# W

$J = 1$

## NOTE ON THE MASS OF THE *W* BOSON

Written March 1998 by C. Caso (Univ. of Genova) and A. Gurtu (Tata Inst.)

Till 1995 the production and study of the $W$ boson was the exclusive domain of the $\overline{p}p$ colliders at CERN and FNAL. $W$ production in these hadron colliders is tagged by a high $p_T$ lepton from $W$ decay. Owing to unknown parton–parton effective energy and missing energy in the longitudinal direction, the experiments reconstruct only the transverse mass of the $W$ and derive the $W$ mass from comparing the transverse mass distribution with Monte Carlo predictions as a function of $M_W$.

In 1996 the energy of LEP was increased in two steps to 161 GeV and 172 GeV, allowing the production of pairs of $W$ bosons. A precise knowledge of the $e^+e^-$ centre of mass energy enables one to reconstruct the $W$ mass even if one of them decays leptonically. At LEP two methods have been used to obtain the $W$ mass. In the first method the measured $W$–pair production cross sections, $\sigma(e^+e^- \rightarrow W^+W^-)$, have been used to determine the $W$ mass using the Standard Model based dependence of this cross section on $M_W$ (see Fig. 1). At 161 GeV, which is just above the $W$–pair production threshold, this dependence is a much more sensitive function of the $W$ mass than at higher energies.

In the second method, which is used at the higher energies, the $W$ mass has been determined by directly reconstructing the $W$ from its decay products.

Each LEP experiment has combined their own mass values properly taking into account the common systematic errors. We have then combined their values into a LEP average leading to: $m_W = 80.49 \pm 0.14$ GeV. The error includes in the systematics a LEP energy uncertainty of ± 30 MeV and, in the case of the reconstruction method for the $q\overline{q}q\overline{q}$ channel, a possible effect of "color reconnection" and "Bose–Einstein correlations" between quarks from different $W$'s. In our combination, the last two effects have been treated as 100% correlated between the experiments.

OUR AVERAGE is obtained by combining this LEP value with other measurements assuming no common systematics.

Combining published and unpublished preliminary Collider and LEP results (as of end of March 1998) yields an average $W$-boson mass of $80.375 \pm 0.064$ GeV ($80.40 \pm 0.09$ GeV for $p$–$p$ Colliders and $80.35 \pm 0.09$ GeV for LEP).

The Standard Model prediction from the electroweak fit, excluding the direct $W$ mass measurements from LEP and Tevatron, gives a $W$–boson mass of $80.364 \pm 0.035$ GeV.

## *W* MASS

OUR FIT uses the $W$ and $Z$ mass, mass difference, and mass ratio measurements.

| *VALUE* (GeV) | *EVTS* | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **80.41 ± 0.10 OUR FIT** | | | | |
| **80.41 ± 0.10 OUR AVERAGE** | | | | |
| 80.22 ± 0.41 ±0.07 | 72 | [1] ABREU 98B | DLPH | $E^{ee}_{cm}$= 172.14 GeV |
| 80.32 ± 0.30 ±0.094 | 96 | [2] ACKERSTAFF 98D | OPAL | $E^{ee}_{cm}$= 172.12 GeV |
| 80.5 $^{+1.4}_{-2.2}$ $^{+0.5}_{-0.6}$ | 104 | [3] ACKERSTAFF 98D | OPAL | $E^{ee}_{cm}$= 172.12 GeV |
| 80.80 ± 0.32 ±0.114 | 95 | [4] BARATE 98B | ALEP | $E^{ee}_{cm}$= 172.09 GeV |
| 80.40 ± 0.44 ±0.095 | 29 | [5] ABREU 97 | DLPH | $E^{ee}_{cm}$= 161.3 GeV |
| 80.80 $^{+0.48}_{-0.42}$ ±0.03 | 20 | [6] ACCIARRI 97 | L3 | $E^{ee}_{cm}$= 161.3 GeV |
| 80.5 $^{+1.4}_{-2.4}$ ±0.3 | 94 | [7] ACCIARRI 97M | L3 | $E^{ee}_{cm}$= 172.13 GeV |
| 80.71 $^{+0.34}_{-0.35}$ ±0.09 | 101 | [8] ACCIARRI 97S | L3 | $E^{ee}_{cm}$= 172.13 GeV |

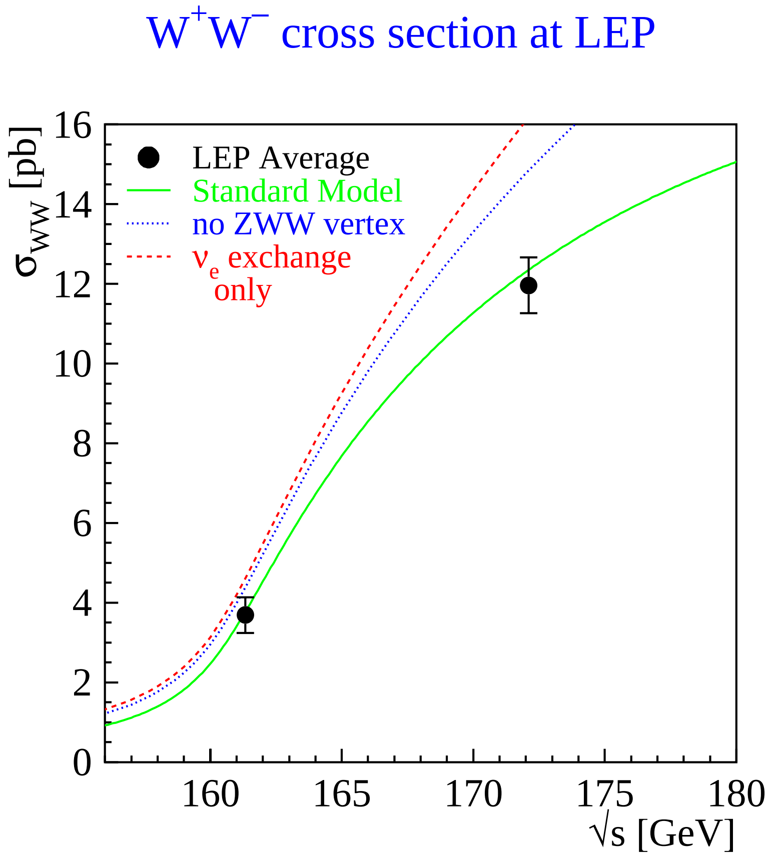


**Figure 1:** The $W$–pair cross section as a function of the center–of–mass energy. The data points are the LEP averages. The solid line is the Standard Model prediction. For comparison the figure contains also the cross section if the $ZWW$ coupling did not exist (dotted line), or if only the $t$–channel $\nu_e$ exchange diagram existed (dashed line).

| | | | | | | |
|---|---|---|---|---|---|---|
| 80.14 ± 0.34 ±0.095 | 32 | [9] BARATE | 97 | ALEP | $E^{ee}_{\rm cm}$= 161.3 GeV |
| 81.17 $^{+1.15}_{-1.62}$ | 106 | [10] BARATE | 97S | ALEP | $E^{ee}_{\rm cm}$= 172.09 GeV |
| 80.350± 0.140±0.230 | 5982 | [11] ABACHI | 96E | D0 | $E^{p\overline{p}}_{\rm cm}$= 1.8 TeV |
| 80.40 $^{+0.44}_{-0.41}$ $^{+0.09}_{-0.10}$ | 23 | [12] ACKERSTAFF | 96B | OPAL | $E^{ee}_{\rm cm}$= 161.3 GeV |
| 80.410± 0.180 | 8986 | [13] ABE | 95P | CDF | $E^{p\overline{p}}_{\rm cm}$= 1.8 TeV |
| 79.91 ± 0.39 | 1722 | [14] ABE | 90G | CDF | $E^{p\overline{p}}_{\rm cm}$= 1.8 TeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 84 $^{+10}_{-7}$ | 13 | [15] AID | 96D | H1 | $e^{\pm} p \rightarrow \nu_e(\overline{\nu}_e) + X$ $\sqrt{s} \approx 300$ GeV |
| 80.84 ± 0.22 ±0.83 | 2065 | [16] ALITTI | 92B | UA2 | See $W/Z$ ratio below |
| 80.79 ± 0.31 ±0.84 | | [17] ALITTI | 90B | UA2 | $E^{p\overline{p}}_{\rm cm}$= 546,630 GeV |
| 80.0 ± 3.3 ±2.4 | 22 | [18] ABE | 89I | CDF | $E^{p\overline{p}}_{\rm cm}$= 1.8 TeV |
| 82.7 ± 1.0 ±2.7 | 149 | [19] ALBAJAR | 89 | UA1 | $E^{p\overline{p}}_{\rm cm}$= 546,630 GeV |
| 81.8 $^{+6.0}_{-5.3}$ ±2.6 | 46 | [20] ALBAJAR | 89 | UA1 | $E^{p\overline{p}}_{\rm cm}$= 546,630 GeV |
| 89 ± 3 ±6 | 32 | [21] ALBAJAR | 89 | UA1 | $E^{p\overline{p}}_{\rm cm}$= 546,630 GeV |
| 81. ± 5. | 6 | ARNISON | 83 | UA1 | $E^{ee}_{\rm cm}$= 546 GeV |
| 80. $^{+10.}_{-6.}$ | 4 | BANNER | 83B | UA2 | Repl. by ALITTI 90B |

[1] ABREU 98B obtain this value from a fit to the reconstructed $W$ mass distribution. The $W$ width was taken as its Standard Model value at the fitted $W$ mass. The systematic error includes ±0.03 GeV due to the beam energy uncertainty and ±0.05 GeV due to the possible color reconnection and Bose-Einstein effects in the purely hadronic final state. Combining with ABREU 97 authors find: $M(W) = 80.33 \pm 0.30 \pm 0.06 \pm 0.03$ (LEP) GeV.

[2] ACKERSTAFF 98D obtain this value from a fit to the reconstructed $W$ mass distribution. The $W$ width was taken as its Standard Model value at the fitted $W$ mass. When both $W$ mass and width are varied they obtain $M(W) = 80.30 \pm 0.27 \pm 0.095$ GeV. The systematic error includes ±0.03 GeV due to the beam energy uncertainty and ±0.05 GeV due to the possible color reconnection and Bose-Einstein effects in the purely hadronic final state. Combining both values of ACKERSTAFF 98D with ACKERSTAFF 96B authors find: $M(W) = 80.35 \pm 0.24 \pm 0.07 \pm 0.03$ (LEP) GeV.

[3] ACKERSTAFF 98D derive this value from their measured $W W$ production cross section $\sigma_{W W}$ =12.3 ± 1.3 ± 0.4 pb using the Standard Model dependence of $\sigma_{W W}$ on $M_W$ at the given c.m. energy.

[4] BARATE 98B obtain this value from a fit to the reconstructed $W$ mass distribution. The $W$ width was taken as its Standard Model value at the fitted $W$ mass. The systematic error includes ±0.03 GeV due to the beam energy uncertainty and ±0.032 GeV due to the possible color reconnection and Bose-Einstein effects in the purely hadronic final state. Combining with the $M_W$ values from cross section measurements at 161 and 172 GeV (BARATE 97 and BARATE 97S) authors find: $M(W) = 80.51 \pm 0.23 \pm 0.08$ GeV.

[5] ABREU 97 derive this value from their measured $W$-$W$ production cross section $\sigma_{WW} = 3.67^{+0.97}_{-0.85} \pm 0.19$ pb using the Standard Model dependence of $\sigma_{WW}$ on $M_W$ at the given c.m. energy. The systematics include an error of ±0.03 GeV arising from the beam energy uncertainty.

[6] ACCIARRI 97 derive this value from their measured $W$-$W$ production cross section $\sigma_{WW} = 2.89^{+0.81}_{-0.70} \pm 0.14$ pb using the Standard Model dependence of $\sigma_{WW}$ on $M_W$ at the given c.m. energy. Statistical and systematic errors are added in quadrature

and the last error of $\pm 0.03$ GeV arises from the beam energy uncertainty. The same result is given by a fit of the production cross sections to the data.

[7] ACCIARRI 97M derive this value from their measured $WW$ production cross section $\sigma_{WW} = 12.27^{+1.41}_{-1.32} \pm 0.23$ pb using the Standard Model dependence of $\sigma_{WW}$ on $M_W$ at the given c.m. energy. Combining with ACCIARRI 97 authors find $M(W) = 80.78^{+0.45}_{-0.41} \pm 0.03$ GeV where the last error is due to beam energy uncertainty.

[8] ACCIARRI 97S obtain this value from a fit to the reconstructed $W$ mass distribution. The $W$ width was taken as its Standard Model value at the fitted $W$ mass. When both $W$ mass and width are varied they obtain $M(W) = 80.72^{+0.31}_{-0.33} \pm 0.09$ GeV. The systematic error includes $\pm 0.03$ GeV due to the beam energy uncertainty and $\pm 0.05$ GeV due to the possible color reconnection and Bose-Einstein effects in the purely hadronic final state. Combining with ACCIARRI 97 and ACCIARRI 97M authors find: $M(W) = 80.75^{+0.26}_{-0.27} \pm 0.03$ (LEP) GeV.

[9] BARATE 97 derive this value from their measured $W$-$W$ production cross section $\sigma_{WW} = 4.23 \pm 0.73 \pm 0.19$ pb using the Standard Model dependence of $\sigma_{WW}$ on $M_W$ at the given c.m. energy. The systematics include an error of $\pm 0.03$ GeV arising from the beam energy uncertainty.

[10] BARATE 97S derive this value from their measured $WW$ production cross section $\sigma_{WW} = 11.71 \pm 1.23 \pm 0.28$ pb using the Standard Model dependence of $\sigma_{WW}$ on $M_W$ at the given c.m. energy. The errors quoted on the mass are statistical only. Combining with BARATE 97 authors find: $M(W) = 80.20 \pm 0.33 \pm 0.09 \pm 0.03$ (LEP) GeV.

[11] ABACHI 96E fit the transverse mass distribution of 5982 $W \rightarrow e\nu_e$ decays. An error of $\pm 160$ MeV due to the uncertainty in the absolute energy scale of the EM calorimeter is included in the total systematics.

[12] ACKERSTAFF 96B derive this value from an analysis of the predicted $M_W$ dependence of their accepted four-fermion cross section, explicitly taking into account interference effects. The systematics include an error of $\pm 0.03$ GeV arising from the beam energy uncertainty.

[13] ABE 95P use 3268 $W \rightarrow \mu\nu_\mu$ events to find $M = 80.310 \pm 0.205 \pm 0.130$ GeV and 5718 $W \rightarrow e\nu_e$ events to find $M = 80.490 \pm 0.145 \pm 0.175$ GeV. The result given here combines these while accounting for correlated uncertainties.

[14] ABE 90G result from $W \rightarrow e\nu$ is $79.91 \pm 0.35 \pm 0.24 \pm 0.19$(scale) GeV and from $W \rightarrow \mu\nu$ is $79.90 \pm 0.53 \pm 0.32 \pm 0.08$(scale) GeV.

[15] AID 96D derive this value as a propagator mass using the $Q^2$ shape and magnitude of the $e^\pm$ charged-current cross sections. $Q^2 > 5000$ GeV$^2$ events with $p_T$ of the outgoing lepton $> 25$ GeV/$c$ are used.

[16] ALITTI 92B result has two contributions to the systematic error ($\pm 0.83$); one ($\pm 0.81$) cancels in $m_W/m_Z$ and one ($\pm 0.17$) 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.

[17] There are two contributions to the systematic error ($\pm 0.84$): one ($\pm 0.81$) which cancels in $m_W/m_Z$ and one ($\pm 0.21$) which is non-cancelling. These were added in quadrature.

[18] ABE 89I systematic error dominated by the uncertainty in the absolute energy scale.

[19] ALBAJAR 89 result is from a total sample of 299 $W \rightarrow e\nu$ events.

[20] ALBAJAR 89 result is from a total sample of 67 $W \rightarrow \mu\nu$ events.

[21] ALBAJAR 89 result is from $W \rightarrow \tau\nu$ events.

## $W/Z$ MASS RATIO

The fit uses the $W$ and $Z$ mass, mass difference, and mass ratio measurements.

| *VALUE* | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **0.8818±0.0011 OUR FIT** | | | | | |
| **0.8813±0.0036±0.0019** | 156 | [22] ALITTI | 92B | UA2 | $E_{\rm cm}^{p\overline{p}}$= 630 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 0.8831±0.0048±0.0026 | | [22] ALITTI | 90B | UA2 | $E_{\rm cm}^{p\overline{p}}$= 546,630 GeV |

[22] Scale error cancels in this ratio.

## $m_Z - m_W$

The fit uses the $W$ and $Z$ mass, mass difference, and mass ratio measurements.

| *VALUE* (GeV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **10.78±0.10 OUR FIT** | | | | |
| **10.4 ±1.4 ±0.8** | ALBAJAR | 89 | UA1 | $E_{\rm cm}^{p\overline{p}}$= 546,630 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 11.3 ±1.3 ±0.9 | ANSARI | 87 | UA2 | $E_{\rm cm}^{p\overline{p}}$= 546,630 GeV |

## $m_{W^+} - m_{W^-}$

Test of $CPT$ invariance.

| *VALUE* (GeV) | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **−0.19±0.58** | 1722 | ABE | 90G | CDF | $E_{\rm cm}^{p\overline{p}}$= 1.8 TeV |

## $W$ WIDTH

The CDF and DØ widths labelled "extracted value" are obtained by measuring $R= [\sigma(W)/\sigma(Z)]\ [\Gamma(W \rightarrow e\nu_e)]/(\mathrm{B}(Z \rightarrow ee)\Gamma(W))$ where the bracketed quantities can be calculated with plausible reliability. $\Gamma(W)$ is then extracted by using a value of $\mathrm{B}(Z \rightarrow ee)$ measured at LEP. The UA1 and UA2 widths used $R = [\sigma(W)/\sigma(Z)]\ [\Gamma(W \rightarrow e\nu_e)/\Gamma(Z \rightarrow ee)]\ \Gamma(Z)/\Gamma(W)$ and the measured value of $\Gamma(Z)$. The Standard Model prediction is 2.067 ± 0.021 (ROSNER 94).

| *VALUE* (GeV) | *CL%* | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|---|
| **2.06 ±0.06 OUR AVERAGE** | | | | | | |
| $1.30\ ^{+0.70}_{-0.55}$ ±0.18 | | 92 | [23] ACKERSTAFF | 98D | OPAL | $E_{\rm cm}^{ee}$= 172.12 GeV |
| $1.74\ ^{+0.88}_{-0.78}$ ±0.25 | | 101 | [24] ACCIARRI | 97S | L3 | $E_{\rm cm}^{ee}$= 172.13 GeV |
| 2.044±0.093 | | 13k | [25] ABACHI | 95D | D0 | Extracted value |
| 2.11 ±0.28 ±0.16 | | 58 | [26] ABE | 95C | CDF | Direct meas. |
| 2.064±0.060±0.059 | | | [27] ABE | 95W | CDF | Extracted value |
| $2.10\ ^{+0.14}_{-0.13}$ ±0.09 | | 3559 | [28] ALITTI | 92 | UA2 | Extracted value |
| $2.18\ ^{+0.26}_{-0.24}$ ±0.04 | | | [29] ALBAJAR | 91 | UA1 | Extracted value |

• • • We do not use the following data for averages, fits, limits, etc. • • •

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2.16 | $\pm 0.17$ | | | | [30] ABE | 92I | CDF | Repl. by ABE 95W |
| 2.12 | $\pm 0.20$ | | | | [31] ABE | 90 | CDF | Repl. by ABE 92I |
| 2.30 | $\pm 0.19$ | $\pm 0.06$ | | | [32] ALITTI | 90C | UA2 | Extracted value |
| 2.8 | $^{+1.4}_{-1.5}$ | $\pm 1.3$ | | 149 | [33] ALBAJAR | 89 | UA1 | $E^{p\overline{p}}_{\rm cm}$= 546,630 GeV |
| <7 | | | 90 | 251 | ANSARI | 87 | UA2 | $E^{p\overline{p}}_{\rm cm}$= 546,630 GeV |
| <7 | | | 90 | 119 | APPEL | 86 | UA2 | $E^{p\overline{p}}_{\rm cm}$= 546,630 GeV |
| <6.5 | | | 90 | 86 | [34] ARNISON | 86 | UA1 | Repl. by ALBAJAR 89 |

[23] ACKERSTAFF 98D obtain this value from a fit to the reconstructed $W$ mass distribution.

[24] ACCIARRI 97S obtain this value from a fit to the reconstructed $W$ mass distribution.

[25] ABACHI 95D measured $R = 10.90 \pm 0.49$ and used the measured value $B(Z \to \ell\ell) = (3.367 \pm 0.006)\%$ from LEP.

[26] ABE 95C use the tail of the transverse mass distribution of $W \to e\nu_e$ decays.

[27] ABE 95W measured $R = 10.90 \pm 0.32 \pm 0.29$. They use $m_W$=80.23 $\pm$ 0.18 GeV, $\sigma(W)/\sigma(Z) = 3.35 \pm 0.03$, $\Gamma(W \to e\nu) = 225.9 \pm 0.9$ MeV, $\Gamma(Z \to e^+e^-) = 83.98 \pm 0.18$ MeV, and $\Gamma(Z) = 2.4969 \pm 0.0038$ GeV.

[28] 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.

[29] 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.

[30] ABE 92I report $1216 \pm 38^{+27}_{-31}$ $W \to \mu\nu$ and $106 \pm 10^{+0.2}_{-1}$ $Z \to \mu^+\mu^-$ events which are combined with 2426 $W \to e\nu$ events of ABE 91C to derive the ratio $\sigma_W\, B(W \to \ell\nu)/\sigma_Z\, B(Z \to \ell^+\ell^-) = 10.0 \pm 0.6 \pm 0.4$. Finally the value of $\Gamma(Z)$ measured by LEP 92 is used to extract $\Gamma(W)$.

[31] 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 $\Gamma(W \to e\nu)/\Gamma(Z \to ee) = 2.70 \pm 0.02$. This yields $\Gamma(W)/\Gamma(Z) = 0.85 \pm 0.08$. The quoted error for $\Gamma(W)$ includes systematic uncertainties. $E^{p\overline{p}}_{\rm cm} = 1.8$ TeV.

[32] 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. $E^{p\overline{p}}_{\rm cm} = 546,630$ GeV.

[33] ALBAJAR 89 result is from a total sample of 299 $W \to e\nu$ events.

[34] 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 $-e(\kappa-\lambda)/m_W^2$. A description of the parameterization of these moments and additional references can be found in HAGIWARA 87 and BAUR 88. The parameter $\Lambda$ 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. • • • | | | |
| | [35] ABACHI | 97B | D0 |
| | [36] ABE | 95G | CDF |
| | [37] ALITTI | 92C | UA2 |
| | [38] SAMUEL | 92 | THEO |
| | [39] SAMUEL | 91 | THEO |
| | [40] GRIFOLS | 88 | THEO |
| | [41] GROTCH | 87 | THEO |
| | [42] VANDERBIJ | 87 | THEO |
| | [43] GRAU | 85 | THEO |
| | [44] SUZUKI | 85 | THEO |
| | [45] HERZOG | 84 | THEO |

[35] ABACHI 97B obtain the 95% CL limits (for $\Lambda = 1.5$ TeV) $-0.93 < \Delta\kappa < 0.94$ for $\lambda = 0$ and $-0.31 < \lambda < 0.29$ for $\Delta\kappa = 0$ in $\overline{p}p \rightarrow W\gamma + X$ ($W \rightarrow \ell\nu_\ell$, with $\ell = e,\mu$) at $\sqrt{s} = 1.8$ TeV.

[36] ABE 95G report $-1.3 < \kappa < 3.2$ for $\lambda$=0 and $-0.7 < \lambda < 0.7$ for $\kappa$=1 in $p\overline{p} \rightarrow e\nu_e\gamma X$ and $\mu\nu_\mu\gamma X$ at $\sqrt{s} = 1.8$ TeV.

[37] 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 $-3.6 < \lambda < 3.5$.

[38] 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.

[39] 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 $\kappa = 1-\Delta\kappa$.

[40] GRIFOLS 88 uses deviation from $\rho$ parameter to set limit $\Delta\kappa \lesssim 65\ (M_W^2/\Lambda^2)$.

[41] 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.

[42] 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 $\rho$ parameter of the Standard Model to determine $\Delta\kappa$.

[43] GRAU 85 uses the muon anomaly to derive a coupled limit on the anomalous magnetic dipole and electric quadrupole ($\lambda$) moments $1.05 > \Delta\kappa \ln(\Lambda/m_W) + \lambda/2 > -2.77$. In the Standard Model $\lambda = 0$.

[44] 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 $\rho$ parameter and obtains a very qualitative, order-of-magnitude limit $|\Delta\kappa| \lesssim 150\ (m_W/\Lambda)^4$ if $|\Delta\kappa| \ll 1$.

[45] 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 ($\Gamma_i/\Gamma$) | Confidence level |
|---|---|---|---|---|
| $\Gamma_1$ | $\ell^+\nu$ | [a] | $(10.74\pm0.33)$ % | |
| $\Gamma_2$ | $e^+\nu$ | | $(10.9\ \pm0.4\ )$ % | |
| $\Gamma_3$ | $\mu^+\nu$ | | $(10.2\ \pm0.5\ )$ % | |
| $\Gamma_4$ | $\tau^+\nu$ | | $(11.3\ \pm0.8\ )$ % | |
| $\Gamma_5$ | hadrons | | $(67.8\ \pm1.0\ )$ % | |
| $\Gamma_6$ | $\pi^+\gamma$ | | $< 2.2 \times 10^{-4}$ | 95% |

[a] $\ell$ indicates each type of lepton ($e$, $\mu$, and $\tau$), not sum over them.

## CONSTRAINED FIT INFORMATION

Overall fits are performed to determine the branching ratios of the $W$. For each LEP experiment the correlation matrix of the leptonic branching ratios is used. A first fit determines three individual leptonic branching ratios, B($W \to e\nu_e$), B($W \to \mu\nu_\mu$), and B($W \to \tau\nu_\tau$). This fit has a $\chi^2 =$ 9.0 for 17 degrees of freedom. The second fit assumes lepton universality and determines the leptonic branching ratio B($W \to \ell\nu_\ell$), from which one also derives the hadronic branching ratio, assuming B($W \to$ hadrons) = 1–3·B($W \to \ell\nu_\ell$). This fit has a $\chi^2 = 10.9$ for 19 degrees of freedom.

## $W$ BRANCHING RATIOS

The LEP collaborations obtain the $W$ branching ratios by a fit to their measured cross sections of the final states $e^+e^- \to W^+W^- \to q\overline{q}e\nu_e$, $q\overline{q}\mu\nu_\mu$, $q\overline{q}\tau\nu_\tau$, $q\overline{q}q\overline{q}$, $\ell\nu_\ell\ell\nu_\ell$. The leptonic branching ratios and $\sigma(e^+e^- \to W^+W^-)$ at the respective center-of-mass energies are the fitted parameters. Two fits are performed, one without and one assuming lepton universality. The hadronic branching ratio is derived from the second fit assuming B($W \to$ hadrons) = 1–3 · B($W \to \ell\nu_\ell$).

### $\Gamma(\ell^+\nu)/\Gamma_{\text{total}}$ — $\Gamma_1/\Gamma$

$\ell$ indicates average over $e$, $\mu$, and $\tau$ modes, not sum over modes.

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

| *VALUE* | | *EVTS* | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **0.1074±0.0033 OUR FIT** | | | | | |
| **0.108 ±0.005 OUR AVERAGE** | | | | | |
| 0.113 ±0.012 ±0.003 | avg | 52 | ABREU 98B | DLPH | $E^{ee}_{cm}$ = 161.3 + 172.14 GeV |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 0.101 | $^{+0.011}_{-0.010}$ | ±0.002 | avg | 61 | | ACKERSTAFF | 98D OPAL | $E^{ee}_{cm}$= 161.3 + 172.12 GeV |
| 0.119 | $^{+0.013}_{-0.012}$ | ±0.002 | avg | 51 | | ACCIARRI | 97M L3 | $E^{ee}_{cm}$= 161.3 + 172.13 GeV |
| 0.104 | ±0.008 | | avg | 3642 | [46] | ABE | 92I CDF | $E^{p\overline{p}}_{cm}$= 1.8 TeV |

[46] $1216 \pm 38^{+27}_{-31}$ $W \rightarrow \mu\nu$ events from ABE 92I and 2426 $W \rightarrow e\nu$ events of ABE 91C. ABE 92I give the inverse quantity as 9.6 ± 0.7 and we have inverted.

## $\Gamma(e^+\nu)/\Gamma_{total}$ $\Gamma_2/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

| *VALUE* | | | | *EVTS* | | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|---|---|---|---|---|
| **0.109** | **±0.004** | **OUR FIT** | | | | | | |
| **0.109** | **±0.004** | **OUR AVERAGE** | | | | | | |
| 0.102 | $^{+0.038}_{-0.032}$ | ±0.003 | f&a | 16 | | ABREU | 98B DLPH | $E^{ee}_{cm}$= 161.3 + 172.14 GeV |
| 0.098 | $^{+0.022}_{-0.020}$ | ±0.003 | f&a | 21 | | ACKERSTAFF | 98D OPAL | $E^{ee}_{cm}$= 161.3 + 172.12 GeV |
| 0.165 | $^{+0.037}_{-0.033}$ | ±0.005 | f&a | 23 | | ACCIARRI | 97M L3 | $E^{ee}_{cm}$= 161.3 + 172.13 GeV |
| 0.097 | ±0.02 | ±0.005 | f&a | 21 | | BARATE | 97S ALEP | $E^{ee}_{cm}$= 161.3 + 172.09 GeV |
| 0.1094 | ±0.0033 | ±0.0031 | f&a | | [47] | ABE | 95W CDF | $E^{p\overline{p}}_{cm}$= 1.8 TeV |
| 0.10 | ±0.014 | $^{+0.02}_{-0.03}$ | f&a | 248 | [48] | ANSARI | 87C UA2 | $E^{p\overline{p}}_{cm}$= 546,630 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | | | |
| 0.106 | ±0.0096 | | | 2426 | [49] | ABE | 91C CDF | Repl. by ABE 94B |
| seen | | | | 299 | [50] | ALBAJAR | 89 UA1 | $E^{p\overline{p}}_{cm}$= 546,630 GeV |
| seen | | | | 119 | | APPEL | 86 UA2 | $E^{p\overline{p}}_{cm}$= 546,630 GeV |
| seen | | | | 172 | | ARNISON | 86 UA1 | Repl. by ALBAJAR 89 |

[47] ABE 95W result is from a measurement of $\sigma B(W \rightarrow e\nu)/\sigma B(Z \rightarrow e^+e^-) = 10.90 \pm 0.32 \pm 0.29$, the theoretical prediction for the cross section ratio, the experimental knowledge of $\Gamma(Z \rightarrow e^+e^-) = 83.98 \pm 0.18$ MeV, and $\Gamma(Z) = 2.4969 \pm 0.0038$.

[48] 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: $\sigma(546\ \text{GeV}) = 4.7^{+1.4}_{-0.7}$ nb and $\sigma(630\ \text{GeV}) = 5.8^{+1.8}_{-1.0}$ nb. See ALTARELLI 85B.

[49] 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 $\Gamma(Z \rightarrow e^+e^-)/\Gamma(Z \rightarrow \text{all})$.

[50] ALBAJAR 89 experiment determines values of branching ratio times production cross section.

### $\Gamma(\mu^+\nu)/\Gamma_{total}$ — $\Gamma_3/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

| VALUE | | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **0.102±0.005 OUR FIT** | | | | | | |
| **0.097±0.007 OUR AVERAGE** | | | | | | |
| $0.107^{+0.032}_{-0.027}\pm0.003$ | f&a | 20 | ABREU | 98B | DLPH | $E^{ee}_{cm}$= 161.3 + 172.14 GeV |
| $0.073^{+0.019}_{-0.017}\pm0.002$ | f&a | 16 | ACKERSTAFF | 98D | OPAL | $E^{ee}_{cm}$= 161.3 + 172.12 GeV |
| $0.084^{+0.028}_{-0.024}\pm0.003$ | f&a | 13 | ACCIARRI | 97M | L3 | $E^{ee}_{cm}$= 161.3 + 172.13 GeV |
| 0.112±0.02 ±0.006 | f&a | 25 | BARATE | 97S | ALEP | $E^{ee}_{cm}$= 161.3 + 172.09 GeV |
| 0.10 ±0.01 | f&a | 1216 | [51] ABE | 92I | CDF | $E^{p\overline{p}}_{cm}$= 1.8 TeV |

[51] ABE 92I quote the inverse quantity as 9.9 ± 1.2 which we have inverted.

### $\Gamma(\tau^+\nu)/\Gamma_{total}$ — $\Gamma_4/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

| VALUE | | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **0.113±0.008 OUR FIT** | | | | | | |
| **0.124±0.017 OUR AVERAGE** | | | | | | |
| $0.134^{+0.050}_{-0.048}\pm0.007$ | f&a | 16 | ABREU | 98B | DLPH | $E^{ee}_{cm}$= 161.3 + 172.14 GeV |
| $0.140^{+0.030}_{-0.028}\pm0.005$ | f&a | 23 | ACKERSTAFF | 98D | OPAL | $E^{ee}_{cm}$= 161.3 + 172.12 GeV |
| $0.109^{+0.042}_{-0.039}\pm0.005$ | f&a | 15 | ACCIARRI | 97M | L3 | $E^{ee}_{cm}$= 161.3 + 172.13 GeV |
| 0.113±0.027±0.006 | f&a | 37 | BARATE | 97S | ALEP | $E^{ee}_{cm}$= 161.3 + 172.09 GeV |

### $\Gamma(\text{hadrons})/\Gamma_{total}$ — $\Gamma_5/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

| VALUE | | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **0.678±0.010 OUR FIT** | | | | | | |
| **0.672±0.017 OUR AVERAGE** | | | | | | |
| $0.660^{+0.036}_{-0.037}\pm0.009$ | avg | 57 | ABREU | 98B | DLPH | $E^{ee}_{cm}$= 161.3 + 172.14 GeV |
| $0.698^{+0.030}_{-0.032}\pm0.007$ | avg | 52 | ACKERSTAFF | 98D | OPAL | $E^{ee}_{cm}$= 161.3 + 172.12 GeV |
| $0.642^{+0.037}_{-0.038}\pm0.005$ | avg | 70 | ACCIARRI | 97M | L3 | $E^{ee}_{cm}$= 161.3 + 172.13 GeV |
| 0.677±0.031±0.007 | avg | 65 | BARATE | 97S | ALEP | $E^{ee}_{cm}$= 161.3 + 172.09 GeV |

## $\Gamma(\mu^+\nu)/\Gamma(e^+\nu)$ — $\Gamma_3/\Gamma_2$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

| VALUE | | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **0.94±0.05 OUR FIT** | | | | | | |
| **0.97±0.06 OUR AVERAGE** | | | | | | |
| 0.89±0.10 | f&a | 13k | [52] ABACHI | 95D | D0 | $E_{cm}^{p\overline{p}}$= 1.8 TeV |
| 1.02±0.08 | f&a | 1216 | [53] ABE | 92I | CDF | $E_{cm}^{p\overline{p}}$= 1.8 TeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| 1.00±0.14±0.08 | | 67 | ALBAJAR | 89 | UA1 | $E_{cm}^{p\overline{p}}$= 546,630 GeV |
| $1.24^{+0.6}_{-0.4}$ | | 14 | ARNISON | 84D | UA1 | Repl. by ALBAJAR 89 |

[52] ABACHI 95D obtain this result from the measured $\sigma_W$B($W \rightarrow \mu\nu$)= 2.09 ± 0.23 ± 0.11 nb and $\sigma_W$B($W \rightarrow e\nu$)= 2.36 ± 0.07 ± 0.13 nb in which the first error is the combined statistical and systematic uncertainty, the second reflects the uncertainty in the luminosity.

[53] ABE 92I obtain $\sigma_W$B($W \rightarrow \mu\nu$)= 2.21 ± 0.07 ± 0.21 and combine with ABE 91C $\sigma_W$ B(($W \rightarrow e\nu$)) to give a ratio of the couplings from which we derive this measurement.

## $\Gamma(\tau^+\nu)/\Gamma(e^+\nu)$ — $\Gamma_4/\Gamma_2$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

| VALUE | | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **1.03 ±0.07 OUR FIT** | | | | | | |
| **1.00 ±0.08 OUR AVERAGE** | | | | | | |
| 0.94 ±0.14 | f&a | 179 | [54] ABE | 92E | CDF | $E_{cm}^{p\overline{p}}$= 1.8 TeV |
| 1.04 ±0.08 ±0.08 | f&a | 754 | [55] ALITTI | 92F | UA2 | $E_{cm}^{p\overline{p}}$= 630 GeV |
| 1.02 ±0.20 ±0.12 | f&a | 32 | ALBAJAR | 89 | UA1 | $E_{cm}^{p\overline{p}}$= 546,630 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| 0.995±0.112±0.083 | | 198 | ALITTI | 91C | UA2 | Repl. by ALITTI 92F |
| 1.02 ±0.20 ±0.10 | | 32 | ALBAJAR | 87 | UA1 | Repl. by ALBAJAR 89 |

[54] ABE 92E use two procedures for selecting $W \rightarrow \tau\nu_\tau$ events. The missing $E_T$ trigger leads to $132 \pm 14 \pm 8$ events and the $\tau$ trigger to $47 \pm 9 \pm 4$ events. Proper statistical and systematic correlations are taken into account to arrive at $\sigma$B($W \rightarrow \tau\nu$) = 2.05 ± 0.27 nb. Combined with ABE 91C result on $\sigma$B($W \rightarrow e\nu$), ABE 92E quote a ratio of the couplings from which we derive this measurement.

[55] This measurement is derived by us from the ratio of the couplings of ALITTI 92F.

## $\Gamma(\pi^+\gamma)/\Gamma(e^+\nu)$ — $\Gamma_6/\Gamma_2$

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **$< 2.0 \times 10^{-3}$** | 95 | ABE | 96I | CDF | $E_{cm}^{p\overline{p}}$= 1.8 TeV |
| $< 4.9 \times 10^{-3}$ | 95 | [56] ALITTI | 92D | UA2 | $E_{cm}^{p\overline{p}}$= 630 GeV |
| $<58 \times 10^{-3}$ | 95 | [57] ALBAJAR | 90 | UA1 | $E_{cm}^{p\overline{p}}$= 546, 630 GeV |

[56] ALITTI 92D limit is $3.8 \times 10^{-3}$ at 90%CL.

[57] ALBAJAR 90 obtain < 0.048 at 90%CL.

# *W* REFERENCES


| | | | | |
|---|---|---|---|---|
| ABREU | 98B | EPJ C1 (accepted) | P. Abreu+ | (DELPHI Collab.) |
| CERN-PPE/97-160 | | | | |
| ACKERSTAFF | 98D | EPJ C1 395 | K. Ackerstaff+ | (OPAL Collab.) |
| BARATE | 98B | PL B422 384 | R. Barate+ | (ALEPH Collab.) |
| ABACHI | 97B | PRL 78 3634 | S. Abachi+ | (D0 Collab.) |
| ABREU | 97 | PL B397 158 | +Adam, Adye, Adzic+ | (DELPHI Collab.) |
| ACCIARRI | 97 | PL B398 223 | +Adriani, Aguilar-Benitez, Ahlen+ | (L3 Collab.) |
| ACCIARRI | 97M | PL B407 419 | M. Acciarri+ | (L3 Collab.) |
| ACCIARRI | 97S | PL B413 176 | M. Acciarri+ | (L3 Collab.) |
| BARATE | 97 | PL B401 347 | +Buskulic, Decamp, Ghez+ | (ALEPH Collab.) |
| BARATE | 97S | PL B415 435 | R. Barate+ | (ALEPH Collab.) |
| ABACHI | 96E | PRL 77 3309 | +Abbott, Abolins, Acharya+ | (D0 Collab.) |
| ABE | 96I | PRL 76 2852 | +Albrow, Amendolia, Amidei, Antos+ | (CDF Collab.) |
| ACKERSTAFF | 96B | PL B389 416 | +Alexander, Allison, Altekamp+ | (OPAL Collab.) |
| AID | 96D | PL B379 319 | +Andreev, Andrieu, Appuhn+ | (H1 Collab.) |
| ABACHI | 95D | PRL 75 1456 | +Abbott, Abolins, Acharya+ | (D0 Collab.) |
| ABE | 95C | PRL 74 341 | +Albrow, Amidei, Antos, Anway-Wiese+ | (CDF Collab.) |
| ABE | 95G | PRL 74 1936 | +Albrow, Amidei, Antos+ | (CDF Collab.) |
| ABE | 95P | PRL 75 11 | +Albrow, Amidei, Antos, Anway-Wiese+ | (CDF Collab.) |
| Also | 95Q | PR D52 4784 | Abe, Albrow, Amidei, Antos, Anway-Wiese+ | (CDF Collab.) |
| ABE | 95W | PR D52 2624 | +Albrow, Amendolia, Amidei, Antos+ | (CDF Collab.) |
| Also | 94B | PRL 73 220 | Abe, Albrow, Amidei, Anway-Wiese+ | (CDF Collab.) |
| ABE | 94B | PRL 73 220 | +Albrow, Amidei, Anway-Wiese+ | (CDF Collab.) |
| ROSNER | 94 | PR D49 1363 | +Worah, Takeuchi | (EFI, FNAL) |
| ABE | 92E | PRL 68 3398 | +Amidei, Apollinari, Atac+ | (CDF Collab.) |
| ABE | 92I | PRL 69 28 | +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.) |
| ALITTI | 92C | PL B277 194 | +Ambrosini, Ansari, Autiero, Bareyre+ | (UA2 Collab.) |
| ALITTI | 92D | PL B277 203 | +Ambrosini, Ansari, Autiero, Bareyre+ | (UA2 Collab.) |
| ALITTI | 92F | PL B280 137 | +Ambrosini, Ansari, Autiero, Bareyre+ | (UA2 Collab.) |
| LEP | 92 | PL B276 247 | +ALEPH, DELPHI, L3, OPAL | (LEP Collabs.) |
| SAMUEL | 92 | PL B280 124 | +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 | 84D | PL 134B 469 | +Astbury, Aubert, Bacci+ | (UA1 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.) |
| BANNER | 83B | PL 122B 476 | +Battiston, Bloch, Bonaudi+ | (UA2 Collab.) |