8 ± 2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
-8	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
-3 ± 4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

N(1720) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	$N\eta$	2–6 %
Γ_3	ΛK	3–10 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	>35 %
Γ_6	$\Delta\pi$	5–15 %
Γ_7	$\Delta(1232)\pi$, P-wave	
Γ_8	$N\rho$	25–75 %
Γ_9	$N\rho$, $S=1/2$, P-wave	
Γ_{10}	$N\rho$, $S=3/2$, P-wave	
Γ_{11}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	10–15 %
Γ_{12}	$p\gamma$	
Γ_{13}	$p\gamma$, helicity=1/2	
Γ_{14}	$p\gamma$, helicity=3/2	
Γ_{15}	$n\gamma$	
Γ_{16}	$n\gamma$, helicity=1/2	
Γ_{17}	$n\gamma$, helicity=3/2	

N(1720) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10 to 0.20 OUR ESTIMATE				
0.13±0.05	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.10±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.14±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.08	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.09	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
−0.11	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.09	[5] BAKER	78	DPWA	See SAXON 80
−0.06±0.02	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
−0.09	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to \Sigma K$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.051 to 0.087	[6] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to \Delta(1232)\pi$, P-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.17	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to N\rho$, $S=1/2$, P-wave — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.34±0.05	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
−0.26	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.40	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to N\rho$, $S=3/2$, P-wave — $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.15	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ — $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.19	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

N(1720) PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$N(1720) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.044±0.066	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.004±0.007	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.051±0.009	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.071±0.010	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.038±0.050	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.111±0.047	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1720) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.024±0.006	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.040±0.016	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.058±0.010	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.011±0.011	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.014±0.040	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.063±0.032	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1720) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.002±0.005	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.019±0.033	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.001±0.038	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.003±0.034	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.007±0.020	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1720) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.015±0.019	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.139±0.039	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.134±0.044	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.018±0.028	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.051±0.051	BARBOUR	78	DPWA	$\gamma N \to \pi N$

N(1720) $\gamma p \to \Lambda K^+$ AMPLITUDES

For definitions, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(1720) \to \Lambda K^+$ — (E_{1+} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
9.52	TANABE	89	DPWA

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(1720) \to \Lambda K^+$ — (M_{1+} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3.18	TANABE	89	DPWA

$p\gamma \to N(1720) \to \Lambda K^+$ phase angle θ — (E_{1+} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−103.4	TANABE	89	DPWA

N(1720) FOOTNOTES

[1] The two BAKER 77 entries are from an IPWA using the Barrelet-zero method and from a conventional energy-dependent analysis.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] The overall phase of BAKER 78 copulings has been changed to agree with previous conventions.

[6] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

$N(1720)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BAKER	78	NP B141 29	+Blissett, Bloodworth, Broome+	(RL, CAMB) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
KNASEL	75	PR D11 1	+Lindquist, Nelson+	(CHIC, WUSL, OSU, ANL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1900)$ P_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$ Status: $*$

OMITTED FROM SUMMARY TABLE

$N(1900)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1900 OUR ESTIMATE				
1879±17	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$N(1900)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
498±78	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$N(1900)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\pi\pi$
Γ_3	$N\rho$, $S=1/2$, P-wave

$N(1900)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.26±0.06	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1900) \to N\rho$, $S=1/2$, P-wave $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.34±0.03	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$N(1900)$ REFERENCES

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT)
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)

$N(1990)$ F_{17}

$I(J^P) = \frac{1}{2}(\frac{7}{2}^+)$ Status: $**$

OMITTED FROM SUMMARY TABLE

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

The various analyses do not agree very well with one another.

$N(1990)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1990 OUR ESTIMATE				
2086± 28	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
2018	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1970± 50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2005±150	HOEHLER	79	IPWA	$\pi N \to \pi N$
1999	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
535±120	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
295	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
350±120	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
350±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
216	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1900±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
260±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$N(1990)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
5±4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−8±4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(1990)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	ΛK
Γ_4	ΣK
Γ_5	$N\pi\pi$
Γ_6	$p\gamma$, helicity=1/2
Γ_7	$p\gamma$, helicity=3/2
Γ_8	$n\gamma$, helicity=1/2
Γ_9	$n\gamma$, helicity=3/2

$N(1990)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.06±0.02	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.06±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.04±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1990) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.043	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1990) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.01	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
−0.021±0.033	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1990) \to \Sigma K$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.010 to 0.023	[1] DEANS	75	DPWA	$\pi N \to \Sigma K$
0.06	LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 1)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1990) \to N\pi\pi$ — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1990)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$N(1990) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.030±0.029	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.001±0.040	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
0.040	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.086±0.060	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.004±0.025	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.004	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.001	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.078±0.030	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.069	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.178	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.116±0.045	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.072	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990)$ FOOTNOTES

[1] The range given for DEANS 75 is from the four best solutions.

$N(1990)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
LANGBEIN	73	NP B53 251	+Wagner	(MUNI) IJP

$N(2000)$ F_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Older results have been retained simply because there is little information at all about this possible state.

$N(2000)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2000 OUR ESTIMATE				
1903±87	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1882±10	HOEHLER	79	IPWA	$\pi N \to \pi N$
2025	AYED	76	IPWA	$\pi N \to \pi N$
1970	[1] LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 2)
2175	ALMEHED	72	IPWA	$\pi N \to \pi N$
1930	DEANS	72	MPWA	$\gamma p \to \Lambda K$ (sol. D)

$N(2000)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
490±310	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
95± 20	HOEHLER	79	IPWA	$\pi N \to \pi N$
157	AYED	76	IPWA	$\pi N \to \pi N$
170	[1] LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 2)
150	ALMEHED	72	IPWA	$\pi N \to \pi N$
112	DEANS	72	MPWA	$\gamma p \to \Lambda K$ (sol. D)

$N(2000)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	ΛK
Γ_4	ΣK
Γ_5	$N\pi\pi$
Γ_6	$\Delta(1232)\pi$, P-wave
Γ_7	$N\rho$, S=3/2, P-wave
Γ_8	$N\rho$, S=3/2, F-wave
Γ_9	$p\gamma$

$N(2000)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.08±0.05	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.04±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.08	AYED	76	IPWA	$\pi N \to \pi N$
0.25	ALMEHED	72	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2000) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.03	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2000) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2000) \to \Sigma K$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.022	[2] DEANS	75	DPWA	$\pi N \to \Sigma K$
0.05	[1] LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 2)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2000) \to \Delta(1232)\pi$, P-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.10±0.06	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2000) \to N\rho$, S=3/2, P-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.22±0.08	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2000) \to N\rho$, S=3/2, F-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.11±0.06	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(2000) \to \Lambda K$ — $(\Gamma_9\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.0022	DEANS	72	MPWA	$\gamma p \to \Lambda K$ (sol. D)

$N(2000)$ FOOTNOTES

[1] Not seen in solution 1 of LANGBEIN 73.
[2] Value given is from solution 1 of DEANS 75; not present in solutions 2, 3, or 4.

$N(2000)$ REFERENCES

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
AYED	76	CEA-N-1921 Thesis		(SACL) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LANGBEIN	73	NP B53 251	+Wagner	(MUNI) IJP
ALMEHED	72	NP B40 157	+Lovelace	(LUND, RUTG) IJP
DEANS	72	PR D6 1906	+Jacobs, Lyons, Montgomery	(SFLA) IJP

$N(2080)$ D_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: **

OMITTED FROM SUMMARY TABLE

There is some evidence for two resonances in this wave between 1800 and 2200 MeV (see CUTKOSKY 80). However, the solution of HOEHLER 79 is quite different.

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(2080)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2080 OUR ESTIMATE				
1804± 55	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1920	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
1880±100	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2060± 80	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1900	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
2081± 20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1880	BAKER	79	DPWA	$\pi^- p \to n\eta$

$N(2080)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
450±185	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
320	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
180± 60	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower m)
300±100	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher m)
240	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
265± 40	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
87	BAKER	79	DPWA	$\pi^- p \to n\eta$

$N(2000)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1880±100	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower m)
2050± 70	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher m)
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
160±80	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower m)
200±80	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher m)
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$N(2080)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
− 2±14	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower m)
30±20	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher m)

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
10± 5	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower m)
0±52	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher m)

$N(2080)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	ΛK
Γ_4	ΣK
Γ_5	$N\pi\pi$
Γ_6	$\Delta(1232)\pi$, S-wave
Γ_7	$\Delta(1232)\pi$, D-wave
Γ_8	$N\rho$, S=3/2, S-wave
Γ_9	$N(\pi\pi)^{I=0}_{S\text{-wave}}$
Γ_{10}	$p\gamma$, helicity=1/2
Γ_{11}	$p\gamma$, helicity=3/2
Γ_{12}	$n\gamma$, helicity=1/2
Γ_{13}	$n\gamma$, helicity=3/2
Γ_{14}	$p\gamma$

$N(2080)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.23±0.03	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.10±0.04	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower m)
0.14±0.07	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher m)
0.06±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2080) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.065	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2080) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.04	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
+0.03	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2080) \to \Sigma K$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.014 to 0.037	[2] DEANS	75	DPWA	$\pi N \to \Sigma K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2000) \to \Delta(1232)\pi$, S-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.09±0.09	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2080) \to \Delta(1232)\pi$, D-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.22±0.07	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2080) \to N\rho$, S=3/2, S-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.24±0.06	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2080) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.25±0.06	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(2080) \to N\eta$ — $(\Gamma_{14}\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.0037	HICKS	73	MPWA	$\gamma p \to p\eta$

$N(2080)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$N(2080) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.020±0.008	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.026±0.052	DEVENISH	74	DPWA	$\gamma N \to \pi N$

$N(2080) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.017±0.011	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.128±0.057	DEVENISH	74	DPWA	$\gamma N \to \pi N$

$N(2080) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.007 ± 0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.053 ± 0.083	DEVENISH	74	DPWA	$\gamma N \to \pi N$

$N(2080) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.053 ± 0.034	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.100 ± 0.141	DEVENISH	74	DPWA	$\gamma N \to \pi N$

$N(2080)$ FOOTNOTES

[1] CUTKOSKY 80 finds a lower mass D_{13} resonance, as well as one in this region. Both are listed here.
[2] The range given for DEANS 75 is from the four best solutions. Disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

$N(2080)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY 92 PR D (to be pub.) +Saleski (KENT) IJP
Also 84 PR D30 904 Manley, Arndt, Goradia, Teplitz (VPI)
ARNDT 91 PR D43 2131 +Li, Roper, Workman, Ford (VPI, TELE) IJP
BELL 83 NP B222 389 +Blissett, Broome, Daley, Hart, Lintern+ (RL) IJP
PDG 82 PL 111B Roos, Porter, Aguilar-Benitez+ (HELS, CIT, CERN)
AWAJI 81 Bonn Conf. 352 +Kajikawa (NAGO)
Also 82 NP B197 365 Fujii, Hayashii, Iwata, Kajikawa+ (NAGO)
CUTKOSKY 80 Toronto Conf. 19 +Forsyth, Babcock, Kelly, Hendrick (CMU, LBL) IJP
Also 79 PR D20 2839 Cutkosky, Forsyth, Hendrick, Kelly (CMU, LBL) IJP
SAXON 80 NP B162 522 +Baker, Bell, Blissett, Bloodworth+ (RHEL, BRIS) IJP
BAKER 79 NP B156 93 +Brown, Clark, Davies, Depagter, Evans+ (RHEL) IJP
HOEHLER 79 PDAT 12-1 +Kaiser, Koch, Pietarinen (KARL) IJP
Also 80 Toronto Conf. 3 Koch (KARL) IJP
WINNIK 77 NP B128 66 +Toaff, Revel, Goldberg, Berny (HAIF) I
DEANS 75 NP B96 90 +Mitchell, Montgomery+ (SFLA, ALAH) IJP
DEVENISH 74 PL 52B 227 +Lyth, Rankin (DESY, LANC, BONN) IJP
HICKS 73 PR D7 2614 +Deans, Jacobs, Lyons+ (CMU, ORNL, SFLA) IJP

$N(2090)$ S_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

Any structure in the S_{11} wave above 1800 MeV is listed here. A few early results that are now obsolete have been omitted.

$N(2090)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2090 OUR ESTIMATE				
1928 ± 59	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
2180 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1880 ± 20	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2090)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
414 ± 157	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
350 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
95 ± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2090)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2150 ± 70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1937 or 1949	[1] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

$-2\times$ IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
139 or 131	[1] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

$N(2090)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
40 ± 20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0 ± 60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2090)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΛK
Γ_3	$N\pi\pi$

$N(2090)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10 ± 0.10	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.18 ± 0.08	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.09 ± 0.05	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2090) \to \Lambda K$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$N(2090)$ FOOTNOTES

[1] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

$N(2090)$ REFERENCES

MANLEY 92 PR D (to be pub.) +Saleski (KENT) IJP
Also 84 PR D30 904 Manley, Arndt, Goradia, Teplitz (VPI)
CUTKOSKY 80 Toronto Conf. 19 +Forsyth, Babcock, Kelly, Hendrick (CMU, LBL) IJP
Also 79 PR D20 2839 Cutkosky, Forsyth, Hendrick, Kelly (CMU, LBL)
SAXON 80 NP B162 522 +Baker, Bell, Blissett, Bloodworth+ (RHEL, BRIS) IJP
HOEHLER 79 PDAT 12-1 +Kaiser, Koch, Pietarinen (KARL) IJP
Also 80 Toronto Conf. 3 Koch (KARL) IJP
LONGACRE 78 PR D17 1795 +Lasinski, Rosenfeld, Smadja+ (LBL, SLAC)

$N(2100)$ P_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

$N(2100)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2100 OUR ESTIMATE				
1885 ± 30	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
2125 ± 75	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2050 ± 20	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2100)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
113 ± 44	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
260 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
200 ± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2100)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2120 ± 40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$-2\times$ IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
240 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$N(2100)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
11 ± 7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
8 ± 6	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

N(2100) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\pi\pi$
Γ_3	$\Delta(1232)\pi$, P-wave

N(2100) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.15±0.06	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
0.12±0.03	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
0.10±0.04	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(2100) \rightarrow \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.19±0.08	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$

N(2100) REFERENCES

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP

N(2190) G_{17}

$I(J^P) = \frac{1}{2}(\frac{7}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

N(2190) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2100 to 2200 (≈ 2190) OUR ESTIMATE				
2127± 9	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
2200±70	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
2140±12	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
2140±40	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2098	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
2180	SAXON	80	DPWA	$\pi^- p \rightarrow \Lambda K^0$
2140	BAKER	79	DPWA	$\pi^- p \rightarrow n\eta$
2117	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$

N(2190) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350 to 550 (≈ 450) OUR ESTIMATE				
550± 50	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
500±150	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
390± 30	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
270± 50	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
238	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
80	SAXON	80	DPWA	$\pi^- p \rightarrow \Lambda K^0$
319	BAKER	79	DPWA	$\pi^- p \rightarrow n\eta$
220	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$

N(2190) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2060	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
2100±50	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
464	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
400±160	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

N(2190) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
39	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
22±14	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−38	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
−13±20	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

N(2190) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	$N\eta$	1–3 %
Γ_3	ΛK	0.2–0.4 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	20–40 %
Γ_6	$N\rho$	20–40 %
Γ_7	$N\rho$, S=3/2, D-wave	
Γ_8	$p\gamma$, helicity=1/2	
Γ_9	$p\gamma$, helicity=3/2	
Γ_{10}	$n\gamma$, helicity=1/2	
Γ_{11}	$n\gamma$, helicity=3/2	

N(2190) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.2 OUR ESTIMATE				
0.22±0.01	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
0.12±0.06	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
0.14±0.02	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
0.16±0.04	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(2190) \rightarrow N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.052	BAKER	79	DPWA	$\pi^- p \rightarrow n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(2190) \rightarrow \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.02	BELL	83	DPWA	$\pi^- p \rightarrow \Lambda K^0$
−0.02	SAXON	80	DPWA	$\pi^- p \rightarrow \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(2190) \rightarrow \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.014 to 0.019	[1] DEANS	75	DPWA	$\pi N \rightarrow \Sigma K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(2190) \rightarrow N\rho$, S=3/2, D-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.25±0.03	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$

N(2190) PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$N(2190) \rightarrow p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.055	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
−0.030	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$

$N(2190) \rightarrow p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.081	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
+0.180	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$

$N(2190) \rightarrow n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.042	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
−0.085	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$

$N(2190) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.126	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.007	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190)$ $\gamma p \to \Lambda K^+$ AMPLITUDES

For definitions, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$.

$(\Gamma_i \Gamma_f)^{½}/\Gamma_{total}$ in $p\gamma \to N(2190) \to \Lambda K^+$ (E_{4-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2.04	TANABE	89	DPWA

$(\Gamma_i \Gamma_f)^{½}/\Gamma_{total}$ in $p\gamma \to N(2190) \to \Lambda K^+$ (M_{4-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−5.78	TANABE	89	DPWA

$p\gamma \to N(2190) \to \Lambda K^+$ phase angle θ (E_{4-} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−27.5	TANABE	89	DPWA

$N(2190)$ FOOTNOTES

[1] The range given for DEANS 75 is from the four best solutions. Disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

$N(2190)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP

$N(2200)$ D_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

The mass is not well determined. A few early results have been omitted.

$N(2200)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2200 OUR ESTIMATE				
1900	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
2180±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1920	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
2228±30	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2200)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
130	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
400±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
220	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
310± 50	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2200)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2100±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
360±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2200)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0±17	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−20±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2200)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	ΛK

$N(2200)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.07±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i \Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \to N(2200) \to N\eta$ $(\Gamma_1 \Gamma_2)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.066	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i \Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \to N(2200) \to \Lambda K$ $(\Gamma_1 \Gamma_3)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.03	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
−0.05	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$N(2200)$ REFERENCES

BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP

$N(2220)$ H_{19}

$I(J^P) = \frac{1}{2}(\frac{9}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(2220)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2180 to 2310 (≈ 2220) OUR ESTIMATE				
2230± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2205± 10	HOEHLER	79	IPWA	$\pi N \to \pi N$
2300±100	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2050	BAKER	79	DPWA	$\pi^- p \to n\eta$

$N(2220)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
320 to 550 (≈ 400) OUR ESTIMATE				
500±150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
365± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$
450±150	HENDRY	78	MPWA	$\pi N \to \pi N$

$N(2220)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2253	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
2160±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
640	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
480±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

N(2220) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
40	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
32±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−75	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
−32±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

N(2220) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	$N\eta$	0.5–1.0 %
Γ_3	ΛK	

N(2220) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.2 OUR ESTIMATE				
0.15±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.18±0.015	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.12±0.04	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2220) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.034	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2220) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not required	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

N(2220) REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

N(2250) G_{19}

$I(J^P) = \frac{1}{2}(\frac{9}{2}^-)$ Status: ****

N(2250) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2170 to 2310 (≈ 2250) OUR ESTIMATE				
2250± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2268± 15	HOEHLER	79	IPWA	$\pi N \to \pi N$
2200±100	HENDRY	78	MPWA	$\pi N \to \pi N$

N(2250) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
290 to 470 (≈ 400) OUR ESTIMATE				
480±120	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
300± 40	HOEHLER	79	IPWA	$\pi N \to \pi N$
350±100	HENDRY	78	MPWA	$\pi N \to \pi N$

N(2250) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2243	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
2150±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
650	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
360±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

N(2250) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
38	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
13±7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−28	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
−15±6	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

N(2250) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	$N\eta$	1–3 %
Γ_3	ΛK	<0.6 %

N(2250) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE				
0.10±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.10±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.09±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2250) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.043	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2250) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.02	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

N(2250) REFERENCES

ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$N(2600)$ $I_{1,11}$

$I(J^P) = \frac{1}{2}(\frac{11}{2}^-)$ Status: ∗∗∗

N(2600) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2550 to 2750 (≈ 2600) OUR ESTIMATE				
2577 ± 50	HOEHLER	79	IPWA	$\pi N \to \pi N$
2700 ± 100	HENDRY	78	MPWA	$\pi N \to \pi N$

N(2600) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
500 to 800 (≈ 650) OUR ESTIMATE				
400 ± 100	HOEHLER	79	IPWA	$\pi N \to \pi N$
900 ± 100	HENDRY	78	MPWA	$\pi N \to \pi N$

N(2600) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–10 %

N(2600) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.1 OUR ESTIMATE				
0.05 ± 0.01	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.08 ± 0.02	HENDRY	78	MPWA	$\pi N \to \pi N$

N(2600) REFERENCES

HOEHLER 79 PDAT 12-1 +Kaiser, Koch, Pietarinen (KARL) IJP
Also 80 Toronto Conf. 3 Koch (KARL) IJP
HENDRY 78 PRL 41 222 (IND, LBL) IJP
Also 81 ANP 136 1 Hendry (IND)

$N(2700)$ $K_{1,13}$

$I(J^P) = \frac{1}{2}(\frac{13}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

N(2700) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2700 OUR ESTIMATE				
2612 ± 45	HOEHLER	79	IPWA	$\pi N \to \pi N$
3000 ± 100	HENDRY	78	MPWA	$\pi N \to \pi N$

N(2700) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350 ± 50	HOEHLER	79	IPWA	$\pi N \to \pi N$
900 ± 150	HENDRY	78	MPWA	$\pi N \to \pi N$

N(2700) DECAY MODES

	Mode
Γ_1	$N\pi$

N(2700) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.04 ± 0.01	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.07 ± 0.02	HENDRY	78	MPWA	$\pi N \to \pi N$

N(2700) REFERENCES

HOEHLER 79 PDAT 12-1 +Kaiser, Koch, Pietarinen (KARL) IJP
Also 80 Toronto Conf. 3 Koch (KARL) IJP
HENDRY 78 PRL 41 222 (IND, LBL) IJP
Also 81 ANP 136 1 Hendry (IND)

$N(\sim 3000$ Region) Partial-Wave Analyses

OMITTED FROM SUMMARY TABLE

We list here miscellaneous high-mass candidates for isospin-1/2 resonances found in partial-wave analyses.

Our 1982 edition had an $N(3245)$, an $N(3690)$, and an $N(3755)$, each a narrow peak seen in a production experiment. Since nothing has been heard from them since the 1960's, we declare them to be dead. There was also an $N(3030)$, deduced from total cross-section and 180° elastic cross-section measurements; it is the KOCH 80 $L_{1,15}$ state below.

N(~ 3000) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 3000 OUR ESTIMATE				
2600	KOCH	80	IPWA	$\pi N \to \pi N$ D_{13}
3100	KOCH	80	IPWA	$\pi N \to \pi N$ $L_{1,15}$ wave
3500	KOCH	80	IPWA	$\pi N \to \pi N$ $M_{1,17}$ wave
3500 to 4000	KOCH	80	IPWA	$\pi N \to \pi N$ $N_{1,19}$ wave
3500 ± 200	HENDRY	78	MPWA	$\pi N \to \pi N$ $L_{1,15}$ wave
3800 ± 200	HENDRY	78	MPWA	$\pi N \to \pi N$ $M_{1,17}$ wave
4100 ± 200	HENDRY	78	MPWA	$\pi N \to \pi N$ $N_{1,19}$ wave

N(~ 3000) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1300 ± 200	HENDRY	78	MPWA	$\pi N \to \pi N$ $L_{1,15}$ wave
1600 ± 200	HENDRY	78	MPWA	$\pi N \to \pi N$ $M_{1,17}$ wave
1900 ± 300	HENDRY	78	MPWA	$\pi N \to \pi N$ $N_{1,19}$ wave

N(~ 3000) DECAY MODES

	Mode
Γ_1	$N\pi$

N(~ 3000) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.055 ± 0.02	HENDRY	78	MPWA	$\pi N \to \pi N$ $L_{1,15}$ wave
0.040 ± 0.015	HENDRY	78	MPWA	$\pi N \to \pi N$ $M_{1,17}$ wave
0.030 ± 0.015	HENDRY	78	MPWA	$\pi N \to \pi N$ $N_{1,19}$ wave

N(~ 3000) REFERENCES

KOCH 80 Toronto Conf. 3 (KARL) IJP
HENDRY 78 PRL 41 222 (IND, LBL) IJP
Also 81 ANP 136 1 Hendry (IND) IJP

Δ BARYONS
($S = 0$, $I = 3/2$)

$\Delta^{++} = uuu$, $\Delta^{+} = uud$, $\Delta^{0} = udd$, $\Delta^{-} = ddd$

$\Delta(1232)$ P_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1977 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

Δ(1232) MASSES

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1230 to 1234 (≈ 1232) OUR ESTIMATE				
1231 ± 1	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1232 ± 3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1233 ± 2	HOEHLER	79	IPWA	$\pi N \to \pi N$

Δ(1232)++ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1230.9±0.3	KOCH	80B	IPWA	$\pi N \to \pi N$
1230.6±0.2	ZIDELL	80	DPWA	$\pi N \to \pi N$ 0–350 MeV
1231.1±0.2	PEDRONI	78		$\pi N \to \pi N$ 70–370 MeV

Δ(1232)+ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1234.9±1.4	MIROSHNIC...	79		Fit photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1231.6	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1231.2	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1231.8	BERENDS	75	IPWA	$\gamma p \to \pi N$

Δ(1232)0 MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1233.6±0.5	KOCH	80B	IPWA	$\pi N \to \pi N$
1232.5±0.3	ZIDELL	80	DPWA	$\pi N \to \pi N$ 0–350 MeV
1233.8±0.2	PEDRONI	78		$\pi N \to \pi N$ 70–370 MeV

$\Delta^0 - \Delta^{++}$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2.7±0.3	[1] PEDRONI	78	See the masses

Δ(1232) WIDTHS

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
115 to 125 (≈ 120) OUR ESTIMATE				
118±4	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
120±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
116±5	HOEHLER	79	IPWA	$\pi N \to \pi N$

Δ(1232)++ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
111.0±1.0	KOCH	80B	IPWA	$\pi N \to \pi N$
113.2±0.3	ZIDELL	80	DPWA	$\pi N \to \pi N$ 0–350 MeV
111.3±0.5	PEDRONI	78		$\pi N \to \pi N$ 70–370 MeV

Δ(1232)+ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
131.1±2.4	MIROSHNIC...	79		Fit photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •				
111.2	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
111.0	BARBOUR	78	DPWA	$\gamma N \to \pi N$

Δ(1232)0 WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
113.0±1.5	KOCH	80B	IPWA	$\pi N \to \pi N$
121.3±0.4	ZIDELL	80	DPWA	$\pi N \to \pi N$ 0–350 MeV
117.9±0.9	PEDRONI	78		$\pi N \to \pi N$ 70–370 MeV

$\Delta^0 - \Delta^{++}$ WIDTH DIFFERENCE

VALUE (MeV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
6.6±1.0	PEDRONI	78	See the widths

Δ(1232) POLE POSITIONS

REAL PART, MIXED CHARGES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1210	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1210±1	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1210	ARNDT	85	DPWA	See ARNDT 91

−IMAGINARY PART, MIXED CHARGES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
50±1	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
50	ARNDT	85	DPWA	See ARNDT 91

REAL PART, Δ(1232)++

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1210.70±0.16	[2] ZIDELL	80	DPWA	$\pi N \to \pi N$ 0–350 MeV
1209.6 ±0.5	[3] VASAN	76B		Fit to CARTER 73
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1210.4 ±0.17	[4] ZIDELL	78		
1210.5 to 1210.8	[5] VASAN	76B		Fit to CARTER 73

−IMAGINARY PART, Δ(1232)++

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
49.61 ±0.12	[2] ZIDELL	80	DPWA	$\pi N \to \pi N$ 0–350 MeV
50.4 ±0.5	[3] VASAN	76B		Fit to CARTER 73
• • • We do not use the following data for averages, fits, limits, etc. • • •				
49.745±0.14	[4] ZIDELL	78		
49.9 to 50.0	[5] VASAN	76B		Fit to CARTER 73

REAL PART, Δ(1232)+

VALUE (MeV)	DOCUMENT ID		COMMENT
1206.9±0.9 to 1210.5 ± 1.8	MIROSHNIC...	79	Fit photoproduction
1208.0±2.0	CAMPBELL	76	Fit photoproduction

−IMAGINARY PART, Δ(1232)+

VALUE (MeV)	DOCUMENT ID		COMMENT
55.6±1.0 to 58.3 ± 1.1	MIROSHNIC...	79	Fit photoproduction
53.0±2.0	CAMPBELL	76	Fit photoproduction

REAL PART, Δ(1232)0

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1210.30±0.36	[2] ZIDELL	80	DPWA	$\pi N \to \pi N$ 0–350 MeV
1210.75±0.6	[3] VASAN	76B		Fit to CARTER 73
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1209.5 ±0.41	[4] ZIDELL	78		
1210.2	[5] VASAN	76B		Fit to CARTER 73

−IMAGINARY PART, Δ(1232)0

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
54.0 ±0.26	[2] ZIDELL	80	DPWA	$\pi N \to \pi N$ 0–350 MeV
52.8 ±0.6	[3] VASAN	76B		Fit to CARTER 73
• • • We do not use the following data for averages, fits, limits, etc. • • •				
52.45±0.2	[4] ZIDELL	78		
52.9 to 53.1	[5] VASAN	76B		Fit to CARTER 73

Δ(1232) ELASTIC POLE RESIDUES

ABSOLUTE VALUE, MIXED CHARGES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
52	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
53±2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE, MIXED CHARGES

VALUE (rad)	DOCUMENT ID		TECN	COMMENT
−0.54	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
−0.82±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

ABSOLUTE VALUE, Δ(1232)++

VALUE (MeV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
52.4 to 53.2	[3] VASAN	76B	Fit to CARTER 73
52.1 to 52.4	[5] VASAN	76B	Fit to CARTER 73

PHASE, Δ(1232)++

VALUE (rad)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.822 to −0.833	[3] VASAN	76B	Fit to CARTER 73
−0.823 to −0.830	[5] VASAN	76B	Fit to CARTER 73

ABSOLUTE VALUE, Δ(1232)0

VALUE (MeV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
54.8 to 55.0	[3] VASAN	76B	Fit to CARTER 73
55.2 to 55.3	[5] VASAN	76B	Fit to CARTER 73

PHASE, Δ(1232)0

VALUE (rad)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.840 to −0.847	[3] VASAN	76B	Fit to CARTER 73
−0.848 to −0.856	[5] VASAN	76B	Fit to CARTER 73

$\Delta(1232)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	99.3–99.5 %
Γ_2	$N\gamma$	0.56–0.66 %
Γ_3	$N\gamma$, helicity=1/2	
Γ_4	$N\gamma$, helicity=3/2	

$\Delta(1232)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.993 to 0.995 OUR ESTIMATE				
1.0	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1.0	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1.0	HOEHLER	79	IPWA	$\pi N \to \pi N$

$\Delta(1232)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$\Delta(1232) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.133 ± 0.007	ARNDT	90B	IPWA	$\gamma N \to \pi N$
-0.145 ± 0.015	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
-0.138 ± 0.004	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.147 ± 0.001	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
-0.145 ± 0.001	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
-0.136 ± 0.006	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
-0.142 ± 0.007	BARBOUR	78	DPWA	$\gamma N \to \pi N$
-0.141 ± 0.004	FELLER	76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.137	ARNDT	90B	DPWA	$\gamma N \to \pi N$
-0.140	[6] NOELLE	78		$\gamma N \to \pi N$

$\Delta(1232) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.244 ± 0.008	ARNDT	90B	IPWA	$\gamma N \to \pi N$
-0.263 ± 0.026	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
-0.259 ± 0.006	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.264 ± 0.002	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
-0.261 ± 0.002	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
-0.247 ± 0.010	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
-0.271 ± 0.010	BARBOUR	78	DPWA	$\gamma N \to \pi N$
-0.256 ± 0.003	FELLER	76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.246	ARNDT	90B	DPWA	$\gamma N \to \pi N$
-0.247	[6] NOELLE	78		$\gamma N \to \pi N$

$\Delta(1232) \to N\gamma$, E_2/M_1 ratio

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.0107 ± 0.0037	DAVIDSON	90	FIT	$\gamma N \to \pi N$
$-0.015\ \pm0.002$	DAVIDSON	86	FIT	$\gamma N \to \pi N$
$-0.013\ \pm0.005$	PDG	86	FIT	$\gamma N \to \pi N$
$+0.037\ \pm0.004$	TANABE	85	FIT	$\gamma N \to \pi N$

$\Delta(1232)$ PHASE OF M1+(3/2) PHOTOPRODUCTION MULTIPOLE AMPLITUDE POLE RESIDUE

Information on the phase (and magnitude) of the M1+(3/2) multipole amplitude pole residue is contained implicitly in the paper of MIROSHNICHENKO 79. They find that the phase is consistent with being equai to that of the elastic pole residue.

$\Delta(1232)^{++}$ MAGNETIC MOMENT

The values are extracted from UCLA and SIN data on $\pi^+ p$ bremsstrahlung using a variety of different theoretical approximations and methods. Our estimate is *only* a rough guess of the range we expect the moment to lie within.

VALUE (μ_N)	DOCUMENT ID		COMMENT
3.7 to 7.5 OUR ESTIMATE			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$4.52\pm0.50\pm0.45$	BOSSHARD	91	$\pi^+ p \to \pi^+ p\gamma$ (SIN data)
3.7 to 4.2	LIN	91B	$\pi^+ p \to \pi^+ p\gamma$ (from UCLA data)
4.6 to 4.9	LIN	91B	$\pi^+ p \to \pi^+ p\gamma$ (from SIN data)
5.6 to 7.5	WITTMAN	88	$\pi^+ p \to \pi^+ p\gamma$ (from UCLA data)
6.9 to 9.8	HELLER	87	$\pi^+ p \to \pi^+ p\gamma$ (from UCLA data)
4.7 to 6.7	NEFKENS	78	$\pi^+ p \to \pi^+ p\gamma$ (UCLA data)

$\Delta(1232)$ FOOTNOTES

[1] Using $\pi^\pm d$ as well, PEDRONI 78 determine $(M^- - M^{++}) + (M^0 - M^+)/3 = 4.6 \pm 0.2$ MeV.
[2] The accuracy claimed by ZIDELL 80 on the real part is considerably better than is allowed by uncertainties in the beam momentum.
[3] This VASAN 76B value is from fits to the coulomb-barrier-corrected CARTER 73 phase shift.
[4] ZIDELL 78 fits the nuclear phase shift without coulomb barrier corrections.
[5] This VASAN 76B value is from fits to the CARTER 73 nuclear phase shift without coulomb barrier corrections.
[6] Converted to our conventions using $M = 1232$ MeV, $\Gamma = 110$ MeV from NOELLE 78.

$\Delta(1232)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BOSSHARD	91	PR D44 1962	+Amsler+	(ZURI, LBL, PSI, LAUS, UCLA, CATH)
Also	90	PRL 64 2619	Bosshard+	(CATH, LAUS, LBL, PSI, UCLA, ZURI)
LIN	91B	PR C44 1819	+Liou, Ding	(CUNY, CSOK)
Also	91	PR C43 R930	Lin, Liou	(CUNY)
ARNDT	90B	PR C42 1864	+Workman, Li, Roper	(VPI)
DAVIDSON	90	PR D42 20	+Mukhopadhyay	(RPI)
WITTMAN	88	PR C37 2075		(TRIU)
HELLER	87	PR C35 718	+Kumano, Martinez, Moniz	(LANL, MIT, ILL)
DAVIDSON	86	PRL 56 804	+Mukhopadhyay, Wittman	(RPI)
PDG	86	PL 170B	Aguilar-Benitez, Porter+	(CERN, CIT+)
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
TANABE	85	PR C31 1876	+Ohta	(TOKY)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
KOCH	80B	NP A336 331	+Pietarinen	(KARL) IJP
ZIDELL	80	PR D21 1255	+Arndt, Roper	(VPI) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
MIROSHNIC...	79	SJNP 29 94 Translated from YAF 29 188.	Miroshnichenko, Nikiforov, Sanin+	(KHAR) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
NEFKENS	78	PR D18 3911	+Arman, Ballagh, Glodis, Haddock+	(UCLA, CATH) IJP
NOELLE	78	PTP 60 778		(NAGO)
PEDRONI	78	NP A300 321	+Gabathuler, Domingo, Hirt+	(SIN, ISNG, KARL+) IJP
ZIDELL	78	LNC 21 140	+Arndt, Roper	(VPI) IJP
CAMPBELL	76	PR D14 2431	+Shaw, Ball	(BOIS, UCI, UTAH) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
VASAN	76B	NP B106 535		(CMU) IJP
Also	76	NP B106 526	Vasan	(CMU) IJP
BERENDS	75	NP B84 342	+Donnachie	(LEID, MCHS)
CARTER	73	NP B58 378	+Bugg, Carter	(CAVE, LOQM) IJP

$\Delta(1600)$ P_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

The various analyses are not in good agreement.

$\Delta(1600)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1550 to 1700 (≈ 1600) OUR ESTIMATE				
1706 ± 10	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1600 ± 50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1522 ± 13	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1690	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
1560	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1640	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1600)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
250 to 450 (≈ 350) OUR ESTIMATE				
$430\pm\ 73$	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
300 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
$220\pm\ 40$	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
250	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
180	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
300	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1600)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1612	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1550±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1581	ARNDT	85	DPWA	See ARNDT 91
1609 or 1610	[3] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1541 or 1542	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
230	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
200±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
300	ARNDT	85	DPWA	See ARNDT 91
323 or 325	[3] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
178 or 178	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$\Delta(1600)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
5	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
−15±6	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−15	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
8±8	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1600)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–25 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	75–90 %
Γ_4	$\Delta\pi$	50–60 %
Γ_5	$\Delta(1232)\pi$, P-wave	
Γ_6	$\Delta(1232)\pi$, F-wave	
Γ_7	$N\rho$	5–20 %
Γ_8	$N\rho$, S=1/2, P-wave	
Γ_9	$N\rho$, S=3/2, P-wave	
Γ_{10}	$N\rho$, S=3/2, F-wave	
Γ_{11}	$N(1440)\pi$	20–30 %
Γ_{12}	$N(1440)\pi$, P-wave	
Γ_{13}	$N\gamma$, helicity=1/2	
Γ_{14}	$N\gamma$, helicity=3/2	

$\Delta(1600)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10 to 0.25 OUR ESTIMATE				
0.12±0.02	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.18±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.21±0.06	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1600) \to \Sigma K$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.006 to 0.042	[4] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1600) \to \Delta(1232)\pi$, P-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.29±0.02	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
+0.24±0.05	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
+0.34	[1,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.30	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1600) \to \Delta(1232)\pi$, F-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.07	[1,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1600) \to N\rho$, S=1/2, P-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.10	[1,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1600) \to N\rho$, S=3/2, P-wave — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.10	[1,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1600) \to N(1440)\pi$, P-wave — $(\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.16±0.02	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
+0.23±0.04	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$

$\Delta(1600)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$\Delta(1600) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.039±0.030	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.046±0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.005±0.020	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
0.000±0.030	BARBOUR	78	DPWA	$\gamma N \to \pi N$
0.0 ±0.020	FELLER	76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.200	[6] WADA	84	DPWA	Compton scattering

$\Delta(1600) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.013±0.014	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.025±0.031	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.009±0.020	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
0.000±0.045	BARBOUR	78	DPWA	$\gamma N \to \pi N$
0.0 ±0.015	FELLER	76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.023	WADA	84	DPWA	Compton scattering

$\Delta(1600)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[4] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[5] LONGACRE 77 considers this coupling to be well determined.

[6] WADA 84 is inconsistent with other analyses — see the Note on N and Δ Resonances.

$\Delta(1600)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
BARNHAM	80	NP B168 243	+Glickman, Mier-Jedrzejowicz+	(LOIC)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(1620)$ S_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$\Delta(1620)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1615 to 1675 (≈ 1620) OUR ESTIMATE				
1672 ± 7	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1620 ±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1610 ± 7	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1620	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
1712.8± 6.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1786.7± 2.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1657	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1662	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1580	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1600	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1620)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
120 to 180 (≈ 150) OUR ESTIMATE				
154 ±37	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
140 ±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
139 ±18	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
120	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
228.3±18.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$ (lower mass)
30.0± 6.4	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$ (higher mass)
161	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
180	BARBOUR	78	DPWA	$\gamma N \to \pi N$
120	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
150	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1620)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1587	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1600±15	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1599	ARNDT	85	DPWA	See ARNDT 91
1583 or 1583	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1575 or 1572	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
120	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
120±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
120	ARNDT	85	DPWA	See ARNDT 91
143 or 149	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
119 or 128	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$\Delta(1620)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−9	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
−5±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−12	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
−14±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1620)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	20–30 %
Γ_2	$N\pi\pi$	70–80 %
Γ_3	$\Delta\pi$	40–60 %
Γ_4	$\Delta(1232)\pi$, D-wave	
Γ_5	$N\rho$	20–35 %
Γ_6	$N\rho$, S=1/2, S-wave	
Γ_7	$N\rho$, S=3/2, D-wave	
Γ_8	$N(1440)\pi$	<10 %
Γ_9	$N\gamma$	∼ 0.03 %
Γ_{10}	$N\gamma$, helicity=1/2	

$\Delta(1620)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.2 to 0.3 OUR ESTIMATE				
0.09±0.02	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.25±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.35±0.06	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.60	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$ (lower mass)
0.36	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$ (higher mass)

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1620) \to \Delta(1232)\pi$, D-wave — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.24±0.03	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
−0.33±0.06	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
−0.39	[2,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.40	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1620) \to N\rho$, S=1/2, S-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.15±0.02	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
+0.40±0.10	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
+0.08	[2,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.28	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1620) \to N\rho$, S=3/2, D-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.06±0.02	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
−0.13	[2,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1620) \to N(1440)\pi$ — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.11±0.05	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$

$\Delta(1620)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$\Delta(1620) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.035±0.010	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.010±0.015	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.022±0.007	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.026±0.008	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.021±0.020	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
0.126±0.021	TAKEDA	80	DPWA	$\gamma N \to \pi N$
+0.034±0.028	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.005±0.016	FELLER	76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.066	WADA	84	DPWA	Compton scattering

$\Delta(1620)$ FOOTNOTES

[1] CHEW 80 reports two S_{31} resonances at somewhat higher masses than other analyses. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.
[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.
[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.
[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.
[5] LONGACRE 77 considers this coupling to be well determined.

$\Delta(1620)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARL)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
BARNHAM	80	NP B168 243	+Glickman, Mier-Jedrzejowicz+	(LOIC)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(1700)$ D_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$\Delta(1700)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1670 to 1770 (≈ 1700) OUR ESTIMATE			
1762 ±44	MANLEY 92	IPWA	$\pi N \to N\pi\pi$
1710 ±30	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
1680 ±70	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1650	BARNHAM 80	IPWA	$\pi N \to N\pi\pi$
$1718.4^{+13.1}_{-13.0}$	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
1622	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
1629	BARBOUR 78	DPWA	$\gamma N \to \pi N$
1600	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
1680	[3] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1700)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
200 to 400 (≈ 300) OUR ESTIMATE			
600 ±250	MANLEY 92	IPWA	$\pi N \to N\pi\pi$
280 ± 80	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
230 ± 80	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
160	BARNHAM 80	IPWA	$\pi N \to N\pi\pi$
193.3± 26.0	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
209	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
216	BARBOUR 78	DPWA	$\gamma N \to \pi N$
200	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
240	[3] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1700)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1646	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90
1675±25	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1668	ARNDT 85	DPWA	See ARNDT 91
1681 or 1672	[4] LONGACRE 78	IPWA	$\pi N \to N\pi\pi$
1600 or 1594	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
208	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90
220±40	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
320	ARNDT 85	DPWA	See ARNDT 91
245 or 241	[4] LONGACRE 78	IPWA	$\pi N \to N\pi\pi$
208 or 201	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

$\Delta(1700)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
12	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90
12±3	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
−5	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90
−4±5	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

$\Delta(1700)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	80–90 %
Γ_4	$\Delta\pi$	35–55 %
Γ_5	$\Delta(1232)\pi$, S-wave	
Γ_6	$\Delta(1232)\pi$, D-wave	
Γ_7	$N\rho$	30–50 %
Γ_8	$N\rho$, S=1/2, D-wave	
Γ_9	$N\rho$, S=3/2, S-wave	
Γ_{10}	$N\rho$, S=3/2, D-wave	
Γ_{11}	$N\gamma$	0.14–0.33 %
Γ_{12}	$N\gamma$, helicity=1/2	
Γ_{13}	$N\gamma$, helicity=3/2	

$\Delta(1700)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.10 to 0.20 OUR ESTIMATE			
0.14±0.06	MANLEY 92	IPWA	$\pi N \to N\pi\pi$
0.12±0.03	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
0.20±0.03	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.16	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1700) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.002	LIVANOS 80	DPWA	$\pi p \to \Sigma K$
0.001 to 0.011	[5] DEANS 75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1700) \to \Delta(1232)\pi$, S-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.32±0.06	MANLEY 92	IPWA	$\pi N \to N\pi\pi$
+0.18±0.04	BARNHAM 80	IPWA	$\pi N \to N\pi\pi$
+0.30	[2,6] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
+0.24	[3] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \rightarrow \Delta(1700) \rightarrow \Delta(1232)\pi$, D-wave $\quad (\Gamma_1\Gamma_6)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.08±0.03	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
0.14±0.04	BARNHAM	80	IPWA	$\pi N \rightarrow N\pi\pi$
+0.05	[2,6] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
+0.10	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \rightarrow \Delta(1700) \rightarrow N\rho$, S=1/2, D-wave $\quad (\Gamma_1\Gamma_8)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.17±0.05	BARNHAM	80	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \rightarrow \Delta(1700) \rightarrow N\rho$, S=3/2, S-wave $\quad (\Gamma_1\Gamma_9)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.10±0.03	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
+0.04	[2,6] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
−0.30	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \rightarrow \Delta(1700) \rightarrow N\rho$, S=3/2, D-wave $\quad (\Gamma_1\Gamma_{10})^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.18±0.07	BARNHAM	80	IPWA	$\pi N \rightarrow N\pi\pi$

$\Delta(1700)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$\Delta(1700) \rightarrow N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.111±0.017	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
0.089±0.033	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
0.112±0.006	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.130±0.006	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.123±0.022	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
+0.130±0.037	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
+0.072±0.033	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

$\Delta(1700) \rightarrow N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.107±0.015	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
0.060±0.015	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
0.047±0.007	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.050±0.007	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.102±0.015	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
+0.098±0.036	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
+0.087±0.023	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

$\Delta(1700)$ FOOTNOTES

[1] Problems with CHEW 80 are discussed in section 2.1.11 of HOEHLER 83.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \rightarrow \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[6] LONGACRE 77 considers this coupling to be well determined.

$\Delta(1700)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARL)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
BARNHAM	80	NP B168 243	+Glickman, Mier-Jedrzejowicz+	(LOIC)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(1750)$ P_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^+)$ Status: ∗

OMITTED FROM SUMMARY TABLE

$\Delta(1750)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1750 OUR ESTIMATE				
1744 ±36	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1715.2±21.0	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$
1778.4± 9.0	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$

$\Delta(1750)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
300 ±120	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
93.3± 55.0	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$
23.0± 29.0	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$

$\Delta(1750)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\pi\pi$
Γ_3	$N(1440)\pi$

$\Gamma(N\pi)/\Gamma_{total}$ $\quad \Gamma_1/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.08±0.03	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.18	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$
0.20	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \rightarrow \Delta(1700) \rightarrow N(1440)\pi$ $\quad (\Gamma_1\Gamma_3)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.15±0.03	MANLEY	92	IPWA	$\pi N \rightarrow N\pi\pi$

$\Delta(1750)$ FOOTNOTES

[1] CHEW 80 reports four resonances in the P_{31} wave — see also the $\Delta(1910)$. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

$\Delta(1750)$ REFERENCES

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT)
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARL)
CHEW	80	Toronto Conf. 123		(LBL)

$\Delta(1900)$ S_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$ Status: ∗∗∗

$\Delta(1900)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1850 to 1950 (≈ 1900) OUR ESTIMATE				
1920 ±24	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1890 ±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1908 ±30	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1918.5±23.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1803	CRAWFORD	80	DPWA	$\gamma N \to \pi N$

$\Delta(1900)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
140 to 240 (≈ 200) OUR ESTIMATE				
263 ±39	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
170 ±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
140 ±40	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
93.5±54.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
137	CRAWFORD	80	DPWA	$\gamma N \to \pi N$

$\Delta(1900)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1870±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
2029 or 2025	[1] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
180±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
164 or 163	[1] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

$\Delta(1900)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
9±4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
3±7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1900)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–30 %
Γ_2	ΣK	not seen
Γ_3	$N\pi\pi$	
Γ_4	$\Delta\pi$	
Γ_5	$\Delta(1232)\pi$, D-wave	
Γ_6	$N\rho$	
Γ_7	$N\rho$, S=1/2, S-wave	
Γ_8	$N\rho$, S=3/2, D-wave	
Γ_9	$N(1440)\pi$, S-wave	
Γ_{10}	$N\gamma$, helicity=1/2	

$\Delta(1900)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.3 OUR ESTIMATE				
0.41±0.04	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.10±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.08±0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.28	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1900) \to \Sigma K$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.03	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.076	[2] DEANS	75	DPWA	$\pi N \to \Sigma K$
0.11	LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 1)
0.12	LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 2)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1900) \to \Delta(1232)\pi$, D-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.25±0.07	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1900) \to N\rho$, S=1/2, S-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.14±0.11	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1900) \to N\rho$, S=3/2, D-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.37±0.07	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1900) \to N(1440)\pi$, S-wave — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.16±0.11	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$\Delta(1900)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$\Delta(1900) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.004±0.016	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.029±0.008	AWAJI	81	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.006 to −0.025	CRAWFORD	80	DPWA	$\gamma N \to \pi N$

$\Delta(1900)$ FOOTNOTES

[1] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[2] The value given is from solution 1; the resonance is not present in solutions 2, 3, or 4.

$\Delta(1900)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LANGBEIN	73	NP B53 251	+Wagner	(MUNI) IJP

Δ(1905) F_{35}

$I(J^P) = \frac{3}{2}(\frac{5}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

Δ(1905) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1870 to 1920 (≈ 1905) OUR ESTIMATE				
1881 ±18	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1910 ±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1905 ±20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1960 ±40	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
$1787.0^{+6.0}_{-5.7}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1880	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1892	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1830	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

Δ(1905) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
280 to 440 (≈ 350) OUR ESTIMATE				
327 ± 51	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
400 ±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
260 ± 20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
270 ± 40	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
$66.0^{+24.0}_{-16.0}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
193	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
159	BARBOUR	78	DPWA	$\gamma N \to \pi N$
220	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

Δ(1905) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1794	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1830±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1830	ARNDT	85	DPWA	See ARNDT 91
1813 or 1808	[2] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
230	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
280±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
180	ARNDT	85	DPWA	See ARNDT 91
193 or 187	[2] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

Δ(1905) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
11	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
16±8	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
− 9	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
−19±8	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(1905) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	ΣK	0.1–0.3 %
Γ_3	$N\pi\pi$	85–95 %
Γ_4	$\Delta\pi$	<30 %
Γ_5	$\Delta(1232)\pi$, P-wave	
Γ_6	$\Delta(1232)\pi$, F-wave	
Γ_7	$N\rho$	55–95 %
Γ_8	$N\rho$, S=3/2, P-wave	
Γ_9	$N\rho$, S=3/2, F-wave	
Γ_{10}	$N\rho$, S=1/2, F-wave	
Γ_{11}	$N\gamma$	0.01–0.05 %
Γ_{12}	$N\gamma$, helicity=1/2	
Γ_{13}	$N\gamma$, helicity=3/2	

Δ(1905) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE				
0.12±0.03	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.08±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.15±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.11	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1905) \to \Sigma K$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.015±0.003	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.013	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.021 to 0.054	[3] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1905) \to \Delta(1232)\pi$, P-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.04±0.05	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1905) \to \Delta(1232)\pi$, F-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.02±0.03	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
+0.17	[4] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
+0.06	[5] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
+0.20	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1905) \to N\rho$, S=3/2, P-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.33±0.03	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
+0.26	[4] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
+0.11 to +0.33	[6] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
+0.33	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

Δ(1905) PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$\Delta(1905) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.021±0.010	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.043±0.020	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.022±0.010	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.031±0.009	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.024±0.014	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.033±0.018	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1905) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.056±0.028	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.025±0.023	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.029±0.007	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.045±0.006	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.072±0.035	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.055±0.019	BARBOUR	78	DPWA	$\gamma N \to \pi N$

Δ(1905) FOOTNOTES

[1] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.
[2] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.
[3] The range given for DEANS 75 is from the four best solutions.
[4] A Breit-Wigner fit to the HERNDON 75 IPWA.
[5] A Breit-Wigner fit to the NOVOSELLER 78B IPWA.
[6] A Breit-Wigner fit to the NOVOSELLER 78B IPWA; the phase is near 90°.

$\Delta(1905)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOVOSELLER	78	NP B137 509		(CIT) IJP
NOVOSELLER	78B	NP B137 445		(CIT) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(1910)$ P_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$\Delta(1910)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1870 to 1920 (≈ 1910) OUR ESTIMATE				
1882 ±10	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1910 ±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1888 ±20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1960.1±21.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
$2121.4^{+13.0}_{-14.3}$	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1921	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1899	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1790	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$\Delta(1910)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
190 to 270 (≈ 250) OUR ESTIMATE				
239 ±25	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
225 ±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
280 ±50	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
152.9±60.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
172.2±37.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
351	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
230	BARBOUR	78	DPWA	$\gamma N \to \pi N$
170	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$\Delta(1910)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1950	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1880±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1792 or 1801	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
398	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
200±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
172 or 165	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$\Delta(1910)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−1	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
0±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−37	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
−20±4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1910)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	15–30 %
Γ_2	ΣK	not seen
Γ_3	$N\pi\pi$	70–85 %
Γ_4	$\Delta\pi$	<5 %
Γ_5	$\Delta(1232)\pi$, P-wave	
Γ_6	$N\rho$	5–25 %
Γ_7	$N\rho$, S=3/2, P-wave	
Γ_8	$N(1440)\pi$	50–70 %
Γ_9	$N(1440)\pi$, P-wave	
Γ_{10}	$N\gamma$, helicity=1/2	

$\Delta(1910)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.15 to 0.3 OUR ESTIMATE				
0.23±0.08	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.19±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.24±0.06	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.17	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.40	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1910) \to \Sigma K$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.03	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.019	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.082 to 0.184	[3] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1910) \to \Delta(1232)\pi$, P-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.06	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1910) \to N\rho$, S=3/2, P-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.29	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.17	[4] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1910) \to N(1440)\pi$, P-wave — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.39±0.04	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$\Delta(1910)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$\Delta(1910) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.014±0.030	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.025±0.011	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.012±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.031±0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.005±0.030	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.035±0.021	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1910)$ FOOTNOTES

[1] CHEW 80 reports four resonances in the P_{31} wave — see also the $\Delta(1750)$. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] The range given for DEANS 75 is from the four best solutions.

[4] Evidence for this coupling is weak; see NOVOSELLER 78. This coupling assumes the mass is near 1820 MeV.

$\Delta(1910)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARL)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
NOVOSELLER	78	NP B137 509		(CIT) IJP
Also	78B	NP B137 445	Novoseller	(CIT) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP

$\Delta(1920)$ P_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$\Delta(1920)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1900 to 1970 (≈ 1920) OUR ESTIMATE				
2014 ±16	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1920 ±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1868 ±10	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1840 ±40	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
1955.0±13.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
$2065.0^{+13.6}_{-12.9}$	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$\Delta(1920)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
150 to 300 (≈ 200) OUR ESTIMATE				
152 ± 55	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
300 ±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
220 ± 80	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
200 ± 40	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
88.3± 35.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
62.0± 44.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$\Delta(1920)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1900±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
300±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$\Delta(1920)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−21±7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−12±11	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1920)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–20 %
Γ_2	ΣK	1–3 %
Γ_3	$N\pi\pi$	
Γ_4	$\Delta(1232)\pi$, P-wave	
Γ_5	$N(1440)\pi$, P-wave	
Γ_6	$N\gamma$, helicity=1/2	
Γ_7	$N\gamma$, helicity=3/2	

$\Delta(1920)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.2 OUR ESTIMATE				
0.02±0.02	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.20±0.05	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.14±0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.24	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.18	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1920) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.052±0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.049	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.048 to 0.120	[2] DEANS	75	DPWA	$\pi N \to \Sigma K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1920) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.13±0.04	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.3	[3] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
0.27	[4] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1920) \to N(1440)\pi$, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.06±0.07	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$\Delta(1920)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$\Delta(1920) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.040±0.014	AWAJI	81	DPWA	$\gamma N \to \pi N$

$\Delta(1920) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.023±0.017	AWAJI	81	DPWA	$\gamma N \to \pi N$

$\Delta(1920)$ FOOTNOTES

[1] CHEW 80 reports two P_{33} resonances in this mass region. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

[2] The range given for DEANS 75 is from the four best solutions.

[3] A Breit-Wigner fit to the HERNDON 75 IPWA; the phase is near −90°.

[4] A Breit-Wigner fit to the NOVOSELLER 78B IPWA; the phase is near −90°.

$\Delta(1920)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARL)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
NOVOSELLER	78	NP B137 509		(CIT)
NOVOSELLER	78B	NP B137 445		(CIT)
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)

$\Delta(1930)\ D_{35}$

$I(J^P) = \frac{3}{2}(\frac{5}{2}^-)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

The various analyses are not in good agreement.

$\Delta(1930)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1920 to 1970 (≈ 1930) OUR ESTIMATE				
1956 ±22	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1940 ±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1901 ±15	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1910.0^{+15.0}_{-17.2}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
2000	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
2024	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1930)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
250 to 450 (≈ 350) OUR ESTIMATE				
530 ±140	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
320 ± 60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
195 ± 60	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$74.8^{+17.0}_{-16.0}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
442	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
462	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1930)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2018	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1890±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
398	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
260±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1930)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
14	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
17±7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−6	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
−6±12	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1930)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	ΣK	not seen
Γ_3	$N\pi\pi$	not seen
Γ_4	$N\gamma$, helicity=1/2	
Γ_5	$N\gamma$, helicity=3/2	

$\Delta(1930)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.2 OUR ESTIMATE				
0.18±0.02	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.14±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.04±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.11	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \to \Delta(1930) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.031	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.018 to 0.035	DEANS [1]	75	DPWA	$\pi N \to \Sigma K$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \to \Delta(1930) \to N\pi\pi$ $(\Gamma_1\Gamma_3)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1930)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)\ P_{11}$ Listings.

$\Delta(1930) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.009±0.009	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.030±0.047	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.062±0.064	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1930) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.025±0.011	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.033±0.060	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.019±0.054	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1930)$ FOOTNOTES

[1] The range given for DEANS 75 is from the four best solutions.

$\Delta(1930)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(1940)$ D_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

$\Delta(1940)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1940 OUR ESTIMATE				
2057 ±110	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
2058.1± 34.5	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1940 ±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1940)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
460 ±320	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
198.4± 45.5	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
200 ±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1940)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1900±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1915 or 1926	[1] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
200±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
190 or 186	[1] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

$\Delta(1940)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−6±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
6±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1940)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK
Γ_3	$N\pi\pi$
Γ_4	$\Delta(1232)\pi$, S-wave
Γ_5	$\Delta(1232)\pi$, D-wave
Γ_6	$N\rho$, S=3/2, S-wave
Γ_7	$N\gamma$, helicity=1/2
Γ_8	$N\gamma$, helicity=3/2

$\Delta(1940)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.18±0.12	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.18	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.05±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1940) \to \Sigma K$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1940) \to \Delta(1232)\pi$, S-wave — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.11±0.10	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1940) \to \Delta(1232)\pi$, D-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.27±0.16	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1940) \to N\rho$, S=3/2, S-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.25±0.10	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$\Delta(1940)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$\Delta(1940) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.036±0.058	AWAJI	81	DPWA	$\gamma N \to \pi N$

$\Delta(1940) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.031±0.012	AWAJI	81	DPWA	$\gamma N \to \pi N$

$\Delta(1940)$ FOOTNOTES

[1] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

$\Delta(1940)$ REFERENCES

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)

$\Delta(1950)$ F_{37}

$I(J^P) = \frac{3}{2}(\frac{7}{2}^+)$ Status: ****

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$\Delta(1950)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1940 to 1960 (≈ 1950) OUR ESTIMATE				
1945 ± 2	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
1950 ±15	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1913 ± 8	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1925 ±20	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
$1855.0^{+11.0}_{-10.0}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1902	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1912	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1925	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1950)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
290 to 350 (≈ 300) OUR ESTIMATE				
300 ± 7	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
340 ±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
224 ±10	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
330 ±40	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
$157.2^{+22.0}_{-19.0}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
225	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
198	BARBOUR	78	DPWA	$\gamma N \to \pi N$
240	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1950)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1884	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1890±15	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1858	ARNDT	85	DPWA	See ARNDT 91
1924 or 1924	[2] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
238	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
260±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
238	ARNDT	85	DPWA	See ARNDT 91
258 or 258	[2] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

$\Delta(1950)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
56	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
42±7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−24	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
−27±7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1950)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	35–40 %
Γ_2	ΣK	0.6–0.8 %
Γ_3	$N\pi\pi$	15–40 %
Γ_4	$\Delta\pi$	15–30 %
Γ_5	$\Delta(1232)\pi$, F-wave	
Γ_6	$\Delta(1232)\pi$, H-wave	
Γ_7	$N\rho$	<10 %
Γ_8	$N\rho$, S=1/2, F-wave	
Γ_9	$N\rho$, S=3/2, F-wave	
Γ_{10}	$N\gamma$	0.08–0.17 %
Γ_{11}	$N\gamma$, helicity=1/2	
Γ_{12}	$N\gamma$, helicity=3/2	

$\Delta(1950)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.35 to 0.4 OUR ESTIMATE				
0.38±0.01	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.39±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.38±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.44	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1950) \to \Sigma K$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.053±0.005	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.022 to 0.040	[3] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1950) \to \Delta(1232)\pi$, F-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.27±0.02	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.21	[4] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
0.38	[5] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
+0.32	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1950) \to N\rho$, S=3/2, F-wave — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.24	[6] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
0.43	[7] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
+0.24	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1950)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$ P_{11} Listings.

$\Delta(1950) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.068±0.007	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.091±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.083±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.067±0.014	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.058±0.013	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1950) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.094±0.016	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.101±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.100±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.082±0.017	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.075±0.020	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1950)$ FOOTNOTES

[1] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.
[2] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.
[3] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.
[4] A Breit-Wigner fit to the HERNDON 75 IPWA; the phase is near −60°.
[5] A Breit-Wigner fit to the NOVOSELLER 78B IPWA; the phase is near −60°.
[6] A Breit-Wigner fit to the HERNDON 75 IPWA; the phase is near 120°.
[7] A Breit-Wigner fit to the NOVOSELLER 78B IPWA; the phase is near 120°.

$\Delta(1950)$ REFERENCES

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOVOSELLER	78	NP B137 509		(CIT) IJP
NOVOSELLER	78B	NP B137 445		(CIT) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(2000)$ F_{35}

$I(J^P) = \frac{3}{2}(\frac{5}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

$\Delta(2000)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2000 OUR ESTIMATE				
1752± 32	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
2200±125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2000)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
251± 93	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
400±125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2000)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2150±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2000)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
-14 ± 13	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
8 ± 22	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2000)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\pi\pi$
Γ_3	$\Delta(1232)\pi$, P-wave
Γ_4	$\Delta(1232)\pi$, F-wave
Γ_5	$N\rho$, S=3/2, P-wave

$\Delta(2000)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.02 ± 0.01	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.07 ± 0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2000) \to \Delta(1232)\pi$, P-wave — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.07\pm0.03$	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2000) \to \Delta(1232)\pi$, F-wave — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.09\pm0.04$	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2000) \to N\rho$, S=3/2, P-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.06 ± 0.01	MANLEY	92	IPWA	$\pi N \to N\pi\pi$

$\Delta(2000)$ REFERENCES

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL)
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)

$\Delta(2150)$ S_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

$\Delta(2150)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2150 OUR ESTIMATE				
2047.4 ± 27.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
2203.2 ± 8.4	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
2150 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2150)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
121.6 ± 62.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
120.5 ± 45.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
200 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2150)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2140 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
200 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2150)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4 ± 10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
-6 ± 6	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2150)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

$\Delta(2150)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.41	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.37	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.08 ± 0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2150) \to \Sigma K$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.03	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$\Delta(2150)$ FOOTNOTES

[1] CHEW 80 reports two S_{31} resonances in this mass region. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

$\Delta(2150)$ REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARL)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)

$\Delta(2200)$ G_{37}

$I(J^P) = \frac{3}{2}(\frac{7}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

The various analyses are not in good agreement.

$\Delta(2200)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2200 OUR ESTIMATE				
2200 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2215 ± 60	HOEHLER	79	IPWA	$\pi N \to \pi N$
2280 ± 80	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2280 ± 40	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$\Delta(2200)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
450 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
400 ± 100	HOEHLER	79	IPWA	$\pi N \to \pi N$
400 ± 150	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
400 ± 50	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$\Delta(2200)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2100 ± 50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
340 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2200)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
3 ± 5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
-8 ± 3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2200) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

Δ(2200) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.06±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.05±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.09±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2200) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.014±0.005	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2200) REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Δ(2300) H_{39}

$I(J^P) = \frac{3}{2}(\frac{9}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Δ(2300) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2300 OUR ESTIMATE				
2204.5± 3.4	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
2400 ±125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2217 ± 80	HOEHLER	79	IPWA	$\pi N \to \pi N$
2450 ±100	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2400	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2300) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
32.3± 1.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
425 ±150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
300 ±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
500 ±200	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
200	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2300) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2370±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
420±160	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2300) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
9±4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−3±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2300) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

Δ(2300) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.06±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.03±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.08±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2300) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.017	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2300) REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Δ(2350) D_{35}

$I(J^P) = \frac{3}{2}(\frac{5}{2}^-)$ Status: ∗

OMITTED FROM SUMMARY TABLE

Δ(2350) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2350 OUR ESTIMATE				
2171± 18	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
2400±125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2305± 26	HOEHLER	79	IPWA	$\pi N \to \pi N$

Δ(2350) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
264± 51	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
400±150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
300± 70	HOEHLER	79	IPWA	$\pi N \to \pi N$

Δ(2350) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2400±125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
400±150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2350) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
5±17	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−14±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2350) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

Δ(2350) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.020±0.003	MANLEY	92	IPWA	$\pi N \to N\pi\pi$
0.20 ±0.10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.04 ±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2350) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2350) REFERENCES

MANLEY	92	PR D (to be pub.)	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP

Δ(2390) F_{37}

$I(J^P) = \frac{3}{2}(\frac{7}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

Δ(2390) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2390 OUR ESTIMATE				
2350±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2425± 60	HOEHLER	79	IPWA	$\pi N \to \pi N$

Δ(2390) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
300±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
300± 80	HOEHLER	79	IPWA	$\pi N \to \pi N$

Δ(2390) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2350±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
260±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2390) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0±13	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−12±6	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2390) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

Δ(2390) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.08±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.07±0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2390) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2390) REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP

Δ(2400) G_{39}

$I(J^P) = \frac{3}{2}(\frac{9}{2}^-)$ Status: **

OMITTED FROM SUMMARY TABLE

Δ(2400) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2400 OUR ESTIMATE				
2300±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2468± 50	HOEHLER	79	IPWA	$\pi N \to \pi N$
2200±100	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2400) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
330±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
480±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
450±200	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2400) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2260±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
320±160	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2400) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
7±4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−3±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2400) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

Δ(2400) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.06±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.10±0.03	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2400) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2400) REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Δ(2420) $H_{3,11}$

$I(J^P) = \frac{3}{2}(\frac{11}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

Δ(2420) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2300 to 2500 (≈ 2420) OUR ESTIMATE				
2400 ±125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2416 ± 17	HOEHLER	79	IPWA	$\pi N \to \pi N$
2400 ± 60	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2400	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
2358.0± 9.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

Δ(2420) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
300 to 500 (≈ 400) OUR ESTIMATE				
450 ±150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
340 ± 28	HOEHLER	79	IPWA	$\pi N \to \pi N$
460 ±100	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
400	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
202.2± 45.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

Δ(2420) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2360±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
420±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2420) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
16±8	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−9±11	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2420) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	ΣK	0.1–0.9 %

Δ(2420) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE				
0.08±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.08±0.015	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.11±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2420) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.016	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2420) REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Δ(2750) $I_{3,13}$

$I(J^P) = \frac{3}{2}(\frac{13}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Δ(2750) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2750 OUR ESTIMATE				
2794± 80	HOEHLER	79	IPWA	$\pi N \to \pi N$
2650±100	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2750) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
500±100	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2750) DECAY MODES

	Mode
Γ_1	$N\pi$

Δ(2750) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.04±0.015	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.05±0.01	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2750) REFERENCES

HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Δ(2950) $K_{3,15}$

$I(J^P) = \frac{3}{2}(\frac{15}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Δ(2950) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2950 OUR ESTIMATE				
2990±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
2850±100	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2950) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
330±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
700±200	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2950) DECAY MODES

	Mode
Γ_1	$N\pi$

Δ(2950) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.04±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.03±0.01	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2950) REFERENCES

HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$\Delta(\sim 3000$ Region) Partial-Wave Analyses

OMITTED FROM SUMMARY TABLE

We list here miscellaneous high-mass candidates for isospin-3/2 resonances found in partial-wave analyses.

Our 1982 edition also had a $\Delta(2850)$ and a $\Delta(3230)$. The evidence for them was deduced from total cross-section and 180° elastic cross-section measurements. The $\Delta(2850)$ has been resolved into the $\Delta(2750)$ $I_{3,13}$ and $\Delta(2950)$ $K_{3,15}$. The $\Delta(3230)$ is perhaps related to the $K_{3,13}$ of HENDRY 78 and to the $L_{3,17}$ of KOCH 80.

$\Delta(\sim 3000)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 3000 OUR ESTIMATE				
3300	[1] KOCH	80	IPWA	$\pi N \to \pi N$ $L_{3,17}$ wave
3500	[1] KOCH	80	IPWA	$\pi N \to \pi N$ $M_{3,19}$ wave
2850±150	HENDRY	78	MPWA	$\pi N \to \pi N$ $I_{3,11}$ wave
3200±200	HENDRY	78	MPWA	$\pi N \to \pi N$ $K_{3,13}$ wave
3300±200	HENDRY	78	MPWA	$\pi N \to \pi N$ $L_{3,17}$ wave
3700±200	HENDRY	78	MPWA	$\pi N \to \pi N$ $M_{3,19}$ wave
4100±300	HENDRY	78	MPWA	$\pi N \to \pi N$ $N_{3,21}$ wave

$\Delta(\sim 3000)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
700±200	HENDRY	78	MPWA	$\pi N \to \pi N$ $I_{3,11}$ wave
1000±300	HENDRY	78	MPWA	$\pi N \to \pi N$ $K_{3,13}$ wave
1100±300	HENDRY	78	MPWA	$\pi N \to \pi N$ $L_{3,17}$ wave
1300±400	HENDRY	78	MPWA	$\pi N \to \pi N$ $M_{3,19}$ wave
1600±500	HENDRY	78	MPWA	$\pi N \to \pi N$ $N_{3,21}$ wave

$\Delta(\sim 3000)$ DECAY MODES

	Mode
Γ_1	$N\pi$

$\Delta(\sim 3000)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.06 ±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$ $I_{3,11}$ wave
0.045±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$ $K_{3,13}$ wave
0.03 ±0.01	HENDRY	78	MPWA	$\pi N \to \pi N$ $L_{3,17}$ wave
0.025±0.01	HENDRY	78	MPWA	$\pi N \to \pi N$ $M_{3,19}$ wave
0.018±0.01	HENDRY	78	MPWA	$\pi N \to \pi N$ $N_{3,21}$ wave

$\Delta(\sim 3000)$ FOOTNOTES

[1] In addition, KOCH 80 reports some evidence for an S_{31} $\Delta(2700)$ and a P_{33} $\Delta(2800)$.

$\Delta(\sim 3000)$ REFERENCES

KOCH	80	Toronto Conf. 3		(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Z BARYONS ($S = +1$)

NOTE ON THE $S = +1$ BARYON SYSTEM

The evidence for strangeness +1 baryon resonances was reviewed in our 1976 edition,[1] and has also been reviewed by Kelly[2] and by Oades.[3] New partial-wave analyses[4,5] appeared in 1984 and 1985, and both claimed that the P_{13} and perhaps other waves resonate. However, the results permit no definite conclusion — the same story heard for 20 years. The standards of proof must simply be more severe here than in a channel in which many resonances are already known to exist. The skepticism about baryons not made of three quarks, and the lack of any experimental activity in this area, make it likely that another 20 years will pass before the issue is decided. Nothing new at all has been published in this area since our 1986 edition,[6] and we simply refer to that for listings of the $Z_0(1780)P_{01}$, $Z_0(1865)D_{03}$, $Z_1(1725)P_{11}$, $Z_1(2150)$, and $Z_1(2500)$.

References

1. Particle Data Group, Rev. Mod. Phys. **48**, S188 (1976).
2. R.L. Kelly, in *Proceedings of the Meeting on Exotic Resonances* (Hiroshima, 1978), ed. I. Endo *et al.*
3. G.C. Oades, in *Low and Intermediate Energy Kaon-Nucleon Physics* (1981), ed. E. Ferrari and G. Violini.
4. K. Hashimoto, Phys. Rev. **C29**, 1377 (1984).
5. R.A. Arndt and L.D. Roper, Phys. Rev. **D31**, 2230 (1985).
6. Particle Data Group, Phys. Lett. **170B**, 289 (1986).

Λ BARYONS ($S = -1, I = 0$)

$\Lambda^0 = uds$

Λ

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗∗

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1986 edition (Physics Letters **170B** (1986)) or in earlier editions.

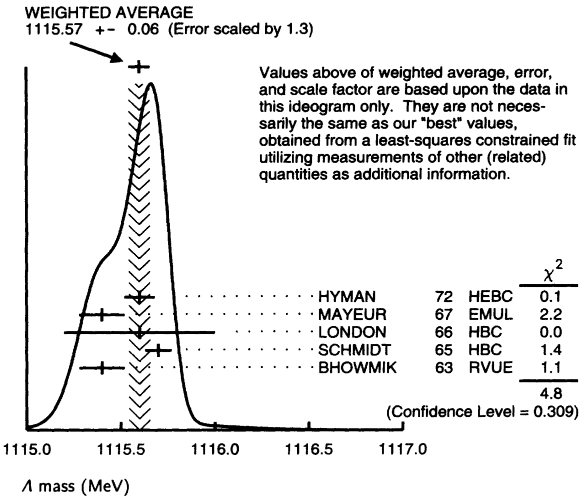
Λ MASS

The fit uses Λ, Σ^+, Σ^0, Σ^- mass and mass-difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN
1115.63±0.05 OUR FIT Error includes scale factor of 1.4.				
1115.57±0.06 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.				
1115.59±0.08	935	HYMAN	72	HEBC
1115.39±0.12	195	MAYEUR	67	EMUL
1115.6 ±0.4		LONDON	66	HBC
1115.65±0.07	488	[1] SCHMIDT	65	HBC
1115.44±0.12		[2] BHOWMIK	63	RVUE

[1] Since our final values for the Σ and Λ masses come from doing an overall fit to all measured masses and mass differences, we use the uncorrelated measurements from SCHMIDT 65 rather than those coming from the overall fit reported in that paper. Since there seems to be no convincing reason to ignore data using range measurements, we include here values depending on proton and pion ranges. The SCHMIDT 65 masses have been reevaluated using our April 1973 proton and $K^{\pm}$ and $\pi^{\pm}$ masses. P. Schmidt, private communication (1974).

[2] The mass has been raised 35 keV to take into account a 46 keV increase in the proton mass and an 11 keV decrease in the $\pi^{\pm}$ mass (note added 1967 edition, Reviews of Modern Physics **39** 1 (1967)).



$\Lambda - \overline{\Lambda}$ MASS DIFFERENCE

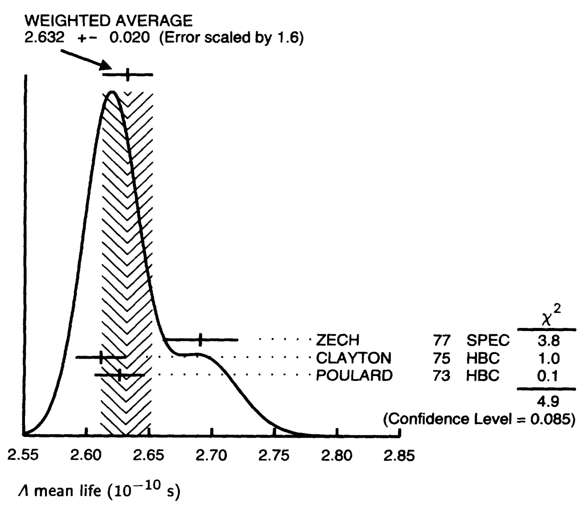
A test of *CPT*.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0.00±0.12 OUR AVERAGE	Error includes scale factor of 2.1.			
−0.29±0.15	BADIER	67	HBC	2.4 GeV/c $\overline{p}p$
0.05±0.06	CHIEN	66	HBC	6.9 GeV/c $\overline{p}p$

Λ MEAN LIFE

Measurements with an error $\geq$ 0.1 × 10^{-10} s have been omitted, and only the latest high-statistics measurements are used for the average.

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
2.632±0.020 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.				
2.69 ±0.03	53k	ZECH	77	SPEC	Neutral hyperon beam
2.611±0.020	34k	CLAYTON	75	HBC	0.96–1.4 GeV/c K^-p
2.626±0.020	36k	POULARD	73	HBC	0.4–2.3 GeV/c K^-p
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.69 ±0.05	6582	ALTHOFF	73B	OSPK	$\pi^+ n \rightarrow \Lambda K^+$
2.54 ±0.04	4572	BALTAY	71B	HBC	K^-p at rest
2.535±0.035	8342	GRIMM	68	HBC	
2.47 ±0.08	2600	HEPP	68	HBC	
2.35 ±0.09	916	BURAN	66	HLBC	
$2.452^{+0.056}_{-0.054}$	2213	ENGELMANN	66	HBC	
2.59 ±0.09	794	HUBBARD	64	HBC	
2.59 ±0.07	1378	SCHWARTZ	64	HBC	
2.36 ±0.06	2239	BLOCK	63	HEBC	



$(\tau_\Lambda - \tau_{\overline{\Lambda}}) / \tau_{\text{AVERAGE}}$, MEAN LIFE DIFFERENCE

A test of *CPT*.

VALUE	DOCUMENT ID		TECN	COMMENT
0.044±0.085	BADIER	67	HBC	2.4 GeV/c $\overline{p}p$

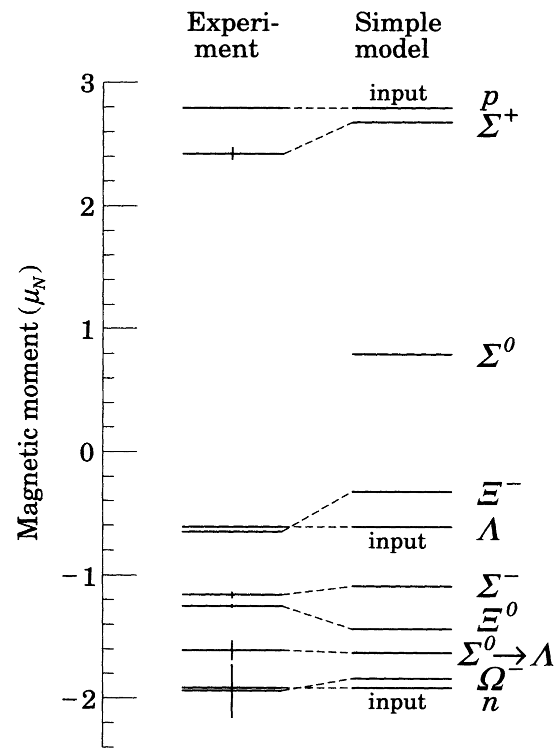
NOTE ON BARYON MAGNETIC MOMENTS

The figure shows the measured magnetic moments of the stable baryons. It also shows the predictions of the simplest quark model, using the measured p, n, and Λ moments as input. In this model, the moments are[1]

$$\mu_p = (4\mu_u - \mu_d)/3 \qquad \mu_n = (4\mu_d - \mu_u)/3$$
$$\mu_{\Sigma^+} = (4\mu_u - \mu_s)/3 \qquad \mu_{\Sigma^-} = (4\mu_d - \mu_s)/3$$
$$\mu_{\Xi^0} = (4\mu_s - \mu_u)/3 \qquad \mu_{\Xi^-} = (4\mu_s - \mu_d)/3$$
$$\mu_\Lambda = \mu_s \qquad \mu_{\Sigma^0} = (2\mu_u + 2\mu_d - \mu_s)/3$$
$$\mu_{\Omega^-} = 3\mu_s$$

and the $\Sigma^0 \rightarrow \Lambda$ transition moment is

$$\mu_{\Sigma^0\Lambda} = (\mu_d - \mu_u)/\sqrt{3}\ .$$



The quark moments that result from this model are $\mu_u = +1.852\,\mu_N$, $\mu_d = -0.972\,\mu_N$, and $\mu_s = -0.613\,\mu_N$. The corresponding effective quark masses, taking the quarks to be Dirac point particles, where $\mu = q\hbar/2m$, are 338, 322, and 510 MeV. As the figure shows, the model gives a good first approximation to the experimental moments. For efforts to make a better model, we refer to the literature.[2]

References

1. See, for example, D.H. Perkins, *Introduction to High Energy Physics* (Addison-Wesley, Reading, MA, 1987), or D. Griffiths, *Introduction to Elementary Particles* (Harper & Row, New York, 1987).
2. See, for example, J. Franklin, Phys. Rev. **D29**, 2648 (1984); H.J. Lipkin, Nucl. Phys. **B241**, 477 (1984); K. Suzuki, H. Kumagai, and Y. Tanaka, Europhys. Lett. **2**, 109 (1986); S.K. Gupta and S.B. Khadkikar, Phys. Rev. **D36**, 307 (1987); M.I. Krivoruchenko, Sov. Jour. Nucl. Phys. **45**, 109 (1987); L. Brekke and J.L. Rosner, Comm. Nucl. Part. Phys. **18**, 83 (1988); K.-T. Chao, Phys. Rev. **D41**, 920 (1990); and references cited therein. Also, see references cited in discussions of results in the experimental papers.

Λ MAGNETIC MOMENT

See the Note on Baryon Magnetic Moments above. Measurements with an error $\geq 0.15\ \mu_N$ have been omitted.

VALUE (μ_N)	EVTS	DOCUMENT ID		TECN	COMMENT
−0.613 ±0.004 OUR AVERAGE					
−0.606 ±0.015	200k	COX	81	SPEC	
−0.6138±0.0047	3M	SCHACHIN...	78	SPEC	
−0.59 ±0.07	350k	HELLER	77	SPEC	
−0.57 ±0.05	1.2M	BUNCE	76	SPEC	
−0.66 ±0.07	1300	DAHL-JENSEN	71	EMUL	200 kG field

Λ ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both T invariance and P invariance.

VALUE (10^{-16} e-cm)	CL%	DOCUMENT ID		TECN
< 1.5	95	[3] PONDROM	81	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<100	95	[4] BARONI	71	EMUL
<500	95	GIBSON	66	EMUL

[3] PONDROM 81 measures $(-3.0 \pm 7.4) \times 10^{-17}$ e-cm.
[4] BARONI 71 measures $(-5.9 \pm 2.9) \times 10^{-15}$ e-cm

Λ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$p\pi^-$	(64.1 ±0.5) %
Γ_2	$n\pi^0$	(35.7 ±0.5) %
Γ_3	$n\gamma$	(1.02±0.33) × 10^{-3}
Γ_4	$p\pi^-\gamma$	[a] (8.5 ±1.4) × 10^{-4}
Γ_5	$pe^-\overline{\nu}_e$	(8.34±0.14) × 10^{-4}
Γ_6	$p\mu^-\overline{\nu}_\mu$	(1.57±0.35) × 10^{-4}

[a] See the Listings below for the pion momentum range used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to 5 branching ratios uses 24 measurements and one constraint to determine 5 parameters. The overall fit has a $\chi^2 = 13.6$ for 20 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−100			
x_3	−9	2		
x_5	46	−46	−4	
x_6	0	0	0	0
	x_1	x_2	x_3	x_5

Λ BRANCHING RATIOS

$\Gamma(p\pi^-)/\Gamma(N\pi)$ — $\Gamma_1/(\Gamma_1+\Gamma_2)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.642±0.005 OUR FIT					
0.640±0.005 OUR AVERAGE					
0.646±0.008	4572	BALTAY	71B	HBC	$K^- p$ at rest
0.635±0.007	6736	DOYLE	69	HBC	$\pi^- p \rightarrow \Lambda K^0$
0.643±0.016	903	HUMPHREY	62	HBC	
0.65 ±0.05		COLUMBIA	60	HBC	
0.627±0.031		CRAWFORD	59B	HBC	

$\Gamma(n\pi^0)/\Gamma(N\pi)$ — $\Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	EVTS	DOCUMENT ID		TECN
0.358±0.005 OUR FIT				
0.304±0.025 OUR AVERAGE				
0.35 ±0.05		BROWN	63	HLBC
0.291±0.034	75	CHRETIEN	63	HLBC
0.28 ±0.08		BAGLIN	60	HLBC
0.43 ±0.14		CRAWFORD	59B	HBC
0.23 ±0.09		EISLER	57	HLBC

$\Gamma(n\gamma)/\Gamma(n\pi^0)$ — Γ_3/Γ_2

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.9 ±0.9 OUR FIT					
2.86±0.74±0.57	24	BIAGI	86	SPEC	SPS hyperon beam

$\Gamma(p\pi^-\gamma)/\Gamma(p\pi^-)$ — Γ_4/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.32±0.22	72	BAGGETT	72C	HBC	π^- < 95 MeV/c

$\Gamma(pe^-\overline{\nu}_e)/\Gamma(p\pi^-)$ — Γ_5/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.301±0.019 OUR FIT					
1.301±0.019 OUR AVERAGE					
1.335±0.056	7111	BOURQUIN	83	SPEC	SPS hyperon beam
1.313±0.024	10k	WISE	80	SPEC	
1.23 ±0.11	544	LINDQUIST	77	SPEC	$\pi^- p \rightarrow K^0 \Lambda$
1.27 ±0.07	1089	KATZ	73	HBC	
1.31 ±0.06	1078	ALTHOFF	71	OSPK	
1.17 ±0.13	86	[5] CANTER	71	HBC	$K^- p$ at rest
1.20 ±0.12	143	[6] MALONEY	69	HBC	
1.17 ±0.18	120	[6] BAGLIN	64	FBC	K^- freon 1.45 GeV/c
1.23 ±0.20	150	[6] ELY	63	FBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.32 ±0.15	218	[5] LINDQUIST	71	OSPK	See LINDQUIST 77

[5] Changed by us from $\Gamma(pe^-\overline{\nu}_e)/\Gamma(N\pi)$ assuming the authors used $\Gamma(p\pi^-)/\Gamma_{total} = 2/3$.
[6] Changed by us from $\Gamma(pe^-\overline{\nu}_e)/\Gamma(N\pi)$ because $\Gamma(pe^-\nu)/\Gamma(p\pi^-)$ is the directly measured quantity.

$\Gamma(p\mu^-\overline{\nu}_\mu)/\Gamma(N\pi)$ — $\Gamma_6/(\Gamma_1+\Gamma_2)$

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.57±0.35 OUR FIT					
1.57±0.35 OUR AVERAGE					
1.4 ±0.5	14	BAGGETT	72B	HBC	$K^- p$ at rest
2.4 ±0.8	9	CANTER	71B	HBC	$K^- p$ at rest
1.3 ±0.7	3	LIND	64	RVUE	
1.5 ±1.2	2	RONNE	64	FBC	

Λ DECAY PARAMETERS

See the Note on Baryon Decay Parameters in the neutron Listings. Some early results have been omitted.

α_- FOR $\Lambda \rightarrow p\pi^-$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.642±0.013 OUR AVERAGE					
0.584±0.046	8500	ASTBURY	75	SPEC	
0.649±0.023	10325	CLELAND	72	OSPK	
0.67 ±0.06	3520	DAUBER	69	HBC	From Ξ decay
0.645±0.017	10130	OVERSETH	67	OSPK	Λ from $\pi^- p$
0.62 ±0.07	1156	CRONIN	63	CNTR	Λ from $\pi^- p$

ϕ ANGLE FOR $\Lambda \rightarrow p\pi^-$ — $(\tan\phi = \beta\ /\ \gamma)$

VALUE (°)	EVTS	DOCUMENT ID		TECN	COMMENT
− 6.5± 3.5 OUR AVERAGE					
− 7.0± 4.5	10325	CLELAND	72	OSPK	Λ from $\pi^- p$
− 8.0± 6.0	10130	OVERSETH	67	OSPK	Λ from $\pi^- p$
13.0±17.0	1156	CRONIN	63	OSPK	Λ from $\pi^- p$

$\alpha_0\ /\ \alpha_- = \alpha(\Lambda \rightarrow n\pi^0)\ /\ \alpha(\Lambda \rightarrow p\pi^-)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.01 ±0.07 OUR AVERAGE					
1.000±0.068	4760	[7] OLSEN	70	OSPK	$\pi^+ n \rightarrow \Lambda K^+$
1.10 ±0.27		CORK	60	CNTR	

[7] OLSEN 70 compares proton and neutron distributions from Λ decay.

$[\alpha_-(\Lambda) + \alpha_+(\overline{\Lambda})]\ /\ [\alpha_-(\Lambda) - \alpha_+(\overline{\Lambda})]$

Zero if *CP* is conserved.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.03±0.06 OUR AVERAGE					
+0.01±0.10	770	TIXIER	88	DM2	$J/\psi \to \Lambda\overline{\Lambda}$
−0.07±0.09	4063	BARNES	87	CNTR	$\overline{p}p \to \overline{\Lambda}\Lambda$ LEAR
−0.02±0.14	10k	[8] CHAUVAT	85	CNTR	pp, $\overline{p}p$ ISR

[8] CHAUVAT 85 actually gives $\alpha_+(\overline{\Lambda})/\alpha_-(\Lambda) = -1.04 \pm 0.29$. Assumes polarization is same in $\overline{p}p \to \overline{\Lambda}$ X and $pp \to \Lambda$ X. Tests of this assumption, based on *C*-invariance and fragmentation, are satisfied by the data.

$g_A\ /\ g_V$ FOR $\Lambda \to pe^-\overline{\nu}_e$

Measurements with fewer than 500 events have been omitted. Where necessary, signs have been changed to agree with our conventions, which are given in the Note on Baryon Decay Parameters in the neutron Listings. The measurements all assume that the form factor $g_2 = 0$. See also the footnote on DWORKIN 90.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.718±0.015 OUR AVERAGE					
−0.719±0.016±0.012	37k	[9] DWORKIN	90	SPEC	$e\nu$ angular corr.
−0.70 ±0.03	7111	BOURQUIN	83	SPEC	$\Xi \to \Lambda\pi^-$
−0.734±0.031	10k	[10] WISE	81	SPEC	$e\nu$ angular correl.
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.63 ±0.06	817	ALTHOFF	73	OSPK	Polarized Λ

[9] The tabulated result assumes the weak-magnetism coupling $w \equiv g_W(0)/g_V(0)$ to be 0.97, as given by the CVC hypothesis and as assumed by the other listed measurements. However, DWORKIN 90 *measures* w to be 0.15 ± 0.30, and then $g_A/g_V = -0.731 \pm 0.016$.

[10] This experiment measures only the absolute value of g_A/g_V.

REFERENCES FOR Λ

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1986 edition (Physics Letters **170B** (1986)) or in earlier editions.

DWORKIN 90 PR D41 780 +Cox, Dukes, Overseth+ (MICH, WISC, RUTG, MINN)
TIXIER 88 PL B212 523 +Ajaltouni, Falvard, Jousset+ (DM2 Collab.)
BARNES 87 PL B199 147 + (CMU, SACL, LANL, VIEN, FREI, ILL, UPPS+)
BIAGI 86 ZPHY C30 201 + (BRIS, CERN, GEVA, HEID, LAUS, LOQM, RAL)
PDG 86 PL 170B Aguilar-Benitez, Porter+ (CERN, CIT+)
CHAUVAT 85 PL 163B 273 +Erhan, Hayes+ (CERN, UDCF, UCLA, SACL)
BOURQUIN 83 ZPHY C21 1 +Brown+ (BRIS, GEVA, HEID, LALO, RL, STRB)
COX 81 PRL 46 877 +Dworkin+ (MICH, WISC, RUTG, MINN, BNL)
PONDROM 81 PR D23 814 +Handler, Sheaff, Cox+ (WISC, MICH, RUTG, MINN)
WISE 81 PL 98B 123 +Jensen, Kreisler, Lomanno, Poster+ (MASA, BNL)
WISE 80 PL 91B 165 +Jensen, Kreisler, Lomanno, Poster+ (MASA, BNL)
SCHACHIN... 78 PRL 41 1348 Schachinger, Bunce, Cox+ (MICH, RUTG, WISC)
HELLER 77 PL 68B 480 +Overseth, Bunce, Dydak+ (MICH, WISC, HEID)
LINDQUIST 77 PR D16 2104 +Swallow, Sumner+ (EFI, OSU, ANL)
Also 76 JP G2 L211 Lindquist, Swallow+ (EFI, WUSL, OSU, ANL)
ZECH 77 NP B124 413 +Dydak, Navarria+ (SIEG, CERN, DORT, HEID)
BUNCE 76 PRL 36 1113 +Handler, March, Martin+ (WISC, MICH, RUTG)
ASTBURY 75 NP B99 30 +Gallivan, Jafar+ (LOIC, CERN, ETH, SACL)
CLAYTON 75 NP B95 130 +Bacon, Butterworth, Waters+ (LOIC, RHEL)
ALTHOFF 73 PL 43B 237 +Brown, Freytag, Heard, Heintze+ (CERN, HEID)
ALTHOFF 73B NP B66 29 +Brown, Freytag, Heard, Heintze+ (CERN, HEID)
KATZ 73 Maryland Thesis (UMD)
POULARD 73 PL 46B 135 +Givernaud, Borg (SACL)
BAGGETT 72B ZPHY 252 362 +Baggett, Eisele, Filthuth, Frehse+ (HEID)
BAGGETT 72C PL 42B 379 +Baggett, Eisele, Filthuth, Frehse, Hepp+ (HEID)
CLELAND 72 NP B40 221 +Conforto, Eaton, Gerber+ (CERN, GEVA, LUND)
HYMAN 72 PR D5 1063 +Bunnell, Derrick, Fields, Katz+ (ANL, CMU)
ALTHOFF 71 PL 37B 531 +Brown, Freytag, Heard, Heintze+ (CERN, HEID)
BALTAY 71B PR D4 670 +Bridgewater, Cooper, Habibi+ (COLU, BING)
BARONI 71 LNC 2 1256 +Petrera, Romano (ROMA)
CANTER 71 PRL 26 868 +Cole, Lee-Franzini, Loveless+ (STON, COLU)
CANTER 71B PRL 27 59 +Cole, Lee-Franzini, Loveless+ (STON, COLU)
DAHL-JENSEN 71 NC 3A 1 + (CERN, ANKA, LAUS, MPIM, ROMA)
LINDQUIST 71 PRL 27 612 +Sumner+ (EFI, WUSL, OSU, ANL)
OLSEN 70 PRL 24 843 +Pondrom, Handler, Limon, Smith+ (WISC, MICH)
DAUBER 69 PR 179 1262 +Berge, Hubbard, Merrill, Miller (LRL)
DOYLE 69 UCRL 18139 Thesis (LRL)
MALONEY 69 PRL 23 425 +Sechi-Zorn (UMD)
GRIMM 68 NC 54A 187 (HEID)
HEPP 68 ZPHY 214 71 +Schleich (HEID)
BADIER 67 PL 25B 152 +Bonnet, Briandet, Sadoulet (EPOL)
MAYEUR 67 U.Libr.Brux.Bul. 32 +Tompa, Wickens (BELG, LOUC)
OVERSETH 67 PRL 19 391 +Roth (MICH, PRIN)
PDG 67 RMP 39 1 Rosenfeld, Barbaro-Galtieri, Podolsky+ (LRL, CERN, YALE)
BURAN 66 PL 20 318 +Eivindson, Skjeggestad, Tofte+ (OSLO)
CHIEN 66 PR 152 1171 +Lach, Sandweiss, Taft, Yeh, Oren+ (YALE, BNL)
ENGELMANN 66 NC 45A 1038 +Filthuth, Alexander+ (HEID, REHO)
GIBSON 66 NC 45A 882 +Green (BRIS)
LONDON 66 PR 143 1034 +Rau, Goldberg, Lichtman+ (BNL, SYRA)
SCHMIDT 65 PR 140B 1328 (COLU)
BAGLIN 64 NC 35 977 +Bingham+ (EPOL, CERN, LOUC, RHEL, BERG)
HUBBARD 64 PR 135B 183 +Berge, Kalbfleisch, Shafer+ (LRL)
LIND 64 PR 135B 1483 +Binford, Good, Stern (WISC)
RONNE 64 PL 11 357 + (CERN, EPOL, LOUC, BERG+)
SCHWARTZ 64 UCRL 11360 Thesis (LRL)
BHOWMIK 63 NC 28 1494 +Goyal (DELH)
BLOCK 63 PR 130 766 +Gessaroli, Ratti+ (NWES, BGNA, SYRA, ORNL)
BROWN 63 PR 130 769 +Kadyk, Trilling, Roe+ (LRL, MICH)
CHRETIEN 63 PR 131 2208 + (BRAN, BROW, HARV, MIT)
CRONIN 63 PR 129 1795 +Overseth (PRIN)
ELY 63 PR 131 868 +Gidal, Kalmus, Oswald, Powell+ (LRL)
HUMPHREY 62 PR 127 1305 +Ross (LRL)
BAGLIN 60 NC 18 1043 +Bloch, Brisson, Hennessy+ (EPOL)
COLUMBIA 60 Rochester Conf. 726 Schwartz+ (COLU)
CORK 60 PR 120 1000 +Kerth, Wenzel, Cronin+ (LRL, PRIN, BNL)
CRAWFORD 59B PRL 2 266 +Cresti, Douglass, Good, Ticho+ (LRL)
EISLER 57 NC 5 1700 +Plano, Samios, Schwartz+ (COLU, BNL)

NOTE ON Λ AND Σ RESONANCES

Introduction: Since our 1990 edition, Dalitz and Deloff have reanalyzed the best old data on the $\Lambda(1405)$; see the Note with the $\Lambda(1405)$ Listing. Otherwise, there are no new results at all on Λ and Σ resonances. The field remains at a standstill and can only be revived if a kaon factory is built. For a proposed experiment at a proposed factory (KAON), see Ref. 1.

What follows is a much abbreviated version of the Note on Λ and Σ Resonances from our 1990 edition. In particular, see that edition for some representative Argand plots from partial-wave analyses.

Table 1 is an attempt to evaluate the status, both overall and channel by channel, of each Λ and Σ resonance in the full Listings. The evaluations are of course partly subjective. A blank indicates there is no evidence at all: either the relevant couplings are small or the resonance does not really exist. The main Baryon Summary Table includes only the established resonances (overall status 3 or 4 stars). A number of the 1- and 2-star entries may eventually disappear, but there are certainly many resonances yet to be discovered underlying the established ones.

Sign conventions for resonance couplings: In terms of the isospin-0 and -1 elastic scattering amplitudes A_0 and A_1, the amplitude for $K^-p \to \overline{K}^0 n$ scattering is $\pm(A_1 - A_0)/2$, where the sign depends on conventions used in conjunction with the Clebsch-Gordan coefficients (such as, is the baryon or the meson the "first" particle). If this reaction is partial-wave analyzed and if the overall phase is chosen so that, say, the $\Sigma(1775)D_{15}$ amplitude at resonance points along the positive imaginary axis (points "up"), then any Σ at resonance will point "up" and any Λ at resonance will point "down" (along the negative imaginary axis). Thus the phase at resonance determines the isospin. The above ignores background amplitudes in the resonating partial waves.

That is the basic idea. In a similar but somewhat more complicated way, the phases of the $\overline{K}N \to \Lambda\pi$ and $\overline{K}N \to \Sigma\pi$ amplitudes for a resonating wave help determine the SU(3) multiplet to which the resonance belongs. Again, a convention has to be adopted for some overall arbitrary phases: which way is "up"? Our convention is that of Levi-Setti[2] and is shown in Figure 1, which also compares experimental results with theoretical predictions for the signs of several resonances. In the Listings, a + or − sign in front of a measurement of an inelastic resonance coupling indicates the sign (the *absence* of a sign means that the sign is not determined, *not* that it is positive). For more details, see Appendix II of our 1982 edition.[3]

Errors on masses and widths: The errors quoted on resonance parameters from partial-wave analyses are often only statistical, and the parameters can change by more than these errors when a different parametrization of the waves is used. Furthermore, the different analyses use more or less the same data, so it is not really appropriate to treat the different determinations of the resonance parameters as independent or to average them together. In any case, the spread of the masses, widths, and branching fractions from the different analyses is certainly a better indication of the uncertainties than are the quoted errors. In the Baryon Summary Table, we usually give a range reflecting the spread of the values rather than a particular value with error.

For three states, the $\Lambda(1520)$, the $\Lambda(1820)$, and the $\Sigma(1775)$, there is enough information to make an overall fit to the various branching fractions. It is then necessary to use the quoted errors, but the errors obtained from the fit should not be taken seriously.

Production experiments: Partial-wave analyses of course separate partial waves, whereas a peak in a cross section or an invariant mass distribution usually cannot be disentangled from background and analyzed for its quantum numbers; and more than one resonance may be contributing to the peak. Results from partial-wave analyses and from production experiments are generally kept separate in the Listings, and in the Baryon Summary Table results from production experiments are used only for the low-mass states. The $\Sigma(1385)$ and $\Lambda(1405)$ of course lie below the $\overline{K}N$ threshold and nearly everything about them is learned from production experiments; and production and formation experiments agree quite well in the case of $\Lambda(1520)$ and results have been combined. There is some disagreement between production and formation experiments in the 1600–1700 MeV region: see the Note on the $\Sigma(1670)$.

References

1. D.V. Bugg and D. Axen, Z. Phys. **C46**, S31 (1990).
2. R. Levi-Setti, in *Proceedings of the Lund International Conference on Elementary Particles* (Lund, 1969), p. 339.
3. Particle Data Group, Phys. Lett. **111B** (1982).

Table 1. The status of the Λ and Σ resonances. Only those with an overall status of *** or **** are included in the main Baryon Summary Table.

			Status as seen in —			
Particle	$L_{I\cdot 2J}$	Overall status	$N\overline{K}$	$\Lambda\pi$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	P_{01}	****		F		$N\pi$(weakly)
$\Lambda(1405)$	S_{01}	****	****	o	****	
$\Lambda(1520)$	D_{03}	****	****	r	****	$\Lambda\pi\pi$, $\Lambda\gamma$
$\Lambda(1600)$	P_{01}	***	***	b	**	
$\Lambda(1670)$	S_{01}	****	****	i	****	$\Lambda\eta$
$\Lambda(1690)$	D_{03}	****	****	d	****	$\Lambda\pi\pi$, $\Sigma\pi\pi$
$\Lambda(1800)$	S_{01}	***	***	d	**	$N\overline{K}^*$, $\Sigma(1385)\pi$
$\Lambda(1810)$	P_{01}	***	***	e	**	$N\overline{K}^*$
$\Lambda(1820)$	F_{05}	****	****	n	****	$\Sigma(1385)\pi$
$\Lambda(1830)$	D_{05}	****	***	F	****	$\Sigma(1385)\pi$
$\Lambda(1890)$	P_{03}	****	****	o	**	$N\overline{K}^*$, $\Sigma(1385)\pi$
$\Lambda(2000)$		*		r	*	$\Lambda\omega$, $N\overline{K}^*$
$\Lambda(2020)$	F_{07}	*	*	b	*	
$\Lambda(2100)$	G_{07}	****	****	i	***	$\Lambda\omega$, $N\overline{K}^*$
$\Lambda(2110)$	F_{05}	***	**	d	*	$\Lambda\omega$, $N\overline{K}^*$
$\Lambda(2325)$	D_{03}	*	*	d		$\Lambda\omega$
$\Lambda(2350)$		***	***	e	*	
$\Lambda(2585)$		**	**	n		
$\Sigma(1193)$	P_{11}	****				$N\pi$(weakly)
$\Sigma(1385)$	P_{13}	****		****	****	
$\Sigma(1480)$		*	*	*	*	
$\Sigma(1560)$		**		**	**	
$\Sigma(1580)$	D_{13}	**	*	*		
$\Sigma(1620)$	S_{11}	**	**	*	*	
$\Sigma(1660)$	P_{11}	***	***	*	**	
$\Sigma(1670)$	D_{13}	****	****	****	****	several others
$\Sigma(1690)$		**	*	**	*	$\Lambda\pi\pi$
$\Sigma(1750)$	S_{11}	***	***	**	*	$\Sigma\eta$
$\Sigma(1770)$	P_{11}	*				
$\Sigma(1775)$	D_{15}	****	****	****	***	several others
$\Sigma(1840)$	P_{13}	*	*	**	*	
$\Sigma(1880)$	P_{11}	**	**	**		$N\overline{K}^*$
$\Sigma(1915)$	F_{15}	****	***	****	***	$\Sigma(1385)\pi$
$\Sigma(1940)$	D_{13}	***	*	***	**	quasi-2-body
$\Sigma(2000)$	S_{11}	*		*		$N\overline{K}^*$, $\Lambda(1520)\pi$
$\Sigma(2030)$	F_{17}	****	****	****	**	several others
$\Sigma(2070)$	F_{15}	*	*		*	
$\Sigma(2080)$	P_{13}	**		**		
$\Sigma(2100)$	G_{17}	*		*	*	
$\Sigma(2250)$		***	***	*	*	
$\Sigma(2455)$		**	*			
$\Sigma(2620)$		**	*			
$\Sigma(3000)$		*	*	*		
$\Sigma(3170)$		*				multi-body

**** Existence is certain, and properties are at least fairly well explored.
*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.
** Evidence of existence is only fair.
* Evidence of existence is poor.

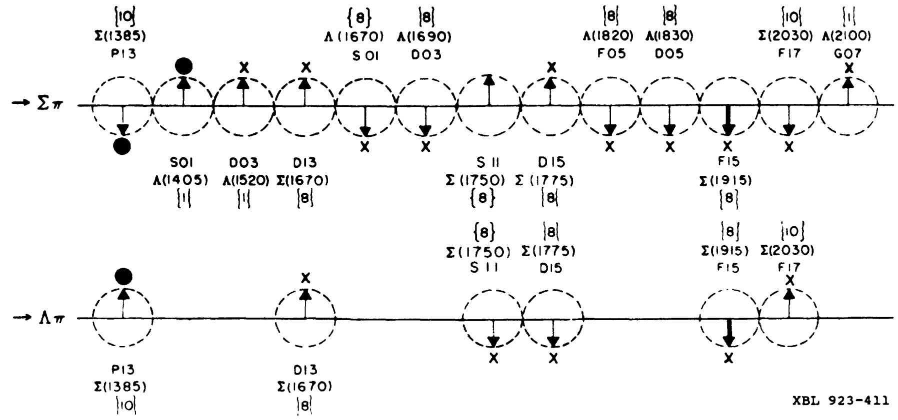


Figure 1. The signs of the imaginary parts of resonating amplitudes in the $\overline{K}N \to \Lambda\pi$ and $\Sigma\pi$ channels. The signs of the $\Sigma(1385)$ and $\Lambda(1405)$, marked with a •, are set by convention, and then the others are determined relative to them. The signs required by the SU(3) assignments of the resonances are shown with an arrow, and the experimentally determined signs are shown with an ×.

$\Lambda(1405)$ S_{01}

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗∗

NOTE ON THE $\Lambda(1405)$

(by R.H. Dalitz, Oxford University)

It is generally accepted that the $\Lambda(1405)$ is a well-established $J^P = 1/2^-$ resonance. It is assigned to the lowest $L = 1$ supermultiplet of the 3-quark system and paired with the $J^P = 3/2^-$ $\Lambda(1520)$. Lying about 30 MeV below the $N\overline{K}$ threshold, the $\Lambda(1405)$ can be observed directly only as a resonance bump in the $(\Sigma\pi)^0$ subsystem in final states of production experiments. It was first reported by ALSTON 61B in the reaction $K^-p \to \Sigma\pi\pi\pi$ at 1.15 GeV/c and has since been seen in at least eight other experiments, so there is no doubt that it exists.

Only two production experiments have had enough events for a detailed analysis: THOMAS 73, with about 400 $\Sigma^\pm\pi^\mp$ events from $\pi^-p \to K^0(\Sigma\pi)^0$ at 1.69 GeV/c; and HEMINGWAY 85, with 766 $\Sigma^+\pi^-$ and 1106 $\Sigma^-\pi^+$ events from $K^-p \to (\Sigma\pi\pi)^+\pi^-$ at 4.2 GeV/c, after the selections $1600 \leq M(\Sigma\pi\pi)^+ \leq 1720$ MeV and momentum transfer ≤ 1.0 (GeV/c)^2 to purify the $\Lambda(1405) \to (\Sigma\pi)^0$ sample. These experiments agree on a mass of about 1395–1400 MeV and a width of about 60 MeV. (Hemingway's mass of 1391 ± 1 MeV is from his best, but unacceptably poor, Breit-Wigner fit.)

The Byers-Fenster tests on these data allow any spin and either parity: neither J nor P has yet been determined *directly.* The early indications for $J^P = 1/2^-$ came from finding $\text{Re}\,A(I=0)$ to be large and negative in a constant-scattering-length analysis of low-energy $N\overline{K}$ reaction data (see KIM 65, SAKITT 65, and earlier references cited therein). The first multichannel energy-dependent K-matrix analysis (KIM 67) strengthened the case for a resonance around 1400–1420 MeV strongly coupled to the $I = 0$ S-wave $N\overline{K}$ system.

THOMAS 73 and HEMINGWAY 85 both found the $\Lambda(1405)$ bump to be asymmetric and not well-fitted by a Breit-Wigner resonance function with constant parameters. The asymmetry involves a rapid fall in intensity as the $N\overline{K}$ threshold energy is approached from below. This is readily understood as due to a strong coupling of the $\Lambda(1405)$ to the S-wave $N\overline{K}$ channel (see DALITZ 81). This striking S-shaped cusp behavior at a new threshold is characteristic of S-wave coupling; the other below-threshold hyperon, the $\Sigma(1385)$, has no such threshold distortion because its $N\overline{K}$ coupling is P-wave. For the $\Lambda(1405)$, this asymmetry is the *sole direct evidence* that $J^P = 1/2^-$.

Following the early work cited above, a considerable literature has developed on proper procedures for phenomenological extrapolation below the $N\overline{K}$ threshold, partly in order to strengthen the evidence for the spin-parity of the $\Lambda(1405)$ and partly to provide an estimate for the amplitude $f(N\overline{K})$ in the unphysical domain below the $N\overline{K}$ threshold, needed for the evaluation of the dispersion relation for $N\overline{K}$ and NK forward scattering amplitudes. For recent reviews, see MILLER 84 and BARRETT 89. In most recent work, the $(\Sigma\pi)^0$ production spectrum is included in the data fitted (see, *e.g.*, CHAO 73, MARTIN 81).

It is now accepted that the data can be fitted only with an S-wave pole in the reaction amplitudes below $N\overline{K}$ threshold (see, however, FINK 90), but there is still controversy about the physical origin of this pole (for a review, see DALITZ 81 and DALITZ 82). Two extreme possibilities are: (a) an $L = 1$ unitary-flavor-singlet *uds* state coupled with the S-wave meson-baryon systems; or (b) an unstable $N\overline{K}$ bound state, analogous to the (stable) deuteron in the NN system. The problem with (a) is that the $\Lambda(1405)$ mass is so much lower than that of its partner, the $\Lambda(1520)$. This requires very large spin-orbit splittings in the QCD-inspired nonrelativistic quark model (see, however, ARIMA 90), and such splittings are considered to be excluded on other grounds (see ISGUR 80, CAPSTICK 86, and CAPSTICK 89). However, if (b) holds, another $J^P = 1/2^- \Lambda$ is needed to replace the $\Lambda(1405)$ in the $L = 1$ supermultiplet, and it would have to lie close to the $\Lambda(1520)$, a region already well-explored by $N\overline{K}$ experiments without result. Intermediate structures are possible; for example, the cloudy bag model allows the configurations (a) and (b) to mix and finds the intensity of configuration (a) in the $\Lambda(1405)$ to be only 14% (VEIT 84, VEIT 85, JENNINGS 86). Such models naturally predict a second $1/2^-$ Λ close to the $\Lambda(1520)$.

The determination of the mass and width of the resonance from $(\Sigma\pi)^0$ data is usually based on the "Watson approximation," which states that the production rate $R(\Sigma\pi)$ of the final $(\Sigma\pi)^0$ state has a mass dependence proportional to $(\sin^2\delta_{\Sigma\pi})/q$, q being the $\Sigma\pi$ c.m. momentum, in a $\Sigma\pi$ mass range where $\delta_{\Sigma\pi}$ is not far from $\pi/2$ and only the $\Sigma\pi$ channel is open, *i.e.*, between the $\Sigma\pi$ and the $N\overline{K}$ thresholds. Then $q\,R(\Sigma\pi)$ is proportional to $\sin^2\delta_{\Sigma\pi}$, and the mass M may be defined as the mass at which $\sin^2\delta_{\Sigma\pi} = 1$. The width Γ may be determined from the rate at which $\delta_{\Sigma\pi}$ goes through $\pi/2$, or from the FWHM; this is a matter of convention.

This determination of M and Γ from the data suffers from the following defects:

(i) The determination of $\sin^2\delta_{\Sigma\pi}$ requires that $R(\Sigma\pi)$ be scaled to give $\sin^2\delta_{\Sigma\pi} = 1$ at the peak for the best fit to the data; *i.e.*, the bump must be *assumed* to arise from a resonance. However, for the $\Lambda(1405)$ this assumption is supported by the analysis of the low-energy $N\overline{K}$ data and its extrapolation below the $N\overline{K}$ threshold.

(ii) Owing to the nearby $N\overline{K}$ threshold, the shape of the best fit to the $M(\Sigma\pi)$ bump is uncertain. For energies below this threshold at $E_{N\overline{K}}$, the general form for $\delta_{\Sigma\pi}$ is

$$q\cot\delta_{\Sigma\pi} = \frac{1+\kappa\alpha}{\gamma+\kappa(\alpha\gamma-\beta^2)}\ .$$

Here α, β, and γ are the (generally energy-dependent) NN, $N\Sigma$, and $\Sigma\Sigma$ elements of the $I = 0$ S-wave K-matrix for the $(\Sigma\pi, N\overline{K})$ system, and κ is the magnitude of the (imaginary) c.m. momentum k_K for the $N\overline{K}$ system below threshold. The elements α, β, γ are real functions of E; they have no branch cuts at the $\Sigma\pi$ and $N\overline{K}$ thresholds, but they are permitted to have poles in E along the real E axis. The resonance asymmetry arises from the effect of κ on $\delta_{\Sigma\pi}$. We note that $\delta_{\Sigma\pi} = \pi/2$ when $\kappa = -1/\alpha$.

Accepting this close connection of $\delta_{\Sigma\pi}$ with the low-energy $N\overline{K}$ data, it is natural to analyze the two sets of data together (*e.g.*, MARTIN 81), and there is now a large body of accurate $N\overline{K}$ data for laboratory momenta between 100 and 300 MeV/c (see MILLER 84). The two sets of data span c.m. energies from 1370 MeV to 1490 MeV, and the K-matrix elements will not be energy independent over such a broad range. For the $I = 0$ channels, a linear energy dependence for K^{-1} has been adopted routinely ever since the work of KIM 67, and it is essential when fitting the $q\,R(\Sigma\pi)$ and $N\overline{K}$ data together. However, $q\,R(\Sigma\pi)$ is not always well-fitted in this procedure; the value obtained for M varies a good deal with the type of fit, not a surprising result when the $\Sigma\pi$ mass spectrum contributes only 9 data points in a total of about 200. The mass obtained for the $\Lambda(1405)$ from such an overall fit is not necessarily much better than from a fit using the $q\,R(\Sigma\pi)$ data alone; it may be a function of the representation used—K-matrix, K^{-1}-matrix, relativistic-separable or nonseparable-potentials, etc.— to describe these interactions over the full range of energy. DALITZ 90 fitted the $qR(\Sigma^+\pi^-)$ Hemingway data with each of the first three representations, constrained to the I=0 $N\overline{K}$ threshold scattering length from $E > E_{N\overline{K}}$ data. The (nonseparable) meson-exchange potentials of MÜLLER-GROELING 90, fitted to the $E > E_{N\overline{K}}$ data (and low-energy NK data), predicted an $N\overline{K}$ unstable bound state with mass and width compatible with the $\Lambda(1405)$.

The present status of the $\Lambda(1405)$ thus depends heavily on theoretical arguments, a somewhat unsatisfactory basis for a four-star rating. Nevertheless, there is no reason known to doubt its existence or quantum numbers. A measurement of the energy-level shifts and widths for the atomic levels of kaonic hydrogen (and kaonic deuterium) would give a valuable check on our analyses of the $(\Sigma\pi, N\overline{K})$ amplitudes, since the energy of the K^-p atom lies roughly midway between those for the two sets of data. The three measurements of $(\Delta E - i\Gamma/2)$ for kaonic hydrogen are inconsistent with one another and require that the sign of $\mathrm{Re}[A(I=0) + A(I=1)]$ be opposite that deduced from $N\overline{K}$ reaction data (see BATTY 89). Accurate measurements of $(\Delta E - i\Gamma/2)$ values for kaonic hydrogen are badly needed, but may not be possible until the KAON factory becomes operational.

To settle the nature of the $\Lambda(1405)$ will require much further work, both experimental and theoretical. Higher-statistics experiments on the production and decay of the $\Lambda(1405)$ are needed, but suitable K^- beams will not be available until KAON. The low-energy reaction cross sections, especially for the $\overline{K}^0 p$ interactions, last studied 25 years ago, need to be better determined.

Λ(1405) MASS

PRODUCTION EXPERIMENTS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1406.5± 4.0		[1] DALITZ	91		M-matrix fit
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1391 ± 1	700	[1] HEMINGWAY	85	HBC	$K^- p$ 4.2 GeV/c
~ 1405	400	[2] THOMAS	73	HBC	$\pi^- p$ 1.69 GeV/c
1405	120	BARBARO-...	68B	DBC	$K^- d$ 2.1–2.7 GeV/c
1400 ± 5	67	BIRMINGHAM	66	HBC	$K^- p$ 3.5 GeV/c
1382 ± 8		ENGLER	65	HDBC	$\pi^- p$, $\pi^+ d$ 1.68 GeV/c
1400 ±24		MUSGRAVE	65	HBC	$\overline{p} p$ 3–4 GeV/c
1410		ALEXANDER	62	HBC	$\pi^- p$ 2.1 GeV/c
1405		ALSTON	62	HBC	$K^- p$ 1.2–0.5 GeV/c
1405		ALSTON	61B	HBC	$K^- p$ 1.15 GeV/c

EXTRAPOLATIONS BELOW $N\overline{K}$ THRESHOLD

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1411	[3] MARTIN	81		K-matrix fit
1406	[4] CHAO	73	DPWA	0–range fit (sol. B)
1421	MARTIN	70	RVUE	Constant K-matrix
1416 ±4	MARTIN	69	HBC	Constant K-matrix
1403 ±3	KIM	67	HBC	K-matrix fit
1407.5±1.2	[5] KITTEL	66	HBC	0–effective-range fit
1410.7±1.0	KIM	65	HBC	0–effective-range fit
1409.6±1.7	[5] SAKITT	65	HBC	0–effective-range fit

$\Lambda(1405)$ WIDTH

PRODUCTION EXPERIMENTS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
50 ± 2		[1] DALITZ	91		M-matrix fit
• • • We do not use the following data for averages, fits, limits, etc. • • •					
32 ± 1	700	[1] HEMINGWAY	85	HBC	$K^- p$ 4.2 GeV/c
45 to 55	400	[2] THOMAS	73	HBC	$\pi^- p$ 1.69 GeV/c
35	120	BARBARO-...	68B	DBC	$K^- d$ 2.1–2.7 GeV/c
50 ±10	67	BIRMINGHAM	66	HBC	$K^- p$ 3.5 GeV/c
89 ±20		ENGLER	65	HDBC	
60 ±20		MUSGRAVE	65	HBC	
35 ± 5		ALEXANDER	62	HBC	
50		ALSTON	62	HBC	
20		ALSTON	61B	HBC	

EXTRAPOLATIONS BELOW $N\overline{K}$ THRESHOLD

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
30	[3] MARTIN	81		K-matrix fit
55	[4,6] CHAO	73	DPWA	0–range fit (sol. B)
20	MARTIN	70	RVUE	Constant K-matrix
29 ±6	MARTIN	69	HBC	Constant K-matrix
50 ±5	KIM	67	HBC	K-matrix fit
34.1±4.1	[5] KITTEL	66	HBC	
37.0±3.2	KIM	65	HBC	
28.2±4.1	[5] SAKITT	65	HBC	

$\Lambda(1405)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Sigma\pi$	100 %
Γ_2	$\Lambda\gamma$	
Γ_3	$\Sigma^0\gamma$	
Γ_4	$N\overline{K}$	

$\Lambda(1405)$ PARTIAL WIDTHS

$\Gamma(\Lambda\gamma)$ — Γ_2

VALUE (keV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
27±8	BURKHARDT	91	Isobar model fit

$\Gamma(\Sigma^0\gamma)$ — Γ_3

VALUE (keV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
10 ± 4 or 23 ± 7	BURKHARDT	91	Isobar model fit

$\Lambda(1405)$ BRANCHING RATIOS

$\Gamma(N\overline{K})/\Gamma(\Sigma\pi)$ — Γ_4/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3	95	HEMINGWAY	85	HBC	$K^- p$ 4.2 GeV/c

$\Lambda(1405)$ FOOTNOTES

[1] DALITZ 91 fits the HEMINGWAY 85 data.
[2] THOMAS 73 data is fit by CHAO 73 (see next section).
[3] The MARTIN 81 fit includes the $K^{\pm} p$ forward scattering amplitudes and the dispersion relations they must satisfy.
[4] See also the accompanying paper of THOMAS 73.
[5] Data of SAKITT 65 are used in the fit by KITTEL 66.
[6] An asymmetric shape, with $\Gamma/2 = 41$ MeV below resonance, 14 MeV above.

$\Lambda(1405)$ REFERENCES

BURKHARDT 91 PR C44 607 +Lowe (NOTT, UNM, BIRM)
DALITZ 91 JP G17 289 +Deloff (OXF, WINR)
HEMINGWAY 85 NP B253 742 (CERN) J
MARTIN 81 NP B179 33 (DURH)
CHAO 73 NP B56 46 +Kraemer, Thomas, Martin (RHEL, CMU, LOUC)
THOMAS 73 NP B56 15 +Engler, Fisk, Kraemer (CMU) J
MARTIN 70 NP B16 479 +Ross (DURH)
MARTIN 69 PR 183 1352 +Sakitt (LOUC, BNL)
Also 69B PR 183 1345 Martin, Sakitt (LOUC, BNL)
BARBARO-... 68B PRL 21 573 Barbaro-Galtieri, Chadwick+ (LRL, SLAC)
KIM 67 PRL 19 1074 (YALE)
BIRMINGHAM 66 PR 152 1148 (BIRM, GLAS, LOIC, OXF, RHEL)
KITTEL 66 PL 21 349 +Otter, Wacek (VIEN)
ENGLER 65 PRL 15 224 +Fisk, Kraemer, Meltzer, Westgard+ (CMU, BNL) IJ
KIM 65 PRL 14 29 (COLU)
MUSGRAVE 65 NC 35 735 +Petmezas+ (BIRM, CERN, EPOL, LOIC, SACL)
SAKITT 65 PR 139B 719 +Day, Glasser, Seeman, Friedman+ (UMD, LRL)
ALEXANDER 62 PRL 8 447 +Kalbfleisch, Miller, Smith (LRL) I
ALSTON 62 CERN Conf. 311 +Alvarez, Ferro-Luzzi+ (LRL) I
ALSTON 61B PRL 6 698 +Alvarez, Eberhard, Good+ (LRL) I

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SIEGEL 88 PR C38 2221 +Weise (REGE)
WORKMAN 88 PR D37 3117 +Fearing (TRIU)
SCHNICK 87 PRL 58 1719 +Landau (ORST)
CAPSTICK 86 PR D34 2809 +Isgur (TNTO)
JENNINGS 86 PL B176 229 (TRIU)
MALTMAN 86 PR D34 1372 +Isgur (LANL, TNTO)
ZHONG 86 PL B171 471 +Thomas, Jennings, Barrett (ADLD, TRIU, SURR)
BURKHARDT 85 NP A440 653 +Lowe, Rosenthal (NOTT, BIRM, WMIU)
DAREWYCH 85 PR D32 1765 +Koniuk, Isgur (YORK, TNTO)
VEIT 85 PR D31 1033 +Jennings, Thomas, Barrett (TRIU, ADLD, SURR)
KIANG 84 PR C30 1638 +Kumar, Nogami, VanDijk (DALH, MCMS)
MILLER 84 (LOUC)
Conf. Intersections between Particle and Nuclear Physics, p. 783
VANDIJK 84 PR D30 937 (MCMS)
VEIT 84 PL 137B 415 +Jennings, Barrett, Thomas (TRIU, SURR, CERN)
DALITZ 82 +McGinley, Belyea, Anthony (OXF)
Heidelberg Conf., p. 201
DALITZ 81 +McGinley (OXF)
Low and Intermediate Energy Kaon-Nucleon Physics, p.381
MARTIN 81B Low and Intermediate Energy Kaon-Nucleon Phys., p. 97 (DURH)
OADES 77 NC 42A 462 +Rasche (AARH, ZURI)
SHAW 73 Purdue Conf. 417 (UCI)
BARBARO-... 72 LBL-555 Barbaro-Galtieri (LBL)
DOBSON 72 PR D6 3256 +McElhaney (HAWA)
RAJASEKA... 72 PR D5 610 Rajasekaran (TATA)
CLINE 71 PRL 26 1194 +Laumann, Mapp (WISC)
MARTIN 71 PL 35B 62 +Martin, Ross (DURH, LOUC, RHEL)
DALITZ 67 PR 153 1617 +Wong, Rajasekaran (OXF, BOMB)
DONALD 66 PL 22 711 +Edwards, Lys, Nisar, Moore (LIVP)
KADYK 66 PRL 17 599 +Oren, Goldhaber, Goldhaber, Trilling (LRL)
ABRAMS 65 PR 139B 454 +Sechi-Zorn (UMD)

$\Lambda(1520)$ D_{03}

$I(J^P) = 0(\frac{3}{2}^-)$ Status: ∗∗∗∗

Discovered by FERRO-LUZZI 62; the elaboration in WATSON 63 is the classic paper on the Breit-Wigner analysis of a multichannel resonance.

The measurements of the mass, width, and elasticity published before 1975 are now obsolete and have been omitted. They were last listed in our 1982 edition Physics Letters **111B** (1982).

Production and formation experiments agree quite well, so they are listed together here.

$\Lambda(1520)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1519.5 ±1.0 OUR ESTIMATE					
1519.50±0.18 OUR AVERAGE					
1517.3 ±1.5	300	BARBER	80D	SPEC	$\gamma p \to \Lambda(1520) K^+$
1519 ±1		GOPAL	80	DPWA	$\overline{K} N \to \overline{K} N$
1517.8 ±1.2	5k	BARLAG	79	HBC	$K^- p$ 4.2 GeV/c
1520.0 ±0.5		ALSTON-...	78	DPWA	$\overline{K} N \to \overline{K} N$
1519.7 ±0.3	4k	CAMERON	77	HBC	$K^- p$ 0.96–1.36 GeV/c
1519 ±1		GOPAL	77	DPWA	$\overline{K} N$ multichannel
1519.4 ±0.3	2000	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c

Λ(1520) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
15.6 ±1.0 OUR ESTIMATE					
15.59±0.27 OUR AVERAGE					
16.3 ±3.3	300	BARBER	80D	SPEC	$\gamma p \rightarrow \Lambda(1520) K^+$
16 ±1		GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
14 ±3	677	[1] BARLAG	79	HBC	$K^- p$ 4.2 GeV/c
15.4 ±0.5		ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
16.3 ±0.5	4k	CAMERON	77	HBC	$K^- p$ 0.96–1.36 GeV/c
15.0 ±0.5		GOPAL	77	DPWA	$\overline{K}N$ multichannel
15.5 ±1.6	2000	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c

Λ(1520) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	45 ± 1%
Γ_2	$\Sigma\pi$	42 ± 1%
Γ_3	$\Lambda\pi\pi$	10 ± 1%
Γ_4	$\Sigma(1385)\pi$	
Γ_5	$\Sigma(1385)\pi$ ($\rightarrow \Lambda\pi\pi$)	
Γ_6	$\Lambda(\pi\pi)_{S\text{-wave}}$	
Γ_7	$\Sigma\pi\pi$	0.9 ± 0.1%
Γ_8	$\Lambda\gamma$	0.8 ± 0.2%
Γ_9	$\Sigma^0\gamma$	

CONSTRAINED FIT INFORMATION

An overall fit to 9 branching ratios uses 24 measurements and one constraint to determine 6 parameters. The overall fit has a $\chi^2 =$ 16.5 for 19 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left<\delta x_i \delta x_j\right>/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−63				
x_3	−32	−33			
x_7	−4	−3	−1		
x_8	−9	−8	−4	0	
x_9	−24	−21	−10	−1	−2
	x_1	x_2	x_3	x_7	x_8

Λ(1520) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

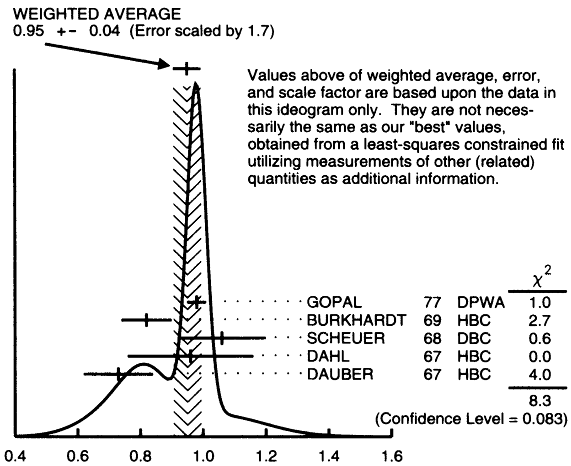
VALUE	DOCUMENT ID		TECN	COMMENT
0.45 ±0.01 OUR ESTIMATE				
0.448±0.007 OUR FIT Error includes scale factor of 1.2.				
0.455±0.011 OUR AVERAGE				
0.47 ±0.02	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.45 ±0.03	ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.448±0.014	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.47 ±0.01	GOPAL	77	DPWA	See GOPAL 80
0.42	MAST	76	HBC	$K^- p \rightarrow \overline{K}^0 n$

$\Gamma(\Sigma\pi)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.42 ±0.01 OUR ESTIMATE				
0.421±0.007 OUR FIT Error includes scale factor of 1.2.				
0.423±0.011 OUR AVERAGE				
0.426±0.014	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c
0.418±0.017	BARBARO-...	69B	HBC	$K^- p$ 0.28–0.45 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.46	KIM	71	DPWA	K-matrix analysis

$\Gamma(\Sigma\pi)/\Gamma(N\overline{K})$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.940±0.026 OUR FIT Error includes scale factor of 1.3.				
0.95 ±0.04 OUR AVERAGE Error includes scale factor of 1.7. See the ideogram below.				
0.98 ±0.03	[2] GOPAL	77	DPWA	$\overline{K}N$ multichannel
0.82 ±0.08	BURKHARDT	69	HBC	$K^- p$ 0.8–1.2 GeV/c
1.06 ±0.14	SCHEUER	68	DBC	$K^- N$ 3 GeV/c
0.96 ±0.20	DAHL	67	HBC	$\pi^- p$ 1.6–4 GeV/c
0.73 ±0.11	DAUBER	67	HBC	$K^- p$ 2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.06 ±0.12	BERTHON	74	HBC	Quasi-2-body σ
1.72 ±0.78	MUSGRAVE	65	HBC	



$\Gamma(\Sigma\pi)/\Gamma(N\overline{K})$

$\Gamma(\Lambda\pi\pi)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10 ±0.01 OUR ESTIMATE				
0.095±0.005 OUR FIT Error includes scale factor of 1.2.				
0.096±0.008 OUR AVERAGE Error includes scale factor of 1.6.				
0.091±0.006	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c
0.11 ±0.01	[3] MAST	73B	IPWA	$K^- p \rightarrow \Lambda\pi\pi$

$\Gamma(\Lambda\pi\pi)/\Gamma(N\overline{K})$ Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.213±0.012 OUR FIT Error includes scale factor of 1.2.				
0.202±0.021 OUR AVERAGE				
0.22 ±0.03	BURKHARDT	69	HBC	$K^- p$ 0.8–1.2 GeV/c
0.19 ±0.04	SCHEUER	68	DBC	$K^- N$ 3 GeV/c
0.17 ±0.05	DAHL	67	HBC	$\pi^- p$ 1.6–4 GeV/c
0.21 ±0.18	DAUBER	67	HBC	$K^- p$ 2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.27 ±0.13	BERTHON	74	HBC	Quasi-2-body σ
0.2	KIM	71	DPWA	K-matrix analysis

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi\pi)$ Γ_2/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
4.42±0.25 OUR FIT Error includes scale factor of 1.2.				
3.9 ±0.6 OUR AVERAGE				
3.9 ±1.0	UHLIG	67	HBC	$K^- p$ 0.9–1.0 GeV/c
3.3 ±1.1	BIRMINGHAM	66	HBC	$K^- p$ 3.5 GeV/c
4.5 ±1.0	ARMENTEROS	65C	HBC	

$\Gamma(\Sigma(1385)\pi)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.041±0.005	CHAN	72	HBC	$K^- p \rightarrow \Lambda\pi\pi$

$\Gamma(\Sigma(1385)\pi\ (\rightarrow \Lambda\pi\pi))/\Gamma(\Lambda\pi\pi)$ Γ_5/Γ_3

The $\Lambda\pi\pi$ mode is largely due to $\Sigma(1385)\pi$. Only the values of $(\Sigma(1385)\pi)$ / $(\Lambda 2\pi)$ given by MAST 73B and CORDEN 75 are based on real 3-body partial-wave analyses. The discrepancy between the two results is essentially due to the different hypotheses made concerning the shape of the $(\pi\pi)_{S\text{-wave}}$ state.

VALUE	DOCUMENT ID		TECN	COMMENT
0.58±0.22	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c
0.82±0.10	[4] MAST	73B	IPWA	$K^- p \rightarrow \Lambda\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.39±0.10	[5] BURKHARDT	71	HBC	$K^- p \rightarrow (\Lambda\pi\pi)\pi$

$\Gamma(\Lambda(\pi\pi)_{S\text{-wave}})/\Gamma(\Lambda\pi\pi)$ Γ_6/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
0.20±0.08	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c

$\Gamma(\Sigma\pi\pi)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.009 ±0.001 OUR ESTIMATE				
0.0086±0.0005 OUR FIT				
0.0086±0.0005 OUR AVERAGE				
0.007 ±0.002	[6] CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c
0.0085±0.0006	[7] MAST	73	MPWA	$K^- p \rightarrow \Sigma\pi\pi$
0.010 ±0.0015	BARBARO-...	69B	HBC	$K^- p$ 0.28–0.45 GeV/c

$\Gamma(\Lambda\gamma)/\Gamma_{total}$ — Γ_8/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.008 ±0.002 OUR ESTIMATE					
0.0079±0.0014 OUR FIT					
0.0080±0.0014	238	MAST	68B	HBC	Using $\Gamma(N\overline{K})/\Gamma_{total}$=0.45

$\Gamma(\Sigma^0\gamma)/\Gamma_{total}$ — Γ_9/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0195±0.0034 OUR FIT				
0.02 ±0.0035	[8] MAST	68B	HBC	Not measured; see note

$\Lambda(1520)$ FOOTNOTES

[1] From the best-resolution sample of $\Lambda\pi\pi$ events only.
[2] The $\overline{K}N \to \Sigma\pi$ amplitude at resonance is $+0.46 \pm 0.01$.
[3] Assumes $\Gamma(N\overline{K})/\Gamma_{total} = 0.46 \pm 0.02$.
[4] Both $\Sigma(1385)\pi$ DS_{03} and $\Sigma(\pi\pi)$ DP_{03} contribute.
[5] The central bin (1514–1524 MeV) gives 0.74 ± 0.10; other bins are lower by 2-to-5 standard deviations.
[6] Much of the $\Sigma\pi\pi$ decay proceeds via $\Sigma(1385)\pi$.
[7] Assumes $\Gamma(N\overline{K})/\Gamma_{total} = 0.46$.
[8] Calculated from $\Gamma(\Lambda\gamma)/\Gamma_{total}$, assuming SU(3). Needed to constrain the sum of all the branching ratios to be unity.

$\Lambda(1520)$ REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
BARBER	80D	ZPHY C7 17	+Dainton, Lee, Marshall+	(DARE, LANC, SHEF)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
BARLAG	79	NP B149 220	+Blokzijl, Jongejans+	(AMST, CERN, NIJM, OXF)
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MAST	76	PR D14 13	+Alston-Garnjost, Bangerter+	(LBL)
CORDEN	75	NP B84 306	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM)
BERTHON	74	NC 21A 146	+Tristram+	(CDEF, RHEL, SACL, STRB)
MAST	73	PR D7 3212	+Bangerter, Alston-Garnjost+	(LBL) IJP
MAST	73B	PR D7 5	+Bangerter, Alston-Garnjost+	(LBL) IJP
CHAN	72	PRL 28 256	+Button-Shafer, Hertzbach, Kofler+	(MASA, YALE)
BURKHARDT	71	NP B27 64	+Filthuth, Kluge+	(HEID, CERN, SACL)
KIM	71	PRL 27 356		(HARV) IJP
Also	70	Duke Conf. 161	Kim	(HARV) IJP
BARBARO-...	69B	Lund Conf. 352	Barbaro-Galtieri, Bangerter, Mast, Tripp	(LRL)
Also	70	Duke Conf. 95	Tripp	(LRL)
BURKHARDT	69	NP B14 106	+Filthuth, Kluge+	(HEID, EFI, CERN, SACL)
MAST	68B	PRL 21 1715	+Alston-Garnjost, Bangerter, Galtieri+	(LRL)
SCHEUER	68	NP B8 503	+Merrill, Verglas, DeWitt+	(SABRE Collab.)
DAHL	67	PR 163 1377	+Hardy, Hess, Kirz, Miller	(LRL)
DAUBER	67	PL 24B 525	+Malamud, Schlein, Slater, Stork	(UCLA)
UHLIG	67	PR 155 1448	+Charlton, Condon, Glasser, Yodh+	(UMD, NRL)
BIRMINGHAM	66	PR 152 1148		(BIRM, GLAS, LOIC, OXF, RHEL)
ARMENTEROS	65C	PL 19 338	+Ferro-Luzzi+	(CERN, HEID, SACL)
MUSGRAVE	65	NC 35 735	+Petmezas+	(BIRM, CERN, EPOL, LOIC, SACL)
WATSON	63	PR 131 2248	+Ferro-Luzzi, Tripp	(LRL) IJP
FERRO-LUZZI	62	PRL 8 28	+Tripp, Watson	(LRL) IJP

$\Lambda(1600)$ P_{01}

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗

See also the $\Lambda(1810)$ P_{01}. There are quite possibly two P_{01} states in this region.

$\Lambda(1600)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1560 to 1700 (≈ 1600) OUR ESTIMATE				
1568± 20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1703±100	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1573± 25	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1596± 6	KANE	74	DPWA	$K^-p \to \Sigma\pi$
1620± 10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1572 or 1617	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1646± 7	[2] CARROLL	76	DPWA	Isospin-0 total σ
1570	KIM	71	DPWA	K-matrix analysis

$\Lambda(1600)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50 to 250 (≈ 150) OUR ESTIMATE				
116± 20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
593±200	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
147± 50	GOPAL	77	DPWA	$\overline{K}N$ multichannel
175± 20	KANE	74	DPWA	$K^-p \to \Sigma\pi$
60± 10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
247 or 271	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
20	[2] CARROLL	76	DPWA	Isospin-0 total σ
50	KIM	71	DPWA	K-matrix analysis

$\Lambda(1600)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	15–30 %
Γ_2	$\Sigma\pi$	10–60 %

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1600)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.15 to 0.30 OUR ESTIMATE				
0.23±0.04	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.14±0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
0.25±0.15	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.24±0.04	GOPAL	77	DPWA	See GOPAL 80
0.30 or 0.29	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1600) \to \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.16±0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.33±0.11	KANE	74	DPWA	$K^-p \to \Sigma\pi$
0.28±0.09	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.39 or −0.39	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
not seen	HEPP	76B	DPWA	$K^-N \to \Sigma\pi$

$\Lambda(1600)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] A total cross-section bump with $(J+1/2)$ Γ_{el} / $\Gamma_{total} = 0.04$.

$\Lambda(1600)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEID, MPIM) IJP
KANE	74	LBL-2452		(LBL) IJP
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP
KIM	71	PRL 27 356		(HARV) IJP

$\Lambda(1670)$ S_{01}

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗∗

The measurements of the mass, width, and elasticity published before 1974 are now obsolete and have been omitted. They were last listed in our 1982 edition Physics Letters **111B** (1982).

$\Lambda(1670)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1660 to 1680 (≈ 1670) OUR ESTIMATE				
1670.8±1.7	KOISO	85	DPWA	$K^-p \to \Sigma\pi$
1667 ±5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1671 ±3	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1670 ±5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1675 ±2	HEPP	76B	DPWA	$K^-N \to \Sigma\pi$
1679 ±1	KANE	74	DPWA	$K^-p \to \Sigma\pi$
1665 ±5	PREVOST	74	DPWA	$K^-N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1664	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Lambda(1670)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
25 to 50 (≈ 35) OUR ESTIMATE				
34.1± 3.7	KOISO	85	DPWA	$K^-p \to \Sigma\pi$
29 ± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
29 ± 5	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
45 ±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
46 ± 5	HEPP	76B	DPWA	$K^-N \to \Sigma\pi$
40 ± 3	KANE	74	DPWA	$K^-p \to \Sigma\pi$
19 ± 5	PREVOST	74	DPWA	$K^-N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
12	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Lambda(1670)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	15–25 %
Γ_2	$\Sigma\pi$	20–60 %
Γ_3	$\Lambda\eta$	15–35 %
Γ_4	$\Sigma(1385)\pi$	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1670)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.15 to 0.25 OUR ESTIMATE				
0.18±0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.17±0.03	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.20±0.03	GOPAL	77	DPWA	See GOPAL 80
0.15	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1670) \to \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.26±0.02	KOISO	85	DPWA	$K^-p \to \Sigma\pi$
−0.31±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.29±0.03	HEPP	76B	DPWA	$K^-N \to \Sigma\pi$
−0.23±0.03	LONDON	75	HLBC	$K^-p \to \Sigma^0\pi^0$
−0.27±0.02	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.13	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1670) \to \Lambda\eta$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.20±0.05	BAXTER	73	DPWA	$K^-p \to$ neutrals
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.24	KIM	71	DPWA	K-matrix analysis
0.26	ARMENTEROS	69C	HBC	
0.20 or 0.23	BERLEY	65	HBC	

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1670) \to \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.18±0.05	PREVOST	74	DPWA	$K^-N \to \Sigma(1385)\pi$

$\Lambda(1670)$ FOOTNOTES

[1] MARTIN 77 obtains identical resonance parameters from a T-matrix pole and from a Breit-Wigner fit.

$\Lambda(1670)$ REFERENCES

KOISO	85	NP A433 619	+Sai, Yamamoto, Kofler	(TOKY, MASA)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEID, MPIM) IJP
LONDON	75	NP B85 289	+Yu, Boyd+	(BNL, CERN, EPOL, ORSA, TORI)
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
BAXTER	73	NP B67 125	+Buckingham, Corbett, Dunn+	(OXF) IJP
KIM	71	PRL 27 356		(HARV) IJP
Also	70	Duke Conf. 161	Kim	(HARV) IJP
ARMENTEROS	69C	Lund Paper 229	+Baillon+	(CERN, HEID, SACL) IJP
Values are quoted in LEVI-SETTI 69.				
BERLEY	65	PRL 15 641	+Connolly, Hart, Rahm, Stonehill+	(BNL) IJP

$\Lambda(1690)$ D_{03}

$I(J^P) = 0(\frac{3}{2}^-)$ Status: ∗∗∗∗

The measurements of the mass, width, and elasticity published before 1974 are now obsolete and have been omitted. They were last listed in our 1982 edition Physics Letters **111B** (1982).

$\Lambda(1690)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1685 to 1695 (≈ 1690) OUR ESTIMATE				
1695.7±2.6	KOISO	85	DPWA	$K^-p \to \Sigma\pi$
1690 ±5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1692 ±5	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1690 ±5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1690 ±3	HEPP	76B	DPWA	$K^-N \to \Sigma\pi$
1689 ±1	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1687 or 1689	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1692 ±4	CARROLL	76	DPWA	Isospin-0 total σ

$\Lambda(1690)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50 to 70 (≈ 60) OUR ESTIMATE				
67.2± 5.6	KOISO	85	DPWA	$K^-p \to \Sigma\pi$
61 ± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
64 ±10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
60 ± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
82 ± 8	HEPP	76B	DPWA	$K^-N \to \Sigma\pi$
60 ± 4	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
62 or 62	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
38	CARROLL	76	DPWA	Isospin-0 total σ

$\Lambda(1690)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	20–30 %
Γ_2	$\Sigma\pi$	20–40 %
Γ_3	$\Lambda\pi\pi$	~ 25 %
Γ_4	$\Sigma\pi\pi$	~ 20 %
Γ_5	$\Lambda\eta$	
Γ_6	$\Sigma(1385)\pi$, S-wave	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1690)$ BRANCHING RATIOS

The sum of all the quoted branching ratios is more than 1.0. The two-body ratios are from partial-wave analyses, and thus probably are more reliable than the three-body ratios, which are determined from bumps in cross sections. Of the latter, the $\Sigma\pi\pi$ bump looks more significant. (The error given for the $\Lambda\pi\pi$ ratio looks unreasonably small.) Hardly any of the $\Sigma\pi\pi$ decay can be via $\Sigma(1385)$, for then seven times as much $\Lambda\pi\pi$ decay would be required. See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.2 to 0.3 OUR ESTIMATE				
0.23±0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.22±0.03	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.24±0.03	GOPAL	77	DPWA	See GOPAL 80
0.28 or 0.26	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1690) \to \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.34±0.02	KOISO	85	DPWA	$K^-p \to \Sigma\pi$
−0.25±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.29±0.03	HEPP	76B	DPWA	$K^-N \to \Sigma\pi$
−0.28±0.03	LONDON	75	HLBC	$K^-p \to \Sigma^0\pi^0$
−0.28±0.02	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.30 or −0.28	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1690) \to \Lambda\eta$ — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.00±0.03	BAXTER	73	DPWA	$K^-p \to$ neutrals

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1690) \to \Lambda\pi\pi$ $(\Gamma_1\Gamma_3)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.25 ± 0.02	[2] BARTLEY	68	HDBC	$K^- p \to \Lambda\pi\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1690) \to \Sigma\pi\pi$ $(\Gamma_1\Gamma_4)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.21	ARMENTEROS	68C	HDBC	$K^- N \to \Sigma\pi\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1690) \to \Sigma(1385)\pi$, S-wave $(\Gamma_1\Gamma_6)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.27\pm0.04$	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$

$\Lambda(1690)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit. Another D_{03} Λ at 1966 MeV is also suggested by MARTIN 77, but is very uncertain.

[2] BARTLEY 68 uses only cross-section data. The enhancement is not seen by PREVOST 71.

$\Lambda(1690)$ REFERENCES

KOISO	85	NP A433 619	+Sai, Yamamoto, Kofler	(TOKY, MASA)	
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)	
GOPAL	80	Toronto Conf. 159		(RHEL)	IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN)	IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN)	IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL)	IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS)	IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)	
Also	77C	NP B126 285	Martin, Pidcock	(LOUC)	IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL)	I
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEID, MPIM)	IJP
LONDON	75	NP B85 289	+Yu, Boyd+	(BNL, CERN, EPOL, ORSA, TORI)	
KANE	74	LBL-2452		(LBL)	IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)	
BAXTER	73	NP B67 125	+Buckingham, Corbett, Dunn+	(OXF)	IJP
PREVOST	71	Amsterdam Conf.		(CERN, HEID, SACL)	
ARMENTEROS	68C	NP B8 216	+Baillon+	(CERN, HEID, SACL)	I
BARTLEY	68	PRL 21 1111	+Chu, Dowd, Greene+	(TUFT, FSU, BRAN)	I

$\Lambda(1800)$ S_{01}

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗

This is the second resonance in the S_{01} wave, the first being the $\Lambda(1670)$.

$\Lambda(1800)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1720 to 1850 (≈ 1800) OUR ESTIMATE				
1841 ± 10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1725 ± 20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1825 ± 20	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1830 ± 20	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1767 or 1842	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1780	KIM	71	DPWA	K-matrix analysis
1872 ± 10	BRICMAN	70B	DPWA	$\overline{K}N \to \overline{K}N$

$\Lambda(1800)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
200 to 400 (≈ 300) OUR ESTIMATE				
228 ± 20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
185 ± 20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
230 ± 20	GOPAL	77	DPWA	$\overline{K}N$ multichannel
70 ± 15	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
435 or 473	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
40	KIM	71	DPWA	K-matrix analysis
100 ± 20	BRICMAN	70B	DPWA	$\overline{K}N \to \overline{K}N$

$\Lambda(1800)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	25–40 %
Γ_2	$\Sigma\pi$	seen
Γ_3	$\Sigma(1385)\pi$	seen
Γ_4	$N\overline{K}^*(892)$	seen
Γ_5	$N\overline{K}^*(892)$, $S=1/2$, S-wave	
Γ_6	$N\overline{K}^*(892)$, $S=3/2$, D-wave	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1800)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.25 to 0.40 OUR ESTIMATE				
0.36 ± 0.04	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.28 ± 0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
0.35 ± 0.15	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.37 ± 0.05	GOPAL	77	DPWA	See GOPAL 80
1.21 or 0.70	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.80	KIM	71	DPWA	K-matrix analysis
0.18 ± 0.02	BRICMAN	70B	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1800) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.08 ± 0.05	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.74 or -0.43	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.24	KIM	71	DPWA	K-matrix analysis

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1800) \to \Sigma(1385)\pi$ $(\Gamma_1\Gamma_3)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.056\pm0.028$	[2] CAMERON	78	DPWA	$K^- p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1800) \to N\overline{K}^*(892)$, $S=1/2$, S-wave $(\Gamma_1\Gamma_5)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.17 ± 0.03	[2] CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1800) \to N\overline{K}^*(892)$, $S=3/2$, D-wave $(\Gamma_1\Gamma_6)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.13 ± 0.04	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$\Lambda(1800)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] The published sign has been changed to be in accord with the baryon-first convention.

$\Lambda(1800)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL)	IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN)	IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN)	IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC)	IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC)	IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL)	IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS)	IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)	
Also	77C	NP B126 285	Martin, Pidcock	(LOUC)	IJP
LANGBEIN	72	NP B47 477	+Wagner	(MPIM)	IJP
KIM	71	PRL 27 356		(HARV)	IJP
Also	70	Duke Conf. 161	Kim	(HARV)	IJP
BRICMAN	70B	PL 33B 511	+Ferro-Luzzi, Lagnaux	(CERN)	IJP

$\Lambda(1810)$ P_{01}

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗

Almost all the recent analyses contain a P_{01} state, and sometimes two of them, but the masses, widths, and branching ratios vary greatly. See also the $\Lambda(1600)$ P_{01}.

$\Lambda(1810)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1750 to 1850 (≈ 1810) OUR ESTIMATE				
1841 ± 20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1853 ± 20	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1735 ± 5	CARROLL	76	DPWA	Isospin-0 total σ
1746 ± 10	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$
1780 ± 20	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1861 or 1953	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1755	KIM	71	DPWA	K-matrix analysis
1800	ARMENTEROS	70	HBC	$\overline{K}N \to \overline{K}N$
1750	ARMENTEROS	70	HBC	$\overline{K}N \to \Sigma\pi$
1690 ± 10	BARBARO-...	70	HBC	$\overline{K}N \to \Sigma\pi$
1740	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$
1745	ARMENTEROS	68B	HBC	$\overline{K}N \to \overline{K}N$

$\Lambda(1810)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50 to 250 (≈ 150) OUR ESTIMATE				
164 ± 20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
90 ± 20	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$
166 ± 20	GOPAL	77	DPWA	$\overline{K}N$ multichannel
46 ± 20	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$
120 ± 10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
535 or 585	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
28	CARROLL	76	DPWA	Isospin-0 total σ
35	KIM	71	DPWA	K-matrix analysis
30	ARMENTEROS	70	HBC	$\overline{K}N \to \overline{K}N$
70	ARMENTEROS	70	HBC	$\overline{K}N \to \Sigma\pi$
22	BARBARO-...	70	HBC	$\overline{K}N \to \Sigma\pi$
300	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$
147	ARMENTEROS	68B	HBC	

$\Lambda(1810)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	20–50 %
Γ_2	$\Sigma\pi$	10–40 %
Γ_3	$\Sigma(1385)\pi$	seen
Γ_4	$N\overline{K}^*(892)$	30–60 %
Γ_5	$N\overline{K}^*(892)$, S=1/2, P-wave	
Γ_6	$N\overline{K}^*(892)$, S=3/2, P-wave	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1810)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.2 to 0.5 OUR ESTIMATE				
0.24 ± 0.04	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.36 ± 0.05	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.21 ± 0.04	GOPAL	77	DPWA	See GOPAL 80
0.52 or 0.49	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.30	KIM	71	DPWA	K-matrix analysis
0.15	ARMENTEROS	70	DPWA	$\overline{K}N \to \overline{K}N$
0.55	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$
0.4	ARMENTEROS	68B	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1810) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.24 ± 0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.25 or +0.23	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
$<$ 0.01	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
0.17	KIM	71	DPWA	K-matrix analysis
+0.20	[2] ARMENTEROS	70	DPWA	$\overline{K}N \to \Sigma\pi$
-0.13 ± 0.03	BARBARO-...	70	DPWA	$\overline{K}N \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1810) \to \Sigma(1385)\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.18\pm0.10$	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1810) \to N\overline{K}^*(892)$, S=1/2, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.14 ± 0.03	[2] CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1810) \to N\overline{K}^*(892)$, S=3/2, P-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.35\pm0.06$	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$\Lambda(1810)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] The published sign has been changed to be in accord with the baryon-first convention.

$\Lambda(1810)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP
KIM	71	PRL 27 356		(HARV) IJP
Also	70	Duke Conf. 161	Kim	(HARV) IJP
ARMENTEROS	70	Duke Conf. 123	+Baillon+	(CERN, HEID, SACL) IJP
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP
BAILEY	69	UCRL 50617 Thesis		(LLL) IJP
ARMENTEROS	68B	NP B8 195	+Baillon+	(CERN, HEID, SACL) IJP

$\Lambda(1820)$ F_{05}

$I(J^P) = 0(\frac{5}{2}^+)$ Status: ∗∗∗∗

This resonance is the cornerstone for all partial-wave analyses in this region. Most of the results published before 1973 are now obsolete and have been omitted. They may be found in our 1982 edition Physics Letters **111B** (1982).

Most of the quoted errors are statistical only; the systematic errors due to the particular parametrizations used in the partial-wave analyses are not included. For this reason we do not calculate weighted averages for the mass and width.

$\Lambda(1820)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1815 to 1825 (≈ 1820) OUR ESTIMATE				
1823 ± 3	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1819 ± 2	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1822 ± 2	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1821 ± 2	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1830	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
1817 or 1819	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Lambda(1820)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
70 to 90 (≈ 80) OUR ESTIMATE				
77 ± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
72 ± 5	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
81 ± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
87 ± 3	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
82	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
76 or 76	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Lambda(1820)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	55–65 %
Γ_2	$\Sigma\pi$	8–14 %
Γ_3	$\Sigma(1385)\pi$	5–10 %
Γ_4	$\Sigma(1385)\pi$, P-wave	
Γ_5	$\Sigma(1385)\pi$, F-wave	
Γ_6	$\Lambda\eta$	
Γ_7	$\Sigma\pi\pi$	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1820)$ BRANCHING RATIOS

Errors quoted do not include uncertainties in the parametrizations used in the partial-wave analyses and are thus too small. See also "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.55 to 0.65 OUR ESTIMATE				
0.58 ± 0.02	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.60 ± 0.03	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.51	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
0.57 ± 0.02	GOPAL	77	DPWA	See GOPAL 80
0.59 or 0.58	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Lambda(1820) \rightarrow \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.28±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.28±0.01	KANE	74	DPWA	$K^-p \rightarrow \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.25 or −0.25	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Lambda(1820) \rightarrow \Lambda\eta$ — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN
$-0.096^{+0.040}_{-0.020}$	RADER	73	MPWA

$\Gamma(\Sigma\pi\pi)/\Gamma_{total}$ — Γ_7/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
no clear signal	[2] ARMENTEROS	68C	HDBC	$K^-N \rightarrow \Sigma\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Lambda(1820) \rightarrow \Sigma(1385)\pi$, P-wave — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.167±0.054	[3] CAMERON	78	DPWA	$K^-p \rightarrow \Sigma(1385)\pi$
+0.27 ±0.03	PREVOST	74	DPWA	$K^-N \rightarrow \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Lambda(1820) \rightarrow \Sigma(1385)\pi$, F-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.065±0.029	[3] CAMERON	78	DPWA	$K^-p \rightarrow \Sigma(1385)\pi$

Λ(1820) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] There is a suggestion of a bump, enough to be consistent with what is expected from $\Sigma(1385) \rightarrow \Sigma\pi$ decay.
[3] The published sign has been changed to be in accord with the baryon-first convention.

Λ(1820) REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
RADER	73	NC 16A 178	+Barloutaud+	(SACL, HEID, CERN, RHEL, CDEF)
ARMENTEROS	68C	NP B8 216	+Baillon+	(CERN, HEID, SACL) I

Λ(1830) D_{05}

$I(J^P) = 0(\frac{5}{2}^-)$ Status: ∗∗∗∗

For results published before 1973 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

The best evidence for this resonance is in the $\Sigma\pi$ channel.

Λ(1830) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1810 to 1830 (≈ 1830) OUR ESTIMATE				
1831±10	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1825±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1825± 1	KANE	74	DPWA	$K^-p \rightarrow \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1817 or 1818	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

Λ(1830) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
60 to 110 (≈ 95) OUR ESTIMATE				
100±10	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
94±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
119± 3	KANE	74	DPWA	$K^-p \rightarrow \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
56 or 56	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

Λ(1830) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	3–10 %
Γ_2	$\Sigma\pi$	35–75 %
Γ_3	$\Sigma(1385)\pi$	>15 %
Γ_4	$\Sigma(1385)\pi$, D-wave	
Γ_5	$\Lambda\eta$	

The above branching fractions are our estimates, not fits or averages.

Λ(1830) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.03 to 0.10 OUR ESTIMATE				
0.08±0.03	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.02±0.02	ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.04±0.03	GOPAL	77	DPWA	See GOPAL 80
0.04 or 0.04	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Lambda(1830) \rightarrow \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.17±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.15±0.01	KANE	74	DPWA	$K^-p \rightarrow \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.17 or −0.17	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Lambda(1830) \rightarrow \Lambda\eta$ — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN
−0.044±0.020	RADER	73	MPWA

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Lambda(1830) \rightarrow \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.141±0.014	[2] CAMERON	78	DPWA	$K^-p \rightarrow \Sigma(1385)\pi$
+0.13 ±0.03	PREVOST	74	DPWA	$K^-N \rightarrow \Sigma(1385)\pi$

Λ(1830) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] The CAMERON 78 upper limit on G-wave decay is 0.03. The published sign has been changed to be in accord with the baryon-first convention.

Λ(1830) REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
RADER	73	NC 16A 178	+Barloutaud+	(SACL, HEID, CERN, RHEL, CDEF)

$\Lambda(1890)$ P_{03}

$I(J^P) = 0(\frac{3}{2}^+)$ Status: ∗∗∗∗

For results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

The $J^P = 3/2^+$ assignment is consistent with all available data (including polarization) and recent partial-wave analyses. The dominant inelastic modes remain unknown.

$\Lambda(1890)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1850 to 1910 (≈ 1890) OUR ESTIMATE				
1897± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1908±10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1900± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1894±10	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1856 or 1868	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1900	[2] NAKKASYAN	75	DPWA	$K^-p \to \Lambda\omega$

$\Lambda(1890)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
60 to 200 (≈ 100) OUR ESTIMATE				
74±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
119±20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
72±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
107±10	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
191 or 193	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
100	[2] NAKKASYAN	75	DPWA	$K^-p \to \Lambda\omega$

$\Lambda(1890)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	20–35 %
Γ_2	$\Sigma\pi$	3–10 %
Γ_3	$\Sigma(1385)\pi$	seen
Γ_4	$\Sigma(1385)\pi$, P-wave	
Γ_5	$\Sigma(1385)\pi$, F-wave	
Γ_6	$N\overline{K}^*(892)$	seen
Γ_7	$N\overline{K}^*(892)$, S=1/2, P-wave	
Γ_8	$\Lambda\omega$	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1890)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.20 to 0.35 OUR ESTIMATE				
0.20±0.02	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.34±0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
0.24±0.04	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.18±0.02	GOPAL	77	DPWA	See GOPAL 80
0.36 or 0.34	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1890) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.09±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.15 or +0.14	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1890) \to \Lambda\omega$ $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
seen	BACCARI	77	IPWA	$K^-p \to \Lambda\omega$
0.032	[2] NAKKASYAN	75	DPWA	$K^-p \to \Lambda\omega$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1890) \to \Sigma(1385)\pi$, P-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.03	CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1890) \to \Sigma(1385)\pi$, F-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.126±0.055	[3] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1890) \to N\overline{K}^*(892)$ $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.07±0.03	[3,4] CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$\Lambda(1890)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] Found in one of two best solutions.
[3] The published sign has been changed to be in accord with the baryon-first convention.
[4] Upper limits on the P_3 and F_3 waves are each 0.03.

$\Lambda(1890)$ REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEID, MPIM) IJP
NAKKASYAN	75	NP B93 85		(CERN) IJP

$\Lambda(2000)$

$I(J^P) = 0(?^?)$ Status: ∗

OMITTED FROM SUMMARY TABLE

We list here all the ambiguous resonance possibilities with a mass around 2 GeV. The proposed quantum numbers are D_3 (BARBARO-GALTIERI 70 in $\Sigma\pi$), D_3+F_5, P_3+D_5, or P_1+D_3 (BRANDSTETTER 72 in $\Lambda\omega$), and S_1 (CAMERON 78B in $N\overline{K}^*$). The first two of the above analyses should now be considered obsolete. See also NAKKASYAN 75.

$\Lambda(2000)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2000 OUR ESTIMATE				
2030±30	CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$
1935 to 1971	[1] BRANDSTET...	72	DPWA	$K^-p \to \Lambda\omega$
1951 to 2034	[1] BRANDSTET...	72	DPWA	$K^-p \to \Lambda\omega$
2010±30	BARBARO-...	70	DPWA	$K^-p \to \Sigma\pi$

$\Lambda(2000)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
125±25	CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$
180 to 240	[1] BRANDSTET...	72	DPWA	(lower mass)
73 to 154	[1] BRANDSTET...	72	DPWA	(higher mass)
130±50	BARBARO-...	70	DPWA	$K^-p \to \Sigma\pi$

$\Lambda(2000)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Sigma\pi$
Γ_3	$\Lambda\omega$
Γ_4	$N\overline{K}^*(892)$, S=1/2, S-wave
Γ_5	$N\overline{K}^*(892)$, S=3/2, D-wave

$\Lambda(2000)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2000) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.20±0.04	BARBARO-...	70	DPWA	$K^-p \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2000) \to \Lambda\omega$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.17 to 0.25	[1] BRANDSTET...	72	DPWA	(lower mass)
0.04 to 0.15	[1] BRANDSTET...	72	DPWA	(higher mass)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2000) \to N\overline{K}^*(892)$, S=1/2, S-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.12±0.03	[2] CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2000) \to N\overline{K}^*(892)$, S=3/2, D-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.09\pm0.03$	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$\Lambda(2000)$ FOOTNOTES

[1] The parameters quoted here are ranges from the three best fits; the lower state probably has $J \le 3/2$, and the higher one probably has $J \le 5/2$.

[2] The published sign has been changed to be in accord with the baryon-first convention.

$\Lambda(2000)$ REFERENCES

CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
NAKKASYAN	75	NP B93 85		(CERN) IJP
BRANDSTET...	72	NP B39 13	Brandstetter, Butterworth+	(RHEL, CDEF, SACL)
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP

$\Lambda(2020)$ F_{07}

$I(J^P) = 0(\frac{7}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

In LITCHFIELD 71, need for the state rests solely on a possibly inconsistent polarization measurement at 1.784 GeV/c. HEMINGWAY 75 does not require this state. GOPAL 77 does not need it in either $N\overline{K}$ or $\Sigma\pi$. With new $K^- n$ angular distributions included, DECLAIS 77 sees it. However, this and other new data are included in GOPAL 80 and the state is not required. BACCARI 77 weakly supports it.

$\Lambda(2020)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2020 OUR ESTIMATE				
2140	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$
2117	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
2100 ± 30	LITCHFIELD	71	DPWA	$K^- p \to \overline{K}N$
2020 ± 20	BARBARO-...	70	DPWA	$K^- p \to \Sigma\pi$

$\Lambda(2020)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
128	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$
167	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
120 ± 30	LITCHFIELD	71	DPWA	$K^- p \to \overline{K}N$
160 ± 30	BARBARO-...	70	DPWA	$K^- p \to \Sigma\pi$

$\Lambda(2020)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Sigma\pi$
Γ_3	$\Lambda\omega$

$\Lambda(2020)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
0.05 ± 0.02	LITCHFIELD	71	DPWA	$K^- p \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2020) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.15 ± 0.02	BARBARO-...	70	DPWA	$K^- p \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2020) \to \Lambda\omega$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.05	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$

$\Lambda(2020)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL)
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL)
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEID, MPIM) IJP
LITCHFIELD	71	NP B30 125	+..., Lesquoy+	(RHEL, CDEF, SACL) IJP
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP

$\Lambda(2100)$ G_{07}

$I(J^P) = 0(\frac{7}{2}^-)$ Status: ****

Discovered by COOL 66 and by WOHL 66. Most of the results published before 1973 are now obsolete and have been omitted. They may be found in our 1982 edition Physics Letters **111B** (1982).

This entry only includes results from partial-wave analyses. Parameters of peaks seen in cross sections and in invariant-mass distributions around 2100 MeV used to be listed in a separate entry immediately following. It may be found in our 1986 edition Physics Letters **170B** (1986).

$\Lambda(2100)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2090 to 2110 (≈ 2100) OUR ESTIMATE				
2104 ± 10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
2106 ± 30	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
2110 ± 10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
2105 ± 10	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
2115 ± 10	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2094	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$
2094	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
2110 or 2089	[1] NAKKASYAN	75	DPWA	$K^- p \to \Lambda\omega$

$\Lambda(2100)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
100 to 250 (≈ 200) OUR ESTIMATE				
157 ± 40	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
250 ± 30	GOPAL	77	DPWA	$\overline{K}N$ multichannel
241 ± 30	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
152 ± 15	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
98	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$
250	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
244 or 302	[1] NAKKASYAN	75	DPWA	$K^- p \to \Lambda\omega$

$\Lambda(2100)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	25–35 %
Γ_2	$\Sigma\pi$	~ 5 %
Γ_3	$\Lambda\eta$	<3 %
Γ_4	ΞK	<3 %
Γ_5	$\Lambda\omega$	<8 %
Γ_6	$N\overline{K}^*(892)$	10–20 %
Γ_7	$N\overline{K}^*(892)$, S=1/2, G-wave	
Γ_8	$N\overline{K}^*(892)$, S=3/2, D-wave	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(2100)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.25 to 0.35 OUR ESTIMATE				
0.34 ± 0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.24 ± 0.06	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
0.31 ± 0.03	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.29	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
0.30 ± 0.03	GOPAL	77	DPWA	See GOPAL 80

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.12\pm0.04$	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$+0.11\pm0.01$	KANE	74	DPWA	$K^- p \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to \Lambda\eta$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.050 ± 0.020	RADER	73	MPWA	$K^- p \to \Lambda\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to \Xi K$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.035±0.018	LITCHFIELD	71	DPWA	$K^- p \to \Xi K$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.003	MULLER	69B	DPWA	$K^- p \to \Xi K$
0.05	TRIPP	67	RVUE	$K^- p \to \Xi K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to \Lambda\omega$ — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.070	[2] BACCARI	77	DPWA	GD_{37} wave
+0.011	[2] BACCARI	77	DPWA	GG_{17} wave
+0.008	[2] BACCARI	77	DPWA	GG_{37} wave
0.122 or 0.154	[1] NAKKASYAN	75	DPWA	$K^- p \to \Lambda\omega$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to N\overline{K}^*(892)$, $S=3/2$, D-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.21±0.04	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to N\overline{K}^*(892)$, $S=1/2$, G-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.04±0.03	[3] CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$\Lambda(2100)$ FOOTNOTES

[1] The NAKKASYAN 75 values are from the two best solutions found. Each has the $\Lambda(2100)$ and one additional resonance (P_3 or F_5).

[2] Note that the three for BACCARI 77 entries are for three different waves.

[3] The published sign has been changed to be in accord with the baryon-first convention. The upper limit on the G_3 wave is 0.03.

$\Lambda(2100)$ REFERENCES

PDG	86	PL 170B	Aguilar-Benitez, Porter+	(CERN, CIT+)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
DEBELLEFON	78	NC 42A 403	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEID, MPIM) IJP
NAKKASYAN	75	NP B93 85		(CERN) IJP
KANE	74	LBL-2452		(LBL) IJP
RADER	73	NC 16A 178	+Barloutaud+	(SACL, HEID, CERN, RHEL, CDEF)
LITCHFIELD	71	NP B30 125	+..., Lesquoy+	(RHEL, CDEF, SACL) IJP
MULLER	69B	UCRL 19372 Thesis		(LRL)
TRIPP	67	NP B3 10	+Leith+	(LRL, SLAC, CERN, HEID, SACL)
COOL	66	PRL 16 1228	+Giacomelli, Kycia, Leontic, Lundby+	(BNL)
WOHL	66	PRL 17 107	+Solmitz, Stevenson	(LRL) IJP

$\Lambda(2110)$ F_{05}

$I(J^P) = 0(\frac{5}{2}^+)$ Status: ∗∗∗

For results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982). All the references have been retained.

This resonance is in the Baryon Summary Table, but the evidence for it could be better.

$\Lambda(2110)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2090 to 2140 (≈ 2110) OUR ESTIMATE				
2092±25	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
2125±25	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$
2106±50	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
2140±20	DEBELLEFON	77	DPWA	$K^- p \to \Sigma\pi$
2100±50	GOPAL	77	DPWA	$\overline{K}N$ multichannel
2112± 7	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2137	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$
2103	[1] NAKKASYAN	75	DPWA	$K^- p \to \Lambda\omega$

$\Lambda(2110)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
150 to 250 (≈ 200) OUR ESTIMATE				
245±25	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
160±30	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$
251±50	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
140±20	DEBELLEFON	77	DPWA	$K^- p \to \Sigma\pi$
200±50	GOPAL	77	DPWA	$\overline{K}N$ multichannel
190±30	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
132	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$
391	[1] NAKKASYAN	75	DPWA	$K^- p \to \Lambda\omega$

$\Lambda(2110)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	5–25 %
Γ_2	$\Sigma\pi$	10–40 %
Γ_3	$\Lambda\omega$	seen
Γ_4	$\Sigma(1385)\pi$	seen
Γ_5	$\Sigma(1385)\pi$, P-wave	
Γ_6	$N\overline{K}^*(892)$	10–60 %
Γ_7	$N\overline{K}^*(892)$, $S=1/2$, F-wave	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(2110)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.25 OUR ESTIMATE				
0.07±0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.27±0.06	[2] DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.07±0.03	GOPAL	77	DPWA	See GOPAL 80

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2110) \to \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.14±0.01	DEBELLEFON	77	DPWA	$K^- p \to \Sigma\pi$
+0.20±0.03	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.10±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2110) \to \Lambda\omega$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.05	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$
0.112	[1] NAKKASYAN	75	DPWA	$K^- p \to \Lambda\omega$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2110) \to \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.071±0.025	[3] CAMERON	78	DPWA	$K^- p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2110) \to N\overline{K}^*(892)$ — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.17±0.04	[4] CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$\Lambda(2110)$ FOOTNOTES

[1] Found in one of two best solutions.

[2] The published error of 0.6 was a misprint.

[3] The CAMERON 78 upper limit on F-wave decay is 0.03. The sign here has been changed to be in accord with the baryon-first convention.

[4] The published sign has been changed to be in accord with the baryon-first convention. The CAMERON 78B upper limits on the P_3 and F_3 waves are each 0.03.

$\Lambda(2110)$ REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
DEBELLEFON	78	NC 42A 403	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
DEBELLEFON	77	NC 37A 175	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
NAKKASYAN	75	NP B93 85		(CERN) IJP
KANE	74	LBL-2452		(LBL) IJP

Λ(2325) D_{03}

$I(J^P) = 0(\frac{3}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

BACCARI 77 finds this state with either $J^P = 3/2^-$ or $3/2^+$ in a energy-dependent partial-wave analyses of $K^- p \to \Lambda\omega$ from 2070 to 2436 MeV. A subsequent semi-energy-independent analysis from threshold to 2436 MeV selects $3/2^-$. DEBELLEFON 78 (same group) also sees this state in an energy-dependent partial-wave analysis of $K^- p \to \overline{K}N$ data, and finds $J^P = 3/2^-$ or $3/2^+$. They again prefer $J^P = 3/2^-$, but only on the basis of model-dependent considerations.

Λ(2325) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2325 OUR ESTIMATE				
2342±30	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
2327±20	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$

Λ(2325) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
177±40	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
160±40	BACCARI	77	IPWA	$K^- p \to \Lambda\omega$

Λ(2325) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\omega$

Λ(2325) BRANCHING RATIOS

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.19±0.06	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2325) \to \Lambda\omega$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.06±0.02	[1] BACCARI	77	IPWA	DS_{33} wave
0.05±0.02	[1] BACCARI	77	DPWA	DD_{13} wave
0.08±0.03	[1] BACCARI	77	DPWA	DD_{33} wave

Λ(2325) FOOTNOTES

[1] Note that the three BACCARI 77 entries are for three different waves.

Λ(2325) REFERENCES

DEBELLEFON	78	NC 42A 403	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP

Λ(2350) H_{09}

$I(J^P) = 0(\frac{9}{2}^+)$ Status: * * *

DAUM 68 favors $J^P = 7/2^-$ or $9/2^+$. BRICMAN 70 favors $9/2^+$. LASINSKI 71 suggests three states in this region using a Pomeron + resonances model. There are now also three formation experiments from the College de France-Saclay group, DEBELLEFON 77, BACCARI 77, and DEBELLEFON 78, which find $9/2^+$ in energy-dependent partial-wave analyses of $\overline{K}N \to \Sigma\pi$, $\Lambda\omega$, and $N\overline{K}$.

Λ(2350) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2340 to 2370 (≈ 2350) OUR ESTIMATE				
2370±50	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
2365±20	DEBELLEFON	77	DPWA	$K^- p \to \Sigma\pi$
2358± 6	BRICMAN	70	CNTR	Total, charge exchange
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2372	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$
2344±15	COOL	70	CNTR	$K^- p$, $K^- d$ total
2360±20	LU	70	CNTR	$\gamma p \to K^+ Y^*$
2340± 7	BUGG	68	CNTR	$K^- p$, $K^- d$ total

Λ(2350) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
100 to 250 (≈ 150) OUR ESTIMATE				
204±50	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
110±20	DEBELLEFON	77	DPWA	$K^- p \to \Sigma\pi$
324±30	BRICMAN	70	CNTR	Total, charge exchange
• • • We do not use the following data for averages, fits, limits, etc. • • •				
257	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$
190	COOL	70	CNTR	$K^- p$, $K^- d$ total
55	LU	70	CNTR	$\gamma p \to K^+ Y^*$
140±20	BUGG	68	CNTR	$K^- p$, $K^- d$ total

Λ(2350) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	~ 12 %
Γ_2	$\Sigma\pi$	~ 10 %
Γ_3	$\Lambda\omega$	

The above branching fractions are our estimates, not fits or averages.

Λ(2350) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
~ 0.12 OUR ESTIMATE				
0.12±0.04	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2350) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.11±0.02	DEBELLEFON	77	DPWA	$K^- p \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2350) \to \Lambda\omega$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.05	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$

Λ(2350) REFERENCES

DEBELLEFON	78	NC 42A 403	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
DEBELLEFON	77	NC 37A 175	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
LASINSKI	71	NP B29 125		(EFI) IJP
BRICMAN	70	PL 31B 152	+Ferro-Luzzi, Perreau+	(CERN, CAEN, SACL)
COOL	70	PR D1 1887	+Giacomelli, Kycia, Leontic, Li+	(BNL) I
Also	66	PRL 16 1228	Cool, Giacomelli, Kycia, Leontic, Lundby+	(BNL) I
LU	70	PR D2 1846	+Greenberg, Hughes, Minehart, Mori+	(YALE)
BUGG	68	PR 168 1466	+Gilmore, Knight+	(RHEL, BIRM, CAVE) I
DAUM	68	NP B7 19	+Erne, Lagnaux, Sens, Steuer, Udo	(CERN) JP

Λ(2585) Bumps

$I(J^P) = 0(?^?)$ Status: * *

OMITTED FROM SUMMARY TABLE

Λ(2585) MASS (BUMPS)

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2585 OUR ESTIMATE				
2585±45	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total
2530±25	LU	70	CNTR	$\gamma p \to K^+ Y^*$

Λ(2585) WIDTH (BUMPS)

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
300	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total
150	LU	70	CNTR	$\gamma p \to K^+ Y^*$

Λ(2585) DECAY MODES (BUMPS)

	Mode
Γ_1	$N\overline{K}$

$\Lambda(2585)$ BRANCHING RATIOS (BUMPS)

$(J+\frac{1}{2}) \times \Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

J is not known, so only $(J+\frac{1}{2}) \times \Gamma(N\overline{K})/\Gamma_{total}$ can be given.

VALUE	DOCUMENT ID		TECN	COMMENT
1	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total
0.12 ± 0.12	[1] BRICMAN	70	CNTR	Total, charge exchange

$\Lambda(2585)$ FOOTNOTES (BUMPS)

[1] The resonance is at the end of the region analyzed — no clear signal.

$\Lambda(2585)$ REFERENCES (BUMPS)

ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL) I
Also	66	PRL 16 1228	Cool, Giacomelli, Kycia, Leontic, Lundby+	(BNL) I
BRICMAN	70	PL 31B 152	+Ferro-Luzzi, Perreau+	(CERN, CAEN, SACL)
LU	70	PR D2 1846	+Greenberg, Hughes, Minehart, Mori+	(YALE)

Σ BARYONS
$(S = -1, I = 1)$

$\Sigma^+ = uus$, $\Sigma^0 = uds$, $\Sigma^- = dds$

Σ^+

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗∗∗

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1986 edition (Physics Letters **170B** (1986)) or in earlier editions.

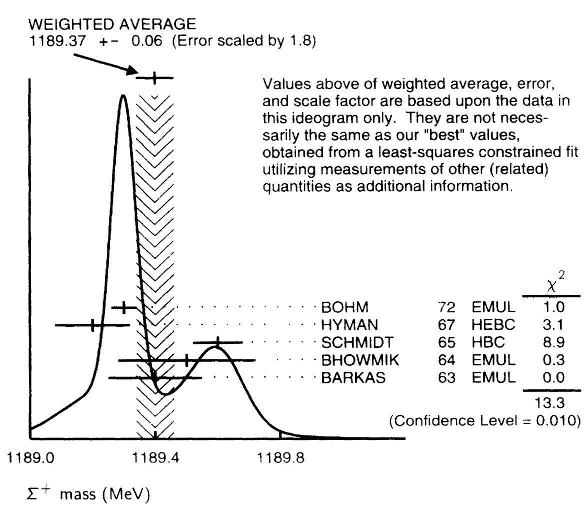
Σ^+ MASS

The fit uses Σ^+, Σ^0, Σ^-, and Λ mass and mass-difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1189.37±0.07 OUR FIT	Error includes scale factor of 2.1.				
1189.37±0.06 OUR AVERAGE	Error includes scale factor of 1.8. See the ideogram below.				
1189.33 ± 0.04	607	[1] BOHM	72	EMUL	
1189.16 ± 0.12		HYMAN	67	HEBC	
1189.61 ± 0.08	4205	SCHMIDT	65	HBC	See note with Λ mass
1189.48 ± 0.22	58	[2] BHOWMIK	64	EMUL	
1189.38 ± 0.15	144	[2] BARKAS	63	EMUL	

[1] BOHM 72 is updated with our 1973 K^-, π^-, and π^0 masses (Reviews of Modern Physics **45** No. 2 Pt. II (1973)).

[2] These masses have been raised 30 keV to take into account a 46 keV increase in the proton mass and a 21 keV decrease in the π^0 mass (note added 1967 edition, Reviews of Modern Physics **39** 1 (1967)).



Σ^+ MEAN LIFE

Measurements with an error $\geq 0.1 \times 10^{-10}$ s have been omitted.

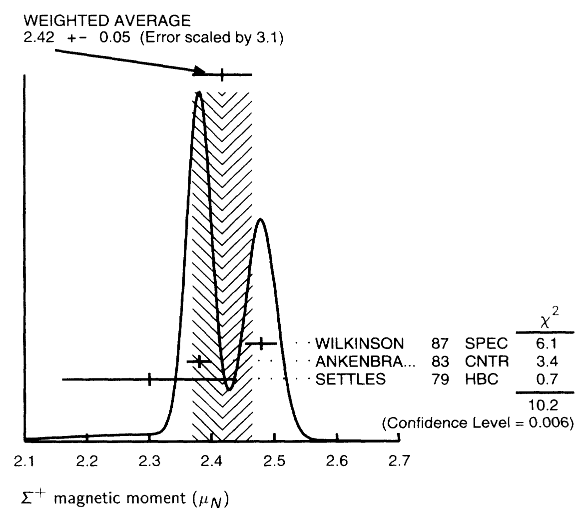
VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
0.799±0.004 OUR AVERAGE					
0.798 ± 0.005	30k	MARRAFFINO	80	HBC	$K^- p$ 0.42–0.5 GeV/c
0.807 ± 0.013	5719	CONFORTO	76	HBC	$K^- p$ 1–1.4 GeV/c
0.83 ± 0.04	526	BAKKER	71	DBC	$K^- n \to \Sigma^+ \pi^- \pi^-$
0.795 ± 0.010	20k	EISELE	70	HBC	$K^- p$ at rest
0.803 ± 0.008	10664	BARLOUTAUD	69	HBC	$K^- p$ 0.4–1.2 GeV/c
0.83 ± 0.032	1300	[3] CHANG	66	HBC	
0.80 ± 0.07	381	COOK	66	OSPK	
0.84 ± 0.09	181	BALTAY	65	HBC	
0.76 ± 0.03	900	CARAYAN...	65	HBC	
$0.749^{+0.056}_{-0.052}$	192	GRARD	62	HBC	
0.765 ± 0.04	456	HUMPHREY	62	HBC	

[3] We have increased the CHANG 66 error of 0.018; see our 1970 edition, Reviews of Modern Physics **42** No. 1 (1970).

Σ^+ MAGNETIC MOMENT

See the Note on Baryon Magnetic Moments in the Λ Listings. Measurements with an error $\geq 0.3\ \mu_N$ have been omitted.

VALUE (μ_N)	EVTS	DOCUMENT ID		TECN	COMMENT
2.42 ±0.05 OUR AVERAGE	Error includes scale factor of 3.1. See the ideogram below.				
$2.479\pm0.012\pm0.022$	137k	WILKINSON	87	SPEC	400 GeV pBe
2.38 ± 0.02	44k	ANKENBRA...	83	CNTR	210 GeV hyperon beam
2.30 ± 0.14	14k	SETTLES	79	HBC	$K^- p$ 0.42–0.50 GeV/c



Σ^+ DECAY MODES

	Mode		Fraction (Γ_i/Γ)		Confidence level
Γ_1	$p\pi^0$		(51.57 ± 0.30) %		
Γ_2	$n\pi^+$		(48.30 ± 0.30) %		
Γ_3	$p\gamma$		$(1.25\pm0.07) \times 10^{-3}$		
Γ_4	$n\pi^+\gamma$	[a]	$(4.5\pm0.5) \times 10^{-4}$		
Γ_5	$\Lambda e^+ \nu_e$		$(2.0\pm0.5) \times 10^{-5}$		
	$\Delta S = \Delta Q$ (SQ) or Flavor-Changing neutral current (FC) violating modes				
Γ_6	$n e^+ \nu_e$	SQ	< 5	$\times 10^{-6}$	90%
Γ_7	$n \mu^+ \nu_\mu$	SQ	< 3.0	$\times 10^{-5}$	90%
Γ_8	$p e^+ e^-$	FC	< 7	$\times 10^{-6}$	

[a] See the Listings below for the pion momentum range used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to 2 branching ratios uses 13 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 7.5 for 11 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−100	
x_3	9	−11
	x_1	x_2

Σ^+ BRANCHING RATIOS

$\Gamma(n\pi^+)/\Gamma(N\pi)$ — $\Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.4836±0.0030 OUR FIT					
0.4836±0.0030 OUR AVERAGE					
0.4828±0.0036	10k	[4] MARRAFFINO	80	HBC	$K^- p$ 0.42–0.5 GeV/c
0.488 ±0.008	1861	NOWAK	78	HBC	
0.484 ±0.015	537	TOVEE	71	EMUL	
0.488 ±0.010	1331	BARLOUTAUD	69	HBC	$K^- p$ 0.4–1.2 GeV/c
0.46 ±0.02	534	CHANG	66	HBC	
0.490 ±0.024	308	HUMPHREY	62	HBC	

[4] MARRAFFINO 80 actually gives $\Gamma(p\pi^0)/\Gamma(\text{total}) = 0.5172 \pm 0.0036$.

$\Gamma(p\gamma)/\Gamma(p\pi^0)$ — Γ_3/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.43±0.14 OUR FIT					
2.43±0.14 OUR AVERAGE					
$2.81\pm0.39^{+0.21}_{-0.43}$	408	HESSEY	89	CNTR	$K^- p \to \Sigma^+\pi^-$ at rest
2.52±0.28	190	[5] KOBAYASHI	87	CNTR	$\pi^+ p \to \Sigma^+ K^+$
$2.46^{+0.30}_{-0.35}$	155	BIAGI	85	CNTR	CERN hyperon beam
2.11±0.38	46	MANZ	80	HBC	$K^- p \to \Sigma^+\pi^-$
2.1 ±0.3	45	ANG	69B	HBC	$K^- p$ at rest
2.76±0.51	31	GERSHWIN	69B	HBC	$K - p \to \Sigma^+\pi^-$
3.7 ±0.8	24	BAZIN	65	HBC	$K^- p$ at rest

[5] KOBAYASHI 87 actually gives $\Gamma(p\gamma)/\Gamma(\text{total}) = (1.30 \pm 0.15) \times 10^{-3}$.

$\Gamma(n\pi^+\gamma)/\Gamma(n\pi^+)$ — Γ_4/Γ_2

The π^+ momentum cuts differ, so we do not average the results but simply use the latest value in the Summary Table.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.93±0.10	180	EBENHOH	73	HBC	$\pi^+ < 150$ MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.27±0.05	29	ANG	69B	HBC	$\pi^+ < 110$ MeV/c
~ 1.8		BAZIN	65B	HBC	$\pi^+ < 116$ MeV/c

$\Gamma(\Lambda e^+\nu_e)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	COMMENT
2.0±0.5 OUR AVERAGE					
1.6±0.7	5	BALTAY	69	HBC	$K^- p$ at rest
2.9±1.0	10	EISELE	69	HBC	$K^- p$ at rest
2.0±0.8	6	BARASH	67	HBC	$K^- p$ at rest

$\Gamma(ne^+\nu_e)/\Gamma(n\pi^+)$ — Γ_6/Γ_2

Test of $\Delta S = \Delta Q$ rule. Experiments with an effective denominator less than 100,000 have been omitted.

EFFECTIVE DENOM.	EVTS	DOCUMENT ID		TECN	COMMENT
< 1.1 × 10^{-5} OUR LIMIT		Our 90% CL limit = (2.3 events)/(effective denominator sum). [Number of events increased to 2.3 for a 90% confidence level.]			
111000	0	[6] EBENHOH	74	HBC	$K^- p$ at rest
105000	0	[6] SECHI-ZORN	73	HBC	$K^- p$ at rest

[6] Effective denominator calculated by us.

$\Gamma(n\mu^+\nu_\mu)/\Gamma(n\pi^+)$ — Γ_7/Γ_2

Test of $\Delta S = \Delta Q$ rule.

EFFECTIVE DENOM.	EVTS	DOCUMENT ID		TECN
< 6.2 × 10^{-5} OUR LIMIT		Our 90% CL limit = (6.7 events)/(effective denominator sum). [Number of events increased to 6.7 for a 90% confidence level.]		
33800	0	BAGGETT	69B	HBC
62000	2	[7] EISELE	69B	HBC
10150	0	[8] COURANT	64	HBC
1710	0	[8] NAUENBERG	64	HBC
120	1	GALTIERI	62	EMUL

[7] Effective denominator calculated by us.
[8] Effective denominator taken from EISELE 67.

$\Gamma(pe^+e^-)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-6})	DOCUMENT ID		TECN	COMMENT
<7	[9] ANG	69B	HBC	$K^- p$ at rest

[9] ANG 69B found three pe^+e^- events in agreement with $\gamma \to e^+e^-$ conversion from $\Sigma^+ \to p\gamma$. The limit given here is for neutral currents.

$\Gamma(\Sigma^+ \to ne^+\nu_e)/\Gamma(\Sigma^- \to ne^-\overline{\nu}_e)$

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.009 OUR LIMIT			Our 90% CL limit, using $\Gamma(ne^+\nu_e)/\Gamma(n\pi^+)$ above.			
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.019	90	0	EBENHOH	74	HBC	$K^- p$ at rest
<0.018	90	0	SECHI-ZORN	73	HBC	$K^- p$ at rest
<0.12	95	0	COLE	71	HBC	$K^- p$ at rest
<0.03	90	0	EISELE	69B	HBC	See EBENHOH 74

$\Gamma(\Sigma^+ \to n\mu^+\nu_\mu)/\Gamma(\Sigma^- \to n\mu^-\overline{\nu}_\mu)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
<0.12 OUR LIMIT		Our 90% CL limit, using $\Gamma(n\mu^+\nu_\mu)/\Gamma(n\pi^+)$ above.			
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.06^{+0.045}_{-0.03}$	2	EISELE	69B	HBC	$K^- p$ at rest

$\Gamma(\Sigma^+ \to n\ell^+\nu)/\Gamma(\Sigma^- \to n\ell^-\overline{\nu})$

Test of $\Delta S = \Delta Q$ rule.

VALUE	EVTS	DOCUMENT ID		TECN
<0.043 OUR LIMIT		Our 90% CL limit, using $\left[\Gamma(ne^+\nu_e) + \Gamma(n\mu^+\nu_\mu)\right]/\Gamma(n\pi^+)$.		
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.08	1	NORTON	69	HBC
<0.034	0	BAGGETT	67	HBC

Σ^+ DECAY PARAMETERS

See the Note on Baryon Decay Parameters in the neutron Listings. A few early results have been omitted.

α_0 FOR $\Sigma^+ \to p\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$-0.980^{+0.017}_{-0.015}$ OUR FIT					
$-0.980^{+0.017}_{-0.013}$ OUR AVERAGE					
$-0.945^{+0.055}_{-0.042}$	1259	[10] LIPMAN	73	OSPK	$\pi^+ p \to \Sigma^+$
−0.940±0.045	16k	BELLAMY	72	ASPK	$\pi^+ p \to \Sigma^+ K^+$
$-0.98\ ^{+0.05}_{-0.02}$	1335	[11] HARRIS	70	OSPK	$\pi^+ p \to \Sigma^+ K^+$
−0.999±0.022	32k	BANGERTER	69	HBC	$K^- p$ 0.4 GeV/c

[10] Decay protons scattered off aluminum.
[11] Decay protons scattered off carbon.

ϕ_0 ANGLE FOR $\Sigma^+ \to p\pi^0$ — $(\tan\phi_0 = \beta / \gamma)$

VALUE (°)	EVTS	DOCUMENT ID		TECN	COMMENT
36 ±34 OUR AVERAGE					
$38.1^{+35.7}_{-37.1}$	1259	[12] LIPMAN	73	OSPK	$\pi^+ p \to \Sigma^+ K^+$
22 ±90		[13] HARRIS	70	OSPK	$\pi^+ p \to \Sigma^+ K^+$

[12] Decay proton scattered off aluminum.
[13] Decay protons scattered off carbon.

α_+ / α_0

Older results have been omitted.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.069±0.013 OUR FIT					
−0.073±0.021	23k	MARRAFFINO	80	HBC	$K^- p$ 0.42–0.5 GeV/c

α_+ FOR $\Sigma^+ \to n\pi^+$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.068±0.013 OUR FIT					
0.066±0.016 OUR AVERAGE					
0.037±0.049	4101	BERLEY	70B	HBC	
0.069±0.017	35k	BANGERTER	69	HBC	$K^- p$ 0.4 GeV/c

ϕ_+ ANGLE FOR $\Sigma^+ \to n\pi^+$ — $(\tan\phi_+ = \beta / \gamma)$

VALUE (°)	EVTS	DOCUMENT ID		TECN	COMMENT
167±20 OUR AVERAGE		Error includes scale factor of 1.1.			
184±24	1054	[14] BERLEY	70B	HBC	
143±29	560	BANGERTER	69B	HBC	$K^- p$ 0.4 GeV/c

[14] Changed from 176 to 184° to agree with our sign convention.

α_γ FOR $\Sigma^+ \to p\gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.83±0.12 OUR AVERAGE					
−0.86±0.13±0.04	190	KOBAYASHI	87	CNTR	$\pi^+ p \to \Sigma^+ K^+$
$-0.53^{+0.38}_{-0.36}$	46	MANZ	80	HBC	$K^- p \to \Sigma^+\pi^-$
$-1.03^{+0.52}_{-0.42}$	61	GERSHWIN	69B	HBC	$K^- p \to \Sigma^+\pi^-$

REFERENCES FOR Σ^+

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1986 edition (Physics Letters **170B** (1986)) or in earlier editions.

HESSEY 89 ZPHY C42 175 +Booth, Fickinger, Gall+ (BNL-811 Collab.)
KOBAYASHI 87 PRL 59 868 +Haba, Homma, Kawai, Miyake+ (KYOT)
WILKINSON 87 PRL 58 855 +Handler+ (WISC, MICH, RUTG, MINN)
PDG 86 PL 170B Aguilar-Benitez, Porter+ (CERN, CIT+)
BIAGI 85 ZPHY C28 495 +Bourquin+ (BRIS, CERN, GEVA, HEID+)
ANKENBRA... 83 PRL 51 863 Ankenbrandt, Berge+ (FNAL, IOWA, ISU, YALE)
MANZ 80 PL 96B 217 +Reucroft, Settles, Wolf+ (MPIM, VAND)
MARRAFFINO 80 PR D21 2501 +Reucroft, Roos, Waters+ (VAND, MPIM)
SETTLES 79 PR D20 2154 +Manz, Matt, Hansl, Herynek+ (MPIM, VAND)
NOWAK 78 NP B139 61 +Armstrong, Davis+ (LOUC, BELG, DURH, WARS)
CONFORTO 76 NP B105 189 +Gopal, Kalmus, Litchfield, Ross+ (RHEL, LOIC)
EBENHOH 74 ZPHY 266 367 +Eisele, Engelmann, Filthuth, Hepp+ (HEID)
EBENHOH 73 ZPHY 264 413 +Eisele, Filthuth, Hepp, Leitner, Thouw+ (HEID)
LIPMAN 73 PL 43B 89 +Uto, Walker, Montgomery+ (RHEL, SUSS, LOWC)
PDG 73 RMP 45 No. 2 Pt. II Lasinski, Barbaro-Galtieri, Kelly+ (LBL, BRAN, CERN+)
SECHI-ZORN 73 PR D8 12 +Snow (UMD)
BELLAMY 72 PL 39B 299 +Anderson, Crawford+ (LOWC, RHEL, SUSS)
BOHM 72 NP B48 1 + (BERL, UBEL, BRUX, IASD, DUUC, LOUC+)
Also 73 IIHE-73.2 Nov Bohm (BERL, UBEL, BRUX, IASD, DUUC, LOUC+)
BAKKER 71 LNC 1 37 +Hoogland, Kluyver, Massard+ (SABRE Collab.)
COLE 71 PR D4 631 +Lee-Franzini, Loveless, Baltay+ (STON, COLU)
TOVEE 71 NP B33 493 + (LOUC, UBEL, BERL, BRUX, DUUC, WARS)
BERLEY 70B PR D1 2015 +Yamin, Hertzbach, Kofler+ (BNL, MASA, YALE)
EISELE 70 ZPHY 238 372 +Filthuth, Hepp, Presser, Zech (HEID)
HARRIS 70 PRL 24 165 +Overseth, Pondrom, Dettmann (MICH, WISC)
PDG 70 RMP 42 No. 1 Barbaro-Galtieri, Derenzo, Price+ (LRL, BRAN, CERN+)
ANG 69B ZPHY 228 151 +Ebenhoh, Eisele, Engelmann, Filthuth+ (HEID)
BAGGETT 69B MDDP-TR-973 Thesis (UMD)
BALTAY 69 PRL 22 615 +Franzini, Newman, Norton+ (COLU, STON)
BANGERTER 69 UCRL 19244 Thesis (LRL)
BANGERTER 69B PR 187 1821 +Alston-Garnjost, Galtieri, Gershwin+ (LRL)
BARLOUTAUD 69 NP B14 153 +DeBellefon, Granet+ (SACL, CERN, HEID)
EISELE 69 ZPHY 221 1 +Engelmann, Filthuth, Fohlisch, Hepp+ (HEID)
Also 64 PRL 13 291 Willis, Courant+ (BNL, CERN, HEID, UMD)
EISELE 69B ZPHY 221 401 +Engelmann, Filthuth, Fohlisch, Hepp+ (HEID)
GERSHWIN 69B PR 188 2077 +Alston-Garnjost, Bangerter+ (LRL)
Also 69 UCRL 19246 Thesis Gershwin (LRL)
NORTON 69 Nevis 175 Thesis (COLU)
BAGGETT 67 PRL 19 1458 +Day, Glasser, Kehoe, Knop+ (UMD)
Also 68 Vienna Abs. 374 Baggett, Kehoe (UMD)
Also 68B Private Comm. Baggett (UMD)
BARASH 67 PRL 19 181 +Day, Glasser, Kehoe, Knop+ (UMD)
EISELE 67 ZPHY 205 409 +Engelmann, Filthuth, Folish, Hepp+ (HEID)
HYMAN 67 PL 25B 376 +Loken, Pewitt, McKenzie+ (ANL, CMU, NWES)
PDG 67 RMP 39 1 Rosenfeld, Barbaro-Galtieri, Podolsky+ (LRL, CERN, YALE)
CHANG 66 PR 151 1081 (COLU)
Also 65 Nevis 145 Thesis Chang (COLU)
COOK 66 PRL 17 223 +Ewart, Masek, Orr, Platner (WASH)
BALTAY 65 PR 140B 1027 +Sandweiss, Culwick, Kopp+ (YALE, BNL)
BAZIN 65 PRL 14 154 +Blumenfeld, Nauenberg+ (PRIN, COLU)
BAZIN 65B PR 140B 1358 +Plano, Schmidt+ (PRIN, RUTG, COLU)
CARAYAN... 65 PR 138B 433 Carayannopoulos, Tautfest, Willmann (PURD)
SCHMIDT 65 PR 140B 1328 (COLU)
BHOWMIK 64 NP 53 22 +Jain, Mathur, Lakshmi (DELH)
COURANT 64 PR 136B 1791 +Filthuth+ (CERN, HEID, UMD, NRL, BNL)
NAUENBERG 64 PRL 12 679 +Marateck+ (COLU, RUTG, PRIN)
BARKAS 63 PRL 11 26 +Dyer, Heckman (LRL)
Also 61 UCRL 9450 Thesis Dyer (LRL)
GALTIERI 62 PRL 9 26 +Barkas, Heckman, Patrick, Smith (LRL)
GRARD 62 PR 127 607 +Smith (LRL)
HUMPHREY 62 PR 127 1305 +Ross (LRL)

Σ^0

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗∗∗

The spin and parity have not been measured directly. They are of course assumed to be the same as for the Σ^+ and Σ^-.

Σ^0 MASS

The fit uses Σ^+, Σ^0, Σ^-, and Λ mass and mass-difference measurements.

VALUE (MeV)	DOCUMENT ID
1192.55±0.10 OUR FIT	Error includes scale factor of 1.4.

$\Sigma^- - \Sigma^0$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
4.89±0.08 OUR FIT	Error includes scale factor of 1.2.				
4.86±0.08 OUR AVERAGE	Error includes scale factor of 1.2.				
4.87±0.12	37	DOSCH	65	HBC	
5.01±0.12	12	SCHMIDT	65	HBC	See note with Λ mass
4.75±0.1	18	BURNSTEIN	64	HBC	

$\Sigma^0 - \Lambda$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
76.92±0.10 OUR FIT	Error includes scale factor of 1.4.				
76.55±0.25 OUR AVERAGE					
76.23±0.55	109	COLAS	75	HLBC	$\Sigma^0 \to \Lambda\gamma$
76.63±0.28	208	SCHMIDT	65	HBC	See note with Λ mass

Σ^0 MEAN LIFE

These lifetimes are deduced from measurements of the cross sections for the Primakoff process $\Lambda \to \Sigma^0$ in nuclear Coulomb fields. An alternative expression of the same information is the Σ^0-Λ transition magnetic moment given in the following section. The relation is $(\mu_{\Sigma\Lambda}/\mu_N)^2\ \tau = 1.92951 \times 10^{-19}$ s (see DEVLIN 86).

VALUE (10^{-20} s)	DOCUMENT ID		TECN	COMMENT
7.4±0.7 OUR EVALUATION	Using $\mu_{\Sigma\Lambda}$ (see the above note).			
$6.5^{+1.7}_{-1.1}$	[1] DEVLIN	86	SPEC	Primakoff effect
7.6±0.5±0.7	[2] PETERSEN	86	SPEC	Primakoff effect
• • • We do not use the following data for averages, fits, limits, etc. • • •				
5.8±1.3	[1] DYDAK	77	SPEC	See DEVLIN 86

[1] DEVLIN 86 is a recalculation of the results of DYDAK 77 removing a numerical approximation made in that work.
[2] An additional uncertainty of the Primakoff formalism is estimated to be < 5%.

$|\mu(\Sigma^0 \to \Lambda)|$ TRANSITION MAGNETIC MOMENT

See the note in the Σ^0 mean-life section above. Also, see the Note on Baryon Magnetic Moments in the Λ Listings.

VALUE (μ_N)	DOCUMENT ID		TECN	COMMENT
1.61±0.08 OUR AVERAGE				
$1.72^{+0.17}_{-0.19}$	[3] DEVLIN	86	SPEC	Primakoff effect
1.59±0.05±0.07	[4] PETERSEN	86	SPEC	Primakoff effect
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.82^{+0.25}_{-0.18}$	[3] DYDAK	77	SPEC	See DEVLIN 86

[3] DEVLIN 86 is a recalculation of the results of DYDAK 77 removing a numerical approximation made in that work.
[4] An additional uncertainty of the Primakoff formalism is estimated to be < 2.5%.

Σ^0 DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Lambda\gamma$	100 %	
Γ_2	$\Lambda\gamma\gamma$	< 3 %	90%
Γ_3	$\Lambda e^+ e^-$	[a] 5×10^{-3}	

[a] A theoretical value using QED; see the Full Listings.

Σ^0 BRANCHING RATIOS

$\Gamma(\Lambda\gamma\gamma)/\Gamma_{total}$ Γ_2/Γ

VALUE	CL%	DOCUMENT ID		TECN
<0.03	90	COLAS	75	HLBC

$\Gamma(\Lambda e^+ e^-)/\Gamma_{total}$ Γ_3/Γ

VALUE	DOCUMENT ID		COMMENT
0.00545	FEINBERG	58	Theoretical QED calculation

REFERENCES FOR Σ^0

DEVLIN 86 PR D34 1626 +Petersen, Beretvas (RUTG)
PETERSEN 86 PRL 57 949 +Beretvas, Devlin, Luk+ (RUTG, WISC, MICH, MINN)
DYDAK 77 NP B118 1 +Navarria, Overseth, Steffen+ (CERN, DORT, HEID)
COLAS 75 NP B91 253 +Farwell, Ferrer, Six (ORSA)
DOSCH 65 PL 14 239 +Engelmann, Filthuth, Hepp, Kluge+ (HEID)
SCHMIDT 65 PR 140B 1328 (COLU)
BURNSTEIN 64 PRL 13 66 +Day, Kehoe, Zorn, Snow (UMD)
FEINBERG 58 PR 109 1019 (BNL)

Σ^-

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗∗∗

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1986 edition (Physics Letters **170B** (1986)) or in earlier editions.

Σ^- MASS

The fit uses Σ^+, Σ^0, Σ^-, and Λ mass and mass-difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1197.43 ±0.06 OUR FIT Error includes scale factor of 1.6.					
1197.50 ±0.05 OUR AVERAGE					
1197.532±0.057		GALL	88	CNTR	Σ^- Pb, Σ^- W atoms
1197.43 ±0.08	3000	SCHMIDT	65	HBC	See note with Λ mass
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1197.24 ±0.15		[1] DUGAN	75	CNTR	Exotic atoms

[1] GALL 88 concludes that the DUGAN 75 mass needs to be reevaluated.

Σ^- − Σ^+ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN
8.07±0.09 OUR FIT Error includes scale factor of 1.9.				
8.09±0.16 OUR AVERAGE				
7.91±0.23	86	BOHM	72	EMUL
8.25±0.25	2500	DOSCH	65	HBC
8.25±0.40	87	BARKAS	63	EMUL

Σ^- − Λ MASS DIFFERENCE

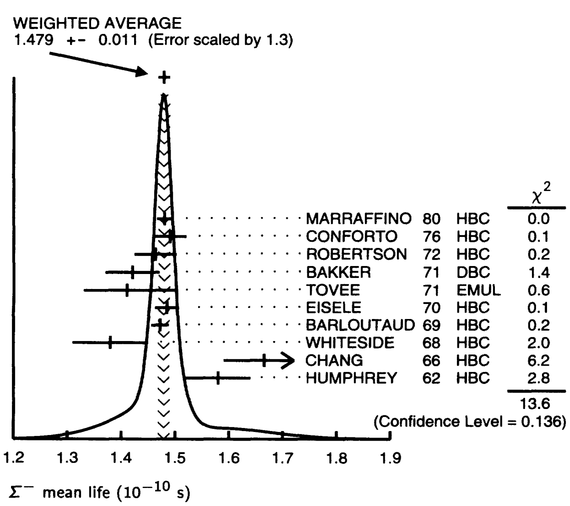
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
81.81±0.07 OUR FIT Error includes scale factor of 1.5.					
81.69±0.07 OUR AVERAGE					
81.64±0.09	2279	HEPP	68	HBC	
81.80±0.13	85	SCHMIDT	65	HBC	See note with Λ mass
81.70±0.19		BURNSTEIN	64	HBC	

Σ^- MEAN LIFE

Measurements with an error $\geq 0.2 \times 10^{-10}$ s have been omitted.

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
1.479±0.011 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.					
1.480±0.014	16k	MARRAFFINO	80	HBC	$K^- p$ 0.42–0.5 GeV/c
1.49 ±0.03	8437	CONFORTO	76	HBC	$K^- p$ 1–1.4 GeV/c
1.463±0.039	2400	ROBERTSON	72	HBC	$K^- p$ 0.25 GeV/c
1.42 ±0.05	1383	BAKKER	71	DBC	$K^- N \to \Sigma^- \pi\pi$
1.41 $^{+0.09}_{-0.08}$		TOVEE	71	EMUL	
1.485±0.022	100k	EISELE	70	HBC	$K^- p$ at rest
1.472±0.016	10k	BARLOUTAUD	69	HBC	$K^- p$ 0.4–1.2 GeV/c
1.38 ±0.07	506	WHITESIDE	68	HBC	$K^- p$ at rest
1.666±0.075	3267	[2] CHANG	66	HBC	$K^- p$ at rest
1.58 ±0.06	1208	HUMPHREY	62	HBC	$K^- p$ at rest

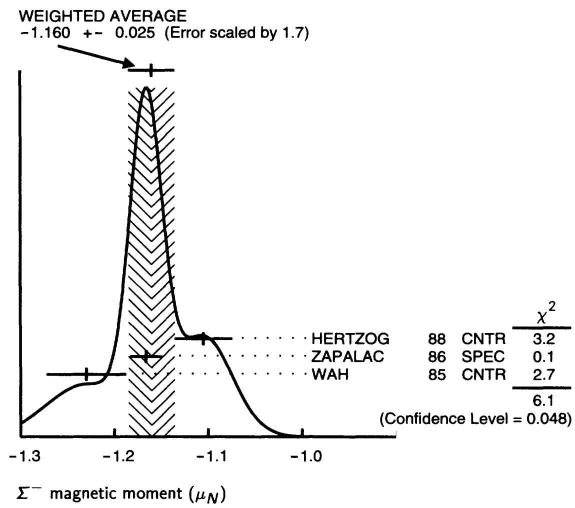
[2] We have increased the CHANG 66 error of 0.018; see our 1970 edition, Reviews of Modern Physics **42** No. 1 (1970).



Σ^- MAGNETIC MOMENT

See the Note on Baryon Magnetic Moments in the Λ Listings. Measurements with an error $\geq 0.3\ \mu_N$ have been omitted.

VALUE (μ_N)	EVTS	DOCUMENT ID		TECN	COMMENT
−1.160±0.025 OUR AVERAGE Error includes scale factor of 1.7. See the ideogram below.					
−1.105±0.029±0.010		HERTZOG	88	CNTR	Σ^- Pb, Σ^- W atoms
−1.166±0.014±0.010	671k	ZAPALAC	86	SPEC	$n e^- \nu$, $n\pi^-$ decays
−1.23 ±0.03 ±0.03		WAH	85	CNTR	pCu → Σ^- X
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.89 ±0.14	516k	DECK	83	SPEC	pBe → Σ^- X



Σ^- DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$n\pi^-$	(99.848±0.005) %
Γ_2	$n\pi^-\gamma$	[a] (4.6 ±0.6) $\times 10^{-4}$
Γ_3	$ne^-\overline{\nu}_e$	(1.017±0.034) $\times 10^{-3}$
Γ_4	$n\mu^-\overline{\nu}_\mu$	(4.5 ±0.4) $\times 10^{-4}$
Γ_5	$\Lambda e^-\overline{\nu}_e$	(5.73 ±0.27) $\times 10^{-5}$

[a] See the Listings below for the pion momentum range used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to 3 branching ratios uses 16 measurements and one constraint to determine 4 parameters. The overall fit has a χ^2 = 8.7 for 13 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_3	−64		
x_4	−77	0	
x_5	−5	0	0
	x_1	x_3	x_4

Σ^- BRANCHING RATIOS

$\Gamma(n\pi^-\gamma)/\Gamma(n\pi^-)$ — Γ_2/Γ_1

The π^+ momentum cuts differ, so we do not average the results but simply use the latest value in the Summary Table.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.46±0.06	292	EBENHOH	73	HBC	$\pi^+ < 150$ MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.10±0.02	23	ANG	69B	HBC	$\pi^- < 110$ MeV/c
~ 1.1		BAZIN	65B	HBC	$\pi^- < 166$ MeV/c

$\Gamma(n e^- \overline{\nu}_e)/\Gamma(n\pi^-)$ — Γ_3/Γ_1

Measurements with an error $\geq 0.2 \times 10^{-3}$ have been omitted.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.019±0.034 OUR FIT					
$1.019^{+0.031}_{-0.036}$ OUR AVERAGE					
0.96 ±0.05	2847	BOURQUIN	83C	SPEC	SPS hyperon beam
$1.09\ ^{+0.06}_{-0.08}$	601	[3] EBENHOH	74	HBC	$K^- p$ at rest
$1.05\ ^{+0.07}_{-0.13}$	455	[3] SECHI-ZORN	73	HBC	$K^- p$ at rest
0.97 ±0.15	57	COLE	71	HBC	$K^- p$ at rest
1.11 ±0.09	180	BIERMAN	68	HBC	

[3] An additional negative systematic error is included for internal radiative corrections and latest form factors; see BOURQUIN 83C.

$\Gamma(n \mu^- \overline{\nu}_\mu)/\Gamma(n\pi^-)$ — Γ_4/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.45±0.04 OUR FIT					
0.45±0.04 OUR AVERAGE					
0.38±0.11	13	COLE	71	HBC	$K^- p$ at rest
0.43±0.06	72	ANG	69	HBC	$K^- p$ at rest
0.43±0.09	56	BAGGETT	69	HBC	$K^- p$ at rest
0.56±0.20	11	BAZIN	65B	HBC	$K^- p$ at rest
0.66±0.15	22	COURANT	64	HBC	

$\Gamma(\Lambda e^- \overline{\nu}_e)/\Gamma(n\pi^-)$ — Γ_5/Γ_1

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
0.574±0.027 OUR FIT					
0.574±0.027 OUR AVERAGE					
0.561±0.031	1620	[4] BOURQUIN	82	SPEC	SPS hyperon beam
0.63 ±0.11	114	THOMPSON	80	ASPK	Hyperon beam
0.52 ±0.09	31	BALTAY	69	HBC	$K^- p$ at rest
0.69 ±0.12	31	EISELE	69	HBC	$K^- p$ at rest
0.64 ±0.12	35	BARASH	67	HBC	$K^- p$ at rest
0.75 ±0.28	11	COURANT	64	HBC	$K^- p$ at rest

[4] The value is from BOURQUIN 83B, and includes radiation corrections and new acceptance.

Σ^- DECAY PARAMETERS

See the Note on Baryon Decay Parameters in the neutron Listings. Older, outdated results have been omitted.

α_- FOR $\Sigma^- \rightarrow n\pi^-$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.068±0.008 OUR AVERAGE					
−0.062±0.024	28k	HANSL	78	HBC	$K^- p \rightarrow \Sigma^- \pi^+$
−0.067±0.011	60k	BOGERT	70	HBC	$K^- p$ 0.4 GeV/c
−0.071±0.012	51k	BANGERTER	69	HBC	$K^- p$ 0.4 GeV/c

ϕ ANGLE FOR $\Sigma^- \rightarrow n\pi^-$ — $(\tan\phi = \beta / \gamma)$

VALUE (°)	EVTS	DOCUMENT ID		TECN	COMMENT
10±15 OUR AVERAGE					
+ 5±23	1092	[5] BERLEY	70B	HBC	n rescattering
14±19	1385	BANGERTER	69B	HBC	$K^- p$ 0.4 GeV/c

[5] BERLEY 70B changed from −5 to +5° to agree with our sign convention.

g_A/g_V FOR $\Sigma^- \rightarrow n e^- \overline{\nu}_e$

Measurements with fewer than 500 events have been omitted. Where necessary, signs have been changed to agree with our conventions, which are given in the Note on Baryon Decay Parameters in the neutron Listings. What is actually listed is $|g_1/f_1 - 0.237 g_2/f_1|$. This reduces to $g_A/g_V \equiv g_1(0)/f_1(0)$ on making the usual assumption that $g_2 = 0$. See also the note on HSUEH 88.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.340±0.017 OUR AVERAGE					
+0.327±0.007±0.019	50k	[6] HSUEH	88	SPEC	Σ^- 250 GeV
+0.34 ±0.05	4456	[7] BOURQUIN	83C	SPEC	SPS hyperon beam
0.385±0.037	3507	[8] TANENBAUM	74	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.29 ±0.07	25k	HSUEH	85	SPEC	See HSUEH 88
$0.17\ ^{+0.07}_{-0.09}$	519	DECAMP	77	ELEC	Hyperon beam

[6] The sign is, *with our conventions*, unambiguously positive. The value assumes, as usual, that $g_2 = 0$. If g_2 is included in the fit, than (with our sign convention) $g_2 = -0.56 \pm 0.37$, with a corresponding reduction of g_A/g_V to $+0.20 \pm 0.08$.

[7] BOURQUIN 83C favors the positive sign by at least 2.6 standard deviations.

[8] TANENBAUM 74 gives 0.435 ± 0.035, assuming no q^2 dependence in g_A and g_V. The listed result allows q^2 dependence, and is taken from HSUEH 88.

$f_2(0)/f_1(0)$ FOR $\Sigma^- \rightarrow n e^- \overline{\nu}_e$

The signs have been changed to be in accord with our conventions, given in the Note on Baryon Decay Parameters in the neutron Listings.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.97±0.14 OUR AVERAGE					
+0.96±0.07±0.13	50k	HSUEH	88	SPEC	Σ^- 250 GeV
+1.02±0.34	4456	BOURQUIN	83C	SPEC	SPS hyperon beam

TRIPLE CORRELATION COEFFICIENT D for $\Sigma^- \rightarrow n e^- \overline{\nu}_e$

The coefficient D of the term $D\mathbf{P}\cdot(\mathbf{p}_e \times \mathbf{p}_\nu)$ in the $\Sigma^- \rightarrow n e^- \overline{\nu}$ decay angular distribution. A nonzero value would indicate a violation of time-reversal invariance.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.11±0.10	50k	HSUEH	88	SPEC	Σ^- 250 GeV

NOTE ON $\Sigma^- \rightarrow \Lambda e^- \overline{\nu}_e$ DECAY

The vector part of the hadronic amplitude for the decay $\Sigma^- \rightarrow \Lambda e^- \overline{\nu}_e$ is of special interest because the vector weak current is proportional to an isospin rotation of the isovector part of the electromagnetic current. This strong form of CVC predicts that

$$f_1(q^2) = 0 \quad \text{for} \quad 0 < q^2 \leq (m_{\Sigma^-} - m_\Lambda)^2 ,$$

and also relates $f_2(0)$ to the $\Sigma^0\Lambda$ transition magnetic moment or to the amplitude for the decay $\Sigma^0 \rightarrow \Lambda\gamma$ by

$$\begin{aligned} f_2(0) &= -\sqrt{2}\ \mu_{\Sigma^0\Lambda}/e\hbar \\ &= -\sqrt{3/2}\ \mu_n/e\hbar \qquad \text{[by SU(3)]} \\ &= 1.17\ m_p^{-1} . \end{aligned}$$

No SU(3) symmetry is assumed here except in the relation of $\mu_{\Sigma^0\Lambda}$ to the magnetic moment of the neutron, μ_n.

The experimental data were analyzed on the assumption that $f_1(q^2) = 0$ and $f_2(q^2) = f_2(0)$ over the entire kinematical range of q^2 for $\Sigma^- \rightarrow \Lambda e^- \overline{\nu}_e$. The results are listed in the ratio of $g_{WM} = -m_{\Sigma^-}\ f_2(0)$ to $g_A = g_1(0)$.

See also the Note on Baryon Decay Parameters in the neutron section of the Full Listings.

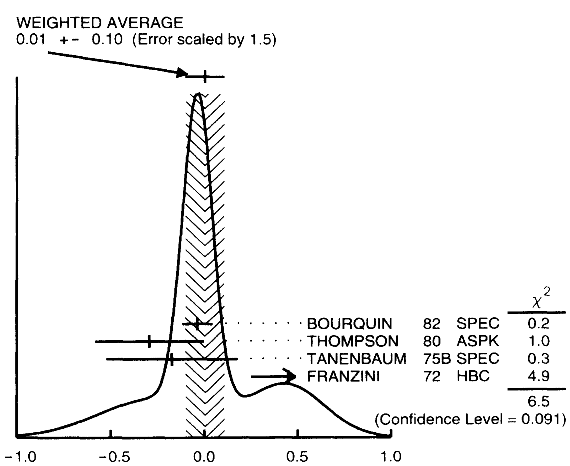
g_V/g_A FOR $\Sigma^- \rightarrow \Lambda e^- \nu$

For the sign convention, see the Note on Baryon Decay Parameters in the neutron Listings. The value is predicted to be zero by conserved vector current theory. The values averaged assume CVC-SU(3) weak magnetism term.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.01 ±0.10 OUR AVERAGE		Error includes scale factor of 1.5. See the ideogram below.			
−0.034±0.080	1620	[9] BOURQUIN	82	SPEC	SPS hyperon beam
−0.29 ±0.29	114	THOMPSON	80	ASPK	BNL hyperon beam
−0.17 ±0.35	55	TANENBAUM	75B	SPEC	BNL hyperon beam
+0.45 ±0.20	186	[9,10] FRANZINI	72	HBC	

[9] The sign has been changed to agree with our convention.

[10] The FRANZINI 72 value includes the events of earlier papers.



g_V/g_A for $\Sigma^- \rightarrow \Lambda e^- \nu$

g_{WM}/g_A FOR $\Sigma^- \rightarrow \Lambda e^- \nu$

The values quoted assume the CVC prediction $g_V = 0$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
2.4 ±1.7 OUR AVERAGE					
1.75±3.5	114	THOMPSON	80	ASPK	BNL hyperon beam
3.5 ±4.5	55	TANENBAUM	75B	SPEC	BNL hyperon beam
2.4 ±2.1	186	FRANZINI	72	HBC	

REFERENCES FOR Σ^-

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1986 edition (Physics Letters **170B** (1986)) or in earlier editions.

GALL	88	PRL 60 186	+Austin+	(BOST, MIT, WILL, CIT, CMU, WYOM)
HERTZOG	88	PR D37 1142	+Eckhause+	(WILL, BOST, MIT, CIT, CMU, WYOM)
HSUEH	88	PR D38 2056	+	(CHIC, ELMT, FNAL, IOWA, ISU, LENI, YALE)
PDG	86	PL 170B	Aguilar-Benitez, Porter+	(CERN, CIT+)
ZAPALAC	86	PRL 57 1526	+	(EFI, ELMT, FNAL, IOWA, ISU, LENI, YALE)
HSUEH	85	PRL 54 2399	+Muller+	(CHIC, ELMT, FNAL, ISU, LENI, YALE)
WAH	85	PRL 55 2551	+Cardello, Cooper, Teig+	(FNAL, IOWA, ISU)
BOURQUIN	83B	ZPHY C21 27	+	(BRIS, GEVA, HEID, LALO, RL, STRB)
BOURQUIN	83C	ZPHY C21 17	+	(BRIS, GEVA, HEID, LALO, RL, STRB)
DECK	83	PR D28 1	+Beretvas, Devlin, Luk+	(RUTG, WISC, MICH, MINN)
BOURQUIN	82	ZPHY C12 307	+Brown+	(BRIS, GEVA, HEID, LALO, RL, STRB)
MARRAFFINO	80	PR D21 2501	+Reucroft, Roos, Waters+	(VAND, MPIM)
THOMPSON	80	PR D21 25	+Cleland, Cooper, Dris, Engels+	(PITT, BNL)
HANSL	78	NP B132 45	+Manz, Matt, Reucroft, Settles+	(MPIM, VAND)
DECAMP	77	PL 66B 295	+Badier, Bland, Chollet, Gaillard+	(LALO, EPOL)
CONFORTO	76	NP B105 189	+Gopal, Kalmus, Litchfield, Ross+	(RHEL, LOIC)
DUGAN	75	NP A254 396	+Asano, Chen, Cheng, Hu, Lidofsky+	(COLU, YALE)
TANENBAUM	75B	PR D12 1871	+Hungerbuhler+	(YALE, FNAL, BNL)
EBENHOH	74	ZPHY 266 367	+Eisele, Engelmann, Filthuth, Hepp+	(HEID)
TANENBAUM	74	PRL 33 175	+Hungerbuhler+	(YALE, FNAL, BNL)
EBENHOH	73	ZPHY 264 413	+Eisele, Filthuth, Hepp, Leitner, Thouw+	(HEID)
SECHI-ZORN	73	PR D8 12	+Snow	(UMD)
BOHM	72	NP B48 1	+	(BERL, UBEL, BRUX, IASD, DUUC, LOUC+)
FRANZINI	72	PR D6 2417	+	(COLU, HEID, UMD, STON)
ROBERTSON	72	Thesis		(IIT)
BAKKER	71	LNC 1 37	+Hoogland, Kluyver, Massard+	(SABRE Collab.)
COLE	71	PR D4 631	+Lee-Franzini, Loveless, Baltay+	(STON, COLU)
Also	69	Nevis 175 Thesis	Norton	(COLU)
TOVEE	71	NP B33 493	+	(LOUC, UBEL, BERL, BRUX, DUUC, WARS)
BERLEY	70B	PR D1 2015	+Yamin, Hertzbach, Kofler+	(BNL, MASA, YALE)
BOGERT	70	PR D2 6	+Lucas, Taft, Willis, Berley+	(BNL, MASA, YALE)
EISELE	70	ZPHY 238 372	+Filthuth, Hepp, Presser, Zech	(HEID)
PDG	70	RMP 42 No. 1	Barbaro-Galtieri, Derenzo, Price+	(LRL, BRAN, CERN+)
ANG	69	ZPHY 223 103	+Eisele, Engelmann, Filthuth+	(HEID)
ANG	69B	ZPHY 228 151	+Ebenhoh, Eisele, Engelmann, Filthuth+	(HEID)
BAGGETT	69	PRL 23 249	+Kehoe, Snow	(UMD)
BALTAY	69	PRL 22 615	+Franzini, Newman, Norton+	(COLU, STON)
BANGERTER	69	UCRL 19244 Thesis		(LRL)
BANGERTER	69B	PR 187 1821	+Alston-Garnjost, Galtieri, Gershwin+	(LRL)
BARLOUTAUD	69	NP B14 153	+DeBellefon, Granet+	(SACL, CERN, HEID)
EISELE	69	ZPHY 221 1	+Engelmann, Filthuth, Fohlisch, Hepp+	(HEID)
BIERMAN	68	PRL 20 1459	+Kounosu, Nauenberg+	(PRIN)
HEPP	68	ZPHY 214 71	+Schleich	(HEID)
WHITESIDE	68	NC 54A 537	+Gollub	(OBER)
BARASH	67	PRL 19 181	+Day, Glasser, Kehoe, Knop+	(UMD)
CHANG	66	PR 151 1081		(COLU)
BAZIN	65B	PR 140B 1358	+Plano, Schmidt+	(PRIN, RUTG, COLU)
DOSCH	65	PL 14 239	+Engelmann, Filthuth, Hepp, Kluge+	(HEID)
Also	66	PR 151 1081	Chang	(COLU)
SCHMIDT	65	PR 140B 1328		(COLU)
BURNSTEIN	64	PRL 13 66	+Day, Kehoe, Zorn, Snow	(UMD)
COURANT	64	PR 136B 1791	+Filthuth+	(CERN, HEID, UMD, NRL, BNL)
BARKAS	63	PRL 11 26	+Dyer, Heckman	(LRL)
HUMPHREY	62	PR 127 1305	+Ross	(LRL)

$\Sigma(1385)$ P_{13}

$I(J^P) = 1(\frac{3}{2}^+)$ Status: ∗∗∗∗

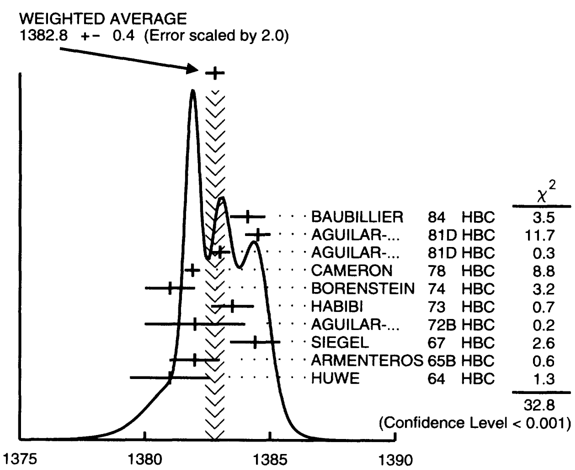
Discovered by ALSTON 60. Early measurements of the mass and width for combined charge states have been omitted. They may be found in our 1984 edition Reviews of Modern Physics **56** No. 2 Pt. II (1984).

We average only the most significant determinations. We do not average results from inclusive experiments with large backgrounds or results which are not accompanied by some discussion of experimental resolution. Nevertheless systematic differences between experiments remain. (See the ideograms in the Listings below.) These differences could arise from interference effects that change with production mechanism and/or beam momentum. They can also be accounted for in part by differences in the parametrizations employed. (See BORENSTEIN 74 for a discussion on this point.) Thus BORENSTEIN 74 uses a Breit-Wigner with energy-independent width, since a *P*-wave was found to give unsatisfactory fits. CAMERON 78 uses the same form. On the other hand HOLMGREN 77 obtains a good fit to their $\Lambda\pi$ spectrum with a *P*-wave Breit-Wigner, but includes the partial width for the $\Sigma\pi$ decay mode in the parametrization. AGUILAR-BENITEZ 81D gives masses and widths for five different Breit-Wigner shapes. The results vary considerably. Only the best-fit *S*-wave results are given here.

$\Sigma(1385)$ MASSES

$\Sigma(1385)^+$ MASS

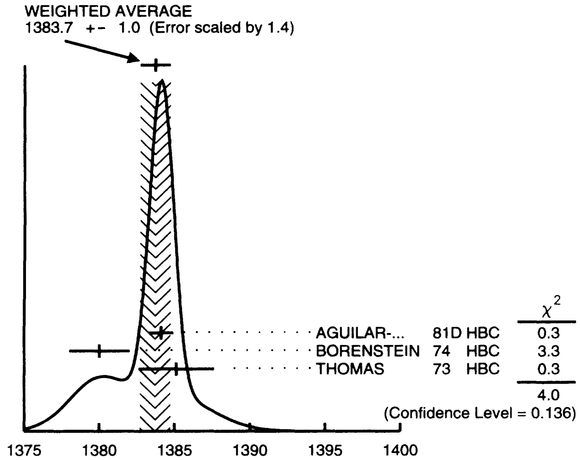
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1382.8±0.4 OUR AVERAGE	Error includes scale factor of 2.0. See the ideogram below.				
1384.1±0.7	1897	BAUBILLIER	84	HBC	$K^- p$ 8.25 GeV/c
1384.5±0.5	5256	AGUILAR-...	81D	HBC	$K^- p \rightarrow \Lambda\pi\pi$ 4.2 GeV/c
1383.0±0.4	9361	AGUILAR-...	81D	HBC	$K^- p \rightarrow \Lambda 3\pi$ 4.2 GeV/c
1381.9±0.3	6900	CAMERON	78	HBC	$K^- p$ 0.96–1.36 GeV/c
1381 ±1	6846	BORENSTEIN	74	HBC	$K^- p$ 2.18 GeV/c
1383.5±0.85	2300	HABIBI	73	HBC	$K^- p \rightarrow \Lambda\pi\pi$
1382 ±2	400	AGUILAR-...	72B	HBC	$K^- p \rightarrow \Lambda\pi$'s
1384.4±1.0	1260	SIEGEL	67	HBC	$K^- p$ 2.1 GeV/c
1382 ±1	750	ARMENTEROS	65B	HBC	$K^- p$ 0.9–1.2 GeV/c
1381.0±1.6	859	HUWE	64	HBC	$K^- p$ 1.22 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1385.1±1.2	600	BAKER	80	HYBR	$\pi^+ p$ 7 GeV/c
1383.2±1.0	750	BAKER	80	HYBR	$K^- p$ 7 GeV/c
1381 ±2	7k	[1] BAUBILLIER	79B	HBC	$K^- p$ 8.25 GeV/c
1391 ±2	2k	CAUTIS	79	HYBR	$\pi^+ p/K^- p$ 11.5 GeV
1390 ±2	100	[1] SUGAHARA	79B	HBC	$\pi^- p$ 6 GeV/c
1385 ±3	22k	[1,2] BARREIRO	77B	HBC	$K^- p$ 4.2 GeV/c
1385 ±1	2594	HOLMGREN	77	HBC	See AGUILAR 81D
1380 ±2		[1] BARDADIN-...	75	HBC	$K^- p$ 14.3 GeV/c
1382 ±1	3740	[3] BERTHON	74	HBC	$K^- p$ 1263–1843 MeV/c
1390 ±6	46	AGUILAR-...	70B	HBC	$K^- p \rightarrow \Sigma\pi$'s 4 GeV/$c$
1383 ±8	62	[4] BIRMINGHAM	66	HBC	$K^- p$ 3.5 GeV/c
1378 ±5	135	LONDON	66	HBC	$K^- p$ 2.24 GeV/c
1384.3±1.9	250	[4] SMITH	65	HBC	$K^- p$ 1.8 GeV/c
1382.6±2.1	250	[4] SMITH	65	HBC	$K^- p$ 1.95 GeV/c
1375.0±3.9	170	COOPER	64	HBC	$K^- p$ 1.45 GeV/c
1376.0±3.9	154	[4] ELY	61	HLBC	$K^- p$ 1.11 GeV/c



$\Sigma(1385)^+$ mass (MeV)

$\Sigma(1385)^0$ MASS

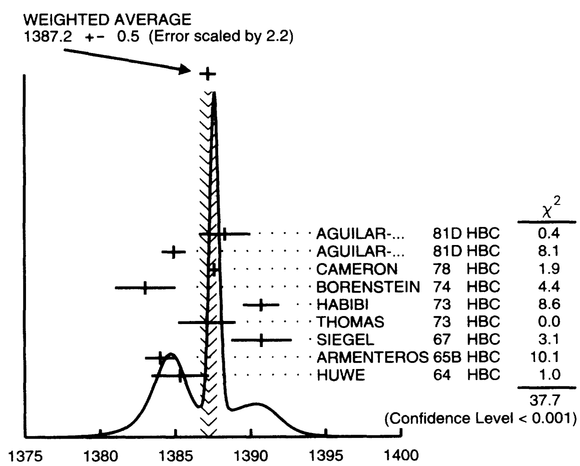
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1383.7±1.0 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.				
1384.1±0.8	5722	AGUILAR-...	81D	HBC	$K^- p \rightarrow \Lambda 3\pi$ 4.2 GeV/c
1380 ±2	3100	[5] BORENSTEIN	74	HBC	$K^- p \rightarrow \Lambda 3\pi$ 2.18 GeV/c
1385.1±2.5	240	[4] THOMAS	73	HBC	$\pi^- p \rightarrow \Lambda\pi^0 K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1389 ±3	500	[6] BAUBILLIER	79B	HBC	$K^- p$ 8.25 GeV/c



$\Sigma(1385)^0$ mass (MeV)

$\Sigma(1385)^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1387.2±0.5 OUR AVERAGE	Error includes scale factor of 2.2. See the ideogram below.				
1388.3±1.7	620	AGUILAR-...	81D	HBC	$K^- p \to \Lambda\pi\pi$ 4.2 GeV/c
1384.9±0.8	3346	AGUILAR-...	81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
1387.6±0.3	9720	CAMERON	78	HBC	$K^- p$ 0.96–1.36 GeV/c
1383 ±2	2303	BORENSTEIN	74	HBC	$K^- p$ 2.18 GeV/c
1390.7±1.2	1900	HABIBI	73	HBC	$K^- p \to \Lambda\pi\pi$
1387.1±1.9	630	[4] THOMAS	73	HBC	$\pi^- p \to \Lambda\pi^- K^+$
1390.7±2.0	370	SIEGEL	67	HBC	$K^- p$ 2.1 GeV/c
1384 ±1	1380	ARMENTEROS	65B	HBC	$K^- p$ 0.9–1.2 GeV/c
1385.3±1.9	1086	[4] HUWE	64	HBC	$K^- p$ 1.15–1.30 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1383 ±1	4.5k	[1] BAUBILLIER	79B	HBC	$K^- p$ 8.25 GeV/c
1380 ±6	150	[1] SUGAHARA	79B	HBC	$\pi^- p$ 6 GeV/c
1387 ±3	12k	[1,2] BARREIRO	77B	HBC	$K^- p$ 4.2 GeV/c
1391 ±3	193	HOLMGREN	77	HBC	See AGUILAR 81D
1383 ±2		[1] BARDADIN-...	75	HBC	$K^- p$ 14.3 GeV/c
1389 ±1	3060	[3] BERTHON	74	HBC	$K^- p$ 1263–1843 MeV/c
1389 ±9	15	LONDON	66	HBC	$K^- p$ 2.24 GeV/c
1391.5±2.6	120	[4] SMITH	65	HBC	$K^- p$ 1.8 GeV/c
1399.8±2.2	58	[4] SMITH	65	HBC	$K^- p$ 1.95 GeV/c
1392.0±6.2	200	COOPER	64	HBC	$K^- p$ 1.45 GeV/c
1382 ±3	93	DAHL	61	DBC	$K^- d$ 0.45 GeV/c
1376.0±4.4	224	[4] ELY	61	HLBC	$K^- p$ 1.11 GeV/c



$\Sigma(1385)^-$ mass (MeV)

$\Sigma(1385)^-$ – $\Sigma(1385)^+$ MASS DIFFERENCE

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−2 to +6	95	[7] BORENSTEIN	74	HBC	$K^- p$ 2.18 GeV/c
7.2±1.4		[7] HABIBI	73	HBC	$K^- p \to \Lambda\pi\pi$
6.3±2.0		[7] SIEGEL	67	HBC	$K^- p$ 2.1 GeV/c
11 ±9		[7] LONDON	66	HBC	$K^- p$ 2.24 GeV/c
9 ±6		LONDON	66	HBC	$\Lambda 3\pi$ events
2.0±1.5		[7] ARMENTEROS	65B	HBC	$K^- p$ 0.9–1.2 GeV/c
7.2±2.1		[7] SMITH	65	HBC	$K^- p$ 1.8 GeV/c
17.2±2.0		[7] SMITH	65	HBC	$K^- p$ 1.95 GeV/c
17 ±7		[7] COOPER	64	HBC	$K^- p$ 1.45 GeV/c
4.3±2.2		[7] HUWE	64	HBC	$K^- p$ 1.22 GeV/c
0.0±4.2		[7] ELY	61	HLBC	$K^- p$ 1.11 GeV/c

$\Sigma(1385)^0$ – $\Sigma(1385)^+$ MASS DIFFERENCE

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−4 to +4	95	[7] BORENSTEIN	74	HBC	$K^- p$ 2.18 GeV/c

$\Sigma(1385)^-$ – $\Sigma(1385)^0$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.0±2.4	[7] THOMAS	73	HBC	$\pi^- p \to \Lambda\pi^- K^+$

$\Sigma(1385)$ WIDTHS

$\Sigma(1385)^+$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
35.8± 0.8 OUR AVERAGE					
37.2± 2.0	1897	BAUBILLIER	84	HBC	$K^- p$ 8.25 GeV/c
35.1± 1.7	5256	AGUILAR-...	81D	HBC	$K^- p \to \Lambda\pi\pi$ 4.2 GeV/c
37.5± 2.0	9361	AGUILAR-...	81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
35.5± 1.9	6900	CAMERON	78	HBC	$K^- p$ 0.96–1.36 GeV/c
34.0± 1.6	6846	[8] BORENSTEIN	74	HBC	$K^- p$ 2.18 GeV/c
38.3± 3.2	2300	[9] HABIBI	73	HBC	$K^- p \to \Lambda\pi\pi$
32.5± 6.0	400	AGUILAR-...	72B	HBC	$K^- p \to \Lambda\pi$'s
36 ± 4	1260	[9] SIEGEL	67	HBC	$K^- p$ 2.1 GeV/c
32.0± 4.7	750	[9] ARMENTEROS	65B	HBC	$K^- p$ 0.95–1.20 GeV/c
46.5± 6.4	859	[9] HUWE	64	HBC	$K^- p$ 1.15–1.30 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
40 ± 3	600	BAKER	80	HYBR	$\pi^+ p$ 7 GeV/c
37 ± 2	750	BAKER	80	HYBR	$K^- p$ 7 GeV/c
37 ± 2	7k	[1] BAUBILLIER	79B	HBC	$K^- p$ 8.25 GeV/c
30 ± 4	2k	CAUTIS	79	HYBR	$\pi^+ p/K^- p$ 11.5 GeV
30 ± 6	100	[1] SUGAHARA	79B	HBC	$\pi^- p$ 6 GeV/c
43 ± 5	22k	[1,2] BARREIRO	77B	HBC	$K^- p$ 4.2 GeV/c
34 ± 2	2594	HOLMGREN	77	HBC	See AGUILAR 81D
40.0± 3.2		[1] BARDADIN-...	75	HBC	$K^- p$ 14.3 GeV/c
48 ± 3	3740	[3] BERTHON	74	HBC	$K^- p$ 1263–1843 MeV/c
33 ±20	46	[9] AGUILAR-...	70B	HBC	$K^- p \to \Sigma\pi$'s 4 GeV/c
25 ±32	62	[9] BIRMINGHAM	66	HBC	$K^- p$ 3.5 GeV/c
30.3± 7.5	250	[9] SMITH	65	HBC	$K^- p$ 1.8 GeV/c
33.1± 8.3	250	[9] SMITH	65	HBC	$K^- p$ 1.95 GeV/c
51 ±16	170	[9] COOPER	64	HBC	$K^- p$ 1.45 GeV/c
48 ±16	154	[9] ELY	61	HLBC	$K^- p$ 1.11 GeV/c

$\Sigma(1385)^0$ WIDTH

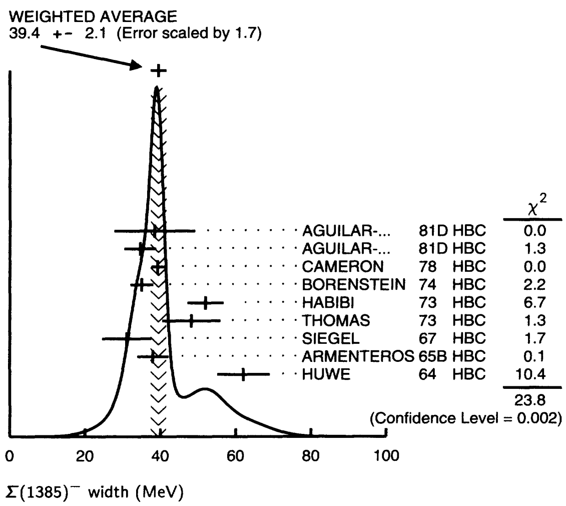
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
36 ± 5 OUR AVERAGE					
34.8± 5.6	5722	AGUILAR-...	81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
39.3±10.2	240	[9] THOMAS	73	HBC	$\pi^- p \to \Lambda\pi^0 K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
53 ± 8	3100	[10] BORENSTEIN	74	HBC	$K^- p \to \Lambda 3\pi$ 2.18 GeV/c
30 ± 9	106	CURTIS	63	OSPK	$\pi^- p$ 1.5 GeV/c

$\Sigma(1385)^-$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
39.4± 2.1 OUR AVERAGE	Error includes scale factor of 1.7. See the ideogram below.				
38.4±10.7	620	AGUILAR-...	81D	HBC	$K^- p \to \Lambda\pi\pi$ 4.2 GeV/c
34.6± 4.2	3346	AGUILAR-...	81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
39.2± 1.7	9720	CAMERON	78	HBC	$K^- p$ 0.96–1.36 GeV/c
35 ± 3	2303	[8] BORENSTEIN	74	HBC	$K^- p$ 2.18 GeV/c
51.9± 4.8	1900	[9] HABIBI	73	HBC	$K^- p \to \Lambda\pi\pi$
48.2± 7.7	630	[9] THOMAS	73	HBC	$\pi^- p \to \Lambda\pi^- K^0$
31.0± 6.5	370	[9] SIEGEL	67	HBC	$K^- p$ 2.1 GeV/c
38.0± 4.1	1382	[9] ARMENTEROS	65B	HBC	$K^- p$ 0.95–1.20 GeV/c
62 ± 7	1086	HUWE	64	HBC	$K^- p$ 1.15–1.30 GeV/c

• • • We do not use the following data for averages, fits, limits, etc. • • •

44 ± 4	4.5k	[1] BAUBILLIER	79B	HBC	$K^- p$ 8.25 GeV/c
58 ± 4	150	[1] SUGAHARA	79B	HBC	$\pi^- p$ 6 GeV/c
45 ± 5	12k	[1,2] BARREIRO	77B	HBC	$K^- p$ 4.2 GeV/c
35 ±10	193	HOLMGREN	77	HBC	See AGUILAR 81D
47 ± 6		[1] BARDADIN-...	75	HBC	$K^- p$ 14.3 GeV/c
40 ± 3	3060	[3] BERTHON	74	HBC	$K^- p$ 1263–1843 MeV/c
29.2±10.6	120	[9] SMITH	65	HBC	$K^- p$ 1.80 GeV/c
17.1± 8.9	58	[9] SMITH	65	HBC	$K^- p$ 1.95 GeV/c
88 ±24	200	[9] COOPER	64	HBC	$K^- p$ 1.45 GeV/c
40		DAHL	61	DBC	$K^- d$ 0.45 GeV/c
66 ±18	224	[9] ELY	61	HLBC	$K^- p$ 1.11 GeV/c



$\Sigma(1385)$ POLE POSITIONS

$\Sigma(1385)^+$ REAL PART

VALUE	DOCUMENT ID	COMMENT
1379±1	LICHTENBERG74	Extrapolates HABIBI 73

$\Sigma(1385)^+$ −IMAGINARY PART

VALUE	DOCUMENT ID	COMMENT
17.5±1.5	LICHTENBERG74	Extrapolates HABIBI 73

$\Sigma(1385)^-$ REAL PART

VALUE	DOCUMENT ID	COMMENT
1383±1	LICHTENBERG74	Extrapolates HABIBI 73

$\Sigma(1385)^-$ −IMAGINARY PART

VALUE	DOCUMENT ID	COMMENT
22.5±1.5	LICHTENBERG74	Extrapolates HABIBI 73

$\Sigma(1385)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\pi$	88±2 %
Γ_2	$\Sigma\pi$	12±2 %
Γ_3	$\Lambda\gamma$	
Γ_4	$\Sigma\gamma$	
Γ_5	$N\overline{K}$	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(1385)$ BRANCHING RATIOS

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.135±0.011 OUR AVERAGE					
0.20 ±0.06	DIONISI	78B	HBC	±	$K^- p \to Y^* K \overline{K}$
0.16 ±0.03	BERTHON	74	HBC	+	$K^- p$ 1.26–1.84 GeV/c
0.11 ±0.02	BERTHON	74	HBC	−	$K^- p$ 1.26–1.84 GeV/c
0.21 ±0.05	BORENSTEIN	74	HBC	+	$K^- p \to \Lambda\pi^+\pi^-$, $\Sigma^0\pi^+\pi^-$
0.18 ±0.04	MAST	73	MPWA	±	$K^- p \to \Lambda\pi^+\pi^-$, $\Sigma^0\pi^+\pi^-$
0.10 ±0.05	THOMAS	73	HBC	−	$\pi^- p \to \Lambda K\pi$, $\Sigma K\pi$
0.16 ±0.07	AGUILAR-...	72B	HBC	+	$K^- p$ 3.9, 4.6 GeV/c
0.13 ±0.04	COLLEY	71B	DBC	−0	$K^- N$ 1.5 GeV/c
0.13 ±0.04	PAN	69	HBC	+	$\pi^+ p \to \Lambda K\pi$, $\Sigma K\pi$
0.08 ±0.06	LONDON	66	HBC	+	$K^- p$ 2.24 GeV/c
0.163±0.041	ARMENTEROS	65B	HBC	±	$K^- p$ 0.95–1.20 GeV/c
0.09 ±0.04	HUWE	64	HBC	±	$K^- p$ 1.2–1.7 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.04	ALSTON	62	HBC	±0	$K^- p$ 1.15 GeV/c
0.04 ±0.04	BASTIEN	61	HBC	±	

$\Gamma(\Lambda\gamma)/\Gamma_{total}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.17±0.17	1	MEISNER	72	HBC	1 event only

$\Gamma(\Lambda\gamma)/\Gamma(\Lambda\pi)$ — Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.06	90	COLAS	75	HLBC	$K^- p$ 575–970 MeV

$\Gamma(\Sigma\gamma)/\Gamma(\Lambda\pi)$ — Γ_4/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	90	COLAS	75	HLBC	$K^- p$ 575–970 MeV

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1385) \to \Lambda\pi$ — $(\Gamma_5\Gamma_1)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		CHG	COMMENT
+0.586±0.319	[11] DEVENISH	74B	0	Fixed-t dispersion rel.

$\Sigma(1385)$ FOOTNOTES

[1] From fit to inclusive $\Lambda\pi$ spectrum.
[2] Includes data of HOLMGREN 77.
[3] The errors are statistical only. The resolution is not unfolded.
[4] The error is enlarged to $\Gamma/\sqrt{N}$. See the note on the $K^*(892)$ mass in the 1984 edition.
[5] From a fit to $\Lambda\pi^0$ with the width fixed at 34 MeV.
[6] From fit to inclusive $\Lambda\pi^0$ spectrum with the width fixed at 40 MeV.
[7] Redundant with data in the mass Listings.
[8] Results from $\Lambda\pi^+\pi^-$ and $\Lambda\pi^+\pi^-\pi^0$ combined by us.
[9] The error is enlarged to $4\Gamma/\sqrt{N}$. See the note on the $K^*(892)$ mass in the 1984 edition.
[10] Consistent with +, 0, and − widths equal.
[11] An extrapolation of the parametrized amplitude below threshold.

$\Sigma(1385)$ REFERENCES

BAUBILLIER	84	ZPHY C23 213	+	(BIRM, CERN, GLAS, MSU, LPNP)
PDG	84	RMP 56 No. 2 Pt. II	Wohl, Cahn, Rittenberg+	(LBL, CIT, CERN)
AGUILAR-...	81D	AFIS A77 144	Aguilar-Benitez, Salicio	(MADR)
BAKER	80	NP B166 207	+Chima, Dornan, Gibbs, Hall, Miller+	(LOIC)
BAUBILLIER	79B	NP B148 18	+	(BIRM, CERN, GLAS, MSU, LPNP)
CAUTIS	79	NP B156 507	+Ballam, Bouchez, Carroll, Chadwick+	(SLAC)
SUGAHARA	79B	NP B156 237	+Ochiai, Fukui, Cooper+	(KEK, OSKC, KINK)
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC)
DIONISI	78B	PL 78B 154	+Armenteros, Diaz	(CERN, AMST, NIJM, OXF)
BARREIRO	77B	NP B126 319	+Berge, Ganguli, Blokzijl+	(CERN, AMST, NIJM)
HOLMGREN	77	NP B119 261	+Aguilar-Benitez, Kluyver+	(CERN, AMST, NIJM)
BARDADIN-...	75	NP B98 418	Bardadin-Otwinowska+	(SACL, EPOL, RHEL)
COLAS	75	NP B91 253	+Farwell, Ferrer, Six	(ORSA)
BERTHON	74	NC 21A 146	+Tristram+	(CDEF, RHEL, SACL, STRB)
BORENSTEIN	74	PR D9 3006	+Kalbfleisch, Strand+	(BNL, MICH)
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
LICHTENBERG	74	PR D10 3865		(IND)
Also	74B	Private Comm.	Lichtenberg	(IND)
HABIBI	73	Nevis 199 Thesis		(COLU)
Also	73	Purdue Conf. 387	Baltay, Bridgewater, Cooper+	(COLU, BING)
MAST	73	PR D7 3212	+Bangerter, Alston-Garnjost+	(LBL) IJP
Also	73B	PR D7 5	Mast, Bangerter, Alston-Garnjost+	(LBL) IJP
THOMAS	73	NP B56 15	+Engler, Fisk, Kraemer	(CMU) JP
AGUILAR-...	72B	PR D6 29	Aguilar-Benitez, Chung, Eisner, Samios	(BNL)
MEISNER	72	NC 12A 62		(UNC, LBL)
COLLEY	71B	NP B31 61	+Cox, Eastwood, Fry+	(BIRM, EDIN, GLAS, LOIC)
AGUILAR-...	70B	PRL 25 58	Aguilar-Benitez, Barnes, Bassano+	(BNL, SYRA)
PAN	69	PRL 23 808	+Forman	(PENN) I
SIEGEL	67	UCRL 18041 Thesis		(LRL)
BIRMINGHAM	66	PR 152 1148		(BIRM, GLAS, LOIC, OXF, RHEL)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA) J
ARMENTEROS	65B	PL 19 75	+	(CERN, HEID, SACL)
SMITH	65	UCLA Thesis		(UCLA)
COOPER	64	PL 8 365	+Filthuth, Fridman, Malamud+	(CERN, AMST)
HUWE	64	UCRL 11291 Thesis		(LRL) JP
Also	69	PR 180 1824	Huwe	(LRL)
CURTIS	63	PR 132 1771	+Coffin, Meyer, Terwilliger	(MICH) J
ALSTON	62	CERN Conf. 311	+Alvarez, Ferro-Luzzi+	(LRL)
BASTIEN	61	PRL 6 702	+Ferro-Luzzi, Rosenfeld	(LRL)
DAHL	61	PRL 6 142	+Horwitz, Miller, Murray, White	(LRL)
ELY	61	PRL 7 461	+Fung, Gidal, Pan, Powell, White	(LRL) J
ALSTON	60	PRL 5 520	+Alvarez, Eberhard, Good, Graziano+	(LRL) I

$\Sigma(1480)$ Bumps

$I(J^P) = 1(?^?)$ Status: *

OMITTED FROM SUMMARY TABLE

These are peaks seen in $\Lambda\pi$ and $\Sigma\pi$ spectra in the reaction $\pi^+ p \to (Y\pi)K^+$ at 1.7 GeV/c. Also, the Y polarization oscillates in the same region.

MILLER 70 suggests a possible alternate explanation in terms of a reflection of $N(1675) \to \Lambda K$ decay. However, such an explanation for the $(\Sigma^+\pi^0)K^+$ channel in terms of $\Delta(1650) \to \Sigma K$ decay seems unlikely (see PAN 70). In addition such reflections would also have to account for the oscillation of the Y polarization in the 1480 MeV region.

HANSON 71, with less data than PAN 70, can neither confirm nor deny the existence of this state. MAST 75 sees no structure in this region in $K^- p \to \Lambda\pi^0$.

ENGELEN 80 performs a multichannel analysis of $K^- p \to p\overline{K}^0\pi^-$ at 4.2 GeV/c. They observe a 3.5 standard-deviation signal at 1480 MeV in $p\overline{K}^0$ which cannot be explained as a reflection of any competing channel.

$\Sigma(1480)$ MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 1480 OUR ESTIMATE						
1480	120	ENGELEN	80	HBC	+	$K^- p \to (p\overline{K}^0)\pi^-$
1485±10		CLINE	73	MPWA	−	$K^- d \to (\Lambda\pi^-)p$
1479±10		PAN	70	HBC	+	$\pi^+ p \to (\Lambda\pi^+)K^+$
1465±15		PAN	70	HBC	+	$\pi^+ p \to (\Sigma\pi)K^+$

$\Sigma(1480)$ WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
80±20	120	ENGELEN	80	HBC	+	$K^- p \to (p\overline{K}^0)\pi^-$
40±20		CLINE	73	MPWA	−	$K^- d \to (\Lambda\pi^-)p$
31±15		PAN	70	HBC	+	$\pi^+ p \to (\Lambda\pi^+)K^+$
30±20		PAN	70	HBC	+	$\pi^+ p \to (\Sigma\pi)K^+$

$\Sigma(1480)$ DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

$\Sigma(1480)$ BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$ Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	CHG
0.82±0.51	PAN	70	HBC	+

$\Gamma(N\overline{K})/\Gamma(\Lambda\pi)$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	CHG
0.72±0.50	PAN	70	HBC	+

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
small	CLINE	73	MPWA	$K^- d \to (\Lambda\pi^-)p$

$\Sigma(1480)$ REFERENCES (PRODUCTION EXPERIMENTS)

ENGELEN	80	NP B167 61	+Jongejans, Dionisi+	(NIJM, AMST, CERN, OXF)
MAST	75	PR D11 3078	+Alston-Garnjost, Bangerter+	(LBL)
CLINE	73	LNC 6 205	+Laumann, Mapp	(WISC) IJP
HANSON	71	PR D4 1296	+Kalmus, Louie	(LBL) I
MILLER	70	Duke Conf. 229		(PURD)
PAN	70	PR D2 49	+Forman, Ko, Hagopian, Selove	(PENN)
Also	69	PRL 23 808	Pan, Forman	(PENN) I
Also	69B	PRL 23 806	Pan, Forman	(PENN) I

$\Sigma(1560)$ Bumps

$I(J^P) = 1(?^?)$ Status: **

OMITTED FROM SUMMARY TABLE

This entry lists peaks reported in mass spectra around 1560 MeV without implying that they are necessarily related.

DIONISI 78B observes a 6 standard-deviation enhancement at 1553 MeV in the charged $\Lambda/\Sigma\pi$ mass spectra from $K^- p \to (\Lambda/\Sigma)\pi K\overline{K}$ at 4.2 GeV/c. In a CERN ISR experiment, LOCKMAN 78 reports a narrow 6 standard-deviation enhancement at 1572 MeV in $\Lambda\pi^\pm$ from the reaction $pp \to \Lambda\pi^+\pi^- X$. These enhancements are unlikely to be associated with the $\Sigma(1580)$ (which has not been confirmed by several recent experiments – see the next entry in the Listings).

CARROLL 76 observes a bump at 1550 MeV (as well as one at 1580 MeV) in the isospin-1 $\overline{K}N$ total cross section, but uncertainties in cross section measurements outside the mass range of the experiment preclude estimating its significance.

See also MEADOWS 80 for a review of this state.

$\Sigma(1560)$ MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 1560 OUR ESTIMATE						
1553±7	121	DIONISI	78B	HBC	±	$K^- p \to (Y\pi)K\overline{K}$
1572±4	40	LOCKMAN	78	SPEC	±	$pp \to \Lambda\pi^+\pi^- X$

$\Sigma(1560)$ WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
79±30	121	DIONISI	78B	HBC	±	$K^- p \to (Y\pi)K\overline{K}$
15± 6	40	[1] LOCKMAN	78	SPEC	±	$pp \to \Lambda\pi^+\pi^- X$

$\Sigma(1560)$ DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\pi$	seen
Γ_2	$\Sigma\pi$	

$\Sigma(1560)$ BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(\Sigma\pi)/[\Gamma(\Lambda\pi)+\Gamma(\Sigma\pi)]$ $\Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.35±0.12	DIONISI	78B	HBC	±	$K^- p \to (Y\pi)K\overline{K}$

$\Gamma(\Lambda\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	LOCKMAN	78	SPEC	±	$pp \to \Lambda\pi^+\pi^- X$

$\Sigma(1560)$ FOOTNOTES (PRODUCTION EXPERIMENTS)

[1] The width observed by LOCKMAN 78 is consistent with experimental resolution.

$\Sigma(1560)$ REFERENCES (PRODUCTION EXPERIMENTS)

MEADOWS	80	Toronto Conf. 283		(CINC)
DIONISI	78B	PL 78B 154	+Armenteros, Diaz	(CERN, AMST, NIJM, OXF) I
LOCKMAN	78	CEN DPHPE 78-01	+Meyer, Rander, Poster, Schlein+	(UCLA, SACL)
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I

$\Sigma(1580)$ D_{13}

$I(J^P) = 1(\frac{3}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Seen in the isospin-1 $\overline{K}N$ cross section at BNL (LI 73, CARROLL 76) and in a partial-wave analysis of $K^- p \to \Lambda\pi^0$ for c.m. energies 1560–1600 MeV by LITCHFIELD 74. LITCHFIELD 74 finds $J^P = 3/2^-$. Not seen by ENGLER 78 or by CAMERON 78C (with larger statistics in $K^0_L p \to \Lambda\pi^+$ and $\Sigma^0\pi^+$).

$\Sigma(1580)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1580 OUR ESTIMATE				
1583±4	[1] CARROLL	76	DPWA	Isospin-1 total σ
1582±4	[2] LITCHFIELD	74	DPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(1580)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
15	[1] CARROLL	76	DPWA	Isospin-1 total σ
11±4	[2] LITCHFIELD	74	DPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(1580)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

$\Sigma(1580)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
+0.03±0.01	[2] LITCHFIELD	74	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1580) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	CAMERON	78C	HBC	$K^0_L p \to \Lambda\pi^+$
not seen	ENGLER	78	HBC	$K^0_L p \to \Lambda\pi^+$
+0.10±0.02	[2] LITCHFIELD	74	DPWA	$K^- p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1580) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	CAMERON	78C	HBC	$K^0_L p \to \Sigma^0\pi^+$
not seen	ENGLER	78	HBC	$K^0_L p \to \Sigma^0\pi^+$
+0.03±0.04	[2] LITCHFIELD	74	DPWA	$\overline{K}N$ multichannel

$\Sigma(1580)$ FOOTNOTES

[1] CARROLL 76 sees a total-cross-section bump with $(J+1/2)\ \Gamma_{el}\ /\ \Gamma_{total} = 0.06$.

[2] The main effect observed by LITCHFIELD 74 is in the $\Lambda\pi$ final state; the $\overline{K}N$ and $\Sigma\pi$ couplings are estimated from a multichannel fit including total-cross-section data of LI 73.

$\Sigma(1580)$ REFERENCES

CAMERON	78C	NP B132 189	+Capiluppi+	(BGNA, EDIN, GLAS, PISA, RHEL) I
ENGLER	78	PR D18 3061	+Keyes, Kraemer, Tanaka, Cho+	(CMU, ANL)
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
LITCHFIELD	74	PL 51B 509		(CERN) IJP
LI	73	Purdue Conf. 283		(BNL) I

OTHER RELATED PAPERS

ENGLER	76	PL 63B 231	+Keyes, Kraemer, Schlereth, Tanaka+	(CMU, ANL) I

$\Sigma(1620)$ S_{11}

$I(J^P) = 1(\frac{1}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

The S_{11} state at 1697 MeV reported by VANHORN 75 is tentatively listed under the $\Sigma(1750)$. CARROLL 76 sees two bumps in the isospin-1 total cross section near this mass.

Production experiments are listed separately in the next entry.

$\Sigma(1620)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1620 OUR ESTIMATE				
1600± 6	[1] MORRIS	78	DPWA	$K^- n \to \Lambda\pi^-$
1608± 5	[2] CARROLL	76	DPWA	Isospin-1 total σ
1633±10	[3] CARROLL	76	DPWA	Isospin-1 total σ
1630±10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
1620	KIM	71	DPWA	K-matrix analysis

$\Sigma(1620)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
87±19	[1] MORRIS	78	DPWA	$K^- n \to \Lambda\pi^-$
15	[2] CARROLL	76	DPWA	Isospin-1 total σ
10	[3] CARROLL	76	DPWA	Isospin-1 total σ
65±20	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
40	KIM	71	DPWA	K-matrix analysis

$\Sigma(1620)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

$\Sigma(1620)$ BRANCHING RATIOS

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.22±0.02	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
0.05	KIM	71	DPWA	K-matrix analysis

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1620) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.12±0.02	[1] MORRIS	78	DPWA	$K^- n \to \Lambda\pi^-$
not seen	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
0.15	KIM	71	DPWA	K-matrix analysis

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1620) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
0.40±0.06	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
0.08	KIM	71	DPWA	K-matrix analysis

$\Sigma(1620)$ FOOTNOTES

[1] MORRIS 78 obtains an equally good fit without including this resonance.

[2] Total cross-section bump with $(J+1/2)\ \Gamma_{el}\ /\ \Gamma_{total}$ is 0.06 seen by CARROLL 76.

[3] Total cross-section bump with $(J+1/2)\ \Gamma_{el}\ /\ \Gamma_{total}$ is 0.04 seen by CARROLL 76.

$\Sigma(1620)$ REFERENCES

MORRIS	78	PR D17 55	+Albright, Colleraine, Kimel, Lannutti	(FSU) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEID, MPIM) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP
KIM	71	PRL 27 356		(HARV) IJP
Also	70	Duke Conf. 161	Kim	(HARV) IJP

$\Sigma(1620)$ Production Experiments

$I(J^P) = 1(?^?)$

OMITTED FROM SUMMARY TABLE

Formation experiments are listed separately in the previous entry.

The results of CRENNELL 69B at 3.9 GeV/c are not confirmed by SABRE 70 at 3.0 GeV/c. However, at 4.5 GeV/c, AMMANN 70 sees a peak at 1642 MeV which on the basis of branching ratios they do not associate with the $\Sigma(1670)$. See MILLER 70 for a review of these conflicts.

$\Sigma(1620)$ MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 1620 OUR ESTIMATE						
1642 ± 12		AMMANN	70	DBC		$K^- N$ 4.5 GeV/c
1618 ± 3	20	BLUMENFELD	69	HBC	+	$K^0_L p$
1619 ± 8		CRENNELL	69B	DBC	±	$K^- N \to \Lambda\pi\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1616 ± 8		CRENNELL	68	DBC	±	See CRENNELL 69B

$\Sigma(1620)$ WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
55 ± 24		AMMANN	70	DBC		$K^- N$ 4.5 GeV/c
30 ± 10	20	BLUMENFELD	69	HBC	+	
72^{+22}_{-15}		CRENNELL	69B	DBC	±	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
66 ± 16		CRENNELL	68	DBC	±	See CRENNELL 69B

$\Sigma(1620)$ DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Lambda\pi\pi$
Γ_5	$\Sigma(1385)\pi$
Γ_6	$\Lambda(1405)\pi$

$\Sigma(1620)$ BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(\Lambda\pi\pi)/\Gamma(\Lambda\pi)$ — Γ_4/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	CHG
~ 2.5	14	BLUMENFELD	69	HBC	+

$\Gamma(N\overline{K})/\Gamma(\Lambda\pi)$ — Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.4 ± 0.4	AMMANN	70	DBC		$K^- p$ 4.5 GeV/c
0.0 ± 0.1	CRENNELL	68	DBC	+	See CRENNELL 69B

$\Gamma(\Lambda\pi)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG
large	CRENNELL	68	DBC	±

$\Gamma(\Sigma(1385)\pi)/\Gamma(\Lambda\pi)$ — Γ_5/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.3	95	AMMANN	70	DBC		$K^- p$ 4.5 GeV/c
0.2 ± 0.1		CRENNELL	68	DBC	±	

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$ — Γ_3/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.1	95	AMMANN	70	DBC	$K^- N$ 4.5 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Lambda\pi)$ — Γ_6/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.7 ± 0.4	AMMANN	70	DBC	$K^- p$ 4.5 GeV/c

$\Sigma(1620)$ REFERENCES (PRODUCTION EXPERIMENTS)

AMMANN	70	PRL 24 327	+Garfinkel, Carmony, Gutay+	(PURD, IND)
Also	73	PR D7 1345	Ammann, Carmony, Garfinkel+	(PURD, IUPU)
MILLER	70	Duke Conf. 229		(PURD)
SABRE	70	NP B16 201	Barloutaud, Merril, Schever+	(SABRE Collab.)
BLUMENFELD	69	PL 29B 58	+Kalbfleisch	(BNL) I
CRENNELL	69B	Lund Paper 183	+Karshon, Lai, O'Neil, Scarr+	(BNL, CUNY) I
Results are quoted in LEVI-SETTI 69C.				
Also	69C	Lund Conf.	Levi-Setti	(EFI)
CRENNELL	68	PRL 21 648	+Delaney, Flaminio, Karshon+	(BNL, CUNY) I

$\Sigma(1660)$ P_{11}

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗∗

For results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

$\Sigma(1660)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1630 to 1690 (≈ 1660) OUR ESTIMATE				
1665.1 ± 11.2	[1] KOISO	85	DPWA	$K^- p \to \Sigma\pi$
1670 ± 10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1679 ± 10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1676 ± 15	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1668 ± 25	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
1670 ± 20	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1565 or 1597	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1660 ± 30	[3] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1671 ± 2	[4] PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(1660)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
40 to 200 (≈ 100) OUR ESTIMATE				
81.5 ± 22.2	[1] KOISO	85	DPWA	$K^- p \to \Sigma\pi$
152 ± 20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
38 ± 10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
120 ± 20	GOPAL	77	DPWA	$\overline{K}N$ multichannel
230^{+165}_{-60}	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
250 ± 110	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
202 or 217	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel
80 ± 40	[3] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
81 ± 10	[4] PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(1660)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	10–30 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	seen

$\Sigma(1660)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.3 OUR ESTIMATE				
0.12 ± 0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.10 ± 0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.04	GOPAL	77	DPWA	See GOPAL 80
0.27 or 0.29	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1660) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$0.12^{+0.12}_{-0.04}$	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.10 or −0.11	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel
-0.04 ± 0.02	[3] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$+0.16 \pm 0.01$	[4] PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1660) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.13 ± 0.04	[1] KOISO	85	DPWA	$K^-p \to \Sigma\pi$
-0.16 ± 0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
-0.11 ± 0.01	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.34 or -0.37	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel
not seen	HEPP	76B	DPWA	$K^-N \to \Sigma\pi$

$\Sigma(1660)$ FOOTNOTES

[1] The evidence of KOISO 85 is weak.
[2] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[3] From solution 1 of BAILLON 75; not present in solution 2.
[4] From solution 2 of PONTE 75; not present in solution 1.

$\Sigma(1660)$ REFERENCES

KOISO	85	NP A433 619	+Sai, Yamamoto, Kofler	(TOKY, MASA)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEID, MPIM) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
PONTE	75	PR D12 2597	+Hertzbach, Button-Shafer+	(MASA, TENN, UCR) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
KANE	74	LBL-2452		(LBL) IJP

NOTE ON THE $\Sigma(1670)$ REGION

Production experiments: The measured $\Sigma\pi/\Sigma\pi\pi$ branching ratio for $\Sigma(1670)$ particles produced in the reaction $K^-p \to \pi^-\Sigma(1670)^+$ is strongly dependent on momentum transfer. This was first discovered by EBERHARD 69, who suggested that there exist two Σ resonances with the same mass and quantum numbers: one with a large $\Sigma\pi\pi$ — mainly $\Lambda(1405)\pi$ — branching fraction produced peripherally, and the other with a large $\Sigma\pi$ branching fraction produced at larger angles. The experimental results were confirmed by AGUILAR-BENITEZ 70, ASPELL 74, ESTES 74, and TIMMERMANS 76. If, in fact, there are two resonances, the most likely quantum numbers for both the $\Sigma\pi$ and the $\Lambda(1405)\pi$ states are D_{13}. There is also possibly a third Σ, the $\Sigma(1690)$ in the Listings, the main evidence for which is a large $\Lambda\pi/\Sigma\pi$ branching ratio. These topics have been reviewed by EBERHARD 73 and by MILLER 70.

Formation experiments: Two states are also observed near this mass in formation experiments. One of these, the $\Sigma(1670)D_{13}$, has the same quantum numbers as those observed in production and has a large $\Sigma\pi/\Sigma\pi\pi$ branching ratio; it may well be the $\Sigma(1670)$ produced at larger angles (see TIMMERMANS 76). The other state, the $\Sigma(1660)P_{11}$, has different quantum numbers, its $\Sigma\pi/\Sigma\pi\pi$ branching ratio is unknown, and its relation to the produced $\Sigma(1670)$ states is obscure.

$\Sigma(1670)$ D_{13}

$I(J^P) = 1(\frac{3}{2}^-)$ Status: ∗∗∗∗

For most results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

Results from production experiments are listed separately in the next entry.

$\Sigma(1670)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1665 to 1685 (≈ 1670) OUR ESTIMATE				
1665.1 ± 4.1	KOISO	85	DPWA	$K^-p \to \Sigma\pi$
1682 ± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1679 ± 10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1670 ± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1670 ± 6	HEPP	76B	DPWA	$K^-N \to \Sigma\pi$
1685 ± 20	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1659^{+12}_{-5}	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
1670 ± 2	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1667 or 1668	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1650	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$
1671 ± 3	PONTE	75	DPWA	$K^-p \to \Lambda\pi^0$ (sol. 1)
1655 ± 2	PONTE	75	DPWA	$K^-p \to \Lambda\pi^0$ (sol. 2)

$\Sigma(1670)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
40 to 80 (≈ 60) OUR ESTIMATE				
65.0 ± 7.3	KOISO	85	DPWA	$K^-p \to \Sigma\pi$
79 ± 10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
56 ± 20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
50 ± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
56 ± 3	HEPP	76B	DPWA	$K^-N \to \Sigma\pi$
85 ± 25	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
32 ± 11	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
79 ± 6	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
46 or 46	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
80	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$
44 ± 11	PONTE	75	DPWA	$K^-p \to \Lambda\pi^0$ (sol. 1)
76 ± 5	PONTE	75	DPWA	$K^-p \to \Lambda\pi^0$ (sol. 2)

$\Sigma(1670)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	7–13 %
Γ_2	$\Lambda\pi$	5–15 %
Γ_3	$\Sigma\pi$	30–60 %
Γ_4	$\Lambda\pi\pi$	
Γ_5	$\Sigma\pi\pi$	
Γ_6	$\Sigma(1385)\pi$	
Γ_7	$\Sigma(1385)\pi$, S-wave	
Γ_8	$\Lambda(1405)\pi$	
Γ_9	$\Lambda(1520)\pi$	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(1670)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.07 to 0.13 OUR ESTIMATE				
0.10 ± 0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.11 ± 0.03	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.08 ± 0.03	GOPAL	77	DPWA	See GOPAL 80
0.07 or 0.07	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1670) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.17 ± 0.03	[2] MORRIS	78	DPWA	$K^-n \to \Lambda\pi^-$
0.13 ± 0.02	[2] MORRIS	78	DPWA	$K^-n \to \Lambda\pi^-$
$+0.10\pm0.02$	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$+0.06\pm0.02$	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$+0.09\pm0.02$	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
$+0.018\pm0.060$	DEVENISH	74B		Fixed-t dispersion rel.

• • • We do not use the following data for averages, fits, limits, etc. • • •

+0.08 or +0.08	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
+0.05	DEBELLEFON 76	IPWA	$K^- p \to \Lambda\pi^0$
0.08 ±0.01	PONTE 75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 1)
0.17 ±0.01	PONTE 75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 2)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1670) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.20±0.02	KOISO 85	DPWA	$K^- p \to \Sigma\pi$
+0.21±0.02	GOPAL 77	DPWA	$\overline{K}N$ multichannel
+0.20±0.01	HEPP 76B	DPWA	$K^- N \to \Sigma\pi$
+0.21±0.03	KANE 74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
+0.18 or +0.17	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$\Gamma(\Lambda\pi\pi)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.11	ARMENTEROS 68E	HBC	$K^- p$ (Γ_1=0.09)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1670) \to \Sigma(1385)\pi$, S-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.11±0.03	PREVOST 74	DPWA	$K^- N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.17±0.02	[3] SIMS 68	DBC	$K^- N \to \Lambda\pi\pi$

$\Gamma(\Sigma\pi\pi)/\Gamma_{total}$ — Γ_5/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.14	[4] ARMENTEROS 68E	HBC	$K^- p$, $K^- d$ (Γ_1=0.09)

$\Gamma(\Lambda(1405)\pi)/\Gamma_{total}$ — Γ_8/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.06	ARMENTEROS 68E	HBC	$K^- p$, $K^- d$ (Γ_1=0.09)

$\Gamma_i\Gamma_f/\Gamma^2_{total}$ in $N\overline{K} \to \Sigma(1670) \to \Lambda(1405)\pi$ — $\Gamma_1\Gamma_8/\Gamma^2$

VALUE	DOCUMENT ID	TECN	COMMENT
0.007±0.002	[5] BRUCKER 70	DBC	$K^- N \to \Sigma\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.03	BERLEY 69	HBC	$K^- p$ 0.6–0.82 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Sigma(1385)\pi)$ — Γ_8/Γ_6

VALUE	DOCUMENT ID	TECN	COMMENT
0.23±0.08	BRUCKER 70	DBC	$K^- N \to \Sigma\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1670) \to \Lambda(1520)\pi$ — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
0.081±0.016	[6] CAMERON 77	DPWA	P-wave decay

$\Sigma(1670)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] Results are with and without an S_{11} $\Sigma(1620)$ in the fit.
[3] SIMS 68 uses only cross-section data. Result used as upper limit only.
[4] Ratio only for $\Sigma 2\pi$ system in $I = 1$, which cannot be $\Sigma(1385)$.
[5] Assuming the $\Lambda(1405)\pi$ cross-section bump is due only to $3/2^-$ resonance.
[6] The CAMERON 77 upper limit on F-wave decay is 0.03.

$\Sigma(1670)$ REFERENCES

KOISO	85	NP A433 619	+Sai, Yamamoto, Kofler	(TOKY, MASA)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
MORRIS	78	PR D17 55	+Albright, Colleraine, Kimel, Lannutti	(FSU) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEID, MPIM) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
PONTE	75	PR D12 2597	+Hertzbach, Button-Shafer+	(MASA, TENN, UCR) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
BRUCKER	70	Duke Conf. 155	+Harrison, Sims, Albright, Chandler+	(FSU) I
BERLEY	69	PL 30B 430	+Hart, Rahm, Willis, Yamamoto	(BNL)
ARMENTEROS	68E	PL 28B 521	+Baillon+	(CERN, HEID, SACL) I
SIMS	68	PRL 21 1413	+Albright, Bartley, Meer+	(FSU, TUFT, BRAN)

$\Sigma(1670)$ Bumps

$I(J^P) = 1(?^?)$

OMITTED FROM SUMMARY TABLE

Formation experiments are listed separately in the preceding entry.

Probably there are two states at the same mass with the same quantum numbers, one decaying to $\Sigma\pi$ and $\Lambda\pi$, the other to $\Lambda(1405)\pi$. See the note in front of the preceding entry.

$\Sigma(1670)$ MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
≈ 1670 OUR ESTIMATE					
1670± 4		[1] CARROLL 76	DPWA		Isospin-1 total σ
1675±10		[2] HEPP 76	DBC	−	$K^- N$ 1.6–1.75 GeV/c
1665± 1		APSELL 74	HBC		$K^- p$ 2.87 GeV/c
1688± 2 or 1683 ± 5	1200	BERTHON 74	HBC	0	Quasi-2-body σ
1670± 6		AGUILAR-... 70B	HBC		$K^- p \to \Sigma\pi\pi$ 4 GeV
1668±10		AGUILAR-... 70B	HBC		$K^- p \to \Sigma 3\pi$ 4 GeV
1660±10		ALVAREZ 63	HBC	+	$K^- p$ 1.51 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1668±10	150	[3] FERRERSORIA 81	OMEG	−	$\pi^- p$ 9,12 GeV/c
1655 to 1677		TIMMERMANS 76	HBC	+	$K^- p$ 4.2 GeV/c
1665± 5		BUGG 68	CNTR		$K^- p$, d total σ
1661± 9	70	PRIMER 68	HBC	+	See BARNES 69E
1685		ALEXANDER 62C	HBC	−0	$\pi^- p$ 2–2.2 GeV/c

$\Sigma(1670)$ WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
67.0± 2.4		APSELL 74	HBC		$K^- p$ 2.87 GeV/c
110 ±12		AGUILAR-... 70B	HBC		$K^- p \to \Sigma\pi\pi$ 4 GeV
$135\ ^{+40}_{-30}$		AGUILAR-... 70B	HBC		$K^- p \to \Sigma 3\pi$ 4 GeV
40 ±10		ALVAREZ 63	HBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
90 ±20	150	[3] FERRERSORIA 81	OMEG	−	$\pi^- p$ 9,12 GeV/c
52		[1] CARROLL 76	DPWA		Isospin-1 total σ
48 to 63		TIMMERMANS 76	HBC	+	$K^- p$ 4.2 GeV/c
30 ±15		BUGG 68	CNTR		
60 ±20	70	PRIMER 68	HBC	+	See BARNES 69E
45		ALEXANDER 62C	HBC	−0	

$\Sigma(1670)$ DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Lambda\pi\pi$
Γ_5	$\Sigma\pi\pi$
Γ_6	$\Sigma(1385)\pi$
Γ_7	$\Lambda(1405)\pi$

$\Sigma(1670)$ BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(N\overline{K})/\Gamma(\Sigma\pi)$ — Γ_1/Γ_3

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
<0.03		TIMMERMANS 76	HBC	+	$K^- p$ 4.2 GeV/c
<0.10		BERTHON 74	HBC	0	Quasi-2-body σ
<0.2		AGUILAR-... 70B	HBC		
<0.26		BARNES 69E	HBC	+	$K^- p$ 3.9–5 GeV/c
0.025		BUGG 68	CNTR	0	Assuming $J = 3/2$
<0.24	0	PRIMER 68	HBC	+	$K^- p$ 4.6–5 GeV/c
<0.6		LONDON 66	HBC	+	$K^- p$ 2.25 GeV/c
<0.19	0	ALVAREZ 63	HBC	+	$K^- p$ 1.15 GeV/c
≥ 0.5 ±0.25		SMITH 63	HBC	−0	

$\Gamma(\Lambda\pi)/\Gamma(\Sigma\pi)$ — Γ_2/Γ_3

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.76 ± 0.09		ESTES 74	HBC	0	$K^- p$ 2.1,2.6 GeV/c
0.45 ± 0.15		BARNES 69E	HBC	+	$K^- p$ 3.9–5 GeV/c
0.15 ± 0.07		HUWE 69	HBC	+	
0.11 ± 0.06	33	BUTTON-... 68	HBC	+	$K^- p$ 1.7 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$\le 0.45\pm0.07$		TIMMERMANS 76	HBC	+	$K^- p$ 4.2 GeV/c
0.55 ± 0.11		BERTHON 74	HBC	0	Quasi-2-body σ
0	0	PRIMER 68	HBC	+	See BARNES 69E
<0.6		LONDON 66	HBC	+	$K^- p$ 2.25 GeV/c
1.2	130	ALVAREZ 63	HBC	+	$K^- p$ 1.15 GeV/c
1.2		SMITH 63	HBC	−0	

$\Gamma(\Lambda\pi\pi)/\Gamma(\Sigma\pi)$ — Γ_4/Γ_3

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
<0.6		LONDON 66	HBC	+	$K^- p$ 2.25 GeV/c
0.56	90	ALVAREZ 63	HBC	+	$K^- p$ 1.15 GeV/c
0.17		SMITH 63	HBC	−0	

$\Gamma(\Sigma\pi\pi)/\Gamma(\Sigma\pi)$ — Γ_5/Γ_3

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
largest at small angles		ESTES 74	HBC	0	$K^- p$ 2.1,2.6 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.2		[2] HEPP 76	DBC	−	$K^- N$ 1.6–1.75 GeV/c
0.56	180	ALVAREZ 63	HBC	+	$K^- p$ 1.15 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Sigma\pi)$ — Γ_7/Γ_3

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
$1.8\ \pm0.3$ to 0.02 ± 0.07		[3,4] TIMMERMANS 76	HBC	+	$K^- p$ 4.2 GeV/c
largest at small angles		ESTES 74	HBC	±	$K^- p$ 2.1,2.6 GeV/c
$3.0\ \pm1.6$	50	LONDON 66	HBC	+	$K^- p$ 2.25 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.58 ± 0.20	17	PRIMER 68	HBC	+	See BARNES 69E

$\Gamma(\Sigma\pi)/\Gamma(\Sigma\pi\pi)$ — Γ_3/Γ_5

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
varies with prod. angle	[5] APSELL 74	HBC	+	$K^- p$ 2.87 GeV/c
1.39 ± 0.16	BERTHON 74	HBC	0	Quasi-2-body σ
2.5 to 0.24	[4] EBERHARD 69	HBC		$K^- p$ 2.6 GeV/c
<0.4	BIRMINGHAM 66	HBC	+	$K^- p$ 3.5 GeV/c
0.30 ± 0.15	LONDON 66	HBC	+	$K^- p$ 2.25 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Sigma\pi\pi)$ — Γ_7/Γ_5

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.97 ± 0.08	TIMMERMANS 76	HBC		$K^- p$ 4.2 GeV/c
1.00 ± 0.02	APSELL 74	HBC		$K^- p$ 2.87 GeV/c
$0.90^{+0.10}_{-0.16}$	EBERHARD 65	HBC	+	$K^- p$ 2.45 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Sigma(1385)\pi)$ — Γ_7/Γ_6

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
<0.8	EBERHARD 65	HBC	+	$K^- p$ 2.45 GeV/c

$\Gamma(\Lambda\pi\pi)/\Gamma(\Sigma\pi\pi)$ — Γ_4/Γ_5

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.35 ± 0.2	BIRMINGHAM 66	HBC	+	$K^- p$ 3.5 GeV/c

$\Gamma(\Lambda\pi)/\Gamma(\Sigma\pi\pi)$ — Γ_2/Γ_5

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
<0.2	BIRMINGHAM 66	HBC	+	$K^- p$ 3.5 GeV/c

$\Gamma(\Lambda\pi)/[\Gamma(\Lambda\pi)+\Gamma(\Sigma\pi)]$ — $\Gamma_2/(\Gamma_2+\Gamma_3)$

VALUE	DOCUMENT ID	TECN
<0.6	AGUILAR-... 70B	HBC

$\Gamma(\Sigma(1385)\pi)/\Gamma(\Sigma\pi)$ — Γ_6/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
$\le 0.21\pm0.05$	TIMMERMANS 76	HBC	$K^- p$ 4.2 GeV/c

$\Sigma(1670)$ QUANTUM NUMBERS (PRODUCTION EXPERIMENTS)

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
$J^P = 3/2^-$	400	BUTTON-... 68	HBC	±	$\Sigma^0\pi$
$J^P = 3/2^-$		EBERHARD 67	HBC	+	$\Lambda(1405)\pi$
$J^P = 3/2^+$		LEVEQUE 65	HBC		$\Lambda(1405)\pi$

$\Sigma(1670)$ FOOTNOTES

[1] Total cross-section bump with $(J+1/2)\ \Gamma_{el}\ /\ \Gamma_{total} = 0.23$.
[2] Enhancements in $\Sigma\pi$ and $\Sigma\pi\pi$ cross sections.
[3] Backward production in the $\Lambda\pi^- K^+$ final state.
[4] Depending on production angle.
[5] APSELL 74, ESTES 74, and TIMMERMANS 76 find strong branching ratio dependence on production angle, as in earlier production experiments.

$\Sigma(1670)$ REFERENCES (PRODUCTION EXPERIMENTS)

FERRERSORIA 81 NP B178 373 +Treille, Rivet, Volte+ (CERN, CDEF, EPOL, LALO)
CARROLL 76 PRL 37 806 +Chiang, Kycia, Li, Mazur, Michael+ (BNL) I
HEPP 76 NP B115 82 +Braun, Grimm, Stroebele+ (CERN, HEID, MPIM) I
TIMMERMANS 76 NP B112 77 +Engelen+ (NIJM, CERN, AMST, OXF) JP
APSELL 74 PR D10 1419 +Ford, Gourevitch+ (BRAN, UMD, SYRA, TUFT) I
BERTHON 74 NC 21A 146 +Tristram+ (CDEF, RHEL, SACL, STRB)
ESTES 74 LBL-3827 Thesis (LBL)
AGUILAR-... 70B PRL 25 58 Aguilar-Benitez, Barnes, Bassano+ (BNL, SYRA)
BARNES 69E BNL 13823 +Chung, Eisner, Flaminio+ (BNL, SYRA)
EBERHARD 69 PRL 22 200 +Friedman, Pripstein, Ross (LRL)
HUWE 69 PR 180 1824 (LRL)
BUGG 68 PR 168 1466 +Gilmore, Knight+ (RHEL, BIRM, CAVE) I
BUTTON-... 68 PRL 21 1123 Button-Shafer (MASA, LRL) JP
PRIMER 68 PRL 20 610 +Goldberg, Jaeger, Barnes, Dornan+ (SYRA, BNL)
EBERHARD 67 PR 163 1446 +Pripstein, Shively, Kruse, Swanson (LRL, ILL) IJP
BIRMINGHAM 66 PR 152 1148 (BIRM, GLAS, LOIC, OXF, RHEL)
LONDON 66 PR 143 1034 +Rau, Goldberg, Lichtman+ (BNL, SYRA) IJ
EBERHARD 65 PRL 14 466 +Shively, Ross, Siegal, Ficenec+ (LRL, ILL) I
LEVEQUE 65 PL 18 69 + (SACL, EPOL, GLAS, LOIC, OXF, RHEL) JP
ALVAREZ 63 PRL 10 184 +Alston, Ferro-Luzzi, Huwe+ (LRL) I
SMITH 63 Athens Conf. 67 (LRL)
ALEXANDER 62C CERN Conf. 320 +Jacobs, Kalbfleisch, Miller+ (LRL) I

$\Sigma(1690)$ Bumps

$I(J^P) = 1(?^?)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

See the note preceding the $\Sigma(1670)$ Listings. Seen in production experiments only, mainly in $\Lambda\pi$.

$\Sigma(1690)$ MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
≈ 1690 OUR ESTIMATE					
1698 ± 20	70	[1] GODDARD 79	HBC	+	$\pi^+ p$ 10.3 GeV/c
1707 ± 20	40	[2] GODDARD 79	HBC	+	$\pi^+ p$ 10.3 GeV/c
1698 ± 20	15	ADERHOLZ 69	HBC	+	$\pi^+ p$ 8 GeV/c
$1682\pm\ 2$	46	BLUMENFELD 69	HBC	+	$K^0_L p$
1700 ± 20		MOTT 69	HBC	+	$K^- p$ 5.5 GeV/c
1694 ± 24	60	[3] PRIMER 68	HBC	+	$K^- p$ 4.6–5 GeV/c
$1700\pm\ 6$		[4] SIMS 68	HBC	−	$K^- N \to \Lambda\pi\pi$
1715 ± 12	30	COLLEY 67	HBC	+	$K^- p$ 6 GeV/c

$\Sigma(1690)$ WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
$240\pm\ 60$	70	[1] GODDARD 79	HBC	+	$\pi^+ p$ 10.3 GeV/c
$130^{+100}_{-\ 60}$	40	[2] GODDARD 79	HBC	+	$\pi^+ p$ 10.3 GeV/c
$142\pm\ 40$	15	ADERHOLZ 69	HBC	+	$\pi^+ p$ 8 GeV/c
$25\pm\ 10$	46	BLUMENFELD 69	HBC	+	$K^0_L p$
$130\pm\ 25$		MOTT 69	HBC	+	$K^- p$ 5.5 GeV/c
$105\pm\ 35$	60	[3] PRIMER 68	HBC	+	$K^- p$ 4.6–5 GeV/c
$62\pm\ 14$		[4] SIMS 68	HBC	−	$K^- N \to \Lambda\pi\pi$
$100\pm\ 35$	30	COLLEY 67	HBC	+	$K^- p$ 6 GeV/c

$\Sigma(1690)$ DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Sigma(1385)\pi$
Γ_5	$\Lambda\pi\pi$ (including $\Sigma(1385)\pi$)

$\Sigma(1690)$ BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(N\overline{K})/\Gamma(\Lambda\pi)$ — Γ_1/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
small		GODDARD	79	HBC	+	$\pi^+ p$ 10.2 GeV/c
<0.2		MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c
0.4±0.25	18	COLLEY	67	HBC	+	6/30 events

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$ — Γ_3/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
small		GODDARD	79	HBC	+	$\pi^+ p$ 10.2 GeV/c
<0.4	90	MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c
0.3±0.3		COLLEY	67	HBC	+	4/30 events

$\Gamma(\Sigma(1385)\pi)/\Gamma(\Lambda\pi)$ — Γ_4/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.5	MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c

$\Gamma(\Lambda\pi\pi$ (including $\Sigma(1385)\pi))/\Gamma(\Lambda\pi)$ — Γ_5/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
2.0±0.6	BLUMENFELD	69	HBC	+	31/15 events
0.5±0.25	COLLEY	67	HBC	+	15/30 events

$\Gamma(\Sigma(1385)\pi)/\Gamma(\Lambda\pi\pi$ (including $\Sigma(1385)\pi))$ — Γ_4/Γ_5

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
large	SIMS	68	HBC	−	$K^- N \to \Lambda\pi\pi$
small	COLLEY	67	HBC	+	$K^- p$ 6 GeV/c

$\Sigma(1690)$ FOOTNOTES (PRODUCTION EXPERIMENTS)

[1] From $\pi^+ p \to (\Lambda\pi^+)K^+$. $J > 1/2$ is not required by the data.
[2] From $\pi^+ p \to (\Lambda\pi^+)(K\pi)^+$. $J > 1/2$ is indicated, but large background precludes a definite conclusion.
[3] See the $\Sigma(1670)$ Listings. AGUILAR-BENITEZ 70B with three times the data of PRIMER 68 find no evidence for the $\Sigma(1690)$.
[4] This analysis, which is difficult and requires several assumptions and shows no unambiguous $\Sigma(1690)$ signal, suggests $J^P = 5/2^+$. Such a state would lead all previously known Y^* trajectories.

$\Sigma(1690)$ REFERENCES (PRODUCTION EXPERIMENTS)

GODDARD 79 PR D19 1350 +Key, Luste, Prentice, Yoon, Gordon+ (TNTO, BNL) IJ
AGUILAR-... 70B PRL 25 58 Aguilar-Benitez, Barnes, Bassano+ (BNL, SYRA)
ADERHOLZ 69 NP B11 259 +Bartsch+ (AACH, BERL, CERN, JAGL, WARS) I
BLUMENFELD 69 PL 29B 58 +Kalbfleisch (BNL) I
MOTT 69 PR 177 1966 +Ammar, Davis, Kropac, Slate+ (NWES, ANL) I
Also 67 PRL 18 266 Derrick, Fields, Loken, Ammar+ (ANL, NWES) I
PRIMER 68 PRL 20 610 +Goldberg, Jaeger, Barnes, Dornan+ (SYRA, BNL) I
SIMS 68 PRL 21 1413 +Albright, Bartley, Meer+ (FSU, TUFT, BRAN) I
COLLEY 67 PL 24B 489 (BIRM, GLAS, LOIC, MUNI, OXF, RHEL) I

$\Sigma(1750)$ S_{11}

$I(J^P) = 1(\frac{1}{2}^-)$ Status: ***

For most results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

There is evidence for this state in many partial-wave analyses, but with wide variations in the mass, width, and couplings. The latest analyses indicated significant couplings to $N\overline{K}$ and $\Lambda\pi$, as well as to $\Sigma\eta$ whose threshold is at 1746 MeV (JONES 74).

$\Sigma(1750)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1730 to 1800 (≈ 1750) OUR ESTIMATE				
1756±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1770±10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1770±15	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1800 or 1813	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1715±10	[2] CARROLL	76	DPWA	Isospin-1 total σ
1730	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
1780±30	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1)
1700±30	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 2)
1697^{+20}_{-10}	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
1785±12	CHU	74	DBC	Fits $\sigma(K^- n \to \Sigma^-\eta)$
1760± 5	[3] JONES	74	HBC	Fits $\sigma(K^- p \to \Sigma^0\eta)$
1739±10	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$

$\Sigma(1750)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
60 to 160 (≈ 90) OUR ESTIMATE				
64±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
161±20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
60±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
117 or 119	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
10	[2] CARROLL	76	DPWA	Isospin-1 total σ
110	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
140±30	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1)
160±50	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 2)
66^{+14}_{-12}	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
89±33	CHU	74	DBC	Fits $\sigma(K^- n \to \Sigma^-\eta)$
92± 7	[3] JONES	74	HBC	Fits $\sigma(K^- p \to \Sigma^0\eta)$
108±20	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$

$\Sigma(1750)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	10–40 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	<8 %
Γ_4	$\Sigma\eta$	15–55 %
Γ_5	$\Sigma(1385)\pi$	
Γ_6	$\Lambda(1520)\pi$	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(1750)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.4 OUR ESTIMATE				
0.14±0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.33±0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.15±0.03	GOPAL	77	DPWA	See GOPAL 80
0.06 or 0.05	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1750) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.04 ±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.10 or −0.09	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
−0.12	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
−0.12 ±0.02	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1)
−0.13 ±0.03	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 2)
−0.13 ±0.04	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
−0.120±0.077	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1750) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.09±0.05	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.06 or +0.06	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.13±0.02	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1750) \to \Sigma\eta$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.23±0.01	[3] JONES	74	HBC	Fits $\sigma(K^- p \to \Sigma^0\eta)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	CLINE	69	DBC	Threshold bump

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1750) \to \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.18±0.15	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1750) \to \Lambda(1520)\pi$ — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.032±0.021	CAMERON	77	DPWA	P-wave decay

$\Sigma(1750)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] A total cross-section bump with $(J+1/2)\ \Gamma_{el}\ /\ \Gamma_{total} = 0.30$.
[3] An *S*-wave Breit-Wigner fit to the threshold cross section with no background and errors statistical only.

$\Sigma(1750)$ REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
CHU	74	NC 20A 35	+Bartley+	(PLAT, TUFT, BRAN) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
JONES	74	NP B73 141		(CHIC) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP
CLINE	69	LNC 2 407	+Laumann, Mapp	(WISC)

$\Sigma(1770)\ P_{11}$

$I(J^P) = 1(\frac{1}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

Evidence for this state now rests solely on solution 1 of BAILLON 75, (see the footnotes) but the $\Lambda\pi$ partial-wave amplitudes of this solution are in disagreement with amplitudes from most other $\Lambda\pi$ analyses.

$\Sigma(1770)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1770 OUR ESTIMATE				
1738±10	[1] GOPAL	77	DPWA	$\overline{K}N$ multichannel
1770±20	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1772	[3] KANE	72	DPWA	$K^-p \to \Sigma\pi$

$\Sigma(1770)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
72±10	[1] GOPAL	77	DPWA	$\overline{K}N$ multichannel
80±30	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
80	[3] KANE	72	DPWA	$K^-p \to \Sigma\pi$

$\Sigma(1770)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

$\Sigma(1770)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.14±0.04	[1] GOPAL	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1770) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.08±0.02	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1770) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.108	[3] KANE	72	DPWA	$K^-p \to \Sigma\pi$

$\Sigma(1770)$ FOOTNOTES

[1] Required to fit the isospin-1 total cross section of CARROLL 76 in the $\overline{K}N$ channel. The addition of new K^-p polarization and K^-n differential cross-section data in GOPAL 80 find it to be more consistent with the $\Sigma(1660)\ P_{11}$.
[2] From solution 1 of BAILLON 75; not present in solution 2.
[3] Not required in KANE 74, which supersedes KANE 72.

$\Sigma(1770)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL)
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
KANE	74	LBL-2452		(LBL) IJP
KANE	72	PR D5 1583		(LBL)

$\Sigma(1775)\ D_{15}$

$I(J^P) = 1(\frac{5}{2}^-)$ Status: ****

Discovered by GALTIERI 63, this resonance plays the same role as cornerstone for isospin-1 analyses in this region as the $\Lambda(1820)$ does in the isospin-0 channel.

For most results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

$\Sigma(1775)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1770 to 1780 (≈ 1775) OUR ESTIMATE				
1778± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1777± 5	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1774± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1775±10	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1774±10	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
1772± 6	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1772 or 1777	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1765	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$

$\Sigma(1775)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
105 to 135 (≈ 120) OUR ESTIMATE				
137±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
116±10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
130±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
125±15	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
146±18	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
154±10	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
102 or 103	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
120	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$

$\Sigma(1775)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	37–43%
Γ_2	$\Lambda\pi$	14–20%
Γ_3	$\Sigma\pi$	2–5%
Γ_4	$\Sigma(1385)\pi$	8–12%
Γ_5	$\Sigma(1385)\pi$, *D*-wave	
Γ_6	$\Lambda(1520)\pi$	17–23%
Γ_7	$\Sigma\pi\pi$	

The above branching fractions are our estimates, not fits or averages.

CONSTRAINED FIT INFORMATION

An overall fit to 8 branching ratios uses 16 measurements and one constraint to determine 5 parameters. The overall fit has a $\chi^2 =$ 63.9 for 12 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i\delta x_j\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−30			
x_3	−17	−21		
x_4	−37	−49	−14	
x_6	−81	6	8	16
	x_1	x_2	x_3	x_4

$\Sigma(1775)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances. Also, the errors quoted do not include uncertainties due to the parametrization used in the partial-wave analyses and are thus too small.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.37 to 0.43 OUR ESTIMATE				
0.45 ±0.04 OUR FIT Error includes scale factor of 3.1.				
0.391±0.017 OUR AVERAGE				
0.40 ±0.02	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.37 ±0.03	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.41 ±0.03	GOPAL	77	DPWA	See GOPAL 80
0.37 or 0.36	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1775) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.305±0.018 OUR FIT Error includes scale factor of 2.4.				
−0.262±0.015 OUR AVERAGE				
−0.28 ±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.25 ±0.02	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$-0.28\ ^{+0.04}_{-0.05}$	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
−0.259±0.048	DEVENISH	74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.29 or −0.28	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
−0.30	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1775) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.105±0.025 OUR FIT Error includes scale factor of 3.1.				
0.098±0.016 OUR AVERAGE Error includes scale factor of 1.8.				
+0.13 ±0.02	GOPAL	77	DPWA	$\overline{K}N$ multichannel
0.09 ±0.01	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.08 or +0.08	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1775) \to \Lambda(1520)\pi$ — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.315±0.010 OUR FIT Error includes scale factor of 1.5.				
0.303±0.009 OUR AVERAGE Signs on measurements were ignored.				
−0.305±0.010	[2] CAMERON	77	DPWA	$K^-p \to \Lambda(1520)\pi^0$
0.31 ±0.02	BARLETTA	72	DPWA	$K^-p \to \Lambda(1520)\pi^0$
0.27 ±0.03	ARMENTEROS	65C	HBC	$K^-p \to \Lambda(1520)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1775) \to \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.211±0.022 OUR FIT Error includes scale factor of 2.8.				
0.188±0.010 OUR AVERAGE Signs on measurements were ignored.				
−0.184±0.011	[3] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$
+0.20 ±0.02	PREVOST	74	DPWA	$K^-N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.32 ±0.06	SIMS	68	DBC	$K^-N \to \Lambda\pi\pi$
0.24 ±0.03	ARMENTEROS	67C	HBC	$K^-p \to \Lambda\pi\pi$

$\Gamma(\Lambda\pi)/\Gamma(N\overline{K})$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.46±0.09 OUR FIT Error includes scale factor of 2.9.				
0.33±0.05	UHLIG	67	HBC	K^-p 0.9 GeV/c

$\Gamma(\Sigma\pi\pi)/\Gamma_{total}$ — Γ_7/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.12	[4] ARMENTEROS	68C	HDBC	$K^-N \to \Sigma\pi\pi$

$\Gamma(\Sigma(1385)\pi)/\Gamma(N\overline{K})$ — Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.22±0.07 OUR FIT Error includes scale factor of 3.6.				
0.25±0.09	UHLIG	67	HBC	K^-p 0.9 GeV/c

$\Gamma(\Lambda(1520)\pi)/\Gamma(N\overline{K})$ — Γ_6/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.49±0.11 OUR FIT Error includes scale factor of 3.5.				
0.28±0.05	UHLIG	67	HBC	K^-p 0.9 GeV/c

$\Sigma(1775)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] This rate combines P-wave- and F-wave decays. The CAMERON 77 results for the separate P-wave- and F-wave decays are -0.303 ± 0.010 and -0.037 ± 0.014. The published signs have been changed here to be in accord with the baryon-first convention.

[3] The CAMERON 78 upper limit on G-wave decay is 0.03.

[4] For about 3/4 of this, the $\Sigma\pi$ system has $I = 0$ and is almost entirely $\Lambda(1520)$. For the rest, the $\Sigma\pi$ has $I = 1$, which is about what is expected from the known $\Sigma(1775) \to \Sigma(1385)\pi$ rate, as seen in $\Lambda\pi\pi$.

$\Sigma(1775)$ REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
BARLETTA	72	NP B40 45		(EFI) IJP
Also	66	PRL 17 841	Fenster, Gelfand, Harmsen+	(CHIC, ANL, CERN) IJP
ARMENTEROS	68C	NP B8 216	+Baillon+	(CERN, HEID, SACL) I
SIMS	68	PRL 21 1413	+Albright, Bartley, Meer+	(FSU, TUFT, BRAN)
ARMENTEROS	67C	ZPHY 202 486	+Ferro-Luzzi+	(CERN, HEID, SACL)
UHLIG	67	PR 155 1448	+Charlton, Condon, Glasser, Yodh+	(UMD, NRL)
ARMENTEROS	65C	PL 19 338	+Ferro-Luzzi+	(CERN, HEID, SACL) IJP
GALTIERI	63	PL 6 296	+Hussain, Tripp	(LRL) IJ

$\Sigma(1840)$ P_{13}

$I(J^P) = 1(\frac{3}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

For the time being, we list together here all resonance claims in the P_{13} wave between 1700 and 1900 MeV.

$\Sigma(1840)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1840 OUR ESTIMATE				
1798 or 1802	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1720± 30	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1925±200	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
1840± 10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$\Sigma(1840)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
93 or 93	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
120±30	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$65\ ^{+50}_{-20}$	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
120±10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$\Sigma(1840)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

$\Sigma(1840)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0 or 0	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.37±0.13	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1840) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.03 or +0.03	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
+0.11 ±0.02	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
+0.06 ±0.04	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
+0.122±0.078	DEVENISH	74B		Fixed-t dispersion rel.
0.20 ±0.04	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1840) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.04 or −0.04	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.15±0.04	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$\Sigma(1840)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] From solution 1 of BAILLON 75; not present in solution 2.

Σ(1840) REFERENCES

MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP

$\Sigma(1880)$ P_{11}

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

A P_{11} resonance is suggested by several partial-wave analyses, but with wide variations in the mass and other parameters. We list here all claims which lie well above the P_{11} $\Sigma(1770)$.

Σ(1880) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1880 OUR ESTIMATE				
1826±20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1870±10	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$
1847 or 1863	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1960±30	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1985±50	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
1898	[3] LEA	73	DPWA	Multichannel K-matrix
~ 1850	ARMENTEROS	70	IPWA	$\overline{K}N \to \overline{K}N$
1950±50	BARBARO-...	70	DPWA	$K^- N \to \Lambda\pi$
1920±30	LITCHFIELD	70	DPWA	$K^- N \to \Lambda\pi$
1850	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$
1882±40	SMART	68	DPWA	$K^- N \to \Lambda\pi$

Σ(1880) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
86± 15	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
80± 10	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$
216 or 220	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
260± 40	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
220±140	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
222	[3] LEA	73	DPWA	Multichannel K-matrix
~ 30	ARMENTEROS	70	IPWA	$\overline{K}N \to \overline{K}N$
200± 50	BARBARO-...	70	DPWA	$K^- N \to \Lambda\pi$
170± 40	LITCHFIELD	70	DPWA	$K^- N \to \Lambda\pi$
200	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$
222±150	SMART	68	DPWA	$K^- N \to \Lambda\pi$

Σ(1880) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$N\overline{K}^*(892)$, S=1/2, P-wave
Γ_5	$N\overline{K}^*(892)$, S=3/2, P-wave

Σ(1880) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.06±0.02	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.27 or 0.27	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.31	[3] LEA	73	DPWA	Multichannel K-matrix
0.20	ARMENTEROS	70	IPWA	$\overline{K}N \to \overline{K}N$
0.22	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1880) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.24 or −0.24	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
−0.12 ±0.02	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$+0.05\ ^{+0.07}_{-0.02}$	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
−0.169±0.119	DEVENISH	74B		Fixed-t dispersion rel.
−0.30	[3] LEA	73	DPWA	Multichannel K-matrix
−0.09 ±0.04	BARBARO-...	70	DPWA	$K^- N \to \Lambda\pi$
−0.14 ±0.03	LITCHFIELD	70	DPWA	$K^- N \to \Lambda\pi$
−0.11 ±0.03	SMART	68	DPWA	$K^- N \to \Lambda\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1880) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.30 or +0.29	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
not seen	[3] LEA	73	DPWA	Multichannel K-matrix

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1880) \to N\overline{K}^*(892)$, S=1/2, P-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.05±0.03	[4] CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1880) \to N\overline{K}^*(892)$, S=3/2, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.11±0.03	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

Σ(1880) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] From solution 1 of BAILLON 75; not present in solution 2.
[3] Only unconstrained states from table 1 of LEA 73 are listed.
[4] The published sign has been changed to be in accord with the baryon-first convention.

Σ(1880) REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
LEA	73	NP B56 77	+Martin, Moorhouse+	(RHEL, LOUC, GLAS, AARH) IJP
ARMENTEROS	70	Duke Conf. 123	+Baillon+	(CERN, HEID, SACL) IJP
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP
LITCHFIELD	70	NP B22 269		(RHEL) IJP
BAILEY	69	UCRL 50617 Thesis		(LLL) IJP
SMART	68	PR 169 1330		(LRL) IJP

$\Sigma(1915)$ F_{15}

$I(J^P) = 1(\frac{5}{2}^+)$ Status: ∗∗∗∗

Discovered by COOL 66. For results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

This entry only includes results from partial-wave analyses. Parameters of peaks seen in cross sections and invariant-mass distributions in this region used to be listed in in a separate entry immediately following. They may be found in our 1986 edition Physics Letters **170B** (1986).

Σ(1915) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1900 to 1935 (≈ 1915) OUR ESTIMATE				
1937±20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1894± 5	[1] CORDEN	77C		$K^- n \to \Sigma\pi$
1909± 5	[1] CORDEN	77C		$K^- n \to \Sigma\pi$
1920±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1900± 4	[2] CORDEN	76	DPWA	$K^- n \to \Lambda\pi^-$
1920±30	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1914±10	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
1920^{+15}_{-20}	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
1920± 5	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
1925 or 1933	[3] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1915	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$

Σ(1915) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
80 to 160 (≈ 120) OUR ESTIMATE				
161±20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
107±14	[1] CORDEN	77C		$K^- n \to \Sigma\pi$
85±13	[1] CORDEN	77C		$K^- n \to \Sigma\pi$
130±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
75±14	[2] CORDEN	76	DPWA	$K^- n \to \Lambda\pi^-$
70±20	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
85±15	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
102±18	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
162±25	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
171 or 173	[3] MARTIN	77	DPWA	$\overline{K}N$ multichannel
60	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(1915)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	5–15 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	seen
Γ_4	$\Sigma(1385)\pi$	<5 %
Γ_5	$\Sigma(1385)\pi$, P-wave	
Γ_6	$\Sigma(1385)\pi$, F-wave	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(1915)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE				
0.03±0.02	[4] GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.14±0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
0.11±0.04	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.05±0.03	GOPAL	77	DPWA	See GOPAL 80
0.08 or 0.08	[3] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1915) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.09 ±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.10 ±0.01	[2] CORDEN	76	DPWA	$K^-n \to \Lambda\pi^-$
−0.06 ±0.02	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
−0.09 ±0.02	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
−0.087±0.056	DEVENISH	74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.09 or −0.09	[3] MARTIN	77	DPWA	$\overline{K}N$ multichannel
−0.10	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1915) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.17±0.01	[1] CORDEN	77C		$K^-n \to \Sigma\pi$
−0.15±0.02	[1] CORDEN	77C		$K^-n \to \Sigma\pi$
−0.19±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.16±0.03	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.05 or −0.05	[3] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1915) \to \Sigma(1385)\pi$, P-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.01	CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1915) \to \Sigma(1385)\pi$, F-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.039±0.009	[5] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$

$\Sigma(1915)$ FOOTNOTES

[1] The two entries for CORDEN 77C are from two different acceptable solutions.
[2] Preferred solution 3; see CORDEN 76 for other possibilities.
[3] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[4] The mass and width are fixed to the GOPAL 77 values due to the low elasticity.
[5] The published sign has been changed to be in accord with the baryon-first convention.

$\Sigma(1915)$ REFERENCES

PDG	86	PL 170B	Aguilar-Benitez, Porter+	(CERN, CIT+)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CORDEN	77C	NP B125 61	+Cox, Kenyon, O'Neale, Stubbs, Sumorok+	(BIRM) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
CORDEN	76	NP B104 382	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEID, MPIM) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
COOL	66	PRL 16 1228	+Giacomelli, Kycia, Leontic, Lundby+	(BNL)

$\Sigma(1940)$ D_{13}

$I(J^P) = 1(\frac{3}{2}^-)$ Status: ∗∗∗

For results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

Not all analyses require this state. It is not required by the GOYAL 77 analysis of $K^-n \to (\Sigma\pi)^-$ nor by the GOPAL 80 analysis of $K^-n \to K^-n$. See also HEMINGWAY 75.

$\Sigma(1940)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1900 to 1950 (≈ 1940) OUR ESTIMATE				
1920±50	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1950±30	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1949^{+40}_{-60}	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
1935±80	KANE	74	DPWA	$K^-p \to \Sigma\pi$
1940±20	LITCHFIELD	74B	DPWA	$K^-p \to \Lambda(1520)\pi^0$
1950±20	LITCHFIELD	74C	DPWA	$K^-p \to \Delta(1232)\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1886 or 1893	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1940	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$, F_{17} wave

$\Sigma(1940)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
150 to 300 (≈ 220) OUR ESTIMATE				
170±25	CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$
300±80	GOPAL	77	DPWA	$\overline{K}N$ multichannel
150±75	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
160^{+70}_{-40}	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
330±80	KANE	74	DPWA	$K^-p \to \Sigma\pi$
60±20	LITCHFIELD	74B	DPWA	$K^-p \to \Lambda(1520)\pi^0$
70^{+30}_{-20}	LITCHFIELD	74C	DPWA	$K^-p \to \Delta(1232)\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
157 or 159	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Sigma(1940)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	<20 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	seen
Γ_4	$\Sigma(1385)\pi$	seen
Γ_5	$\Sigma(1385)\pi$, S-wave	
Γ_6	$\Lambda(1520)\pi$	seen
Γ_7	$\Lambda(1520)\pi$, P-wave	
Γ_8	$\Lambda(1520)\pi$, F-wave	
Γ_9	$\Delta(1232)\overline{K}$	seen
Γ_{10}	$\Delta(1232)\overline{K}$, S-wave	
Γ_{11}	$\Delta(1232)\overline{K}$, D-wave	
Γ_{12}	$N\overline{K}^*(892)$	seen
Γ_{13}	$N\overline{K}^*(892)$, S=3/2, S-wave	

$\Sigma(1940)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
<0.2 OUR ESTIMATE				
<0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
0.14 or 0.13	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1940) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.06 ±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.04 ±0.02	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$-0.05\ ^{+0.03}_{-0.02}$	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
−0.153±0.070	DEVENISH	74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.15 or −0.14	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1940) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.08 ± 0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
-0.14 ± 0.04	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$+0.16$ or $+0.16$	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1940) \to \Lambda(1520)\pi$, P-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.03	CAMERON	77	DPWA	$K^-p \to \Lambda(1520)\pi^0$
-0.11 ± 0.04	LITCHFIELD	74B	DPWA	$K^-p \to \Lambda(1520)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1940) \to \Lambda(1520)\pi$, F-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.062 ± 0.021	CAMERON	77	DPWA	$K^-p \to \Lambda(1520)\pi^0$
-0.08 ± 0.04	LITCHFIELD	74B	DPWA	$K^-p \to \Lambda(1520)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1940) \to \Delta(1232)\overline{K}$, S-wave — $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.16 ± 0.05	LITCHFIELD	74C	DPWA	$K^-p \to \Delta(1232)\overline{K}$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1940) \to \Delta(1232)\overline{K}$, D-wave — $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.14 ± 0.05	LITCHFIELD	74C	DPWA	$K^-p \to \Delta(1232)\overline{K}$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1940) \to \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.066\pm0.025$	[2] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1940) \to N\overline{K}^*(892)$ — $(\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.09 ± 0.02	[3] CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$\Sigma(1940)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] The published sign has been changed to be in accord with the baryon-first convention.
[3] Upper limits on the D_1 and D_3 waves are each 0.03.

$\Sigma(1940)$ REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL)
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
GOYAL	77	PR D16 2746	+Sodhi	(DELH)
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEID, MPIM) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
LITCHFIELD	74B	NP B74 19	+Hemingway, Baillon+	(CERN, HEID) IJP
LITCHFIELD	74C	NP B74 39	+Hemingway, Baillon+	(CERN, HEID) IJP

$\Sigma(2000)$ S_{11}

$I(J^P) = 1(\frac{1}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

We list here all reported S_{11} states lying above the $\Sigma(1750)$ S_{11}.

$\Sigma(2000)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2000 OUR ESTIMATE				
1944 ± 15	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1955 ± 15	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1755 or 1834	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
2004 ± 40	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$

$\Sigma(2000)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
215 ± 25	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
170 ± 40	GOPAL	77	DPWA	$\overline{K}N$ multichannel
413 or 450	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
116 ± 40	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$

$\Sigma(2000)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Lambda(1520)\pi$
Γ_5	$N\overline{K}^*(892)$, S=1/2, S-wave
Γ_6	$N\overline{K}^*(892)$, S=3/2, D-wave

$\Sigma(2000)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.51 ± 0.05	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.44 ± 0.05	GOPAL	77	DPWA	See GOPAL 80
0.62 or 0.57	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2000) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.08 ± 0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
-0.19 or -0.18	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
not seen	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$+0.07^{+0.02}_{-0.01}$	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2000) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.20\pm0.04$	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$+0.26$ or $+0.24$	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2000) \to \Lambda(1520)\pi$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.081\pm0.021$	[2] CAMERON	77	DPWA	P-wave decay

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2000) \to N\overline{K}^*(892)$, S=1/2, S-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.10\pm0.02$	[2] CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2000) \to N\overline{K}^*(892)$, S=3/2, D-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.07 ± 0.03	CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$\Sigma(2000)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] The published sign has been changed to be in accord with the baryon-first convention.

$\Sigma(2000)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP

$\Sigma(2030)$ F_{17}

$I(J^P) = 1(\frac{7}{2}^+)$ Status: ∗∗∗∗

Discovered by COOL 66 and by WOHL 66. For most results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

This entry only includes results from partial-wave analyses. Parameters of peaks seen in cross sections and invariant-mass distributions around 2030 MeV may be found in our 1984 edition, Reviews of Modern Physics **56** No. 2 Pt. II (1984).

$\Sigma(2030)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2025 to 2040 (≈ 2030) OUR ESTIMATE				
2036± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
2038±10	CORDEN	77B		$K^- N \to N\overline{K}^*$
2040± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
2030± 3	[1] CORDEN	76	DPWA	$K^- n \to \Lambda\pi^-$
2035±15	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
2038±10	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
2042±11	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
2020± 6	KANE	74	DPWA	$K^- p \to \Sigma\pi$
2035±10	LITCHFIELD	74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$
2020±30	LITCHFIELD	74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$
2025±10	LITCHFIELD	74D	DPWA	$K^- p \to \Lambda(1820)\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2027 to 2057	GOYAL	77	DPWA	$K^- N \to \Sigma\pi$
2030	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(2030)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
150 to 200 (≈ 180) OUR ESTIMATE				
172±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
137±40	CORDEN	77B		$K^- N \to N\overline{K}^*$
190±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
201± 9	[1] CORDEN	76	DPWA	$K^- n \to \Lambda\pi^-$
180±20	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
172±15	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
178±13	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
111± 5	KANE	74	DPWA	$K^- p \to \Sigma\pi$
160±20	LITCHFIELD	74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$
200±30	LITCHFIELD	74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
260	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
126 to 195	GOYAL	77	DPWA	$K^- N \to \Sigma\pi$
160	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
70 to 125	LITCHFIELD	74D	DPWA	$K^- p \to \Lambda(1820)\pi^0$

$\Sigma(2030)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	17–23 %
Γ_2	$\Lambda\pi$	17–23 %
Γ_3	$\Sigma\pi$	5–10 %
Γ_4	ΞK	<2 %
Γ_5	$\Sigma(1385)\pi$	5–15 %
Γ_6	$\Sigma(1385)\pi$, *F*-wave	
Γ_7	$\Lambda(1520)\pi$	10–20 %
Γ_8	$\Lambda(1520)\pi$, *D*-wave	
Γ_9	$\Lambda(1520)\pi$, *G*-wave	
Γ_{10}	$\Delta(1232)\overline{K}$	10–20 %
Γ_{11}	$\Delta(1232)\overline{K}$, *F*-wave	
Γ_{12}	$\Delta(1232)\overline{K}$, *H*-wave	
Γ_{13}	$N\overline{K}^*(892)$	<5 %
Γ_{14}	$N\overline{K}^*(892)$, S=1/2, *F*-wave	
Γ_{15}	$N\overline{K}^*(892)$, S=3/2, *F*-wave	
Γ_{16}	$\Lambda(1820)\pi$, *P*-wave	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(2030)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.17 to 0.23 OUR ESTIMATE				
0.19±0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.18±0.03	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.15	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
0.24±0.02	GOPAL	77	DPWA	See GOPAL 80

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2030) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.18 ±0.02	GOPAL	77	DPWA	$\overline{K}N$ multichannel
+0.20 ±0.01	[1] CORDEN	76	DPWA	$K^- n \to \Lambda\pi^-$
+0.18 ±0.02	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
+0.20 ±0.01	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
+0.195±0.053	DEVENISH	74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.20	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2030) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.09 ±0.01	[2] CORDEN	77C		$K^- n \to \Sigma\pi$
−0.06 ±0.01	[2] CORDEN	77C		$K^- n \to \Sigma\pi$
−0.15 ±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.10 ±0.01	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.085±0.02	[3] GOYAL	77	DPWA	$K^- N \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2030) \to \Xi K$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.023	MULLER	69B	DPWA	$K^- p \to \Xi K$
<0.05	BURGUN	68	DPWA	$K^- p \to \Xi K$
<0.05	TRIPP	67	RVUE	$K^- p \to \Xi K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2030) \to \Lambda(1820)\pi$, *P*-wave — $(\Gamma_1\Gamma_{16})^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.14±0.02	CORDEN	75B	DBC	$K^- n \to N\overline{K}\pi^-$
0.18±0.04	LITCHFIELD	74D	DPWA	$K^- p \to \Lambda(1820)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2030) \to \Lambda(1520)\pi$, *D*-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.114±0.010	[4] CAMERON	77	DPWA	$K^- p \to \Lambda(1520)\pi^0$
0.14 ±0.03	LITCHFIELD	74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.10 ±0.03	[5] CORDEN	75B	DBC	$K^- n \to N\overline{K}\pi^-$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2030) \to \Lambda(1520)\pi$, *G*-wave — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.146±0.010	[4] CAMERON	77	DPWA	$K^- p \to \Lambda(1520)\pi^0$
0.02 ±0.02	LITCHFIELD	74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2030) \to \Delta(1232)\overline{K}$, *F*-wave — $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.16±0.03	LITCHFIELD	74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.17±0.03	[5] CORDEN	75B	DBC	$K^- n \to N\overline{K}\pi^-$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2030) \to \Delta(1232)\overline{K}$, *H*-wave — $(\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.00±0.02	LITCHFIELD	74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2030) \to \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.153±0.026	[4] CAMERON	78	DPWA	$K^- p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2030) \to N\overline{K}^*(892)$, S=1/2, F-wave — $(\Gamma_1\Gamma_{14})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.06\pm0.03$	[4] CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$
-0.02 ± 0.01	CORDEN	77B		$K^-d \to NN\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2030) \to N\overline{K}^*(892)$, S=3/2, F-wave — $(\Gamma_1\Gamma_{15})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.04\pm0.03$	[6] CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$
-0.12 ± 0.02	CORDEN	77B		$K^-d \to NN\overline{K}^*$

$\Sigma(2030)$ FOOTNOTES

[1] Preferred solution 3; see CORDEN 76 for other possibilities.
[2] The two entries for CORDEN 77C are from two different acceptable solutions.
[3] This coupling is extracted from unnormalized data.
[4] The published sign has been changed to be in accord with the baryon-first convention.
[5] An upper limit.
[6] The upper limit on the G_3 wave is 0.03.

$\Sigma(2030)$ REFERENCES

PDG	84	RMP 56 No. 2 Pt. II	Wohl, Cahn, Rittenberg+	(LBL, CIT, CERN)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
CORDEN	77B	NP B121 365	+Cox, Kenyon, O'Neale, Stubbs, Sumorok+	(BIRM) IJP
CORDEN	77C	NP B125 61	+Cox, Kenyon, O'Neale, Stubbs, Sumorok+	(BIRM) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
GOYAL	77	PR D16 2746	+Sodhi	(DELH) IJP
CORDEN	76	NP B104 382	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
CORDEN	75B	NP B92 365	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEID, MPIM) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
LITCHFIELD	74B	NP B74 19	+Hemingway, Baillon+	(CERN, HEID) IJP
LITCHFIELD	74C	NP B74 39	+Hemingway, Baillon+	(CERN, HEID) IJP
LITCHFIELD	74D	NP B74 12	+Hemingway, Baillon+	(CERN, HEID) IJP
MULLER	69B	UCRL 19372 Thesis		(LRL)
BURGUN	68	NP B8 447	+Meyer, Pauli, Tallini+	(SACL, CDEF, RHEL)
TRIPP	67	NP B3 10	+Leith+	(LRL, SLAC, CERN, HEID, SACL)
COOL	66	PRL 16 1228	+Giacomelli, Kycia, Leontic, Lundby+	(BNL)
WOHL	66	PRL 17 107	+Solmitz, Stevenson	(LRL) IJP

$\Sigma(2070)$ F_{15}

$I(J^P) = 1(\frac{5}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

This state suggested by BERTHON 70B finds support in GOPAL 80 with new K^-p polarization and K^-n angular distributions. The very broad state seen in KANE 72 is not required in the later (KANE 74) analysis of $\overline{K}N \to \Sigma\pi$.

$\Sigma(2070)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2070 OUR ESTIMATE				
2051 ± 25	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
2057	KANE	72	DPWA	$K^-p \to \Sigma\pi$
2070 ± 10	BERTHON	70B	DPWA	$K^-p \to \Sigma\pi$

$\Sigma(2070)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
300 ± 30	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
906	KANE	72	DPWA	$K^-p \to \Sigma\pi$
140 ± 20	BERTHON	70B	DPWA	$K^-p \to \Sigma\pi$

$\Sigma(2070)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Sigma\pi$

$\Sigma(2070)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.08 ± 0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2070) \to \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.104$	KANE	72	DPWA	$K^-p \to \Sigma\pi$
$+0.12\pm0.02$	BERTHON	70B	DPWA	$K^-p \to \Sigma\pi$

$\Sigma(2070)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
KANE	74	LBL-2452		(LBL)
KANE	72	PR D5 1583		(LBL)
BERTHON	70B	NP B24 417	+Vrana, Butterworth+	(CDEF, RHEL, SACL) IJP

$\Sigma(2080)$ P_{13}

$I(J^P) = 1(\frac{3}{2}^+)$ Status: **

OMITTED FROM SUMMARY TABLE

Suggested by some but not all partial-wave analyses across this region.

$\Sigma(2080)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2080 OUR ESTIMATE				
2091 ± 7	[1] CORDEN	76	DPWA	$K^-n \to \Lambda\pi^-$
2070 to 2120	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$
2120 ± 40	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1)
2140 ± 40	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 2)
2082 ± 4	COX	70	DPWA	See CORDEN 76
2070 ± 30	LITCHFIELD	70	DPWA	$K^-N \to \Lambda\pi$

$\Sigma(2080)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
186 ± 48	[1] CORDEN	76	DPWA	$K^-n \to \Lambda\pi^-$
100	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$
240 ± 50	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1)
200 ± 50	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 2)
87 ± 20	COX	70	DPWA	See CORDEN 76
250 ± 40	LITCHFIELD	70	DPWA	$K^-N \to \Lambda\pi$

$\Sigma(2080)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$

$\Sigma(2080)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2080) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.10 ± 0.03	[1] CORDEN	76	DPWA	$K^-n \to \Lambda\pi^-$
-0.10	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$
-0.13 ± 0.04	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1 and 2)
-0.16 ± 0.03	COX	70	DPWA	See CORDEN 76
-0.09 ± 0.03	LITCHFIELD	70	DPWA	$K^-N \to \Lambda\pi$

$\Sigma(2080)$ FOOTNOTES

[1] Preferred solution 3; see CORDEN 76 for other possibilities, including a D_{15} at this mass.

$\Sigma(2080)$ REFERENCES

CORDEN	76	NP B104 382	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
Also	75	NP B90 1	De Bellefon, Berthon, Brunet+	(CDEF, SACL) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
COX	70	NP B19 61	+Islam, Colley+	(BIRM, EDIN, GLAS, LOIC) IJP
LITCHFIELD	70	NP B22 269		(RHEL) IJP

$\Sigma(2100)$ G_{17}

$I(J^P) = 1(\frac{7}{2}^-)$ Status: $*$

OMITTED FROM SUMMARY TABLE

$\Sigma(2100)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2100 OUR ESTIMATE				
2060±20	BARBARO-...	70	DPWA	$K^- p \to \Lambda \pi^0$
2120±30	BARBARO-...	70	DPWA	$K^- p \to \Sigma \pi$

$\Sigma(2100)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
70±30	BARBARO-...	70	DPWA	$K^- p \to \Lambda \pi^0$
135±30	BARBARO-...	70	DPWA	$K^- p \to \Sigma \pi$

$\Sigma(2100)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

$\Sigma(2100)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2100) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.07±0.02	BARBARO-...	70	DPWA	$K^- p \to \Lambda \pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2100) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.13±0.02	BARBARO-...	70	DPWA	$K^- p \to \Sigma \pi$

$\Sigma(2100)$ REFERENCES

BARBARO-... 70 Duke Conf. 173 Barbaro-Galtieri (LRL) IJP

$\Sigma(2250)$

$I(J^P) = 1(?^?)$ Status: $***$

Results from partial-wave analyses are too weak to warrant separating them from the production and cross-section experiments. LASINSKI 71 in $\overline{K}N$ using a Pomeron + resonances model, and DEBELLEFON 76, DEBELLEFON 77, and DEBELLEFON 78 in energy-dependent partial-wave analyses of $\overline{K}N \to \Lambda\pi$, $\Sigma\pi$, and $N\overline{K}$, respectively, suggest two resonances around this mass.

$\Sigma(2250)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2210 to 2280 (≈ 2250) OUR ESTIMATE				
2270±50	DEBELLEFON	78	DPWA	D_5 wave
2210±30	DEBELLEFON	78	DPWA	G_9 wave
2275±20	DEBELLEFON	77	DPWA	D_5 wave
2215±20	DEBELLEFON	77	DPWA	G_9 wave
2300±30	[1] DEBELLEFON	75B	HBC	$K^- p \to \Xi^{*0} K^0$
2251^{+30}_{-20}	VANHORN	75	DPWA	$K^- p \to \Lambda \pi^0$, F_5 wave
2280±14	AGUILAR-...	70B	HBC	$K^- p$ 3.9, 4.6 GeV/c
2237±11	BRICMAN	70	CNTR	Total, charge exchange
2255±10	COOL	70	CNTR	$K^- p$, $K^- d$ total
2250± 7	BUGG	68	CNTR	$K^- p$, $K^- d$ total
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2260	DEBELLEFON	76	IPWA	D_5 wave
2215	DEBELLEFON	76	IPWA	G_9 wave
2250±20	LU	70	CNTR	$\gamma p \to K^+ Y^*$
2245	BLANPIED	65	CNTR	$\gamma p \to K^+ Y^*$
2299± 6	BOCK	65	HBC	$\overline{p}p$ 5.7 GeV/c

$\Sigma(2250)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
60 to 150 (≈ 100) OUR ESTIMATE				
120±40	DEBELLEFON	78	DPWA	D_5 wave
80±20	DEBELLEFON	78	DPWA	G_9 wave
70±20	DEBELLEFON	77	DPWA	D_5 wave
60±20	DEBELLEFON	77	DPWA	G_9 wave
130±20	[1] DEBELLEFON	75B	HBC	$K^- p \to \Xi^{*0} K^0$
192±30	VANHORN	75	DPWA	$K^- p \to \Lambda \pi^0$, F_5 wave
100±20	AGUILAR-...	70B	HBC	$K^- p$ 3.9, 4.6 GeV/c
164±50	BRICMAN	70	CNTR	Total, charge exchange
230±20	BUGG	68	CNTR	$K^- p$, $K^- d$ total
• • • We do not use the following data for averages, fits, limits, etc. • • •				
100	DEBELLEFON	76	IPWA	D_5 wave
140	DEBELLEFON	76	IPWA	G_9 wave
170	COOL	70	CNTR	$K^- p$, $K^- d$ total
125	LU	70	CNTR	$\gamma p \to K^+ Y^*$
150	BLANPIED	65	CNTR	$\gamma p \to K^+ Y^*$
21^{+17}_{-21}	BOCK	65	HBC	$\overline{p}p$ 5.7 GeV/c

$\Sigma(2250)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	<10 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	seen
Γ_4	$N\overline{K}\pi$	
Γ_5	$\Xi(1530)K$	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(2250)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
<0.1 OUR ESTIMATE				
0.08±0.02	DEBELLEFON	78	DPWA	D_5 wave
0.02±0.01	DEBELLEFON	78	DPWA	G_9 wave

$(J+\frac{1}{2}) \times \Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.16±0.12	BRICMAN	70	CNTR	Total, charge exchange
0.42	COOL	70	CNTR	$K^- p$, $K^- d$ total
0.47	BUGG	68	CNTR	

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2250) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.16±0.03	VANHORN	75	DPWA	$K^- p \to \Lambda \pi^0$, F_5 wave
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.11	DEBELLEFON	76	IPWA	D_5 wave
−0.10	DEBELLEFON	76	IPWA	G_9 wave
−0.18	BARBARO-...	70	DPWA	$K^- p \to \Lambda \pi^0$, G_9 wave

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2250) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.06±0.02	DEBELLEFON	77	DPWA	D_5 wave
−0.03±0.02	DEBELLEFON	77	DPWA	G_9 wave
+0.07	BARBARO-...	70	DPWA	$K^- p \to \Sigma \pi$, G_9 wave

$\Gamma(N\overline{K})/\Gamma(\Sigma\pi)$ — Γ_1/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.18	BARNES	69	HBC	1 standard dev. limit

$\Gamma(\Lambda\pi)/\Gamma(\Sigma\pi)$ — Γ_2/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.18	BARNES	69	HBC	1 standard dev. limit

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2250) \to \Xi(1530)K$ — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.18±0.04	[1] DEBELLEFON	75B	HBC	$K^- p \to \Xi^{*0} K^0$

$\Sigma(2250)$ FOOTNOTES

[1] Seen in the (initial and final state) D_5 wave. Isospin not determined.

Σ(2250) REFERENCES

DEBELLEFON 78 NC 42A 403 De Bellefon, Berthon, Billoir+ (CDEF, SACL) IJP
DEBELLEFON 77 NC 37A 175 De Bellefon, Berthon, Billoir+ (CDEF, SACL) IJP
DEBELLEFON 76 NP B109 129 De Bellefon, Berthon (CDEF) IJP
Also 75 NP B90 1 De Bellefon, Berthon, Brunet+ (CDEF, SACL) IJP
DEBELLEFON 75B NC 28A 289 De Bellefon, Berthon, Billoir+ (CDEF, SACL)
VANHORN 75 NP B87 145 (LBL) IJP
Also 75B NP B87 157 VanHorn (LBL) IJP
LASINSKI 71 NP B29 125 (EFI) IJP
AGUILAR-... 70B PRL 25 58 Aguilar-Benitez, Barnes, Bassano+ (BNL, SYRA)
BARBARO-... 70 Duke Conf. 173 Barbaro-Galtieri (LRL) IJP
BRICMAN 70 PL 31B 152 +Ferro-Luzzi, Perreau+ (CERN, CAEN, SACL)
COOL 70 PR D1 1887 +Giacomelli, Kycia, Leontic, Li+ (BNL) I
Also 66 PRL 16 1228 Cool, Giacomelli, Kycia, Leontic, Lundby+ (BNL) I
LU 70 PR D2 1846 +Greenberg, Hughes, Minehart, Mori+ (YALE)
BARNES 69 PRL 22 479 +Flaminio, Montanet, Samios+ (BNL, SYRA)
BUGG 68 PR 168 1466 +Gilmore, Knight+ (RHEL, BIRM, CAVE) I
BLANPIED 65 PRL 14 741 +Greenberg, Hughes, Kitching, Lu+ (YALE, CEA)
BOCK 65 PL 17 166 +Cooper, French, Kinson+ (CERN, SACL)

Σ(2455) Bumps

$I(J^P) = 1(?^?)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

There is also some slight evidence for Y^* states in this mass region from the reaction $\gamma p \rightarrow K^+ X$ — see GREENBERG 68.

Σ(2455) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 2455 OUR ESTIMATE				
2455±10	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total
2455± 7	BUGG	68	CNTR	$K^- p$, $K^- d$ total

Σ(2455) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
140	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total
100±20	BUGG	68	CNTR	

Σ(2455) DECAY MODES

	Mode
Γ_1	$N\overline{K}$

Σ(2455) BRANCHING RATIOS

$(J+\frac{1}{2}) \times \Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.39	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total
0.05±0.05	[1] BRICMAN	70	CNTR	Total, charge exchange
0.3	BUGG	68	CNTR	

Σ(2455) FOOTNOTES

[1] Fit of total cross section given by BRICMAN 70 is poor in this region.

Σ(2455) REFERENCES

ABRAMS 70 PR D1 1917 +Cool, Giacomelli, Kycia, Leontic, Li+ (BNL) I
Also 67E PRL 19 678 Abrams, Cool, Giacomelli, Kycia, Leontic+ (BNL)
BRICMAN 70 PL 31B 152 +Ferro-Luzzi, Perreau+ (CERN, CAEN, SACL)
BUGG 68 PR 168 1466 +Gilmore, Knight+ (RHEL, BIRM, CAVE) I
GREENBERG 68 PRL 20 221 +Hughes, Lu, Minehart+ (YALE)

Σ(2620) Bumps

$I(J^P) = 1(?^?)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Σ(2620) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 2620 OUR ESTIMATE				
2542±22	DIBIANCA	75	DBC	$K^- N \rightarrow \Xi K \pi$
2620±15	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total

Σ(2620) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
221±81	DIBIANCA	75	DBC	$K^- N \rightarrow \Xi K \pi$
175	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total

Σ(2620) DECAY MODES

	Mode
Γ_1	$N\overline{K}$

Σ(2620) BRANCHING RATIOS

$(J+\frac{1}{2}) \times \Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.32	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total
0.36±0.12	BRICMAN	70	CNTR	Total, charge exchange

Σ(2620) REFERENCES

DIBIANCA 75 NP B98 137 +Endorf (CMU)
ABRAMS 70 PR D1 1917 +Cool, Giacomelli, Kycia, Leontic, Li+ (BNL) I
Also 67E PRL 19 678 Abrams, Cool, Giacomelli, Kycia, Leontic+ (BNL)
BRICMAN 70 PL 31B 152 +Ferro-Luzzi, Perreau+ (CERN, CAEN, SACL)

Σ(3000) Bumps

$I(J^P) = 1(?^?)$ Status: ∗

OMITTED FROM SUMMARY TABLE

Seen as an enhancement in $\Lambda\pi$ and $\overline{K}N$ invariant mass spectra and in the missing mass of neutrals recoiling against a K^0.

Σ(3000) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
≈ 3000 OUR ESTIMATE					
3000	EHRLICH	66	HBC	0	$\pi^- p$ 7.91 GeV/c

Σ(3000) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$

Σ(3000) REFERENCES

EHRLICH 66 PR 152 1194 +Selove, Yuta (PENN) I

$\Sigma(3170)$ Bumps

$I(J^P) = 1(?^?)$ Status: *

OMITTED FROM SUMMARY TABLE

Seen by AMIRZADEH 79 as a narrow 6.5-standard-deviation enhancement in the reaction $K^- p \to Y^{*+} \pi^-$ using data from independent high statistics bubble chamber experiments at 8.25 and 6.5 GeV/c. The dominant decay modes are multibody, multistrange final states and the production is via isospin-3/2 baryon exchange. Isospin 1 is favored.

Not seen in a $K^- p$ experiment in LASS at 11 GeV/c (ASTON 85B).

$\Sigma(3170)$ MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
≈ 3170 OUR ESTIMATE					
3170±5	35	AMIRZADEH	79	HBC	$K^- p \to Y^{*+} \pi^-$

$\Sigma(3170)$ WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
<20	35	[1] AMIRZADEH	79	HBC	$K^- p \to Y^{*+} \pi^-$

$\Sigma(3170)$ DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda K \overline{K} \pi$'s	seen
Γ_2	$\Sigma K \overline{K} \pi$'s	seen
Γ_3	$\Xi K \pi$'s	seen

$\Sigma(3170)$ BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(\Lambda K \overline{K} \pi\text{'s})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	AMIRZADEH	79	HBC	$K^- p \to Y^{*+} \pi^-$

$\Gamma(\Sigma K \overline{K} \pi\text{'s})/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	AMIRZADEH	79	HBC	$K^- p \to Y^{*+} \pi^-$

$\Gamma(\Xi K \pi\text{'s})/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	AMIRZADEH	79	HBC	$K^- p \to Y^{*+} \pi^-$

$\Sigma(3170)$ FOOTNOTES (PRODUCTION EXPERIMENTS)

[1] Observed width consistent with experimental resolution.

$\Sigma(3170)$ REFERENCES (PRODUCTION EXPERIMENTS)

ASTON	85B	PR D32 2270	+Carnegie+	(SLAC, CARL, CNRC, CINC)
AMIRZADEH	79	PL 89B 125	+	(BIRM, CERN, GLAS, MSU, LPNP, CAMB+) I
Also	80	Toronto Conf. 263	Kinson+	(BIRM, CERN, GLAS, MSU, LPNP) I

Ξ BARYONS
$(S = -2, I = 1/2)$

$\Xi^0 = uss$, $\Xi^- = dss$

Ξ^0

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ****

The parity has not actually been measured, but + is of course expected.

Ξ^0 MASS

The fit uses the Ξ^0, Ξ^-, and $\overline{\Xi}^+$ mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN
1314.9±0.6 OUR FIT				
1314.8±0.8 OUR AVERAGE				
1315.2±0.92	49	WILQUET	72	HLBC
1313.4±1.8	1	PALMER	68	HBC

$\Xi^- - \Xi^0$ MASS DIFFERENCE

The fit uses the Ξ^0, Ξ^-, and $\overline{\Xi}^+$ mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
6.4±0.6 OUR FIT					
6.3±0.7 OUR AVERAGE					
6.9±2.2	29	LONDON	66	HBC	
6.1±0.9	88	PJERROU	65B	HBC	
6.8±1.6	23	JAUNEAU	63	FBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
6.1±1.6	45	CARMONY	64B	HBC	See PJERROU 65B

Ξ^0 MEAN LIFE

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
2.90±0.09 OUR AVERAGE					
2.83±0.16	6300	[1] ZECH	77	SPEC	Neutral hyperon beam
$2.88^{+0.21}_{-0.19}$	652	BALTAY	74	HBC	1.75 GeV/c $K^- p$
$2.90^{+0.32}_{-0.27}$	157	[2] MAYEUR	72	HLBC	2.1 GeV/c K^-
$3.07^{+0.22}_{-0.20}$	340	DAUBER	69	HBC	
3.0 ±0.5	80	PJERROU	65B	HBC	
$2.5^{+0.4}_{-0.3}$	101	HUBBARD	64	HBC	
$3.9^{+1.4}_{-0.8}$	24	JAUNEAU	63	FBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$3.5^{+1.0}_{-0.8}$	45	CARMONY	64B	HBC	See PJERROU 65B

[1] The ZECH 77 result is $\tau_{\Xi^0} = [2.77-(\tau_\Lambda-2.69)] \times 10^{-10}$ s, in which we use $\tau_\Lambda = 2.63 \times 10^{-10}$ s.
[2] The MAYEUR 72 value is modified by the erratum.

Ξ^0 MAGNETIC MOMENT

See the Note on Baryon Magnetic Moments in the Λ Listings.

VALUE (μ_N)	EVTS	DOCUMENT ID		TECN
−1.250±0.014 OUR AVERAGE				
−1.253±0.014	270k	COX	81	SPEC
−1.20 ±0.06	42k	BUNCE	79	SPEC

Ξ^0 DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Lambda \pi^0$	100 %	
Γ_2	$\Lambda \gamma$	$(1.06\pm0.16) \times 10^{-3}$	
Γ_3	$\Sigma^0 \gamma$	$(3.6 \pm0.4) \times 10^{-3}$	
Γ_4	$\Sigma^+ e^- \overline{\nu}_e$	$< 1.1 \times 10^{-3}$	90%
Γ_5	$\Sigma^+ \mu^- \overline{\nu}_\mu$	$< 1.1 \times 10^{-3}$	90%

$\Delta S = \Delta Q$ (SQ) or $\Delta S = 2$ (ΔS) violating modes

Γ_6	$\Sigma^- e^+ \nu_e$	SQ	<	9	$\times 10^{-4}$	90%
Γ_7	$\Sigma^- \mu^+ \nu_\mu$	SQ	<	9	$\times 10^{-4}$	90%
Γ_8	$p\pi^-$	ΔS	<	4	$\times 10^{-5}$	90%
Γ_9	$p e^- \overline{\nu}_e$	ΔS	<	1.3	$\times 10^{-3}$	
Γ_{10}	$p \mu^- \overline{\nu}_\mu$	ΔS	<	1.3	$\times 10^{-3}$	

Ξ^0 BRANCHING RATIOS

$\Gamma(\Lambda\gamma)/\Gamma(\Lambda\pi^0)$ — Γ_2/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.06±0.12±0.11	116	JAMES	90	SPEC	FNAL hyperons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5 ±5	1	YEH	74	HBC	Effective denom.=200

$\Gamma(\Sigma^0\gamma)/\Gamma(\Lambda\pi^0)$ — Γ_3/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
3.56±0.42±0.10		85	TEIGE	89	SPEC	FNAL hyperons
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 8	90		BENSINGER	88	MPS2	$K^- W$ 6 GeV/c
<65	90	0–1	YEH	74	HBC	Effective denom.=60

$\Gamma(\Sigma^+ e^- \overline{\nu}_e)/\Gamma(\Lambda\pi^0)$ — Γ_4/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 1.1	90	0	YEH	74	HBC	Effective denom.=2100
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 1.5			DAUBER	69	HBC	
< 7			HUBBARD	66	HBC	
<13			TICHO	63	HBC	

$\Gamma(\Sigma^+ \mu^- \overline{\nu}_\mu)/\Gamma(\Lambda\pi^0)$ — Γ_5/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.1	90	0	YEH	74	HBC	Effective denom.=2100
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.5			DAUBER	69	HBC	
<7			HUBBARD	66	HBC	

$\Gamma(\Sigma^- e^+ \nu_e)/\Gamma(\Lambda\pi^0)$ — Γ_6/Γ_1

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.9	90	0	YEH	74	HBC	Effective denom.=2500
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.5			DAUBER	69	HBC	
<6			HUBBARD	66	HBC	

$\Gamma(\Sigma^- \mu^+ \nu_\mu)/\Gamma(\Lambda\pi^0)$ — Γ_7/Γ_1

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.9	90	0	YEH	74	HBC	Effective denom.=2500
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.5			DAUBER	69	HBC	
<6			HUBBARD	66	HBC	

$\Gamma(p\pi^-)/\Gamma(\Lambda\pi^0)$ — Γ_8/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 3.6	90		GEWENIGER	75	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 180	90	0	YEH	74	HBC	Effective denom.=1300
< 90			DAUBER	69	HBC	
< 500			HUBBARD	66	HBC	
<2700			TICHO	63	HBC	

$\Gamma(p e^- \overline{\nu}_e)/\Gamma(\Lambda\pi^0)$ — Γ_9/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 1.3			DAUBER	69	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 3.4	90	0	YEH	74	HBC	Effective denom.=670
< 6			HUBBARD	66	HBC	
<27			TICHO	63	HBC	

$\Gamma(p \mu^- \overline{\nu}_\mu)/\Gamma(\Lambda\pi^0)$ — Γ_{10}/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

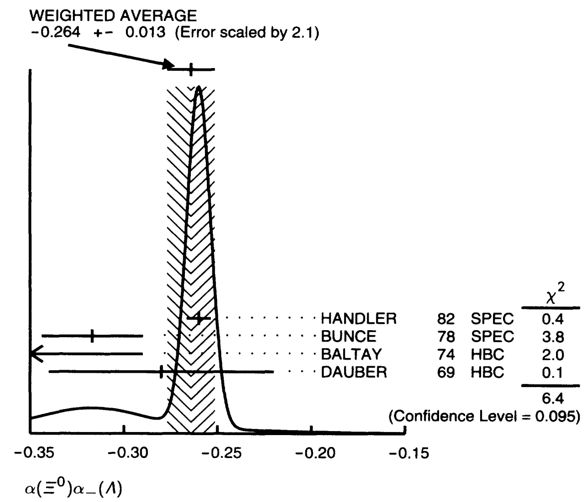
VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.3			DAUBER	69	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<3.5	90	0	YEH	74	HBC	Effective denom.=664
<6			HUBBARD	66	HBC	

Ξ^0 DECAY PARAMETERS

See the Note on Baryon Decay Parameters in the neutron Listings.

$\alpha(\Xi^0)\,\alpha_-(\Lambda)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.264±0.013 OUR AVERAGE	Error includes scale factor of 2.1. See the ideogram below.				
−0.260±0.004±0.005	300k	HANDLER	82	SPEC	FNAL hyperons
−0.317±0.027	6075	BUNCE	78	SPEC	FNAL hyperons
−0.35 ±0.06	505	BALTAY	74	HBC	$K^- p$ 1.75 GeV/c
−0.28 ±0.06	739	DAUBER	69	HBC	$K^- p$ 1.7–2.6 GeV/c



α FOR $\Xi^0 \to \Lambda\pi^0$

The above average, $\alpha(\Xi^0)\alpha_-(\Lambda) = -0.264 \pm 0.013$, where the error includes a scale factor of 2.1, divided by our current average $\alpha_-(\Lambda) = 0.642 \pm 0.013$, gives the following value for $\alpha(\Xi^0)$.

VALUE	DOCUMENT ID
−0.411±0.022 OUR EVALUATION	Error includes scale factor of 2.1.

ϕ ANGLE FOR $\Xi^0 \to \Lambda\pi^0$ ($\tan\phi = \beta/\gamma$)

VALUE (°)	EVTS	DOCUMENT ID		TECN	COMMENT
21±12 OUR AVERAGE					
16±17	652	BALTAY	74	HBC	1.75 GeV/c $K^- p$
38±19	739	DAUBER [3]	69	HBC	
− 8±30	146	BERGE [4]	66	HBC	

[3] DAUBER 69 uses $\alpha_\Lambda = 0.647 \pm 0.020$.

[4] The errors have been multiplied by 1.2 due to approximations used for the Ξ polarization; see DAUBER 69 for a discussion.

α FOR $\Xi^0 \to \Lambda\gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
+0.43±0.44	87	JAMES	90	SPEC	FNAL hyperons

α FOR $\Xi^0 \to \Sigma^0\gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
+0.20±0.32±0.05	85	TEIGE	89	SPEC	FNAL hyperons

REFERENCES FOR Ξ^0

JAMES	90	PRL 64 843	+Heller, Border, Dworkin+	(MINN, MICH, WISC, RUTG)
TEIGE	89	PRL 63 2717	+Beretvas, Caracappa, Devlin+	(RUTG, MICH, MINN)
BENSINGER	88	PL B215 195	+Fortner, Kirsch, Piekarz+	(BRAN, DUKE, NDAM, SMAS)
HANDLER	82	PR D25 639	+Grobel, Pondrom+	(WISC, MICH, MINN, RUTG)
COX	81	PRL 46 877	+Dworkin+	(MICH, WISC, RUTG, MINN, BNL)
BUNCE	79	PL 86B 386	+Overseth, Cox+	(BNL, MICH, RUTG, WISC)
BUNCE	78	PR D18 633	+Handler, March, Martin+	(WISC, MICH, RUTG)
ZECH	77	NP B124 413	+Dydak, Navarria+	(SIEG, CERN, DORT, HEID)
GEWENIGER	75	PL 57B 193	+Gjesdal, Presser+	(CERN, HEID)
BALTAY	74	PR D9 49	+Bridgewater, Cooper, Gershwin+	(COLU, BING) J
YEH	74	PR D10 3545	+Gaigalas, Smith, Zendle, Baltay+	(BING, COLU)
MAYEUR	72	NP B47 333	+VanBinst, Wilquet+	(BRUX, CERN, TUFT, LOUC)
Also	73	NP B53 268 erratum	Mayeur	
WILQUET	72	PL 42B 372	+Fliagine, Guy+	(BRUX, CERN, TUFT, LOUC)
DAUBER	69	PR 179 1262	+Berge, Hubbard, Merrill, Miller	(LRL)
PALMER	68	PL 26B 323	+Radojicic, Rau, Richardson+	(BNL, SYRA)
BERGE	66	PR 147 945	+Eberhard, Hubbard, Merrill+	(LRL)
HUBBARD	66	UCRL 11510 Thesis		(LRL)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA)
PJERROU	65B	PRL 14 275	+Schlein, Slater, Smith, Stork, Ticho	(UCLA)
Also	65	Thesis	Pjerrou	(UCLA)
CARMONY	64B	PRL 12 482	+Pjerrou, Schlein, Slater, Stork+	(UCLA)
HUBBARD	64	PR 135B 183	+Berge, Kalbfleisch, Shafer+	(LRL)
JAUNEAU	63	PL 4 49	+	(EPOL, CERN, LOUC, RHEL, BERG)
Also	63C	Siena Conf. 1 1	Jauneau+	(EPOL, CERN, LOUC, RHEL, BERG)
TICHO	63	BNL Conf. 410		(UCLA)

Ξ^-

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

The parity has not actually been measured, but + is of course expected.

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1986 edition (Physics Letters **170B** (1986)) or in earlier editions.

Ξ^- MASS

The fit uses the Ξ^-, $\overline{\Xi}^+$, and Ξ^0 mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1321.32±0.13 OUR FIT					
1321.34±0.14 OUR AVERAGE					
1321.46±0.34	632	DIBIANCA	75	DBC	4.9 GeV/c $K^- d$
1321.12±0.41	268	WILQUET	72	HLBC	
1321.87±0.51	195	[1] GOLDWASSER	70	HBC	5.5 GeV/c $K^- p$
1321.67±0.52	6	CHIEN	66	HBC	6.9 GeV/c $\overline{p}p$
1321.4 ±1.1	299	LONDON	66	HBC	
1321.3 ±0.4	149	PJERROU	65B	HBC	
1321.1 ±0.3	241	[2] BADIER	64	HBC	
1321.4 ±0.4	517	[2] JAUNEAU	63D	FBC	
1321.1 ±0.65	62	[2] SCHNEIDER	63	HBC	

[1] GOLDWASSER 70 uses $m(\Lambda) = 1115.58$ MeV.
[2] These masses have been increased 0.09 MeV because the Λ mass increased.

$\overline{\Xi}^+$ MASS

The fit uses the Ξ^-, $\overline{\Xi}^+$, and Ξ^0 mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1321.32±0.13 OUR FIT					
1321.20±0.33 OUR AVERAGE					
1321.6 ±0.8	35	VOTRUBA	72	HBC	10 GeV/c $K^+ p$
1321.2 ±0.4	34	STONE	70	HBC	
1320.69±0.93	5	CHIEN	66	HBC	6.9 GeV/c $\overline{p}p$

Ξ^- MEAN LIFE

Measurements with an error > 0.2×10^{-10} s or with systematic errors not included have been omitted.

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
1.639±0.015 OUR AVERAGE					
1.652±0.051	32k	BOURQUIN	84	SPEC	Hyperon beam
1.665±0.065	41k	BOURQUIN	79	SPEC	Hyperon beam
1.609±0.028	4286	HEMINGWAY	78	HBC	4.2 GeV/c $K^- p$
1.67 ±0.08		DIBIANCA	75	DBC	4.9 GeV/c $K^- d$
1.63 ±0.03	4303	BALTAY	74	HBC	1.75 GeV/c $K^- p$
1.73 $^{+0.08}_{-0.07}$	680	MAYEUR	72	HLBC	2.1 GeV/c K^-
1.61 ±0.04	2610	DAUBER	69	HBC	
1.80 ±0.16	299	LONDON	66	HBC	
1.70 ±0.12	246	PJERROU	65B	HBC	
1.69 ±0.07	794	HUBBARD	64	HBC	
1.86 $^{+0.15}_{-0.14}$	517	JAUNEAU	63D	FBC	

$\overline{\Xi}^+$ MEAN LIFE

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
1.6 ±0.3	34	STONE	70	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.55 $^{+0.35}_{-0.20}$	35	[3] VOTRUBA	72	HBC	10 GeV/c $K^+ p$
1.9 $^{+0.7}_{-0.5}$	12	[3] SHEN	67	HBC	
1.51±0.55	5	[3] CHIEN	66	HBC	6.9 GeV/c $\overline{p}p$

[3] The error is statistical only.

Ξ^- MAGNETIC MOMENT

See the Note on Baryon Magnetic Moments in the Λ Listings.

VALUE (μ_N)	EVTS	DOCUMENT ID		TECN	COMMENT
−0.6507±0.0025 OUR AVERAGE					
−0.6505±0.0025	4.36M	DURYEA	92	SPEC	800 GeV p Be
−0.661 ±0.036 ±0.036	44k	TROST	89	SPEC	$\Xi^- \sim$ 250 GeV
−0.69 ±0.04	218k	RAMEIKA	84	SPEC	400 GeV pBe
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.674 ±0.021 ±0.020	122k	HO	90	SPEC	See DURYEA 92
−2.1 ±0.8	2436	COOL	74	OSPK	1.8 GeV/c $K^- p$
−0.1 ±2.1	2724	BINGHAM	70B	OSPK	1.8 GeV/c $K^- p$

$\overline{\Xi}^+$ MAGNETIC MOMENT

See the Note on Baryon Magnetic Moments in the Λ Listings.

VALUE (μ_N)	EVTS	DOCUMENT ID		TECN	COMMENT
+0.657±0.028±0.020	70k	HO	90	SPEC	800 GeV pBe

Ξ^- DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Lambda\pi^-$		100 %	
Γ_2	$\Sigma^-\gamma$		(2.3±1.0) × 10^{-4}	
Γ_3	$\Lambda e^-\overline{\nu}_e$		(5.5±0.3) × 10^{-4}	
Γ_4	$\Lambda\mu^-\overline{\nu}_\mu$		(3.5±3.5) × 10^{-4}	
Γ_5	$\Sigma^0 e^-\overline{\nu}_e$		(8.7±1.7) × 10^{-5}	
Γ_6	$\Sigma^0\mu^-\overline{\nu}_\mu$		< 8 × 10^{-4}	90%
Γ_7	$\Xi^0 e^-\overline{\nu}_e$		< 2.3 × 10^{-3}	90%
	$\Delta S = 2$ (ΔS) violating modes			
Γ_8	$n\pi^-$	ΔS	< 1.9 × 10^{-5}	90%
Γ_9	$ne^-\overline{\nu}_e$	ΔS	< 3.2 × 10^{-3}	90%
Γ_{10}	$n\mu^-\overline{\nu}_\mu$	ΔS	< 1.5 %	90%
Γ_{11}	$p\pi^-\pi^-$	ΔS	< 4 × 10^{-4}	90%
Γ_{12}	$p\pi^- e^-\overline{\nu}_e$	ΔS	< 4 × 10^{-4}	90%
Γ_{13}	$p\pi^-\mu^-\overline{\nu}_\mu$	ΔS	< 4 × 10^{-4}	90%

Ξ^- BRANCHING RATIOS

A number of early results have been omitted.

$\Gamma(\Sigma^-\gamma)/\Gamma(\Lambda\pi^-)$ Γ_2/Γ_1

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.27±1.02	9	BIAGI	87B	SPEC	SPS hyperon beam

$\Gamma(\Lambda e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ Γ_3/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.564±0.031	2857	BOURQUIN	83	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.30 ±0.13	11	THOMPSON	80	ASPK	Hyperon beam

$\Gamma(\Lambda\mu^-\overline{\nu}_\mu)/\Gamma(\Lambda\pi^-)$ Γ_4/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.35±0.35		1	YEH	74	HBC	Effective denom.=2859
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 2.3	90	0	THOMPSON	80	ASPK	Effective denom.=1017
< 1.3			DAUBER	69	HBC	
<12			BERGE	66	HBC	

$\Gamma(\Sigma^0 e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ Γ_5/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.087±0.017	154	BOURQUIN	83	SPEC	SPS hyperon beam

$\Gamma(\Sigma^0\mu^-\overline{\nu}_\mu)/\Gamma(\Lambda\pi^-)$ Γ_6/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.76	90	0	YEH	74	HBC	Effective denom.=3026
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<5			BERGE	66	HBC	

$[\Gamma(\Lambda e^-\overline{\nu}_e) + \Gamma(\Sigma^0 e^-\overline{\nu}_e)]/\Gamma(\Lambda\pi^-)$ $(\Gamma_3+\Gamma_5)/\Gamma_1$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.651±0.031	3011	[4] BOURQUIN	83	SPEC	SPS hyperon beam
0.68 ±0.22	17	[5] DUCLOS	71	OSPK	

[4] See the separate BOURQUIN 83 values for $\Gamma(\Lambda e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ and $\Gamma(\Sigma^0 e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ above.
[5] DUCLOS 71 cannot distinguish Σ^0's from Λ's. The Cabibbo theory predicts the Σ^0 rate is about a factor 6 smaller than the Λ rate.

$\Gamma(\Xi^0 e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ Γ_7/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<2.3	90	0	YEH	74	HBC	Effective denom.=1000

$\Gamma(n\pi^-)/\Gamma(\Lambda\pi^-)$ Γ_8/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.019	90		BIAGI	82B	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<3.0	90	0	YEH	74	HBC	Effective denom.=760
<1.1			DAUBER	69	HBC	
<5.0			FERRO-LUZZI	63	HBC	

$\Gamma(n e^- \overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ — Γ_9/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 3.2	90	0	YEH	74	HBC	Effective denom.=715
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<10	90		BINGHAM	65	RVUE	

$\Gamma(n \mu^- \overline{\nu}_\mu)/\Gamma(\Lambda\pi^-)$ — Γ_{10}/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<15.3	90	0	YEH	74	HBC	Effective denom.=150

$\Gamma(p \pi^- \pi^-)/\Gamma(\Lambda\pi^-)$ — Γ_{11}/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<3.7	90	0	YEH	74	HBC	Effective denom.=6200

$\Gamma(p \pi^- e^- \overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ — Γ_{12}/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<3.7	90	0	YEH	74	HBC	Effective denom.=6200

$\Gamma(p \pi^- \mu^- \overline{\nu}_\mu)/\Gamma(\Lambda\pi^-)$ — Γ_{13}/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

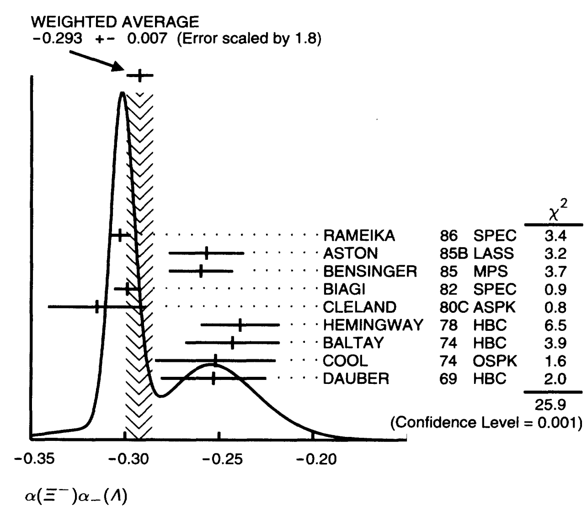
VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<3.7	90	0	YEH	74	HBC	Effective denom.=6200

Ξ^- DECAY PARAMETERS

See the Note on Baryon Decay Parameters in the neutron Listings.

$\alpha(\Xi^-)\alpha_-(\Lambda)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.293±0.007 OUR AVERAGE	Error includes scale factor of 1.8. See the ideogram below.				
−0.303±0.004±0.004	192k	RAMEIKA	86	SPEC	400 GeV pBe
−0.257±0.020	11k	ASTON	85B	LASS	11 GeV/c $K^- p$
−0.260±0.017	21k	BENSINGER	85	MPS	5 GeV/c $K^- p$
−0.299±0.007	150k	BIAGI	82	SPEC	SPS hyperon beam
−0.315±0.026	9046	CLELAND	80C	ASPK	BNL hyperon beam
−0.239±0.021	6599	HEMINGWAY	78	HBC	4.2 GeV/c $K^- p$
−0.243±0.025	4303	BALTAY	74	HBC	1.75 GeV/c $K^- p$
−0.252±0.032	2436	COOL	74	OSPK	1.8 GeV/c $K^- p$
−0.253±0.028	2781	DAUBER	69	HBC	



α FOR $\Xi^- \to \Lambda\pi^-$

The above average, $\alpha(\Xi^-)\ \alpha_-(\Lambda) = -0.293 \pm 0.007$, where the error includes a scale factor of 1.8, divided by our current average $\alpha_-(\Lambda) = 0.642 \pm 0.013$, gives the following value for $\alpha(\Xi^-)$.

VALUE	DOCUMENT ID
−0.456±0.014 OUR EVALUATION	Error includes scale factor of 1.8.

ϕ ANGLE FOR $\Xi^- \to \Lambda\pi^-$ — $(\tan\phi = \beta/\gamma)$

VALUE (°)	EVTS	DOCUMENT ID		TECN	COMMENT
4 ± 4 OUR AVERAGE					
5 ±10	11k	ASTON	85B	LASS	$K^- p$
14.7±16.0	21k	[6] BENSINGER	85	MPS	5 GeV/c $K^- p$
11 ± 9	4303	BALTAY	74	HBC	1.75 GeV/c $K^- p$
5 ±16	2436	COOL	74	OSPK	1.8 GeV/c $K^- p$
−26 ±30	2724	BINGHAM	70B	OSPK	
−14 ±11	2781	DAUBER	69	HBC	Uses $\alpha_\Lambda = 0.647 \pm 0.020$
0 ±12	1004	[7] BERGE	66	HBC	
0 ±20.4	364	[7] LONDON	66	HBC	Using $\alpha_\Lambda = 0.62$
54 ±30	356	[7] CARMONY	64B	HBC	

[6] BENSINGER 85 used $\alpha_\Lambda = 0.642 \pm 0.013$.

[7] The errors have been multiplied by 1.2 due to approximations used for the Ξ polarization; see DAUBER 69 for a discussion.

g_A / g_V FOR $\Xi^- \to \Lambda e^- \overline{\nu}_e$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.25±0.05	1992	[8] BOURQUIN	83	SPEC	SPS hyperon beam

[8] BOURQUIN 83 assumes that $g_2 = 0$. Also, the sign has been changed to agree with our conventions, given in the Note on Baryon Decay Parameters in the neutron Listings.

REFERENCES FOR Ξ^-

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1986 edition (Physics Letters **170B** (1986)) or in earlier editions.

DURYEA	92	PRL (submitted)	+Guglielmo, Heller+	(MINN, FNAL, MICH, RUTG)
HO	90	PRL 65 1713	+Longo, Nguyen, Luk+	(MICH, FNAL, MINN, RUTG)
Also	91	PR D44 1713	Ho, Longo, Nguyen, Luk+	(MICH, FNAL, MINN, RUTG)
TROST	89	PR D40 1703	+McCliment, Newsom, Hseuh, Mueller+	(FNAL-715 Collab.)
BIAGI	87B	ZPHY C35 143	+	(BRIS, CERN, GEVA, HEID, LAUS, LOQM, RAL)
PDG	86	PL 170B	Aguilar-Benitez, Porter+	(CERN, CIT+)
RAMEIKA	86	PR D33 3172	+Beretvas, Deck+	(RUTG, MICH, WISC, MINN)
ASTON	85B	PR D32 2270	+Carnegie+	(SLAC, CARL, CNRC, CINC)
BENSINGER	85	NP B252 561	+	(CHIC, ELMT, FNAL, ISU, LENI, SMAS)
BOURQUIN	84	NP B241 1	+	(BRIS, GEVA, HEID, LALO, RAL, STRB)
RAMEIKA	84	PRL 52 581	+Beretvas, Deck+	(RUTG, MICH, WISC, MINN)
BOURQUIN	83	ZPHY C21 1	+Brown+	(BRIS, GEVA, HEID, LALO, RL, STRB)
BIAGI	82	PL 112B 265	+	(BRIS, CAMB, GEVA, HEID, LAUS, LOQM, RL)
BIAGI	82B	PL 112B 277	+	(LOQM, GEVA, RL, HEID, CAMB, LAUS, BRIS)
CLELAND	80C	PR D21 12	+Cooper, Dris, Engels, Herbert+	(PITT, BNL)
THOMPSON	80	PR D21 25	+Cleland, Cooper, Dris, Engels+	(PITT, BNL)
BOURQUIN	79	PL 87B 297	+	(BRIS, GEVA, HEID, ORSA, RHEL, STRB)
HEMINGWAY	78	NP B142 205	+Armenteros+	(CERN, ZEEM, NIJM, OXF)
DIBIANCA	75	NP B98 137	+Endorf	(CMU)
BALTAY	74	PR D9 49	+Bridgewater, Cooper, Gershwin+	(COLU, BING) J
COOL	74	PR D10 792	+Giacomelli, Jenkins, Kycia, Leontic, Li+	(BNL)
Also	72	PRL 29 1630	Cool, Giacomelli, Jenkins, Kycia, Leontic+	(BNL)
YEH	74	PR D10 3545	+Gaigalas, Smith, Zendle, Baltay+	(BING, COLU)
MAYEUR	72	NP B47 333	+VanBinst, Wilquet+	(BRUX, CERN, TUFT, LOUC)
VOTRUBA	72	NP B45 77	+Safder, Ratcliffe	(BIRM, EDIN)
WILQUET	72	PL 42B 372	+Fliagine, Guy+	(BRUX, CERN, TUFT, LOUC)
DUCLOS	71	NP B32 493	+Freytag, Heintze, Heinzelmann, Jones+	(CERN)
BINGHAM	70B	PR D1 3010	+Cook, Humphrey, Sander+	(UCSD, WASH)
GOLDWASSER	70	PR D1 1960	+Schultz	(ILL)
STONE	70	PL 32B 515	+Berlinghieri, Bromberg, Cohen, Ferbel+	(ROCH)
DAUBER	69	PR 179 1262	+Berge, Hubbàrd, Merrill, Miller	(LRL) J
SHEN	67	PL 25B 443	+Firestone, Goldhaber	(UCB, LRL)
BERGE	66	PR 147 945	+Eberhard, Hubbard, Merrill+	(LRL)
CHIEN	66	PR 152 1171	+Lach, Sandweiss, Taft, Yeh, Oren+	(YALE, BNL)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA)
BINGHAM	65	PRSL 285 202		(CERN)
PJERROU	65B	PRL 14 275	+Schlein, Slater, Smith, Stork, Ticho	(UCLA)
Also	65	Thesis	Pjerrou	(UCLA)
BADIER	64	Dubna Conf. 1 593	+Demoulin, Barloutaud+	(EPOL, SACL, ZEEM)
CARMONY	64B	PRL 12 482	+Pjerrou, Schlein, Slater, Stork+	(UCLA) J
HUBBARD	64	PR 135B 183	+Berge, Kalbfleisch, Shafer+	(LRL)
FERRO-LUZZI	63	PR 130 1568	+Alston-Garnjost, Rosenfeld, Wojcicki	(LRL)
JAUNEAU	63D	Siena Conf. 4	+	(EPOL, CERN, LOUC, RHEL, BERG)
Also	63B	PL 5 261	Jauneau+	(EPOL, CERN, LOUC, RHEL, BERG)
SCHNEIDER	63	PL 4 360		(CERN)

OTHER RELATED PAPERS

PONDROM 85 PRPL 122 57 (WISC)
Review of FNAL hyperon experiments.

NOTE ON Ξ RESONANCES

The accompanying table gives our evaluation of the present status of the Ξ resonances. Not much is known about Ξ resonances. This is because (1) they can only be produced as a part of a final state, and so the analysis is more complicated than if direct formation were possible, (2) the production cross sections are small (typically a few μb), and (3) the final states are topologically complicated and difficult to study with electronic techniques. Thus early information about Ξ resonances came entirely from bubble chamber experiments, where the numbers of events are small, and only in recent years have electronic experiments made significant contributions. However, there is nothing new at all on Ξ resonances since our 1988 edition.

For a detailed earlier review, see Meadows.[1]

Reference

1. B.T. Meadows, in *Proceedings of the IVth International Conference on Baryon Resonances* (Toronto, 1980), ed. N. Isgur, p. 283.

Table 1. The status of the Ξ resonances. Only those with an overall status of *** or **** are included in the Baryon Summary Table.

Particle	$L_{2I \cdot 2J}$	Overall status	Status as seen in — $\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels
Ξ(1318)	P_{11}	****					Decays weakly
Ξ(1530)	P_{13}	****	****				
Ξ(1620)		*	*				
Ξ(1690)		***		***	**		
Ξ(1820)	D_{13}	***	**	***	**	**	
Ξ(1950)		***	**	**		*	
Ξ(2030)	1	***		**	***		
Ξ(2120)		*		*			
Ξ(2250)		**					3-body decays
Ξ(2370)	1	**					3-body decays
Ξ(2500)		*		*	*		3-body decays

**** Existence is certain, and properties are at least fairly well explored.
*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.
** Evidence of existence is only fair.
* Evidence of existence is poor.

Ξ(1530) P_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$ Status: ****

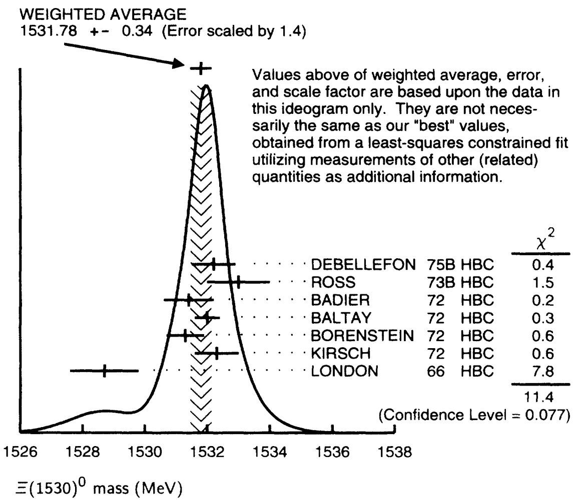
This is the only Ξ resonance whose properties are all reasonably well known. Spin-parity $3/2^+$ is favored by the data.

We use only those determinations of the mass and width that are accompanied by some discussion of systematics and resolution.

Ξ(1530) MASSES

$\Xi(1530)^0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1531.80±0.32 OUR FIT	Error includes scale factor of 1.3.				
1531.78±0.34 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.				
1532.2 ±0.7		DEBELLEFON	75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
1533 ±1		ROSS	73B	HBC	$K^- p \to \Xi \overline{K} \pi(\pi)$
1531.4 ±0.8	59	BADIER	72	HBC	$K^- p$ 3.95 GeV/c
1532.0 ±0.4	1262	BALTAY	72	HBC	$K^- p$ 1.75 GeV/c
1531.3 ±0.6	324	BORENSTEIN	72	HBC	$K^- p$ 2.2 GeV/c
1532.3 ±0.7	286	KIRSCH	72	HBC	$K^- p$ 2.87 GeV/c
1528.7 ±1.1	76	LONDON	66	HBC	$K^- p$ 2.24 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1532.1 ±0.4	1244	ASTON	85B	LASS	$K^- p$ 11 GeV/c
1532.1 ±0.6	2700	[1] BAUBILLIER	81B	HBC	$K^- p$ 8.25 GeV/c
1530 ±1	450	BIAGI	81	SPEC	SPS hyperon beam
1527 ±6	80	SIXEL	79	HBC	$K^- p$ 10 GeV/c
1535 ±4	100	SIXEL	79	HBC	$K^- p$ 16 GeV/c
1533.6 ±1.4	97	BERTHON	74	HBC	Quasi-2-body σ



$\Xi(1530)^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1535.0±0.6 OUR FIT					
1535.2±0.8 OUR AVERAGE					
1534.5±1.2		DEBELLEFON	75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
1535.3±2.0		ROSS	73B	HBC	$K^- p \to \Xi \overline{K} \pi(\pi)$
1536.2±1.6	185	KIRSCH	72	HBC	$K^- p$ 2.87 GeV/c
1535.7±3.2	38	LONDON	66	HBC	$K^- p$ 2.24 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1540 ±3	48	BERTHON	74	HBC	Quasi-2-body σ
1534.7±1.1	334	BALTAY	72	HBC	$K^- p$ 1.75 GeV/c

$\Xi(1530)^-$ – $\Xi(1530)^0$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
3.2±0.6 OUR FIT				
2.9±0.9 OUR AVERAGE				
2.7±1.0	BALTAY	72	HBC	$K^- p$ 1.75 GeV/c
2.0±3.2	MERRILL	66	HBC	$K^- p$ 1.7–2.7 GeV/c
5.7±3.0	PJERROU	65B	HBC	$K^- p$ 1.8–1.95 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.9±1.8	[2] KIRSCH	72	HBC	$K^- p$ 2.87 GeV/c
7 ±4	[2] LONDON	66	HBC	$K^- p$ 2.24 GeV/c

Ξ(1530) WIDTHS

$\Xi(1530)^0$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
9.1±0.5 OUR AVERAGE					
9.5±1.2		DEBELLEFON	75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
9.1±2.4		ROSS	73B	HBC	$K^- p \to \Xi \overline{K} \pi(\pi)$
11 ±2		BADIER	72	HBC	$K^- p$ 3.95 GeV/c
9.0±0.7		BALTAY	72	HBC	$K^- p$ 1.75 GeV/c
8.4±1.4		BORENSTEIN	72	HBC	$\Xi^- \pi^+$
11.0±1.8		KIRSCH	72	HBC	$\Xi^- \pi^+$
7 ±7		BERGE	66	HBC	$K^- p$ 1.5–1.7 GeV/c
8.5±3.5		LONDON	66	HBC	$K^- p$ 2.24 GeV/c
7 ±2		SCHLEIN	63B	HBC	$K^- p$ 1.8, 1.95 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
12.8±1.0	2700	[1] BAUBILLIER	81B	HBC	$K^- p$ 8.25 GeV/c
19 ±6	80	[3] SIXEL	79	HBC	$K^- p$ 10 GeV/c
14 ±5	100	[3] SIXEL	79	HBC	$K^- p$ 16 GeV/c

$\Xi(1530)^-$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
$9.9^{+1.7}_{-1.9}$ OUR AVERAGE			
9.6 ± 2.8	DEBELLEFON 75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
8.3 ± 3.6	ROSS 73B	HBC	$K^- p \to \Xi \overline{K} \pi(\pi)$
$7.8^{+3.5}_{-7.8}$	BALTAY 72	HBC	$K^- p$ 1.75 GeV/c
16.2 ± 4.6	KIRSCH 72	HBC	$\Xi^- \pi^0$, $\Xi^0 \pi^-$

$\Xi(1530)$ POLE POSITIONS

$\Xi(1530)^0$ REAL PART

VALUE	DOCUMENT ID	COMMENT
1531.6 ± 0.4	LICHTENBERG74	Using HABIBI 73

$\Xi(1530)^0$ IMAGINARY PART

VALUE	DOCUMENT ID	COMMENT
4.45 ± 0.35	LICHTENBERG74	Using HABIBI 73

$\Xi(1530)^-$ REAL PART

VALUE	DOCUMENT ID	COMMENT
1534.4 ± 1.1	LICHTENBERG74	Using HABIBI 73

$\Xi(1530)^-$ IMAGINARY PART

VALUE	DOCUMENT ID	COMMENT
$3.9^{+1.75}_{-3.9}$	LICHTENBERG74	Using HABIBI 73

$\Xi(1530)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Xi\pi$	100 %	
Γ_2	$\Xi\gamma$	<4 %	90%

$\Xi(1530)$ BRANCHING RATIOS

$\Gamma(\Xi\gamma)/\Gamma_{total}$ — Γ_2/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.04	90	KALBFLEISCH 75	HBC	$K^- p$ 2.18 GeV/c

$\Xi(1530)$ FOOTNOTES

[1] BAUBILLIER 81B is a fit to the inclusive spectrum. The resolution (5 MeV) is not unfolded.
[2] Redundant with data in the mass Listings.
[3] SIXEL 79 doesn't unfold the experimental resolution of 15 MeV.

$\Xi(1530)$ REFERENCES

ASTON	85B	PR D32 2270	+Carnegie+	(SLAC, CARL, CNRC, CINC)
BAUBILLIER	81B	NP B192 1	+	(BIRM, CERN, GLAS, MSU, LPNP)
BIAGI	81	ZPHY C9 305	+	(BRIS, CAMB, GEVA, HEID, LAUS, LOQM, RHEL)
SIXEL	79	NP B159 125	+Bottcher+	(AACH, BERL, CERN, LOIC, VIEN)
DEBELLEFON	75B	NC 28A 289	De Bellefon, Berthon, Billoir+	(CDEF, SACL)
KALBFLEISCH	75	PR D11 987	+Strand, Chapman	(BNL, MICH)
BERTHON	74	NC 21A 146	+Tristram+	(CDEF, RHEL, SACL, STRB)
LICHTENBERG	74	PR D10 3865		(IND)
Also	74B	Private Comm.	Lichtenberg	(IND)
HABIBI	73	Nevis 199 Thesis		(COLU)
ROSS	73B	Purdue Conf. 355	+Lloyd, Radojicic	(OXF)
BADIER	72	NP B37 429	+Barrelet, Charlton, Videau	(EPOL)
BALTAY	72	PL 42B 129	+Bridgewater, Cooper, Gershwin+	(COLU, BING)
BORENSTEIN	72	PR D5 1559	+Danburg, Kalbfleisch+	(BNL, MICH) I
KIRSCH	72	NP B40 349	+Schmidt, Chang+	(BRAN, UMD, SYRA, TUFT) I
BERGE	66	PR 147 945	+Eberhard, Hubbard, Merrill+	(LRL) I
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA) IJ
MERRILL	66	UCRL 16455 Thesis		(LRL) JP
PJERROU	65B	PRL 14 275	+Schlein, Slater, Smith, Stork, Ticho	(UCLA)
SCHLEIN	63B	PRL 11 167	+Carmony, Pjerrou, Slater, Stork, Ticho	(UCLA) IJP

OTHER RELATED PAPERS

MAZZUCATO	81	NP B178 1	+Pennino+	(AMST, CERN, NIJM, OXF)
BRIEFEL	77	PR D16 2706	+Gourevitch, Chang+	(BRAN, UMD, SYRA, TUFT)
BRIEFEL	75	PR D12 1859	+Gourevitch+	(BRAN, UMD, SYRA, TUFT)
HUNGERBU...	74	PR D10 2051	Hungerbuhler, Majka+	(YALE, FNAL, BNL, PITT)
BUTTON-...	66	PR 142 883	Button-Shafer, Lindsey, Murray, Smith	(LRL) JP

$\Xi(1620)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: $*$

J, P need confirmation.

OMITTED FROM SUMMARY TABLE

What little evidence there is consists of weak signals in the $\Xi\pi$ channel. A number of other experiments (e.g., BORENSTEIN 72 and HASSALL 81) have looked for but not seen any effect.

$\Xi(1620)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
≈ 1620 OUR ESTIMATE				
$1624\pm\ 3$	31	BRIEFEL 77	HBC	$K^- p$ 2.87 GeV/c
1633 ± 12	34	DEBELLEFON 75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
$1606\pm\ 6$	29	ROSS 72	HBC	$K^- p$ 3.1–3.7 GeV/c

$\Xi(1620)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
22.5	31	[1] BRIEFEL 77	HBC	$K^- p$ 2.87 GeV/c
$40\ \pm15$	34	DEBELLEFON 75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
$21\ \pm\ 7$	29	ROSS 72	HBC	$K^- p \to \Xi^- \pi^+ K^{*0}(892)$

$\Xi(1620)$ DECAY MODES

	Mode
Γ_1	$\Xi\pi$

$\Xi(1620)$ FOOTNOTES

[1] The fit is insensitive to values between 15 and 30 MeV.

$\Xi(1620)$ REFERENCES

HASSALL	81	NP B189 397	+Ansorge, Carter, Neale+	(CAMB, MSU)
BRIEFEL	77	PR D16 2706	+Gourevitch, Chang+	(BRAN, UMD, SYRA, TUFT)
Also	70	Duke Conf. 317	Briefel+	(BRAN, UMD, SYRA, TUFT)
Also	75	PR D12 1859	Briefel, Gourevitch+	(BRAN, UMD, SYRA, TUFT)
DEBELLEFON	75B	NC 28A 289	De Bellefon, Berthon, Billoir+	(CDEF, SACL)
BORENSTEIN	72	PR D5 1559	+Danburg, Kalbfleisch+	(BNL, MICH) I
ROSS	72	PL 38B 177	+Buran, Lloyd, Mulvey, Radojicic	(OXF) I

OTHER RELATED PAPERS

HUNGERBU...	74	PR D10 2051	Hungerbuhler, Majka+	(YALE, FNAL, BNL, PITT)
SCHMIDT	73	Purdue Conf. 363		(BRAN)
KALBFLEISCH	70	Duke Conf. 331		(BNL) I
APSELL	69	PRL 23 884	+	(BRAN, UMD, SYRA, TUFT)
BARTSCH	69	PL 28B 439	+	(AACH, BERL, CERN, LOIC, VIEN)

$\Xi(1690)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: $***$

DIONISI 78 sees a threshold enhancement in both the neutral and negatively charged $\Sigma\overline{K}$ mass spectra in $K^- p \to (\Sigma\overline{K})K\pi$ at 4.2 GeV/c. The data from the $\Sigma\overline{K}$ channels alone cannot distinguish between a resonance and a large scattering length. Weaker evidence at the same mass is seen in the corresponding $\Lambda\overline{K}$ channels, and a coupled-channel analysis yields results consistent with a new Ξ.

BIAGI 81 sees an enhancement at 1700 MeV in the diffractively produced ΛK^- system. A peak is also observed in the $\Lambda\overline{K}^0$ mass spectrum at 1660 MeV that is consistent with a 1720 MeV resonance decaying to $\Sigma^0\overline{K}^0$, with the γ from the Σ^0 decay not detected.

BIAGI 87 provides further confirmation of this state in diffractive dissociation of Ξ^- into ΛK^-. The significance claimed is 6.7 standard deviations.

$\Xi(1690)$ MASSES

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID
1690 ± 10 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

$\Xi(1690)^0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1699 ± 5	175	[1] DIONISI 78	HBC	$K^- p$ 4.2 GeV/c
1684 ± 5	183	[2] DIONISI 78	HBC	$K^- p$ 4.2 GeV/c

Ξ(1690)⁻ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1691.1 ± 1.9 ± 2.0	104	BIAGI	87	SPEC	Ξ^- Be 116 GeV
1700 ± 10	150	[3] BIAGI	81	SPEC	Ξ^- H 100, 135 GeV
1694 ± 6	45	[4] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c

Ξ(1690) WIDTHS

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID
<50 OUR ESTIMATE	

Ξ(1690)⁰ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
44 ± 23	175	[1] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c
20 ± 4	183	[2] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c

Ξ(1690)⁻ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 8	90	104	BIAGI	87	SPEC	Ξ^- Be 116 GeV
47 ± 14		150	[3] BIAGI	81	SPEC	Ξ^- H 100, 135 GeV
26 ± 6		45	[4] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c

Ξ(1690) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda \overline{K}$	seen
Γ_2	$\Sigma \overline{K}$	seen
Γ_3	$\Xi \pi$	
Γ_4	$\Xi^- \pi^+ \pi^0$	
Γ_5	$\Xi^- \pi^+ \pi^-$	possibly seen
Γ_6	$\Xi(1530) \pi$	

Ξ(1690) BRANCHING RATIOS

$\Gamma(\Lambda \overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
seen	104	BIAGI	87	SPEC	−	Ξ^- Be 116 GeV

$\Gamma(\Sigma \overline{K})/\Gamma(\Lambda \overline{K})$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
2.7 ± 0.9	DIONISI	78	HBC	0	$K^- p$ 4.2 GeV/c
3.1 ± 1.4	DIONISI	78	HBC	−	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi \pi)/\Gamma(\Sigma \overline{K})$ — Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.09	DIONISI	78	HBC	0	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi^- \pi^+ \pi^0)/\Gamma(\Sigma \overline{K})$ — Γ_4/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.04	DIONISI	78	HBC	0	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi^- \pi^+ \pi^-)/\Gamma_{total}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
possibly seen	4	BIAGI	87	SPEC	−	Ξ^- Be 116 GeV

$\Gamma(\Xi^- \pi^+ \pi^-)/\Gamma(\Sigma \overline{K})$ — Γ_5/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.03	DIONISI	78	HBC	−	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi(1530) \pi)/\Gamma(\Sigma \overline{K})$ — Γ_6/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.06	DIONISI	78	HBC	−	$K^- p$ 4.2 GeV/c

Ξ(1690) FOOTNOTES

[1] From a fit to the $\Sigma^+ K^-$ spectrum.
[2] From a coupled-channel analysis of the $\Sigma^+ K^-$ and $\Lambda \overline{K}^0$ spectra.
[3] A fit to the inclusive spectrum from $\Xi^- N \rightarrow \Lambda K^-$ X.
[4] From a coupled-channel analysis of the $\Sigma^0 K^-$ and ΛK^- spectra.

Ξ(1690) REFERENCES

BIAGI 87 ZPHY C34 15 + (BRIS, CERN, GEVA, HEID, LAUS, LOQM, RAL) I
BIAGI 81 ZPHY C9 305 + (BRIS, CAMB, GEVA, HEID, LAUS, LOQM, RHEL)
DIONISI 78 PL 80B 145 +Diaz, Armenteros+ (CERN, AMST, NIJM, OXF) I

Ξ(1820) D_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗∗

The clearest evidence is an 8-standard-deviation peak in ΛK^- seen by GAY 76. TEODORO 78 favors J=3/2, but cannot make a parity discrimination. BIAGI 87C is consistent with J=3/2 and favors negative parity for this J value.

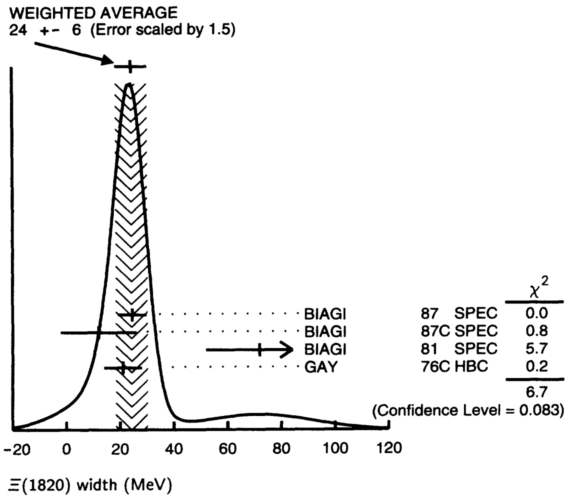
Ξ(1820) MASS

We only average the measurements that appear to us to be most significant and best determined.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1823 ± 5 OUR ESTIMATE						
1823.4 ± 1.4 OUR AVERAGE						
1819.4 ± 3.1 ± 2.0	280	[1] BIAGI	87	SPEC	0	Ξ^- Be → (ΛK^-) X
1826 ± 3 ± 1	54	BIAGI	87C	SPEC	0	Ξ^- Be → $(\Lambda \overline{K}^0)$ X
1822 ± 6		JENKINS	83	MPS	−	$K^- p \rightarrow K^+$ (MM)
1830 ± 6	300	BIAGI	81	SPEC	−	SPS hyperon beam
1823 ± 2	130	GAY	76C	HBC	−	$K^- p$ 4.2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1797 ± 19	74	BRIEFEL	77	HBC	0	$K^- p$ 2.87 GeV/c
1829 ± 9	68	BRIEFEL	77	HBC	−0	$\Xi(1530)\pi$
1860 ± 14	39	BRIEFEL	77	HBC	−	$\Sigma^- \overline{K}^0$
1870 ± 9	44	BRIEFEL	77	HBC	0	$\Lambda \overline{K}^0$
1813 ± 4	57	BRIEFEL	77	HBC	−	ΛK^-
1807 ± 27		DIBIANCA	75	DBC	−0	$\Xi \pi \pi$, $\Xi^* \pi$
1762 ± 8	28	[2] BADIER	72	HBC	−0	$\Xi \pi$, $\Xi \pi \pi$, $Y K$
1838 ± 5	38	[2] BADIER	72	HBC	−0	$\Xi \pi$, $\Xi \pi \pi$, $Y K$
1830 ± 10	25	[3] CRENNELL	70B	DBC	−0	3.6, 3.9 GeV/c
1826 ± 12		[4] CRENNELL	70B	DBC	−0	3.6, 3.9 GeV/c
1830 ± 10	40	ALITTI	69	HBC	−	Λ, $\Sigma \overline{K}$
1814 ± 4	30	BADIER	65	HBC	0	$\Lambda \overline{K}^0$
1817 ± 7	29	SMITH	65C	HBC	−0	$\Lambda \overline{K}^0$, ΛK^-
1770		HALSTEINSLID	63	FBC	−0	K^- freon 3.5 GeV/c

Ξ(1820) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
24^{+15}_{-10} OUR ESTIMATE						
24 ± 6 OUR AVERAGE Error includes scale factor of 1.5. See the ideogram below.						
24.6 ± 5.3	280	[1] BIAGI	87	SPEC	0	Ξ^- Be → (ΛK^-) X
12 ± 14 ± 1.7	54	BIAGI	87C	SPEC	0	Ξ^- Be → $(\Lambda \overline{K}^0)$ X
72 ± 20	300	BIAGI	81	SPEC	−	SPS hyperon beam
21 ± 7	130	GAY	76C	HBC	−	$K^- p$ 4.2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •						
99 ± 57	74	BRIEFEL	77	HBC	0	$K^- p$ 2.87 GeV/c
52 ± 34	68	BRIEFEL	77	HBC	−0	$\Xi(1530)\pi$
72 ± 17	39	BRIEFEL	77	HBC	−	$\Sigma^- \overline{K}^0$
44 ± 11	44	BRIEFEL	77	HBC	0	$\Lambda \overline{K}^0$
26 ± 11	57	BRIEFEL	77	HBC	−	ΛK^-
85 ± 58		DIBIANCA	75	DBC	−0	$\Xi \pi \pi$, $\Xi^* \pi$
51 ± 13		[2] BADIER	72	HBC	−0	Lower mass
58 ± 13		[2] BADIER	72	HBC	−0	Higher mass
103^{+38}_{-24}		[3] CRENNELL	70B	DBC	−0	3.6, 3.9 GeV/c
48^{+36}_{-19}		[4] CRENNELL	70B	DBC	−0	3.6, 3.9 GeV/c
55^{+40}_{-20}		ALITTI	69	HBC	−	Λ, $\Sigma \overline{K}$
12 ± 4		BADIER	65	HBC	0	$\Lambda \overline{K}^0$
30 ± 7		SMITH	65B	HBC	−0	$\Lambda \overline{K}$
< 80		HALSTEINSLID	63	FBC	−0	K^- freon 3.5 GeV/c



$\Xi(1820)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda \overline{K}$	large
Γ_2	$\Sigma \overline{K}$	small
Γ_3	$\Xi \pi$	small
Γ_4	$\Xi(1530)\pi$	small
Γ_5	$\Xi \pi \pi$ (not $\Xi(1530)\pi$)	

$\Xi(1820)$ BRANCHING RATIOS

The dominant modes seem to be $\Lambda \overline{K}$ and (perhaps) $\Xi(1530)\pi$, but the branching fractions are very poorly determined.

$\Gamma(\Lambda \overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.30±0.15	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c

$\Gamma(\Xi\pi)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.10±0.10	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c

$\Gamma(\Xi\pi)/\Gamma(\Lambda \overline{K})$ — Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.36	95	GAY	76C	HBC	−	$K^- p$ 4.2 GeV/c
0.20±0.20		BADIER	65	HBC	0	$K^- p$ 3 GeV/c

$\Gamma(\Xi\pi)/\Gamma(\Xi(1530)\pi)$ — Γ_3/Γ_4

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
$\mathbf{1.5^{+0.6}_{-0.4}}$	APSELL	70	HBC	0	$K^- p$ 2.87 GeV/c

$\Gamma(\Sigma \overline{K})/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.30±0.15	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.02	TRIPP	67	RVUE		Use SMITH 65C

$\Gamma(\Sigma \overline{K})/\Gamma(\Lambda \overline{K})$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.24±0.10	GAY	76C	HBC	−	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi(1530)\pi)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.30±0.15	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	ASTON	85B	LASS		$K^- p$ 11 GeV/c
not seen	[5] HASSALL	81	HBC		$K^- p$ 6.5 GeV/c
<0.25	[6] DAUBER	69	HBC		$K^- p$ 2.7 GeV/c

$\Gamma(\Xi(1530)\pi)/\Gamma(\Lambda \overline{K})$ — Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.38±0.27 OUR AVERAGE	Error includes scale factor of 2.3.				
1.0 ±0.3	GAY	76C	HBC	−	$K^- p$ 4.2 GeV/c
0.26±0.13	SMITH	65C	HBC	−0	$K^- p$ 2.45–2.7 GeV/c

$\Gamma(\Xi\pi\pi$ (not $\Xi(1530)\pi))/\Gamma(\Lambda \overline{K})$ — Γ_5/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.30±0.20	BIAGI	87	SPEC	−	Ξ^- Be 116 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.14	[7] BADIER	65	HBC	0	1 st. dev. limit
>0.1	SMITH	65C	HBC	−0	$K^- p$ 2.45–2.7 GeV/c

$\Gamma(\Xi\pi\pi$ (not $\Xi(1530)\pi))/\Gamma(\Xi(1530)\pi)$ — Γ_5/Γ_4

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
consistent with zero	GAY	76C	HBC	−	$K^- p$ 4.2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.3±0.5	[8] APSELL	70	HBC	0	$K^- p$ 2.87 GeV/c

$\Xi(1820)$ FOOTNOTES

[1] BIAGI 87 also sees weak signals in the in the $\Xi^- \pi^+ \pi^-$ channel at 1782.6 ± 1.4 MeV (Γ = 6.0 ± 1.5 MeV) and 1831.9 ± 2.8 MeV (Γ = 9.6 ± 9.9 MeV).
[2] BADIER 72 adds all channels and divides the peak into lower and higher mass regions. The data can also be fitted with a single Breit-Wigner of mass 1800 MeV and width 150 MeV.
[3] From a fit to inclusive $\Xi\pi$, $\Xi\pi\pi$, and ΛK^- spectra.
[4] From a fit to inclusive $\Xi\pi$ and $\Xi\pi\pi$ spectra only.
[5] Including $\Xi\pi\pi$.
[6] DAUBER 69 uses in part the same data as SMITH 65C.
[7] For the decay mode $\Xi^- \pi^+ \pi^0$ only. This limit includes $\Xi(1530)\pi$.
[8] Or less. Upper limit for the 3-body decay.

$\Xi(1820)$ REFERENCES

BIAGI	87	ZPHY C34 15	+	(BRIS, CERN, GEVA, HEID, LAUS, LOQM, RAL)	
BIAGI	87C	ZPHY C34 175	+	(BRIS, CERN, GEVA, HEID, LAUS, LOQM, RAL)	JP
ASTON	85B	PR D32 2270	+Carnegie+	(SLAC, CARL, CNRC, CINC)	
JENKINS	83	PRL 51 951	+Albright, Diamond+	(FSU, BRAN, LBL, CINC, SMAS)	
BIAGI	81	ZPHY C9 305	+	(BRIS, CAMB, GEVA, HEID, LAUS, LOQM, RHEL)	
HASSALL	81	NP B189 397	+Ansorge, Carter, Neale+	(CAMB, MSU)	
TEODORO	78	PL 77B 451	+Diaz, Dionisi, Blokzijl+	(AMST, CERN, NIJM, OXF)	JP
BRIEFEL	77	PR D16 2706	+Gourevitch, Chang+	(BRAN, UMD, SYRA, TUFT)	
Also	69	PRL 23 884	Apsell+	(BRAN, UMD, SYRA, TUFT)	
GAY	76	NC 31A 593	+Jeanneret, Bogdanski+	(NEUC, LAUS, LIVP, LPNP)	
GAY	76C	PL 62B 477	+Armenteros, Berge+	(AMST, CERN, NIJM)	IJ
DIBIANCA	75	NP B98 137	+Endorf	(CMU)	
BADIER	72	NP B37 429	+Barrelet, Charlton, Videau	(EPOL)	
APSELL	70	PRL 24 777	+	(BRAN, UMD, SYRA, TUFT)	I
CRENNELL	70B	PR D1 847	+Karshon, Lai, O'Neall, Scarr, Schumann	(BNL)	
ALITTI	69	PRL 22 79	+Barnes, Flaminio, Metzger+	(BNL, SYRA)	I
DAUBER	69	PR 179 1262	+Berge, Hubbard, Merrill, Miller	(LRL)	
TRIPP	67	NP B3 10	+Leith+	(LRL, SLAC, CERN, HEID, SACL)	
BADIER	65	PL 16 171	+Demoulin, Goldberg+	(EPOL, SACL, AMST)	I
SMITH	65B	Athens Conf. 251	+Lindsey	(LRL)	
SMITH	65C	PRL 14 25	+Lindsey, Button-Shafer, Murray	(LRL)	IJP
HALSTEINSLID	63	Siena Conf. 1 73	+	(BERG, CERN, EPOL, RHEL, LOUC)	I

OTHER RELATED PAPERS

TEODORO	78	PL 77B 451	+Diaz, Dionisi, Blokzijl+	(AMST, CERN, NIJM, OXF)	JP
BRIEFEL	75	PR D12 1859	+Gourevitch+	(BRAN, UMD, SYRA, TUFT)	
SCHMIDT	73	Purdue Conf. 363		(BRAN)	
MERRILL	68	PR 167 1202	+Shafer	(LRL)	
SMITH	64	PRL 13 61	+Lindsey, Murray, Button-Shafer+	(LRL)	IJP

$\Xi(1950)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗∗∗

We list here everything reported between 1875 and 2000 MeV. The accumulated evidence for a Ξ near 1950 MeV seems strong enough to include a $\Xi(1950)$ in the main Baryon Table, but not much can be said about its properties. In fact, there may be more than one Ξ near this mass.

$\Xi(1950)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1950±15 OUR ESTIMATE					
1944± 9	129	BIAGI	87	SPEC	Ξ^- Be → $(\Xi^- \pi^+)\pi^-$ X
1963± 5±2	63	BIAGI	87C	SPEC	Ξ^- Be → $(\Lambda \overline{K}^0)$ X
1937± 7	150	BIAGI	81	SPEC	SPS hyperon beam
1961±18	139	BRIEFEL	77	HBC	2.87 $K^- p \to \Xi^- \pi^+$ X
1936±22	44	BRIEFEL	77	HBC	2.87 $K^- p \to \Xi^0 \pi^-$ X
1964±10	56	BRIEFEL	77	HBC	$\Xi(1530)\pi$
1900±12		DIBIANCA	75	DBC	$\Xi\pi$
1952±11	25	ROSS	73C		$(\Xi\pi)^-$
1956± 6	29	BADIER	72	HBC	$\Xi\pi$, $\Xi\pi\pi$, YK
1955±14	21	GOLDWASSER	70	HBC	$\Xi\pi$
1894±18	66	DAUBER	69	HBC	$\Xi\pi$
1930±20	27	ALITTI	68	HBC	$\Xi^- \pi^+$
1933±16	35	BADIER	65	HBC	$\Xi^- \pi^+$

$\Xi(1950)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
60±20 OUR ESTIMATE				
100±31	129	BIAGI 87	SPEC	$\Xi^- \text{Be} \to (\Xi^- \pi^+)\pi^- X$
25±15±1.2	63	BIAGI 87C	SPEC	$\Xi^- \text{Be} \to (\Lambda \overline{K}^0)$ X
60± 8	150	BIAGI 81	SPEC	SPS hyperon beam
159±57	139	BRIEFEL 77	HBC	2.87 $K^- p \to \Xi^- \pi^+ X$
87±26	44	BRIEFEL 77	HBC	2.87 $K^- p \to \Xi^0 \pi^- X$
60±39	56	BRIEFEL 77	HBC	$\Xi(1530)\pi$
63±78		DIBIANCA 75	DBC	$\Xi\pi$
38±10		ROSS 73C		$(\Xi\pi)^-$
35±11	29	BADIER 72	HBC	$\Xi\pi$, $\Xi\pi\pi$, YK
56±26	21	GOLDWASSER 70	HBC	$\Xi\pi$
98±23	66	DAUBER 69	HBC	$\Xi\pi$
80±40	27	ALITTI 68	HBC	$\Xi^- \pi^+$
140±35	35	BADIER 65	HBC	$\Xi^- \pi^+$

$\Xi(1950)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda \overline{K}$	seen
Γ_2	$\Sigma \overline{K}$	possibly seen
Γ_3	$\Xi\pi$	seen
Γ_4	$\Xi(1530)\pi$	
Γ_5	$\Xi\pi\pi$ (not $\Xi(1530)\pi$)	

$\Xi(1950)$ BRANCHING RATIOS

$\Gamma(\Sigma\overline{K})/\Gamma(\Lambda\overline{K})$ Γ_2/Γ_1

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<2.3	90	0	BIAGI 87C	SPEC	Ξ^- Be 116 GeV

$\Gamma(\Sigma\overline{K})/\Gamma_{total}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
possibly seen	17	HASSALL 81	HBC	$K^- p$ 6.5 GeV/c

$\Gamma(\Xi\pi)/\Gamma(\Xi(1530)\pi)$ Γ_3/Γ_4

VALUE	DOCUMENT ID	TECN
$2.8^{+0.7}_{-0.6}$	APSELL 70	HBC

$\Gamma(\Xi\pi\pi$ (not $\Xi(1530)\pi))/\Gamma(\Xi(1530)\pi)$ Γ_5/Γ_4

VALUE	DOCUMENT ID	TECN
0.0±0.3	APSELL 70	HBC

$\Xi(1950)$ REFERENCES

BIAGI 87 ZPHY C34 15 + (BRIS, CERN, GEVA, HEID, LAUS, LOQM, RAL)
BIAGI 87C ZPHY C34 175 + (BRIS, CERN, GEVA, HEID, LAUS, LOQM, RAL)
BIAGI 81 ZPHY C9 305 + (BRIS, CAMB, GEVA, HEID, LAUS, LOQM, RHEL)
HASSALL 81 NP B189 397 +Ansorge, Carter, Neale+ (CAMB, MSU)
BRIEFEL 77 PR D16 2706 +Gourevitch, Chang+ (BRAN, UMD, SYRA, TUFT)
Also 70 Duke Conf. 317 Briefel+ (BRAN, UMD, SYRA, TUFT)
DIBIANCA 75 NP B98 137 +Endorf (CMU)
ROSS 73C Purdue Conf. 345 +Lloyd, Radojicic (OXF)
BADIER 72 NP B37 429 +Barrelet, Charlton, Videau (EPOL)
APSELL 70 PRL 24 777 + (BRAN, UMD, SYRA, TUFT) I
GOLDWASSER 70 PR D1 1960 +Schultz (ILL)
DAUBER 69 PR 179 1262 +Berge, Hubbard, Merrill, Miller (LRL) I
ALITTI 68 PRL 21 1119 +Flaminio, Metzger, Radojicic+ (BNL, SYRA) I
BADIER 65 PL 16 171 +Demoulin, Goldberg+ (EPOL, SACL, AMST) I

$\Xi(2030)$

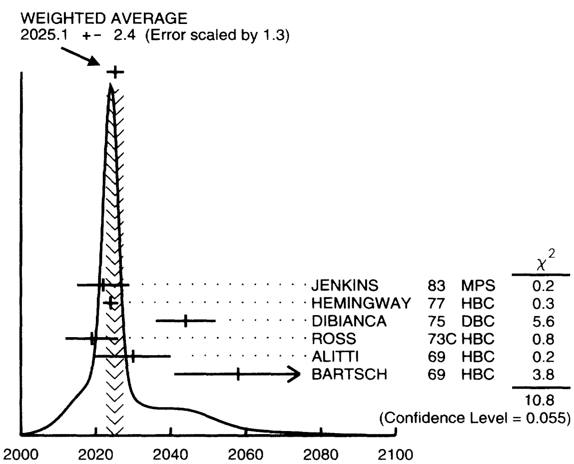
$I(J^P) = \frac{1}{2}(\geq \frac{5}{2}^?)$ Status: ∗∗∗

The evidence for this state has been much improved by HEMINGWAY 77, who see an eight standard deviation enhancement in $\Sigma\overline{K}$ and a weaker coupling to $\Lambda\overline{K}$. ALITTI 68 and HEMINGWAY 77 observe no signals in the $\Xi\pi\pi$ (or $\Xi(1530)\pi$) channel, in contrast to DIBIANCA 75. The decay $(\Lambda/\Sigma)\overline{K}\pi$ reported by BARTSCH 69 is also not confirmed by HEMINGWAY 77.

A moments analysis of the HEMINGWAY 77 data indicates at a level of three standard deviations that $J \geq 5/2$.

$\Xi(2030)$ MASS

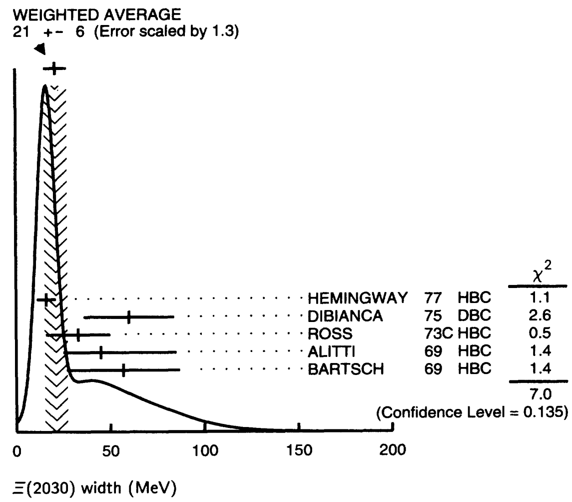
VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
2025 ± 5 OUR ESTIMATE					
2025.1± 2.4 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.				
2022 ± 7		JENKINS 83	MPS	−	$K^- p \to K^+$ MM
2024 ± 2	200	HEMINGWAY 77	HBC	−	$K^- p$ 4.2 GeV/c
2044 ± 8		DIBIANCA 75	DBC	−0	$\Xi\pi\pi$, $\Xi^*\pi$
2019 ± 7	15	ROSS 73C	HBC	−0	$\Sigma\overline{K}$
2030 ±10	42	ALITTI 69	HBC	−	$K^- p$ 3.9–5 GeV/c
2058 ±17	40	BARTSCH 69	HBC	−0	$K^- p$ 10 GeV/c



$\Xi(2030)$ mass (MeV)

$\Xi(2030)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
20^{+15}_{-5} OUR ESTIMATE					
21± 6 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.				
16± 5	200	HEMINGWAY 77	HBC	−	$K^- p$ 4.2 GeV/c
60±24		DIBIANCA 75	DBC	−0	$\Xi\pi\pi$, $\Xi^*\pi$
33±17	15	ROSS 73C	HBC	−0	$\Sigma\overline{K}$
45^{+40}_{-20}		ALITTI 69	HBC	−	$K^- p$ 3.9–5 GeV/c
57±30		BARTSCH 69	HBC	−0	$K^- p$ 10 GeV/c



$\Xi(2030)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda \overline{K}$	~ 20 %
Γ_2	$\Sigma \overline{K}$	~ 80 %
Γ_3	$\Xi \pi$	small
Γ_4	$\Xi(1530)\pi$	small
Γ_5	$\Xi \pi \pi$ (not $\Xi(1530)\pi$)	small
Γ_6	$\Lambda \overline{K} \pi$	small
Γ_7	$\Sigma \overline{K} \pi$	small

$\Xi(2030)$ BRANCHING RATIOS

$\Gamma(\Xi\pi)/[\Gamma(\Lambda\overline{K}) + \Gamma(\Sigma\overline{K}) + \Gamma(\Xi\pi) + \Gamma(\Xi(1530)\pi)]$ — **$\Gamma_3/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4)$**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.30	ALITTI	69	HBC	–	1 standard dev. limit

$\Gamma(\Xi\pi)/\Gamma(\Sigma\overline{K})$ — **Γ_3/Γ_2**

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.19	95	HEMINGWAY	77	HBC	–	$K^- p$ 4.2 GeV/c

$\Gamma(\Lambda\overline{K})/[\Gamma(\Lambda\overline{K}) + \Gamma(\Sigma\overline{K}) + \Gamma(\Xi\pi) + \Gamma(\Xi(1530)\pi)]$ — **$\Gamma_1/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4)$**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.25±0.15	ALITTI	69	HBC	–	$K^- p$ 3.9–5 GeV/c

$\Gamma(\Lambda\overline{K})/\Gamma(\Sigma\overline{K})$ — **Γ_1/Γ_2**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.22±0.09	HEMINGWAY	77	HBC	–	$K^- p$ 4.2 GeV/c

$\Gamma(\Sigma\overline{K})/[\Gamma(\Lambda\overline{K}) + \Gamma(\Sigma\overline{K}) + \Gamma(\Xi\pi) + \Gamma(\Xi(1530)\pi)]$ — **$\Gamma_2/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4)$**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.75±0.20	ALITTI	69	HBC	–	$K^- p$ 3.9–5 GeV/c

$\Gamma(\Xi(1530)\pi)/[\Gamma(\Lambda\overline{K}) + \Gamma(\Sigma\overline{K}) + \Gamma(\Xi\pi) + \Gamma(\Xi(1530)\pi)]$ — **$\Gamma_4/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4)$**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.15	ALITTI	69	HBC	–	1 standard dev. limit

$[\Gamma(\Xi(1530)\pi) + \Gamma(\Xi\pi\pi\ (\text{not}\ \Xi(1530)\pi))]/\Gamma(\Sigma\overline{K})$ — **$(\Gamma_4+\Gamma_5)/\Gamma_2$**

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.11	95	[1] HEMINGWAY	77	HBC	–	$K^- p$ 4.2 GeV/c

$\Gamma(\Lambda\overline{K}\pi)/\Gamma_{total}$ — **Γ_6/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	BARTSCH	69	HBC	$K^- p$ 10 GeV

$\Gamma(\Lambda\overline{K}\pi)/\Gamma(\Sigma\overline{K})$ — **Γ_6/Γ_2**

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.32	95	HEMINGWAY	77	HBC	–	$K^- p$ 4.2 GeV/c

$\Gamma(\Sigma\overline{K}\pi)/\Gamma_{total}$ — **Γ_7/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	BARTSCH	69	HBC	$K^- p$ 10 GeV

$\Gamma(\Sigma\overline{K}\pi)/\Gamma(\Sigma\overline{K})$ — **Γ_7/Γ_2**

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.04	95	[2] HEMINGWAY	77	HBC	–	$K^- p$ 4.2 GeV/c

$\Xi(2030)$ FOOTNOTES

[1] For the decay mode $\Xi^- \pi^+ \pi^-$ only.
[2] For the decay mode $\Sigma^\pm K^- \pi^\mp$ only.

$\Xi(2030)$ REFERENCES

JENKINS	83	PRL 51 951	+Albright, Diamond+	(FSU, BRAN, LBL, CINC, SMAS)
HEMINGWAY	77	PL 68B 197	+Armenteros+	(AMST, CERN, NIJM, OXF) IJ
Also	76C	PL 62B 477	Gay, Armenteros, Berge+	(AMST, CERN, NIJM)
DIBIANCA	75	NP B98 137	+Endorf	(CMU)
ROSS	73C	Purdue Conf. 345	+Lloyd, Radojicic	(OXF)
ALITTI	69	PRL 22 79	+Barnes, Flaminio, Metzger+	(BNL, SYRA) I
BARTSCH	69	PL 28B 439	+	(AACH, BERL, CERN, LOIC, VIEN)
ALITTI	68	PRL 21 1119	+Flaminio, Metzger, Radojicic+	(BNL, SYRA)

$\Xi(2120)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: *
J, P need confirmation.

OMITTED FROM SUMMARY TABLE

$\Xi(2120)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
≈ 2120 OUR ESTIMATE					
2137±4	18	[1] CHLIAPNIK...	79	HBC	$K^+ p$ 32 GeV/c
2123±7		[2] GAY	76C	HBC	$K^- p$ 4.2 GeV/c

$\Xi(2120)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
<20	18	[1] CHLIAPNIK...	79	HBC	$K^+ p$ 32 GeV/c
25±12		[2] GAY	76C	HBC	$K^- p$ 4.2 GeV/c

$\Xi(2120)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda \overline{K}$	seen

$\Xi(2120)$ BRANCHING RATIOS

$\Gamma(\Lambda\overline{K})/\Gamma_{total}$ — **Γ_1/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
seen	[1] CHLIAPNIK...	79	HBC	$K^+ p \rightarrow (\overline{\Lambda} K^+) X$
seen	[2] GAY	76C	HBC	$K^- p$ 4.2 GeV/c

$\Xi(2120)$ FOOTNOTES

[1] CHLIAPNIKOV 79 does not uniquely identify the K^+ in the $(\overline{\Lambda} K^+)$ X final state. It also reports bumps with fewer events at 2240, 2540, and 2830 MeV.
[2] GAY 76C sees a 4-standard deviation signal. However, HEMINGWAY 77, with more events from the same experiment points out that the signal is greatly reduced if a cut is made on the 4-momentum u. This suggests an anomalous production mechanism if the $\Xi(2120)$ is real.

$\Xi(2120)$ REFERENCES

CHLIAPNIK...	79	NP B158 253	Chliapnikov, Gerdyukov+	(CERN, BELG, MONS)
HEMINGWAY	77	PL 68B 197	+Armenteros+	(AMST, CERN, NIJM, OXF)
GAY	76C	PL 62B 477	+Armenteros, Berge+	(AMST, CERN, NIJM)

Ξ(2250)

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗∗
J, P need confirmation.

OMITTED FROM SUMMARY TABLE

The evidence for this state is mixed. BARTSCH 69 sees a bump of not much statistical significance in $\Lambda\overline{K}\pi$, $\Sigma\overline{K}\pi$, and $\Xi\pi\pi$ mass spectra. GOLDWASSER 70 sees a narrower bump in $\Xi\pi\pi$ at a higher mass. Not seen by HASSALL 81 with 45 events/μb at 6.5 GeV/c. Seen by JENKINS 83. Perhaps seen by BIAGI 87.

Ξ(2250) MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 2250 OUR ESTIMATE						
2189± 7	66	BIAGI	87	SPEC	−	Ξ^- Be → $(\Xi^-\pi^+\pi^-)$ X
2214± 5		JENKINS	83	MPS	−	$K^-p \to K^+$ MM
2295±15	18	GOLDWASSER	70	HBC	−	K^-p 5.5 GeV/c
2244±52	35	BARTSCH	69	HBC		K^-p 10 GeV/c

Ξ(2250) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
46±27	66	BIAGI	87	SPEC	−	Ξ^- Be → $(\Xi^-\pi^+\pi^-)$ X
< 30		GOLDWASSER	70	HBC	−	K^-p 5.5 GeV/c
130±80		BARTSCH	69	HBC		

Ξ(2250) DECAY MODES

	Mode
Γ_1	$\Xi\pi\pi$
Γ_2	$\Lambda\overline{K}\pi$
Γ_3	$\Sigma\overline{K}\pi$

Ξ(2250) REFERENCES

BIAGI 87 ZPHY C34 15 + (BRIS, CERN, GEVA, HEID, LAUS, LOQM, RAL)
JENKINS 83 PRL 51 951 +Albright, Diamond+ (FSU, BRAN, LBL, CINC, SMAS)
HASSALL 81 NP B189 397 +Ansorge, Carter, Neale+ (CAMB, MSU)
GOLDWASSER 70 PR D1 1960 +Schultz (ILL)
BARTSCH 69 PL 28B 439 + (AACH, BERL, CERN, LOIC, VIEN)

Ξ(2370)

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗∗
J, P need confirmation.

OMITTED FROM SUMMARY TABLE

Ξ(2370) MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 2370 OUR ESTIMATE						
2356±10		JENKINS	83	MPS	−	$K^-p \to K^+$ MM
2370	50	HASSALL	81	HBC	−0	K^-p 6.5 GeV/c
2373± 8	94	AMIRZADEH	80	HBC	−0	K^-p 8.25 GeV/c
2392±27		DIBIANCA	75	DBC		$\Xi 2\pi$

Ξ(2370) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
80	50	HASSALL	81	HBC	−0	K^-p 6.5 GeV/c
80±25	94	AMIRZADEH	80	HBC	−0	K^-p 8.25 GeV/c
75±69		DIBIANCA	75	DBC		$\Xi 2\pi$

Ξ(2370) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\overline{K}\pi$ Includes $\Gamma_4 + \Gamma_6$.	seen
Γ_2	$\Sigma\overline{K}\pi$ Includes $\Gamma_5 + \Gamma_6$.	seen
Γ_3	$\Omega^- K$	
Γ_4	$\Lambda\overline{K}^*(892)$	
Γ_5	$\Sigma\overline{K}^*(892)$	
Γ_6	$\Sigma(1385)\overline{K}$	

Ξ(2370) BRANCHING RATIOS

$\Gamma(\Lambda\overline{K}\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	AMIRZADEH	80	HBC	−0	K^-p 8.25 GeV/c

$\Gamma(\Sigma\overline{K}\pi)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	AMIRZADEH	80	HBC	−0	K^-p 8.25 GeV/c

$[\Gamma(\Lambda\overline{K}\pi) + \Gamma(\Sigma\overline{K}\pi)]/\Gamma_{total}$ $(\Gamma_1+\Gamma_2)/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
seen	50	HASSALL	81	HBC	−0	K^-p 6.5 GeV/c

$\Gamma(\Omega^- K)/\Gamma_{total}$ Γ_3/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.09±0.04	[1] KINSON	80	HBC	−	K^-p 8.25 GeV/c

$[\Gamma(\Lambda\overline{K}^*(892)) + \Gamma(\Sigma\overline{K}^*(892))]/\Gamma_{total}$ $(\Gamma_4+\Gamma_5)/\Gamma$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.22±0.13	[1] KINSON	80	HBC	−	K^-p 8.25 GeV/c

$\Gamma(\Sigma(1385)\overline{K})/\Gamma_{total}$ Γ_6/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.12±0.08	[1] KINSON	80	HBC	−	K^-p 8.25 GeV/c

Ξ(2370) FOOTNOTES

[1] KINSON 80 is a reanalysis of AMIRZADEH 80 with 50% more events.

Ξ(2370) REFERENCES

JENKINS 83 PRL 51 951 +Albright, Diamond+ (FSU, BRAN, LBL, CINC, SMAS)
HASSALL 81 NP B189 397 +Ansorge, Carter, Neale+ (CAMB, MSU)
AMIRZADEH 80 PL 90B 324 + (BIRM, CERN, GLAS, MSU, LPNP) I
KINSON 80 Toronto Conf. 263 + (BIRM, CERN, GLAS, MSU, LPNP) I
DIBIANCA 75 NP B98 137 +Endorf (CMU)

Ξ(2500)

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗
J, P need confirmation.

OMITTED FROM SUMMARY TABLE

The ALITTI 69 peak might be instead the Ξ(2370) or might be neither the Ξ(2370) nor the Ξ(2500).

Ξ(2500) MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 2500 OUR ESTIMATE						
2505±10		JENKINS	83	MPS	−	$K^-p \to K^+$ MM
2430±20	30	ALITTI	69	HBC	−	K^-p 4.6–5 GeV/c
2500±10	45	BARTSCH	69	HBC	−0	K^-p 10 GeV/c

Ξ(2500) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG
150^{+60}_{-40}	ALITTI	69	HBC	−
59±27	BARTSCH	69	HBC	−0

Ξ(2500) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Xi\pi$	
Γ_2	$\Lambda\overline{K}$	
Γ_3	$\Sigma\overline{K}$	
Γ_4	$\Xi\pi\pi$	seen
Γ_5	$\Xi(1530)\pi$	
Γ_6	$\Lambda\overline{K}\pi + \Sigma\overline{K}\pi$	seen

Ξ(2500) BRANCHING RATIOS

$\Gamma(\Xi\pi)/[\Gamma(\Xi\pi) + \Gamma(\Lambda\overline{K}) + \Gamma(\Sigma\overline{K}) + \Gamma(\Xi(1530)\pi)]$ $\Gamma_1/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_5)$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.5	ALITTI	69	HBC	1 standard dev. limit

$\Gamma(\Lambda\overline{K})/[\Gamma(\Xi\pi)+\Gamma(\Lambda\overline{K})+\Gamma(\Sigma\overline{K})+\Gamma(\Xi(1530)\pi)]$ — $\Gamma_2/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_5)$

VALUE	DOCUMENT ID		TECN	CHG
0.5±0.2	ALITTI	69	HBC	−

$\Gamma(\Sigma\overline{K})/[\Gamma(\Xi\pi)+\Gamma(\Lambda\overline{K})+\Gamma(\Sigma\overline{K})+\Gamma(\Xi(1530)\pi)]$ — $\Gamma_3/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_5)$

VALUE	DOCUMENT ID		TECN	CHG
0.5±0.2	ALITTI	69	HBC	−

$\Gamma(\Xi(1530)\pi)/[\Gamma(\Xi\pi)+\Gamma(\Lambda\overline{K})+\Gamma(\Sigma\overline{K})+\Gamma(\Xi(1530)\pi)]$ — $\Gamma_5/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_5)$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.2	ALITTI	69	HBC	1 standard dev. limit

$\Gamma(\Xi\pi\pi)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	CHG
seen	BARTSCH	69	HBC	−0

$[\Gamma(\Lambda\overline{K}\pi)+\Gamma(\Sigma\overline{K}\pi)]/\Gamma_{total}$ — Γ_6/Γ

VALUE	DOCUMENT ID		TECN	CHG
seen	BARTSCH	69	HBC	−0

$\Xi(2500)$ REFERENCES

JENKINS 83 PRL 51 951 +Albright, Diamond+ (FSU, BRAN, LBL, CINC, SMAS)
ALITTI 69 PRL 22 79 +Barnes, Flaminio, Metzger+ (BNL, SYRA) I
BARTSCH 69 PL 28B 439 + (AACH, BERL, CERN, LOIC, VIEN)

Ω BARYONS
$(S=-3,\ I=0)$

$\Omega^- = sss$

Ω^-

$I(J^P) = 0(\frac{3}{2}^+)$ Status: ∗∗∗∗

The unambiguous discovery in both production and decay was by BARNES 64. The quantum numbers have not actually been measured, but follow from the assignment of the particle to the baryon decuplet. DEUTSCHMANN 78 and BAUBILLIER 78 rule out $J=1/2$ and find consistency with $J=3/2$.

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1986 edition (Physics Letters **170B** (1986)) or in earlier editions.

Ω^- MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1672.43±0.32 OUR AVERAGE					
1673 ±1	100	HARTOUNI	85	SPEC	80–280 GeV K^0_L C
1673.0 ±0.8	41	BAUBILLIER	78	HBC	8.25 GeV/c K^-p
1671.7 ±0.6	27	HEMINGWAY	78	HBC	4.2 GeV/c K^-p
1673.4 ±1.7	4	[1] DIBIANCA	75	DBC	4.9 GeV/c K^-d
1673.3 ±1.0	3	PALMER	68	HBC	K^-p 4.6, 5 GeV/c
1671.8 ±0.8	3	SCHULTZ	68	HBC	K^-p 5.5 GeV/c
1674.2 ±1.6	5	SCOTTER	68	HBC	K^-p 6 GeV/c
1672.1 ±1.0	1	[2] FRY	55	EMUL	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1671.43±0.78	13	[3] DEUTSCH...	73	HBC	K^-p 10 GeV/c
1671.9 ±1.2	6	[3] SPETH	69	HBC	See DEUTSCHMANN 73
1673.0 ±8.0	1	ABRAMS	64	HBC	$\to \Xi^-\pi^0$
1670.6 ±1.0	1	[2] FRY	55B	EMUL	
1615	1	[4] EISENBERG	54	EMUL	

[1] DIBIANCA 75 gives a mass for each event. We quote the average.

[2] The FRY 55 and FRY 55B events were identified as Ω^- by ALVAREZ 73. The masses assume decay to ΛK^- at rest. For FRY 55B, decay from an atomic orbit could Doppler shift the K^- energy and the resulting Ω^- mass by several MeV. This shift is negligible for FRY 55 because the Ω decay is approximately perpendicular to its orbital velocity, as is known because the Λ strikes the nucleus (L.Alvarez, private communication 1973). We have calculated the error assuming that the orbital n is 4 or larger.

[3] Excluded from the average; the Ω^- lifetimes measured by the experiments differ significantly from other measurements.

[4] The EISENBERG 54 mass was calculated for decay in flight. ALVAREZ 73 has shown that the Ω interacted with an Ag nucleus to give $K^-\Xi$Ag.

$\overline{\Omega}^+$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1672.6±0.7 OUR AVERAGE					
1672 ±1	72	HARTOUNI	85	SPEC	80–280 GeV K^0_L C
1673.1±1.0	1	FIRESTONE	71B	HBC	12 GeV/c K^+d

Ω^- MEAN LIFE

Measurements with an error $> 0.1\times10^{-10}$ s have been omitted.

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
0.822±0.012 OUR AVERAGE					
0.811±0.037	1096	LUK	88	SPEC	pBe 400 GeV
0.823±0.013	12k	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.822±0.028	2437	BOURQUIN	79B	SPEC	See BOURQUIN 84

Ω^- MAGNETIC MOMENT

VALUE (μ_N)	EVTS	DOCUMENT ID		TECN	COMMENT
−1.94±0.17±0.14	25k	DIEHL	91	SPEC	Spin-transfer production

Ω^- DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	ΛK^-	(67.8±0.7) %	
Γ_2	$\Xi^0\pi^-$	(23.6±0.7) %	
Γ_3	$\Xi^-\pi^0$	(8.6±0.4) %	
Γ_4	$\Xi^-\pi^+\pi^-$	$(4.3^{+3.4}_{-1.3})\times10^{-4}$	
Γ_5	$\Xi(1530)^0\pi^-$	$(6.4^{+5.1}_{-2.0})\times10^{-4}$	
Γ_6	$\Xi^0e^-\overline{\nu}_e$	$(5.6\pm2.8)\times10^{-3}$	
Γ_7	$\Xi^-\gamma$	$<2.2\times10^{-3}$	90%
	$\Delta S=2$ (ΔS) violating modes		
Γ_8	$\Lambda\pi^-$	ΔS $<1.9\times10^{-4}$	90%

Ω^- BRANCHING RATIOS

The BOURQUIN 84 values (which include results of BOURQUIN 79B, a separate experiment) are much more accurate than any other results, and so the other results have been omitted.

$\Gamma(\Lambda K^-)/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.678±0.007	14k	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.686±0.013	1920	BOURQUIN	79B	SPEC	See BOURQUIN 84

$\Gamma(\Xi^0\pi^-)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.236±0.007	1947	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.234±0.013	317	BOURQUIN	79B	SPEC	See BOURQUIN 84

$\Gamma(\Xi^-\pi^0)/\Gamma_{total}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.086±0.004	759	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.080±0.008	145	BOURQUIN	79B	SPEC	See BOURQUIN 84

$\Gamma(\Xi^-\pi^+\pi^-)/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
$4.3^{+3.4}_{-1.3}$	4	BOURQUIN	84	SPEC	SPS hyperon beam

$\Gamma(\Xi(1530)^0\pi^-)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
$6.4^{+5.1}_{-2.0}$	4	[5] BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 20	1	BOURQUIN	79B	SPEC	See BOURQUIN 84

[5] The same 4 events as in the previous mode, with the isospin factor to take into account $\Xi(1530)^0\to\Xi^0\pi^0$ decays included.

$\Gamma(\Xi^0 e^- \overline{\nu}_e)/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
5.6±2.8	14	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 10	3	BOURQUIN	79B	SPEC	See BOURQUIN 84

$\Gamma(\Xi^- \gamma)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<2.2	90	9	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<3.1	90	0	BOURQUIN	79B	SPEC	See BOURQUIN 84

$\Gamma(\Lambda \pi^-)/\Gamma_{total}$ — Γ_8/Γ

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 1.9	90	0	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<13	90	0	BOURQUIN	79B	SPEC	See BOURQUIN 84

Ω^- DECAY PARAMETERS

α FOR $\Omega^- \to \Lambda K^-$

Some early results have been omitted.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.026±0.026 OUR AVERAGE					
−0.034±0.079	1743	LUK	88	SPEC	pBe 400 GeV
−0.025±0.028	12k	BOURQUIN	84	SPEC	SPS hyperon beam

α FOR $\Omega^- \to \Xi^0 \pi^-$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
+0.09±0.14	1630	BOURQUIN	84	SPEC	SPS hyperon beam

α FOR $\Omega^- \to \Xi^- \pi^0$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
+0.05±0.21	614	BOURQUIN	84	SPEC	SPS hyperon beam

REFERENCES FOR Ω^-

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1986 edition (Physics Letters **170B**) or in earlier editions.

DIEHL	91	PRL 67 804	+Teige, Thompson, Zou+	(RUTG, FNAL, MICH, MINN)
LUK	88	PR D38 19	+Beretvas, Deck+	(RUTG, WISC, MICH, MINN)
PDG	86	PL 170B	Aguilar-Benitez, Porter+	(CERN, CIT+)
HARTOUNI	85	PRL 54 628	+Atiya, Holmes, Knapp, Lee+	(COLU, ILL, FNAL)
BOURQUIN	84	NP B241 1	+	(BRIS, GEVA, HEID, LALO, RAL, STRB)
Also	79	PL 87B 297	Bourquin+	(BRIS, GEVA, HEID, ORSA, RHEL, STRB)
BOURQUIN	79B	PL 88B 192	+	(BRIS, GEVA, HEID, LALO, RAL)
BAUBILLIER	78	PL 78B 342	+	(BIRM, CERN, GLAS, MSU, LPNP) J
DEUTSCH...	78	PL 73B 96	Deutschmann+	(AACH, BERL, CERN, INNS, LOIC+) J
HEMINGWAY	78	NP B142 205	+Armenteros+	(CERN, ZEEM, NIJM, OXF)
DIBIANCA	75	NP B98 137	+Endorf	(CMU)
ALVAREZ	73	PR D8 702		(LBL)
DEUTSCH...	73	NP B61 102	Deutschmann, Kaufmann, Besliv+	(ABCLV Collab.)
FIRESTONE	71B	PRL 26 410	+Goldhaber, Lissauer, Sheldon, Trilling	(LRL)
SPETH	69	PL 29B 252	+	(AACH, BERL, CERN, LOIC, VIEN)
PALMER	68	PL 26B 323	+Radojicic, Rau, Richardson+	(BNL, SYRA)
SCHULTZ	68	PR 168 1509	+	(ILL, ANL, NWES, WISC)
SCOTTER	68	PL 26B 474	+	(BIRM, GLAS, LOIC, MUNI, OXF)
ABRAMS	64	PRL 13 670	+Burnstein, Glasser+	(UMD, NRL)
BARNES	64	PRL 12 204	+Connolly, Crennell, Culwick+	(BNL)
FRY	55	PR 97 1189	+Schneps, Swami	(WISC)
FRY	55B	NC 2 346	+Schneps, Swami	(WISC)
EISENBERG	54	PR 96 541		(CORN)

$\Omega(2250)^-$

$I(J^P) = 0(?^?)$ Status: ∗∗∗

$\Omega(2250)^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2252± 9 OUR AVERAGE					
2253±13	44	ASTON	87B	LASS	$K^- p$ 11 GeV/c
2251± 9±8	78	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2250)^-$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
55±18 OUR AVERAGE					
81±38	44	ASTON	87B	LASS	$K^- p$ 11 GeV/c
48±20	78	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2250)^-$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Xi^- \pi^+ K^-$	seen
Γ_2	$\Xi(1530)^0 K^-$	seen

$\Omega(2250)^-$ BRANCHING RATIOS

$\Gamma(\Xi(1530)^0 K^-)/\Gamma(\Xi^- \pi^+ K^-)$ — Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
~ 1.0	44	ASTON	87B	LASS	$K^- p$ 11 GeV/c
0.70±0.20	49	BIAGI	86B	SPEC	Ξ^- Be 116 GeV/c

$\Omega(2250)^-$ REFERENCES

ASTON	87B	PL B194 579	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, TOKY)
BIAGI	86B	ZPHY C31 33	+	(LOQM, GEVA, RAL, HEID, LAUS, BRIS, CERN)

$\Omega(2380)^-$

Status: ∗∗

OMITTED FROM SUMMARY TABLE

$\Omega(2380)^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
≈ 2380 OUR ESTIMATE					
2384±9±8	45	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2380)^-$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
26±23	45	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2380)^-$ DECAY MODES

	Mode
Γ_1	$\Xi^- \pi^+ K^-$
Γ_2	$\Xi(1530)^0 K^-$
Γ_3	$\Xi^- \overline{K}^*(892)^0$

$\Omega(2380)^-$ BRANCHING RATIOS

$\Gamma(\Xi(1530)^0 K^-)/\Gamma(\Xi^- \pi^+ K^-)$ — Γ_2/Γ_1

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.44	90	9	BIAGI	86B	SPEC	Ξ^- Be 116 GeV/c

$\Gamma(\Xi^- \overline{K}^*(892)^0)/\Gamma(\Xi^- \pi^+ K^-)$ — Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.5±0.3	21	BIAGI	86B	SPEC	Ξ^- Be 116 GeV/c

$\Omega(2380)^-$ REFERENCES

BIAGI	86B	ZPHY C31 33	+	(LOQM, GEVA, RAL, HEID, LAUS, BRIS, CERN)

$\Omega(2470)^-$

Status: ∗∗

OMITTED FROM SUMMARY TABLE

A peak in the $\Omega^-\pi^+\pi^-$ mass spectrum with a signal significance claimed to be at least 5.5 standard deviations. There is no reason to seriously doubt the existence of this state, but unless the evidence is overwhelming we usually wait for confirmation from a second experiment before elevating peaks to the Summary Table.

$\Omega(2470)^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2474±12	59	ASTON	88G	LASS	$K^- p$ 11 GeV/c

$\Omega(2470)^-$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
72±33	59	ASTON	88G	LASS	$K^- p$ 11 GeV/c

$\Omega(2470)^-$ DECAY MODES

	Mode
Γ_1	$\Omega^-\pi^+\pi^-$

$\Omega(2470)^-$ REFERENCES

ASTON 88G PL B215 799 +Awaji, Bienz, Bird+ (SLAC, NAGO, CINC, TOKY)

CHARMED BARYONS
($C = +1$)

$\Lambda_c^+ = udc,\ \Sigma_c^{++} = uuc,\ \Sigma_c^+ = udc,\ \Sigma_c^0 = ddc,$
$\Xi_c^+ = usc,\ \Xi_c^0 = dsc,\ \Omega_c^0 = ssc$

NOTE ON CHARMED BARYONS

Figs. 1(a) and 1(b) show the SU(4) multiplets that have as their "ground floors" (a) the SU(3) octet that contains the nucleon, and (b) the SU(3) decuplet that contains the $\Delta(1232)$. All the particles in a given SU(4) multiplet have the same spin and parity. The only charmed baryons that have been discovered each contain one charmed quark and belong to the first floor of the multiplet shown in Fig. 1(a). Fig. 2 shows this first floor, pulled apart into two SU(3) multiplets, a $\overline{\mathbf{3}}$ that contains the $\Lambda_c(2285)$ and the $\Xi_c(2470)$, both of which decay weakly, and a **6** that contains the $\Sigma_c(2455)$, which decays strongly to $\Lambda_c\pi$. A second Ξ_c and an Ω_c remain to be discovered to fill out the **6**, and a host of other baryons with one or more charmed quarks are needed to fill out the full SU(4) multiplets in Fig. 1. Furthermore, *every* N or Δ baryon resonance "starts" a multiplet like that in Fig. 1(a) or 1(b), so the woods are full of charmed baryons, most of which no doubt will forever remain undiscovered.

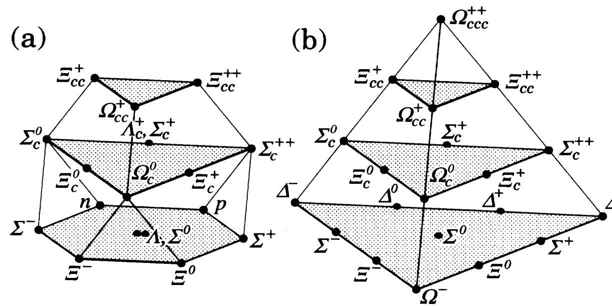


Fig. 1. SU(4) multiplets of baryons made of u, d, s, and c quarks. (a) The 20-plet with an SU(3) octet on the "ground floor." (b) The 20-plet with an SU(3) decuplet on the ground floor.

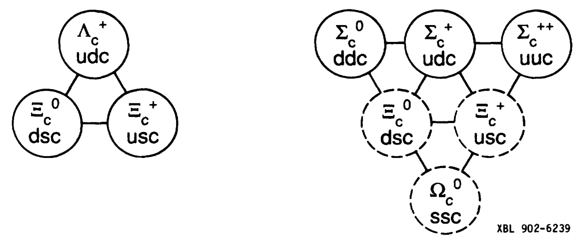


Fig. 2. The SU(3) multiplets on the "first floor" of the SU(4) multiplet of Fig. 1(a). The particles in dashed circles have yet to be discovered.

The states of the $\overline{\mathbf{3}}$ multiplet are antisymmetric under interchange of the two light quarks (the u, d, and s quarks), and the states of the **6** multiplet are symmetric under interchange of these quarks. Actually, there is probably some mixing between the pure $\overline{\mathbf{3}}$ and **6** Ξ_c states (they have the same I, J, and P quantum numbers) to form the physical Ξ_c states.

It need hardly be said that the flavor symmetries Fig. 1 displays are very badly broken, but the figure is the simplest way to see what charmed baryons should exist.

For an entry into the literature on models of charmed baryons, see Ref. 1. For a review of recent experimental results, see Ref. 2. For a review of both theory and experiment, see Ref. 3.

References

1. K. Maltman and N. Isgur, Phys. Rev. **D22**, 1701 (1980); S. Capstick and N. Isgur, Phys. Rev. **D34**, 2809 (1986); W. Kwong, J.L. Rosner, and C. Quigg, Ann. Rev. Nucl. and Part. Sci. **37**, 325 (1987); and S. Fleck and J.M. Richard, Part. World **1**, 67 (1990).
2. S.R. Klein, Int. J. Mod. Phys. **A5**, 1457 (1990).
3. J.G. Körner and H.W. Siebert, Ann. Rev. Nucl. and Part. Sci. **41**, (1991), to be published.

Λ_c^+

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗∗

J has not actually been measured yet. $J = 1/2$ is of course expected. The quark content is udc.

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1986 edition (Physics Letters **170B** (1986)) or in earlier editions.

Λ_c^+ MASS

We only average the measurements with an error less than 5 MeV. It also is clear that the early values around 2260 MeV were too low.

The fit also uses $(\Sigma_c - \Lambda_c^+)$ mass-difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2284.9± 0.6 OUR FIT					
2284.9± 0.6 OUR AVERAGE					
2284.7± 0.6± 0.7	1134	AVERY	91	CLEO	Six modes
2281.7± 2.7± 2.6	29	ALVAREZ	90B	SILI	$pK^-\pi^+$ + c.c.
2285.8± 0.6± 1.2	101	BARLAG	89	ACCM	$pK^-\pi^+$ + c.c.
2284.7± 2.3± 0.5	5	AGUILAR-...	88B	LEBC	$pK^-\pi^+$ + c.c.
2283.1± 1.7± 2.0	628	ALBRECHT	88C	ARG	$pK^-\pi^+$, $p\overline{K}^0$, $\Lambda 3\pi$
2286.2± 1.7± 0.7	97	ANJOS	88B	TPS	$pK^-\pi^+$ + c.c.
2281 ± 3	2	JONES	87	HBC	$pK^-\pi^+$
2283 ± 3	3	BOSETTI	82	HBC	$pK^-\pi^+$
2290 ± 3	1	CALICCHIO	80	HYBR	$pK^-\pi^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2301 ±17	4	ADAMOVICH	87	EMUL	γA 20–70 GeV/c
2285.6± 1.1	14	BARLAG	87	ACCM	See BARLAG 89
2305 ± 3 ± 6	621	CHAUVAT	87	SPEC	pp 63 GeV ISR
2293 ± 6 ±30	78	DIESBURG	87	SPEC	$nA \sim 600$ GeV
2300 ±25	1	AMMAR	86	EMUL	$\Sigma^+\pi^+\pi^-$
2266 ±13	8	USHIDA	86	EMUL	Wideband ν
2268 ± 6	187	ALEEV	84	BIS2	$\Lambda\pi^+\pi^+\pi^-$, $pK^0_S\pi^+\pi^-$
2270 ±15	3	KITAGAKI	82	DBC	$\Sigma^0\pi^+$
2284 ± 5	55	RUSSELL	81	SPEC	$p\overline{K}^0$ + c.c.
2285 ± 6	39	ABRAMS	80	MRK2	$pK^-\pi^+$ + c.c.
2260 ±20	1	ALLASIA	80	EMUL	$pK^-\pi^+$
2275 ±10	19	KITAGAKI	80	DBC	$\Lambda\pi^+$, $p\overline{K}^0$
2257 ±10	6	BALTAY	79	HLBC	$\Lambda\pi^+$
2254 ±12	1	CNOPS	79	DBC	$pK^*(892)^-\pi^+$
2262 ±10	30	[1] GIBONI	79	SPEC	$pK^-\pi^+$
2260 ±10	60	KNAPP	76	SPEC	$\overline{\Lambda}2\pi^-\pi^+$
2260 ±20	1	CAZZOLI	75	HBC	$\Lambda 2\pi^+\pi^-$

[1] GIBONI 79 has been changed from 2255 ± 4 MeV by the authors; see KERNAN 79.

Λ_c^+ MEAN LIFE

Measurements with an error $\geq 1.0 \times 10^{-13}$ s have been omitted.

VALUE (10^{-13} s)	EVTS	DOCUMENT ID		TECN	COMMENT
$1.91^{+0.15}_{-0.12}$ OUR AVERAGE					
1.8 ±0.3 ±0.3	29	ALVAREZ	90	SILI	γ, $\Lambda_c^+ \to pK^-\pi^+$
2.0 ±0.3 ±0.3	90	FRABETTI	90	SILI	γBe, $\Lambda_c^+ \to pK^-\pi^+$
$1.96^{+0.23}_{-0.20}$	101	BARLAG	89	ACCM	$pK^-\pi^+$ + c.c.
$1.2\ ^{+0.5}_{-0.3}$	9	AGUILAR-...	88B	LEBC	
2.2 ±0.3 ±0.2	97	ANJOS	88B	TPS	$pK^-\pi^+$ + c.c.
$2.3\ ^{+0.9}_{-0.6}$ ±0.4	11	ADAMOVICH	87	EMUL	γA 20–70 GeV/c
$1.1\ ^{+0.8}_{-0.4}$	9	AMENDOLIA	87	SPEC	γGe-Si, $pK^-\pi^+\pi^0$
$2.0\ ^{+0.7}_{-0.5}$	13	USHIDA	86	EMUL	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.4\ ^{+0.5}_{-0.3}$ ±0.3	14	BARLAG	87	ACCM	See BARLAG 89

Λ_c^+ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor
	Hadronic modes with a p and one K		
Γ_1	$p\overline{K}^0$	(1.6±0.4) %	
Γ_2	$pK^-\pi^+$	(3.2±0.7) %	
Γ_3	$p\overline{K}^*(892)^0$	[a] (8.8±2.9) × 10^{-3}	
Γ_4	$\Delta(1232)^{++}K^-$	(6.6±3.0) × 10^{-3}	
Γ_5	$p\overline{K}^0\pi^+\pi^-$	(1.7±0.6) %	1.2
Γ_6	$pK^-\pi^+\pi^0$	seen	
Γ_7	$pK^*(892)^-\pi^+$	seen	
Γ_8	$\Delta(1232)\overline{K}^*(892)$	seen	
Γ_9	$pK^-\pi^+\pi^+\pi^-$	(7 ±5) × 10^{-4}	
	Modes with a p and zero or two K's		
Γ_{10}	$p\pi^+\pi^-$	(2.2±1.3) × 10^{-3}	
Γ_{11}	$pf_0(975)$	[a] (1.8±1.2) × 10^{-3}	
Γ_{12}	$p\pi^+\pi^+\pi^-\pi^-$	(1.2±0.8) × 10^{-3}	
Γ_{13}	pK^+K^-	(1.6±0.9) × 10^{-3}	
Γ_{14}	$p\phi$	[a] (1.3±0.9) × 10^{-3}	
	Hadronic modes with a hyperon		
Γ_{15}	Λ anything	(27 ±9) %	
Γ_{16}	$\Lambda\pi^+$	(5.8±1.6) × 10^{-3}	
Γ_{17}	$\Lambda\pi^+\pi^+\pi^-$	(2.1±0.5) %	
Γ_{18}	$\Sigma^0\pi^+$	(5.5±2.6) × 10^{-3}	
Γ_{19}	$\Sigma^\pm$ anything	(10 ±5) %	
Γ_{20}	$\Sigma^+\pi^+\pi^-$	(10 ±8) %	
Γ_{21}	$\Xi^-K^+\pi^+$	(4.8±1.9) × 10^{-3}	
Γ_{22}	p hadrons		
	Semileptonic modes		
Γ_{23}	e^+ anything	(4.5±1.7) %	
Γ_{24}	pe^+ anything	(1.8±0.9) %	
Γ_{25}	Λe^+ anything	(1.2±0.4) %	
Γ_{26}	$\Lambda\mu^+$ anything	(1.1±0.7) %	
Γ_{27}	dummy mode used by fit	(91.8±1.8) %	

[a] Includes all the decay modes of the resonances.

CONSTRAINED FIT INFORMATION

An overall fit to 7 branching ratios uses 13 measurements and one constraint to determine 5 parameters. The overall fit has a $\chi^2 =$ 13.4 for 9 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left<\delta x_i \delta x_j\right>/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_5	52			
x_{17}	79	41		
x_{25}	44	23	35	
x_{27}	−91	−73	−83	−60
	x_2	x_5	x_{17}	x_{25}

Λ_c^+ BRANCHING RATIOS

$\Gamma(p\overline{K}^0)/\Gamma(pK^-\pi^+)$ — Γ_1/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.49±0.07 OUR AVERAGE					
0.44±0.07±0.05	133	AVERY	91	CLEO	e^+e^- 10.5 GeV
0.55±0.17±0.14	45	ANJOS	90	TPS	γBe 70–260 GeV
0.62±0.15±0.03	73	ALBRECHT	88C	ARG	e^+e^- 10 GeV
0.5 ±0.25	12	WEISS	80	MRK2	e^+e^- 5.2 GeV

$\Gamma(pK^-\pi^+)/\Gamma_{total}$ — Γ_2/Γ

Most of the other modes are measured relative to this mode.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.032±0.007 OUR FIT						
0.031±0.007 OUR AVERAGE						
0.043±0.010±0.008			[2] AVERY	91	CLEO	e^+e^- 10.5 GeV
0.041±0.024		208	[3] ALBRECHT	88E	ARG	
0.022±0.010		39	ABRAMS	80	MRK2	e^+e^- 5.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.044	90	6	[4] AGUILAR-...	88B	LEBC	pp 27.4 GeV

[2] AVERY 91 uses the same method as does ALBRECHT 88E (see the footnote below). Although the value is presented in AVERY 91 as not completely final, it is indeed the final result (G. Moneti, private communication).

[3] ALBRECHT 88E use their result $B(B \to \Lambda_c^+ X) \cdot B(\Lambda_c^+ \to pK^-\pi^+) = (0.30 \pm 0.12 \pm 0.06)\%$ plus $B(B \to \Lambda_c^+ X) = (7.4 \pm 2.9)\%$ from other measurements of inclusive proton and Λ yields in B decays.

[4] The AGUILAR-BENITEZ 88B lower limit is, on the face of it, in disagreement with the ABRAMS 80 measurement. However, the limit assumes that $\tau(\Lambda_c) = 1.2 \times 10^{-13}$ s, and it "decreases by 20% [to >0.035] assuming a lifetime of 1.7×10^{-13} s instead." Our average for $\tau(\Lambda_c)$ is still higher (see the mean-life section), which would further reduce the limit. The two experiments then do not disagree so badly. Given the very limited statistics and the uncertainties all around, we include the ABRAMS 80 result, which claims to be a measurement rather than a limit, in our average.

$\Gamma(p\overline{K}^*(892)^0)/\Gamma(pK^-\pi^+)$ — Γ_3/Γ_2

Corrected for the $\overline{K}^{*0} \to \overline{K}^0\pi^0$ mode.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.27±0.07 OUR AVERAGE					
0.35±0.11		BARLAG	90D	ACCM	π^- 230 GeV
0.42±0.24	12	BASILE	81B	CNTR	$pp \to \Lambda_c^+ e^- X$
0.18±0.10		WEISS	80	MRK2	e^+e^- 5.2 GeV

$\Gamma(\Delta(1232)^{++}K^-)/\Gamma(pK^-\pi^+)$ — Γ_4/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.20±0.08 OUR AVERAGE Error includes scale factor of 1.3.					
0.40±0.17	17	BASILE	81B	CNTR	$pp \to \Lambda_c^+ e^- X$
0.17±0.07		WEISS	80	MRK2	e^+e^- 5.2 GeV

$\Gamma(p\overline{K}^0\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_5/Γ_2

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.54±0.17 OUR FIT Error includes scale factor of 1.4.						
0.49±0.17 OUR AVERAGE Error includes scale factor of 1.4.						
0.43±0.12±0.04		83	AVERY	91	CLEO	e^+e^- 10.5 GeV
0.98±0.36±0.08		12	BARLAG	90D	ACCM	π^- 230 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.7	90		ANJOS	90	TPS	γBe 70–260 GeV

$\Gamma(pK^-\pi^+\pi^0)/\Gamma_{total}$ — Γ_6/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	44	AMENDOLIA	87	SPEC	γGe-Si

$\Gamma(pK^*(892)^-\pi^+)/\Gamma_{total}$ — Γ_7/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	1	CNOPS	79	DBC	νN in BNL 7-ft

$\Gamma(\Delta(1232)\overline{K}^*(892))/\Gamma_{total}$ — Γ_8/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	35	AMENDOLIA	87	SPEC	γGe-Si

$\Gamma(pK^-\pi^+\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_9/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.022±0.015	BARLAG	90D	ACCM	π^- 230 GeV

$\Gamma(p\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{10}/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.069±0.036	BARLAG	90D	ACCM	π^- 230 GeV

$\Gamma(pf_0(975))/\Gamma(pK^-\pi^+)$ — Γ_{11}/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.055±0.036	BARLAG	90D	ACCM	π^- 230 GeV

$\Gamma(p\pi^+\pi^+\pi^-\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{12}/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.036±0.023	BARLAG	90D	ACCM	π^- 230 GeV

$\Gamma(pK^+K^-)/\Gamma(pK^-\pi^+)$ — Γ_{13}/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.048±0.027	BARLAG	90D	ACCM	π^- 230 GeV

$\Gamma(p\phi)/\Gamma(pK^-\pi^+)$ — Γ_{14}/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.040±0.027	BARLAG	90D	ACCM	π^- 230 GeV

$\Gamma(\Lambda\text{ anything})/\Gamma_{total}$ — Γ_{15}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.27±0.09 OUR AVERAGE					
0.49±0.24		ADAMOVICH	87	EMUL	γA 20–70 GeV/c
0.23±0.10	8	[5] ABE	86	HYBR	20 GeV γp

[5] ABE 86 includes Λ's from Σ^0 decay.

$\Gamma(\Lambda\pi^+)/\Gamma(pK^-\pi^+)$ — Γ_{16}/Γ_2

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.180±0.032 OUR AVERAGE						
0.18 ±0.03 ±0.04			ALBRECHT	92	ARG	$e^+e^- \sim$ 10.4 GeV
0.18 ±0.03 ±0.03		87	AVERY	91	CLEO	e^+e^- 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.33	90		ANJOS	90	TPS	γBe 70–260 GeV
<0.16	90		ALBRECHT	88C	ARG	e^+e^- 10 GeV
<0.8	90		WEISS	80	MRK2	e^+e^- 5.2 GeV

$\Gamma(\Lambda\pi^+)/\Gamma(p\overline{K}^0)$ — Γ_{16}/Γ_1

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.4	90	40	RUSSELL	81	SPEC	Photoproduction
$0.51^{+0.62}_{-0.27}$		9	KITAGAKI	80	DBC	νd in FNAL 15-ft
$0.67^{+0.78}_{-0.35}$		5	[6] BALTAY	79	HLBC	ν Ne-H in 15-ft

[6] Calculated by KITAGAKI 80 from BALTAY 79 results.

$\Gamma(\Lambda\pi^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{17}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.021±0.005 OUR FIT					
0.028±0.007±0.011	70	[7] BOWCOCK	85	CLEO	e^+e^- 10.5 GeV

[7] See BOWCOCK 85 for assumptions made on charm production and Λ_c production from charm to get this result.

$\Gamma(\Lambda\pi^+\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{17}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.64±0.10 OUR FIT					
0.66±0.11 OUR AVERAGE					
0.65±0.11±0.12	289	AVERY	91	CLEO	e^+e^- 10.5 GeV
0.82±0.29±0.27	44	ANJOS	90	TPS	γBe 70–260 GeV
0.94±0.41±0.13	10	BARLAG	90D	ACCM	π^- 230 GeV
0.61±0.16±0.04	105	ALBRECHT	88C	ARG	e^+e^- 10 GeV

$\Gamma(p\overline{K}^0\pi^+\pi^-)/\Gamma(\Lambda\pi^+\pi^+\pi^-)$ — Γ_5/Γ_{17}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.84±0.27 OUR FIT Error includes scale factor of 1.2.					
4.3 ±1.2	130	ALEEV	84	BIS2	nC 40–70 GeV

$\Gamma(\Sigma^\pm\text{ anything})/\Gamma_{total}$ — Γ_{19}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.1 ±0.05	5	ABE	86	HYBR	20 GeV γp

$\Gamma(\Sigma^0\pi^+)/\Gamma(pK^-\pi^+)$ — Γ_{18}/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.17±0.06±0.04	ALBRECHT	92	ARG	$e^+e^- \sim$ 10.4 GeV

$\Gamma(\Sigma^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{20}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.10±0.08		ADAMOVICH	87	EMUL	γA 20–70 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	1	AMMAR	86	EMUL	νA

$\Gamma(\Xi^-K^+\pi^+)/\Gamma(pK^-\pi^+)$ — Γ_{21}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.15±0.04±0.03	30	AVERY	91	CLEO	e^+e^- 10.5 GeV

$\Gamma(p\text{ hadrons})/\Gamma_{total}$ — Γ_{22}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.41±0.24	ADAMOVICH	87	EMUL	γA 20–70 GeV/c

$\Gamma(e^+\text{ anything})/\Gamma_{total}$ — Γ_{23}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.045±0.017	VELLA	82	MRK2	e^+e^- 4.5–6.8 GeV

$\Gamma(pe^+\text{ anything})/\Gamma_{total}$ — Γ_{24}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.018±0.009	[8] VELLA	82	MRK2	e^+e^- 4.5–6.8 GeV

[8] VELLA 82 includes protons from Λ decay.

$\Gamma(\Lambda e^+\text{ anything})/\Gamma_{total}$ — Γ_{25}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.012±0.004 OUR FIT						
0.011±0.008			[9] VELLA	82	MRK2	e^+e^- 4.5–6.8 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.022	90	1	BALLAGH	81	HYBR	ν Ne-H in 15-ft

[9] VELLA 82 includes Λ's from Σ^0 decay.

$\Gamma(\Lambda e^+\text{ anything})/\Gamma(pK^-\pi^+)$ — Γ_{25}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.36±0.12 OUR FIT					
0.37±0.11±0.08	73	ALBRECHT	91G	ARG	$e^+e^- \approx$ 10.4 GeV

$\Gamma(\Lambda\mu^+\text{ anything})/\Gamma(pK^-\pi^+)$ — Γ_{26}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.35±0.18±0.09	30	ALBRECHT	91G	ARG	$e^+e^- \approx$ 10.4 GeV

$\Gamma(\Lambda e^+\text{ anything})/\Gamma(\Lambda\text{ anything})$ — Γ_{25}/Γ_{15}

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.027±0.017	[10] SON	82	DBC	νd in FNAL 15-ft

[10] SON 82 uses own data and $\Lambda\mu^-e^+$ events of MURTAGH 79.

$\Gamma(\Lambda\pi^+\pi^+\pi^-)/\Gamma(\Lambda e^+ \text{ anything})$ — Γ_{17}/Γ_{25}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.7	90	KLEIN	89	MRK2	e^+e^- 29 GeV

Λ_c^+ DECAY PARAMETERS

See the Note on Baryon Decay Parameters in the neutron Listings.

α FOR $\Lambda_c^+ \to \Lambda\pi^+$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−1.03±0.29 OUR AVERAGE					
−0.96±0.42		ALBRECHT	92	ARG	$e^+e^- \sim$ 10.4 GeV
−1.1 ±0.4	86	AVERY	90B	CLEO	$e^+e^- \sim$ 10.6 GeV

Λ_c^+ REFERENCES

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1986 edition (Physics Letters **170B** (1986)) or in earlier editions.

ALBRECHT 92 PL B274 239 +Ehrlichmann, Hamacher, Krueger+ (ARGUS Collab.)
ALBRECHT 91G PL B269 234 +Ehrlichmann, Hamacher+ (ARGUS Collab.)
AVERY 91 PR D43 3599 +Besson, Garren, Yelton+ (CLEO Collab.)
ALVAREZ 90 ZPHY C47 539 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
ALVAREZ 90B PL B246 256 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
ANJOS 90 PR D41 801 +Appel, Bean+ (FNAL-TPS Collab.)
AVERY 90B PRL 65 2842 +Besson, Garren, Yelton, Kinoshita+ (CLEO Collab.)
BARLAG 90D ZPHY C48 29 +Becker, Boehringer, Bosman+ (ACCMOR Collab.)
FRABETTI 90 PL B251 639 +Bogart, Cheung, Coteus+ (FNAL-E687 Collab.)
BARLAG 89 PL B218 374 +Becker, Boehringer, Bosman+ (ACCMOR Collab.)
KLEIN 89 PRL 62 2444 +Himel, Abrams, Amidei, Baden+ (Mark II Collab.)
AGUILAR-... 88B ZPHY C40 321 Aguilar-Benitez, Allison, Bailly+ (LEBC-EHS Collab.)
Also 87 PL B189 254 Aguilar-Benitez, Allison, Bailly+ (LEBC-EHS Collab.)
Also 87B PL B199 462 Aguilar-Benitez, Allison, Bailly+ (LEBC-EHS Collab.)
Also 88 SJNP 48 833 Begalli, Otter, Schulte, Gensch+ (LEBC-EHS Collab.)
Translated from YAF 48 1310.
ALBRECHT 88C PL B207 109 + (ARGUS Collab.)
ALBRECHT 88E PL B210 263 +Boeckmann, Glaeser+ (ARGUS Collab.)
ANJOS 88B PRL 60 1379 +Appel+ (FNAL-TPS Collab.)
ADAMOVICH 87 EPL 4 887 +Alexandrov, Bolta+ (Photon Emulsion Collab.)
Also 87 SJNP 46 447 Viaggi, Gessaroli+ (Photon Emulsion Collab.)
Translated from YAF 46 799.
AMENDOLIA 87 ZPHY C36 513 +Bagliesi, Batignani, Beck+ (CERN NA1 Collab.)
BARLAG 87 PL B184 283 + (ACCMOR Collab.)
CHAUVAT 87 PL B199 304 +Cousins, Hayes+ (CERN, UCLA, SACL, UDCF)
DIESBURG 87 PRL 59 2711 +Ladbury+ (COLO, ILL, FNAL, BGNA, MILA, INFN)
JONES 87 ZPHY C36 593 +Jones+ (BIRM, CERN, LOIC, MPIM, OXF, LOUC)
ABE 86 PR D33 1 + (SLAC Hybrid Facility Photon Collab.)
AMMAR 86 JETPL 43 515 +Ammosov, Bakic, Baranov, Burnett+ (ITEP)
Translated from ZETFP 43 401.
PDG 86 PL 170B Aguilar-Benitez, Porter+ (CERN, CIT+)
USHIDA 86 PRL 56 1767 +Kondo+ (AICH, FNAL, GIFU, GYEO, KOBE, SEOU+)
BOWCOCK 85 PRL 55 923 +Giles, Hassard, Kinoshita+ (CLEO Collab.)
ALEEV 84 ZPHY C23 333 +Arefiev, Balandin, Berdyshev+ (BIS-2 Collab.)
BOSETTI 82 PL 109B 234 +Graessler+ (AACH, BONN, CERN, MPIM, OXF)
KITAGAKI 82 PRL 48 299 +Tanaka, Yuta+ (TOHO, IIT, UMD, STON, TUFT)
SON 82 PRL 49 1128 +Snow, Chang+ (UMD, IIT, STON, TOHO, TUFT)
VELLA 82 PRL 48 1515 +Trilling, Abrams, Alam+ (SLAC, LBL, UCB)
BALLAGH 81 PR D24 7 +Bingham+ (LBL, UCB, FNAL, HAWA, WASH, WISC)
BASILE 81B NC 62A 14 +Romeo+ (CERN, BGNA, PGIA, FRAS)
RUSSELL 81 PRL 46 799 +Avery, Butler, Gladding+ (ILL, FNAL, COLU)
ABRAMS 80 PRL 44 10 +Alam, Blocker, Boyarski+ (SLAC, LBL)
ALLASIA 80 NP B176 13 + (ANKA, LIBH, CERN, DUUC, LOUC, KEYN+)
CALICCHIO 80 PL 93B 521 + (BARI, BIRM, BRUX, CERN, EPOL, RHEL+)
KITAGAKI 80 PRL 45 955 +Tanaka, Yuta+ (TOHO, IIT, UMD, STON, TUFT)
WEISS 80 Toronto Conf. 319 (SLAC)
BALTAY 79 PRL 42 1721 +Caroumbalis, French, Hibbs+ (COLU, BNL)
CNOPS 79 PRL 42 197 +Connolly, Kahn, Kirk, Murtagh, Palmer+ (BNL)
GIBONI 79 PL 85B 437 + (AACH, CERN, HARV, MUNI, NWES, UCR)
KERNAN 79 Lepton Conf. FNAL (UCR)
MURTAGH 79 Fermilab Symp. 277 (FNAL)
KNAPP 76 PRL 37 882 +Lee, Leung, Smith+ (COLU, HAWA, ILL, FNAL)
CAZZOLI 75 PRL 34 1125 +Cnops, Connolly, Louttit, Murtagh+ (BNL)

$\Sigma_c(2455)$

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗∗∗

J^P not confirmed. $1/2^+$ is the quark model prediction.

$\Sigma_c(2455)$ MASSES

The mass measurements in this section are redundant with the mass difference measurements that follow. We get the masses by adding the $\Sigma_c(2455) - \Lambda_c^+$ mass differences to the Λ_c^+ mass.

$\Sigma_c(2455)^{++}$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2452.7± 0.7 OUR FIT						
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2449 ± 3	2	JONES	87	HBC	++	νp in BEBC
2480	1	ADAMOVICH	84	EMUL	++	γA (OMEGA)
2454 ± 5	1	BOSETTI	82	HBC	++	See JONES 87
2425 ±10	6	BALTAY	79	HLBC	++	ν Ne-H in 15-ft
>2439	1	BARISH	77B	DBC	++	νd in 12-ft
2426 ±12	1	CAZZOLI	75	HBC	++	νp in BNL 7-ft

$\Sigma_c(2455)^+$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2452.9±3.1 OUR FIT						
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2457 ±4	1	CALICCHIO	80	HBC	+	νp in BEBC-TST

$\Sigma_c(2455)^0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2452.5± 0.8 OUR FIT						
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2462 ±26	1	AMMAR	86	EMUL	0	νA
~ 2460	9	KNAPP	76	SPEC	0	γBe

$\Sigma_c(2455) - \Lambda_c^+$ MASS DIFFERENCES

$\Sigma_c^{++} - \Lambda_c^+$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
167.8± 0.4 OUR FIT						
167.7± 0.4 OUR AVERAGE						
167.8± 0.4±0.3	54	BOWCOCK	89	CLEO	++	e^+e^- 10 GeV
168.2± 0.5±1.6	92	ALBRECHT	88D	ARG	++	e^+e^- 10 GeV
167.4± 0.5±2.0	46	DIESBURG	87	SPEC	++	$nA \sim$ 600 GeV
167 ± 1	2	JONES	87	HBC	++	νp in BEBC
168 ± 3	6	BALTAY	79	HLBC	++	ν Ne-H in 15-ft
• • • We do not use the following data for averages, fits, limits, etc. • • •						
166 ± 1	1	BOSETTI	82	HBC	++	See JONES 87
166 ±15	1	CAZZOLI	75	HBC	++	νp in BNL 7-ft

$\Sigma_c^+ - \Lambda_c^+$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
168.0±3.0 OUR FIT						
168 ±3	1	CALICCHIO	80	HBC	+	νp in BEBC-TST

$\Sigma_c^0 - \Lambda_c^+$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
167.6±0.6 OUR FIT Error includes scale factor of 1.1.						
168.4±1.0±0.3	14	ANJOS	89D	TPS	0	γBe 90–260 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
167.9±0.5±0.3	48	[1] BOWCOCK	89	CLEO	0	e^+e^- 10 GeV
167.0±0.5±1.6	70	[1] ALBRECHT	88D	ARG	0	e^+e^- 10 GeV
178.2±0.4±2.0	85	[2] DIESBURG	87	SPEC	0	$nA \sim$ 600 GeV
163 ±2	1	AMMAR	86	EMUL	0	νA

[1] This result enters the fit through the $\Sigma_c^{++} - \Sigma_c^0$ mass difference given in the next section.
[2] See the note in the $\Sigma_c^{++} - \Sigma_c^0$ mass difference section below.

$\Sigma_c(2455)$ MASS DIFFERENCES

$\Sigma_c^{++} - \Sigma_c^0$ MASS DIFFERENCE

DIESBURG 87 is completely incompatible with the other experiments, which is surprising since it agrees with them about the $\Sigma_c(2455)^{++} - \Lambda_c^+$ mass difference. We go with the majority here.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0.2±0.5 OUR FIT Error includes scale factor of 1.2.				
0.4±0.6 OUR AVERAGE Error includes scale factor of 1.3.				
− 0.1±0.6±0.1	BOWCOCK	89	CLEO	e^+e^- 10 GeV
+ 1.2±0.7±0.3	ALBRECHT	88D	ARG	$e^+e^- \sim$ 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−10.8±2.9	DIESBURG	87	SPEC	$nA \sim$ 600 GeV

$\Sigma_c(2455)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda_c^+\pi$	100 %

$\Sigma_c(2455)$ REFERENCES

ANJOS 89D PRL 62 1721 +Appel, Bean, Bracker, Browder+ (FNAL-TPS Collab.)
BOWCOCK 89 PRL 62 1240 +Kinoshita, Pipkin, Procario, Wilson+ (CLEO Collab.)
ALBRECHT 88D PL B211 489 +Boeckmann, Glaeser+ (ARGUS Collab.)
DIESBURG 87 PRL 59 2711 +Ladbury+ (COLO, ILL, FNAL, BGNA, MILA, INFN)
JONES 87 ZPHY C36 593 +Jones+ (BIRM, CERN, LOIC, MPIM, OXF, LOUC)
AMMAR 86 JETPL 43 515 +Ammosov, Bakic, Baranov, Burnett+ (ITEP)
Translated from ZETFP 43 401.
ADAMOVICH 84 PL 140B 119 +Alexandrov, Bolta, Bravo+ (WA58 Collab.)
BOSETTI 82 PL 109B 234 +Graessler+ (AACH, BONN, CERN, MPIM, OXF)
CALICCHIO 80 PL 93B 521 + (BARI, BIRM, BRUX, CERN, EPOL, RHEL+)
BALTAY 79 PRL 42 1721 +Caroumbalis, French, Hibbs+ (COLU, BNL)
BARISH 77B PR D15 1 +Derrick, Dombeck, Musgrave+ (ANL, PURD)
KNAPP 76 PRL 37 882 +Lee, Leung, Smith+ (COLU, HAWA, ILL, FNAL)
CAZZOLI 75 PRL 34 1125 +Cnops, Connolly, Louttit, Murtagh+ (BNL)

Ξ_c^+

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗

According to the quark model, the Ξ_c^+ (quark content usc) and Ξ_c^0 form an isospin doublet, and the spin-parity ought to be $J^P = 1/2^+$. None of I, J, or P have actually been measured.

Ξ_c^+ MASS

The fit uses the Ξ_c^+ and Ξ_c^0 mass and mass-difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2466.4± 2.1 OUR FIT					
2466.2± 2.2 OUR AVERAGE					
2465.1± 3.6± 1.9	30	ALBRECHT	90F	ARG	e^+e^- at $\Upsilon(4S)$
2467 ± 3 ± 4	23	ALAM	89	CLEO	e^+e^- 10.6 GeV
2466.5± 2.7± 1.2	5	BARLAG	89C	ACCM	π^- Cu 230 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2459 ± 5 ±30	56	[1] COTEUS	87	SPEC	$nA \sim$ 600 GeV
2460 ±25	82	BIAGI	83	SPEC	Σ^- Be 135 GeV

[1] Although COTEUS 87 claims to agree well with BIAGI 83 on the mass and width, there appears to be a discrepancy between the two experiments. BIAGI 83 sees a single peak (stated significance about 6 standard deviations) in the $\Lambda K^-\pi^+\pi^+$ mass spectrum. COTEUS 87 sees *two* peaks in the same spectrum, one at the Ξ_c^+ mass, the other 75 MeV lower. The latter is attributed to $\Xi_c^+ \rightarrow \Sigma^0 K^-\pi^+\pi^+ \rightarrow (\Lambda\gamma)K^-\pi^+\pi^+$, with the γ unseen. The *combined* significance of the double peak is stated to be 5.5 standard deviations. But the absence of any trace of a lower peak in BIAGI 83 seems to us to throw into question the interpretation of the lower peak of COTEUS 87.

Ξ_c^+ MEAN LIFE

VALUE (10^{-13} s)	EVTS	DOCUMENT ID		TECN	COMMENT
$3.0^{+1.0}_{-0.6}$ OUR AVERAGE	Error includes scale factor of 1.1.				
$2.0^{+1.1}_{-0.6}$	6	BARLAG	89C	ACCM	π^- (K^-) Cu 230 GeV
$4.0^{+1.8+1.0}_{-1.2-1.0}$		COTEUS	87	SPEC	$nA \sim$ 600 GeV
$4.8^{+2.9}_{-1.8}$	53	BIAGI	85C	SPEC	Σ^- Be 135 GeV

Ξ_c^+ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda K^-\pi^+\pi^+$	seen
Γ_2	$\Sigma^+ K^-\pi^+$	seen
Γ_3	$\Sigma^0 K^-\pi^+\pi^+$	seen
Γ_4	$\Xi^-\pi^+\pi^+$	seen

Ξ_c^+ BRANCHING RATIOS

$\Gamma(\Lambda K^-\pi^+\pi^+)/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	82	[2] BIAGI	83	SPEC	Σ^- Be 135 GeV

[2] BIAGI 85B look for but do not see the Ξ_c^+ in $pK^-\overline{K}^0\pi^+$ (branching fraction <0.08 with 90% CL), $p2K^-2\pi^+$ (<0.03, 90% CL), $\Omega^-K^+\pi^+$, $\Lambda K^{*0}\pi^+$, and $\Sigma(1385)^+K^-\pi^+$.

$\Gamma(\Sigma^+K^-\pi^+)/\Gamma(\Xi^-\pi^+\pi^+)$ — Γ_2/Γ_4

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.09^{+0.13+0.03}_{-0.06-0.02}$	5	BARLAG	89C	ACCM	2 $\Sigma^+K^-\pi^+$, 3 $\Xi^-\pi^+\pi^+$

$\Gamma(\Sigma^0K^-\pi^+\pi^+)/\Gamma(\Lambda K^-\pi^+\pi^+)$ — Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.84±0.36	102	[3] COTEUS	87	SPEC	$nA \sim$ 600 GeV

[3] See, however, the note on the COTEUS 87 Ξ_c^+ mass measurement.

$\Gamma(\Xi^-\pi^+\pi^+)/\Gamma_{total}$ — Γ_4/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	23	ALAM	89	CLEO	e^+e^- 10.6 GeV

Ξ_c^+ REFERENCES

ALBRECHT	90F	PL B247 121	+Ehrlichmann, Harder, Kruger, Nau+ (ARGUS Collab.)
ALAM	89	PL B226 401	+Katayama, Kim, Li, Lou, Sun, Bortoletto+ (CLEO Collab.)
BARLAG	89C	PL B233 522	+Boehringer, Bosman+ (ACCMOR Collab.)
COTEUS	87	PRL 59 1530	+Binkley+ (COLO, ILL, FNAL, BGNA, MILA, INFN)
BIAGI	85B	ZPHY C28 175	+ (BRIS, CERN, GEVA, HEID, LAUS, LOQM+)
BIAGI	85C	PL 150B 230	+ (BRIS, CERN, GEVA, HEID, LAUS, LOQM+)
BIAGI	83	PL 122B 455	+ (BRIS, CERN, GEVA, HEID, LAUS, LOQM+)

Ξ_c^0

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗

According to the quark model, the Ξ_c^0 (quark content dsc) and Ξ_c^+ form an isospin doublet, and the spin-parity ought to be $J^P = 1/2^+$. None of I, J, or P have actually been measured.

Ξ_c^0 MASS

The fit uses the Ξ_c^0 and Ξ_c^+ mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2472.7±1.7 OUR FIT					
2472.8±1.7 OUR AVERAGE					
2472.1±2.7±1.6	54	ALBRECHT	90F	ARG	e^+e^- at $\Upsilon(4S)$
2473.3±1.9±1.2	4	BARLAG	90	ACCM	π^- (K^-) Cu 230 GeV
2472 ±3 ±4	19	ALAM	89	CLEO	e^+e^- 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2471 ±3 ±4	14	AVERY	89	CLEO	See ALAM 89

$\Xi_c^0 - \Xi_c^+$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
6.3±2.3 OUR FIT				
6.3±2.3 OUR AVERAGE				
+7.0±4.5±2.2	ALBRECHT	90F	ARG	e^+e^- at $\Upsilon(4S)$
+6.8±3.3±0.5	BARLAG	90	ACCM	π^- (K^-) Cu 230 GeV
+5 ±4 ±1	ALAM	89	CLEO	$\Xi_c^0 \rightarrow \Xi^-\pi^+$, $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$

Ξ_c^0 MEAN LIFE

VALUE (10^{-13} s)	EVTS	DOCUMENT ID		TECN	COMMENT
$0.82^{+0.59}_{-0.30}$	4	BARLAG	90	ACCM	π^- (K^-) Cu 230 GeV

Ξ_c^0 DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Xi^-\pi^+$	seen
Γ_2	$\Xi^-\pi^+\pi^+\pi^-$	seen
Γ_3	$pK^-\overline{K}^*(892)^0$	seen

Ξ_c^0 BRANCHING RATIOS

$\Gamma(\Xi^-\pi^+)/\Gamma(\Xi^-\pi^+\pi^+\pi^-)$ — Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.30±0.12±0.05	ALBRECHT	90F	ARG	e^+e^- at $\Upsilon(4S)$

Ξ_c^0 REFERENCES

ALBRECHT	90F	PL B247 121	+Ehrlichmann, Harder, Kruger, Nau+ (ARGUS Collab.)
BARLAG	90	PL B236 495	+Becker, Boehringer, Bosman+ (ACCMOR Collab.)
ALAM	89	PL B226 401	+Katayama, Kim, Li, Lou, Sun, Bortoletto+ (CLEO Collab.)
AVERY	89	PRL 62 863	+Besson, Garren, Yelton, Bowcock+ (CLEO Collab.)

Ω_c^0

$I(J^P) = ?(?^?)$ Status: ∗
I, J, P need confirmation.

OMITTED FROM SUMMARY TABLE

A cluster of three $\Xi^-K^-\pi^+\pi^+$ events. The $\Omega_c^0 - \Xi_c^+$ mass difference is 280 ± 10 MeV. The existence of the effect and its interpretation as being the Ω_c^0 (quark content ssc) need confirmation.

Ω_c^0 MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2740±20	3	BIAGI	85B	SPEC	Σ^- Be →

Ω_c^0 REFERENCES

BIAGI	85B	ZPHY C28 175	+ (BRIS, CERN, GEVA, HEID, LAUS, LOQM+)

BOTTOM (BEAUTY) BARYON
($B = -1$)

$\Lambda_b^0 = udb$

Λ_b^0

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗

In the quark model, a Λ_b^0 is an isospin-0 udb state. The lowest Λ_b^0 ought to have $J^P = 1/2^+$. None of I, J, or P have actually been measured.

Λ_b^0 MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
5641± 50 OUR AVERAGE					
5640± 50±30	16	[1] ALBAJAR	91E	UA1	$p\overline{p}$ 630 GeV
5640^{+100}_{-210}	52	BARI	91	SFM	$\Lambda_b^0 \to pD^0\pi^-$
5650^{+150}_{-200}	90	BARI	91	SFM	$\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 5750	4	[2] ARENTON	86	FMPS	$\Lambda K_S^0 2\pi^+ 2\pi^-$
5425^{+175}_{-75}		[3] BASILE	81	SFM	62 GeV pp

[1] ALBAJAR 91E claims 16 ± 5 events above a background of 9 ± 1 events, a significance of about 5 standard deviations.
[2] The decay of the Λ_b^0 to the final state observed by ARENTON 86 is Cabibbo suppressed, whereas the decay of a Ξ_b^0 to this final state is allowed. ARENTON 86 thus only claims to have observed a baryon which probably has a b quark and has a D^0 among the decay products, not necessarily the Λ_b^0.
[3] The first claim to have discovered the Λ_b^0 was reported by BASILE 81. In contrast, DRIJARD 82 reported no observation of Λ_b^0, and this led to some discussion in BASILE 82 and DRIJARD 82B. Further evidence for the Λ_b^0 was again reported by the first authors in BARI 91 (see above) in a second, upgraded experiment where two different Λ_b^0 decay modes were observed.

Λ_b^0 DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$J/\psi(1S)\Lambda$	seen
Γ_2	$pD^0\pi^-$	seen
Γ_3	$\Lambda_c^+\pi^+\pi^-\pi^-$	seen
Γ_4	$\Lambda K^0 2\pi^+ 2\pi^-$	

Λ_b^0 BRANCHING RATIOS

$\Gamma(J/\psi(1S)\Lambda)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen OUR NEW UNCHECKED EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.018±0.011	[4] ALBAJAR	91E	UA1	$J/\psi(1S) \to \mu^+\mu^-$

[4] The ALBAJAR 91E value assumes the Λ_b production fraction is 10% of the beauty cross section.

$\Gamma(pD^0\pi^-)/\Gamma_{total}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	52	BARI	91	SFM	$D^0 \to K^-\pi^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen		BASILE	81	SFM	$D^0 \to K^-\pi^+$

$\Gamma(\Lambda_c^+\pi^+\pi^-\pi^-)/\Gamma_{total}$ Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	90	BARI	91	SFM	$\Lambda_c^+ \to pK^-\pi^+$

$\Gamma(\Lambda K^0 2\pi^+ 2\pi^-)/\Gamma_{total}$ Γ_4/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	4	[5] ARENTON	86	FMPS	$\Lambda K_S^0 2\pi^+ 2\pi^-$

[5] See the footnote to the ARENTON 86 mass value.

Λ_b^0 REFERENCES

ALBAJAR	91E	PL B273 540	+Albrow, Allkofer, Ankoviak+	(UA1 Collab.)
BARI	91	NC 104A 1787	+Basile, Bruni, Cara Romeo+	(CERN R422 Collab.)
ARENTON	86	NP B274 707	+Chen, Cormell, Dieterle+	(ARIZ, NDAM, VAND)
BASILE	82	NC 68A 289	+Bonvicini, Romeo+	(CERN R415 Collab.)
DRIJARD	82	PL 108B 361	+	(CERN, CDEF, DORT, HEID, LAPP, WARS)
DRIJARD	82B	CERN-EP/82-31	+	(CERN, CDEF, DORT, HEID, LAPP, WARS)
BASILE	81	LNC 31 97	+Bonvicini, Romeo+	(CERN R415 Collab.)

NOTE ON DIBARYON RESONANCES

Dibaryons were reviewed in our 1986 edition [1] and have been reviewed more extensively by Locher, Sainio, and Svarc [2]. We no longer compile data on dibaryons. See our 1988 edition [3] for our last compilation.

References

1. Particle Data Group, Phys. Lett. **170B**, 337 (1986).
2. M.P. Locher, M.E. Sainio, and A. Svarc, Adv. Nucl. Phys. **17**, 47 (1986).
3. Particle Data Group, Phys. Lett. **B204**, 472 (1988).

SEARCHES*

Notes in the Search Listings

* See Sec. V for searches for Higgs bosons, other heavy bosons, and axions and other very light bosons, Sec. VI for searches for heavy leptons and for neutrino mixing, and Sec. VII for searches for top and fourth-generation hadrons.

SEARCHES FOR FREE QUARKS, MONOPOLES, SUPERSYMMETRY, COMPOSITENESS, etc.

Free Quark Searches

NOTE ON QUARK SEARCHES

The basis for much of the theory of particle scattering and hadron spectroscopy is the construction of the hadrons from a set of fractionally charged constituents (quarks). A central but unproven hypothesis of this theory, Quantum Chromodynamics, is that quarks cannot be observed as free particles but are confined to mesons and baryons.

Experiments show that it is at best difficult to "unglue" quarks. Accelerator searches at increasing energies have produced no evidence for free quarks, while only a few cosmic-ray and matter searches have produced uncorroborated events.

This compilation is only a guide to the literature, since the quoted experimental limits are often only indicative. Reviews can be found in Refs. 1–3.

References

1. P.F. Smith, Ann. Rev. Nucl. and Part. Sci. **39**, 73 (1989).
2. L. Lyons, Phys. Reports **129**, 225 (1985).
3. M. Marinelli and G. Morpurgo, Phys. Reports **85**, 161 (1982).

Quark Production Cross Section — Accelerator Searches

(a) For cross section read cross-section ($\bar{q}q$ X)/cross-section ($\mu^+\mu^-$).

(b) For cross section read fraction of fragments.

X-SECT (cm^2)		CHG (e/3)	MASS (GeV)	ENERGY (GeV)	BEAM	EVTS	DOCUMENT ID		TECN
<3.8E−28				14.5A	^{28}Si–Pb	0	[1] HE	91	PLAS
<3.2E−28				14.5A	^{28}Si–Cu	0	[1] HE	91	PLAS
<1.E−4	a	+2	<3.5	10	e^+e^-	0	BOWCOCK	89B	CLEO
<1.E−4	a	±1,2,4	<4	10	e^+e^-	0	ALBRECHT	85G	ARG
<6.E−5	b	±1,2	1	540	$p\bar{p}$	0	BANNER	85	UA2
<5.E−3	a	−4	1–8	29	e^+e^-	0	AIHARA	84	TPC
<1.E−2	a	±1,2	1–13	29	e^+e^-	0	AIHARA	84B	TPC
<2.E−4	b	±1		72	^{40}Ar	0	[2] BARWICK	84	CNTR
<1.E−40		±1,2	<10		$p,\nu,\bar{\nu}$	0	BERGSMA	84B	CHRM
<1.E−4	a	±2	<0.4	1.4	e^+e^-	0	BONDAR	84	OLYA
<5.E−1	a	±1,2	<13	29	e^+e^-	0	GURYN	84	CNTR
<1.E−36		±1,2	<9	200	μ	0	AUBERT	83C	SPEC
<3.E−3	b	±1,2	<2	540	$p\bar{p}$	0	BANNER	83	CNTR
<1.E−4	b	±1,2		106	^{56}Fe	0	LINDGREN	83	CNTR
<3.E−3	b	>|±0.1|		74	^{40}Ar	0	[2] PRICE	83	PLAS
<1.E−2	a	±1,2	<14	29	e^+e^-	0	MARINI	82B	CNTR
<8.E−2	a	±1,2	<12	29	e^+e^-	0	ROSS	82	CNTR
<2.E−10		±2,4	1–3	200	p	0	[3] BUSSIERE	80	CNTR
<5.E−38		+1,2	>5	300	p	0	[4,5] STEVENSON	79	CNTR
<1.E−33		±1	<20	52	pp	0	BASILE	78	SPEC
<9.E−39		±1,2	<6	400	p	0	[4] ANTREASYAN	77	SPEC
<8.E−35		+1,2	<20	52	pp	0	[6] FABJAN	75	CNTR
<5.E−38		−1,2	4–9	200	p	0	NASH	74	CNTR
<1.E−32		+2,4	4–24	52	pp	0	ALPER	73	SPEC
<5.E−31		+1,2,4	<12	300	p	0	LEIPUNER	73	CNTR
<6.E−34		±1,2	<13	52	pp	0	BOTT	72	CNTR
<1.E−36		−4	4	70	p	0	ANTIPOV	71	CNTR
<1.E−35		±1,2	2	28	p	0	[7] ALLABY	69B	CNTR
<4.E−37		−2	<5	70	p	0	[3] ANTIPOV	69	CNTR
<3.E−37		−1,2	2–5	70	p	0	[7] ANTIPOV	69B	CNTR
<1.E−35		+1,2	<7	30	p	0	DORFAN	65	CNTR
<2.E−35		−2	<2.5–5	30	p	0	[8] FRANZINI	65B	CNTR
<5.E−35		+1,2	<2.2	21	p	0	BINGHAM	64	HLBC
<1.E−32		+1,2	<4.0	28	p	0	BLUM	64	HBC
<1.E−35		+1,2	<2.5	31	p	0	[8] HAGOPIAN	64	HBC
<1.E−34		+1	<2	28	p	0	LEIPUNER	64	CNTR
<1.E−33		+1,2	<2.4	24	p	0	MORRISON	64	HBC

[1] HE 91 limits are for charges of the form $N\pm1/3$ from 23/3 to 38/3.
[2] Bound to nuclei.
[3] Hadronic or leptonic quarks.
[4] Cross section cm^2/GeV^2.
[5] 3×10^{-5} <lifetime $<1\times10^{-3}$ s.
[6] Includes BOTT 72 results.
[7] Assumes isotropic cm production.
[8] Cross section inferred from flux.

Quark Differential Production Cross Section — Accelerator Searches

X-SECT (cm^2/sr/GeV)	CHG e/3	MASS (GeV)	ENERGY (GeV)	BEAM	EVTS	DOCUMENT ID		TECN
<4.E−36	−2,4	1.5–6	70	p	0	BALDIN	76	CNTR
<2.E−33	±4	5–20	52	pp	0	ALBROW	75	SPEC
<5.E−34	<7	7–15	44	pp	0	JOVANOV...	75	CNTR
<5.E−35			20	γ	0	[9] GALIK	74	CNTR
<9.E−35	−1,2		200	p	0	NASH	74	CNTR
<4.E−36	−4	2.3–2.7	70	p	0	ANTIPOV	71	CNTR
<3.E−35	±1,2	<2.7	27	p	0	ALLABY	69B	CNTR
<7.E−38	−1,2	<2.5	70	p	0	ANTIPOV	69B	CNTR

[9] Cross section in cm^2/sr/equivalent quanta.

Quark Flux — Accelerator Searches

The definition of FLUX depends on the experiment

(a) is the ratio of measured free quarks to predicted free quarks if there is no "confinement."
(b) is the probability of fractional charge on nuclear fragments.
(c) is the 90%CL upper limit on fractionally charged particles produced per incident ion.
(d) is quarks per collision.
(e) is quark production cross section ratio to $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$.
(f) is quark flux per charged particle.
(g) is the flux per ν-event.
(h) is quark yield per π^- yield.

FLUX		CHG (e/3)	MASS (GeV)	ENRGY (GeV)	BEAM	EVTS	DOCUMENT ID		TECN
<6.4E−5	g	1			$\nu,\bar{\nu}$	1	BASILE	91	CNTR
<3.7E−5	g	2			$\nu,\bar{\nu}$	0	BASILE	91	CNTR
<1.9E−4	c			14.5A	^{28}Si–Pb	0	[10] HE	91	PLAS
<3.9E−4	c			14.5A	^{28}Si–Cu	0	[10] HE	91	PLAS
<1.E−9	c	±1,2,4		14.5A	^{16}O–Ar	0	MATIS	91	MDRP
<5.1E−10	c	±1,2,4		14.5A	^{16}O–Hg	0	MATIS	91	MDRP
<8.1E−9	c	±1,2,4		14.5A	Si–Hg	0	MATIS	91	MDRP
<1.7E−6	c	±1,2,4		60A	^{16}O–Hg	0	MATIS	91	MDRP
<3.5E−7	c	±1,2,4		200A	^{16}O–Hg	0	MATIS	91	MDRP
<1.3E−6	c	±1,2,4		200A	S–Hg	0	MATIS	91	MDRP
<3E−2	e	2	19–27	52–60	e^+e^-	0	ADACHI	90C	TOPZ
<3E−2	e	4	<24	52–60	e^+e^-	0	ADACHI	90C	TOPZ
<1.E−6	d	±1,2		60	^{16}O–Hg	0	CALLOWAY	89	MDRP
<3.5E−7	d	±1,2		200	^{16}O–Hg	0	CALLOWAY	89	MDRP
<1.3E−6	d	±1,2		200	S–Hg	0	CALLOWAY	89	MDRP
<1.2E−10	d	±1	1	800	p–Hg	0	MATIS	89	MDRP
<1.1E−10	d	±2	1	800	p–Hg	0	MATIS	89	MDRP
<1.2E−10	d	±1	1	800	p–N_2	0	MATIS	89	MDRP
<7.7E−11	d	±2	1	800	p–N_2	0	MATIS	89	MDRP
<6.E−9	h	−5	0.9–2.3	12	p	0	NAKAMURA	89	SPEC
<5.E−5	g	1,2	<0.5		$\nu,\bar{\nu}d$	0	ALLASIA	88	BEBC
<3.E−4	b	See note		14.5	^{16}O–Pb	0	[11] HOFFMANN	88	PLAS
<2.E−4	b	See note		200	^{16}O–Pb	0	[12] HOFFMANN	88	PLAS
<2.E−4	a	±1,2	<300	320	$\bar{p}p$	0	LYONS	87	MLEV
<1.E−9	c	±1,2,4,5		14.5	^{16}O–Hg	0	SHAW	87	MDRP
<3.E−3	d	−1,2,3,4,6	<5	2	Si–Si	0	[13] ABACHI	86C	CNTR
<3.E−4	e	±2	1.8–2	7	e^+e^-	0	WEISS	81	MRK2
<5.E−2	e	+1,2,4,5	2–12	27	e^+e^-	0	BARTEL	80	JADE
<2.E−5	g	+1,2			ν	0	[14,15] BASILE	80	CNTR
<3.E−10	f	±2,4	1–3	200	p	0	[16] BOZZOLI	79	CNTR
<6.E−11	f	±1	<21	52	pp	0	BASILE	78	SPEC
<5.E−3	g				ν_μ	0	BASILE	78B	CNTR
<2.E−9	f	±1	<26	62	pp	0	BASILE	77	SPEC
<7.E−10	f	+1,2	<20	52	p	0	[17] FABJAN	75	CNTR
		+1,2	>4.5		γ	0	[14,15] GALIK	74	CNTR
		+1,2	>1.5	12	e^-	0	[14,15] BELLAMY	68	CNTR
		+1,2	>0.9		γ	0	[14] BATHOW	67	CNTR
		+1,2	>0.9	6	γ	0	[14] FOSS	67	CNTR

[10] HE 91 limits are for charges of the form $N\pm1/3$ from 23/3 to 38/3, and correspond to cross-section limits of 380μb (Pb) and 320μb (Cu).
[11] The limits apply to projectile fragment charges of 17, 19, 20, 22, 23 in units of $e/3$.
[12] The limits apply to projectile fragment charges of 16, 17, 19, 20, 22, 23 in units of $e/3$.
[13] Flux limits and mass range depend on charge.
[14] Leptonic quark.
[15] Hadronic quark.
[16] Quark lifetimes $>1\times10^{-8}$ s.
[17] One candidate m <0.17 GeV.

Quark Flux — Cosmic Ray Searches

Shielding values followed with an asterisk indicate altitude in km. Shielding values not followed with an asterisk indicate sea level in kg/cm^2.

FLUX (/cm^2/s/sr)	CHG (e/3)	MASS (GeV)	SHIELDING	EVTS	DOCUMENT ID		TECN
<2.1E−15	±1			0	MORI	91	KAM2
<2.3E−15	±2			0	MORI	91	KAM2
<2.E−10	±1,2		0.3	0	WADA	88	CNTR
	±4		0.3	12	[18] WADA	88	CNTR
	±4		0.3	9	[19] WADA	86	CNTR
<1.E−12	±2,3/2		−70.	0	[20] KAWAGOE	84B	PLAS
<9.E−10	±1,2		0.3	0	WADA	84B	CNTR
<4.E−9	±4		0.3	7	WADA	84B	CNTR
<2.E−12	±1,2,3		−0.3 *	0	MASHIMO	83	CNTR
<3.E−10	±1,2		0.3	0	MARINI	82	CNTR
<2.E−11	±1,2			0	MASHIMO	82	CNTR
<8.E−10	±1,2		0.3	0	[20] NAPOLITANO	82	CNTR
				3	[21] YOCK	78	CNTR
<1.E−9				0	[22] BRIATORE	76	ELEC
<2.E−11	+1			0	[23] HAZEN	75	CC
<2.E−10	+1,2			0	KRISOR	75	CNTR
<1.E−7	+1,2.			0	[23,24] CLARK	74B	CC
<3.E−10	+1	>20		0	KIFUNE	74	CNTR
<8.E−11	+1			0	[23] ASHTON	73	CNTR
<2.E−8	+1,2			0	HICKS	73B	CNTR
<5.E−10	+4		2.8 *	0	BEAUCHAMP	72	CNTR
<1.E−10	+1,2			0	[23] BOHM	72B	CNTR
<1.E−10	+1,2		2.8 *	0	COX	72	ELEC
<3.E−10	+2			0	CROUCH	72	CNTR
<3.E−8			7	0	[22] DARDO	72	CNTR
<4.E−9	+1			0	[23] EVANS	72	CC
<2.E−9		>10		0	[22] TONWAR	72	CNTR
<2.E−10	+1		2.8 *	0	CHIN	71	CNTR
<3.E−10	+1,2			0	[23] CLARK	71B	CC
<1.E−10	+1,2			0	[23] HAZEN	71	CC
<5.E−10	+1,2		3.5 *	0	BOSIA	70	CNTR
	+1,2	<6.5		1	[23] CHU	70	HLBC
<2.E−9	+1			0	FAISSNER	70B	CNTR
<2.E−10	+1,2		0.8 *	0	KRIDER	70	CNTR
<5.E−11	+2			4	CAIRNS	69	CC
<8.E−10	+1,2	<10		0	FUKUSHIMA	69	CNTR
	+2			1	[23,25] MCCUSKER	69	CC
<1.E−10		>5	1.7,3.6	0	[22] BJORNBOE	68	CNTR
<1.E−8	±1,2,4		6.3,.2 *	0	[20] BRIATORE	68	CNTR
<3.E−8		>2		0	FRANZINI	68	CNTR
<9.E−11	±1,2			0	GARMIRE	68	CNTR
<4.E−10	±1			0	HANAYAMA	68	CNTR
<3.E−8		>15		0	KASHA	68	OSPK
<2.E−10	+2			0	KASHA	68B	CNTR
<2.E−10	+4			0	KASHA	68C	CNTR
<2.E−10	+2		6	0	BARTON	67	CNTR
<2.E−7	+4		0.008,0.5 *	0	BUHLER	67	CNTR
<5.E−10	1,2		0.008,0.5 *	0	BUHLER	67B	CNTR
<4.E−10	+1,2			0	GOMEZ	67	CNTR
<2.E−9	+2			0	KASHA	67	CNTR
<2.E−10	+2		220	0	BARTON	66	CNTR
<2.E−9	+1,2		0.5 *	0	BUHLER	66	CNTR
<3.E−9	+1,2			0	KASHA	66	CNTR
<2.E−9	+1,2			0	LAMB	66	CNTR
<2.E−8	+1,2	>7	2.8 *	0	DELISE	65	CNTR
<5.E−8	+2	>2.5	0.5 *	0	MASSAM	65	CNTR
<2.E−8	+1		2.5 *	0	BOWEN	64	CNTR
<2.E−7	+1		0.8	0	SUNYAR	64	CNTR

[18] Distribution in celestial sphere was described as anisotropic.
[19] With telescope axis at zenith angle 40° to the south.
[20] Leptonic quarks.
[21] Lifetime $> 10^{-8}$ s; charge ±0.70, 0.68, 0.42; and mass >4.4, 4.8, and 20 GeV, respectively.
[22] Time delayed air shower search.
[23] Prompt air shower search.
[24] Also $e/4$ and $e/6$ charges.
[25] No events in subsequent experiments.

Quark Density — Matter Searches

For a recent review, see SMITH 89.

QUARKS/ NUCLEON	CHG (e/3)	MASS (GeV)	MATERIAL/METHOD	EVTS	DOCUMENT ID	
<4.E−20	±1,2		meteorites/mag. levitation	0	JONES	89
<1.E−19	±1,2		various/spectrometer	0	MILNER	87
<5.E−22	±1,2		W/levitation	0	SMITH	87
<3.E−20	+1,2		org liq/droplet tower	0	VANPOLEN	87
<6.E−20	−1,2		org liq/droplet tower	0	VANPOLEN	87
<3.E−21	±1		Hg drops-untreated	0	SAVAGE	86
<3.E−22	±1,2		levitated niobium	0	SMITH	86
<2.E−26	±1,2		^{4}He/levitation	0	SMITH	86B
<2.E−20	>±1	0.2–250	niobium+tungs/ion	0	MILNER	85
<1.E−21	±1		levitated niobium	0	SMITH	85
	+1,2	<100	niobium/mass spec	0	KUTSCHERA	84
<5.E−22			levitated steel	0	MARINELLI	84
<9.E−20	±<13		water/oil drop	0	JOYCE	83
<2.E−21	>|±1/2|		levitated steel	0	LIEBOWITZ	83
<1.E−19	±1,2		photo ion spec	0	VANDESTEEG	83
<2.E−20			mercury/oil drop	0	[26] HODGES	81
1.E−20	+1		levitated niobium	4	[27] LARUE	81
1.E−20	−1		levitated niobium	4	[27] LARUE	81
<1.E−21			levitated steel	0	MARINELLI	80B
<6.E−16			helium/mass spec	0	BOYD	79
1.E−20	+1		levitated niobium	2	[27] LARUE	79
<4.E−28			earth+/ion beam	0	OGOROD...	79
<5.E−15	+1		tungs./mass spec	0	BOYD	78
<5.E−16	+3	<1.7	hydrogen/mass spec	0	BOYD	78B
<1.E−21	±2,4		water/ion beam	0	LUND	78
<6.E−15	>1/2		levitated tungsten	0	PUTT	78
<1.E−22			metals/mass spec	0	SCHIFFER	78
<5.E−15			levitated tungsten ox	0	BLAND	77
<3.E−21			levitated iron	0	GALLINARO	77
2.E−21	−1		levitated niobium	1	[27] LARUE	77
4.E−21	+1		levitated niobium	2	[27] LARUE	77
<1.E−13	+3	<7.7	hydrogen/mass spec	0	MULLER	77
<5.E−27			water+/ion beam	0	OGOROD...	77
<1.E−21			lunar+/ion spec	0	STEVENS	76
<1.E−15	+1	<60	oxygen+/ion spec	0	ELBERT	70
<5.E−19			levitated graphite	0	MORPURGO	70
<5.E−23			water+/atom beam	0	COOK	69
<1.E−17	±1,2		levitated graphite	0	BRAGINSK	68
<1.E−17			water+/uv spec	0	RANK	68
<3.E−19	±1		levitated iron	0	STOVER	67
<1.E−10			sun/uv spec	0	[28] BENNETT	66
<1.E−17	+1,2		meteorites+/ion beam	0	CHUPKA	66
<1.E−16	±1		levitated graphite	0	GALLINARO	66
<1.E−22			argon/electrometer	0	HILLAS	59
	−2		levitated oil	0	MILLIKAN	10

[26] Also set limits for $Q = \pm e/6$.
[27] Note that in PHILLIPS 88 these authors report a subtle magnetic effect which could account for the apparent fractional charges.
[28] Limit inferred by JONES 77B.

REFERENCES FOR Free Quark Searches

BASILE	91	NC 104A 405	+Berbiers, Cara Romeo+	(BGNA, INFN, CERN, PLRM+)
HE	91	PR C44 1672	+Price	(UCB)
MATIS	91	NP A525 513c	+Pugh, Alba, Bland, Calloway+	(LBL, SFSU, UCI, LANL)
MORI	91	PR D43 2843	+Oyama, Suzuki, Takahashi+	(Kamiokande II Collab.)
ADACHI	90C	PL B244 352	+Aihara, Doser, Enomoto+	(TOPAZ Collab.)
BOWCOCK	89B	PR D40 263	+Kinoshita, Mauskopf, Pipkin+	(CLEO Collab.)
CALLOWAY	89	PL B232 549	+Alba, Bland, Dickson, Hodges+	(SFSU, UCI, LBL, LANL)
JONES	89	ZPHY C43 349	+Smith, Homer, Lewin, Walford	(LOIC, RAL)
MATIS	89	PR D39 1851	+Pugh, Bland, Calloway+	(LBL, SFSU, UCI, FNAL, LANL)
NAKAMURA	89	PR D39 1261	+Kobayashi, Konaka, Imai, Masaike+	(KYOT, TMTC)
SMITH	89	ARNPS 39 73		(RAL)
ALLASIA	88	PR D37 219	+Angelini, Baldini+	(WA25 Collab.)
HOFFMANN	88	PL B200 583	+Brechtmann, Heinrich, Benton	(USIE, USF)
PHILLIPS	88	NIM A264 125	+Fairbank, Navarro	(STAN)
WADA	88	NC 11C 229	+Yamashita, Yamamoto	(OKAY)
LYONS	87	ZPHY C36 363	+Smith, Homer, Lewin, Walford+	(OXF, RAL, LOIC)
MILNER	87	PR D36 37	+Cooper, Chang, Wilson, Labrenz, McKeown	(CIT)
SHAW	87	PR D36 3533	+Matis, Pugh, Slansky+	(UCI, LBL, LANL, SFSU)
SMITH	87	PL B197 447	+Homer, Lewin, Walford, Jones	(RAL, LOIC)
VANPOLEN	87	PR D36 1983	+Hagstrom, Hirsch	(ANL, LBL)
ABACHI	86C	PR D33 2733	+Shor, Barasch, Carroll+	(UCLA, LBL, UCD)
SAVAGE	86	PL 167B 481	+Bland, Hodges, Huntington, Joyce+	(SFSU)
SMITH	86	PL B171 129	+Homer, Lewin, Walford, Jones	(RAL, LOIC)
SMITH	86B	PL B181 407	+Homer, Lewin, Walford, Jones	(RAL, LOIC)
WADA	86	NC 9C 358		(OKAY)
ALBRECHT	85G	PL 156B 134	+Binder, Harder, Hasemann+	(ARGUS Collab.)
BANNER	85	PL 156B 129	+Bloch, Borer, Borghini+	(UA2 Collab.)
MILNER	85	PRL 54 1472	+Cooper, Chang, Wilson, Labrenz, McKeown	(CIT)
SMITH	85	PL 153B 188	+Homer, Lewin, Walford, Jones	(RAL, LOIC)
AIHARA	84	PRL 52 168	+Alston-Garnjost, Badtke, Bakker+	(TPC Collab.)
AIHARA	84B	PRL 52 2332	+Alston-Garnjost, Badtke, Bakker+	(TPC Collab.)
BARWICK	84	PR D30 691	+Musser, Stevenson	(UCB)
BERGSMA	84B	ZPHY C24 217	+Allaby, Abt, Gemanov+	(CHARM Collab.)
BONDAR	84	JETPL 40 1265	+Kurdadze, Lelchuk, Panin, Sidorov+	(NOVO)
		Translated from ZETFP 40 440.		
GURYN	84	PL 139B 313	+Parker, Fries+	(FRAS, LBL, NWES, STAN, HAWA)
KAWAGOE	84B	LNC 41 604	+Mashimo, Nakamura, Nozaki, Orito	(TOKY)
KUTSCHERA	84	PR D29 791	+Schiffer, Frekers+	(ANL, FNAL)
MARINELLI	84	PL 137B 439	+Morpurgo	(GENO)
WADA	84B	LNC 40 329	+Yamashita, Yamamoto	(OKAY)
AUBERT	83C	PL 133B 461	+Bassompierre, Becks, Best+	(EMC Collab.)
BANNER	83	PL 121B 187	+Bloch, Bonaudi, Borer+	(UA2 Collab.)
JOYCE	83	PRL 51 731	+Abrams, Bland, Johnson, Lindgren+	(SFSU)
LIEBOWITZ	83	PRL 50 1640	+Binder, Ziock	(VIRG)
LINDGREN	83	PRL 51 1621	+Joyce+	(SFSU, UCR, UCI, SLAC, LBL, LANL)
MASHIMO	83	PL 128B 327	+Orito, Kawagoe, Nakamura, Nozaki	(TOKY)
PRICE	83	PRL 50 566	+Tincknell, Tarle, Ahlen, Frankel+	(UCB)
VANDESTEEG	83	PRL 50 1234	+Jongbloets, Wyder	(NIJM)
MARINI	82	PR D26 1777	+Peruzzi, Piccolo+	(FRAS, LBL, NWES, STAN, HAWA)
MARINI	82B	PRL 48 1649	+Peruzzi, Piccolo+	(FRAS, LBL, NWES, STAN, HAWA)
MASHIMO	82	JPSJ 51 3067	+Kawagoe, Koshiba	(TOKY)
NAPOLITANO	82	PR D25 2837	+Besset+	(STAN, FRAS, LBL, NWES, HAWA)
ROSS	82	PL 118B 199	+Ronga, Besset+	(FRAS, LBL, NWES, STAN, HAWA)
HODGES	81	PRL 47 1651	+Abrams, Baden, Bland, Joyce+	(UCR, SFSU)
LARUE	81	PRL 46 967	+Phillips, Fairbank	(STAN)
WEISS	81	PL 101B 439	+Abrams, Alam, Blocker+	(SLAC, LBL, UCB)
BARTEL	80	ZPHY C6 295	+Canzler, Lords, Drumm+	(JADE Collab.)
BASILE	80	LNC 29 251	+Berbiers+	(BGNA, CERN, FRAS, ROMA, BARI)
BUSSIERE	80	NP B174 1	+Giacomelli, Lesquoy+	(BGNA, SACL, LAPP)
MARINELLI	80B	PL 94B 433	+Morpurgo	(GENO)
Also	80	PL 94B 427	Marinelli, Morpurgo	(GENO)
BOYD	79	PRL 43 1288	+Blatt, Donoghue, Dries, Hausman, Suiter	(OSU)

BOZZOLI 79 NP B159 363 +Bussiere, Giacomelli+ (BGNA, LAPP, SACL, CERN)
LARUE 79 PRL 42 142 +Fairbank, Phillips (STAN)
Also 79B PRL 42 1019 Larue, Fairbank, Phillips
OGOROD... 79 JETP 49 953 Ogorodnikov, Samoilov, Solntsev (KIAE)
Translated from ZETF 76 1881.
STEVENSON 79 PR D20 82 (LBL)
BASILE 78 NC 45A 171 +Cara-Romeo, Cifarelli, Contin+ (CERN, BGNA)
BASILE 78B NC 45A 281 +Cara-Romeo, Cifarelli, Contin+ (CERN, BGNA)
BOYD 78 PRL 40 216 +Elmore, Melissinos, Sugarbaker (ROCH)
BOYD 78B PL 72B 484 +Elmore, Nitz, Olsen, Sugarbaker, Warren+ (ROCH)
LUND 78 RA 25 75 +Brandt, Fares (PHIL)
PUTT 78 PR D17 1466 +Yock (AUCK)
SCHIFFER 78 PR D17 2241 +Renner, Gemmell, Mooring (CHIC, ANL)
YOCK 78 PR D18 641 (AUCK)
ANTREASYAN 77 PRL 39 513 +Cocconi, Cronin, Frisch+ (EFI, PRIN)
BASILE 77 NC 40A 41 +Romeo, Cifarelli, Giusti+ (CERN, BGNA)
BLAND 77 PRL 39 369 +Bocobo, Eubank, Royer (SFSU)
GALLINARO 77 PRL 38 1255 +Marinelli, Morpurgo (GENO)
JONES 77B RMP 69 717
LARUE 77 PRL 38 1011 +Fairbank, Hebard (STAN)
MULLER 77 Science 521 +Alvarez, Holley, Stephenson (LBL)
OGOROD... 77 JETP 45 857 Ogorodnikov, Samoilov, Solntsev (KIAE)
Translated from ZETF 72 1633.
BALDIN 76 SJNP 22 264 +Vertogradov, Vishnevsky, Grishkevich+ (JINR)
Translated from YAF 22 512.
BRIATORE 76 NC 31A 553 +Dardo, Piazzoli, Mannocchi+ (LCGT, FRAS, FREI)
STEVENS 76 PR D14 716 +Schiffer, Chupka (ANL)
ALBROW 75 NP B97 189 +Barber+ (CERN, DARE, FOM, LANC, MCHS, UTRE)
FABJAN 75 NP B101 349 +Gruhn, Peak, Sauli, Caldwell+ (CERN, MPIM)
HAZEN 75 NP B95 189 +Hodson, Winterstein, Green, Kass+ (MICH, LEED)
JOVANOV... 75 PL 56B 105 Jovanovich+ (MANI, AACH, CERN, GENO, HARV+)
KRISOR 75 NC 27A 132 (AACH)
CLARK 74B PR D10 2721 +Finn, Hansen, Smith (LLL)
GALIK 74 PR D9 1856 +Jordan, Richter, Seppi, Siemann+ (SLAC, FNAL)
KIFUNE 74 JPSJ 36 629 +Hieda, Kurokawa, Tsunemoto+ (TOKY, KEK)
NASH 74 PRL 32 858 +Yamanouchi, Nease, Sculli (FNAL, CORN, NYU)
ALPER 73 PL 46B 265 + (CERN, LIVP, LUND, BOHR, RHEL, STOH, BERG+)
ASHTON 73 JPA 6 577 +Cooper, Parvaresh, Saleh (DURH)
HICKS 73B NC 14A 65 +Flint, Standil (MANI)
LEIPUNER 73 PRL 31 1226 +Larsen, Sessoms, Smith, Williams+ (BNL, YALE)
BEAUCHAMP 72 PR D6 1211 +Bowen, Cox, Kalbach (ARIZ)
BOHM 72B PRL 28 326 +Diemont, Faissner, Fasold, Krisor+ (AACH)
BOTT 72 PL 40B 693 +Caldwell, Fabjan, Gruhn, Peak+ (CERN, MPIM)
COX 72 PR D6 1203 +Beauchamp, Bowen, Kalbach (ARIZ)
CROUCH 72 PR D5 2667 +Mori, Smith (CASE)
DARDO 72 NC 9A 319 +Navarra, Penengo, Sitte (TORI)
EVANS 72 PRSE A70 143 +Fancey, Muir, Watson (EDIN, LEED)
TONWAR 72 JPA 5 569 +Naranan, Sreekantan (TATA)
ANTIPOV 71 NP B27 374 +Kachanov, Kutjin, Landsberg, Lebedev+ (SERP)
CHIN 71 NC 2A 419 +Hanayama, Hara, Higashi, Tsuji (OSAK)
CLARK 71B PRL 27 51 +Ernst, Finn, Griffin, Hansen, Smith+ (LLL, LBL)
HAZEN 71 PRL 26 582 (MICH)
BOSIA 70 NC 66A 167 +Briatore (TORI)
CHU 70 PRL 24 917 +Kim, Beam, Kwak (OSU, ROSE, KANS)
Also 70B PRL 25 550 Allison, Derrick, Hunt, Simpson, Voyvodic (ANL)
ELBERT 70 NP B20 217 +Erwin, Herb, Nielsen, Petrilak, Weinberg (WISC)
FAISSNER 70B PRL 24 1357 +Holder, Krisor, Mason, Sawaf, Umbach (AACH)
KRIDER 70 PR D1 835 +Bowen, Kalbach (ARIZ)
MORPURGO 70 NIM 79 95 +Gallinaro, Palmieri (GENO)
ALLABY 69B NC 64A 75 +Bianchini, Diddens, Dobinson, Hartung+ (CERN)
ANTIPOV 69 PL 29B 245 +Karpov, Khromov, Landsberg, Lapshin+ (SERP)
ANTIPOV 69B PL 30B 576 +Bolotov, Devishev, Devisheva, Isakov+ (SERP)
CAIRNS 69 PR 186 1394 +McCkusker, Peak, Woolcott (SYDN)
COOK 69 PR 188 2092 +Depasquali, Frauenfelder, Peacock+ (ILL)
FUKUSHIMA 69 PR 178 2058 +Kifune, Kondo, Koshiba+ (TOKY)
MCCUSKER 69 PRL 23 658 +Cairns (SYDN)
BELLAMY 68 PR 166 1391 +Hofstadter, Lakin, Perl, Toner (STAN, SLAC)
BJORNBOE 68 NC B53 241 +Damgard, Hansen+ (BOHR, TATA, BERN, BERG)
BRAGINSK 68 JETP 27 51 +Zeldovich, Martynov, Migulin (MOSU)
Translated from ZETF 54 91.
BRIATORE 68 NC 57A 850 +Castagnoli, Bollini, Massam+ (TORI, CERN, BGNA)
FRANZINI 68 PRL 21 1013 +Shulman (COLU)
GARMIRE 68 PR 166 166 +Leong, Sreekantan (MIT)
HANAYAMA 68 CJP 46 S734 +Hara, Higashi, Kitamura, Miono+ (OSAK)
KASHA 68 PR 172 1297 +Stefanski (BNL, YALE)
KASHA 68B PRL 20 217 +Larsen, Leipuner, Adair (BNL, YALE)
KASHA 68C CJP 46 S730 +Larsen, Leipuner, Adair (BNL, YALE)
RANK 68 PR 176 1635 (MICH)
BARTON 67 PRSL 90 87 (NPOL)
BATHOW 67 PL 25B 163 +Freytag, Schulz, Tesch (DESY)
BUHLER 67 NC 49A 209 +Fortunato, Massam, Zichichi (CERN, BGNA)
BUHLER 67B NC 51A 837 +Dalpiaz, Massam, Zichichi (CERN, BGNA, STRB)
FOSS 67 PL 25B 166 +Garelick, Homma, Lobar, Osborne, Uglum (MIT)
GOMEZ 67 PRL 18 1022 +Kobrak, Moline, Mullins, Orth, VanPutten+ (CIT)
KASHA 67 PR 154 1263 +Leipuner, Wangler, Alspector, Adair (BNL, YALE)
STOVER 67 PR 164 1599 +Moran, Trischka (SYRA)
BARTON 66 PL 21 360 +Stockel (NPOL)
BENNETT 66 PRL 17 1196 (YALE)
BUHLER 66 NC 45A 520 +Fortunato, Massam, Muller+ (CERN, BGNA, STRB)
CHUPKA 66 PRL 17 60 +Schiffer, Stevens (ANL)
GALLINARO 66 PL 23 609 +Morpurgo (GENO)
KASHA 66 PR 150 1140 +Leipuner, Adair (BNL, YALE)
LAMB 66 PRL 17 1068 +Lundy, Novey, Yovanovitch (ANL)
DELISE 65 PR 140B 458 +Bowen (ARIZ)
DORFAN 65 PRL 14 999 +Eades, Lederman, Lee, Ting (COLU)
FRANZINI 65B PRL 14 196 +Leontic, Rahm, Samios, Schwartz (BNL, COLU)
MASSAM 65 NC 40A 589 +Muller, Zichichi (CERN)
BINGHAM 64 PL 9 201 +Dickinson, Diebold, Koch, Leith+ (CERN, EPOL)
BLUM 64 PRL 13 353A +Brandt, Cocconi, Czyzewski, Danysz+ (CERN)
BOWEN 64 PRL 13 728 +Delise, Kalbach, Mortara (ARIZ)
HAGOPIAN 64 PRL 13 280 +Selove, Ehrlich, Leboy, Lanza+ (PENN, BNL)
LEIPUNER 64 PRL 12 423 +Chu, Larsen, Adair (BNL, YALE)
MORRISON 64 PL 9 199 (CERN)
SUNYAR 64 PR 136B 1157 +Schwarzschild, Connors (BNL)
HILLAS 59 Nature 184 B92 +Cranshaw (AERE)
MILLIKAN 10 Phil Mag 19 209 (CHIC)

OTHER RELATED PAPERS

LYONS 85 PRPL C129 225 (OXF)
Review
MARINELLI 82 PRPL 85 161 +Morpurgo (GENO)
Review

Magnetic Monopole Searches

NOTE ON MAGNETIC MONOPOLE SEARCHES

(by W.P. Trower, Virginia Polytechnic Institute and State University)

Although the usual formulation of Maxwell's equations suggests magnetic monopoles, no observed phenomenon requires them for explanation.[1] A monopole anywhere in the universe results in electric charge quantization everywhere, and leads to the prediction of a least magnetic charge $G = e/2\alpha$, the Dirac charge.[2] Recently monopoles have become indispensable in many gauge theories, which endow them with a variety of extraordinarily large masses.

Monopole detectors have predominantly used either induction or ionization. Induction experiments measure the monopole magnetic charge and are independent of monopole electric charge, mass, and velocity. Monopole candidate events (CABRERA 82, CAPLIN 86) in single semiconductor loops have been detected by this method, but no two-loop coincidence has been observed. Ionization experiments rely on a magnetic charge producing more ionization than an electrical charge with the same velocity. However, the ability to distinguish a monopole by ionization diminishes with velocity.

Cosmic rays are the most likely source of massive monopoles, since accelerator energies are insufficient to produce them. Evidence for such monopoles may also be obtained from astrophysical observations.

This compilation is only a guide to the literature, since the quoted experimental limits are often only indicative.

References

1. J.D. Jackson, CERN-77-17 (1977).
2. P.A.M. Dirac, Proc. Royal Soc. London **A133**, 60 (1931).

Monopole Production Cross Section — Accelerator Searches

X-SECT (cm^2)	MASS (GeV)	CHG (g)	ENERGY (GeV)	BEAM	EVTS	DOCUMENT ID		TECN
<2.E−34	<850	≥ 0.5	1800	$p\overline{p}$	0	BERTANI	90	PLAS
<1.2E−33	<800	≥ 1	1800	$p\overline{p}$	0	PRICE	90	PLAS
<1.E−37	<29	1	50–61	e^+e^-	0	KINOSHITA	89	PLAS
<1.E−37	<18	2	50–61	e^+e^-	0	KINOSHITA	89	PLAS
<1.E−38	<17	<1	35	e^+e^-	0	BRAUNSCH...	88B	CNTR
<8.E−37	<24	1	50–52	e^+e^-	0	KINOSHITA	88	PLAS
<1.3E−35	<22	2	50–52	e^+e^-	0	KINOSHITA	88	PLAS
<9.E−37	<4	<0.15	10.6	e^+e^-	0	GENTILE	87	CLEO
<3.E−32	<800	≥ 1	1800	$p\overline{p}$	0	PRICE	87	PLAS
<3.E−38		<3	29	e^+e^-	0	FRYBERGER	84	PLAS
<1.E−31		1,3	540	$p\overline{p}$	0	AUBERT	83B	PLAS
<4.E−38	<10	<6	34	e^+e^-	0	MUSSET	83	PLAS
<8.E−36	<20		52	pp	0	[1] DELL	82	CNTR
<9.E−37	<30	<3	29	e^+e^-	0	KINOSHITA	82	PLAS
<1.E−37	<20	<24	63	pp	0	CARRIGAN	78	CNTR
<1.E−37	<30	<3	56	pp	0	HOFFMANN	78	PLAS
			62	pp	0	[1] DELL	76	SPRK
<4.E−33			300	p	0	[1] STEVENS	76B	SPRK
<1.E−40	<5	<2	70	p	0	[2] ZRELOV	76	CNTR
<2.E−30			300	n	0	[1] BURKE	75	OSPK
<1.E−38			8	ν	0	[3] CARRIGAN	75	HLBC
<5.E−43	<12	<10	400	p	0	EBERHARD	75B	INDU
<2.E−36	<30	<3	60	pp	0	GIACOMELLI	75	PLAS
<5.E−42	<13	<24	400	p	0	CARRIGAN	74	CNTR
<6.E−42	<12	<24	300	p	0	CARRIGAN	73	CNTR
<2.E−36		1	.001	γ	0	[2] BARTLETT	72	CNTR
<1.E−41	<5		70	p	0	GUREVICH	72	EMUL
<1.E−40	<3	<2	28	p	0	AMALDI	63	EMUL
<2.E−40	<3	<2	30	p	0	PURCELL	63	CNTR
<1.E−35	<3	<4	28	p	0	FIDECARO	61	CNTR
<2.E−35	<1	1	6	p	0	BRADNER	59	EMUL

[1] Multiphoton events.
[2] Cherenkov radiation polarization.
[3] Re-examines CERN neutrino experiments.

Monopole Flux — Cosmic Ray Searches

FLUX ($/cm^2/s/sr$)	MASS (GeV)	CHG (g)	COMMENTS ($\beta = v/c$)	EVTS	DOCUMENT ID		TECN
<4.4E−12		1	all β	0	GARDNER	91	INDU
<7.2E−13		1	all β	0	HUBER	91	INDU
<3.7E−15	>E12	1	β=1.E−4	0	[4] ORITO	91	PLAS
<3.2E−16	>E10	1	β>0.05	0	[4] ORITO	91	PLAS
<3.2E−16	>E10–E12	2, 3		0	[4] ORITO	91	PLAS
<3.8E−13		1	all β	0	BERMON	90	INDU
<5.E−16		1	β<1.E−3	0	[5] BEZRUKOV	90	CNTR
<1.8E−14		1	β>1.1E−4	0	[6] BUCKLAND	90	HEPT
<1E−18			3.E−4<β<1.5E−3	0	[7] GHOSH	90	MICA
<7.2E−13		1	all β	0	HUBER	90	INDU
<5.E−12	>E7	1	3.E−4<β<5.E−3	0	BARISH	87	CNTR
<1.E−13			1.E−5<β<1	0	[5] BARTELT	87	SOUD
<1.E−10		1	all β	0	EBISU	87	INDU
<2.E−13			1.E−4<β<6.E−4	0	MASEK	87	HEPT
<2.E−14			4.E−5<β<2.E−4	0	NAKAMURA	87	PLAS
<2.E−14			1.E−3<β<1	0	NAKAMURA	87	PLAS
<5.E−14			9.E−4<β<1.E−2	0	SHEPKO	87	CNTR
<2.E−13			4.E−4<β<1	0	TSUKAMOTO	87	CNTR
<5.E−14		1	all β	1	[8] CAPLIN	86	INDU
<5.E−12		1		0	CROMAR	86	INDU
<1.E−13		1	7.E−4<β	0	HARA	86	CNTR
<7.E−11		1	all β	0	INCANDELA	86	INDU
<1.E−18			4.E−4<β<1.E−3	0	[7] PRICE	86	MICA
<5.E−12		1		0	BERMON	85	INDU
<6.E−12		1		0	CAPLIN	85	INDU
<6.E−10		1		0	EBISU	85	INDU
<3.E−15			5.E−5 ≤ β ≤ 1.E−3	0	[5] KAJITA	85	CNTR
<2.E−21			β<1.E−3	0	[5,9] KAJITA	85	CNTR
<3.E−15			1.E−3<β<1.E−1	0	[5] PARK	85B	CNTR
<5.E−12		1	1.E−4<β<1	0	BATTISTONI	84	NUSX
<7.E−12		1		0	INCANDELA	84	INDU
<7.E−13		1	3.E−4<β	0	[6] KAJINO	84	CNTR
<2.E−12		1	3.E−4<β<1.E−1	0	KAJINO	84B	CNTR
<6.E−13		1	5.E−4<β<1	0	KAWAGOE	84	CNTR
<2.E−14			1.E−3<β	0	[5] KRISHNA...	84	CNTR
<4.E−13		1	6.E−4<β<2.E−3	0	LISS	84	CNTR
<1.E−16			3.E−4<β<1.E−3	0	[7] PRICE	84	MICA
<1.E−13		1	1.E−4<β	0	PRICE	84B	PLAS
<4.E−13		1	6.E−4<β<2.E−3	0	TARLE	84	CNTR
				7	[10] ANDERSON	83	EMUL
<4.E−13		1	1.E−2<β<1.E−3	0	BARTELT	83B	CNTR
<1.E−12		1	7.E−3<β<1	0	BARWICK	83	PLAS
<3.E−13		1	1.E−3<β<4.E−1	0	BONARELLI	83	CNTR
<3.E−12			5.E−4<β<5.E−2	0	[5] BOSETTI	83	CNTR
<4.E−11		1		0	CABRERA	83	INDU
<5.E−15		1	1.E−2<β<1	0	DOKE	83	PLAS
<8.E−15			1.E−4<β<1.E−1	0	[5] ERREDE	83	CNTR
<5.E−12		1	1.E−4<β<3.E−2	0	GROOM	83	CNTR
<2.E−12			6.E−4<β<1	0	MASHIMO	83	CNTR
<1.E−13		1	β=3.E−3	0	ALEXEYEV	82	CNTR
<2.E−12		1	7.E−3<β<6.E−1	0	BONARELLI	82	CNTR
6.E−10		1	all β	1	[11] CABRERA	82	INDU
<2.E−11			1.E−2<β<1.E−1	0	MASHIMO	82	CNTR
<2.E−15			concentrator	0	BARTLETT	81	PLAS
<1.E−13	>1		1.E−3<β	0	KINOSHITA	81B	PLAS
<5.E−11	<E17		3.E−4<β<1.E−3	0	ULLMAN	81	CNTR
<2.E−11			concentrator	0	BARTLETT	78	PLAS
1.E−1	>200	2		1	[12] PRICE	75	PLAS
<2.E−13		>2		0	FLEISCHER	71	PLAS
<1.E−19		>2	obsidian, mica	0	FLEISCHER	69C	PLAS
<5.E−15	<15	<3	concentrator	0	CARITHERS	66	ELEC
<2.E−11		<1–3	concentrator	0	MALKUS	51	EMUL

[4] ORITO 91 limits are functions of velocity. Lowest limits are given here.
[5] Catalysis of nucleon decay; sensitive to assumed catalysis cross section.
[6] Used DKMPR mechanism and Penning effect.
[7] Assumes monopole attaches fermion nucleus.
[8] Limit from combining data of CAPLIN 86, BERMON 85, INCANDELA 84, and CABRERA 83. For a discussion of controversy about CAPLIN 86 observed event, see GUY 87. Also see SCHOUTEN 87.
[9] Based on lack of high- energy solar neutrinos from catalysis in the sun.
[10] Anomalous long-range α (^{4}He) tracks.
[11] CABRERA 82 candidate event has single Dirac charge within ±5%.
[12] ALVAREZ 75, FLEISCHER 75, and FRIEDLANDER 75 explain as fragmenting nucleus. EBERHARD 75 and ROSS 76 discuss conflict with other experiments. HAGSTROM 77 reinterprets as antinucleus. PRICE 78 reassesses.

Monopole Flux — Astrophysics

FLUX ($/cm^2/s/sr$)	MASS (GeV)	CHG (g)	COMMENTS ($\beta = v/c$)	EVTS	DOCUMENT ID		TECN
<1.E−23			Jovian planets		[13] ARAFUNE	85	COSM
<1.E−16	E15		solar trapping	0	BRACCI	85B	COSM
<1.E−18		1		0	[13] HARVEY	84	COSM
<3.E−23			neutron stars		KOLB	84	COSM
<7.E−22			pulsars	0	[13] FREESE	83B	COSM
<1.E−18	<E18	1	intergalactic field	0	[13] REPHAELI	83	COSM
<1.E−23			neutron stars	0	[13] DIMOPOUL...	82	COSM
<5.E−22			neutron stars	0	[13] KOLB	82	COSM
<5.E−15	>E21		galactic halo		SALPETER	82	COSM
<1.E−12	E19	1	β=3.E−3	0	[14] TURNER	82	COSM
<1.E−16		1	galactic field	0	PARKER	70	COSM

[13] Catalysis of nucleon decay.
[14] Re-evaluates PARKER 70 limit for GUT monopoles.

Monopole Density — Matter Searches

DENSITY	CHG (g)	MATERIAL	EVTS	DOCUMENT ID		TECN
<2.E−7/gram	>0.6	Fe ore	0	[15] EBISU	87	INDU
>1.E−14/gram	>1/3	iron aerosols	>1	MIKHAILOV	83	SPEC
<6.E−4/gram		air, seawater	0	CARRIGAN	76	CNTR
<5.E−1/gram	>0.04	11 materials	0	CABRERA	75	INDU
<2.E−4/gram	>0.05	moon rock	0	ROSS	73	INDU
<6.E−7/gram	<140	seawater	0	KOLM	71	CNTR
<1.E−2/gram	<120	manganese nodules	0	FLEISCHER	69	PLAS
<1.E−4/gram	>0	manganese	0	FLEISCHER	69B	PLAS
<2.E−3/gram	<1–3	magnetite, meteor	0	GOTO	63	EMUL
<2.E−2/gram		meteorite	0	PETUKHOV	63	CNTR

[15] Mass 1×10^{14}–1×10^{17} GeV.

Monopole Density — Astrophysics

DENSITY	CHG (g)	MATERIAL	EVTS	DOCUMENT ID		TECN
<1.E−9/gram	1	sun, catalysis	0	[16] ARAFUNE	83	COSM
<6.E−33/nucl	1	moon wake	0	SCHATTEN	83	ELEC
<2.E−28/nucl		earth heat	0	CARRIGAN	80	COSM
<2.E−4/prot		42cm absorption	0	BRODERICK	79	COSM
<2.E−13/m^3		moon wake	0	SCHATTEN	70	ELEC

[16] Catalysis of nucleon decay.

REFERENCES FOR Magnetic Monopole Searches

GARDNER	91	PR D44 622	+Cabrera, Huber, Taber	(STAN)
HUBER	91	PR D44 636	+Cabrera, Taber, Gardner	(STAN)
ORITO	91	PRL 66 1951	+Ichinose, Nakamura+	(TOKY, WASE, NIHO, ICRR)
BERMON	90	PRL 64 839	+Chi, Tsuei+	(IBM, BNL)
BERTANI	90	EPL 12 613	+Giacomelli, Mondardini, Pal+	(BGNA, INFN)
BEZRUKOV	90	SJNP 52 54	+Belolaptikov, Bugaev, Budnev+	(INRM)
		Translated from YAF 52 86.		
BUCKLAND	90	PR D41 2726	+Masek, Vernon, Knapp, Stronsi	(UCSD)
GHOSH	90	EPL 12 25	+Chatterjea	(JADA)
HUBER	90	PRL 64 835	+Cabrera, Tabor, Gardner	(STAN)
PRICE	90	PRL 65 149	+Guiru, Kinoshita	(UCB, HARV)
KINOSHITA	89	PL B228 543	+Fujii, Nakajima+	(HARV, TISA, KEK, UCB, GIFU)
BRAUNSCH...	88B	ZPHY C38 543	Braunschweig, Gerhards, Kirschfink+	(TASSO Collab.)
KINOSHITA	88	PRL 60 1610	+Fujii, Nakajima+	(HARV, TISA, KEK, UCB, GIFU)
BARISH	87	PR D36 2641	+Liu, Lane	(CIT)
BARTELT	87	PR D36 1990	+Courant, Heller+	(Soudan Collab.)
Also	89	PR D40 1701 erratum	Bartelt, Courant, Heller+	(Soudan Collab.)
EBISU	87	PR D36 3359	+Watanabe	(KOBE)
Also	85	JP G11 883	Ebisu, Watanabe	(KOBE)
GENTILE	87	PR D35 1081	+Haas, Hempstead+	(CLEO Collab.)
GUY	87	Nature 325 463		(LOIC)
MASEK	87	PR D35 2758	+Knapp, Miller, Stronski, Vernon, White	(UCSD)
NAKAMURA	87	PL B183 395	+Kawagoe, Yamamoto+	(TOKY, WASE, NIHO)
PRICE	87	PRL 59 2523	+Guoxiao, Kinoshita	(UCB, HARV)
SCHOUTEN	87	JP E20 850	+Caplin, Guy, Hardiman+	(LOIC)
SHEPKO	87	PR D35 2917	+Gagliardi, Green, McIntyre+	(TAMU)
TSUKAMOTO	87	EPL 3 39	+Nagano, Anraku+	(TOKY)
CAPLIN	86	Nature 321 402	+Hardiman, Koratzinos, Schouten	(LOIC)
Also	87	JP E20 850	Schouten, Caplin, Guy, Hardiman+	(LOIC)
Also	87	Nature 325 463	Guy	(LOIC)
CROMAR	86	PRL 56 2561	+Clark, Fickett	(NBSB)
HARA	86	PRL 56 553	+Honda, Ohno+	(TOKY, KYOT, KEK, KOBE)
INCANDELA	86	PR D34 2637	+Frisch, Somalwar, Kuchnir+	(CHIC, FNAL, MICH)
PRICE	86	PRL 56 1226	+Salamon	(UCB)
ARAFUNE	85	PR D32 2586	+Fukugita, Yanagita	(TOKY, KYOT, IBAR)
BERMON	85	PRL 55 1850	+Chaudhari, Chi, Tesche, Tsuei	(IBM)
BRACCI	85B	NP B258 726	+Fiorentini, Mezzorani	(PISA, CAGL)
Also	85	LNC 42 123	Bracci, Fiorentini	(PISA)
CAPLIN	85	Nature 317 234	+Guy, Hardiman, Park, Schouten	(LOIC)
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BATTISTONI	84	PL 133B 454	+Bellotti, Bologna, Campana+	(NUSEX Collab.)
FRYBERGER	84	PR D29 1524	+Coan, Kinoshita, Price	(SLAC, UCB)
HARVEY	84	NP B236 255		(PRIN)
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KAWAGOE	84	LNC 41 315	+Mashimo, Nakamura, Nozaki, Orito	(TOKY)
KOLB	84	APJ 286 702	+Turner	(FNAL, CHIC)
KRISHNA...	84	PL 142B 99	Krishnaswamy, Menon+	(TATA, OSKC, TOKY)
LISS	84	PR D30 884	+Ahlen, Tarle	(UCB, IND, MICH)
PRICE	84	PRL 52 1265	+Guo, Ahlen, Fleischer	(ROMA, UCB, IND, GESC)
PRICE	84B	PL 140B 112		(CERN)
TARLE	84	PRL 52 90	+Ahlen, Liss	(UCB, MICH, IND)
ANDERSON	83	PR D28 2308	+Lord, Strausz, Wilkes	(WASH)

ARAFUNE 83 PL 133B 380 +Fukugita (TOKY, KYOT)
AUBERT 83B PL 120B 465 +Musset, Price, Vialle (CERN, LAPP)
BARTELT 83B PRL 50 655 +Courant, Heller, Joyce, Marshak+ (MINN, ANL)
BARWICK 83 PR D28 2338 +Kinoshita, Price (UCB)
BONARELLI 83 PL 126B 137 +Capiluppi, Dantone (BGNA)
BOSETTI 83 PL 133B 265 +Gorham, Harris, Learned+ (AACH, HAWA, TOKY)
CABRERA 83 PRL 51 1933 +Taber, Gardner, Bourg (STAN)
DOKE 83 PL 129B 370 +Hayahsi, Hamasaki+ (TWAS, TRIK, TTAM, IPCR)
ERREDE 83 PRL 51 245 +Stone, Vander Velde, Bionta+ (IMB Collab.)
FREESE 83B PRL 51 1625 +Turner, Schramm (CHIC)
GROOM 83 PRL 50 573 +Loh, Nelson, Ritson (UTAH, STAN)
MASHIMO 83 PL 128B 327 +Orito, Kawagoe, Nakamura, Nozaki (TOKY)
MIKHAILOV 83 PL 130B 331 (KAZA)
MUSSET 83 PL 128B 333 +Price, Lohrmann (CERN, HAMB)
REPHAELI 83 PL 121B 115 +Turner (CHIC)
SCHATTEN 83 PR D27 1525 (NASA)
ALEXEYEV 82 LNC 35 413 +Boliev, Chudakov, Makoev, Mikheyev+ (INRM)
BONARELLI 82 PL 112B 100 +Capiluppi, Dantone+ (BGNA)
CABRERA 82 PRL 48 1378 (STAN)
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KOLB 82 PRL 49 1373 +Colgate, Harvey (LASL, PRIN)
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ULLMAN 81 PRL 47 289 (LEHM, BNL)
CARRIGAN 80 Nature 288 348 (FNAL)
BRODERICK 79 PR D19 1046 +Ficenec, Teplitz, Teplitz (VPI)
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CARRIGAN 78 PR D17 1754 +Strauss, Giacomelli (FNAL, BGNA)
HOFFMANN 78 LNC 23 357 +Kantardjian, Diliberto, Meddi+ (CERN, ROMA)
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ROSS 76 LBL-4665 (LBL)
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CABRERA 75 Thesis (STAN)
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Also 71 PR D3 56 Carrigan, Nezrick (FNAL)
EBERHARD 75 PR D11 3099 +Ross, Taylor, Alvarez, Oberlack (LBL, MPIM)
EBERHARD 75B LBL-4289 (LBL)
FLEISCHER 75 PRL 35 1412 +Walker (GESC, WUSL)
FRIEDLANDER 75 PRL 35 1167 (WUSL)
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CARRIGAN 73 PR D8 3717 +Nezrick, Strauss (FNAL)
ROSS 73 PR D8 698 +Eberhard, Alvarez, Watt (LBL, SLAC)
Also 71 PR D4 3260 Eberhard, Ross, Alvarez, Watt (LBL, SLAC)
Also 70 Science 167 701 Alvarez, Eberhard, Ross, Watt (LBL, SLAC)
BARTLETT 72 PR D6 1817 +Lahana (COLO)
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Review

Supersymmetric Particle Searches

NOTE ON SUPERSYMMETRY

(by Howard E. Haber, Univ. of Calif., Santa Cruz)

Supersymmetry is an attractive theoretical framework that may permit the consistent unification of particle physics and gravity, which takes place around the Planck scale ($\approx 10^{19}$ GeV).[1–3] However, supersymmetry is clearly not an exact symmetry of nature, and therefore must be broken. In theories of "low-energy" supersymmetry, the effective scale of supersymmetry breaking is tied to the electroweak scale.[4,5] In this way, it is hoped that supersymmetry will ultimately explain the origin of the large hierarchy between the W and Z masses and the Planck scale.

The minimal supersymmetric extension of the Standard Model (MSSM) consists of taking the Standard Model as it is known today (including the as yet undiscovered t-quark) and adding the corresponding supersymmetric partners.[6] In addition, the MSSM contains two Higgs doublets, which is the minimal structure for the Higgs sector of a supersymmetric extension of the Standard Model that generates mass for both "up"-type and "down"-type quarks (and charged leptons).[7,8] Supersymmetric interactions consistent with (global) $B-L$ conservation (B =baryon number and L =lepton number) are included. Finally, the most general soft-supersymmetry-breaking terms are added.[9] If supersymmetry is relevant for explaining the scale of electroweak interactions, then the mass parameters that occur in the soft-supersymmetry-breaking terms must be of order 1 TeV or below.[10] Some bounds on these parameters exist due to the absence of supersymmetry particle production at current accelerators, as well as the absence of any evidence for virtual supersymmetric particle exchange in a variety of Standard Model processes.[11]

As a consequence of $B-L$ invariance, the MSSM possesses a discrete R-parity invariance, where $R=(-1)^{3(B-L)+2S}$ for a particle of spin S.[12] Note that this formula implies that all the ordinary Standard Model particles have even R-parity, whereas the corresponding supersymmetric partners have odd R-parity. The conservation of R-parity in scattering and decay processes has a crucial impact on supersymmetric phenomenology. For example, starting from an initial state involving ordinary (R-even) particles, it follows that supersymmetric particles must be produced in pairs. In general, these particles are highly unstable and decay quickly into lighter states. However, R-parity invariance also implies that the lightest supersymmetric particle (LSP) is absolutely stable, and must eventually be produced at the end of a decay chain of a heavy unstable supersymmetric particle. In order to be consistent with cosmological constraints, the LSP is almost certainly electrically and color neutral.[13] Consequently, the LSP is weakly-interacting in ordinary matter, *i.e.* it behaves like a neutrino and will escape detectors without being directly observed. Thus, the canonical signature for (R-parity conserving) supersymmetric theories is missing (transverse) energy, due to the escape of the LSP. Some model builders attempt to relax the assumption of R-parity conservation.[14] Models of this type must break $B-L$ and are therefore strongly constrained. Nevertheless, because such models cannot be presently ruled out, it is important to allow for the possibility of R-parity violating processes in the search for supersymmetry. In particular, the LSP would be unstable, and this fact (among others) leads to a phenomenology of broken-R-parity models that is very different from that of the MSSM.

In the MSSM, supersymmetry breaking is induced by the soft-supersymmetry breaking terms described above. These terms parametrize our ignorance as to the fundamental mechanism of supersymmetry breaking. If this breaking occurs spontaneously, then (in the absence of supergravity) a massless

Goldstone fermion called the *goldstino* ($\widetilde{G}$) must exist. The goldstino would then be the LSP and could play an important role in supersymmetric phenomenology.[15] In models that incorporate supergravity, this picture changes. If supergravity is spontaneously broken, the goldstino is absorbed ("eaten") by the *gravitino* ($g_{3/2}$), the spin-3/2 partner of the graviton.[16] By this super-Higgs mechanism, the gravitino acquires a mass ($m_{3/2}$). In most models of low-energy supersymmetry, the gravitino mass is of order of the TeV scale, while its couplings are gravitational in strength.[1,17] Such a gravitino would play no role in supersymmetric phenomenology at colliders.

The parameters of the MSSM fall into two classes: a supersymmetry-conserving sector and a supersymmetry-breaking sector. Among the parameters of the supersymmetry conserving sector are: (i) gauge couplings: g_s, g, and g', corresponding to the Standard Model gauge group SU(3)×SU(2)×U(1) respectively; (ii) Higgs Yukawa couplings: λ_e, λ_u, and λ_d (which are 3×3 matrices in flavor space); and (iii) a supersymmetry-conserving Higgs mass parameter μ. The supersymmetry-breaking sector contains the following set of parameters: (i) gaugino Majorana masses M_3, M_2 and M_1 associated with the SU(3), SU(2), and U(1) subgroups of the Standard Model; (ii) scalar mass matrices for the squarks and sleptons; (iii) Higgs-squark-squark trilinear interaction terms (the so-called "A-parameters") and corresponding terms involving the sleptons; and (iv) three scalar Higgs mass parameters—two diagonal and one off-diagonal mass terms for the two Higgs doublets. These three mass parameters can be re-expressed in terms of the two Higgs vacuum expectation values, v_1 and v_2, and one physical Higgs mass. Here, v_1 (v_2) is the vacuum expectation value of the Higgs field which couples exclusively to down-type (up-type) quarks and leptons. Note that $v_1^2 + v_2^2 = (246 \text{ GeV})^2$ is fixed by the W mass (or equivalently by the Fermi constant G_F), while the ratio

$$\tan\beta = v_2/v_1 \qquad (1)$$

is a free parameter of the model. The MSSM contains a number of possible new sources of CP violation. For example, gaugino mass parameters and the A-parameters may be complex. For the most part, complex phases are thought to have little impact on the direct searches for supersymmetric particles, and are usually ignored in experimental analyses.

The supersymmetric partners of the gauge and Higgs bosons are fermions, whose names are obtained by appending "ino" at the end of the corresponding Standard Model particle name. The *gluino* is the color octet Majorana fermion partner of the gluon with mass $M_{\tilde{g}} = |M_3|$. The supersymmetric partners of the electroweak gauge and Higgs bosons (the *gauginos* and *Higgsinos*) can mix. As a result, the physical mass eigenstates are model-dependent linear combinations of these states, called *charginos* and *neutralinos*, which are obtained by diagonalizing the corresponding mass matrices. The chargino mass matrix depends on M_2, μ, $\tan\beta$ and m_W.[18] The corresponding chargino mass eigenstates denoted by $\widetilde{\chi}_1^+$ and $\widetilde{\chi}_2^+$, where the states are ordered such that $M_{\tilde{\chi}_1^+} \leq M_{\tilde{\chi}_2^+}$. The neutralino mass matrix depends on M_1, M_2, μ, $\tan\beta$, m_Z and the weak mixing angle θ_W.[18] The corresponding neutralino eigenstates are usually denoted by $\widetilde{\chi}_i^0$ ($i = 1, \ldots 4$), according to the convention that $M_{\tilde{\chi}_1^0} \leq M_{\tilde{\chi}_2^0} \leq M_{\tilde{\chi}_3^0} \leq M_{\tilde{\chi}_4^0}$. If a chargino or neutralino eigenstate approximates a particular gaugino or Higgsino state, it may be convenient to use the corresponding nomenclature. For example, if M_1 and M_2 are small compared to m_Z (and μ), then the lightest neutralino $\widetilde{\chi}_1^0$ will be nearly a pure photino, $\widetilde{\gamma}$ (the supersymmetric partner of the photon). It is common practice in the literature to reduce the supersymmetric parameter freedom by requiring that all three gaugino mass parameters are equal at some grand unification scale. Then, at the electroweak scale, the gaugino mass parameters can be expressed in terms of one of them (say, M_2). The other two gaugino mass parameters are given by

$$M_3 = (g_s^2/g^2)M_2 \qquad M_1 = (5g'^2/3g^2)M_2 \; . \qquad (2)$$

Having made this assumption, the chargino and neutralino masses and mixing angles depend only on three unknown parameters: the gluino mass, μ, and $\tan\beta$.

The supersymmetric partners of the quarks and leptons are spin-zero bosons: the *squarks*, charged *sleptons* and *sneutrinos*. For a given fermion f, there are two supersymmetric partners $\widetilde{f}_L$ and $\widetilde{f}_R$ which are scalar partners of the corresponding left and right-handed fermion. (There is no $\widetilde{\nu}_R$.) However, in general, $\widetilde{f}_L$ and $\widetilde{f}_R$ are not mass-eigenstates since there is $\widetilde{f}_L$-$\widetilde{f}_R$ mixing which is proportional in strength to the corresponding element of the scalar mass-squared-matrix:[19]

$$M_{LR}^2 = \begin{cases} m_d(A_d - \mu\tan\beta), & \text{for "down"-type } f \\ m_u(A_u - \mu\cot\beta), & \text{for "up"-type } f, \end{cases} \qquad (3)$$

where m_d (m_u) is the mass of the appropriate "down" ("up") type quark or lepton. Here, A_d and A_u are (unknown) soft-supersymmetry-breaking A-parameters and μ and $\tan\beta$ have been defined earlier. Due to the appearance of the *fermion* mass in Eq. 3, one expects M_{LR} to be small compared to the diagonal squark and slepton masses, with the possible exception of the top-squark, since m_t is large. The (diagonal) L and R-type squark and slepton masses are given by[2]

$$M_{\tilde{u}_L}^2 = M_{\widetilde{Q}}^2 + m_u^2 + m_Z^2\cos 2\beta(\tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W) \qquad (4)$$

$$M_{\tilde{u}_R}^2 = M_{\widetilde{U}}^2 + m_u^2 + \tfrac{2}{3}m_Z^2\cos 2\beta\sin^2\theta_W \qquad (5)$$

$$M_{\tilde{d}_L}^2 = M_{\widetilde{Q}}^2 + m_d^2 - m_Z^2\cos 2\beta(\tfrac{1}{2} - \tfrac{1}{3}\sin^2\theta_W) \qquad (6)$$

$$M_{\tilde{d}_R}^2 = M_{\widetilde{D}}^2 + m_d^2 - \tfrac{1}{3}m_Z^2\cos 2\beta\sin^2\theta_W \qquad (7)$$

$$M_{\tilde{\nu}}^2 = M_{\widetilde{L}}^2 + \tfrac{1}{2}m_Z^2\cos 2\beta \qquad (8)$$

$$M_{\tilde{e}_L}^2 = M_{\widetilde{L}}^2 + m_e^2 - m_Z^2\cos 2\beta(\tfrac{1}{2} - \sin^2\theta_W) \qquad (9)$$

$$M_{\tilde{e}_R}^2 = M_{\widetilde{E}}^2 + m_e^2 - m_Z^2\cos 2\beta\sin^2\theta_W \; . \qquad (10)$$

The soft-supersymmetry-breaking parameters: $M_{\widetilde{Q}}$, $M_{\widetilde{U}}$, $M_{\widetilde{D}}$, $M_{\widetilde{L}}$, and $M_{\widetilde{E}}$ are unknown parameters. In the equations above, the notation of first generation fermions has been used and generational indices have been suppressed. Further complications such as intergenerational mixing are possible, although there are some constraints from the nonobservation of flavor changing neutral currents.[20]

Additional assumptions concerning the above parameters at the Planck scale are often invoked in order to reduce the parameter freedom. For example, model-building exercises (based on "low-energy" supergravity models) give[21] $M_{\tilde{L}} \approx M_{\tilde{E}} < M_{\tilde{Q}} \approx M_{\tilde{U}} \approx M_{\tilde{D}}$ with the squark masses somewhere between a factor of 1–4 larger than the slepton masses (neglecting once again generational distinctions). The first two generations are thought to be nearly degenerate in mass, while $M_{\tilde{Q}_3}$ and $M_{\tilde{U}_3}$ are typically reduced by a factor of 1–3 from the other soft-supersymmetry-breaking masses because of renormalization effects due to the heavy top quark mass. As a result, four or five flavors of squarks (with two squark eigenstates per flavor) will be nearly mass-degenerate and somewhat heavier than six flavors of degenerate sleptons (with two per flavor for the charged sleptons and one per flavor for the sneutrinos). The top-squark masses are sensitive to the strength of the $\widetilde{t}_L$–$\widetilde{t}_R$ mixing.

Finally, consider the Higgs sector of the minimal supersymmetric model.[22] Although this is not a supersymmetric sector, supersymmetry imposes very strong constraints on the Higgs bosons of the model. There are five physical Higgs particles in this model: a charged Higgs pair ($H^{\pm}$), two CP-even neutral Higgs bosons (denoted by H_1^0 and H_2^0 where $m_{H_1^0} \leq m_{H_2^0}$ and one CP-odd neutral Higgs boson (A^0). In addition there are two parameters: $\tan\beta$ [defined in Eq. 1] and an angle α which indicates the amount of mixing of the original $Y = \pm 1$ Higgs doublet states in the physical CP-even scalars. The Higgs masses, mixing angle, and Higgs couplings are determined at tree-level in terms of just two parameters: $\tan\beta$ and m_{A^0}. When one-loop radiative corrections are incorporated, additional parameters of the supersymmetric model enter as well via virtual loops. The impact of these corrections may be significant. For example, one can show that at tree-level, the MSSM predicts $m_{H_1^0} \leq m_Z$.[7,8] If true, this would imply that experiments to be performed at LEP-II operating at its maximum energy and luminosity may be able to either discover the Higgs boson or rule out the MSSM. However, this Higgs mass bound need not be respected when radiative corrections are incorporated. The size of the radiative corrections may be surprisingly large! A number of groups have recently addressed the question of one-loop radiative corrections to the light Higgs scalar mass in the MSSM.[23,24] The results indicate a very large positive mass shift to the light Higgs mass if the top-quark mass is large. For example, in Ref. 23, the following upper bound was obtained for $m_{H_1^0}$ (assuming $m_{A^0} > m_Z$) in the limit of $m_Z \ll m_t \ll M_{\tilde{t}}$ [where top-squark ($\tilde{t}_L$–$\tilde{t}_R$) mixing is neglected]

$$m_{H_1^0} \lesssim m_Z^2 + \frac{3g^2 m_Z^4}{16\pi^2 m_W^2}\left\{ \ln\left(\frac{M_{\tilde{t}}^2}{m_t^2}\right)\left[\frac{2m_t^4 - m_t^2 m_Z^2}{m_Z^4}\right] + \frac{m_t^2}{3m_Z^2}\right\}. \quad (11)$$

For $M_{\tilde{t}} = 1$ TeV, Eq. 11 yields a positive mass shift for $m_{H_1^0}$ of about 20 GeV for $m_t = 150$ GeV, and 50 GeV for $m_t = 200$ GeV. Even when $\tan\beta = 1$ (so that $m_{H_1^0} = 0$ at tree-level), there is a large shift in $m^2_{H_1^0}$ due to radiative corrections of similar size. Radiative corrections also alter the tree-level predictions for the H_2^0 and $H^{\pm}$ masses. Clearly, the radiative corrections to the Higgs masses will have a significant impact on the search for the Higgs bosons of the MSSM at LEP and LEP-II.[25]

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MINIMAL SUPERSYMMETRIC STANDARD MODEL ASSUMPTIONS

All results shown below (except where stated otherwise) are based on the Minimal Supersymmetric Standard Model (MSSM) as described in the Note on Supersymmetry. This includes the assumption that R-parity is conserved. In addition the following assumptions are made in most cases:

1) The $\widetilde{\chi}_1^0$ (or $\widetilde{\gamma}$) is the lightest supersymmetric particle (LSP).
2) the mass of exchanged supersymmetric particles is less than about 250 GeV (most limits are not sensitive to this requirement).
3) $m(\widetilde{f}_L) = m(\widetilde{f}_R)$ where $\widetilde{f}_L$ and $\widetilde{f}_R$ refer to the scalar partners of left-and right-handed fermions.

Limits involving different assumptions either are identified with comments or are in the miscellaneous section.

When needed, specific assumptions of the eigenstate content of neutralinos and charginos are indicated (use of the notation $\widetilde{\gamma}$ (photino), $\widetilde{H}$ (Higgsino), $\widetilde{W}$ (w-ino), and $\widetilde{Z}$ (z-ino) indicates the approximation of a pure state was made).

$\widetilde{\chi}_1^0$ MASS LIMIT

If $\widetilde{\chi}_1^0$ is light compared to the Z, it is likely to be dominantly either $\widetilde{\gamma}$ (photino) or $\widetilde{H}$ (higgsino) and to be the lightest supersymmetric particle (LSP). See also neutralino section below.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
>20	95	[1] DECAMP	92	ALEP	$\widetilde{\chi}_1^0$, $\tan\beta>3$
>18.4	90	[2] HIDAKA	91	RVUE	$\widetilde{\chi}_1^0$
none 100 eV – 15 GeV		[3] SREDNICKI	88	COSM	$\widetilde{\gamma}$; $m(\widetilde{f})$=100 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>18.8		[4] BAER	91	RVUE	$\widetilde{\chi}_1^0$; $\tan\beta > 1.6$
		[5] BOTTINO	91	RVUE	Dark matter
		[6] GELMINI	91	COSM	
		[7] KAMIONKOW..	91	RVUE	Dark matter
		[8] MORI	91B	KAMI	Dark matter
		[9] OLIVE	91	COSM	
		[10] ROSZKOWSKI	91	COSM	
		[11] ELLIS	90	ASTR	
		[12] GRIEST	90	COSM	Cosmic density
		[13] GRIFOLS	90	ASTR	$\widetilde{\gamma}$; SN1987A
		[14] KRAUSS	90	ASTR	
> (10–13)	90	[15] ROSZKOWSKI	90	RVUE	$\widetilde{\chi}_1^0$; $\tan\beta \geq 1$
>5 GeV	90	[16] HEARTY	89	ASP	$\widetilde{\gamma}$; for $m(\widetilde{e})$<55 GeV
		[9] OLIVE	89	COSM	
> 100 eV		[17] ELLIS	88B	ASTR	$\widetilde{\gamma}$; SN 1987A
none 4–15 GeV		[18] OLIVE	88	COSM	
none 100 eV – (5–7) GeV		[3] SREDNICKI	88	COSM	$\widetilde{\gamma}$; $m(\widetilde{f})$=60 GeV
none 100 eV–5 GeV		[3] ELLIS	84	COSM	$\widetilde{\gamma}$; for $m(\widetilde{f})$=100 GeV
		[3] GOLDBERG	83	COSM	
		[19] KRAUSS	83	COSM	
		[3] VYSOTSKII	83	COSM	

[1] DECAMP 92 result is within minimal supersymmetry. For $\tan\beta > 2$ the limit is >13 GeV.
[2] HIDAKA 91 limit obtained from LEP and preliminary CDF results (as analyzed in BAER 91) within minimal supersymmetry with gaugino-mass unification condition.
[3] These authors require that relic $\widetilde{\gamma}$'s from the big bang do not generate too large a contribution to the energy density of the universe.
[4] BAER 91 limit obtained from LEP and preliminary CDF results within minimal supersymmetry with gaugino-mass unification condition assuming $\tan\beta > 1.6$.
[5] BOTTINO 91 excluded a region in $M_2-\mu$ plane using upgoing muon data from Kamioka experiment, assuming that the dark matter surrounding us is composed of neutralinos and that the Higgs boson
[6] GELMINI 91 exclude a region in $M_2-\mu$ plane using dark matter searches.
[7] KAMIONKOWSKI 91 excludes a region in the M_2–μ plane using IMB limit on upgoing muons originated by energetic neutrinos from neutralino annihilation in the sun, assuming that the dark matter is composed of neutralinos and that $m(H_1^0) \lesssim 50$ GeV. See Fig. 8 in the paper.
[8] MORI 91B exclude a part of the region in the M_2–μ plane with $m(\widetilde{\chi}_1^0) \lesssim 80$ GeV using a limit on upgoing muons originated by energetic neutrinos from neutralino annihilation in the sun, assuming that the dark matter surrounding us is composed of neutralinos and that $m(H_1^0) \lesssim 80$ GeV.
[9] Mass of the bino (=LSP) is limited to $m(\widetilde{B}) \lesssim 350$ GeV. Mass of the higgsino (=LSP) is limited to $m(\widetilde{H}) \lesssim 1$ TeV.
[10] See Figs. 2, 3 of ROSZKOWSKI 91 for the region in $M_2-\mu$ space consistent with cosmic density.
[11] ELLIS 90 find $m(\widetilde{\chi}_1^0) > 20$ GeV for $\widetilde{\chi}_1^0$ that is mainly gaugino.
[12] Mass of the bino (=LSP) is limited to $m(\widetilde{B}) \lesssim 550$ GeV. Mass of the higgsino (=LSP) is limited to $m(\widetilde{H}) \lesssim 3.2$ TeV.
[13] GRIFOLS 90 argues that SN1987A data exclude a light photino ($\lesssim$ 1 MeV) if $m(\widetilde{q}) <$ 1.1 TeV, $m(\widetilde{e}) < 0.83$ TeV. is not too heavy.
[14] KRAUSS 90 excludes a region in $M_2-\mu$ plane using LEP searches and relic densities from the Big Bang.
[15] ROSZKOWSKI 90 limit obtained from ALEPH and CDF/UA2 results within minimal supersymmetry with gaugino-mass unification condition assuming $\tan\beta \geq 1$.
[16] HEARTY 89 assumed pure $\widetilde{\gamma}$ eigenstate and $m(\widetilde{e}_L) = m(\widetilde{e}_R)$. There is no limit for $m(\widetilde{e})$ >58 GeV. Uses $e^+e^- \rightarrow \gamma\widetilde{\gamma}\widetilde{\gamma}$.
[17] ELLIS 88B argues that the observed neutrino flux from SN 1987A is inconsistent with a light photino if 60 GeV $\lesssim m(\widetilde{q}) \lesssim$ 2.5 TeV. If m(higgsino) is O(100 eV) the same argument leads to limits on the ratio of the two Higgs v.e.v.'s.
[18] OLIVE 88 result assumes that photinos make up the dark matter in the galactic halo. Limit is based on annihilations in the sun and is due to an absence of high energy neutrinos detected in underground experiments. The limit is model dependent.
[19] KRAUSS 83 finds $m(\widetilde{\gamma})$ not 30 eV to 2.5 GeV. KRAUSS 83 takes into account the gravitino decay. Find that limits depend strongly on reheated temperature. For example a new allowed region $m(\widetilde{\gamma})$ = 4–20 MeV exists if m(gravitino) <40 TeV. See figure 2.

$\widetilde{\chi}_2^0$, $\widetilde{\chi}_3^0$, $\widetilde{\chi}_4^0$ (Neutralinos) MASS LIMITS

Neutralinos are unknown mixtures of photinos, z-inos, and neutral higgsinos (the supersymmetric partners of photons and of Z and Higgs bosons). The limits here apply only to $\widetilde{\chi}_2^0$, $\widetilde{\chi}_3^0$, and $\widetilde{\chi}_4^0$. $\widetilde{\chi}_1^0$ is the lightest supersymmetric particle (LSP); see $\widetilde{\chi}_1^0$ Mass Limits. It is not possible to quote rigorous mass limits because they are extremely model dependent; i.e. they depend on branching ratios of various $\widetilde{\chi}^0$ decay modes, on the masses of decay products ($\widetilde{e}$, $\widetilde{\gamma}$, $\widetilde{q}$, $\widetilde{g}$), and on the $\widetilde{e}$ mass exchanged in $e^+e^- \rightarrow \widetilde{\chi}_i^0\widetilde{\chi}_j^0$. Often limits are given as contour plots in the $m(\widetilde{\chi}^0) - m(\widetilde{e})$ plane vs other parameters. When specific assumptions are made, e.g, the neutralino is a pure photino ($\widetilde{\gamma}$), pure z-ino ($\widetilde{Z}$), or pure neutral higgsino ($\widetilde{H}^0$), the neutralinos will be labelled as such.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 45	95	[20] DECAMP	92	ALEP	$\widetilde{\chi}_2^0$, $\tan\beta>3$
> 45	95	[21] HIDAKA	91	RVUE	$\widetilde{\chi}_2^0$
> 70	95	[21] HIDAKA	91	RVUE	$\widetilde{\chi}_3^0$
>108	95	[21] HIDAKA	91	RVUE	$\widetilde{\chi}_4^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[22] ABREU	90G	DLPH	$Z \rightarrow \widetilde{\chi}^0\widetilde{\chi}^0$
		[23] AKRAWY	90N	OPAL	$Z \rightarrow \widetilde{\chi}^0\widetilde{\chi}^0$
> 57	90	[24] BAER	90	RVUE	$\widetilde{\chi}_3^0$; $\Gamma(Z)$; $\tan\beta > 1$
		[25] BARKLOW	90	MRK2	$Z \rightarrow \widetilde{\chi}_1^0\widetilde{\chi}_2^0$, $\widetilde{\chi}_2^0\widetilde{\chi}_2^0$
		[26] DECAMP	90K	ALEP	$Z \rightarrow \widetilde{\chi}^0\widetilde{\chi}^0$
> 41	95	[27] SAKAI	90	AMY	$e^+e^- \rightarrow \widetilde{H}_1^0\widetilde{H}_2^0$ ($\widetilde{H}_2^0 \rightarrow f\bar{f}\widetilde{H}_1^0$)
> 31	95	[28] BEHREND	87B	CELL	$e^+e^- \rightarrow \widetilde{\gamma}\widetilde{Z}$ ($\widetilde{Z} \rightarrow q\bar{q}\widetilde{\gamma}$), $m(\widetilde{e})$ < 70 GeV
> 30	95	[29] BEHREND	87B	CELL	$e^+e^- \rightarrow \widetilde{\gamma}\widetilde{Z}$ ($\widetilde{Z} \rightarrow q\bar{q}\widetilde{g}$)
> 31.3	95	[30] BEHREND	87B	CELL	$e^+e^- \rightarrow \widetilde{H}_1^0\widetilde{H}_2^0$ ($\widetilde{H}_2^0 \rightarrow f\bar{f}\widetilde{H}_1^0$)
> 22	95	[31] BEHREND	87B	CELL	$e^+e^- \rightarrow \gamma\widetilde{\gamma}\widetilde{Z}$ ($\widetilde{Z} \rightarrow \bar{\nu}\nu$)
		[32] AKERLOF	85	HRS	$e^+e^- \rightarrow \widetilde{\gamma}\widetilde{\chi}^0$ ($\widetilde{\chi}^0 \rightarrow q\bar{q}\widetilde{\gamma}$)
none 1–21	95	[33] BARTEL	85L	JADE	$e^+e^- \rightarrow \widetilde{H}_1^0\widetilde{H}_2^0$, $\widetilde{H}_2^0 \rightarrow f\bar{f}\widetilde{H}_1^0$
		[34] BEHREND	85	CELL	$e^+e^- \rightarrow$ monojet + X
> 35	95	[35] ADEVA	84B	MRKJ	$e^+e^- \rightarrow \gamma\widetilde{Z}$ ($\widetilde{Z} \rightarrow \ell\bar{\ell}\widetilde{\gamma}$)
> 28	95	[36] BARTEL	84C	JADE	$e^+e^- \rightarrow \gamma\widetilde{Z}$ ($\widetilde{Z} \rightarrow f\bar{f}\widetilde{\gamma}$)
		[37] ELLIS	84	COSM	

[20] DECAMP 92 result is within minimal supersymmetry. For $\tan\beta > 2$ the limit is >40 GeV; and it disappears for $\tan\beta < 1.6$.
[21] HIDAKA 91 limit obtained from LEP and preliminary CDF results (as analyzed in BAER 91) within minimal supersymmetry with gaugino-mass unification condition.
[22] ABREU 90G exclude $B(Z \rightarrow \widetilde{\chi}_1^0\widetilde{\chi}_2^0) \geq 10^{-3}$ and $B(Z \rightarrow \widetilde{\chi}_2^0\widetilde{\chi}_2^0) \geq 2\times10^{-3}$ assuming $\widetilde{\chi}_2^0 \rightarrow \widetilde{\chi}_1^0 f\bar{f}$ via virtual Z. These exclude certain regions in model parameter space, see their Fig. 5.
[23] AKRAWY 90N exclude $B(Z \rightarrow \widetilde{\chi}_1^0\widetilde{\chi}_2^0) \gtrsim$ 3–5 $\times 10^{-4}$ assuming $\widetilde{\chi}_2^0 \rightarrow \widetilde{\chi}_1^0 f\bar{f}$ or $\widetilde{\chi}_1^0\gamma$ for most accessible masses. These exclude certain regions in model parameter space, see their Fig. 7.
[24] BAER 90 is independent of decay modes. Limit from analysis of supersymmetric parameter space restrictions implied by $\Delta\Gamma(Z) <$ 120 MeV. These result from decays of Z to all combinations of $\widetilde{\chi}_i^{\pm}$ and $\widetilde{\chi}_i^0$. Minimal supersymmetry with $\tan\beta > 1$ is assumed.
[25] See Figs. 4, 5 in BARKLOW 90 for the excluded regions.
[26] DECAMP 90K exclude certain regions in model parameter space, see their figures.
[27] SAKAI 90 assume $m(\widetilde{H}_1^0) = 0$. The limit is for $m(\widetilde{H}_2^0)$.
[28] Pure $\widetilde{\gamma}$ and pure $\widetilde{Z}$ eigenstates. $B(\widetilde{Z} \rightarrow q\bar{q}\widetilde{\gamma}) = 0.60$ and $B(\widetilde{Z} \rightarrow e^+e^-\widetilde{\gamma}) = 0.13$. $m(\widetilde{e}_L) = m(\widetilde{e}_R) < 70$ GeV. $m(\widetilde{\gamma}) < 10$ GeV.
[29] Pure $\widetilde{\gamma}$ and pure $\widetilde{Z}$ eigenstates. $B(\widetilde{Z} \rightarrow q\bar{q}\widetilde{g}) = 1$. $m(\widetilde{e}_L) = m(\widetilde{e}_R) < 70$ GeV. $m(\widetilde{\gamma}) = 0$.
[30] Pure higgsino. The LSP is the other higgsino and is taken massless. Limit degraded if $\widetilde{\chi}^0$ not pure higgsino or if LSP not massless.
[31] Pure $\widetilde{\gamma}$ and pure $\widetilde{Z}$ eigenstates. $B(\widetilde{Z} \rightarrow \bar{\nu}\nu) = 1$. $m(\widetilde{e}_L) = m(\widetilde{e}_R) = 26$ GeV. $m(\widetilde{\gamma}) =$ 10 GeV. No excluded region remains for $m(\widetilde{e})$ >30 GeV.
[32] AKERLOF 85 is e^+e^- monojet search motivated by UA1 monojet events. Observed only one event consistent with $e^+e^- \rightarrow \widetilde{\gamma} + \widetilde{\chi}^0$ where $\widetilde{\chi}^0 \rightarrow$ monojet. Assuming that missing-p_T is due to $\widetilde{\gamma}$, and monojet due to $\widetilde{\chi}^0$, limits dependent on the mixing and $m(\widetilde{e})$ are given, see their figure 4.
[33] BARTEL 85L assume $m(\widetilde{H}_1^0) = 0$, $\Gamma(Z \rightarrow \widetilde{H}_1^0\widetilde{H}_2^0) \gtrsim \frac{1}{2}\Gamma(Z \rightarrow \nu_e\bar{\nu}_e)$. The limit is for $m(\widetilde{H}_2^0)$.

[34] BEHREND 85 find no monojet at E_{cm} = 40–46 GeV. Consider $\widetilde{\chi}^0$ pair production via Z^0. One is assumed as massless and escapes detector. Limit is for the heavier one, decaying into a jet and massless $\widetilde{\chi}^0$. Both $\widetilde{\chi}^0$'s are assumed to be pure higgsino. For these very model-dependent results, BEHREND 85 excludes m = 1.5–19.5 GeV.

[35] ADEVA 84B observed no events with signature of acoplanar lepton pair with missing energy. Above example limit is for $m(\widetilde{\gamma})$ <2 GeV and $m(\widetilde{e})$ <40 GeV, and assumes $B(\widetilde{Z} \to \mu^+\mu^-\widetilde{\gamma}) = B(\widetilde{Z} \to e^+e^-\widetilde{\gamma}) = 0.10$. BR = 0.05 gives 33.5 GeV limit.

[36] BARTEL 84C search for $e^+e^- \to \widetilde{Z} + \widetilde{\gamma}$ with $\widetilde{Z} \to \widetilde{\gamma} + e^+e^-, \mu^+\mu^-, q\overline{q}$, etc. They see no acoplanar events with missing-p_T due to two $\widetilde{\gamma}$'s. Above example limit is for $m(\widetilde{e})$ = 40 GeV and for light stable $\widetilde{\gamma}$ with $B(\widetilde{Z} \to e^+e^-\widetilde{\gamma}) = 0.1$.

[37] ELLIS 84 find if lightest neutralino is stable, then $m(\widetilde{\chi}^0)$ not 100 eV – 2 GeV (for $m(\widetilde{q})$ = 40 GeV). The upper limit depends on $m(\widetilde{q})$ (similar to the $\widetilde{\gamma}$ limit) and on nature of $\widetilde{\chi}^0$. For pure higgsino the higher limit is 5 GeV.

$\widetilde{\chi}_1^\pm$, $\widetilde{\chi}_2^\pm$ (Charginos) MASS LIMITS

Charginos ($\widetilde{\chi}^\pm$'s) are unknown mixtures of w-inos and charged higgsinos (the supersymmetric partners of W and Higgs bosons). Mass limits are relatively model dependent, so assumptions concerning branching ratios need to be specified. When specific assumptions are made, e.g. the chargino is a pure w-ino ($\widetilde{W}$) or pure charged higgsino ($\widetilde{H}^\pm$), the charginos will be labelled as such.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>45.2	95	[38] DECAMP	92	ALEP	$Z \to \widetilde{\chi}^+\widetilde{\chi}^-$, all $m(\widetilde{\chi}_1^0)$
>47	95	[38] DECAMP	92	ALEP	$Z \to \widetilde{\chi}^+\widetilde{\chi}^-$, $m(\widetilde{\chi}_1^0)$ <41 GeV
>99	95	[39] HIDAKA	91	RVUE	$\widetilde{\chi}_2^\pm$
>44.5	95	[40] ABREU	90G	DLPH	$Z \to \widetilde{\chi}^+\widetilde{\chi}^-$, $m(\widetilde{\gamma})$ < 20 GeV
>45	95	[41] AKRAWY	90D	OPAL	$e^+e^- \to \widetilde{\chi}^+\widetilde{\chi}^-$; $m(\widetilde{\gamma})$< 20 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>43	90	[42] DREES	91	RVUE	$\widetilde{\chi}_1^\pm$
>45	95	ABREU	90G	DLPH	Stable $\widetilde{\chi}^\pm$, $\widetilde{\chi}^+\widetilde{\chi}^-$
>28.2	95	ADACHI	90C	TOPZ	Stable $\widetilde{\chi}^\pm$, $\widetilde{\chi}^+\widetilde{\chi}^-$
>45	95	[43] AKESSON	90B	UA2	$p\overline{p} \to ZX$ $(Z \to \widetilde{W}^+\widetilde{W}^-)$
>37	90	[44] BAER	90	RVUE	$\Gamma(Z)$; $\tan\beta > 1$
>45	95	[45] BARKLOW	90	MRK2	$Z \to \widetilde{W}^+\widetilde{W}^-$
>42	95	[46] BARKLOW	90	MRK2	$Z \to \widetilde{H}^+\widetilde{H}^-$
>44.5	95	[47] DECAMP	90C	ALEP	$e^+e^- \to \widetilde{\chi}^+\widetilde{\chi}^-$; $m(\widetilde{\gamma})$ < 28 GeV
>25.5	95	[48] ADACHI	89	TOPZ	$e^+e^- \to \widetilde{\chi}^+\widetilde{\chi}^-$
>44	95	[49] ADEVA	89B	L3	$e^+e^- \to \widetilde{W}^+\widetilde{W}^-$, $\widetilde{W} \to \ell\widetilde{\nu}$ or $\ell\nu\widetilde{\gamma}$
>45	90	[50] ANSARI	87D	UA2	$p\overline{p} \to ZX$ $(Z \to \widetilde{W}^+\widetilde{W}^-$, $\widetilde{W}^\pm \to e^\pm\widetilde{\nu})$
>40		[51] BAER	87B	RVUE	$p\overline{p} \to W/Z\,X$ $(W/Z \to \widetilde{W}, \widetilde{Z}, \widetilde{\gamma})$

[38] DECAMP 92 limit is for a general $\widetilde{\chi}^\pm$ (all contents).

[39] HIDAKA 91 limit obtained from LEP and preliminary CDF results (as analyzed in BAER 91) within minimal supersymmetry with gaugino-mass unification condition.

[40] ABREU 90G limit is for a general $\widetilde{\chi}^\pm$. They assume charginos have a three-body decay such as $\ell^+\nu\widetilde{\gamma}$.

[41] AKRAWY 90D assume charginos have three-body decay such as $\ell^+\nu\widetilde{\gamma}$ (i.e. — $m(\widetilde{\nu})$ > $m(\widetilde{\chi}^+)$). A two-body decay, $\widetilde{\chi}^+ \to \ell\widetilde{\nu}$ would have been seen by their search for acoplanar leptons. The result is independent of the hadronic branching ratio. They search for acoplanar electromagnetic clusters and quark jets.

[42] DREES 91 limit obtained from LEP results within minimal supersymmetry with gaugino-mass unification condition. They make use of DECAMP 90C analysis plus additional constraint from total Z width.

[43] AKESSON 90B assume $\widetilde{W} \to e\widetilde{\nu}$ with B > 20% and $m(\widetilde{\nu})$ = 0. The limit disappears if $m(\widetilde{\nu})$ > 30 GeV.

[44] BAER 90 is independent of decay modes. Limit from analysis of supersymmetric parameter space restrictions implied by $\Delta\Gamma(Z)$ < 120 MeV. These result from decays of Z to all combinations of $\widetilde{\chi}_i^\pm$ and $\widetilde{\chi}_i^0$. Minimal supersymmetry with $\tan\beta$ > 1 is assumed.

[45] BARKLOW 90 assume 100% $\widetilde{W} \to W^*\widetilde{\chi}_1^0$. Valid up to $m(\widetilde{\chi}_1^0) \lesssim [m(\widetilde{W})$ – 5 GeV].

[46] BARKLOW 90 assume 100% $\widetilde{H} \to H^*\widetilde{\chi}_1^0$. Valid up to $m(\widetilde{\chi}_1^0) \lesssim [m(\widetilde{H})$ – 8 GeV].

[47] DECAMP 90C assume charginos have three-body decay such as $\ell^+\nu\widetilde{\gamma}$ (i.e.—$m(\widetilde{\nu})$ > $m(\widetilde{\chi}^+)$), and branching ratio to each lepton is 11%. They search for acoplanar dimuons, dielectrons, and μe events. Limit valid for $m(\widetilde{\gamma})$ < 28 GeV.

[48] ADACHI 89 assume only single photon annihilation in the production. The limit applies for arbitrary decay branching ratios with $B(\widetilde{\chi} \to e\nu\widetilde{\gamma}) + B(\widetilde{\chi} \to \mu\nu\widetilde{\gamma}) + B(\widetilde{\chi} \to \tau\nu\widetilde{\gamma}) + B(\widetilde{\chi} \to q\overline{q}\widetilde{\gamma}) = 1$ (lepton universality is *not* assumed). The limit is for $m(\widetilde{\gamma})$ = 0 but a very similar limit is obtained for $m(\widetilde{\gamma})$ = 10 GeV. For $B(\widetilde{\chi} \to q\overline{q}\widetilde{\gamma}) = 1$, the limit increases to 27.8 GeV.

[49] ADEVA 89B assume for $\ell\nu\widetilde{\gamma}$ ($\ell\widetilde{\nu}$) mode that $B(e) = B(\mu) = B(\tau)$ = 11% (33%) and search for acoplanar dimuons, dielectrons, and μe events. Also assume $m(\widetilde{\gamma})$ < 20 GeV and for $\ell\widetilde{\nu}$ mode that $m(\widetilde{\nu})$ = 10 GeV.

[50] ANSARI 87D looks for high p_T e^+e^- pair with large missing p_T at the CERN $p\overline{p}$ collider at E_{cm} = 546–630 GeV. The limit is valid when $m(\widetilde{\nu}) \lesssim$ 20 GeV, $B(\widetilde{W} \to e\widetilde{\nu}_e)$ = 1/3, and $B(Z \to \widetilde{W}^+\widetilde{W}^-)$ is calculated by assuming pure gaugino eigenstate. See their Fig. 3(b) for excluded region in the $m(\widetilde{W})$–$m(\widetilde{\nu})$ plane.

[51] BAER 87B argue that the charged heavy lepton mass limit of 41 GeV obtained by UA1 collaboration (ALBAJAR 87B) corresponds to the mass limit of 40 GeV under the assumptions that the LSP (photino) has a mass smaller than 8 GeV and that the gaugino-higgsino mixing is parametrized by the three minimal supergravity model parameters. In grand unified theories $m(\widetilde{\gamma})$ < 8 implies $m(\widetilde{g})$ < 50 GeV. For larger gluino masses, this limit can be evaded as discussed in BAER 88.

$\widetilde{\nu}$ (Sneutrino) MASS LIMIT

The limit depends on the number, $N(\widetilde{\nu})$, of sneutrinos assumed to be degenerate in mass. Only $\widetilde{\nu}_L$ (not $\widetilde{\nu}_R$) exist. It is possible that $\widetilde{\nu}$ could be the lightest supersymmetric particle (LSP).

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>41	95	[52] DECAMP	92	ALEP	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=3
>36	95	ABREU	91F	DLPH	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=1
>32	95	[53] ABREU	91F	DLPH	$\Gamma(Z)$; $N(\widetilde{\nu})$=1
>31.2	95	[54] ALEXANDER	91F	OPAL	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=1
>31.4	95	[55] ADEVA	90I	L3	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=1
>39.4	95	[55] ADEVA	90I	L3	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=3
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>38.4	90	[56] DREES	91	RVUE	$\Gamma(Z)$; $N(\widetilde{\nu})$=3
>28.9	90	[56] DREES	91	RVUE	$\Gamma(Z)$; $N(\widetilde{\nu})$=1
none 3–90	90	[57] SATO	91	KAMI	Stable $\widetilde{\nu}_e$ or $\widetilde{\nu}_\mu$, dark matter
none 4–90	90	[57] SATO	91	KAMI	Stable $\widetilde{\nu}_\tau$, dark matter
>36.5	90	[58] BAER	90	RVUE	$\Gamma(Z)$; $N(\widetilde{\nu})$=3

[52] DECAMP 92 limit is from $\Gamma(\text{invisible})/\Gamma(\ell\ell) = 5.91 \pm 0.15$ ($N_\nu = 2.97 \pm 0.07$).

[53] ABREU 91F limit (>32 GeV) is independent of sneutrino decay mode.

[54] ALEXANDER 91F limit is for one species of $\widetilde{\nu}$ and is derived from $\Gamma(\text{invisible, new})/\Gamma(\ell\ell)$ < 0.38.

[55] ADEVA 90I limit is from ΔN_ν < 0.19.

[56] DREES 91 limits from $\Delta\Gamma(Z)$ (nonhadronic) < 38.3 MeV. Independent of decay modes. Minimal supersymmetry assumed.

[57] SATO 91 search for high-energy neutrinos from the sun produced by annihilation of sneutrinos in the sun. Sneutrinos are assumed to be stable and to constitute dark matter in our galaxy. SATO 91 follow the analysis of NG 87, OLIVE 88, and GAISSER 86.

[58] BAER 90 limit from $\Delta\Gamma(Z)$ (nonhadronic) < 53 MeV. Independent of decay modes. Mininal supersymmetry assumed. The 95%CL bound is 35.6 GeV.

$\widetilde{e}$ (Selectron) MASS LIMIT

Limits assume $m(\widetilde{e}_L) = m(\widetilde{e}_R)$ unless otherwise stated.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 45	95	[59] DECAMP	92	ALEP	$m(\widetilde{\chi}_1^0)$ <41 GeV, $\widetilde{e}^+\widetilde{e}^-$
> 65	95	[60,61] HEARTY	89	RVUE	$m(\widetilde{\gamma})$=0; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
> 50	95	HEARTY	89	ASP	$m(\widetilde{\gamma})$<5 GeV; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 42	95	ABREU	90G	DLPH	$m(\widetilde{\gamma})$ < 40 GeV; $\widetilde{e}^+\widetilde{e}^-$
> 38	95	[62] AKESSON	90B	UA2	$m(\widetilde{\gamma})$ = 0; $p\overline{p} \to ZX$ $(Z \to \widetilde{e}^+\widetilde{e}^-)$
> 43.4	95	[63] AKRAWY	90D	OPAL	$m(\widetilde{\gamma})$< 30 GeV; $\widetilde{e}^+\widetilde{e}^-$
> 38.1	90	[64] BAER	90	RVUE	$\widetilde{e}_L$; $\Gamma(Z)$; $\tan\beta > 1$
> 43.5	95	[65] DECAMP	90C	ALEP	$m(\widetilde{\gamma})$ < 36 GeV; $\widetilde{e}^+\widetilde{e}^-$
>830		GRIFOLS	90	ASTR	$m(\widetilde{\gamma})$ < 1 MeV
> 29.9	95	SAKAI	90	AMY	$m(\widetilde{\gamma})$ < 20 GeV; $\widetilde{e}^+\widetilde{e}^-$
> 29	95	TAKETANI	90	VNS	$m(\widetilde{\gamma})$ < 25 GeV; $\widetilde{e}^+\widetilde{e}^-$
> 60		[66] ZHUKOVSKII	90	ASTR	$m(\widetilde{\gamma})$ = 0
> 32	90	[67] ABE	89K	VNS	$e^+e^- \to \gamma\widetilde{\gamma}\widetilde{\gamma}$
> 28	95	[68] ADACHI	89	TOPZ	$m(\widetilde{\gamma}) \lesssim 0.85m(\widetilde{e})$; $\widetilde{e}^+\widetilde{e}^-$
> 41	95	[69] ADEVA	89B	L3	$m(\widetilde{\gamma})$ < 20 GeV; $\widetilde{e}^+\widetilde{e}^-$
> 32	90	[70] ALBAJAR	89	UA1	$p\overline{p} \to W^\pm X$ $(W^\pm \to \widetilde{e}_L\widetilde{\nu})$ $(\widetilde{e}_L \to e\widetilde{\gamma})$
> 14	90	[71] ALBAJAR	89	UA1	$Z \to \widetilde{e}^+\widetilde{e}^-$
> 53	95	[60,72] HEARTY	89	ASP	$m(\widetilde{\gamma})$=0; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
> 35	95	HEARTY	89	ASP	$m(\widetilde{\gamma})$<10 GeV; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
> 51.5	90	[73,74] BEHREND	88B	CELL	$m(\widetilde{\gamma})$ = 0 GeV; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
> 64	95	[73,75] BEHREND	88B	RVUE	$m(\widetilde{\gamma})$ = 0 GeV; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
> 48	90	BEHREND	88B	CELL	$m(\widetilde{\gamma})$ < 5 GeV; $\gamma\widetilde{\gamma}\widetilde{\gamma}$

[59] DECAMP 92 limit is for $m(\widetilde{e}_L) \gg m(\widetilde{e}_R)$; for equal masses the limit would improve. They looked for acoplanar electrons.

[60] HEARTY 89 assume $m(\widetilde{\gamma})$ = 0. The limit is very sensitive to $m(\widetilde{\gamma})$; no limit can be placed for $m(\widetilde{\gamma}) \gtrsim$ 13 GeV.

[61] Results of HEARTY 89, BEHREND 88B, ADEVA 87, and FORD 86 are combined. The limit is reduced to 53 GeV if only one $\widetilde{e}$ state is produced ($\widetilde{e}_L$ or $\widetilde{e}_R$ very heavy).

[62] AKESSON 90B assume $m(\widetilde{\gamma})$ = 0. Very similar limits hold for $m(\widetilde{\gamma}) \lesssim$ 20 GeV.

[63] AKRAWY 90D look for acoplanar electrons. For $m(\widetilde{e}_L) \gg m(\widetilde{e}_R)$, limit is 41.5 GeV, for $m(\widetilde{\gamma})$ < 30 GeV.

[64] BAER 90 limit from $\Delta\Gamma(Z)$ (nonhadronic) < 53 MeV. Independent of decay modes. Mininal supersymmetry and $\tan\beta$ > 1 assumed.

[65] DECAMP 90C look for acoplanar electrons. For $m(\widetilde{e}_L) \gg m(\widetilde{e}_R)$ limit is 42 GeV, for $m(\widetilde{\gamma})$ < 33 GeV.

[66] ZHUKOVSKII 90 set limit by saying the luminosity of a magnetized neutron star due to massless photino emission by electrons be small compared with its neutrino luminosity.

[67] ABE 89K assumed $m(\widetilde{\gamma})$ = 0.

[68] ADACHI 89 assume only photon and photino exchange and $m(\widetilde{e}_L) = m(\widetilde{e}_R)$. The limit for the nondegenerate case is 26 GeV.

[69] ADEVA 89B look for acoplanar electrons.

[70] ALBAJAR 89 limit applies for $\widetilde{e}_L$ when $m(\widetilde{e}_L) = m(\widetilde{\nu}_L)$ and $m(\widetilde{\gamma})$ = 0. See their Fig. 55 for the 90% CL excluded region in the $m(\widetilde{e}_L) - m(\widetilde{\nu}_L)$ plane. For $m(\widetilde{\nu}) = m(\widetilde{\gamma})$ = 0, limit is 50 GeV.

[71] ALBAJAR 89 assume $m(\tilde{\gamma}) = 0$.

[72] The limit is reduced to 43 GeV if only one $\tilde{e}$ state is produced ($\tilde{e}_L$ or $\tilde{e}_R$ very heavy).

[73] BEHREND 88B limits assume pure photino eigenstate and $m(\tilde{e}_L) = m(\tilde{e}_R)$.

[74] The 95% CL limit for BEHREND 88B is 47.5 GeV for $m(\tilde{\gamma}) = 0$. The limit for $m(\tilde{e}_L) \gg m(\tilde{e}_R)$ is 40 GeV at 90% CL.

[75] BEHREND 88B combined their data with those from ASP (HEARTY 87), MAC (FORD 86), and MARK-J (H. Wu, Ph. D. Thesis, University of Hamburg, 1986).

$\tilde{\mu}$ (Smuon) MASS LIMIT

Limits assume $m(\tilde{\mu}_L) = m(\tilde{\mu}_R)$ unless otherwise stated.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>45	95	[76] DECAMP	92	ALEP	$m(\tilde{\chi}^0_1)$ <41 GeV, $\tilde{\mu}^+\tilde{\mu}^-$
>43	95	[77] AKRAWY	90D	OPAL	$m(\tilde{\gamma})$< 30 GeV; $\tilde{\mu}^+\tilde{\mu}^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>36	95	ABREU	90G	DLPH	$m(\tilde{\gamma}) < 33$ GeV; $\tilde{\mu}^+\tilde{\mu}^-$
>38.1	90	[78] BAER	90	RVUE	$\tilde{\mu}_L$; $\Gamma(Z)$; $\tan\beta > 1$
>42.6	95	[79] DECAMP	90C	ALEP	$m(\tilde{\gamma}) < 34$ GeV; $\tilde{\mu}^+\tilde{\mu}^-$
>27	95	SAKAI	90	AMY	$m(\tilde{\gamma}) < 18$ GeV; $\tilde{\mu}^+\tilde{\mu}^-$
>24.5	95	TAKETANI	90	VNS	$m(\tilde{\gamma}) < 15$ GeV; $\tilde{\mu}^+\tilde{\mu}^-$
>24.5	95	[80] ADACHI	89	TOPZ	$m(\tilde{\gamma}) \lesssim 0.8m(\tilde{\mu})$; $\tilde{\mu}^+\tilde{\mu}^-$
>41	95	[81] ADEVA	89B	L3	$m(\tilde{\gamma}) < 20$ GeV; $\tilde{\mu}^+\tilde{\mu}^-$

[76] DECAMP 92 limit is for $m(\tilde{\mu}_L) \gg m(\tilde{\mu}_R)$; for equal masses the limit would improve. They looked for acoplanar muons.

[77] AKRAWY 90D look for acoplanar muons. For $m(\tilde{\mu}_L) \gg m(\tilde{\mu}_R)$, limit is 41.0 GeV, for $m(\tilde{\gamma}) < 30$ GeV.

[78] BAER 90 limit from $\Delta\Gamma(Z)$ (nonhadronic) < 53 MeV. Independent of decay modes. Mininal supersymmetry and $\tan\beta > 1$ assumed.

[79] DECAMP 90C look for acoplanar muons. For $m(\tilde{\mu}_L) \gg m(\tilde{\mu}_R)$ limit is 40 GeV, for $m(\tilde{\gamma}) < 30$ GeV.

[80] ADACHI 89 assume only photon exchange, which gives a conservative limit. $m(\tilde{\mu}_L) = m(\tilde{\mu}_R)$ assumed. The limit for nondegenerate case is 22 GeV.

[81] ADEVA 89B look for acoplanar muons.

$\tilde{\tau}$ (Stau) MASS LIMIT

Limits assume $m(\tilde{\tau}_L) = m(\tilde{\tau}_R)$ unless otherwise stated.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>45	95	[82] DECAMP	92	ALEP	$m(\tilde{\chi}^0_1)$ <38 GeV, $\tilde{\tau}^+\tilde{\tau}^-$
>43.0	95	[83] AKRAWY	90D	OPAL	$m(\tilde{\gamma})$< 23 GeV; $\tilde{\tau}^+\tilde{\tau}^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>35	95	ABREU	90G	DLPH	$m(\tilde{\gamma}) < 25$ GeV; $\tilde{\tau}^+\tilde{\tau}^-$
>38.1	90	[84] BAER	90	RVUE	$\tilde{\tau}_L$; $\Gamma(Z)$; $\tan\beta > 1$
>40.4	95	[85] DECAMP	90C	ALEP	$m(\tilde{\gamma}) < 15$ GeV; $\tilde{\tau}^+\tilde{\tau}^-$
>25	95	SAKAI	90	AMY	$m(\tilde{\gamma}) < 10$ GeV; $\tilde{\tau}^+\tilde{\tau}^-$
>25.5	95	TAKETANI	90	VNS	$m(\tilde{\gamma}) < 15$ GeV; $\tilde{\tau}^+\tilde{\tau}^-$
>21.7	95	[86] ADACHI	89	TOPZ	$m(\tilde{\gamma})$=0; $\tilde{\tau}^+\tilde{\tau}^-$

[82] DECAMP 92 limit is for $m(\tilde{\tau}_L) \gg m(\tilde{\tau}_R)$; for equal masses the limit would improve. They looked for acoplanar particles.

[83] AKRAWY 90D look for acoplanar particles. For $m(\tilde{\tau}_L) \gg m(\tilde{\tau}_R)$, limit is 41.0 GeV, for $m(\tilde{\gamma}) < 23$ GeV.

[84] BAER 90 limit from $\Delta\Gamma(Z)$ (nonhadronic) < 53 MeV. Independent of decay modes. Mininal supersymmetry and $\tan\beta > 1$ assumed.

[85] DECAMP 90C look for acoplanar charged particle pairs. Limit is for $m(\tilde{\tau}_L) = m(\tilde{\tau}_R)$. For $m(\tilde{\gamma}) \leq 24$ GeV, the limit is 37 GeV. For $m(\tilde{\tau}_L) \gg m(\tilde{\tau}_R)$ and $m(\tilde{\gamma}) < 15$ GeV, the limit is 33 GeV.

[86] ADACHI 89 assume only photon exchange, which gives a conservative limit. $m(\tilde{\tau}_L) = m(\tilde{\tau}_R)$ assumed.

Stable $\tilde{\ell}$ (Slepton) MASS LIMIT

Limits on scalar leptons which leave detector before decaying. Limits from Z decays are independent of lepton flavor. Limits from continuum e^+e^- annihilation are also independent of flavor for smuons and staus. However, selectron limits from continuum e^+e^- annihilation depend on flavor because there is an additional contribution from neutralino exchange that in general yields stronger limits. All limits assume $m(\tilde{\ell}_L) = m(\tilde{\ell}_R)$ unless otherwise stated.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>40	95	ABREU	90G	DLPH	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>26.3	95	ADACHI	90C	TOPZ	$\tilde{\mu}$, $\tilde{\tau}$
>38.8	95	AKRAWY	90O	OPAL	$\tilde{\ell}_R$
>27.1	95	[87] SAKAI	90	AMY	
>32.6	95	SODERSTROM	90	MRK2	
>24.5	95	[88] ADACHI	89	TOPZ	

[87] SAKAI 90 limit improves to 30.1 GeV for $\tilde{e}$ if $m(\tilde{\gamma}) \approx m(\tilde{e})$.

[88] ADACHI 89 assume only photon (and photino for $\tilde{e}$) exchange. The limit for $\tilde{e}$ improves to 26 GeV for $m(\tilde{\gamma}) \approx m(\tilde{e})$.

$\tilde{q}$ (Squark) MASS LIMIT

For heavy squarks (m > 60–70 GeV), it is very difficult to arrange for branching ratios for direct decay to photinos to be 100% as assumed by most papers, so realistic limits will be somewhat lower.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 74	90	[89] ALITTI	90	UA2	Any $m(\tilde{q})$; $B(\tilde{q} \to q\tilde{g}$ or $q\tilde{\gamma})$=1
> 106	90	[89] ALITTI	90	UA2	$m(\tilde{q}) = m(\tilde{g})$; $B(\tilde{q} \to q\tilde{\gamma}) = 1$
> 74	90	[90] ABE	89B	CDF	Any $m(\tilde{g}) > m(\tilde{q})$; $B(\tilde{q} \to q\tilde{\gamma})$=1
		[91] BAER	89	RVUE	$p\bar{p}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[92] BAER	91	RVUE	$p\bar{p}$
		[93] BAER	91B	RVUE	$\tilde{t}$
		[94] NOJIRI	91	COSM	
> 45	95	[95] ABREU	90F	DLPH	$Z \to \tilde{q}\bar{\tilde{q}}$, $m(\tilde{\gamma}) < 20$ GeV
> 43	95	[96] ABREU	90F	DLPH	$Z \to \tilde{d}\bar{\tilde{d}}$, $m(\tilde{\gamma}) < 20$ GeV
> 42	95	[97] ABREU	90F	DLPH	$Z \to \tilde{u}\bar{\tilde{u}}$, $m(\tilde{\gamma}) < 20$ GeV
> 27.0	95	ADACHI	90C	TOPZ	Stable $\tilde{u}$, $\tilde{u}\bar{\tilde{u}}$
> 39.2	90	[98] BAER	90	RVUE	$\tilde{d}_L$; $\Gamma(Z)$
> 45	95	[99,100] BARKLOW	90	MRK2	$Z \to \tilde{q}\bar{\tilde{q}}$
> 40	95	[99,101] BARKLOW	90	MRK2	$Z \to \tilde{d}\bar{\tilde{d}}$
> 39	95	[99,102] BARKLOW	90	MRK2	$Z \to \tilde{u}\bar{\tilde{u}}$
		[103] DREES	90	RVUE	$\tilde{t}$
>1100		GRIFOLS	90	ASTR	$m(\tilde{\gamma}) < 1$ MeV
> 24	95	SAKAI	90	AMY	$e^+e^- \to \tilde{d}\bar{\tilde{d}} \to d\bar{d}\tilde{\gamma}\tilde{\gamma}$; $m(\tilde{\gamma}) < 10$ GeV
> 26	95	SAKAI	90	AMY	$e^+e^- \to \tilde{u}\bar{\tilde{u}} \to u\bar{u}\tilde{\gamma}\tilde{\gamma}$; $m(\tilde{\gamma}) < 10$ GeV
> 104	90	ABE	89B	CDF	$m(\tilde{g}) = m(\tilde{q})$; $B(\tilde{q} \to q\tilde{\gamma})$=1
> 26.3	95	[104] ADACHI	89	TOPZ	$e^+e^- \to \tilde{q}\bar{\tilde{q}} \to q\bar{q}\tilde{\gamma}\tilde{\gamma}$
		[105] NATH	88	THEO	$\tau(p \to \nu K)$ in supergravity GUT
> 45	90	[106] ALBAJAR	87D	UA1	Any $m(\tilde{g}) > m(\tilde{q})$
> 75	90	[106] ALBAJAR	87D	UA1	$m(\tilde{g}) = m(\tilde{q})$

[89] ALITTI 90 searched for events having $\geq$ 2 jets with E^1_T > 25 GeV, E^2_T > 15 GeV, $|\eta|$ < 0.85, and $\Delta\phi$ < 160°, with a missing momentum > 40 GeV and no electrons. They assume $\tilde{q} \to q\tilde{\gamma}$ (if $m(\tilde{q}) < m(\tilde{g})$) or $\tilde{q} \to q\tilde{g}$ (if $m(\tilde{q}) > m(\tilde{g})$) decay and $m(\tilde{\gamma}) \lesssim 20$ GeV. Five degenerate squark flavors and $m(\tilde{q}_L) = m(\tilde{q}_R)$ are assumed. Masses below 50 GeV are not excluded by the analysis.

[90] Six degenerate squark flavors and $m(\tilde{q}_L) = m(\tilde{q}_R)$ are assumed. The limit decreases by 20 GeV if only two squark flavors are produced. Not sensitive to $m(\tilde{q}) \lesssim 20$ GeV. Limit holds for $m(\tilde{\gamma})$ = 0–30 GeV.

[91] BAER 89 claim that ABE 89B bound is typically reduced by $\lesssim$ 10 GeV if m(LSP) $\lesssim$ 20–25 GeV.

[92] BAER 91 show that the finite mass of the LSP ($\tilde{\chi}^0_1$) reduces the CDF preliminary bound $m(\tilde{q})$ >170 GeV by 15–20 GeV if $m(\tilde{\chi}^0_1) \approx 20$ GeV, and that the bound disappears for $m(\tilde{\chi}^0_1) > 50$ GeV.

[93] BAER 91B argue that a top squark as light as 45 GeV may have escaped detection at the CDF detector at the Tevatron Collider (45 GeV is the limit from LEP experiments).

[94] NOJIRI 91 argues that a heavy squark should be nearly degenerate with the gluino in minimal supergravity not to overclose the universe.

[95] ABREU 90F assume six degenerate squarks and $m(\tilde{q}_L) = m(\tilde{q}_R)$. $m(\tilde{q}) < 41$ GeV is excluded at 95% CL for m(LSP) < $m(\tilde{q})$ − 2 GeV.

[96] ABREU 90F exclude $m(\tilde{d}) < 38$ GeV at 95% for m(LSP) < $m(\tilde{d})$ − 2 GeV.

[97] ABREU 90F exclude $m(\tilde{u}) < 36$ GeV at 95% for m(LSP) < $m(\tilde{u})$ − 2 GeV.

[98] BAER 90 limit from $\Delta\Gamma(Z)$ < 120 MeV, assuming $m(\tilde{d}_L) = m(\tilde{u}_L) = m(\tilde{e}_L) = m(\tilde{\nu})$. Independent of decay modes. Minimal supergravity assumed.

[99] BARKLOW 90 assume 100% $\tilde{q} \to q\tilde{\gamma}$.

[100] BARKLOW 90 assume five degenerate squarks (left- and right-handed). Valid up to $m(\tilde{\chi}^0_1) \lesssim [m(\tilde{q})$ − 4 GeV].

[101] BARKLOW 90 result valid up to $m(\tilde{\chi}^0_1) \lesssim [m(\tilde{d})$ − 5 GeV].

[102] BARKLOW 90 result valid up to $m(\tilde{\chi}^0_1) \lesssim [m(\tilde{u})$ − 6 GeV].

[103] DREES 90 argue that bounds from Z decay are not valid for $\tilde{t}$ for a certain range of $\tilde{t}_L$–$\tilde{t}_R$ mixing angle.

[104] ADACHI 89 assume only photon exchange, which gives a a conservative limit. The limit is only for one flavor of charge 2/3 $\tilde{q}$. $m(\tilde{q}_L) = m(\tilde{q}_R)$ and $m(\tilde{\gamma}) = 0$ assumed. The limit decreases to 26.1 GeV for $m(\tilde{\gamma})$ = 15 GeV. The limit for nondegenerate case is 24.4 GeV.

[105] NATH 88 uses Kamioka limit of $\tau(p \to \bar{\nu}K^+) > 7 \times 10^{31}$ yrs to constrain squark mass $m(\tilde{q})$ > 1000 GeV by assuming that the proton decay proceeds via an exchange of a color-triplet Higgsino of mass < 10^{16} GeV in the supersymmetric SU(5) GUT. The limit applies for $m(\tilde{\gamma}) \equiv (8/3)\sin^2\theta_W \tilde{m}_2$ > 10 GeV ($\tilde{m}_2$ is the SU(2) gaugino mass) and for a very conservative value of the three-quark proton wave function, barring cancellation between second and third generations. Lower squark mass is allowed if $m(\tilde{\gamma})$ as defined above is smaller.

[106] The limits of ALBAJAR 87D are from $p\bar{p} \to \tilde{q}\bar{\tilde{q}}$ X ($\tilde{q} \to q\tilde{\gamma}$) and assume 5 flavors of degenerate mass squarks each with $m(\tilde{q}_L) = m(\tilde{q}_R)$. They also assume $m(\tilde{g}) > m(\tilde{q})$. These limits apply for $m(\tilde{\gamma}) \lesssim 20$ GeV.

$\tilde{g}$ (Gluino) MASS LIMIT

For heavy gluinos (m > 60–70 GeV), it is very difficult to arrange for branching ratios for direct decay to photinos to be 100% as assumed by most papers, so realistic limits will be somewhat lower.

There is an ongoing controversy (reflected in these Listings) about whether very light $\tilde{g}$'s (1 $\lesssim m(\tilde{g}) \lesssim$ 4 GeV) are ruled out. These papers sometimes make different assumptions and use different calculational techniques.

VALUE (GeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
> 79	90		[107] ALITTI	90	UA2	Any $m(\tilde{q})$; B($\tilde{g} \to q\overline{q}\tilde{\gamma}$) = 1
>106	90		[107] ALITTI	90	UA2	$m(\tilde{q}) = m(\tilde{g})$; B($\tilde{g} \to q\overline{q}\tilde{\gamma}$) = 1
			[108] BAER	89	RVUE	$p\overline{p}$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
			[109] ANTONIADIS	91	RVUE	α_s running
> 1			[110] ANTONIADIS	91	RVUE	$pN \to$ missing energy
			[111] BAER	91	RVUE	$p\overline{p}$
>132	90		[112] HIDAKA	91	RVUE	
			[113] NOJIRI	91	COSM	
> 73	90		[114] ABE	89B	CDF	Any $m(\tilde{q}) > m(\tilde{g})$; B($\tilde{g} \to q\overline{q}\tilde{\gamma}$)=1
>104	90		ABE	89B	CDF	$m(\tilde{q}) = m(\tilde{g})$; B($\tilde{g} \to q\overline{q}\tilde{\gamma}$)=1
			[115] NAKAMURA	89	SPEC	R-Δ^{++}
none 4–53	90		[116] ALBAJAR	87D	UA1	Any $m(\tilde{q}) > m(\tilde{g})$
none 4–75	90		[116] ALBAJAR	87D	UA1	$m(\tilde{q}) = m(\tilde{g})$
none 16–58	90		[117] ANSARI	87D	UA2	$m(\tilde{q}) \lesssim$ 100 GeV
> 3.8	90		[118] ARNOLD	87	EMUL	π^- (350 GeV). $\sigma \sim A^1$
> 3.2	90		[118] ARNOLD	87	EMUL	π^- (350 GeV). $\sigma \sim A^{0.72}$
none 0.6–2.2	90		[119] TUTS	87	CUSB	$\Upsilon(1S) \to \gamma$ + gluinonium
none 1 –4.5	90	0	[120] ALBRECHT	86C	ARG	$1 \times 10^{-11} \lesssim \tau \lesssim 1 \times 10^{-9}$s
none 1–4	90	0	[121] BADIER	86	BDMP	$1 \times 10^{-10} < \tau < 1 \times 10^{-7}$s
none			[122] VOLOSHIN	86	RVUE	If (quasi) stable; $\tilde{g}uud$
none 0.5–2			[123] COOPER-...	85B	BDMP	For $m(\tilde{q})$=300 GeV
none 0.5–4			[123] COOPER-...	85B	BDMP	For $m(\tilde{q})$ <65 GeV
none 0.5–3			[123] COOPER-...	85B	BDMP	For $m(\tilde{q})$=150 GeV
none 2–4			[124] DAWSON	85	RVUE	$\tau > 10^{-7}$ s
none 1–2.5			[124] DAWSON	85	RVUE	For $m(\tilde{q})$=100 GeV
none 0.5–4.1	90		[125] FARRAR	85	RVUE	FNAL beam dump
> 1			[126] GOLDMAN	85	RVUE	Gluononium
>1–2			[127] HABER	85	RVUE	
			[128] BALL	84	CALO	
			[129] BRICK	84	RVUE	
			[130] FARRAR	84	RVUE	
> 2			[131] BERGSMA	83C	RVUE	For $m(\tilde{q})$<100 GeV
			[132] CHANOWITZ	83	RVUE	$\tilde{g}u\overline{d}$, $\tilde{g}uud$
>2–3			[133] KANE	82	RVUE	Beam dump
>1.5–2			FARRAR	78	RVUE	R-hadron

[107] ALITTI 90 searched for events having $\geq$ 2 jets with E_T^1 > 25 GeV, E_T^2 > 15 GeV, $|\eta|$ < 0.85, and $\Delta\phi$ < 160°, with a missing momentum > 40 GeV and no electrons. They assume $\tilde{g} \to q\overline{q}\tilde{\gamma}$ decay and $m(\tilde{\gamma}) \lesssim$ 20 GeV. Masses below 50 GeV are not excluded by the analysis.

[108] BAER 89 claim that ABE 89B bound is reduced by 3–30 GeV due to cascade decays in minimal supergravity.

[109] ANTONIADIS 91 argue that possible light gluinos (< 5 GeV) contradict the observed running of α_s between 5 GeV and $m(Z)$. The significance is less than 2 s.d.

[110] ANTONIADIS 91 intrepret the search for missing energy events in 450 GeV/c pN collisions, AKESSON 91, in terms of light gluinos.

[111] BAER 91 show that the CDF preliminary bound $m(\tilde{g})$ > 150–230 GeV is typically reduced by 10–30 GeV due to cascade decays in minimal supergravity for tanβ > 1.6.

[112] HIDAKA 91 limit obtained from LEP and preliminary CDF results within minimal supersymmetry with gaugino-mass unification condition. HIDAKA 91 limit extracted from BAER 91 analysis.

[113] NOJIRI 91 argues that a heavy gluino should be nearly degenerate with squarks in minimal supergravity not to overclose the universe.

[114] Not sensitive to $m(\tilde{g}) \lesssim$ 30 GeV. Limit holds for $m(\tilde{\gamma})$ = 0–30 GeV.

[115] NAKAMURA 89 searched for a long-lived ($\tau \gtrsim 10^{-7}$ s) charge-($\pm$2) particle with mass $\lesssim$ 1.6 GeV in proton-Pt interactions at 12 GeV and found that the yield is less than 10^{-8} times that of the pion. This excludes R-Δ^{++} (a $\tilde{g}uuu$ state) lighter than 1.6 GeV.

[116] The limits of ALBAJAR 87D are from $p\overline{p} \to \tilde{g}\tilde{g}$ X ($\tilde{g} \to q\overline{q}\tilde{\gamma}$) and assume $m(\tilde{q})$ > $m(\tilde{g})$. These limits apply for $m(\tilde{\gamma}) \lesssim$ 20 GeV and $\tau(\tilde{g}) < 10^{-10}$ s.

[117] The limit of ANSARI 87D assumes $m(\tilde{q}) > m(\tilde{g})$ and $m(\tilde{\gamma}) \approx$ 0.

[118] The limits assmue $m(\tilde{q})$ = 100 GeV. See their figure 3 for limits vs. $m(\tilde{q})$.

[119] The gluino mass is defined by half the bound $\tilde{g}\tilde{g}$ mass. If zero gluino mass gives a $\tilde{g}\tilde{g}$ of mass about 1 GeV as suggested by various glueball mass estimates, then the low-mass bound can be replaced by zero. The high-mass bound is obtained by comparing the data with nonrelativistic potential-model estimates.

[120] ALBRECHT 86C search for secondary decay vertices from $\chi_{b1}(1P) \to \tilde{g}\tilde{g}g$ where $\tilde{g}$'s make long-lived hadrons. See their figure 4 for excluded region in the $m(\tilde{g})-\tau(\tilde{g})$ and $m(\tilde{g})-m(\tilde{q})$ plane. The lower $m(\tilde{g})$ region below $\sim$ 2 GeV may be sensitive to fragmentation effects. Remark that the $\tilde{g}$-hadron mass is expected to be $\sim$ 1 GeV (glueball mass) in the zero $\tilde{g}$ mass limit.

[121] BADIER 86 looked for secondary decay vertices from long-lived $\tilde{g}$-hadrons produced at 300 GeV π^- beam dump. The quoted bound assumes $\tilde{g}$-hadron nucleon total cross section of 10μb. See their figure 7 for excluded region in the $m(\tilde{g})-m(\tilde{q})$ plane for several assumed total cross-section values.

[122] VOLOSHIN 86 rules out stable gluino based on the cosmological argument that predicts too much hydrogen consisting of the charged stable hadron $\tilde{g}uud$. Quasi-stable (τ > 1. $\times 10^{-7}$s) light gluino of $m(\tilde{g})$ <3 GeV is also ruled out by nonobservation of the stable charged particles, $\tilde{g}uud$, in high energy hadron collisions.

[123] COOPER-SARKAR 85B is BEBC beam-dump. Gluinos decaying in dump would yield $\tilde{\gamma}$'s in the detector giving neutral-current-like interactions. For $m(\tilde{q})$ >330 GeV, no limit is set.

[124] DAWSON 85 first limit from neutral particle search. Second limit based on FNAL beam dump experiment.

[125] FARRAR 85 points out that BALL 84 analysis applies only if the $\tilde{g}$'s decay before interacting, i.e. $m(\tilde{q})$ <80$m(\tilde{g})^{1.5}$. FARRAR 85 finds $m(\tilde{g})$ <0.5 not excluded for $m(\tilde{q})$ = 30–1000 GeV and $m(\tilde{g})$ <1.0 not excluded for $m(\tilde{q})$ = 100–500 GeV by BALL 84 experiment.

[126] GOLDMAN 85 use nonobservation of a pseudoscalar $\tilde{g}$-$\tilde{g}$ bound state in radiative ψ decay.

[127] HABER 85 is based on survey of all previous searches sensitive to low mass $\tilde{g}$'s. Limit makes assumptions regarding the lifetime and electric charge of the lightest supersymmetric particle.

[128] BALL 84 is FNAL beam dump experiment. Observed no interactions of $\tilde{\gamma}$ in the calorimeter, where $\tilde{\gamma}$'s are expected to come from pair-produced $\tilde{g}$'s. Search for long-lived $\tilde{\gamma}$ interacting in calorimeter 56m from target. Limit is for $m(\tilde{q})$ = 40 GeV and production cross section proportional to $A^{0.72}$. BALL 84 find no $\tilde{g}$ allowed below 4.1 GeV at CL = 90%. Their figure 1 shows dependence on $m(\tilde{q})$ and A. See also KANE 82.

[129] BRICK 84 reanalyzed FNAL 147 GeV HBC data for R-$\Delta(1232)^{++}$ with $\tau > 10^{-9}$ s and p_{lab} >2 GeV. Set CL = 90% upper limits 6.1, 4.4, and 29 microbarns in pp, $\pi^+ p$, $K^+ p$ collisions respectively. R-Δ^{++} is defined as being $\tilde{g}$ and 3 up quarks. If mass = 1.2–1.5 GeV, then limits may be lower than theory predictions.

[130] FARRAR 84 argues that $m(\tilde{g})$ <100 MeV is not ruled out if the lightest R-hadrons are long-lived. A long lifetime would occur if R-hadrons are lighter than $\tilde{\gamma}$'s or if $m(\tilde{q})$ >100 GeV.

[131] BERGSMA 83C is reanalysis of CERN-SPS beam-dump data. See their figure 1.

[132] CHANOWITZ 83 find in bag-model that charged s-hadron exists which is stable against strong decay if $m(\tilde{g})$ <1 GeV. This is important since tracks from decay of neutral s-hadron cannot be reconstructed to primary vertex because of missed $\tilde{\gamma}$. Charged s-hadron leaves track from vertex.

[133] KANE 82 inferred above $\tilde{g}$ mass limit from retroactive analysis of hadronic collision and beam dump experiments. Limits valid if $\tilde{g}$ decays inside detector.

Unstable $\tilde{\gamma}$ (Photino) MASS LIMIT

The limits below assume that the $\tilde{\gamma}$ decays either into $\gamma\tilde{G}$ (goldstino) or into $\gamma\tilde{H}^0$ (Higgsino).

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[134] ABE	89J	VNS	$e^+e^- \to \tilde{\gamma}\tilde{\gamma}$ ($\tilde{\gamma} \to \gamma\tilde{G}$ or $\gamma\tilde{H}^0$)
>15	95	[135] BEHREND	87B	CELL	$e^+e^- \to \tilde{\gamma}\tilde{\gamma}$ ($\tilde{\gamma} \to \gamma\tilde{G}$ or $\gamma\tilde{H}^0$)
		[136] ADEVA	85	MRKJ	
		[137] BALL	84	CALO	Beam dump
		[138] BARTEL	84B	JADE	
		[138] BEHREND	83	CELL	
		[139] CABIBBO	81	COSM	

[134] ABE 89J exclude $m(\tilde{\gamma})$ = 0.15–25 GeV (95%CL) for d = (100 GeV)^2 and $m(\tilde{e})$ = 40 GeV in the case $\tilde{\gamma} \to \gamma\tilde{G}$, and $m(\tilde{\gamma})$ up to 23 GeV for $m(\tilde{e})$ = 40 GeV in the case $\tilde{\gamma} \to \gamma\tilde{H}^0$.

[135] BEHREND 87B limit is for unstable photinos only. Assumes B($\tilde{\gamma} \to \gamma(\tilde{G}$ or $\tilde{H}^0$)) =1, $m(\tilde{G}$ or $\tilde{H}^0) \ll m(\tilde{\gamma})$ and pure $\tilde{\gamma}$ eigenstate. $m(\tilde{e}_L) = m(\tilde{e}_R)$ < 100 GeV.

[136] ADEVA 85 is sensitive to $\tilde{\gamma}$ decay path <5 cm. With $m(\tilde{e})$ = 50 GeV, limit (CL = 90%) is $m(\tilde{\gamma})$ >20.5 GeV. Assume $\tilde{\gamma}$ decays to photon + goldstino and search for acoplanar photons with large missing p_T.

[137] BALL 84 is FNAL beam dump experiment. Observed no $\tilde{\gamma}$ decay, where $\tilde{\gamma}$'s are expected to come from $\tilde{g}$'s produced at the target. Three possible $\tilde{\gamma}$ lifetimes are considered. Gluino decay to goldstino + gluon is also considered.

[138] BEHREND 83 and BARTEL 84B look for 2γ events from $\tilde{\gamma}$ pair production. With supersymmetric breaking parameter d = (100 GeV)^2 and $m(\tilde{e})$ = 40 GeV the excluded regions at CL = 95% would be $m(\tilde{\gamma})$ = 100 MeV – 13 GeV for BEHREND 83 $m(\tilde{\gamma})$ = 80 MeV – 18 GeV for BARTEL 84B. Limit is also applicable if the $\tilde{\gamma}$ decays radiatively within the detector.

[139] CABIBBO 81 consider $\tilde{\gamma} \to \gamma$ + goldstino. Photino must be either light enough (<30 eV) to satisfy cosmology bound, or heavy enough (>0.3 MeV) to have disappeared at early universe.

Limits on Supersymmetry Breaking Scale, $\Lambda_{SS} = \sqrt{d}$

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[140] ABE	89J	VNS	$e^+e^- \to \tilde{\gamma}\tilde{\gamma}$
		[141] BJORKEN	88	CALO	$e^+e^- \to \tilde{\gamma}\tilde{\gamma}$
> 69	90	[142] BEHREND	86D	CELL	$e^+e^- \to \gamma\tilde{\gamma}\tilde{G}$
>117		[143] FAYET	86	RVUE	$m(\tilde{\gamma})$<20 GeV
>240		[143] FAYET	86	RVUE	0.3<$m(\tilde{\gamma})$<10 GeV
> 9		[144] FAYET	79B	RVUE	$\psi' \to \pi^+\pi^- J/\psi$, $J/\psi \to \tilde{\gamma}\tilde{G}$

[140] See Fig. 15 of ABE 89J for a bound on d as a function of $m(\tilde{\gamma})$.

[141] BJORKEN 88 reports limits on $\sqrt{d}$ for $m(\tilde{\gamma})$ < 50 MeV and for several values of $m(\tilde{e})$ from electron beam-dump experiment. Assume $\tilde{\gamma}$ decays to photon plus gravitino.

[142] The $\tilde{\gamma}$ is assumed to be light and decay outside the detector. The quoted gravitino mass limit $m(\text{gravitino}) > 0.8 \times 10^{-6}$ eV is converted to the lower limit of the supersymmetry breaking scale $\sqrt{d} = \Lambda_{SS}$ via the formula: $m(\text{gravitino}) = \sqrt{4\pi/3}\,(\Lambda_{SS}^2/m(\text{planck}))$ with $m(\text{planck}) = 1.22 \times 10^{19}$ GeV

[143] FAYET 86 uses $e^+ e^- \rightarrow$ single photon data to rule out small supersymmetry breaking scale based on the process $e^+ e^- \rightarrow \tilde{\gamma} \widetilde{G}$ ($\tilde{\gamma} \rightarrow \gamma \widetilde{G}$) or $e^+ e^- \rightarrow \gamma \tilde{\gamma} \widetilde{G}$ where $\widetilde{G}$ denotes a goldstino or a gravitino, respectively, in global or local supersymmetric theories. The limits vanish above $m(\tilde{\gamma}) = 20$ GeV. In local supersymmetric theories, the above bounds can be reinterpreted as the gravitino mass bounds, i.e., $m(\text{gravitino}) > 2.3 \times 10^{-6}$ eV and $m(\text{gravitino}) > 1 \times 10^{-5}$ eV, respectively. These limits are independent of $m(\tilde{f}_L)$ and $m(\tilde{f}_R)$.

[144] This corresponds, in locally supersymmetric theories, to $m(\text{gravitino}) > 1.5 \times 10^{-8}$ eV.

Supersymmetry Miscellaneous Results

Results that do not appear under other headings or that make nonminimal assumptions.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[145] BARBER 84B	RVUE	
	[146] HOFFMAN 83	CNTR	$\pi p \rightarrow n(e^+ e^-)$

[145] BARBER 84B consider that $\tilde{\mu}$ and $\tilde{e}$ may mix leading to $\mu \rightarrow e \tilde{\gamma} \tilde{\gamma}$. They discuss mass-mixing limits from decay dist asym in LBL-TRIUMF data and e^+ polarization in SIN data.

[146] HOFFMAN 83 set CL = 90% limit $d\sigma/dt\,B(e^+ e^-) < 3.5 \times 10^{-32}$ cm^2/GeV^2 for spin-1 partner of Goldstone fermions with $140 < m < 160$ MeV decaying $\rightarrow e^+ e^-$ pair.

REFERENCES FOR Supersymmetric Particle Searches

DECAMP 92 PRPL (to be pub.) +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
CERN-PPE/91-149
ABREU 91F NP B367 511 +Adam, Adami, Adye, Akesson, Alekseev+ (DELPHI Collab.)
AKESSON 91 ZPHY C52 219 +Almehed, Angelis, Atherton, Aubry+ (HELIOS Collab.)
ALEXANDER 91F ZPHY C52 175 +Allison, Allport, Anderson, Arcelli+ (OPAL Collab.)
ANTONIADIS 91 PL B262 109 +Ellis, Nanopoulos (EPOL, CERN, TAMU, HARC)
BAER 91 PR D44 207 +Tata, Woodside (FSU, HAWA, ISU)
BAER 91B PR D44 725 +Drees+ (FSU, DESY, BOMB, UCD, HAWA)
BOTTINO 91 PL B265 57 +de Alfaro, Fornengo, Mignola, Pignone (TORI, INFN)
DREES 91 PR D43 2971 +Tata (CERN, HAWA)
GELMINI 91 NP B351 623 +Gondolo, Roulet (UCLA, TRST)
HIDAKA 91 PR D44 927 (TGAK)
KAMIONKOW... 91 PR D44 3021 Kamionkowski (CHIC, FNAL)
MORI 91B PL B270 89 +Nojiri, Oyama, Suzuki+ (Kamiokande Collab.)
NOJIRI 91 PL B261 76 (KEK)
OLIVE 91 NP B355 208 +Srednicki (MINN, UCSB)
ROSZKOWSKI 91 PL B262 59 (CERN)
SATO 91 PR D44 2220 +Hirata, Kajita, Kifune, Kihara+ (Kamioka Collab.)
ABREU 90F PL B247 148 +Adam, Adami, Adye, Alekseev+ (DELPHI Collab.)
ABREU 90G PL B247 157 +Adam, Adami, Adye, Alekseev+ (DELPHI Collab.)
ADACHI 90C PL B244 352 +Aihara, Doser, Enomoto+ (TOPAZ Collab.)
ADEVA 90I PL B249 341 +Adriani, Aguilar-Benitez, Akbari, Alcarez+ (L3 Collab.)
AKESSON 90B PL B238 442 +Alitti, Ansari, Ansorge+ (UA2 Collab.)
AKRAWY 90D PL B240 261 +Alexander, Allison, Allport+ (OPAL Collab.)
AKRAWY 90N PL B248 211 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
AKRAWY 90O PL B252 290 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ALITTI 90 PL B235 363 +Ansari, Ansorge, Bagnaia, Bareyre+ (UA2 Collab.)
BAER 90 PR D41 3414 +Drees, Tata (FSU, CERN, HAWA)
BARKLOW 90 PRL 64 2984 +Abrams, Adolphsen, Averill, Ballam+ (Mark II Collab.)
DECAMP 90C PL B236 86 +Deschizeaux, Lees, Minard, Crespo+ (ALEPH Collab.)
DECAMP 90K PL B244 541 +Deschizeaux, Goy, Lees+ (ALEPH Collab.)
DREES 90 PL B252 127 +Hikasa (CERN, KEK)
ELLIS 90 PL B245 251 +Nanopoulos, Roszkowski, Schramm (CERN, HARC, TAMU)
GRIEST 90 PR D41 3565 +Kamionkowski, Turner (UCB, CHIC, FNAL)
GRIFOLS 90 NP B331 244 +Masso (BARC)
KRAUSS 90 PRL 64 999 (YALE)
ROSZKOWSKI 90 PL B252 471 (TAMU, HARC)
SAKAI 90 PL B234 534 +Gu, Low, Abe, Fujii+ (AMY Collab.)
SODERSTROM 90 PRL 64 2980 +McKenna, Abrams, Adolphsen, Averill+ (Mark II Collab.)
TAKETANI 90 PL B234 202 +Odaka, Abe, Amako+ (VENUS Collab.)
ZHUKOVSKII 90 SJNP 52 931 +Eminov (MOSU)
Translated from YAF 52 1473.
ABE 89B PRL 62 1825 +Amidei, Apollinari, Ascoli, Atac+ (CDF Collab.)
ABE 89J ZPHY C45 175 +Amako, Arai, Fukawa+ (VENUS Collab.)
ABE 89K PL B232 431 +Amako, Arai, Asano, Chiba+ (VENUS Collab.)
ADACHI 89 PL B218 105 +Aihara, Dijkstra, Enomoto, Fujii+ (TOPAZ Collab.)
ADEVA 89B PL B233 530 +Adriani, Aguilar-Benitez, Akbari+ (L3 Collab.)
ALBAJAR 89 ZPHY C44 15 +Albrow, Allkofer, Arnison, Astbury+ (UA1 Collab.)
BAER 89 PRL 63 352 +Tata, Woodside (FSU, HAWA, OKSU)
HEARTY 89 PR D39 3207 +Rothberg, Young, Johnson, Whitaker+ (ASP Collab.)
Also 87 PRL 58 1711 Hearty, Rothberg, Young, Johnson+ (ASP Collab.)
Also 86 PRL 56 685 Bartha, Burke, Extermann+ (ASP Collab.)
NAKAMURA 89 PR D39 1261 +Kobayashi, Konaka, Imai, Masaike+ (KYOT, TMTC)
OLIVE 89 PL B230 78 +Srednicki (MINN, UCSB)
BAER 88 PR D38 1485 +Hagiwara, Tata (FSU, KEK, WISC)
Also 89B PR D39 989 (erratum) Baer, Hagiwara, Tata (FSU, KEK, WISC)
BEHREND 88B PL B215 186 +Criegee, Dainton, Field+ (CELLO Collab.)
BJORKEN 88 PR D38 3375 +Ecklund, Nelson, Abashian+ (FNAL, SLAC, VPI)
ELLIS 88B PL B215 404 +Olive, Sarkar, Sciama (CERN, MINN, RAL, CAMB)
NATH 88 PR D38 1479 +Arnowitt (NEAS, TAMU)
OLIVE 88 PL B205 553 +Srednicki (MINN, UCSB)
SREDNICKI 88 NP B310 693 +Watkins, Olive (MINN, UCSB)
ADEVA 87 PL B194 167 +Anderhub, Ansari, Becker+ (Mark-J Collab.)
ALBAJAR 87B PL B185 241 +Albrow, Allkofer, Arnison+ (UA1 Collab.)
ALBAJAR 87D PL B198 261 +Albrow, Allkofer+ (UA1 Collab.)
ANSARI 87D PL B195 613 +Bagnaia, Banner+ (UA2 Collab.)
ARNOLD 87 PL B186 435 +Barth+ (LIBH, DUUC, LOUC, BARI, AICH, CERN+)
BAER 87B PR D35 1598 +Hagiwara, Tata (KEK, ANL, WISC)
Also 86 PRL 57 294 Baer, Hagiwara, Tata (ANL, DESY, WISC)
BEHREND 87B ZPHY C35 181 +Buerger, Criegee, Dainton+ (CELLO Collab.)
HEARTY 87 PRL 58 1711 +Rothberg, Young, Johnson+ (ASP Collab.)
NG 87 PL B188 138 +Olive, Srednicki (MINN, UCSB)
TUTS 87 PL B186 233 +Franzini, Youssef, Zhao+ (CUSB Collab.)
ALBRECHT 86C PL 167B 360 +Binder, Harder+ (ARGUS Collab.)
BADIER 86 ZPHY C31 21 +Bemporad, Boucrot, Callot+ (NA3 Collab.)
BEHREND 86D PL B176 247 +Buerger, Criegee, Fenner, Field+ (CELLO Collab.)
FAYET 86 PL B175 471 (ENSP)
FORD 86 PR D33 3472 +Qi, Read+ (MAC Collab.)
GAISSER 86 PR D34 2206 +Steigman, Tilav (BRTD, DELA)
VOLOSHIN 86 SJNP 43 495 +Okun (ITEP)
Translated from YAF 43 779.
ADEVA 85 PL 152B 439 +Becker, Becker-Szendy+ (Mark-J Collab.)
Also 84C PRPL 109 131 Adeva, Barber, Becker+ (Mark-J Collab.)
AKERLOF 85 PL 156B 271 +Bonvicini, Chapman, Errede+ (HRS Collab.)
BARTEL 85L PL 155B 288 +Becker, Cords, Felst, Hagiwara+ (JADE Collab.)
BEHREND 85 PL 161B 182 +Burger, Criegee, Fenner+ (CELLO Collab.)
COOPER-... 85B PL 160B 212 Cooper-Sarkar, Parker, Sarkar+ (WA66 Collab.)
DAWSON 85 PR D31 1581 +Eichten, Quigg (LBL, FNAL)
FARRAR 85 PRL 55 895 (RUTG)
GOLDMAN 85 Physica 15D 181 +Haber (LANL, UCSC)
HABER 85 PRPL 117 75 +Kane (UCSC, MICH)
ADEVA 84B PRL 53 1806 +Barber, Becker, Berdugo+ (Mark-J Collab.)
BALL 84 PRL 53 1314 +Coffin, Gustafson+ (MICH, FIRZ, OSU, FNAL, WISC)
BARBER 84B PL 139B 427 +Shrock (STON)
BARTEL 84B PL 139B 327 +Becker, Bowdery, Cords+ (JADE Collab.)
BARTEL 84C PL 146B 126 +Becker, Bowdery, Cords+ (JADE Collab.)
BRICK 84 PR D30 1134 + (BROW, CAMB, IIT, IND, MIT, MONS, NIJM+)
ELLIS 84 NP B238 453 +Hagelin, Nanopoulos, Olive, Srednicki (CERN)
FARRAR 84 PRL 53 1029 (RUTG)
BEHREND 83 PL 123B 127 +Chen, Fenner, Gumpel+ (CELLO Collab.)
BERGSMA 83C PL 121B 429 +Dorenbosch, Jonker+ (CHARM Collab.)
CHANOWITZ 83 PL 126B 225 +Sharpe (UCB, LBL)
GOLDBERG 83 PRL 50 1419 (NEAS)
HOFFMAN 83 PR D28 660 +Frank, Mischke, Moir, Schardt (LANL, ARZS)
KRAUSS 83 NP B227 556 (HARV)
VYSOTSKII 83 SJNP 37 948 (ITEP)
Translated from YAF 37 1597.
KANE 82 PL 112B 227 +Leveille (MICH)
CABIBBO 81 PL 105B 155 +Farrar, Maiani (ROMA, RUTG)
FAYET 79B PL 84B 421 (CIT)
FARRAR 78 PL 76B 575 +Fayet (CIT)
Also 78B PL 79B 442 Farrar, Fayet (CIT)

Searches for Quark and Lepton Compositeness

NOTE ON SEARCHES FOR QUARK AND LEPTON COMPOSITENESS

If quarks and leptons are made of constituents, then at the scale of constituent binding energies, there should appear new interactions among quarks and leptons. At energies much below the compositeness scale (Λ), these interactions are suppressed by inverse powers of Λ. The dominant effect should come from the lowest dimensional interactions with four fermions (contact terms), whose most general chirally invariant form reads[1]

$$L = \frac{g^2}{2\Lambda^2}\Big[\eta_{LL}\,\overline{\psi}_L\gamma_\mu\psi_L\,\overline{\psi}_L\gamma^\mu\psi_L + \eta_{RR}\,\overline{\psi}_R\gamma_\mu\psi_R\,\overline{\psi}_R\gamma^\mu\psi_R + 2\eta_{LR}\,\overline{\psi}_L\gamma_\mu\psi_L\,\overline{\psi}_R\gamma^\mu\psi_R\Big]\ . \qquad (1)$$

Chiral invariance provides a natural explanation why quark and lepton masses are much smaller than their inverse size Λ. We may determine the scale Λ unambiguously by using the above form of the effective interactions; the conventional method[1] is to fix its scale by setting $g^2/4\pi = g^2(\Lambda)/4\pi = 1$ for the new strong interaction coupling and by setting the largest magnitude of the coefficients $\eta_{\alpha\beta}$ to be unity. In the following, we denote

$$\begin{aligned}
\Lambda &= \Lambda^{\pm}_{LL} \ \text{ for } \ (\eta_{LL},\,\eta_{RR},\,\eta_{LR}) = (\pm 1,\,0,\,0)\ ,\\
\Lambda &= \Lambda^{\pm}_{RR} \ \text{ for } \ (\eta_{LL},\,\eta_{RR},\,\eta_{LR}) = (0,\,\pm 1,\,0)\ ,\\
\Lambda &= \Lambda^{\pm}_{VV} \ \text{ for } \ (\eta_{LL},\,\eta_{RR},\,\eta_{LR}) = (\pm 1,\,\pm 1,\,\pm 1)\ ,\\
\Lambda &= \Lambda^{\pm}_{AA} \ \text{ for } \ (\eta_{LL},\,\eta_{RR},\,\eta_{LR}) = (\pm 1,\,\pm 1,\,\mp 1)\ , \qquad (2)
\end{aligned}$$

as typical examples. Such interactions can arise by constituent interchange (when the fermions have common constituents, e.g., for $ee \rightarrow ee$) and/or by exchange of the binding quanta (whenever binding quanta couple to constituents of both particles).

Another typical consequence of compositeness is the appearance of excited leptons and quarks (ℓ^* and q^*). Phenomenologically, an excited lepton is defined to be a heavy lepton which shares leptonic quantum number with one of the existing leptons (an excited quark is defined similarly). For example, an excited electron e^* is characterized by a nonzero transition-magnetic coupling with electrons. Smallness of the lepton mass and the success of QED prediction for $g-2$ suggest chirality conservation, i.e., an excited lepton should not couple to both left- and right-handed components of the corresponding lepton.

Excited leptons may be classified by SU(2)×U(1) quantum numbers. Typical examples are:

1. Sequential type

$$\begin{pmatrix}\nu^*\\ \ell^*\end{pmatrix}_L, \quad [\nu^*_R], \quad \ell^*_R .$$

ν^*_R is necessary unless ν^* has a Majorana mass.

2. Mirror type

$$[\nu^*_L], \quad \ell^*_L, \quad \begin{pmatrix}\nu^*\\ \ell^*\end{pmatrix}_R .$$

3. Homodoublet type

$$\begin{pmatrix}\nu^*\\ \ell^*\end{pmatrix}_L, \quad \begin{pmatrix}\nu^*\\ \ell^*\end{pmatrix}_R .$$

Similar classification can be made for excited quarks.

Excited fermions can be pair produced via their gauge couplings. The couplings of excited leptons with Z^0 are listed in the following table (for notation see Eq. (1) in "Standard Model of Electroweak Interactions" in Sec. III):

	Sequential type	Mirror type	Homodoublet type
V^{ℓ^*}	$-\frac{1}{2}+2\sin^2\theta_W$	$-\frac{1}{2}+2\sin^2\theta_W$	$-1+2\sin^2\theta_W$
A^{ℓ^*}	$-\frac{1}{2}$	$+\frac{1}{2}$	0
$V^{\nu^*_D}$	$+\frac{1}{2}$	$+\frac{1}{2}$	+1
$A^{\nu^*_D}$	$+\frac{1}{2}$	$-\frac{1}{2}$	0
$V^{\nu^*_M}$	0	0	—
$A^{\nu^*_M}$	+1	−1	—

Here ν^*_D (ν^*_M) stands for Dirac (Majorana) excited neutrino. The corresponding couplings of excited quarks can be easily obtained. Although form factor effects can be present for the gauge couplings at $q^2 \neq 0$, they are usually neglected.

In addition, transition magnetic type couplings with a gauge boson are expected. These couplings can be generally parameterized as follows:

$$\begin{aligned}\mathcal{L} = &\frac{\lambda_\gamma^{(f^*)} e}{2m_{f^*}} \overline{f}^* \sigma^{\mu\nu}(\eta_L \tfrac{1-\gamma_5}{2} + \eta_R \tfrac{1+\gamma_5}{2}) f F_{\mu\nu} \\ &+ \frac{\lambda_Z^{(f^*)} e}{2m_{f^*}} \overline{f}^* \sigma^{\mu\nu}(\eta_L \tfrac{1-\gamma_5}{2} + \eta_R \tfrac{1+\gamma_5}{2}) f Z_{\mu\nu} \\ &+ \frac{\lambda_W^{(\ell^*)} g}{2m_{\ell^*}} \overline{\ell}^* \sigma^{\mu\nu} \tfrac{1-\gamma_5}{2} \nu W_{\mu\nu} \\ &+ \frac{\lambda_W^{(\nu^*)} g}{2m_{\nu^*}} \overline{\nu}^* \sigma^{\mu\nu}(\eta_L \tfrac{1-\gamma_5}{2} + \eta_R \tfrac{1+\gamma_5}{2}) \ell W^\dagger_{\mu\nu} \\ &+ \text{h.c.}\,, \end{aligned} \tag{3}$$

where $g = e/\sin\theta_W$, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the photon field strength, $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$, etc. The normalization of the coupling is chosen such that

$$\max(|\eta_L|, |\eta_R|) = 1 .$$

Chirality conservation requires

$$\eta_L \eta_R = 0 . \tag{4}$$

These couplings can arise from SU(2)×U(1)-invariant higher-dimensional interactions. A well-studied model is the interaction of homodoublet type ℓ^* with the Lagrangian[2,3]

$$\mathcal{L} = \frac{1}{2\Lambda} \overline{L}^* (g f \tfrac{\tau^a}{2} W^a_{\mu\nu} + g' f' Y B_{\mu\nu}) \tfrac{1-\gamma_5}{2} L + \text{h.c.}\,, \tag{5}$$

where L denotes the lepton doublet (ν, ℓ), Λ is the compositeness scale, g, g' are SU(2) and U(1)$_Y$ gauge couplings, and $W^a_{\mu\nu}$ and $B_{\mu\nu}$ are the field strengths for SU(2) and U(1)$_Y$ gauge fields. The same interaction occurs for mirror-type excited leptons. For sequential-type excited leptons, the ℓ^* and ν^* couplings become unrelated, and the couplings receive the extra suppression of (250 GeV)/Λ or m_{L^*}/Λ. In any case, these couplings satisfy the relation

$$\lambda_W = -\sqrt{2}\sin^2\theta_W(\lambda_Z \cot\theta_W + \lambda_\gamma) . \tag{6}$$

The coupling of excited quarks with gluons can be constructed in a similar way.

Some experimental analyses assume the relation $\eta_L = \eta_R = 1$, which violates chiral symmetry. We encode the results of such analyses if the crucial part of the cross section is proportional to the factor $\eta_L^2 + \eta_R^2$ and the limits can be reinterpreted as those for chirality conserving cases $(\eta_L, \eta_R) = (1,0)$ or $(0,1)$ after rescaling λ.

Several different conventions are used by LEP experiments to express the transition magnetic couplings. To facilitate comparison, we reexpress these in terms of λ_Z using the following relations and taking $\sin^2\theta_W = 0.23$. We assume chiral couplings, *i.e.*, $|c| = |d|$ in the notation of Ref. 2.

1. ALEPH (charged lepton and neutrino)

$$\lambda_Z^{\text{ALEPH}} = \frac{1}{2}\lambda_Z \quad \text{(1990 papers)} \tag{7a}$$

$$\frac{2c}{\Lambda} = \frac{\lambda_Z}{m_{\ell^*}[\text{or } m_{\nu^*}]} \quad (\text{for } |c| = |d|) \tag{7b}$$

2. ALEPH (quark)

$$\lambda_u^{\text{ALEPH}} = \frac{\sin\theta_W\cos\theta_W}{\sqrt{(\frac{1}{4} - \frac{2}{3}\sin^2\theta_W + \frac{8}{9}\sin^4\theta_W}} \lambda_Z = 1.11\lambda_Z \tag{8}$$

3. L3 (charged lepton)

$$\lambda^{\text{L3}} = -\frac{\sqrt{2}}{\cot\theta_W - \tan\theta_W}\lambda_Z = -1.10\lambda_Z \tag{9}$$

4. L3 (neutrino)

$$f_Z^{\text{L3}} = \sqrt{2}\lambda_Z \tag{10}$$

5. OPAL (charged lepton)

$$\frac{f^{\text{OPAL}}}{\Lambda} = -\frac{2}{\cot\theta_W - \tan\theta_W}\frac{\lambda_Z}{m_{\ell^*}} = -1.56\frac{\lambda_Z}{m_{\ell^*}} \tag{11}$$

6. OPAL (quark)

$$\frac{f^{\text{OPAL}}c}{\Lambda} = \frac{\lambda_Z}{2m_{q^*}} \quad (\text{for } |c| = |d|) \tag{12}$$

If leptons are made of color triplet and antitriplet constituents, we may expect their color-octet partners. Transitions between the octet leptons (ℓ_8) and the ordinary lepton (ℓ) may take place via the dimension-five interactions

$$\mathcal{L} = \frac{1}{2\Lambda} \sum_{\ell} \left\{ \bar{\ell}_8^{\alpha}\, g_S\, F_{\mu\nu}^{\alpha}\, \sigma^{\mu\nu} \left(\eta_L\, \ell_L + \eta_R\, \ell_R \right) + h.c. \right\} \tag{13}$$

where the summation is over charged leptons and neutrinos. The leptonic chiral invariance implies $\eta_L\ \eta_R = 0$ as before.

References

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2. K. Hagiwara, S. Komamiya, and D. Zeppenfeld, Z. Phys. **C29**, 115 (1985).
3. N. Cabibbo, L. Maiani, and Y. Srivastava, Phys. Lett. **139B**, 459 (1984).

SCALE LIMITS for Contact Interactions: $\Lambda(eeee)$

Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>1.4	95	[1] BRAUNSCH...	88	TASS	Λ^{+}_{LL}
>3.3	95	[1] BRAUNSCH...	88	TASS	Λ^{-}_{LL}
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.7	95	[2] BEHREND	91C	CELL	Λ^{+}_{LL}
>2.8	95	[2] BEHREND	91C	CELL	Λ^{-}_{LL}
>1.3	95	[3] KIM	89	AMY	Λ^{+}_{LL}
>1.3	95	[3] KIM	89	AMY	Λ^{-}_{LL}
>1.1	95	[4] BARTEL	86C	JADE	Λ^{+}_{LL}
>1.4	95	[4] BARTEL	86C	JADE	Λ^{-}_{LL}
>1.17	95	[5] DERRICK	86	HRS	Λ^{+}_{LL}
>0.87	95	[5] DERRICK	86	HRS	Λ^{-}_{LL}
>1.1	95	[6] BERGER	85	PLUT	Λ^{+}_{LL}
>0.76	95	[6] BERGER	85	PLUT	Λ^{-}_{LL}

[1] BRAUNSCHWEIG 88 is at E_{cm} = 12–46.8 GeV. $m(Z)$ = 92 GeV and $\sin^2\theta_W$ = 0.23 assumed.
[2] BEHREND 91C is from data at E_{cm} = 35 GeV.
[3] KIM 89 is at E_{cm} = 50–57 GeV.
[4] BARTEL 86C is at E_{cm} = 12–46.8 GeV. $m(Z)$ = 93 GeV and $\sin^2\theta_W$ = 0.217 assumed.
[5] DERRICK 86 is at E_{cm} = 29 GeV. $m(Z)$ = 93 GeV and $g_V^2 = (-1/2+2\sin^2\theta_W)^2$ = 0.004 assumed.
[6] BERGER 85 is at E_{cm} = 34.7 GeV. $m(Z)$ = 93 GeV and $\sin^2\theta_W$ = 0.217 assumed.

SCALE LIMITS for Contact Interactions: $\Lambda(ee\mu\mu)$

Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>4.4	95	[7] BARTEL	86C	JADE	Λ^{+}_{LL}
>2.1	95	[7] BARTEL	86C	JADE	Λ^{-}_{LL}
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>2.5	95	[8] BEHREND	91C	CELL	Λ^{+}_{LL}
>1.5	95	[8] BEHREND	91C	CELL	Λ^{-}_{LL}
>1.6	95	[9] ABE	90I	VNS	Λ^{+}_{LL}
>2.0	95	[9] ABE	90I	VNS	Λ^{-}_{LL}
>1.9	95	[10] KIM	89	AMY	Λ^{+}_{LL}
>1.0	95	[10] KIM	89	AMY	Λ^{-}_{LL}
>2.9	95	[11] BERGER	85	PLUT	Λ^{+}_{LL}
>0.86	95	[11] BERGER	85	PLUT	Λ^{-}_{LL}

[7] BARTEL 86C is at E_{cm} = 12–46.8 GeV. $m(Z)$ = 93 GeV and $\sin^2\theta_W$ = 0.217 assumed.
[8] BEHREND 91C is from data at E_{cm} between 35 and 43 GeV.
[9] ABE 90I is at E_{cm} = 50–60.8 GeV. $m(Z)$ =91.163 GeV and $\sin^2\theta_W$ = 0.231 assumed.
[10] KIM 89 is at E_{cm} = 50–57 GeV.
[11] BERGER 85 is at E_{cm} = 34.7 GeV. $m(Z)$ = 93 GeV and $\sin^2\theta_W$ = 0.217 assumed.

SCALE LIMITS for Contact Interactions: $\Lambda(ee\tau\tau)$

Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>2.2	95	[12] BARTEL	86	JADE	Λ^{+}_{LL}
>3.2	95	[12] BARTEL	86	JADE	Λ^{-}_{LL}
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>1.6	95	[13] BEHREND	91C	CELL	Λ^{+}_{LL}
>2.3	95	[13] BEHREND	91C	CELL	Λ^{-}_{LL}
>1.8	95	[14] ABE	90I	VNS	Λ^{+}_{LL}
>1.3	95	[14] ABE	90I	VNS	Λ^{-}_{LL}

[12] BARTEL 86 is at E_{cm} = 12–46.8 GeV. $m(Z)$ = 93 GeV and $\sin^2\theta_W$ = 0.217 assumed.
[13] BEHREND 91C is from data at E_{cm} between 35 and 43 GeV.
[14] ABE 90I is at E_{cm} = 50–60.8 GeV. $m(Z)$ =91.163 GeV and $\sin^2\theta_W$ = 0.231 assumed.

SCALE LIMITS for Contact Interactions: $\Lambda(eeqq)$

Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>1.7	95	[15] ABE	91D	CDF	$\Lambda^{+}_{LL}(eeqq)$ (isosinglet)
>2.2	95	[15] ABE	91D	CDF	$\Lambda^{-}_{LL}(eeqq)$ (isosinglet)
>1.2	95	[16] ADACHI	91	TOPZ	$\Lambda^{+}_{LL}(eeqq)$ (flavor-universal)
>1.7	95	[17] ABE	89L	VNS	$\Lambda^{-}_{LL}(eeqq)$ (flavor-universal)
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>1.6	95	[16] ADACHI	91	TOPZ	$\Lambda^{-}_{LL}(eeqq)$ (flavor-universal)
>0.6	95	[18] BEHREND	91C	CELL	Λ^{+}_{LL} $(eecc)$
>1.7	95	[18] BEHREND	91C	CELL	Λ^{-}_{LL} $(eecc)$
>1.1	95	[18] BEHREND	91C	CELL	Λ^{+}_{LL} $(eebb)$
>1.0	95	[18] BEHREND	91C	CELL	Λ^{-}_{LL} $(eebb)$
>0.9	95	[17] ABE	89L	VNS	$\Lambda^{+}_{LL}(eeqq)$ (flavor-universal)
>1.05	95	[19] HAGIWARA	89	RVUE	$\Lambda^{+}_{LL}(eecc)$
>1.61	95	[19] HAGIWARA	89	RVUE	$\Lambda^{-}_{LL}(eecc)$
>1.21	95	[20] HAGIWARA	89	RVUE	$\Lambda^{+}_{LL}(eebb)$
>0.53	95	[20] HAGIWARA	89	RVUE	$\Lambda^{-}_{LL}(eebb)$

[15] ABE 91D limits are from e^+e^- mass distribution in $p\bar{p} \rightarrow e^+e^-$ X at E_{cm} = 1.8 TeV.
[16] ADACHI 91 limits are from differential jet cross section. Universality of $\Lambda(eeqq)$ for five flavors is assumed.
[17] ABE 89L limits are from jet charge asymmetry. Universality of $\Lambda(eeqq)$ for five flavors is assumed.
[18] BEHREND 91C is from data at E_{cm} between 35 and 43 GeV.
[19] The HAGIWARA 89 limit is derived from forward-backward asymmetry measurements of D/D^* mesons by ALTHOFF 83C, BARTEL 84E, and BARINGER 88.
[20] The HAGIWARA 89 limit is derived from forward-backward asymmetry measurement of b hadrons by BARTEL 84D.

SCALE LIMITS for Contact Interactions: $\Lambda(\mu\mu qq)$

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>1.4	95	ABE	92B	CDF	$\Lambda^{+}_{LL}(\mu\mu qq)$ (isosinglet)
>1.6	95	ABE	92B	CDF	$\Lambda^{-}_{LL}(\mu\mu qq)$ (isosinglet)

SCALE LIMITS for Contact Interactions: $\Lambda(\mu\nu_\mu e\nu_e)$

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>3.10	90	[21] JODIDIO	86	SPEC	$\Lambda^{\pm}_{LR}$ from $\mu^+ \rightarrow \bar{\nu}_\mu e^+ \nu_e$

[21] In JODIDIO 86 chirality invariant interactions $L = (g^2/\Lambda^2)\ [\eta_{LL}\ (\bar{\nu}_{\mu L}\gamma^\alpha\mu_L)\ (\bar{e}_L\gamma_\alpha\nu_{eL}) + \eta_{LR}\ (\bar{\nu}_{\mu L}\gamma^\alpha\nu_{eL}\ (\bar{e}_R\gamma_\alpha\mu_R)]$ with $g^2/4\pi = 1$ and $(\eta_{LL},\eta_{LR}) = (0,\pm1)$ are taken. No limits are given for $\Lambda^{\pm}_{LL}$ with $(\eta_{LL},\eta_{LR}) = (\pm1,0)$. For more general constraints with right-handed neutrinos and chirality nonconserving contact interactions, see their text.

SCALE LIMITS for Contact Interactions: $\Lambda(qqqq)$

Limits are for $\Lambda^{\pm}_{LL}$ with color-singlet isoscalar exchanges among u_L's and d_L's only. See EICHTEN 84 for details.

VALUE (TeV)	CL%	DOCUMENT ID	TECN	COMMENT
>0.825	95	[22] ALITTI 91B	UA2	$p\overline{p} \to$ jets inclusive
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>0.700	95	[23] ABE 89	CDF	$p\overline{p} \to$ jets inclusive
>0.330	95	[24] ABE 89H	CDF	$p\overline{p} \to$ dijets
>0.400	95	[25] ARNISON 86C	UA1	$p\overline{p} \to$ jets inclusive
>0.415	95	[26] ARNISON 86D	UA1	$p\overline{p} \to$ dijets
>0.370	95	[27] APPEL 85	UA2	$p\overline{p} \to$ jets inclusive
>0.275	95	[28] BAGNAIA 84C	UA2	Repl. by APPEL 85

[22] ALITTI 91B limit is from inclusive jet cross section in $p\overline{p}$ collisions at $E_{cm} = 630$ GeV. The limit takes into account uncertainties in choice of structure functions and in choice of process scale.

[23] ABE 89 limit is from inclusive jet cross-section data in $p\overline{p}$ collisions at $E_{cm} = 1.8$ TeV. The limit takes into account uncertainties in choice of structure functions and in choice of process scale.

[24] ABE 89H limit is from dijet angular distribution for m(dijet) > 200 GeV at the Fermilab Tevatron Collider with $E_{cm} = 1.8$ TeV. The QCD prediction is quite insensitive to choice of structure functions and choice of process scale.

[25] ARNISON 86C limit is from the study of inclusive high-p_T jet distributions at the CERN $\overline{p}p$ collider ($E_{cm} = 546$ and 630 GeV). The QCD prediction renormalized to the low-p_T region gives a good fit to the data.

[26] ARNISON 86D limit is from the study of dijet angular distribution in the range 240 < m(dijet) < 300 GeV at the CERN $\overline{p}p$ collider ($E_{cm} = 630$ GeV). QCD prediction using EHLQ structure function (EICHTEN 84) with $\Lambda_{QCD} = 0.2$ GeV for the choice of $Q^2 = p_T{}^2$ gives the best fit to the data.

[27] APPEL 85 limit is from the study of inclusive high-p_T jet distributions at the CERN $\overline{p}p$ collider ($E_{cm} = 630$ GeV). The QCD prediction renormalized to the low-p_T region gives a good description of the data.

[28] BAGNAIA 84C limit is from the study of jet p_T and dijet mass distributions at the CERN $\overline{p}p$ collider ($E_{cm} = 540$ GeV). The limit suffers from the uncertainties in comparing the data with the QCD prediction.

MASS LIMITS for Excited e (e^*)

Most e^+e^- experiments assume one-photon or Z exchange. The limits from some e^+e^- experiments which depend on λ have assumed transition couplings which are chirality violating ($\eta_L = \eta_R$). However they can be interpreted as limits for chirality-conserving interactions after multiplying the coupling value λ by $\sqrt{2}$; see Note.

Excited leptons have the same quantum numbers as other ortholeptons. See also the searches for ortholeptons in the "Searches for Heavy Leptons" section.

Limits for Excited e (e^*) from Pair Production

These limits are obtained from $e^+e^- \to e^{*+}e^{*-}$ and thus rely only on the (electroweak) charge of e^*. Form factor effects are ignored unless noted. For the case of limits from Z decay, the e^* coupling is assumed to be of sequential type. Possible t channel contribution from transition magnetic coupling is neglected. All limits assume $e^* \to e\gamma$ decay except the limits(s) from $\Gamma(Z)$.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>46.1	95	DECAMP 92	ALEP	$Z \to e^*e^*$
>45.0	95	ADEVA 90F	L3	$Z \to e^*e^*$
>44.9	95	AKRAWY 90I	OPAL	$Z \to e^*e^*$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>26.1	95	[29] DECAMP 92	ALEP	$Z \to e^*e^*$; $\Gamma(Z)$
>44.6	95	[30] DECAMP 90G	ALEP	$e^+e^- \to e^*e^*$
>30.2	95	ADACHI 89B	TOPZ	$e^+e^- \to e^*e^*$
>28.3	95	KIM 89	AMY	$e^+e^- \to e^*e^*$
>27.9	95	[31] ABE 88B	VNS	$e^+e^- \to e^*e^*$
>23	95	BEHREND 86	CELL	$e^+e^- \to e^*e^*$
none 0.5–3.3		[32] HAYES 82	MRK2	$e^+e^- \to e^*e^*$

[29] Limit is independent of e^* decay mode.

[30] Superceded by DECAMP 92.

[31] ABE 88B limits assume $e^+e^- \to e^{*+}e^{*-}$ with one photon exchange only and $e^* \to e\gamma$ giving $ee\gamma\gamma$.

[32] HAYES 82 is SLAC SPEAR experiment. Their tables 5,6 give cross-section limits for orthoelectron for masses in above range.

Limits for Excited e (e^*) from Single Production

These limits are from $e^+e^- \to e^*e$ or $W \to e^*\nu$ and depend on transition magnetic coupling between e and e^*. All limits assume $e^* \to e\gamma$ decay. Limits from LEP and UA2 are for chiral coupling, whereas all other limits are for nonchiral coupling, $\eta_L = \eta_R = 1$. In most papers, the limit is expressed in the form of an excluded region in the $\lambda - m(e^*)$ plane. See the original papers.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>91	95	[33] DECAMP 92	ALEP	$Z \to ee^*$, $\lambda_Z>1$
>88	95	[33] ADEVA 90F	L3	$Z \to ee^*$, $\lambda_Z>0.5$
>87	95	[33] AKRAWY 90I	OPAL	$Z \to ee^*$, $\lambda_Z>0.5$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>86	95	[33] ADEVA 90F	L3	$Z \to ee^*$, $\lambda_Z>0.04$
>81	95	[33,34] DECAMP 90G	ALEP	$Z \to ee^*$, $\lambda_Z>1$
>50	95	[35] ADACHI 89B	TOPZ	$e^+e^- \to ee^*$, $\lambda_\gamma>0.04$
>56	95	[35] KIM 89	AMY	$e^+e^- \to ee^*$, $\lambda_\gamma>0.03$
none 23–54	95	[35,36] ABE 88B	VNS	$e^+e^- \to ee^*$ $\lambda_\gamma>0.04$
>75	95	[37] ANSARI 87D	UA2	$W \to e^*\nu$; $\lambda_W>0.7$
>63	95	[37] ANSARI 87D	UA2	$W \to e^*\nu$; $\lambda_W>0.2$
>40	95	[37] ANSARI 87D	UA2	$W \to e^*\nu$; $\lambda_W>0.09$
		[35] BEHREND 86	CELL	$e^+e^- \to ee^*$
none 15–27	95	[35,38] BONNEAUD 86	DLCO	$e^+e^- \to ee^*$, $\lambda_\gamma>0.01$
none 0.5–0.9	95	[35,39] GOLUBEV 85B	ND	$e^+e^- \to ee^*$, $\lambda_\gamma>0.005$
		[35,40] BUKIN 82	OLYA	$e^+e^- \to ee^*$

[33] For chirality conserving coupling.

[34] Superceded by DECAMP 92.

[35] $\eta_L = \eta_R = 1$ taken.

[36] ABE 88B limits use $e^+e^- \to ee^*$ where t-channel photon exchange dominates giving $e\gamma(e)$ (quasi-real compton scattering).

[37] ANSARI 87D is at $E_{cm} = 546$–630 GeV.

[38] BONNEAUD 86 mass limit is from the DELCO collaboration at PEP.

[39] GOLUBEV 85B place upper limit for coupling of an excited electron of mass 500–900 MeV to be $\lambda_\gamma{}^2 < 3 \times 10^{-5}$ (CL=95%).

[40] BUKIN 82 is VEPP-2m ring experiment for $e^+e^- \to e^+e^-\gamma$ with $E_{cm} = 0.64$–1.4 GeV. Observed no peak in $m(e\gamma)$ spectrum. Set CL = 95% limit $\lambda_\gamma{}^2 < (0.2\text{–}6)10^{-4}$ for $m(e^*) = 0.2$–1.0 GeV.

Limits for Excited e (e^*) from $e^+e^- \to \gamma\gamma$

These limits are derived from indirect effects due to e^* exchange in the t channel and depend on transition magnetic coupling between e and e^*. All limits are for $\lambda_\gamma = 1$. All limits except ABE 89J are for nonchiral coupling with $\eta_L = \eta_R = 1$.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>116	95	AKRAWY 91F	OPAL	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> 99	95	DECAMP 92	ALEP	
>100	95	ABREU 91E	DLPH	
> 83	95	ADEVA 90K	L3	
> 82	95	AKRAWY 90F	OPAL	
> 68	95	[41] ABE 89J	VNS	$\eta_L=1$, $\eta_R=0$
> 90.2	95	ADACHI 89B	TOPZ	
> 65	95	KIM 89	AMY	
> 84	95	BEHREND 86	CELL	
> 72	95	[42] ADEVA 85	MRKJ	
> 70		[42] ADEVA 84C	MRKJ	
> 58	95	[43] ADEVA 82	MRKJ	
> 3.9	95	HANSON 73	WIRE	

[41] The ABE 89J limit assumes chiral coupling. This corresponds to $\lambda_\gamma = 0.7$ for nonchiral coupling.

[42] ADEVA 84C and ADEVA 85 limits are from $e^-e^+ \to 2\gamma$ with e^* exchange.

[43] ADEVA 82 study $e^+e^- \to e^+e^-\gamma$, $e^+e^-\gamma\gamma$, and $\gamma\gamma$. See their figure 2 for dependence on the coupling.

Indirect Limits for Excited e (e^*)

These limits make use of loop effects involving e^* and are therefore subject to theoretical uncertainty.

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[44] DORENBOS... 89	CHRM	$\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ and $\nu_\mu e \to \nu_\mu e$
	[45] GRIFOLS 86	THEO	$\nu_\mu e \to \nu_\mu e$
	[46] RENARD 82	THEO	$g-2$ of electron

[44] DORENBOSCH 89 obtain the limit $\lambda^2_\lambda \Lambda^2_{cut}/m^2(e^*) < 2.6$ (95% CL), where Λ_{cut} is the cutoff scale, based on the one-loop calculation by GRIFOLS 86. If one assumes that $\Lambda_{cut} = 1$ TeV and $\lambda_\gamma = 1$, one obtains $m(e^*) > 620$ GeV. However, one generally expects $\lambda_\gamma \approx m(e^*)/\Lambda_{cut}$ in composite models.

[45] GRIFOLS 86 uses $\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ data from CHARM Collaboration to derive mass limits which depend on the scale of compositeness.

[46] RENARD 82 derived from $g-2$ data limits on mass and couplings of e^* and μ^*. See figures 2 and 3 of the paper.

MASS LIMITS for Excited μ (μ^*)

Limits for Excited μ (μ^*) from Pair Production

These limits are obtained from $e^+e^- \to \mu^{*+}\mu^{*-}$ and thus rely only on the (electroweak) charge of μ^*. Form factor effects are ignored unless noted. For the case of limits from Z decay, the μ^* coupling is assumed to be of sequential type. All limits assume $\mu^* \to \mu\gamma$ decay except for the limit(s) from $\Gamma(Z)$.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>46.1	95	DECAMP 92	ALEP	$Z \to \mu^*\mu^*$
>45.3	95	ADEVA 90F	L3	$Z \to \mu^*\mu^*$
>44.9	95	AKRAWY 90I	OPAL	$Z \to \mu^*\mu^*$

• • • We do not use the following data for averages, fits, limits, etc. • • •

>26.1	95	[47] DECAMP 92	ALEP	$Z \to \mu^*\mu^*$; $\Gamma(Z)$
>44.6	95	[48,49] DECAMP 90G	ALEP	$e^+e^- \to \mu^*\mu^*$
>29.9	95	[48] ADACHI 89B	TOPZ	$e^+e^- \to \mu^*\mu^*$
>28.3	95	[48] KIM 89	AMY	$e^+e^- \to \mu^*\mu^*$
>23	95	BEHREND 86	CELL	$e^+e^- \to \mu^*\mu^*$
>22	95	[50] BARTEL 84	JADE	$e^+e^- \to \mu^*\mu^*$
		[51] FORD 83	MAC	$e^+e^- \to \mu^*\mu^*$,
>10	95	ADEVA 82	MRKJ	$e^+e^- \to \mu^*\mu^*$
none 0.6–3.3		[49,52] HAYES 82	MRK2	$e^+e^- \to \mu^*\mu^*$

[47] Limit is independent of μ^* decay mode.
[48] Assume one photon or Z production and $\mu^* \to \mu\gamma$ decay.
[49] Superceded by DECAMP 92.
[50] BARTEL 84 observed 270 $\mu^+\mu^-\gamma$ events. Distributions are consistent with QED. $\eta_L = \eta_R = 1$ assumed.
[51] FORD 83 at PEP-MAC (E_{cm} = 29 GeV) set CL = 90% limits $\sigma(\mu^*\mu^*)/\sigma(\mu^+\mu^-) < (1\text{–}2)10^{-3}$ for $m(\mu^*)$ = 2–14 GeV.
[52] HAYES 82 is SLAC SPEAR experiment. Their tables 5,6 give cross-section limits for orthomuon for masses in above range.

Limits for Excited μ (μ^*) from Single Production

These limits are from $e^+e^- \to \mu^*\mu$ and depend on transition magnetic coupling between μ and μ^*. All limits assume $\mu^* \to \mu\gamma$ decay. In most papers, the limit is expressed in the form of an excluded region in the $\lambda - m(\mu^*)$ plane. See the original papers.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>91	95	[53] DECAMP 92	ALEP	$Z \to \mu\mu^*$, $\lambda_Z>1$
>85	95	[53] ADEVA 90F	L3	$Z \to \mu\mu^*$, $\lambda_Z >1$
>87	95	[53] AKRAWY 90I	OPAL	$Z \to \mu\mu^*$, $\lambda_Z >1$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>75	95	[53] ADEVA 90F	L3	$Z \to \mu\mu^*$, $\lambda_Z >0.1$
>80	95	[53,54] DECAMP 90G	ALEP	$e^+e^- \to \mu\mu^*$, $\lambda_Z=1$
>50	95	[55,56] ADACHI 89B	TOPZ	$e^+e^- \to \mu\mu^*$, $\lambda_\gamma=0.7$
>46	95	[55,56] KIM 89	AMY	$e^+e^- \to \mu\mu^*$, $\lambda_\gamma=0.2$
>43	95	[56,57] BEHREND 86	CELL	$e^+e^- \to \mu\mu^*$, $\lambda_\gamma=0.6$
>25	95	[56] ADEVA 85	MRKJ	$e^+e^- \to \mu\mu^*$, $\lambda_\gamma=1$
>34	95	[56,58] BARTEL 84	JADE	$e^+e^- \to \mu\mu^*$, λ_γ = 0.2
		[59] FORD 83	MAC	$e^+e^- \to \mu\mu^*$
		[60] ADEVA 82	MRKJ	$e^+e^- \to \mu\mu^*$

[53] For chirality conserving coupling.
[54] Superceded by DECAMP 92.
[55] Assume one photon or Z production and $\mu^* \to \mu\gamma$ decay.
[56] $\eta_L = \eta_R = 1$ taken.
[57] BEHREND 86 limit is from analysis of $e^+e^- \to \mu^+\mu^-\gamma$ at E_{cm} = 33.–46.8 GeV.
[58] BARTEL 84 observed 270 $\mu^+\mu^-\gamma$ events. Distributions are consistent with QED.
[59] FORD 83 at PEP-MAC (E_{cm} = 29 GeV) set CL = 90% limits $\sigma(\mu^*\mu)/\sigma(\mu^+\mu^-) < (1\text{–}2)10^{-3}$ for $m(\mu^*)$ = 2.5–27 GeV.
[60] ADEVA 82 set limit $\sigma(\mu^*\mu)/\sigma(\mu^+\mu^-) <1\%$ (CL=95%) from $\mu^+\mu^-\gamma$ events.

Indirect Limits for Excited μ (μ^*)

These limits make use of loop effects involving μ^* and are therefore subject to theoretical uncertainty.

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[61] RENARD 82	THEO	$g-2$ of muon

[61] RENARD 82 derived from $g-2$ data limits on mass and couplings of e^* and μ^*. See figures 2 and 3 of the paper.

MASS LIMITS for Excited τ (τ^*)

Limits for Excited τ (τ^*) from Pair Production

These limits are obtained from $e^+e^- \to \tau^{*+}\tau^{*-}$ and thus rely only on the (electroweak) charge of τ^*. Form factor effects are ignored unless noted. For the case of limits from Z decay, the τ^* coupling is assumed to be of sequential type. All limits assume $\tau^* \to \tau\gamma$ decay except for the limit(s) from $\Gamma(Z)$.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>46.0	95	DECAMP 92	ALEP	$Z \to \tau^*\tau^*$
>45.5	95	ADEVA 90L	L3	$Z \to \tau^*\tau^*$
>44.9	95	AKRAWY 90I	OPAL	$Z \to \tau^*\tau^*$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>26.1	95	[62] DECAMP 92	ALEP	$Z \to \tau^*\tau^*$; $\Gamma(Z)$
>41.2	95	[63,64] DECAMP 90G	ALEP	$e^+e^- \to \tau^*\tau^*$
>29.0	95	[63] ADACHI 89B	TOPZ	$e^+e^- \to \tau^*\tau^*$
>22	95	[65] BARTEL 86	JADE	$e^+e^- \to \tau^*\tau^*$
>22.7	95	[66] BEHREND 86	CELL	$e^+e^- \to \tau^*\tau^*$

[62] Limit is independent of τ^* decay mode.
[63] Assume one photon or Z production and $\tau^* \to \tau\gamma$ decay.
[64] Superceded by DECAMP 92.
[65] BARTEL 86 is at E_{cm} = 30–46.78 GeV.
[66] BEHREND 86 limit is at E_{cm} = 33–46.8 GeV.

Limits for Excited τ (τ^*) from Single Production

These limits are from $e^+e^- \to \tau^*\tau$ and depend on transition magnetic coupling between τ and τ^*. All limits assume $\tau^* \to \tau\gamma$ decay. In most papers, the limit is expressed in the form of an excluded region in the $\lambda - m(\tau^*)$ plane. See the original papers.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>90	95	[67] DECAMP 92	ALEP	$Z \to \tau\tau^*$, $\lambda_Z>0.18$
>88	95	[67] ADEVA 90L	L3	$Z \to \tau\tau^*$, $\lambda_Z >1$
>86.5	95	[67] AKRAWY 90I	OPAL	$Z \to \tau\tau^*$, $\lambda_Z >1$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>59	95	[68,69] DECAMP 90G	ALEP	$e^+e^- \to \tau\tau^*$, $\lambda_Z=1$
>40	95	[70,71] BARTEL 86	JADE	$e^+e^- \to \tau\tau^*$, $\lambda_\gamma=1$
>41.4	95	[70,72] BEHREND 86	CELL	$e^+e^- \to \tau\tau^*$, $\lambda_\gamma=1$
>40.8	95	[70,72] BEHREND 86	CELL	$e^+e^- \to \tau\tau^*$, $\lambda_\gamma=0.7$

[67] For chirality conserving coupling.
[68] Assume one photon or Z production and $\tau^* \to \tau\gamma$ decay.
[69] Superceded by DECAMP 92.
[70] $\eta_L = \eta_R = 1$ taken.
[71] BARTEL 86 is at E_{cm} = 30–46.78 GeV.
[72] BEHREND 86 limit is at E_{cm} = 33–46.8 GeV.

MASS LIMITS for Excited Neutrino (ν^*)

Limits for Excited ν (ν^*) from Pair Production

These limits are obtained from $Z \to \nu^*\nu^*$ decay and thus rely only on the (electroweak) charge of ν^*. Form factor effects are ignored unless noted. The ν^* coupling is assumed to be of sequential type. Limits assume $\nu^* \to \nu\gamma$ decay except for the $\Gamma(Z)$ measurement which makes no assumption about decay mode.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>47	95	[73] DECAMP 92	ALEP	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>42.6	95	[74] DECAMP 92	ALEP	$\Gamma(Z)$
>35.4	95	[75,76] DECAMP 90O	ALEP	$\Gamma(Z)$
>46	95	[76,77] DECAMP 90O	ALEP	

[73] Limit is based on $B(Z \to \nu^*\overline{\nu}^*) \times B(\nu^* \to \nu\gamma)^2 < 5 \times 10^{-5}$ (95%CL) assuming Dirac ν^*, $B(\nu^* \to \nu\gamma) = 1$.
[74] Limit is for Dirac ν^*. The limit is 34.6 GeV for Majorana ν^*, 45.4 GeV for homodoublet ν^*.
[75] DECAMP 90O limit is from excess $\Delta\Gamma(Z) <$ 89 MeV. The above value is for Dirac ν^*; 26.6 GeV for Majorana ν^*; 44.8 GeV for homodoublet ν^*.
[76] Superceded by DECAMP 92.
[77] DECAMP 90O limit based on $B(Z \to \nu^*\nu^*) \cdot B(\nu^* \to \nu\gamma)^2 < 7 \times 10^{-5}$ (95%CL), assuming Dirac ν^*, $B(\nu^* \to \nu\gamma) = 1$.

Limits for Excited ν (ν^*) from Single Production

These limits are from $Z \to \nu\nu^*$ and depend on transition magnetic coupling between ν and ν^*. Assumptions about ν^* decay mode are given in footnotes.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>91	95	[78] DECAMP 92	ALEP	$\lambda_Z >1$
>91	95	[79] ADEVA 90O	L3	$\lambda_Z >1$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>74	95	[78] DECAMP 92	ALEP	$\lambda_Z >0.034$
>83	95	[80] ADEVA 90O	L3	$\lambda_Z >0.1$
>74	95	[81] ADEVA 90O	L3	$Z \to \nu_e\nu_e^*$, $\lambda_Z >0.1$
>90	95	[82,83] DECAMP 90O	ALEP	$\lambda_Z >1$
>74.7	95	[82,83] DECAMP 90O	ALEP	$\lambda_Z >0.06$

[78] DECAMP 92 limit is based on $B(Z \to \nu^*\overline{\nu}) \times B(\nu^* \to \nu\gamma) < 2.7 \times 10^{-5}$ (95%CL) assuming Dirac ν^*, $B(\nu^* \to \nu\gamma) = 1$.
[79] ADEVA 90O limit is either for $\nu^* \to \nu\gamma$ or $\nu^* \to eW$.
[80] ADEVA 90O limit is for $\nu^* \to \nu\gamma$.
[81] ADEVA 90O limit is for $\nu^* \to eW$.
[82] DECAMP 90O limit based on $B(Z \to \nu\nu^*) \cdot B(\nu^* \to \nu\gamma) < 6 \times 10^{-5}$ (95%CL), assuming $B(\nu^* \to \nu\gamma) = 1$.
[83] Superceded by DECAMP 92.

MASS LIMITS for Excited q (q^*)

Limits for Excited q (q^*) from Pair Production

These limits are obtained from $e^+e^- \to q^*\overline{q}^*$ and thus rely only on the (electroweak) charge of the q^*. Form factor effects are ignored unless noted. Assumptions about the q^* decay are given in the comments and footnotes.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>45	95	[84] DECAMP 92	ALEP	u (or d)-type, $Z \to q^*q^*$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>40.6	95	[85] DECAMP 92	ALEP	u-type, $\Gamma(Z)$
>44.2	95	[85] DECAMP 92	ALEP	d-type, $\Gamma(Z)$
>21.1	95	[86] BEHREND 86C	CELL	$e(q^*) = -1/3$, $q^* \to qg$
>22.3	95	[86] BEHREND 86C	CELL	$e(q^*) = 2/3$, $q^* \to qg$
>22.5	95	[86] BEHREND 86C	CELL	$e(q^*) = -1/3$, $q^* \to q\gamma$
>23.2	95	[86] BEHREND 86C	CELL	$e(q^*) = 2/3$, $q^* \to q\gamma$

[84] Limit is for $B(q^* \to qg)+B(q^* \to q\gamma)=1$.
[85] These limits are from pair production and independent of decay modes.
[86] BEHREND 86C search for $e^+e^- \to q^*\overline{q}^*$ for $m(q^*) >$5 GeV. But $m <$ 5 GeV excluded by total hadronic cross section. The limits are for point-like photon couplings of excited quarks.

Limits for Excited q (q^*) from Single Production

These limits are from $e^+e^- \to q^*\overline{q}$ or $p\overline{p} \to q^*$ X and depend on transition magnetic couplings between q and q^*. Assumptions about q^* decay mode are given in the footnotes and comments.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>88	95	[87] DECAMP	92	ALEP	$Z \to qq^*$, $\lambda_Z > 1$
>86	95	[87] AKRAWY	90J	OPAL	$Z \to qq^*$, $\lambda_Z > 1.2$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>75	95	[88] DECAMP	92	ALEP	$Z \to qq^*$, $\lambda_Z > 1$
		[89] ALBAJAR	89	UA1	$p\overline{p} \to q^*$ X, $q^* \to qW$
>39	95	[90] BEHREND	86C	CELL	$e^+e^- \to q^*\overline{q}$ ($q^* \to qg, q\gamma$), $\lambda_\gamma = 1$

[87] Assumes $B(q^* \to q\gamma) = 0.1$.

[88] Assumes $B(q^* \to qg) = 1$.

[89] ALBAJAR 89 give $\sigma(q^* \to W + \text{jet})/\sigma(W) < 0.019$ (90% CL) for $m(q^*) > 220$ GeV.

[90] BEHREND 86C has $E_{cm} = 42.5$–46.8 GeV. See their Fig. 3 for excluded region in the $m(q^*)-(\lambda_\gamma/m(q^*))^2$ plane. The limit is for $\lambda_\gamma = 1$ with $\eta_L = \eta_R = 1$.

MASS LIMITS for Color Sextet Quarks (q_6)

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>84	95	[91] ABE	89D	CDF	$p\overline{p} \to q_6\overline{q}_6$

[91] ABE 89D look for pair production of unit-charged particles which leave the detector before decaying. In the above limit the color sextet quark is assumed to fragment into a unit-charged or neutral hadron with equal probability and to have long enough lifetime not to decay within the detector. A limit of 121 GeV is obtained for a color decuplet.

MASS LIMITS for Color Octet Leptons (ℓ_8)

$\lambda \equiv m(\ell_8)/\Lambda$

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>110	90	[92] BARGER	89	RVUE	ν_8: $p\overline{p} \to \nu_8\overline{\nu}_8$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 3.8–29.8	95	[93] KIM	90	AMY	ν_8: $e^+e^- \to$ acoplanar jets
none 3.0–30.3	95	[93] KIM	90	AMY	e_8: $e^+e^- \to ee +$ jets
none 3.5–30.3	95	[93] KIM	90	AMY	μ_8: $e^+e^- \to \mu\mu +$ jets
		[94] KIM	90	AMY	e_8: $e^+e^- \to gg$; R
> 86	95	[95] ABE	89D	CDF	Stable ℓ_8: $p\overline{p} \to \ell_8\overline{\ell}_8$
> 19.8	95	[96] BARTEL	87B	JADE	e_8, μ_8, τ_8: e^+e^-; R
none 5–23.2	95	[96] BARTEL	87B	JADE	μ_8: $e^+e^- \to \mu\mu +$ jets
none 9–21.9	95	[96] BARTEL	87B	JADE	ν_8: $e^+e^- \to$ acoplanar jets
		[97] BARTEL	85K	JADE	e_8: $e^+e^- \to gg$; R

[92] BARGER 89 used ABE 89B limit for events with large missing transverse momentum. Two-body decay $\nu_8 \to \nu g$ is assumed.

[93] KIM 90 is at $E_{cm} = 50$–60.8 GeV. The same assumptions as in BARTEL 87B are used.

[94] KIM 90 result $(m(e_8)\Lambda_M)^{1/2} > 178.4$ GeV (95%CL, $\alpha_s = 0.16$ used) is subject to the same restriction as for BARTEL 85K.

[95] ABE 89D look for pair production of unit-charged particles which leave the detector before decaying. In the above limit the color octet lepton is assumed to fragment into a unit-charged or neutral hadron with equal probability and to have long enough lifetime not to decay within the detector. The limit improves to 99 GeV if it always fragments into a unit-charged hadron.

[96] BARTEL 87B is at $E_{cm} = 46.3$–46.78 GeV. The limits assume ℓ_8 pair production cross sections to be eight times larger than those of the corresponding heavy lepton pair production. This assumption is not valid in general for the weak couplings, and the limit on ν_8 can be sensitive to its $SU(2)_L \times U(1)_Y$ quantum numbers.

[97] In BARTEL 85K, R can be affected by $e^+e^- \to gg$ via e_8 exchange. Their limit $m(e_8) > 173$ GeV (CL=95%) at $\lambda = m(e_8)/\Lambda_M = 1$ ($\eta_L = \eta_R = 1$) is not listed above because the cross section is sensitive to the product $\eta_L\eta_R$, which should be absent in ordinary theory with electronic chiral invariance.

MASS LIMITS for W_8 (Color Octet W Boson)

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[98] ALBAJAR	89	UA1	$p\overline{p} \to W_8$ X, $W_8 \to Wg$

[98] ALBAJAR 89 give $\sigma(W_8 \to W + \text{jet})/\sigma(W) < 0.019$ (90% CL) for $m(W_8) > 220$ GeV.

REFERENCES FOR Searches for Quark and Lepton Compositeness

ABE	92B	PRL (submitted)	+Amidei, Apollianari, Atac, Auchincloss+	(CDF Collab.)
FERMILAB-PUB-91/327-E				
DECAMP	92	PRPL (to be pub.)	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
CERN-PPE/91-149				
ABE	91D	PRL 67 2418	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABREU	91E	PL B268 296	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ADACHI	91	PL B255 613	+Anazawa, Doser, Enomoto+	(TOPAZ Collab.)
AKRAWY	91F	PL B257 531	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ALITTI	91B	PL B257 232	+Ansari, Autiero, Bareyre, Blaylock+	(UA2 Collab.)
BEHREND	91C	ZPHY C51 149	+Criegee, Field, Franke, Jung, Meyer+	(CELLO Collab.)
Also	91B	ZPHY C51 143	Behrend, Criegee, Field, Franke, Jung+	(CELLO Collab.)
ABE	90I	ZPHY C48 13	+Amako, Arai, Asano, Chiba+	(VENUS Collab.)
ADEVA	90F	PL B247 177	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ADEVA	90K	PL B250 199	+Adriani, Aguilar-Benitez, Akbari, Alcarez+	(L3 Collab.)
ADEVA	90L	PL B250 205	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ADEVA	90O	PL B252 525	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
AKRAWY	90F	PL B241 133	+Alexander, Allison, Allport+	(OPAL Collab.)
AKRAWY	90I	PL B244 135	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
AKRAWY	90J	PL B246 285	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
DECAMP	90G	PL B236 501	+Deschizeaux, Lees, Minard+	(ALEPH Collab.)
DECAMP	90O	PL B250 172	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
KIM	90	PL B240 243	+Breedon, Ko, Lander, Maeshima, Malchow+	(AMY Collab.)
ABE	89	PRL 62 613	+Amidei, Apollinari, Ascori, Atac+	(CDF Collab.)
ABE	89B	PRL 62 1825	+Amidei, Apollinari, Ascoli, Atac+	(CDF Collab.)
ABE	89D	PRL 63 1447	+Amidei, Apollinari, Ascoli, Atac+	(CDF Collab.)
ABE	89H	PRL 62 3020	+Amidei, Apollinari, Ascoli, Atac+	(CDF Collab.)
ABE	89J	ZPHY C45 175	+Amako, Arai, Fukawa+	(VENUS Collab.)
ABE	89L	PL B232 425	+Amako, Arai, Asano, Chiba+	(VENUS Collab.)
ADACHI	89B	PL B228 553	+Aihara, Doser, Enomoto, Fujii+	(TOPAZ Collab.)
ALBAJAR	89	ZPHY C44 15	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
BARGER	89	PL B220 464	+Hagiwara, Han, Zeppenfeld	(WISC, KEK)
DORENBOS...	89	ZPHY C41 567	Dorenbosch, Udo, Allaby, Amaldi+	(CHARM Collab.)
HAGIWARA	89	PL B219 369	+Sakuda, Terunuma	(KEK, DURH, HIRO)
KIM	89	PL B223 476	+Kim, Kang, Lee, Myung, Bacala	(AMY Collab.)
ABE	88B	PL B213 400	+Amako, Arai, Asano, Chiba, Chiba+	(VENUS Collab.)
BARINGER	88	PL B206 551	+Bylsma, De Bonte, Koltick, Low+	(HRS Collab.)
BRAUNSCH...	88	ZPHY C37 171	Braunschweig, Gerhards+	(TASSO Collab.)
ANSARI	87D	PL B195 613	+Bagnaia, Banner+	(UA2 Collab.)
BARTEL	87B	ZPHY C36 15	+Becker, Felst+	(JADE Collab.)
ARNISON	86C	PL B172 461	+Albrow, Allkofer+	(UA1 Collab.)
ARNISON	86D	PL B177 244	+Albajar, Albrow+	(UA1 Collab.)
BARTEL	86	ZPHY C31 359	+Becker, Felst, Haidt+	(JADE Collab.)
BARTEL	86C	ZPHY C30 371	+Becker, Cords, Felst, Haidt+	(JADE Collab.)
BEHREND	86	PL 168B 420	+Burger, Criegee, Fenner+	(CELLO Collab.)
BEHREND	86C	PL B181 178	+Buerger, Criegee, Dainton+	(CELLO Collab.)
BONNEAUD	86	PL B177 109	+Courau, Johnson, Yamamoto+	(DELCO Collab.)
DERRICK	86	PL 166B 463	+Gan, Kooijman, Loos+	(HRS Collab.)
GRIFOLS	86	PL 168B 264	+Peris	(BARC)
JODIDIO	86	PR D34 1967	+Balke, Carr, Gidal, Shinsky+	(LBL, NWES, TRIU)
Also	88	PR D37 237 erratum	Jodidio, Balke, Carr+	(LBL, NWES, TRIU)
ADEVA	85	PL 152B 439	+Becker, Becker-Szendy+	(Mark-J Collab.)
APPEL	85	PL 160B 349	+Bagnaia, Banner+	(UA2 Collab.)
BARTEL	85K	PL 160B 337	+Becker, Cords, Eichler+	(JADE Collab.)
BERGER	85	ZPHY C28 1	+Genzel, Lackas, Pielorz+	(PLUTO Collab.)
GOLUBEV	85B	SJNP 41 752	+Druzhinin, Ivanov, Ivanchenko+	(NOVO)
		Translated from YAF 41 1176.		
ADEVA	84C	PRPL 109 131	+Barber, Becker+	(Mark-J Collab.)
BAGNAIA	84C	PL 138B 430	+Banner, Battiston+	(UA2 Collab.)
BARTEL	84	ZPHY C24 223	+Becker, Bowdery, Cords+	(JADE Collab.)
BARTEL	84D	PL 146B 437	+Becker, Bowdery, Cords+	(JADE Collab.)
BARTEL	84E	PL 146B 121	+Becker, Bowdery, Cords, Felst+	(JADE Collab.)
EICHTEN	84	RMP 56 579	+Hinchliffe, Lane, Quigg	(FNAL, LBL, OSU)
ALTHOFF	83C	PL 126B 493	+Fischer, Burkhardt+	(TASSO Collab.)
FORD	83	PRL 51 257	+Read, Smith, Marini+	(MAC Collab.)
ADEVA	82	PRL 48 967	+Barber, Becker, Berdugo+	(Mark-J Collab.)
BUKIN	82	SJNP 35 844	+Kurdadze, Lelchuk, Panin, Sidorov+	(NOVO)
		Translated from YAF 35 1444.		
HAYES	82	PR D25 2869	+Perl, Alam, Boyarski+	(Mark II Collab.)
RENARD	82	PL 116B 264		(CERN)
HANSON	73	LNC 7 587	+Leong, Newman, Law+	(MIT, HARV, CEA, HAIF)

Other Stable Particle Searches

OMITTED FROM SUMMARY TABLE

NOTE ON OTHER STABLE PARTICLE SEARCHES

We collect here those searches which do not appear in any of the above search categories. These include searches for centauros. Also shown are heavy particle searches in accelerator experiments, in cosmic rays, and in matter. Searches are also listed for light particles, highly ionizing particles, penetrating non-neutrino-like particles, and tachyons. Note that axions, supersymmetry, Higgs bosons (and technipions), other heavy bosons, leptoquarks, familons, compositeness, heavy neutrino, and heavy lepton searches appear in separate sections elsewhere.

Centauro Production Cross Section in Accelerator Experiments

VALUE (cm^2)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<0.005\sigma$ (nondiff.)	95	0	[1] ALNER	86	UA5	$p\overline{p}$ collider
$<1. \times 10^{-30}$		0	[2] ARNISON	83B	UA1	$p\overline{p}$ collider
		0	[3] ALPGARD	82	UA5	$p\overline{p}$ collider

[1] ALNER 86 is CERN collider experiment at W_{cm} = 900 GeV. Looked for high multiplicity, low EM content in measured high p_T events from an unbiased sample of 5500 events. No candidates observed.
[2] ARNISON 83B is CERN collider experiment with W_{cm} = 540 GeV. Looked for events with large hadronic and low electromagnetic content. None in 48000 low bias events.
[3] ALPGARD 82 is CERN collider experiment with W_{cm} = 540 GeV (155 TeV lab equivalent). Observed no large charged multiplicity events with photon multiplicity consistent with zero in 3600 inelastic events.

Centauro Production in Cosmic Ray Interactions

A Centauro event is characterized by a hadronic event with high multiplicity, high mean p_T, and unusually small photon energy.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.03	95	0	[4] REN	88	EMUL	e(shower) > 100 TeV
		1	BORISOV	87	EMUL	
			BAYBURINA	81	EMUL	
			LATTES	80	EMUL	

[4] REN 88 limit is for the fraction of Centauro events in the sample of hadronic showers with energy exceeding 100 TeV. No candidates were observed despite a total exposure exceeding that of previous experiments.

Light (between μ and e Masses) Particle MASS

VALUE ($m(e)$)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 110–180	0	[5] VIERTEL	78	CNTR	$\tau > 2. \times 10^{-5}$ s
none 2–13	0	[6] BLAGOV	75	CNTR	Spinor, $\tau > 2 \times 10^{-10}$ s
none 2–10.6	0	[6] BLAGOV	75	CNTR	Scalar, $\tau > 2 \times 10^{-10}$ s
none 5–175	0	COWARD	63	CNTR	Spinor, $\tau > 22 \times 10^{-10}$
none 5–175	0	COWARD	63	CNTR	Scalar, $\tau > 68 \times 10^{-10}$
none 6–25	0	BELOUSOV	60	CNTR	Spinor, $\tau > 1 \times 10^{-8}$
none 2–25	0	GORBUNOV	60	CC	Spinor, $\tau > 1 \times 10^{-9}$

[5] VIERTEL 78 searches for $\mu^+ \rightarrow X^+ \nu$. Finds BR $<8.5 \times 10^{-6}$ in mass range given above (CL = 90%). Best limit BR $<5. \times 10^{-7}$ (CL = 90%) is found at mass = 80 MeV.
[6] BLAGOV 75 bounds on lifetime depend on mass and improve as mass decreases. At 2 GeV the experiment is sensitive to $\tau > 3 \times 10^{-11}$ s for spinor, $\tau > 5 \times 10^{-11}$ s for scalar.

Highly Ionizing Particle Flux

VALUE ($number/m^2$-yr)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.4	95	0	KINOSHITA	81B	PLAS	Z/β 30–100

Tachyon Flux in Cosmic Rays

See SMITH 77 for a review of earlier cosmic ray and accelerator experiments.

VALUE ($number/cm^2$-s-sr)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<2.4 \times 10^{-9}$	90	0	[7] MARINI	82	CNTR	v/c>1.2
$<2.3 \times 10^{-10}$	95	0	[8] BHAT	79	CNTR	
			[9] SMITH	77	CNTR	
			[10] PRESCOTT	76	CNTR	

[7] MARINI 82 is TOF measurement using PEP-counter at sea level.
[8] BHAT 79 is at Ootacamund (2200m above sea). No signal in 3621 hours.
[9] SMITH 77 analyzed more than 200000 showers (223 days) with E > 10^{14} eV scanning 290×10^{-6} s period before each shower. Observed excess 46 ± 40 events does not constitute statistically significant evidence.
[10] PRESCOTT 76 reanalyzed Clay and Crouch('C.C.') 74 data (Nature **248** 28 (1974)). Found apparatus effect, correction for which much reduces the statistical significance of positive 'C.C.' result. Also performed two new experiments one using 'C.C.' apparatus, another with new apparatus. Set upper limit at CL = 95% of about 30 tachyons per shower with average size N = 6×10^5.

Tachyon Searches in e^+e^- Annihilation

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<1. \times 10^{-6}$	90	0	[11] PEREPELITSA	77	CNTR	uv_{eq} <1
$<1. \times 10^{-5}$	90	0	[11] PEREPELITSA	77	CNTR	$1 < uv_{eq} < 15$

[11] PEREPELITSA 77 is Michelson-type experiment for pair-produced tachyons in e^+e^- annihilation (e^+ from Cu isotope). Above limits are for $\sigma(e^+e^- \rightarrow$ tachyon pair$)/\sigma(e^+e^- \rightarrow 2\gamma)$ and uv_{eq} is tachyon velocities times earth equator component of velocity of preferred reference frame.

Searches for Tachyonic Decay (lower limit for mean life)

See LJUBICIC 75 figure 1 for review of earlier experiments.

VALUE (years)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$>4.6 \times 10^{13}$	[12] LJUBICIC	75	ELEC	m(tachyon) >1.1 keV

[12] LJUBICIC 75 used lead oxide cathode and electron multiplier looking for ionization due to tachyonic decay (spontaneous acquisition of energy) of bound-state e^-. Sensitive to proper tachyon mass >1.1 keV. Above limit is obtained from observed e^- emission rate 3/hour.

Production of New Penetrating Non-ν Like States in Beam Dump

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[13] LOSECCO	81	CALO	28 GeV protons

[13] No excess neutral-current events leads to σ(production) × σ(interaction) × acceptance $<2.26 \times 10^{-71}$ $cm^4/nucleon^2$ (CL = 90%) for light neutrals. Acceptance depends on models (0.1 to $4. \times 10^{-4}$).

Branching Fraction of Z^0 to a Pair of Stable Charged Heavy Fermions

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1 \times 10^{-3}$	95	AKRAWY	90O	OPAL	m = 29–40 GeV

Heavy Particle Production Cross Section in e^+e^-

Ratio to $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$. See also entries in Free Quark Search and Magnetic Monopole Searches.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<(10^{-2}–1)$	95		[14] ADACHI	90C	TOPZ	Q = 1, m = 1–16, 18–28 GeV
$<7 \times 10^{-2}$	90		[15] ADACHI	90E	TOPZ	Q = 1, m = 5–25 GeV
$<1.6 \times 10^{-2}$	95	0	[16] KINOSHITA	82	PLAS	Q=3–180, m <14.5 GeV
$<5.0 \times 10^{-2}$	90	0	[17] BARTEL	80	JADE	Q=(3,4,5)/3 2–12 GeV

[14] ADACHI 90C is a KEK-TRISTAN experiment with W_{cm} = 52–60 GeV. The limit is for pair production of a scalar or spin-1/2 particle. See Figs. 3 and 4.
[15] ADACHI 90E is KEK-TRISTAN experiment with W_{cm} = 52–61.4 GeV. The above limit is for inclusive production cross section normalized to $\sigma(e^+e^- \rightarrow \mu^+\mu^-)\cdot\beta(3-\beta^2)/2$, where $\beta = (1 - 4m^2/W^2_{cm})^{1/2}$. See the paper for the assumption about the production mechanism.
[16] KINOSHITA 82 is SLAC PEP experiment at W_{cm} = 29 GeV using lexan and ^{39}Cr plastic sheets sensitive to highly ionizing particles.
[17] BARTEL 80 is DESY-PETRA experiment with W_{cm} = 27–35 GeV. Above limit is for inclusive pair production and ranges between $1. \times 10^{-1}$ and $1. \times 10^{-2}$ depending on mass and production momentum distributions. (See their figures 9, 10, 11).

Heavy Particle Production Cross Section

VALUE (nb)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1	95		18 ABE	89D	CDF	m = 50–200 GeV
<30–130			19 CARROLL	78	SPEC	m=2–2.5 GeV
<100		0	20 LEIPUNER	73	CNTR	m=3–11 GeV

18 ABE 89D look for pair production of unit-charged particles which leave detector before decaying. Limit depends on charge assumed.
19 CARROLL 78 look for neutral, $S = -2$ dihyperon resonance in $pp \to 2K^+$ X. Cross section varies within above limits over mass range and p_{lab} = 5.1–5.9 GeV/c.
20 LEIPUNER 73 is an NAL 300 GeV p experiment. Would have detected particles with lifetime greater than 200 ns.

Heavy Particle Production Cross Section

VALUE (cm^2/N)	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$<(4–0.3) \times 10^{-31}$	95		21 AKESSON	91	CNTR	0	m = 0–5 GeV
$<2.5 \times 10^{-35}$		0	22 GUSTAFSON	76	CNTR	0	$\tau > 10^{-7}$ s

21 AKESSON 91 limit is from weakly interacting neutral long-lived particles produced in pN reaction at 450 GeV/c performed at CERN SPS. Bourquin-Gaillard formula is used as the production model. The above limit is for $\tau > 10^{-7}$ s. For $\tau > 10^{-9}$ s, $\sigma < 10^{-30}$ cm^{-2}/nucleon is obtained.
22 GUSTAFSON 76 is a 300 GeV FNAL experiment looking for heavy (m >2 GeV) long-lived neutral hadrons in the M4 neutral beam. The above typical value is for m = 3 GeV and assumes an interaction cross section of 1 mb. Values as a function of mass and interaction cross section are given in figure 2.

Heavy Particle Production Differential Cross Section

VALUE (cm^2/sr-GeV)	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$<2.6 \times 10^{-36}$	90	0	23 BALDIN	76	CNTR	−	Q= 1, m=2.1–9.4 GeV
$<2.2 \times 10^{-33}$	90	0	24 ALBROW	75	SPEC	±	Q= ±1, m=4–15 GeV
$<1.1 \times 10^{-33}$	90	0	24 ALBROW	75	SPEC	±	Q= ±2, m=6–27 GeV
$<8. \times 10^{-35}$	90	0	25 JOVANOV...	75	CNTR	±	m=15–26 GeV
$<1.5 \times 10^{-34}$	90	0	25 JOVANOV...	75	CNTR	±	Q= ±2, m=3–10 GeV
$<6. \times 10^{-35}$	90	0	25 JOVANOV...	75	CNTR	±	Q= ±2, m=10–26 GeV
$<1. \times 10^{-31}$	90	0	26 APPEL	74	CNTR	±	m=3.2–7.2 GeV
$<5.8 \times 10^{-34}$	90	0	27 ALPER	73	SPEC	±	m=1.5–24 GeV
$<1.2 \times 10^{-35}$	90	0	28 ANTIPOV	71B	CNTR	−	Q=−, m=2.2–2.8
$<2.4 \times 10^{-35}$	90	0	29 ANTIPOV	71C	CNTR	−	Q=−, m=1.2–1.7, 2.1–4
$<2.4 \times 10^{-35}$	90	0	BINON	69	CNTR	−	Q=−, m=1–1.8 GeV
$<1.5 \times 10^{-36}$		0	30 DORFAN	65	CNTR		Be target m=3–7 GeV
$<3.0 \times 10^{-36}$		0	30 DORFAN	65	CNTR		Fe target m=3–7 GeV

23 BALDIN 76 is a 70 GeV Serpukhov experiment. Value is per Al nucleus at θ = 0. For other charges in range −0.5 to −3.0, CL = 90% limit is $(2.6 \times 10^{-36})/|(\text{charge})|$ for mass range (2.1–9.4 GeV) × |(charge)|. Assumes stable particle interacting with matter as do antiprotons.
24 ALBROW 75 is a CERN ISR experiment with E_{cm} = 53 GeV. θ = 40 mr. See figure 5 for mass ranges up to 35 GeV.
25 JOVANOVICH 75 is a CERN ISR 26+26 and 15+15 GeV pp experiment. Figure 4 covers ranges Q = 1/3 to 2 and m = 3 to 26 GeV. Value is per GeV momentum.
26 APPEL 74 is NAL 300 GeV pW experiment. Studies forward production of heavy (up to 24 GeV) charged particles with momenta 24–200 GeV (−charge) and 40–150 GeV (+charge). Above typical value is for 75 GeV and is per GeV momentum per nucleon.
27 ALPER 73 is CERN ISR 26+26 GeV pp experiment. p >0.9 GeV, 0.2 < β <0.65.
28 ANTIPOV 71B is from same 70 GeV p experiment as ANTIPOV 71C and BINON 69.
29 ANTIPOV 71C limit inferred from flux ratio. 70 GeV p experiment.
30 DORFAN 65 is a 30 GeV/c p experiment at BNL. Units are per GeV momentum per nucleus.

Long-Lived Heavy Particle Invariant Cross Section

VALUE (cm^2/GeV^2/N)	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$< 5 \times 10^{-35}$–7×10^{-33}	90	0	31 BERNSTEIN	88	CNTR		
$< 5 \times 10^{-37}$–7×10^{-35}	90	0	31 BERNSTEIN	88	CNTR		
$<2.5 \times 10^{-36}$	90	0	32 THRON	85	CNTR	−	Q= 1, m=4–12 GeV
$<1. \times 10^{-35}$	90	1	32 THRON	85	CNTR	+	Q= 1, m=4–12 GeV
$<6. \times 10^{-33}$	90	0	33 ARMITAGE	79	SPEC		m=1.87 GeV
$<1.5 \times 10^{-33}$	90	0	33 ARMITAGE	79	SPEC		m=1.5–3.0 GeV
		0	34 BOZZOLI	79	CNTR	±	Q = (2/3, 1, 4/3, 2)
$<1.1 \times 10^{-37}$	90	0	35 CUTTS	78	CNTR		m=4–10 GeV
$<3.0 \times 10^{-37}$	90	0	36 VIDAL	78	CNTR		m=4.5–6 GeV

31 BERNSTEIN 88 limits apply at x = 0.2 and p_T = 0. Mass and lifetime dependence of limits are shown in the regions: m = 1.5–7.5 GeV and $\tau = 10^{-8}$–2×10^{-6} s. First number is for hadrons; second is for weakly interacting particles.
32 THRON 85 is FNAL 400 GeV proton experiment. Mass determined from measured velocity and momentum. Limits are for $\tau > 3 \times 10^{-9}$ s.
33 ARMITAGE 79 is CERN-ISR experiment at E_{cm} = 53 GeV. Value is for x = 0.1 and p_T = 0.15. Observed particles at m = 1.87 GeV are found all consistent with being antideuterons.
34 BOZZOLI 79 is CERN-SPS 200 GeV pN experiment. Looks for particle with τ larger than 10^{-8} s. See their figure 11–18 for production cross-section upper limits vs mass.
35 CUTTS 78 is pBe experiment at FNAL sensitive to particles of $\tau > 5 \times 10^{-8}$ s. Value is for −0.3 <x <0 and p_T = 0.175.
36 VIDAL 78 is FNAL 400 GeV proton experiment. Value is for x = 0 and p_T = 0. Puts lifetime limit of $< 5 \times 10^{-8}$ s on particle in this mass range.

Long-Lived Heavy Particle Production (σ(Heavy Particle) / $\sigma(\pi)$)

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<10^{-8}$		37 NAKAMURA	89	SPEC	±	Q= (−5/3,±2)
	0	38 BUSSIERE	80	CNTR	±	Q= (2/3,1,4/3,2)

37 NAKAMURA 89 is KEK experiment with 12 GeV protons on Pt target. The limit applies for mass ≲ 1.6 GeV and lifetime ≳ 10^{-7} s.
38 BUSSIERE 80 is CERN-SPS experiment with 200–240 GeV protons on Be and Al target. See their figures 6 and 7 for cross-section ratio vs mass.

Production and Capture of Long-Lived Massive Particles

VALUE (10^{-36} cm^2)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<20 to 800	0	39 ALEKSEEV	76	ELEC	τ=5 ms to 1 day
<200 to 2000	0	39 ALEKSEEV	76B	ELEC	τ=100 ms to 1 day
<1.4 to 9	0	40 FRANKEL	75	CNTR	τ=50 ms to 10 hours
<0.1 to 9	0	41 FRANKEL	74	CNTR	τ=1 to 1000 hours

39 ALEKSEEV 76 and ALEKSEEV 76B are 61–70 GeV p Serpukhov experiment. Cross section is per Pb nucleus.
40 FRANKEL 75 is extension of FRANKEL 74.
41 FRANKEL 74 looks for particles produced in thick Al targets by 300–400 GeV/c protons.

Heavy Particle Flux in Cosmic Rays

VALUE (number/cm^2-s-sr)	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$\sim 6 \times 10^{-9}$		2	42 SAITO	90			$Q \sim$ 14, $m \sim$ 370$m(p)$
$< 1.4 \times 10^{-12}$	90	0	43 MINCER	85	CALO		$m \geq$ 1 TeV
$< 3.2 \times 10^{-11}$	90	0	44 NAKAMURA	85	CNTR		$m > 1.5 \times 10^{-13}$ gram
			45 SAKUYAMA	83B	PLAS		$m \sim$ 1 TeV
$< 1.7 \times 10^{-11}$	99	0	46 BHAT	82	CC		
$< 1. \times 10^{-9}$	90	0	47 MARINI	82	CNTR	±	Q= 1, $m \sim$ 4.5$m(p)$
$< 3.5 \times 10^{-11}$	90	0	48 ULLMAN	81	CNTR		Planck-mass 10^{19}GeV
$< 7. \times 10^{-11}$	90	0	48 ULLMAN	81	CNTR		m=1. × 10^{-16} GeV or less
$2. \times 10^{-9}$		3	49 YOCK	81	SPRK	±	Q= 1, $m \sim$ 4.5$m(p)$
		3	49 YOCK	81	SPRK		Fractionally charged
3.0×10^{-9}		3	50 YOCK	80	SPRK		$m \sim$ 4.5 $m(p)$
$(4 \pm 1) \times 10^{-11}$		3	GOODMAN	79	ELEC		$m \geq$ 5 GeV
$< 1.3 \times 10^{-9}$	90		51 BHAT	78	CNTR	±	m >1 GeV
$< 1.0 \times 10^{-9}$		0	BRIATORE	76	ELEC		
$< 7. \times 10^{-10}$	90	0	YOCK	75	ELEC	±	Q >7e or <−7e
$> 6. \times 10^{-9}$		5	52 YOCK	74	CNTR		m >6 GeV
$< 3.0 \times 10^{-8}$		0	DARDO	72	CNTR		
$< 1.5 \times 10^{-9}$		0	TONWAR	72	CNTR		m >10 GeV
$< 3.0 \times 10^{-10}$		0	BJORNBOE	68	CNTR		m >5 GeV
$< 5.0 \times 10^{-11}$	90	0	JONES	67	ELEC		m=5–15 GeV

42 SAITO 90 candidates carry about 450 MeV/nucleon. Cannot be accounted for by conventional backgrounds. Consistent with strange quark matter hypothesis.
43 MINCER 85 is high statistics study of calorimeter signals delayed by 20–200 ns. Calibration with AGS beam shows they can be accounted for by rare fluctuations in signals from low-energy hadrons in the shower. Claim that previous delayed signals including BJORNBOE 68, DARDO 72, BHAT 82, SAKUYAMA 83B below may be due to this fake effect.
44 NAKAMURA 85 at KEK searched for quark-matter. These might be lumps of strange quark matter with roughly equal numbers of u, d, s quarks. These lumps or nuclearites were assumed to have $m > 1.5 \times 10^{-13}$ G and velocity/c of 10^{-4}–10^{-3}.
45 SAKUYAMA 83B analyzed 6000 extended air shower events. Increase of delayed particles and change of lateral distribution above 10^{17} eV may indicate production of very heavy parent at top of atmosphere.

[46] BHAT 82 observed 12 events with delay $> 2. \times 10^{-8}$ s and with more than 40 particles. 1 eV has good hadron shower. However all events are delayed in only one of two detectors in cloud chamber, and could not be due to strongly interacting massive particle.

[47] MARINI 82 applied PEP-counter for TOF. Above limit is for velocity = 0.54 of light. Limit is inconsistent with YOCK 80 YOCK 81 events if isotropic dependence on zenith angle is assumed.

[48] ULLMAN 81 is sensitive for heavy slow singly charge particle reaching earth with vertical velocity 100–350 km/s.

[49] YOCK 81 saw another 3 events with $Q = \pm 1$ and m about $4.5m(p)$ as well as 2 events with $m > 5.3m(p)$, $Q = \pm 0.75 \pm 0.05$ and $m > 2.8m(p)$, $Q = \pm 0.70 \pm 0.05$ and 1 event with $m = (9.3 \pm 3.)m(p)$, $Q = \pm 0.89 \pm 0.06$ as possible heavy candidates.

[50] YOCK 80 events are with charge exactly or approximately equal to unity.

[51] BHAT 78 is at Kolar gold fields. Limit is for $\tau > 10^{-6}$ s.

[52] YOCK 74 events could be tritons.

Concentration of Heavy (Charge +1) Stable Particles in Matter

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3 \times 10^{-23}$	90	[53] HEMMICK	90	SPEC	Water, $m = 1000m(p)$
$<2 \times 10^{-21}$	90	[53] HEMMICK	90	SPEC	Water, $m = 5000m(p)$
$<3 \times 10^{-20}$	90	[53] HEMMICK	90	SPEC	Water, $m = 10000m(p)$
$<1. \times 10^{-29}$		SMITH	82B	SPEC	Water, m=30–400$m(p)$
$<2. \times 10^{-28}$		SMITH	82B	SPEC	Water, m=12–1000$m(p)$
$<1. \times 10^{-14}$		SMITH	82B	SPEC	Water, $m >1000$ $m(p)$
$<(0.2\text{–}1.) \times 10^{-21}$		SMITH	79	SPEC	Water, m=6–350 $m(p)$

[53] See HEMMICK 90 Fig. 7 for other masses 100–10000 $m(p)$.

Concentration of Heavy (Charge −1) Stable Particles

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4 \times 10^{-20}$	90	[54] HEMMICK	90	SPEC	C, $M = 100m(p)$
$<8 \times 10^{-20}$	90	[54] HEMMICK	90	SPEC	C, $M = 1000m(p)$
$<2 \times 10^{-16}$	90	[54] HEMMICK	90	SPEC	C, $M = 10000m(p)$
$<6 \times 10^{-13}$	90	[54] HEMMICK	90	SPEC	Li, $M = 1000m(p)$
$<1 \times 10^{-11}$	90	[54] HEMMICK	90	SPEC	Be, $M = 1000m(p)$
$<6 \times 10^{-14}$	90	[54] HEMMICK	90	SPEC	B, $M = 1000m(p)$
$<4 \times 10^{-17}$	90	[54] HEMMICK	90	SPEC	O, $M = 1000m(p)$
$<4 \times 10^{-15}$	90	[54] HEMMICK	90	SPEC	F, $M = 1000m(p)$
$< 1.5 \times 10^{-13}$/nucleon	68	[55] NORMAN	89	SPEC	$^{206}PbX^-$
$< 1.2 \times 10^{-12}$/nucleon	68	[55] NORMAN	87	SPEC	$^{56,58}FeX^-$

[54] See HEMMICK 90 Fig. 7 for other masses 100–10000 $m(p)$.

[55] Bound valid up to $m(X^-) \sim$ 100 TeV.

Long-Lived Particle Search at Hadron Collisions

Limits are for cross section times branching ratio.

VALUE (pb/nucleon)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2	90	0	[56] BADIER	86	BDMP	$\tau = (0.05\text{–}1.) \times 10^{-8}$s

[56] BADIER 86 looked for long-lived particles at 300 GeV π^- beam dump. The limit applies for nonstrongly interaction neutral or charged particles with mass >2 GeV. The limit applies for particle modes, $\mu^+\pi^-$, $\mu^+\mu^-$, $\pi^+\pi^-$ X, $\pi^+\pi^-\pi^\pm$ etc. See their figure 5 for the contours of limits in the mass-τ plane for each mode.

REFERENCES FOR Other Stable Particle Searches

AKESSON 91 ZPHY C52 219 +Almehed, Angelis, Atherton, Aubry+ (HELIOS Collab.)
ADACHI 90C PL B244 352 +Aihara, Doser, Enomoto+ (TOPAZ Collab.)
ADACHI 90E PL B249 336 +Anazawa, Doser, Enomoto, Fujii+ (TOPAZ Collab.)
AKRAWY 90O PL B252 290 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
HEMMICK 90 PR D41 2074 +Elmore+ (ROCH, MICH, OHIO, RAL, LANL, STON)
SAITO 90 PRL 65 2094 +Hatano, Fukada, Oda (ICRR, KOBE)
ABE 89D PRL 63 1447 +Amidei, Apollinari, Ascoli, Atac+ (CDF Collab.)
NAKAMURA 89 PR D39 1261 +Kobayashi, Konaka, Imai, Masaike+ (KYOT, TMTC)
NORMAN 89 PR D39 2499 +Chadwick, Lesko, Larimer, Hoffman (LBL)
BERNSTEIN 88 PR D37 3103 +Shea, Winstein, Cousins, Greenhalgh+ (STAN, WISC)
REN 88 PR D38 1417 +Huo, Lu, Su+ (China-Japan Collab., Mt. Fuji Collab.)
BORISOV 87 PL B190 226 +Cherdyntseva+ (Pamir-Chacaltaya Collab.)
NORMAN 87 PRL 58 1403 +Gazes, Bennett (LBL)
ALNER 86 PL B180 415 +Ansorge, Asman, Booth, Burow+ (UA5 Collab.)
BADIER 86 ZPHY C31 21 +Bemporad, Boucrot, Callot+ (NA3 Collab.)
MINCER 85 PR D32 541 +Freudenreich, Goodman+ (UMD, GMAS, NSF)
NAKAMURA 85 PL 161B 417 +Horie, Takahashi, Tanimori (KEK, TOKY)
THRON 85 PR D31 451 +Cardello, Cooper, Teig+ (YALE, FNAL, IOWA)
ARNISON 83B PL 122B 189 +Astbury, Aubert, Bacci+ (UA1 Collab.)
SAKUYAMA 83B LNC 37 17 +Nuzuki (MEIS)
Also 83 LNC 36 389 Sakuyama, Watanabe (MEIS)
Also 83D NC 78A 147 Sakuyama, Watanabe (MEIS)
Also 83C NC 6C 371 Sakuyama, Watanabe (MEIS)
ALPGARD 82 PL 115B 71 +Ansorge, Asman, Berglund+ (UA5 Collab.)
BHAT 82 PR D25 2820 +Gupta, Murthy, Sreekantan+ (TATA)
KINOSHITA 82 PRL 48 77 +Price, Fryberger (UCB, SLAC)
MARINI 82 PR D26 1777 +Peruzzi, Piccolo+ (FRAS, LBL, NWES, STAN, HAWA)
SMITH 82B NP B206 333 +Bennett, Homer, Lewin, Walford, Smith (RAL)
BAYBURINA 81 NP B191 1 +Borisov+ (LEBD, MOSU, INRM, GEOR, TAJK+)
KINOSHITA 81B PR D24 1707 +Price (UCB)
LOSECCO 81 PL 102B 209 +Sulak, Galik, Horstkotte+ (MICH, PENN, BNL)
ULLMAN 81 PRL 47 289 (LEHM, BNL)
YOCK 81 PR D23 1207 (AUCK)
BARTEL 80 ZPHY C6 295 +Canzler, Lords, Drumm+ (JADE Collab.)
BUSSIERE 80 NP B174 1 +Giacomelli, Lesquoy+ (BGNA, SACL, LAPP)
LATTES 80 PRPL 65 151 +Fukimoto, Hasegawa (CAMP, WASE)
YOCK 80 PR D22 61 (AUCK)
ARMITAGE 79 NP B150 87 +Benz, Bobbink+ (CERN, DARE, FOM, MCHS, UTRE)
BHAT 79 JP G5 L13 +Gopalakrishnan, Gupta, Tonwar (TATA)
BOZZOLI 79 NP B159 363 +Bussiere, Giacomelli+ (BGNA, LAPP, SACL, CERN)
GOODMAN 79 PR D19 2572 +Ellsworth, Ito, Macfall, Siohan+ (UMD)
SMITH 79 NP B149 525 +Bennett (RHEL)
BHAT 78 Pramana 10 115 +Murthy (TATA)
CARROLL 78 PRL 41 777 +Chiang, Johnson, Kycia, Ki+ (BNL, PRIN)
CUTTS 78 PRL 41 363 +Dulude+ (BROW, FNAL, ILL, BARI, MIT, WARS)
VIDAL 78 PL 77B 344 +Herb, Lederman+ (COLU, FNAL, STON, UCB)
VIERTEL 78 LNC 22 235 +Hahn, Schacher (BERN)
PEREPELITSA 77 PL 67B 471 (ITEP)
SMITH 77 CJP 55 1280 +Standil (MANI)
ALEKSEEV 76 SJNP 22 531 +Zaitsev, Kalinina, Kruglov+ (JINR)
Translated from YAF 22 1021.
ALEKSEEV 76B SJNP 23 633 +Zaitsev, Kalinina, Kruglov+ (JINR)
Translated from YAF 23 1190.
BALDIN 76 SJNP 22 264 +Vertogradov, Vishnevsky, Grishkevich+ (JINR)
Translated from YAF 22 512.
BRIATORE 76 NC 31A 553 +Dardo, Piazzoli, Mannocchi+ (LCGT, FRAS, FREI)
GUSTAFSON 76 PRL 37 474 +Ayre, Jones, Longo, Murthy (MICH)
PRESCOTT 76 JP G2 261 (ADLD)
ALBROW 75 NP B97 189 +Barber+ (CERN, DARE, FOM, LANC, MCHS, UTRE)
BLAGOV 75 SJNP 21 158 +Komar, Murashova, Syreishchikova+ (LEBD)
Translated from YAF 21 300.
FRANKEL 75 PR D12 2561 +Frati, Resvanis, Yang, Nezrick (PENN, FNAL)
JOVANOV... 75 PL 56B 105 Jovanovich+ (MANI, AACH, CERN, GENO, HARV+)
LJUBICIC 75 PR D11 696 +Pavlovic, Pisk, Logan (ZAGR, OTTA)
YOCK 75 NP B86 216 (AUCK, SLAC)
APPEL 74 PRL 32 428 +Bourquin, Gaines, Lederman+ (COLU, FNAL)
CLAY 74 NAT 248 28 +Crouch (ADLD)
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DARDO 72 NC 9A 319 +Navarra, Penengo, Sitte (TORI)
TONWAR 72 JPA 5 569 +Naranan, Sreekantan (TATA)
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BINON 69 PL 30B 510 +Duteil, Kachanov, Khromov, Kutyin+ (SERP)
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