# W

$J = 1$

## THE MASS OF THE *W* BOSON

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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 $M_W$.

Beginning 1996 the energy of LEP increased to above 161 GeV, the threshold for $W$–pair production. 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 predicted 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 the higher energies (172 to 208 GeV) at which LEP has run during 1996–2000. 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.

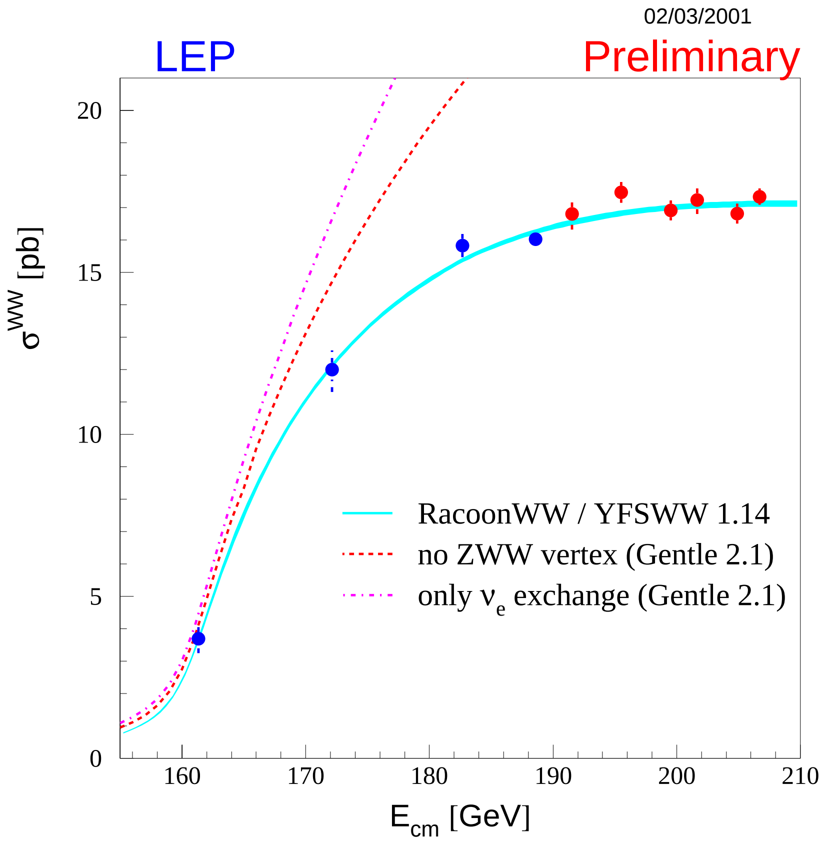


**Figure 1:** The $W$–pair cross section as a function of the center–of–mass energy. The data points are the LEP averages. The solid lines are predictions from different models of $WW$ production. For comparison the figure contains also the cross section if the ZWW coupling did not exist (dashed line), or if only the $t$–channel $\nu_e$ exchange diagram existed (dotted-dashed line). (Figure from `http://lepewwg.web.cern.ch/LEPEWWG/plots/winter2001/m01_sww_no_tgc.eps`)

Each LEP experiment has combined their own mass values properly taking into account the common systematic errors. In order to compute the LEP average $W$ mass each experiment has provided its measured $W$ mass for the $qqqq$ and $qq\ell\nu$ channels at each center-of-mass energy along with a detailed break-up of errors (statistical and uncorrelated, partially correlated and fully correlated systematics [1]). These have been properly combined to obtain a *preliminary* LEP $W$ mass = 80.446±0.040 GeV [2]. Errors due uncertainties in LEP energy (17 MeV) and possible effect of color reconnection (CR) and Bose–Einstein (BE) correlations between quarks from different $W$'s (40 MeV and 25 MeV respectively) are included. The mass difference between $qqqq$ and $qq\ell\nu$ final states (due to possible CR and BE effects) is $+18 \pm 46$ MeV.

The two Tevatron experiments have also carried out the exercise of identifying common systematic errors and averaging with CERN UA2 data obtain an average $W$ mass [3]= 80.452±0.062 GeV.

Combining all the published and unpublished $p$–$\overline{p}$ Collider and LEP results yields an average $W$–boson mass of 80.448±0.034 GeV assuming no common systematics between LEP and hadron collider measurements.

The Standard Model prediction from the electroweak fit, excluding the direct $W$ mass measurements from LEP and Tevatron, gives a $W$–boson mass of $80.368 \pm 0.023$ GeV.

OUR EVALUATION in the listing below is obtained by combining only published LEP and $p$–$\overline{p}$ Collider results using the same procedure as above.

## References


1. The LEP Collaborations: ALEPH, DELPHI, L3, OPAL, the LEP Electroweak Working Group, and the SLD Heavy Flavour and Electroweak Groups, CERN-EP-2001-021, hep-ex/0103048 (March 2001).
2. N. Watson, "$W$ mass and $W^+W^-$ final state interactions," *XXXVI Rencontres de Moriond, "ElectroWeak Interactions and Unified Theories"*, Les Arcs, France (10–17 March 2001).
3. http://www-cdf.fnal.gov/physics/ewk/wmass_new.html.


## *W* MASS

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

To obtain OUR EVALUATION the correlation between systematics is properly taken into account for the LEP experiments (note LEPEWWG/MASS/2001-02 dated March 29, 2001, accessible at http://www.cern.ch/LEPEWWG/wmass/).

| *VALUE* (GeV) | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **80.422± 0.047 OUR EVALUATION** | | | | | |
| **80.43 ± 0.04 OUR FIT** | | | | | |
| 80.432± 0.066±0.045 | 2789 | [1] ABBIENDI | 01F | OPAL | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 80.482± 0.091 | 45394 | [2] ABBOTT | 00 | D0 | $E^{p\overline{p}}_{cm}$= 1.8 TeV |
| 80.418± 0.061±0.047 | 2977 | [3] BARATE | 00T | ALEP | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 80.270± 0.137±0.048 | 809 | [4] ABREU | 99T | DLPH | $E^{ee}_{cm}$= 161+172+ 183 GeV |
| 80.61 ± 0.15 | 801 | [5] ACCIARRI | 99 | L3 | $E^{ee}_{cm}$= 161+172+ 183 GeV |
| 80.41 ± 0.18 | 8986 | [6] ABE | 95P | CDF | $E^{p\overline{p}}_{cm}$= 1.8 TeV |
| 79.91 ± 0.39 | 1722 | [7] ABE | 90G | CDF | $E^{p\overline{p}}_{cm}$= 1.8 TeV |

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

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 79.9 | $\pm$ 2.2 | $\pm$2.3 | 700 | [8] ADLOFF | 01A | H1 | $e^- p \to \nu_e X$, $\sqrt{s} \approx$ 320 GeV |
| 80.9 | $\pm$ 3.7 | $\pm$3.7 | 700 | [9] ADLOFF | 00B | H1 | $e^+ p \to \overline{\nu}_e X$, $\sqrt{s} \approx$ 300 GeV |
| 81.4 | $^{+2.7}_{-2.6}$ | $\pm$ 2.0$^{+3.3}_{-3.0}$ | 1086 | [10] BREITWEG | 00D | ZEUS | $e^+ p \to \overline{\nu}_e X$, $\sqrt{s} \approx$ 300 GeV |
| 80.38 | $\pm$ 0.12 | $\pm$0.05 | 701 | [11] ABBIENDI | 99C | OPAL | Repl. by ABBIENDI 01F |
| 80.49 | $\pm$ 0.43 | $\pm$0.095 | 871 | [12] ABREU | 99K | DLPH | Repl. by ABREU 99T |
| 80.423 | $\pm$ 0.112 | $\pm$0.054 | 812 | [13] BARATE | 99 | ALEP | Repl. by BARATE 00T |
| 80.44 | $\pm$ 0.10 | $\pm$0.07 | 28323 | [14] ABBOTT | 98O | D0 | Repl. by ABBOTT 00 |
| 80.22 | $\pm$ 0.41 | $\pm$0.07 | 72 | [15] ABREU | 98B | DLPH | Repl. by ABREU 99T |
| 80.80 | $^{+0.48}_{-0.42}$ | $\pm$0.03 | 20 | [16] ACCIARRI | 97 | L3 | Repl. by ACCIARRI 99 |
| 80.5 | $^{+1.4}_{-2.4}$ | $\pm$0.3 | 94 | [17] ACCIARRI | 97M | L3 | Repl. by ACCIARRI 99 |
| 80.71 | $^{+0.34}_{-0.35}$ | $\pm$0.09 | 101 | [18] ACCIARRI | 97S | L3 | Repl. by ACCIARRI 99 |
| 80.35 | $\pm$ 0.14 | $\pm$0.23 | 5982 | [19] ABACHI | 96E | D0 | Repl. by ABBOTT 00 |
| 80.84 | $\pm$ 0.22 | $\pm$0.83 | 2065 | [20] ALITTI | 92B | UA2 | See $W/Z$ ratio below |
| 80.79 | $\pm$ 0.31 | $\pm$0.84 | | [21] ALITTI | 90B | UA2 | $E^{p\overline{p}}_{\text{cm}}$= 546,630 GeV |
| 80.0 | $\pm$ 3.3 | $\pm$2.4 | 22 | [22] ABE | 89I | CDF | $E^{p\overline{p}}_{\text{cm}}$= 1.8 TeV |
| 82.7 | $\pm$ 1.0 | $\pm$2.7 | 149 | [23] ALBAJAR | 89 | UA1 | $E^{p\overline{p}}_{\text{cm}}$= 546,630 GeV |
| 81.8 | $^{+6.0}_{-5.3}$ | $\pm$2.6 | 46 | [24] ALBAJAR | 89 | UA1 | $E^{p\overline{p}}_{\text{cm}}$= 546,630 GeV |
| 89 | $\pm$ 3 | $\pm$6 | 32 | [25] ALBAJAR | 89 | UA1 | $E^{p\overline{p}}_{\text{cm}}$= 546,630 GeV |
| 81. | $\pm$ 5. | | 6 | ARNISON | 83 | UA1 | $E^{ee}_{\text{cm}}$= 546 GeV |
| 80. | $^{+10.}_{-6.}$ | | 4 | BANNER | 83B | UA2 | Repl. by ALITTI 90B |

[1] ABBIENDI 01F obtain this value properly combining results obtained from a direct $W$ mass reconstruction at 172, 183, and 189 GeV with that from measurement of the $W$-pair production cross section at 161 GeV. The systematic error includes $\pm$0.017 GeV due to LEP energy uncertainty and $\pm$0.028 GeV due to possible color reconnection and Bose-Einstein effects in the purely hadronic final state.

[2] ABBOTT 00 use $W \to e\nu_e$ events to measure the $W$ mass with a fit to the transverse mass distribution. The result quoted here corresponds to electrons detected both in the forward and in the central calorimeters for the data recorded in 1992–1995. For the large rapidity electrons recorded in 1994–1995, the analysis combines results obtained from $m_T$, $p_T(e)$, and $p_T(\nu)$.

[3] BARATE 00T obtain this value properly combining results obtained from a direct $W$ mass reconstruction at 172, 183, and 189 GeV with those from measurements of $W$-pair production cross sections at 161 and 172 GeV. The systematic error includes $\pm$0.017 GeV due to LEP energy uncertainty and $\pm$0.019 GeV due to possible color reconnection and Bose-Einstein effects in the purely hadronic final state.

[4] ABREU 99T obtain this value properly combining results obtained from a direct $W$ mass reconstruction at 172 and 183 GeV with those from measurement of $W$-pair production cross sections at 161, 172, and 183 GeV. The systematic error includes $\pm$0.021 GeV due to the beam energy uncertainty and $\pm$0.030 GeV due to possible color reconnection and Bose-Einstein effects in the purely hadronic final state.

[5] ACCIARRI 99 obtain this value properly combining results obtained from a direct $W$ mass reconstruction at 172 and 183 GeV with those from the measurements of the total $W$-pair production cross sections at 161 and 172 GeV. The value of the mass obtained from the direct reconstruction at 172 and 183 GeV is $M(W)$= 80.58 $\pm$ 0.14 $\pm$ 0.08 GeV.

[6] 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.

[7] 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.

[8] ADLOFF 01A fit the $Q^2$ dependence ($150 < Q^2 < 30000$ GeV$^2$) of the charged-current double-differential cross sections with a propagator mass fit. The second error includes 2.1 GeV due to the theoretical uncertainties.

[9] ADLOFF 00B fit the $Q^2$ dependence ($300 < Q^2 < 15000$ GeV$^2$) of the charged-current double-differential cross sections with a propagator mass fit. The second error is due to the theoretical uncertainties.

[10] BREITWEG 00D fit the $Q^2$ dependence ($200 < Q^2 < 22500$ GeV$^2$) of the charged-current differential cross sections with a propagator mass fit. The last error is due to the uncertainty on the probability density functions.

[11] ABBIENDI 99C obtain this value properly combining results from a direct $W$ mass reconstruction at 172 and 183 GeV with that from the measurement of the total $W$-pair production cross section at 161 GeV. The systematic error includes an uncertainty of $\pm$0.02 GeV due to the possible color-reconnection and Bose-Einstein effects in the purely hadronic final states and an uncertainty of $\pm$0.02 GeV due to the beam energy.

[12] ABREU 99K derive this value using the Standard Model dependence on $M_W$ of the $W$-$W$ production cross sections measured at 161, 172, and 183 GeV. The systematics include an error of $\pm$0.03 GeV arising from the beam energy uncertainty.

[13] BARATE 99 obtain this value properly combining results from a direct $W$ mass reconstruction at 172 and 183 GeV with those from the measurements of the total $W$-pair production cross sections at 161 and 172 GeV. The systematic error includes $\pm$0.023 GeV due to LEP energy uncertainty and $\pm$0.021 GeV due to theory uncertainty on account of possible color reconnection and Bose-Einstein correlations.

[14] ABBOTT 98O fit the transverse mass distribution of 28323 $W \rightarrow e\nu_e$ events. The systematic error includes a detector related uncertainty of $\pm$60 MeV and a model uncertainty of $\pm$30 MeV. Combining with ABACHI 96E DØ obtain a $W$ mass value of 80.43 $\pm$ 0.11 GeV.

[15] 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 $\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.

[16] 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.

[17] 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.

[18] 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.

[19] 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.

[20] 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.

[21] 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.

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

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

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

[25] 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* |
|---|---|---|---|---|---|
| **0.8820 ±0.0004 OUR FIT** | | | | | |
| 0.8821 ±0.0011 ±0.0008 | 28323 | [26] ABBOTT | 98N | D0 | $E_{\text{cm}}^{p\overline{p}}$= 1.8 TeV |
| 0.88114±0.00154±0.00252 | 5982 | [27] ABBOTT | 98P | D0 | $E_{\text{cm}}^{p\overline{p}}$= 1.8 TeV |
| 0.8813 ±0.0036 ±0.0019 | 156 | [28] ALITTI | 92B | UA2 | $E_{\text{cm}}^{p\overline{p}}$= 630 GeV |

[26] ABBOTT 98N obtain this from a study of 28323 $W \rightarrow e\nu_e$ and 3294 $Z \rightarrow e^+e^-$ decays. Of this latter sample, 2179 events are used to calibrate the electron energy scale.

[27] ABBOTT 98P obtain this from a study of 5982 $W \rightarrow e\nu_e$ events. The systematic error includes an uncertainty of $\pm 0.00175$ due to the electron energy scale.

[28] 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* |
|---|---|---|---|---|
| **10.76±0.04 OUR FIT** | | | | |
| **10.4 ±1.4 ±0.8** | ALBAJAR | 89 | UA1 | $E_{\text{cm}}^{p\overline{p}}$= 546,630 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 11.3 ±1.3 ±0.9 | ANSARI | 87 | UA2 | $E_{\text{cm}}^{p\overline{p}}$= 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 | $E_{\text{cm}}^{p\overline{p}}$= 1.8 TeV |

# $W$ WIDTH

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

To obtain OUR EVALUATION the correlation between systematics is properly taken into account for the LEP experiments (note LEPEWWG/MASS/2001-02 dated March 29, 2001, accessible at http://www.cern.ch/LEPEWWG/wmass/).

| *VALUE* (GeV) | *CL%* | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|---|
| **2.114±0.043 OUR EVALUATION** | | | | | | |
| **2.11 ±0.04 OUR AVERAGE** | | | | | | |
| 2.04 ±0.16 ±0.09 | | 2756 | [29] ABBIENDI | 01F | OPAL | $E^{ee}_{cm}$= 172+183 +189 GeV |
| 2.152±0.066 | | 79176 | [30] ABBOTT | 00B | D0 | Extracted value |
| 2.05 ±0.10 ±0.08 | | 662 | [31] AFFOLDER | 00M | CDF | Direct meas. |
| 2.24 ±0.20 ±0.13 | | 1711 | [32] BARATE | 00T | ALEP | $E^{ee}_{cm}$= 189 GeV |
| 2.48 ±0.40 ±0.10 | | 737 | [33] ABREU | 99T | DLPH | $E^{ee}_{cm}$= 183 GeV |
| 1.97 ±0.34 ±0.17 | | 687 | [34] ACCIARRI | 99 | L3 | $E^{ee}_{cm}$= 172+183 GeV |
| 2.064±0.060±0.059 | | | [35] ABE | 95W | CDF | Extracted value |
| $2.10\ ^{+0.14}_{-0.13}\ \pm0.09$ | | 3559 | [36] ALITTI | 92 | UA2 | Extracted value |
| $2.18\ ^{+0.26}_{-0.24}\ \pm0.04$ | | | [37] ALBAJAR | 91 | UA1 | Extracted value |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| 1.84 ±0.32 ±0.20 | | 674 | [38] ABBIENDI | 99C | OPAL | Repl. by ABBIENDI 01F |
| 2.044±0.097 | | 11858 | [39] ABBOTT | 99H | D0 | Repl. by ABBOTT 00B |
| $2.126\ ^{+0.052}_{-0.048}\ \pm0.035$ | | | [40] BARATE | 99I | ALEP | $E^{ee}_{cm}$= 161+172+183 GeV |
| $1.74\ ^{+0.88}_{-0.78}\ \pm0.25$ | | 101 | [41] ACCIARRI | 97S | L3 | Repl. by ACCIARRI 99 |
| 2.11 ±0.28 ±0.16 | | 58 | [42] ABE | 95C | CDF | Repl. by AFFOLDER 00M |
| 2.30 ±0.19 ±0.06 | | | [43] ALITTI | 90C | UA2 | Extracted value |
| $2.8\ ^{+1.4}_{-1.5}\ \pm1.3$ | | 149 | [44] ALBAJAR | 89 | UA1 | $E^{p\overline{p}}_{cm}$= 546,630 GeV |
| <7 | 90 | 119 | APPEL | 86 | UA2 | $E^{p\overline{p}}_{cm}$= 546,630 GeV |
| <6.5 | 90 | 86 | [45] ARNISON | 86 | UA1 | $E^{p\overline{p}}_{cm}$= 546,630 GeV |

[29] ABBIENDI 01F obtain this value from a fit to the reconstructed $W$ mass distribution using data at 172, 183, and 189 GeV. The systematic error includes ±0.010 GeV due to LEP energy uncertainty and ±0.078 GeV due to possible color reconnection and Bose-Einstein effects in the purely hadronic final state.

[30] ABBOTT 00B measure $R = 10.43 \pm 0.27$ for the $W \to e\nu_e$ decay channel. They use the SM theoretical predictions for $\sigma(W)/\sigma(Z)$ and $\Gamma(W \to e\nu_e)$ and the world average

for B($Z \to ee$). The value quoted here is obtained combining this result ($2.169 \pm 0.070$ GeV) with that of ABBOTT 99H.

[31] AFFOLDER 00M fit the high transverse mass (100–200 GeV) $W \to e\nu_e$ and $W \to \mu\nu_\mu$ events to obtain $\Gamma(W) = 2.04 \pm 0.11(\text{stat}) \pm 0.09(\text{syst})$ GeV. This is combined with the earlier CDF measurement (ABE 95C) to obtain the quoted result.

[32] BARATE 00T obtain this value using $WW \to q\overline{q}q\overline{q}$, $WW \to e\nu_e q\overline{q}$, and $WW \to \mu\nu_\mu q\overline{q}$ decays. The systematic error includes $\pm 0.015$ GeV due to LEP energy uncertainty and $\pm 0.080$ GeV due to possible color reconnection and Bose-Einstein effects in the purely hadronic final state.

[33] ABREU 99T obtain this value using $WW \to \ell\overline{\nu}_\ell q\overline{q}$ and $WW \to q\overline{q}q\overline{q}$ events. The systematic error includes an uncertainty of $\pm 0.080$ GeV due to possible color reconnection and Bose-Einstein effects in the purely hadronic final state.

[34] ACCIARRI 99 obtain this value from a fit to the reconstructed $W$ mass distribution using data at 172 and 183 GeV.

[35] 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.

[36] 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.

[37] 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. This measurement is obtained combining both the electron and muon channels.

[38] ABBIENDI 99C obtain this value from a fit to the reconstructed $W$ mass distribution using data at 172 and 183 GeV. The systematic error includes an uncertainty of $\pm 0.12$ GeV due to the possible color-reconnection and Bose-Einstein effects in the purely hadronic final states and an uncertainty of $\pm 0.01$ GeV due to the beam energy.

[39] ABBOTT 99H measure $R = 10.90 \pm 0.52$ combining electron and muon channels. They use $M_W = 80.39 \pm 0.06$ GeV and the SM theoretical predictions for $\sigma(W)/\sigma(Z)$, B($Z \to \ell\ell$), and $\Gamma(W \to \ell\nu_\ell)$.

[40] BARATE 99I obtain this result with a fit to the $WW$ measured cross sections at 161, 172, and 183 GeV. The theoretical prediction takes into account the sensitivity to the $W$ total width.

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

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

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

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

[45] If systematic error is neglected, result is $2.7^{+1.4}_{-1.5}$ GeV. This is enhanced subsample of 172 total events.

## $W^+$ DECAY MODES

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

| | Mode | | Fraction ($\Gamma_i/\Gamma$) | Confidence level |
|---|---|---|---|---|
| $\Gamma_1$ | $\ell^+\nu$ | [a] | (10.68± 0.12) % | |
| $\Gamma_2$ | $e^+\nu$ | | (10.72± 0.16) % | |
| $\Gamma_3$ | $\mu^+\nu$ | | (10.57± 0.22) % | |
| $\Gamma_4$ | $\tau^+\nu$ | | (10.74± 0.27) % | |
| $\Gamma_5$ | hadrons | | (67.96± 0.35) % | |
| $\Gamma_6$ | $\pi^+\gamma$ | | $< 8 \times 10^{-5}$ | 95% |
| $\Gamma_7$ | $D_s^+\gamma$ | | $< 1.3 \times 10^{-3}$ | 95% |
| $\Gamma_8$ | $cX$ | | (33.6 ± 2.7 ) % | |
| $\Gamma_9$ | $c\overline{s}$ | | $(31 \ {}^{+13}_{-11})$ % | |
| $\Gamma_{10}$ | invisible | [b] | ( 1.4 ± 2.8 ) % | |

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

[b] This represents the width for the decay of the $W$ boson into a charged particle with momentum below detectability, p< 200 MeV.

## $W$ PARTIAL WIDTHS

### $\Gamma$(invisible) $\Gamma_{10}$

This represents the width for the decay of the $W$ boson into a charged particle with momentum below detectability, p< 200 MeV.

| VALUE (MeV) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| $\mathbf{30^{+52}_{-48}\pm 33}$ | [46] BARATE | 99I | ALEP | $E^{ee}_{cm}$= 161+172+183 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| | [47] BARATE | 99L | ALEP | $E^{ee}_{cm}$= 161+172+183 GeV |

[46] BARATE 99I measure this quantity using the dependence of the total cross section $\sigma_{WW}$ upon a change in the total width. The fit is performed to the $WW$ measured cross sections at 161, 172, and 183 GeV. This partial width is < 139 MeV at 95%CL.

[47] BARATE 99L use $W$-pair production to search for effectively invisible $W$ decays, tagging with the decay of the other $W$ boson to Standard Model particles. The partial width for effectively invisible decay is < 27 MeV at 95%CL.

# *W* BRANCHING RATIOS

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 and the common systematic errors among LEP experiments are properly taken into account (see LEP Electroweak Working Group note LEPEWWG/XSEC/2001-02, 30 March 2001, http://lepww.web.cern.ch/lepww/talks_notes/). 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 $\chi^2$ = 11.0 for 22 degrees of freedom. A second fit assumes lepton universality and determines the leptonic branching ratio B($W \to \ell\nu_\ell$) and the hadronic branching ratio is derived as B($W \to$ hadrons) = 1–3 B($W \to \ell\nu$). This fit has a $\chi^2$=11.4 for 24 degrees of freedom.

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

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

Data marked "fit" are used for the fit. The other data is highly correlated with data appearing elsewhere in the Listings and are therefore not used in the fit.

| VALUE | | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **0.1068±0.0012 OUR FIT** | | | | | | |
| 0.1056±0.0020±0.0009 | | 5778 | ABBIENDI,G | 00 | OPAL | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 0.1071±0.0024±0.0014 | | 4843 | ABREU | 00K | DLPH | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 0.1060±0.0023±0.0011 | | 5328 | ACCIARRI | 00V | L3 | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 0.1101±0.0022±0.0011 | | 5258 | BARATE | 00J | ALEP | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 0.1102±0.0052 | fit | 11858 | [48] ABBOTT | 99H | D0 | $E^{p\overline{p}}_{cm}$= 1.8 TeV |
| 0.104 ±0.008 | fit | 3642 | [49] ABE | 92I | CDF | $E^{p\overline{p}}_{cm}$= 1.8 TeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| 0.107 ±0.004 ±0.002 | | 1440 | ABBIENDI | 99D | OPAL | Repl. by ABBIENDI,G 00 |
| 0.1085±0.0048±0.0017 | | 1336 | ABREU | 99K | DLPH | Repl. by ABREU 00K |
| 0.1036±0.0040±0.0017 | | 1322 | BARATE | 99I | ALEP | Repl. by BARATE 00J |
| 0.100 ±0.004 ±0.001 | | 1434 | ACCIARRI | 98P | L3 | Repl. by ACCIARRI 00V |

[48] ABBOTT 99H measure $R \equiv [\sigma_W \, B(W \to \ell\nu_\ell)]/[\sigma_Z \, B(Z \to \ell\ell)] = 10.90 \pm 0.52$ combining electron and muon channels. They use $M_W$ = 80.39 ± 0.06 GeV and the SM theoretical predictions for $\sigma(W)/\sigma(Z)$ and B($Z \to \ell\ell$).

[49] $1216 \pm 38^{+27}_{-31}$ $W \to \mu\nu$ events from ABE 92I and 2426 $W \to e\nu$ events of ABE 91C. ABE 92I give the inverse quantity as 9.6 ± 0.7 and we have inverted.

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

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0.1072±0.0016 OUR FIT** | | | | | |
| 0.1046±0.0042±0.0014 | 801 | ABBIENDI,G | 00 | OPAL | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 0.1044±0.0015±0.0028 | 67318 | [50] ABBOTT | 00B | D0 | $E^{p\overline{p}}_{cm}$= 1.8 TeV |
| 0.1018±0.0054±0.0026 | 527 | ABREU | 00K | DLPH | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 0.1077±0.0045±0.0016 | 715 | ACCIARRI | 00V | L3 | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 0.1135±0.0046±0.0017 | 720 | BARATE | 00J | ALEP | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 0.1094±0.0033±0.0031 | | [51] ABE | 95W | CDF | $E^{p\overline{p}}_{cm}$= 1.8 TeV |
| 0.10 ±0.014 $^{+0.02}_{-0.03}$ | 248 | [52] ANSARI | 87C | UA2 | $E^{p\overline{p}}_{cm}$= 546,630 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 0.117 ±0.009 ±0.002 | 224 | ABBIENDI | 99D | OPAL | Repl. by ABBIENDI,G 00 |
| 0.1012±0.0107±0.0028 | 150 | ABREU | 99K | DLPH | Repl. by ABREU 00K |
| 0.1115±0.0085±0.0024 | 192 | BARATE | 99I | ALEP | Repl. by BARATE 00J |
| 0.105 ±0.009 ±0.002 | 173 | ACCIARRI | 98P | L3 | Repl. by ACCIARRI 00V |
| seen | 119 | APPEL | 86 | UA2 | $E^{p\overline{p}}_{cm}$= 546,630 GeV |
| seen | 172 | ARNISON | 86 | UA1 | $E^{p\overline{p}}_{cm}$= 546,630 GeV |

[50] ABBOTT 00B measure $R \equiv [\sigma_W B(W \to e\nu_e)]/[\sigma_Z B(Z \to ee)] = 10.43 \pm 0.27$ for the $W \to e\nu_e$ decay channel. They use the SM theoretical prediction for $\sigma(W)/\sigma(Z)$ and the world average for $B(Z \to ee)$.

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

[52] 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.

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

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0.1057±0.0022 OUR FIT** | | | | | |
| 0.1050±0.0041±0.0012 | 803 | ABBIENDI,G | 00 | OPAL | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 0.1092±0.0048±0.0012 | 649 | ABREU | 00K | DLPH | $E^{ee}_{cm}$= 161+172+183 +189 GeV |

| | | | | | |
|---|---|---|---|---|---|
| 0.0990±0.0046±0.0015 | 617 | ACCIARRI | 00V | L3 | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 0.1110±0.0044±0.0016 | 710 | BARATE | 00J | ALEP | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 0.10 ±0.01 | 1216 | [53] ABE | 92I | CDF | $E^{p\overline{p}}_{cm}$= 1.8 TeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 0.102 ±0.008 ±0.002 | 193 | ABBIENDI | 99D | OPAL | Repl. by ABBIENDI,G 00 |
| 0.1139±0.0096±0.0023 | 186 | ABREU | 99K | DLPH | Repl. by ABREU 00K |
| 0.1006±0.0078±0.0021 | 179 | BARATE | 99I | ALEP | Repl. by BARATE 00J |
| 0.102 ±0.009 ±0.002 | 160 | ACCIARRI | 98P | L3 | Repl. by ACCIARRI 00V |

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

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

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0.1074±0.0027 OUR FIT** | | | | | |
| 0.1075±0.0052±0.0021 | 794 | ABBIENDI,G | 00 | OPAL | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 0.1105±0.0075±0.0032 | 579 | ABREU | 00K | DLPH | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 0.1124±0.0062±0.0022 | 536 | ACCIARRI | 00V | L3 | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 0.1051±0.0055±0.0022 | 607 | BARATE | 00J | ALEP | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 0.101 ±0.010 ±0.003 | 183 | ABBIENDI | 99D | OPAL | Repl. by ABBIENDI,G 00 |
| 0.1095±0.0149±0.0041 | 142 | ABREU | 99K | DLPH | Repl. by ABREU 00K |
| 0.0976±0.0101±0.0033 | 160 | BARATE | 99I | ALEP | Repl. by BARATE 00J |
| 0.090 ±0.012 ±0.003 | 123 | ACCIARRI | 98P | L3 | Repl. by ACCIARRI 00V |

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

OUR FIT value is obtained by a fit to the lepton branching ratio data assuming lepton universality.

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0.6796±0.0035 OUR FIT** | | | | | |
| **0.679 ±0.004 OUR AVERAGE** | | | | | |
| 0.6832±0.0061±0.0028 | 5778 | ABBIENDI,G | 00 | OPAL | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| 0.6789±0.0073±0.0043 | 4843 | ABREU | 00K | DLPH | $E^{ee}_{cm}$= 161+172+183 +189 GeV |

| | | | | | |
|---|---|---|---|---|---|
| $0.6820 \pm 0.0068 \pm 0.0033$ | 5328 | ACCIARRI | 00V | L3 | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| $0.6697 \pm 0.0065 \pm 0.0032$ | 5258 | BARATE | 00J | ALEP | $E^{ee}_{cm}$= 161+172+183 +189 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $0.679 \pm 0.012 \pm 0.005$ | 1440 | ABBIENDI | 99D | OPAL | Repl. by ABBIENDI,G 00 |
| $0.6746 \pm 0.0143 \pm 0.0052$ | 1336 | ABREU | 99K | DLPH | Repl. by ABREU 00K |
| $0.6893 \pm 0.0121 \pm 0.0051$ | 1322 | BARATE | 99I | ALEP | Repl. by BARATE 00J |
| $0.701 \pm 0.013 \pm 0.004$ | 1434 | ACCIARRI | 98P | L3 | Repl. by ACCIARRI 00V |

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

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0.986±0.024 OUR FIT** | | | | | |
| $0.89 \pm 0.10$ | 13k | [54] ABACHI | 95D | D0 | $E^{p\overline{p}}_{cm}$= 1.8 TeV |
| $1.02 \pm 0.08$ | 1216 | [55] ABE | 92I | CDF | $E^{p\overline{p}}_{cm}$= 1.8 TeV |
| $1.00 \pm 0.14 \pm 0.08$ | 67 | ALBAJAR | 89 | UA1 | $E^{p\overline{p}}_{cm}$= 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 |

[54] 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.

[55] 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.

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

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **1.002±0.029 OUR FIT** | | | | | |
| $0.961 \pm 0.061$ | 980 | [56] ABBOTT | 00D | D0 | $E^{p\overline{p}}_{cm}$= 1.8 TeV |
| $0.94 \pm 0.14$ | 179 | [57] ABE | 92E | CDF | $E^{p\overline{p}}_{cm}$= 1.8 TeV |
| $1.04 \pm 0.08 \pm 0.08$ | 754 | [58] ALITTI | 92F | UA2 | $E^{p\overline{p}}_{cm}$= 630 GeV |
| $1.02 \pm 0.20 \pm 0.12$ | 32 | ALBAJAR | 89 | UA1 | $E^{p\overline{p}}_{cm}$= 546,630 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $0.995 \pm 0.112 \pm 0.083$ | 198 | ALITTI | 91C | UA2 | Repl. by ALITTI 92F |
| $1.02 \pm 0.20 \pm 0.10$ | 32 | ALBAJAR | 87 | UA1 | Repl. by ALBAJAR 89 |

[56] ABBOTT 00D measure $\sigma_W \times$B($W \rightarrow \tau\nu_\tau$) = 2.22 ± 0.09 ± 0.10 ± 0.10 nb. Using the ABBOTT 00B result $\sigma_W \times$B($W \rightarrow e\nu_e$) = 2.31 ± 0.01 ± 0.05 ± 0.10 nb, they quote the ratio of the couplings from which we derive this measurement.

[57] ABE 92E use two procedures for selecting $W \rightarrow \tau\nu_\tau$ events. The missing $E_T$ trigger leads to 132 ± 14 ± 8 events and the $\tau$ trigger to 47 ± 9 ± 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.

[58] 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 |
|---|---|---|---|---|
| **$< 7 \times 10^{-4}$** | 95 | ABE 98H | CDF | $E^{p\overline{p}}_{\rm cm}$= 1.8 TeV |
| $< 4.9 \times 10^{-3}$ | 95 | [59] ALITTI 92D | UA2 | $E^{p\overline{p}}_{\rm cm}$= 630 GeV |
| $<58 \times 10^{-3}$ | 95 | [60] ALBAJAR 90 | UA1 | $E^{p\overline{p}}_{\rm cm}$= 546, 630 GeV |

[59] ALITTI 92D limit is $3.8 \times 10^{-3}$ at 90%CL.
[60] ALBAJAR 90 obtain $< 0.048$ at 90%CL.

### $\Gamma(D_s^+\gamma)/\Gamma(e^+\nu)$ — $\Gamma_7/\Gamma_2$

| VALUE | CL% | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|---|
| **$<1.2 \times 10^{-2}$** | 95 | ABE 98P | CDF | $E^{p\overline{p}}_{\rm cm}$= 1.8 TeV |

### $\Gamma(c X)/\Gamma(\text{hadrons})$ — $\Gamma_8/\Gamma_5$

| VALUE | EVTS | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|---|
| **0.49 ±0.04 OUR AVERAGE** | | | | |
| 0.481±0.042±0.032 | 3005 | [61] ABBIENDI 00V | OPAL | $E^{ee}_{\rm cm}$= 183 + 189 GeV |
| 0.51 ±0.05 ±0.03 | 746 | [62] BARATE 99M | ALEP | $E^{ee}_{\rm cm}$= 172 + 183 GeV |

[61] ABBIENDI 00V tag $W \rightarrow cX$ decays using measured jet properties, lifetime information, and leptons produced in charm decays. From this result, and using the additional measurements of $\Gamma(W)$ and B($W \rightarrow$ hadrons), $|V_{cs}|$ is determined to be $0.969 \pm 0.045 \pm 0.036$.
[62] BARATE 99M tag $c$ jets using a neural network algorithm. From this measurement $|V_{cs}|$ is determined to be $1.00 \pm 0.11 \pm 0.07$.

### $R_{cs} = \Gamma(c\overline{s})/\Gamma(\text{hadrons})$ — $\Gamma_9/\Gamma_5$

| VALUE | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|
| **$0.46^{+0.18}_{-0.14}\pm0.07$** | [63] ABREU 98N | DLPH | $E^{ee}_{\rm cm}$= 161+172 GeV |

[63] ABREU 98N tag $c$ and $s$ jets by identifying a charged kaon as the highest momentum particle in a hadronic jet. They also use a lifetime tag to independently identify a $c$ jet, based on the impact parameter distribution of charged particles in a jet. From this measurement $|V_{cs}|$ is determined to be $0.94^{+0.32}_{-0.26} \pm 0.13$.

## AVERAGE PARTICLE MULTIPLICITIES IN HADRONIC W DECAY

Summed over particle and antiparticle, when appropriate.

### $\langle N_{charged} \rangle$

| VALUE | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|
| **19.3 ±0.4 OUR AVERAGE** | | | |
| 19.3 ±0.3 ±0.3 | [64] ABBIENDI 99N | OPAL | $E^{ee}_{\rm cm}$= 183 GeV |
| 19.23±0.74 | [65] ABREU 98C | DLPH | $E^{ee}_{\rm cm}$= 172 GeV |

[64] ABBIENDI 99N use the final states $W^+W^- \rightarrow q\overline{q}\ell\overline{\nu}_\ell$ to derive this value.
[65] ABREU 98C combine results from both the fully hadronic as well semileptonic $WW$ final states after demonstrating that the $W$ decay charged multiplicity is independent of the topology within errors.

## TRIPLE GAUGE COUPLINGS (TGC'S)

Revised March 2000 by C. Caso (Univ. of Genova) and A. Gurtu (Tata Inst.)

Fourteen independent couplings, 7 each for $ZWW$ and $\gamma WW$, completely describe the $VWW$ vertices within the most general framework of the electroweak Standard Model (SM) consistent with Lorentz invariance and $U(1)$ gauge invariance. Of each of the 7 TGC's, 3 conserve $C$ and $P$ individually, 3 violate $CP$, and one TGC violates $C$ and $P$ individually while conserving $CP$. Assumption of $C$ and $P$ conservation and electromagnetic gauge invariance reduces the independent $VWW$ couplings to five: one common set is $(\kappa_\gamma, \kappa_Z, \lambda_\gamma, \lambda_Z, g_1^Z)$, where $\kappa_\gamma = \kappa_Z = g_1^Z = 1$ and $\lambda_\gamma = \lambda_Z = 0$ in the Standard Model at the tree level. The $W$ magnetic dipole moment, $\mu_W$, and the $W$ electric quadrupole moment, $q_W$, are expressed as $\mu_W = e\ (1 + \kappa_\gamma + \lambda_\gamma)/2M_W$ and $q_W = -e\ (\kappa_\gamma - \lambda_\gamma)/M_W^2$.

Precision measurements of suitable observables at LEP1 has already led to an exploration of much of the TGC parameter space. Three linear combinations of the TGC's, $\alpha_{W\phi}$, $\alpha_{B\phi}$ and $\alpha_W$, have been proposed to investigate the leftover "blind" directions in the $CP$-conserving TGC parameter space, and two linear couplings, $\widetilde{\alpha}_{BW}$ and $\widetilde{\alpha}_W$ in the $CP$-violating TGC parameter space (see *e.g.*, papers by Hagiwara [1], Bilenky [2], and Gounaris [3,4]). The relations between these parameters and those contained in the above set, expressed as *deviations* from the SM, are $\Delta g_1^Z = \alpha_{W\phi}/c_w^2$, $\Delta\kappa_\gamma = \alpha_{W\phi} + \ \alpha_{B\phi}$, $\Delta\kappa_Z = \alpha_{W\phi} - \ t_w^2 \alpha_{B\phi}$ and $\lambda_\gamma = \lambda_Z = \alpha_W$, where $c_w$ and $t_w$ are the cosine and tangent of the electroweak mixing angle. Similarly, $\widetilde{\kappa}_\gamma = \widetilde{\alpha}_{BW}, \widetilde{\kappa}_Z = t_w^2 \widetilde{\alpha}_{BW}$ and $\widetilde{\lambda}_\gamma = \widetilde{\lambda}_Z = \widetilde{\alpha}_W$ within the $CP$-violating sector. The LEP Collaborations have recently agreed to express their results directly in terms of the parameters $\Delta g_1^Z$, $\Delta\kappa_\gamma$ and $\lambda_\gamma$.

At LEP2 the $VWW$ coupling arises in $W$-pair production via $s$-channel exchange or in single $W$ production via the radiation of a virtual photon off the incident $e^+$ or $e^-$. At the TEVATRON hard photon bremstrahlung off a produced $W$ or $Z$ signals the presence of a triple gauge vertex. In order to extract the value of one TGC the others are generally kept fixed to their SM values.

## References


1. K. Hagiwara *et al.*, Nucl. Phys. **B282**, 253 (1987).
2. M. Bilenky *et al.*, Nucl. Phys. **B409**, 22 (1993).
3. G. Gounaris *et al.*, CERN 96-01 525.
4. G. Gounaris *et al.*, Eur. Phys. J. **C2**, 365 (1998).


### $\Delta g_1^Z$

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **$0.01\ ^{+0.09}_{-0.08}$ OUR AVERAGE** | | | | | |
| $0.01\ ^{+0.13}_{-0.12}$ | 853 | [66] ABBIENDI | 99D | OPAL | $E^{ee}_{cm}$= 161+172+ 183 GeV |
| $-0.04\ ^{+0.14}_{-0.12}$ | 566 | [67] ABREU | 99L | DLPH | $E^{ee}_{cm}$= 183 GeV |
| $0.11\ ^{+0.19}_{-0.18} \pm 0.10$ | 1154 | [68] ACCIARRI | 99Q | L3 | $E^{ee}_{cm}$= 161+172+ 183 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $-0.018 \pm 0.026$ | | [69] EBOLI | 00 | THEO | LEP1, SLC+ Tevatron |
| | 331 | [70] ABBOTT | 99I | D0 | $E^{p\overline{p}}_{cm}$= 1.8 TeV |
| $-0.017 \pm 0.018\ ^{+0.018}_{-0.003}$ | | [71] MOLNAR | 99 | THEO | LEP1, SLAC+Tevatron |

[66] ABBIENDI 99D combine results from $W^+ W^-$ production at different energies. The 95% confidence interval is $-0.23 < \Delta g_1^Z < 0.26$.

[67] ABREU 99L use $W^+ W^-$, $W e \nu_e$, and $\nu \overline{\nu} \gamma$ final states. The 95% confidence interval is $-0.28 < \Delta g_1^Z < 0.24$.

[68] ACCIARRI 99Q study $W$-pair, single-$W$, and single photon events.

[69] EBOLI 00 extract this indirect value of the coupling studying the non-universal one-loop contributions to the experimental value of the $Z \rightarrow b\overline{b}$ width ($\Lambda$=1 TeV is assumed).

[70] ABBOTT 99I perform a simultaneous fit to the $W\gamma$, $WW \rightarrow$ dilepton, $WW/WZ \rightarrow e\nu jj$, $WW/WZ \rightarrow \mu\nu jj$, and $WZ \rightarrow$ trilepton data samples. For $\Lambda$ = 2.0 TeV, the 95%CL limits are $-0.37 < \Delta g_1^Z < 0.57$, fixing $\lambda_Z = \Delta\kappa_Z = 0$ and assuming Standard Model values for the $WW\gamma$ couplings.

[71] MOLNAR 99 extract this value indirectly by fitting high energy electroweak data within the framework of the Standard Model. The central value of the Higgs mass used is 300 GeV and the quoted systematic error is due to its variation between 90 to 1000 GeV.

## $\Delta\kappa_\gamma$

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0.02 ±0.12 OUR AVERAGE** | | | | | |
| $-0.04\ ^{+0.15}_{-0.17}\ \pm0.09$ | 137 | [72] ACCIARRI | 00N | L3 | $E^{ee}_{cm}$= 130–189 GeV |
| $0.11\ ^{+0.52}_{-0.37}$ | 853 | [73] ABBIENDI | 99D | OPAL | $E^{ee}_{cm}$= 161+172+ 183 GeV |
| $-0.08\ \pm0.34$ | 331 | [74] ABBOTT | 99I | D0 | $E^{p\overline{p}}_{cm}$= 1.8 TeV |
| $0.19\ ^{+0.32}_{-0.34}$ | 566 | [75] ABREU | 99L | DLPH | $E^{ee}_{cm}$= 183 GeV |
| $0.11\ \pm0.25\ \pm0.17$ | 1154 | [76] ACCIARRI | 99Q | L3 | $E^{ee}_{cm}$= 161+172+ 183 GeV |
| $0.05\ ^{+1.15}_{-1.10}\ \pm0.25$ | 207 | [77] BARATE,R | 98 | ALEP | $E^{ee}_{cm}$= 161+172+183 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [78] BREITWEG | 00 | ZEUS | $e^+ p \to e^+ W^\pm X$, $\sqrt{s} \approx$ 300 GeV |
| | 15 | [79] BARATE | 99L | ALEP | $E^{ee}_{cm}$= 161+172+183 GeV |
| $0.016\pm0.019\ ^{+0.009}_{-0.013}$ | | [80] MOLNAR | 99 | THEO | LEP1, SLAC+Tevatron |
| $0.06\ ^{+0.27}_{-0.26}$ | 86 | [81] ACCIARRI | 98N | L3 | Repl. by ACCIARRI 00N |

[72] ACCIARRI 00N study single $W$ production in $e^+e^-$ interactions from 130 to 189 GeV. This study is largely complementary to ACCIARRI 99Q. The 95% CL limits are $-0.44 < \Delta\kappa_\gamma < 0.29$ (for $\lambda_\gamma$=0). When both couplings $\lambda_\gamma$ and $\kappa_\gamma$ are floated freely in the fit, one obtains $\Delta\kappa_\gamma = -0.07 \pm 0.16 \pm 0.09$.

[73] ABBIENDI 99D combine results from $W^+W^-$ production at different energies. The 95% confidence interval is $-0.55 < \Delta\kappa_\gamma < 1.28$.

[74] ABBOTT 99I perform a simultaneous fit to the $W\gamma$, $WW \to$ dilepton, $WW/WZ \to e\nu jj$, $WW/WZ \to \mu\nu jj$, and $WZ \to$ trilepton data samples. For $\Lambda$ = 2.0 TeV, the 95%CL limits are $-0.25 < \Delta\kappa_\gamma < 0.39$.

[75] ABREU 99L use $W^+W^-$, $We\nu_e$, and $\nu\overline{\nu}\gamma$ final states. The 95% confidence interval is $-0.46 < \Delta\kappa_\gamma < 0.84$.

[76] ACCIARRI 99Q study $W$-pair, single-$W$, and single photon events.

[77] BARATE,R 98 study single photon production in $e^+e^-$ interactions from 161 to 183 GeV. A likelihood fit is performed to the cross section and to the photon energy and angular distributions, taking into account systematic uncertainties. The 95%CL limits are $-2.2 < \Delta\kappa_\gamma < 2.3$.

[78] BREITWEG 00 search for $W$ production in events with large hadronic $p_T$. For $p_T$ >20 GeV, the upper limit on the cross section gives the 95%CL limit $-4.7 < \Delta\kappa_\gamma < 1.5$ (for $\lambda_\gamma$=0).

[79] BARATE 99L study single $W$ production in $e^+e^-$ interactions from 161 to 183 GeV. They obtain 95%CL limits of $-1.6 < \kappa_\gamma < 1.5$, which we convert to $-2.6 < \Delta\kappa_\gamma < 0.5$ for $\lambda_\gamma$=0.

[80] MOLNAR 99 extract this value indirectly by fitting high energy electroweak data within the framework of the Standard Model. The central value of the Higgs mass used is 300 GeV and the quoted systematic error is due to its variation between 90 to 1000 GeV.

[81] ACCIARRI 98N study single $W$ production in $e^+e^-$ interactions from 130 to 183 GeV. The 95%CL limits are $-0.46 < \Delta\kappa_\gamma < 0.57$.

## $\lambda_\gamma$

| VALUE | EVTS | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|---|
| **$-0.04^{+0.07}_{-0.06}$ OUR AVERAGE** | | | | |
| $-0.26^{+0.53}_{-0.19}\pm0.13$ | 137 | [82] ACCIARRI 00N | L3 | $E^{ee}_{cm}$= 130–189 GeV |
| $-0.10^{+0.13}_{-0.12}$ | 853 | [83] ABBIENDI 99D | OPAL | $E^{ee}_{cm}$= 161+172+ 183 GeV |
| $0.00^{+0.10}_{-0.09}$ | 331 | [84] ABBOTT 99I | D0 | $E^{p\overline{p}}_{cm}$= 1.8 TeV |
| $-0.15^{+0.19}_{-0.15}$ | 566 | [85] ABREU 99L | DLPH | $E^{ee}_{cm}$= 183 GeV |
| $0.10^{+0.22}_{-0.20}\pm0.10$ | 1154 | [86] ACCIARRI 99Q | L3 | $E^{ee}_{cm}$= 161+172+ 183 GeV |
| $-0.05^{+1.55}_{-1.45}\pm0.30$ | 207 | [87] BARATE,R 98 | ALEP | $E^{ee}_{cm}$= 161+172+183 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| | | [88] BREITWEG 00 | ZEUS | $e^+ p \rightarrow e^+ W^\pm X$, $\sqrt{s}\approx$ 300 GeV |
| $-0.50\pm0.73$ | | [89] EBOLI 00 | THEO | LEP1, SLC+ Tevatron |
| | 15 | [90] BARATE 99L | ALEP | $E^{ee}_{cm}$= 161+172+183 GeV |
| $-0.48^{+0.44}_{-0.21}$ | 86 | [91] ACCIARRI 98N | L3 | Repl. by ACCIARRI 00N |

[82] ACCIARRI 00N study single $W$ production in $e^+e^-$ interactions from 130 to 189 GeV. This study is largely complementary to ACCIARRI 99Q. The 95% CL limits are $-0.67 < \lambda_\gamma < 0.59$ (for $\kappa_\gamma$=1). When both couplings $\lambda_\gamma$ and $\kappa_\gamma$ are floated freely in the fit, one obtains $\lambda_\gamma = -0.31^{+0.68}_{-0.19} \pm 0.13$.

[83] ABBIENDI 99D combine results from $W^+W^-$ production at different energies. The 95% confidence interval is $-0.33 < \lambda_\gamma < 0.16$.

[84] ABBOTT 99I perform a simultaneous fit to the $W\gamma$, $WW \rightarrow$ dilepton, $WW/WZ \rightarrow e\nu jj$, $WW/WZ \rightarrow \mu\nu jj$, and $WZ \rightarrow$ trilepton data samples. For $\Lambda$ = 2.0 TeV, the 95%CL limits are $-0.18 < \lambda_\gamma < 0.19$.

[85] ABREU 99L use $W^+W^-$, $We\nu_e$, and $\nu\overline{\nu}\gamma$ final states. The 95% confidence interval is $-0.44 < \lambda_\gamma < 0.24$.

[86] ACCIARRI 99Q study $W$-pair, single-$W$, and single photon events.

[87] BARATE,R 98 study single photon production in $e^+e^-$ interactions from 161 to 183 GeV. A likelihood fit is performed to the cross section and to the photon energy and angular distributions, taking into account systematic uncertainties. The 95%CL limits are $-3.1 < \lambda_\gamma < 3.2$.

[88] BREITWEG 00 search for $W$ production in events with large hadronic $p_T$. For $p_T$ >20 GeV, the upper limit on the cross section gives the 95%CL limit $-3.2 < \lambda_\gamma < 3.2$ (for $\Delta\kappa_\gamma$=0).

[89] EBOLI 00 extract this indirect value of the coupling studying the non-universal one-loop contributions to the experimental value of the $Z \rightarrow b\overline{b}$ width ($\Lambda$=1 TeV is assumed).

[90] BARATE 99L study single $W$ production in $e^+e^-$ interactions from 161 to 183 GeV. The 95%CL limits are $-1.6 < \lambda_\gamma < 1.6$ for $\Delta\kappa_\gamma$=0.

[91] ACCIARRI 98N study single $W$ production in $e^+e^-$ interactions from 130 to 183 GeV. The 95%CL limits are $-0.86 < \lambda_\gamma < 0.75$.

## $\Delta g_5^Z$

This coupling is $CP$ conserving but $C$ and $P$ violating.

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| $\mathbf{-0.44^{+0.23}_{-0.22}\pm0.12}$ | 1154 | [92] ACCIARRI | 99Q | L3 | $E^{ee}_{cm}$= 161+172+ 183 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $-0.16\pm0.23$ | | [93] EBOLI | 00 | THEO | LEP1, SLC+ Tevatron |

[92] ACCIARRI 99Q study $W$-pair, single-$W$, and single photon events.
[93] EBOLI 00 extract this indirect value of the coupling studying the non-universal one-loop contributions to the experimental value of the $Z \to b\overline{b}$ width ($\Lambda$=1 TeV is assumed).

## $\alpha_{W\phi}$

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0.05±0.20 OUR AVERAGE** | | | | | |
| $0.22^{+0.25}_{-0.28}\pm0.06$ | 89 | [94] ABREU | 98K | DLPH | $E^{ee}_{cm}$=161+172 GeV |
| $-0.14^{+0.27}_{-0.25}{}^{+0.14}_{-0.12}$ | 78 | [95] BARATE | 98Y | ALEP | $E^{ee}_{cm}$= 172 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | 331 | [96] ABBOTT | 99I | D0 | $E^{p\overline{p}}_{cm}$= 1.8 TeV |

[94] ABREU 98K obtain this result using both $W$ pair production and single $W$ ($We\nu_e$) production.
[95] BARATE 98Y obtain this value using semileptonic and hadronic decay modes in $W$ pair production.
[96] ABBOTT 99I perform a simultaneous fit to the $W\gamma$, $WW \to$ dilepton, $WW/WZ \to e\nu jj$, $WW/WZ \to \mu\nu jj$, and $WZ \to$ trilepton data samples. For $\Lambda$ = 2.0 TeV, the 95%CL limits are $-0.18 < \alpha_{W\phi} < 0.36$, fixing $\alpha_{B\phi}=\alpha_W=0$.

## $\alpha_W$

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0.1 ±0.4 OUR AVERAGE** | | | | | |
| $0.11^{+0.48}_{-0.49}\pm0.09$ | 89 | [97] ABREU | 98K | DLPH | $E^{ee}_{cm}$=161+172 GeV |
| $0.06^{+0.56}_{-0.50}{}^{+0.12}_{-0.20}$ | 78 | [98] BARATE | 98Y | ALEP | $E^{ee}_{cm}$= 172 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | 331 | [99] ABBOTT | 99I | D0 | $E^{p\overline{p}}_{cm}$= 1.8 TeV |

[97] ABREU 98K obtain this result using both $W$ pair production and single $W$ ($We\nu_e$) production.
[98] BARATE 98Y obtain this value using semileptonic and hadronic decay modes in $W$ pair production.
[99] ABBOTT 99I perform a simultaneous fit to the $W\gamma$, $WW \to$ dilepton, $WW/WZ \to e\nu jj$, $WW/WZ \to \mu\nu jj$, and $WZ \to$ trilepton data samples. For $\Lambda$ = 2.0 TeV, the 95%CL limits are $-0.18 < \alpha_W < 0.19$, fixing $\alpha_{B\phi}=\alpha_{W\phi}=0$.

### $\alpha_{B\phi}$

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **$0.4\ ^{+0.5}_{-0.8}$ OUR AVERAGE** | | | | | |
| $0.22^{+0.66}_{-0.83}\pm0.24$ | 89 | [100] ABREU | 98K | DLPH | $E^{ee}_{\rm cm}$=161+172 GeV |
| $1.01^{+0.71}_{-1.75}\pm0.33$ | 78 | [101] BARATE | 98Y | ALEP | $E^{ee}_{\rm cm}$= 172 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | 331 | [102] ABBOTT | 99I | D0 | $E^{p\overline{p}}_{\rm cm}$= 1.8 TeV |

[100] ABREU 98K obtain this result using both $W$ pair production and single $W$ ($W e \nu_e$) production.

[101] BARATE 98Y obtain this value using semileptonic and hadronic decay modes in $W$ pair production.

[102] ABBOTT 99I perform a simultaneous fit to the $W\gamma$, $WW \rightarrow$ dilepton, $WW/WZ \rightarrow e\nu jj$, $WW/WZ \rightarrow \mu\nu jj$, and $WZ \rightarrow$ trilepton data samples. For $\Lambda = 2.0$ TeV, the 95%CL limits are $-0.67 < \alpha_{B\phi} < 0.56$, fixing $\alpha_{W\phi}$=$\alpha_W$=0.

### $\widetilde{\alpha}_{BW}$

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **$0.11^{+0.71}_{-0.88}\pm0.09$** | 89 | [103] ABREU | 98K | DLPH | $E^{ee}_{\rm cm}$=161+172 GeV |

[103] ABREU 98K obtain this result using both $W$ pair production and single $W$ ($W e \nu_e$) production.

### $\widetilde{\alpha}_{W}$

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **$0.19^{+0.28}_{-0.41}\pm0.11$** | 89 | [104] ABREU | 98K | DLPH | $E^{ee}_{\rm cm}$=161+172 GeV |

[104] ABREU 98K obtain this result using both $W$ pair production and single $W$ ($W e \nu_e$) production.

# *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. • • • | | | |
| | [105] ABE | 95G | CDF |
| | [106] ALITTI | 92C | UA2 |
| | [107] SAMUEL | 92 | THEO |
| | [108] SAMUEL | 91 | THEO |
| | [109] GRIFOLS | 88 | THEO |
| | [110] GROTCH | 87 | THEO |
| | [111] VANDERBIJ | 87 | THEO |
| | [112] GRAU | 85 | THEO |
| | [113] SUZUKI | 85 | THEO |
| | [114] HERZOG | 84 | THEO |

[105] 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.

[106] 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 $-3.6 < \lambda < 3.5$.

[107] 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.

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

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

[110] 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.

[111] 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 $\Delta\kappa$.

[112] 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 $\lambda = 0$.

[113] 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 $|\Delta\kappa| \ll 1$.

[114] 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.

## ANOMALOUS $W/Z$ QUARTIC COUPLINGS

Written January 2001 by C. Caso (Univ. of Genova) and A. Gurtu (Tata Inst.)

The Standard Model predictions for $WWWW$, $WWZZ$, $WWZ\gamma$, $WW\gamma\gamma$, and $ZZ\gamma\gamma$ couplings are small at LEP, but expected to become important at a TeV Linear Collider. Outside the Standard Model framework such possible couplings, $a_0, a_c, a_n$, are expressed in terms of the following dimension-6 operators [1,2];

$$L_6^0 = -\frac{e^2}{16\Lambda^2}\, a_0\, F^{\mu\nu}\, F_{\mu\nu}\vec{W}^{\alpha} \cdot \vec{W}_{\alpha}$$

$$L_6^c = -\frac{e^2}{16\Lambda^2}\, a_c\, F^{\mu\alpha}\, F_{\mu\beta}\vec{W}^{\beta} \cdot \vec{W}_{\alpha}$$

$$L_6^n = -i\frac{e^2}{16\Lambda^2}\, a_n \epsilon_{ijk}\, W_{\mu\alpha}^{(i)}\, W_{\nu}^{(j)}\, W^{(k)\alpha} F^{\mu\nu}$$

where $F, W$ are photon and $W$ fields, $L_6^0$ and $L_6^c$ conserve $C$, $P$ separately and generate anomalous $W^+W^-\gamma\gamma$ and $ZZ\gamma\gamma$ couplings, $L_6^n$ violates $CP$ and generates an anomalous $W^+W^-Z\gamma$ coupling, and $\Lambda$ is a scale for new physics. For the $ZZ\gamma\gamma$ coupling the $CP$-violating term represented by $L_6^n$ does not contribute.

At LEP the processes studied in search of these quartic couplings are $e^+e^- \rightarrow WW\gamma$, $e^+e^- \rightarrow \gamma\gamma\nu\overline{\nu}$, and $e^+e^- \rightarrow Z\gamma\gamma$ and limits are set on the quantities $a_0/\Lambda^2, a_c/\Lambda^2, a_n/\Lambda^2$. The sensitive measured variables are the cross sections for these processes as well as the energy and angular distributions of the photon and recoil mass to the photon pair.

Combining results from all LEP experiments and channels, the limits presented at the Osaka Conference [3] are $-0.0049 < a_0/\Lambda^2 < 0.0056$, $-0.0054 < a_c/\Lambda^2 < 0.0098$, $-0.45 < a_n/\Lambda^2 < 0.41$.

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3. S. Spagnolo: "Measurement of Quartic Gauge Boson Couplings", Electroweak parallel session, *XXXth International Conference on High Energy Physics*, Osaka, Japan, July 27 – August 2, 2000.


### $a_0/\Lambda^2$, $a_c/\Lambda^2$, $a_n/\Lambda^2$

| VALUE | DOCUMENT ID | | TECN |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| | [115] ACCIARRI | 00T | L3 |
| | [116] ABBIENDI | 99U | OPAL |

[115] ACCIARRI 00T select 42 $e^+ e^- \rightarrow W^+ W^- \gamma$ events at 189 GeV, where $E_\gamma > 5$ GeV and the photon is well isolated. They also select 35 acoplanar $e^+ e^- \rightarrow \nu\overline{\nu}\gamma\gamma$ events at 183 and 189 GeV, where the photon energies are $> 5$ and $> 1$ GeV and the photon polar angles are between 14° and 166°. Using the shape and normalization of the photon spectra in the $W^+ W^- \gamma$ events together with the cross section of the final state $\nu\overline{\nu}\gamma\gamma$, they obtain the following one-parameter 95% CL limits: $-0.043$ GeV$^{-2}$ $< a_0/\Lambda^2 <$ 0.043 GeV$^{-2}$, $-0.08$ GeV$^{-2}$ $< a_c/\Lambda^2 <$ 0.13 GeV$^{-2}$, $-0.41$ GeV$^{-2}$ $< a_n/\Lambda^2 <$ 0.37 GeV$^{-2}$.

[116] ABBIENDI 99U select 17 $e^+ e^- \rightarrow W^+ W^- \gamma$ events at 189 GeV, where $E_\gamma >$10 GeV and the photon is well isolated. The photon energy spectrum is used to set the 95% CL limits $-0.070$ GeV$^{-2}$ $< a_0/\Lambda^2 <$ 0.070 GeV$^{-2}$, $-0.13$ GeV$^{-2}$ $< a_c/\Lambda^2 <$ 0.19 GeV$^{-2}$, $-0.61$ GeV$^{-2}$ $< a_n/\Lambda^2 <$ 0.57 GeV$^{-2}$.

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| ACCIARRI | 97 | PL B398 223 | M. Acciarri *et al.* | (L3 Collab.) |
| ACCIARRI | 97M | PL B407 419 | M. Acciarri *et al.* | (L3 Collab.) |
| ACCIARRI | 97S | PL B413 176 | M. Acciarri *et al.* | (L3 Collab.) |
| ABACHI | 96E | PRL 77 3309 | S. Abachi *et al.* | (D0 Collab.) |
| ABACHI | 95D | PRL 75 1456 | S. Abachi *et al.* | (D0 Collab.) |
| ABE | 95C | PRL 74 341 | F. Abe *et al.* | (CDF Collab.) |
| ABE | 95G | PRL 74 1936 | F. Abe *et al.* | (CDF Collab.) |
| ABE | 95P | PRL 75 11 | F. Abe *et al.* | (CDF Collab.) |
| Also | 95Q | PR D52 4784 | F. Abe *et al.* | (CDF Collab.) |
| ABE | 95W | PR D52 2624 | F. Abe *et al.* | (CDF Collab.) |
| Also | 94B | PRL 73 220 | F. Abe *et al.* | (CDF Collab.) |
| ROSNER | 94 | PR D49 1363 | J.L. Rosner, M.P. Worah, T. Takeuchi | (EFI, FNAL) |
| ABE | 92E | PRL 68 3398 | F. Abe *et al.* | (CDF Collab.) |
| ABE | 92I | PRL 69 28 | F. Abe *et al.* | (CDF Collab.) |
| ALITTI | 92 | PL B276 365 | J. Alitti *et al.* | (UA2 Collab.) |
| ALITTI | 92B | PL B276 354 | J. Alitti *et al.* | (UA2 Collab.) |
| ALITTI | 92C | PL B277 194 | J. Alitti *et al.* | (UA2 Collab.) |
| ALITTI | 92D | PL B277 203 | J. Alitti *et al.* | (UA2 Collab.) |
| ALITTI | 92F | PL B280 137 | J. Alitti *et al.* | (UA2 Collab.) |
| SAMUEL | 92 | PL B280 124 | M.A. Samuel *et al.* | (OKSU, CARL) |
| ABE | 91C | PR D44 29 | F. Abe *et al.* | (CDF Collab.) |
| ALBAJAR | 91 | PL B253 503 | C. Albajar *et al.* | (UA1 Collab.) |
| ALITTI | 91C | ZPHY C52 209 | J. Alitti *et al.* | (UA2 Collab.) |
| SAMUEL | 91 | PRL 67 9 | M.A. Samuel *et al.* | (OKSU, CARL) |
| Also | 91C | PRL 67 2920 erratum | M.A. Samuel *et al.* | |
| ABE | 90 | PRL 64 152 | F. Abe *et al.* | (CDF Collab.) |
| Also | 91C | PR D44 29 | F. Abe *et al.* | (CDF Collab.) |
| ABE | 90G | PRL 65 2243 | F. Abe *et al.* | (CDF Collab.) |
| Also | 91B | PR D43 2070 | F. Abe *et al.* | (CDF Collab.) |
| ALBAJAR | 90 | PL B241 283 | C. Albajar *et al.* | (UA1 Collab.) |
| ALITTI | 90B | PL B241 150 | J. Alitti *et al.* | (UA2 Collab.) |
| ALITTI | 90C | ZPHY C47 11 | J. Alitti *et al.* | (UA2 Collab.) |
| ABE | 89I | PRL 62 1005 | F. Abe *et al.* | (CDF Collab.) |
| ALBAJAR | 89 | ZPHY C44 15 | C. Albajar *et al.* | (UA1 Collab.) |
| BAUR | 88 | NP B308 127 | U. Baur, D. Zeppenfeld | (FSU, WISC) |
| GRIFOLS | 88 | IJMP A3 225 | J.A. Grifols, S. Peris, J. Sola | (BARC, DESY) |
| Also | 87 | PL B197 437 | J.A. Grifols, S. Peris, J. Sola | (BARC, DESY) |
| ALBAJAR | 87 | PL B185 233 | C. Albajar *et al.* | (UA1 Collab.) |
| ANSARI | 87 | PL B186 440 | R. Ansari *et al.* | (UA2 Collab.) |
| ANSARI | 87C | PL B194 158 | R. Ansari *et al.* | (UA2 Collab.) |
| GROTCH | 87 | PR D36 2153 | H. Grotch, R.W. Robinett | (PSU) |
| HAGIWARA | 87 | NP B282 253 | K. Hagiwara *et al.* | (KEK, UCLA, FSU) |
| VANDERBIJ | 87 | PR D35 1088 | J.J. van der Bij | (FNAL) |
| APPEL | 86 | ZPHY C30 1 | J.A. Appel *et al.* | (UA2 Collab.) |
| ARNISON | 86 | PL 166B 484 | G.T.J. Arnison *et al.* | (UA1 Collab.) J |
| ALTARELLI | 85B | ZPHY C27 617 | G. Altarelli, R.K. Ellis, G. Martinelli | (CERN+) |
| GRAU | 85 | PL 154B 283 | A. Grau, J.A. Grifols | (BARC) |
| SUZUKI | 85 | PL 153B 289 | M. Suzuki | (LBL) |
| ARNISON | 84D | PL 134B 469 | G.T.J. Arnison *et al.* | (UA1 Collab.) |
| HERZOG | 84 | PL 148B 355 | F. Herzog | (WISC) |
| Also | 84B | PL 155B 468 erratum | F. Herzog | (WISC) |

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| ARNISON | 83 | PL 122B 103 | G.T.J. Arnison *et al.* | (UA1 Collab.) |
| BANNER | 83B | PL 122B 476 | M. Banner *et al.* | (UA2 Collab.) |