



$$J = 1$$

THE MASS OF THE W BOSON

Revised March 2003 by C. Caso (University of Genova) and A. Gurtu (Tata Institute).

Till 1995 the production and study of the W boson was the exclusive domain of the $\bar{p}p$ 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^- center-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.

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

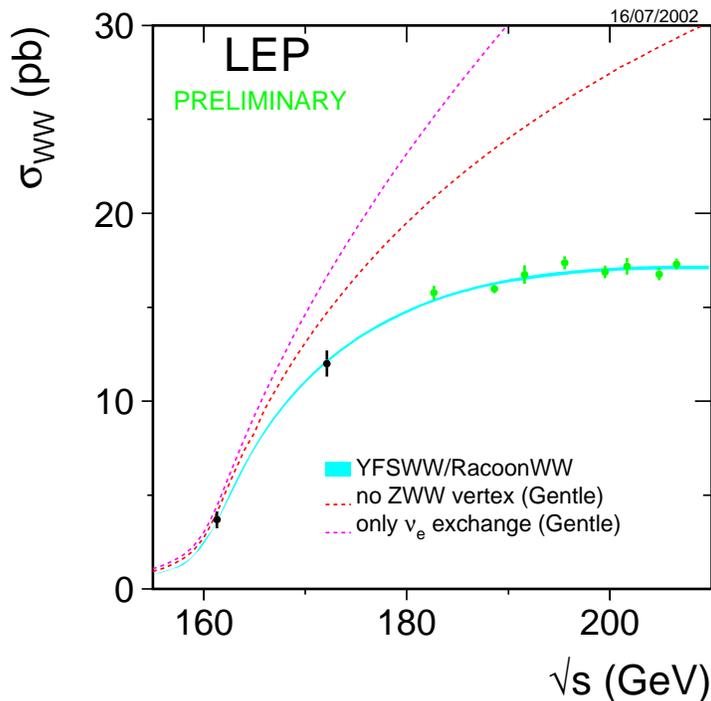


Figure 1: The W -pair cross section as a function of the center-of-mass energy. The data points are the LEP averages. The solid lines are predictions from different models of WW production. For comparison the figure contains also the cross section if the ZWW coupling did not exist (dashed line), or if only the t -channel ν_e exchange diagram existed (dotted-dashed line). (Figure from http://lepewwg.web.cern.ch/LEPEWWG/lepww/4f/Summer02/wwxsec_nocouplings_2002.eps)

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 = 80.412 ± 0.042 GeV [2]. Errors due to uncertainties in LEP energy (17 MeV) and possible effect of color reconnection (CR) and Bose–Einstein (BE) correlations between quarks from different W 's are included. The mass difference between $qqqq$ and $qq\ell\nu$ final states (due to possible CR and BE effects) is $+22 \pm 43$ 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] = 80.454 ± 0.059 GeV.

Combining the above W mass values from LEP and hadron colliders, which are based on all published and unpublished results, and assuming no common systematics between them, yields an average W mass of 80.426 ± 0.034 GeV.

Finally a fit to this directly determined W mass together with measurements on the ratio of W to Z mass (M_W/M_Z) and on their mass difference ($M_Z - M_W$) yields a world average W -boson mass of 80.425 ± 0.033 GeV.

The Standard Model prediction from the electroweak fit, using Z -pole data plus m_{top} measurement, gives a W -boson mass of 80.380 ± 0.023 GeV [2,4].

OUR FIT in the listing below is obtained by combining only published LEP and $p\text{-}\bar{p}$ 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 Group, CERN-EP-2002-091, hep-ex/0212036 (17 December 2002).
2. P. Perez, “ W mass measurement at LEP,” XXXVIIIth Rencontres de Moriond on Electroweak Interactions and Unified Theories (Les Arcs, France, 15-22 March 2003); The LEP Collaborations ALEPH, DELPHI, L3, OPAL, and the LEP W Working Group, Note LEPEWWG/MASS/2003-01, dated 27 March 2003, at <http://lepewwg.web.cern.ch/LEPEWWG/lepww/mw/Winter03/>.
3. A. Kotwal *et al.*, The Tevatron Electroweak Working Group, Fermilab Note, FERMILAB-FN-716 (1 July 2002).
4. The LEP Collaborations ALEPH, DELPHI, L3, OPAL, the LEP Electroweak Working Group and the SLD Heavy Flavour Group, Note LEPEWWG/2003-01, dated 8 April 2003, at <http://lepewwg.web.cern.ch/LEPEWWG/stanmod/>.

W MASS

To obtain the world average, common systematics between experiments are properly taken into account. The procedure for averaging the LEP data is given in the note LEPEWWG/MASS/2002-01 (March 11, 2002), accessible at http://lepewwg.web.cern.ch/LEPEWWG/lepww/mw/pdg_2002/. The LEP average W mass is 80.400 ± 0.056 GeV. The combined $p\bar{p}$ collider data yields an average W mass of 80.454 ± 0.059 GeV (KOTWAL 02).

OUR FIT uses these average LEP and $p\bar{p}$ collider W mass values together with the Z mass, the W to Z mass ratio, and mass difference measurements.

<u>VALUE (GeV)</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
80.425 ± 0.038 OUR FIT				
80.483 ± 0.084	49247	1 ABAZOV	02D D0	$E_{cm}^{p\bar{p}} = 1.8$ TeV
80.432 ± 0.066 ± 0.045	2789	2 ABBIENDI	01F OPAL	$E_{cm}^{ee} = 161+172+183+189$ GeV
80.359 ± 0.074 ± 0.049	3077	3 ABREU	01K DLPH	$E_{cm}^{ee} = 161+172+183+189$ GeV

80.433 ± 0.079	53841	4	AFFOLDER	01E CDF	$E_{\text{cm}}^{p\bar{p}} = 1.8 \text{ TeV}$
$80.418 \pm 0.061 \pm 0.047$	2977	5	BARATE	00T ALEP	$E_{\text{cm}}^{ee} = 161+172+183$ $+189 \text{ GeV}$
80.61 ± 0.15	801	6	ACCIARRI	99 L3	$E_{\text{cm}}^{ee} = 161+172+183$ GeV
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●					
$80.3 \pm 2.1 \pm 1.2 \pm 1.0$	645	7	CHEKANOV	02C ZEUS	$e^- p \rightarrow \nu_e X, \sqrt{s} = 318$ GeV
$79.9 \pm 2.2 \pm 2.3$	700	8	ADLOFF	01A H1	$e^- p \rightarrow \nu_e X, \sqrt{s} \approx$ 320 GeV
80.482 ± 0.091	45394	9	ABBOTT	00 D0	Repl. by ABAZOV 02D
$80.9 \pm 3.7 \pm 3.7$	700	10	ADLOFF	00B H1	$e^+ p \rightarrow \bar{\nu}_e X, \sqrt{s} \approx$ 300 GeV
$81.4^{+2.7}_{-2.6} \pm 2.0^{+3.3}_{-3.0}$	1086	11	BREITWEG	00D ZEUS	$e^+ p \rightarrow \bar{\nu}_e X, \sqrt{s} \approx$ 300 GeV
$80.38 \pm 0.12 \pm 0.05$	701	12	ABBIENDI	99C OPAL	Repl. by ABBIENDI 01F
$80.270 \pm 0.137 \pm 0.048$	809	13	ABREU	99T DLPH	Repl. by ABREU 01K
$80.423 \pm 0.112 \pm 0.054$	812	14	BARATE	99 ALEP	Repl. by BARATE 00T
$80.80^{+0.48}_{-0.42} \pm 0.03$	20	15	ACCIARRI	97 L3	Repl. by ACCIARRI 99
$80.5^{+1.4}_{-2.4} \pm 0.3$	94	16	ACCIARRI	97M L3	Repl. by ACCIARRI 99
$80.71^{+0.34}_{-0.35} \pm 0.09$	101	17	ACCIARRI	97S L3	Repl. by ACCIARRI 99
80.41 ± 0.18	8986	18	ABE	95P CDF	Repl. by AF- FOLDER 01E
$80.84 \pm 0.22 \pm 0.83$	2065	19	ALITTI	92B UA2	See W/Z ratio below
$80.79 \pm 0.31 \pm 0.84$		20	ALITTI	90B UA2	$E_{\text{cm}}^{p\bar{p}} = 546,630 \text{ GeV}$
$80.0 \pm 3.3 \pm 2.4$	22	21	ABE	89I CDF	$E_{\text{cm}}^{p\bar{p}} = 1.8 \text{ TeV}$
$82.7 \pm 1.0 \pm 2.7$	149	22	ALBAJAR	89 UA1	$E_{\text{cm}}^{p\bar{p}} = 546,630 \text{ GeV}$
$81.8^{+6.0}_{-5.3} \pm 2.6$	46	23	ALBAJAR	89 UA1	$E_{\text{cm}}^{p\bar{p}} = 546,630 \text{ GeV}$
$89 \pm 3 \pm 6$	32	24	ALBAJAR	89 UA1	$E_{\text{cm}}^{p\bar{p}} = 546,630 \text{ GeV}$
$81. \pm 5.$	6		ARNISON	83 UA1	$E_{\text{cm}}^{ee} = 546 \text{ GeV}$
$80.^{+10.}_{-6.}$	4		BANNER	83B UA2	Repl. by ALITTI 90B

¹ ABAZOV 02D improve the measurement of the W -boson mass including $W \rightarrow e\nu_e$ events in which the electron is close to a boundary of a central electromagnetic calorimeter module. Properly combining the results obtained by fitting $m_T(W)$, $p_T(e)$, and $p_T(\nu)$, this sample provides a mass value of $80.574 \pm 0.405 \text{ GeV}$. The value reported here is a combination of this measurement with all previous $D\bar{D}$ W -boson mass measurements.

² 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 $\pm 0.017 \text{ GeV}$ due to LEP energy uncertainty and $\pm 0.028 \text{ GeV}$ due to possible color reconnection and Bose-Einstein effects in the purely hadronic final state.

³ ABREU 01K 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, 172, and 183 GeV. The systematic error includes $\pm 0.017 \text{ GeV}$ due to the beam energy uncertainty and $\pm 0.033 \text{ GeV}$ due to possible color reconnection and Bose-Einstein effects in the purely hadronic final state.

⁴ AFFOLDER 01E fit the transverse mass spectrum of 30115 $W \rightarrow e\nu_e$ events ($M_W = 80.473 \pm 0.065 \pm 0.092 \text{ GeV}$) and of 14740 $W \rightarrow \mu\nu_\mu$ events ($M_W = 80.465 \pm 0.100 \pm 0.103 \text{ GeV}$) obtained in the run IB (1994-95). Combining the electron and muon results, accounting for correlated uncertainties, yields $M_W = 80.470 \pm 0.089 \text{ GeV}$. They combine

- this value with their measurement of ABE 95P reported in run IA (1992-93) to obtain the quoted value.
- ⁵ 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 ± 0.017 GeV due to LEP energy uncertainty and ± 0.019 GeV due to possible color reconnection and Bose-Einstein effects in the purely hadronic final state.
 - ⁶ 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.
 - ⁷ CHEKANOV 02C fit the Q^2 dependence ($200 < Q^2 < 60000 \text{ GeV}^2$) 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.
 - ⁸ ADLOFF 01A fit the Q^2 dependence ($150 < Q^2 < 30000 \text{ GeV}^2$) 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 ABBOTT 00 use $W \rightarrow e\nu_e$ 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 $p_T(\nu)$.
 - ¹⁰ ADLOFF 00B fit the Q^2 dependence ($300 < Q^2 < 15000 \text{ GeV}^2$) of the charged-current double-differential cross sections with a propagator mass fit. The second error is due to the theoretical uncertainties.
 - ¹¹ BREITWEG 00D fit the Q^2 dependence ($200 < Q^2 < 22500 \text{ GeV}^2$) 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.
 - ¹² 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 ± 0.02 GeV due to the possible color-reconnection and Bose-Einstein effects in the purely hadronic final states and an uncertainty of ± 0.02 GeV due to the beam energy.
 - ¹³ 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 ± 0.021 GeV due to the beam energy uncertainty and ± 0.030 GeV due to possible color reconnection and Bose-Einstein effects in the purely hadronic final state.
 - ¹⁴ 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 ± 0.023 GeV due to LEP energy uncertainty and ± 0.021 GeV due to theory uncertainty on account of possible color reconnection and Bose-Einstein correlations.
 - ¹⁵ ACCIARRI 97 derive this value from their measured W - W production cross section $\sigma_{WW} = 2.89_{-0.70}^{+0.81} \pm 0.14$ pb using the Standard Model dependence of σ_{WW} on M_W at the given c.m. energy. Statistical and systematic errors are added in quadrature and the last error of ± 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.
 - ¹⁶ ACCIARRI 97M derive this value from their measured W W production cross section $\sigma_{WW} = 12.27_{-1.32}^{+1.41} \pm 0.23$ pb using the Standard Model dependence of σ_{WW} on M_W at the given c.m. energy. Combining with ACCIARRI 97 authors find $M(W) = 80.78_{-0.41}^{+0.45} \pm 0.03$ GeV where the last error is due to beam energy uncertainty.
 - ¹⁷ 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 $M(W) = 80.72_{-0.33}^{+0.31} \pm 0.09$ 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 with ACCIARRI 97 and ACCIARRI 97M authors find: $M(W) = 80.75^{+0.26}_{-0.27} \pm 0.03$ (LEP) GeV.

- 18 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.
- 19 ALITTI 92B result has two contributions to the systematic error (± 0.83); one (± 0.81) cancels in m_W/m_Z and one (± 0.17) is noncancelling. These were added in quadrature. We choose the ALITTI 92B value without using the LEP m_Z value, because we perform our own combined fit.
- 20 There are two contributions to the systematic error (± 0.84): one (± 0.81) which cancels in m_W/m_Z and one (± 0.21) which is non-cancelling. These were added in quadrature.
- 21 ABE 89I systematic error dominated by the uncertainty in the absolute energy scale.
- 22 ALBAJAR 89 result is from a total sample of 299 $W \rightarrow e\nu$ events.
- 23 ALBAJAR 89 result is from a total sample of 67 $W \rightarrow \mu\nu$ events.
- 24 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.

<u>VALUE</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
0.88197 ± 0.00042 OUR FIT				
0.8821 ± 0.0011 ± 0.0008	28323	25 ABBOTT	98N D0	$E_{cm}^{p\bar{p}} = 1.8$ TeV
0.88114 ± 0.00154 ± 0.00252	5982	26 ABBOTT	98P D0	$E_{cm}^{p\bar{p}} = 1.8$ TeV
0.8813 ± 0.0036 ± 0.0019	156	27 ALITTI	92B UA2	$E_{cm}^{p\bar{p}} = 630$ GeV

- 25 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.
- 26 ABBOTT 98P obtain this from a study of 5982 $W \rightarrow e\nu_e$ events. The systematic error includes an uncertainty of ± 0.00175 due to the electron energy scale.
- 27 Scale error cancels in this ratio.

$m_Z - m_W$

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

<u>VALUE (GeV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
10.763 ± 0.038 OUR FIT			
10.4 ± 1.4 ± 0.8	ALBAJAR	89 UA1	$E_{cm}^{p\bar{p}} = 546,630$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
11.3 ± 1.3 ± 0.9	ANSARI	87 UA2	$E_{cm}^{p\bar{p}} = 546,630$ GeV

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

Test of CPT invariance.

<u>VALUE (GeV)</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
-0.19 ± 0.58	1722	ABE	90G CDF	$E_{cm}^{p\bar{p}} = 1.8$ TeV

W WIDTH

The CDF and $D\bar{O}$ widths labelled “extracted value” are obtained by measuring $R = [\sigma(W)/\sigma(Z)] [\Gamma(W \rightarrow \ell\nu_\ell)] / (B(Z \rightarrow \ell\ell)\Gamma(W))$ where the bracketed quantities can be calculated with plausible reliability. $\Gamma(W)$ is then extracted by using a value of $B(Z \rightarrow \ell\ell)$ measured at LEP. The UA1 and UA2 widths used $R = [\sigma(W)/\sigma(Z)] [\Gamma(W \rightarrow \ell\nu_\ell) / \Gamma(Z \rightarrow \ell\ell)] \Gamma(Z) / \Gamma(W)$ and the measured value of $\Gamma(Z)$. The Standard Model prediction is 2.0921 ± 0.0025 GeV (see Review on “Electroweak model and constraints on new physics” in this Edition).

To obtain OUR FIT, the correlation between systematics for the Direct Measurements is properly taken into account. The following notes may be consulted for details as well as the respective average values: for the LEP experiments the note LEPEWWG/MASS/2002-01 (http://lepewwg.web.cern.ch/LEPEWWG/lepww/mw/pdg_2002/) of 11 March 2002 and for the Tevatron experiments the note FERMILAB-FN-716 of 1 July 2002 (KOTWAL 02). The respective average values (2.17 ± 0.12 GeV from LEP and 2.115 ± 0.105 GeV from Tevatron) yield an average W width of 2.139 ± 0.079 GeV coming from direct measurements. Combined with the Extracted Values one obtains the quoted value.

<u>VALUE (GeV)</u>	<u>CL%</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
2.124±0.041 OUR FIT					
2.23 $^{+0.15}_{-0.14}$ ±0.10		294	²⁸ ABAZOV	02E D0	Direct meas.
2.04 ±0.16 ±0.09		2756	²⁹ ABBIENDI	01F OPAL	$E_{cm}^{ee} = 172+183$ +189 GeV
2.266±0.176±0.076		3005	³⁰ ABREU	01K DLPH	$E_{cm}^{ee} = 183+189$ GeV
2.152±0.066		79176	³¹ ABBOTT	00B D0	Extracted value
2.05 ±0.10 ±0.08		662	³² AFFOLDER	00M CDF	Direct meas.
2.24 ±0.20 ±0.13		1711	³³ BARATE	00T ALEP	$E_{cm}^{ee} = 189$ GeV
1.97 ±0.34 ±0.17		687	³⁴ ACCIARRI	99 L3	$E_{cm}^{ee} = 172+183$ GeV
2.064±0.060±0.059			³⁵ ABE	95W CDF	Extracted value
2.10 $^{+0.14}_{-0.13}$ ±0.09		3559	³⁶ ALITTI	92 UA2	Extracted value
2.18 $^{+0.26}_{-0.24}$ ±0.04			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 ABBI- ENDI 01F
2.044±0.097		11858	³⁹ ABBOTT	99H D0	Repl. by AB- BOTT 00B
2.48 ±0.40 ±0.10		737	⁴⁰ ABREU	99T DLPH	Repl. by ABREU 01K
2.126 $^{+0.052}_{-0.048}$ ±0.035			⁴¹ BARATE	99I ALEP	$E_{cm}^{ee} =$ 161+172+183 GeV
1.74 $^{+0.88}_{-0.78}$ ±0.25		101	⁴² ACCIARRI	97S L3	Repl. by ACCIA- RRI 99

2.11 ±0.28 ±0.16	58	43	ABE	95C	CDF	Repl. by AF-FOLDER 00M
2.30 ±0.19 ±0.06		44	ALITTI	90C	UA2	Extracted value
2.8 ^{+1.4} / _{-1.5} ±1.3	149	45	ALBAJAR	89	UA1	$E_{\text{cm}}^{p\bar{p}} = 546,630$ GeV
<7	90	119	APPEL	86	UA2	$E_{\text{cm}}^{p\bar{p}} = 546,630$ GeV
<6.5	90	86	46 ARNISON	86	UA1	$E_{\text{cm}}^{p\bar{p}} = 546,630$ GeV

²⁸ ABAZOV 02E obtain this result fitting the high-end tail (90–200 GeV) of the transverse-mass spectrum in semileptonic $W \rightarrow e\nu_e$ decays.

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 ABREU 01K obtain this value properly combining results obtained at 183 and 189 GeV using $WW \rightarrow \ell\bar{\nu}_\ell q\bar{q}$ and $WW \rightarrow q\bar{q}q\bar{q}$ decays. The systematic error includes an uncertainty of ± 0.052 GeV due to possible color reconnection and Bose-Einstein effects in the purely hadronic final state.

³¹ ABBOTT 00B measure $R = 10.43 \pm 0.27$ for the $W \rightarrow e\nu_e$ decay channel. They use the SM theoretical predictions for $\sigma(W)/\sigma(Z)$ and $\Gamma(W \rightarrow e\nu_e)$ and the world average for $B(Z \rightarrow ee)$. The value quoted here is obtained combining this result (2.169 ± 0.070 GeV) with that of ABBOTT 99H.

³² AFFOLDER 00M fit the high transverse mass (100–200 GeV) $W \rightarrow e\nu_e$ and $W \rightarrow \mu\nu_\mu$ 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.

³³ BARATE 00T obtain this value using $WW \rightarrow q\bar{q}q\bar{q}$, $WW \rightarrow e\nu_e q\bar{q}$, and $WW \rightarrow \mu\nu_\mu q\bar{q}$ decays. The systematic error includes ± 0.015 GeV due to LEP energy uncertainty and ± 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, $\sigma(W)/\sigma(Z) = 3.35 \pm 0.03$, $\Gamma(W \rightarrow e\nu) = 225.9 \pm 0.9$ MeV, $\Gamma(Z \rightarrow e^+e^-) = 83.98 \pm 0.18$ 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 ± 0.12 GeV due to the possible color-reconnection and Bose-Einstein effects in the purely hadronic final states and an uncertainty of ± 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 $\sigma(W)/\sigma(Z)$, $B(Z \rightarrow \ell\ell)$, and $\Gamma(W \rightarrow \ell\nu_\ell)$.

⁴⁰ ABREU 99T obtain this value using $WW \rightarrow \ell\bar{\nu}_\ell q\bar{q}$ and $WW \rightarrow q\bar{q}q\bar{q}$ events. The systematic error includes an uncertainty of ± 0.080 GeV due to possible color reconnection and Bose-Einstein effects in the purely hadronic final state.

- ⁴¹ BARATE 99I obtain this result with a fit to the $W W$ measured cross sections at 161, 172, and 183 GeV. The theoretical prediction takes into account the sensitivity to the W total width.
- ⁴² ACCIARRI 97S obtain this value from a fit to the reconstructed W mass distribution.
- ⁴³ ABE 95C use the tail of the transverse mass distribution of $W \rightarrow e \nu_e$ decays.
- ⁴⁴ 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. $E_{\text{cm}}^{p\bar{p}} = 546,630$ GeV.
- ⁴⁵ ALBAJAR 89 result is from a total sample of 299 $W \rightarrow e \nu$ events.
- ⁴⁶ 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 (Γ_i/Γ)	Confidence level
Γ_1 $\ell^+ \nu$	[a] $(10.68 \pm 0.12) \%$	
Γ_2 $e^+ \nu$	$(10.72 \pm 0.16) \%$	
Γ_3 $\mu^+ \nu$	$(10.57 \pm 0.22) \%$	
Γ_4 $\tau^+ \nu$	$(10.74 \pm 0.27) \%$	
Γ_5 hadrons	$(67.96 \pm 0.35) \%$	
Γ_6 $\pi^+ \gamma$	< 8	$\times 10^{-5}$ 95%
Γ_7 $D_s^+ \gamma$	< 1.3	$\times 10^{-3}$ 95%
Γ_8 cX	$(33.6 \pm 2.7) \%$	
Γ_9 $c\bar{s}$	$(31^{+13}_{-11}) \%$	
Γ_{10} invisible	[b] $(1.4 \pm 2.8) \%$	

[a] ℓ indicates each type of lepton (e , μ , and τ), 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

$\Gamma(\text{invisible})$

Γ_{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
$30^{+52}_{-48} \pm 33$	⁴⁷ BARATE	99I ALEP	$E_{\text{cm}}^{ee} = 161+172+183$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	⁴⁸ BARATE	99L ALEP	$E_{\text{cm}}^{ee} = 161+172+183$ GeV

- 47 BARATE 99I measure this quantity using the dependence of the total cross section σ_{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.
- 48 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, accessible at <http://lepewwg.web.cern.ch/LEPEWWG/lepww/4f/PDG01>). A first fit determines three individual leptonic branching ratios, $B(W \rightarrow e\nu_e)$, $B(W \rightarrow \mu\nu_\mu)$, and $B(W \rightarrow \tau\nu_\tau)$. 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 $B(W \rightarrow \ell\nu_\ell)$ and the hadronic branching ratio is derived as $B(W \rightarrow \text{hadrons}) = 1-3 B(W \rightarrow \ell\nu)$. This fit has a $\chi^2=11.4$ for 24 degrees of freedom.

The LEP $W \rightarrow \ell\nu$ data are obtained by the Collaborations using individual leptonic channels and are, therefore, not included in the overall fits to avoid double counting.

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

ℓ indicates average over e , μ , and τ modes, not sum over modes.

Γ_1/Γ

<u>VALUE</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
0.1068 ± 0.0012 OUR FIT				
0.1056 ± 0.0020 ± 0.0009	5778	ABBIENDI,G	00 OPAL	$E_{\text{cm}}^{ee} = 161+172+183+189$ GeV
0.1071 ± 0.0024 ± 0.0014	4843	ABREU	00K DLPH	$E_{\text{cm}}^{ee} = 161+172+183+189$ GeV
0.1060 ± 0.0023 ± 0.0011	5328	ACCIARRI	00V L3	$E_{\text{cm}}^{ee} = 161+172+183+189$ GeV
0.1101 ± 0.0022 ± 0.0011	5258	BARATE	00J ALEP	$E_{\text{cm}}^{ee} = 161+172+183+189$ GeV
0.1102 ± 0.0052	11858	49 ABBOTT	99H D0	$E_{\text{cm}}^{pp} = 1.8$ TeV
0.104 ± 0.008	3642	50 ABE	92I CDF	$E_{\text{cm}}^{pp} = 1.8$ 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

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

50 $1216 \pm 38^{+27}_{-31}$ $W \rightarrow \mu\nu$ 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.

$\Gamma(e^+ \nu)/\Gamma_{\text{total}}$					Γ_2/Γ
<u>VALUE</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>	
0.1072 ± 0.0016 OUR FIT					
0.1046 ± 0.0042 ± 0.0014	801	ABBIENDI,G	00 OPAL	$E_{\text{cm}}^{ee} = 161+172+183$ $+189$ GeV	
0.1044 ± 0.0015 ± 0.0028	67318	⁵¹ ABBOTT	00B D0	$E_{\text{cm}}^{pp} = 1.8$ TeV	
0.1018 ± 0.0054 ± 0.0026	527	ABREU	00K DLPH	$E_{\text{cm}}^{ee} = 161+172+183$ $+189$ GeV	
0.1077 ± 0.0045 ± 0.0016	715	ACCIARRI	00v L3	$E_{\text{cm}}^{ee} = 161+172+183$ $+189$ GeV	
0.1135 ± 0.0046 ± 0.0017	720	BARATE	00J ALEP	$E_{\text{cm}}^{ee} = 161+172+183$ $+189$ GeV	
0.1094 ± 0.0033 ± 0.0031		⁵² ABE	95W CDF	$E_{\text{cm}}^{pp} = 1.8$ TeV	
0.10 ± 0.014 ^{+0.02} _{-0.03}	248	⁵³ ANSARI	87C UA2	$E_{\text{cm}}^{pp} = 546,630$ 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 ABBI- ENDI,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 ACCIA- RRI 00v
seen	119	APPEL	86 UA2	$E_{\text{cm}}^{pp} = 546,630$ GeV
seen	172	ARNISON	86 UA1	$E_{\text{cm}}^{pp} = 546,630$ GeV

⁵¹ ABBOTT 00B measure $R \equiv [\sigma_W B(W \rightarrow e\nu_e)]/[\sigma_Z B(Z \rightarrow ee)] = 10.43 \pm 0.27$ for the $W \rightarrow e\nu_e$ decay channel. They use the SM theoretical prediction for $\sigma(W)/\sigma(Z)$ and the world average for $B(Z \rightarrow ee)$.

⁵² 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 $\Gamma(Z) = 2.4969 \pm 0.0038$ GeV.

⁵³ 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.

$\Gamma(\mu^+ \nu)/\Gamma_{\text{total}}$					Γ_3/Γ
<u>VALUE</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>	
0.1057 ± 0.0022 OUR FIT					
0.1050 ± 0.0041 ± 0.0012	803	ABBIENDI,G	00 OPAL	$E_{\text{cm}}^{ee} = 161+172+183$ $+189$ GeV	
0.1092 ± 0.0048 ± 0.0012	649	ABREU	00K DLPH	$E_{\text{cm}}^{ee} = 161+172+183$ $+189$ GeV	
0.0990 ± 0.0046 ± 0.0015	617	ACCIARRI	00v L3	$E_{\text{cm}}^{ee} = 161+172+183$ $+189$ GeV	
0.1110 ± 0.0044 ± 0.0016	710	BARATE	00J ALEP	$E_{\text{cm}}^{ee} = 161+172+183$ $+189$ GeV	
0.10 ± 0.01	1216	⁵⁴ ABE	92I CDF	$E_{\text{cm}}^{pp} = 1.8$ 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 ABBI- ENDI,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 ACCIA- RRI 00V

⁵⁴ ABE 92I quote the inverse quantity as 9.9 ± 1.2 which we have inverted.

$\Gamma(\tau^+ \nu) / \Gamma_{\text{total}}$ Γ_4 / Γ

<u>VALUE</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
0.1074 ± 0.0027 OUR FIT				
0.1075 ± 0.0052 ± 0.0021	794	ABBIENDI,G	00 OPAL	$E_{\text{cm}}^{ee} = 161+172+183$ +189 GeV
0.1105 ± 0.0075 ± 0.0032	579	ABREU	00K DLPH	$E_{\text{cm}}^{ee} = 161+172+183$ +189 GeV
0.1124 ± 0.0062 ± 0.0022	536	ACCIARRI	00V L3	$E_{\text{cm}}^{ee} = 161+172+183$ +189 GeV
0.1051 ± 0.0055 ± 0.0022	607	BARATE	00J ALEP	$E_{\text{cm}}^{ee} = 161+172+183$ +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 ABBI- ENDI,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 ACCIA- RRI 00V

$\Gamma(\text{hadrons}) / \Gamma_{\text{total}}$ Γ_5 / Γ

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

<u>VALUE</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
0.6796 ± 0.0035 OUR FIT				
0.679 ± 0.004 OUR AVERAGE				
0.6832 ± 0.0061 ± 0.0028	5778	ABBIENDI,G	00 OPAL	$E_{\text{cm}}^{ee} = 161+172+183$ +189 GeV
0.6789 ± 0.0073 ± 0.0043	4843	ABREU	00K DLPH	$E_{\text{cm}}^{ee} = 161+172+183$ +189 GeV
0.6820 ± 0.0068 ± 0.0033	5328	ACCIARRI	00V L3	$E_{\text{cm}}^{ee} = 161+172+183$ +189 GeV
0.6697 ± 0.0065 ± 0.0032	5258	BARATE	00J ALEP	$E_{\text{cm}}^{ee} = 161+172+183$ +189 GeV

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

0.679 ± 0.012 ± 0.005	1440	ABBIENDI	99D OPAL	Repl. by ABBI- ENDI,G 00
0.6746 ± 0.0143 ± 0.0052	1336	ABREU	99K DLPH	Repl. by ABREU 00K
0.6893 ± 0.0121 ± 0.0051	1322	BARATE	99I ALEP	Repl. by BARATE 00J
0.701 ± 0.013 ± 0.004	1434	ACCIARRI	98P L3	Repl. by ACCIA- RRI 00V

$\Gamma(\mu^+ \nu)/\Gamma(e^+ \nu)$ Γ_3/Γ_2

<u>VALUE</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
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0.986 ± 0.024 OUR FIT

0.89 ± 0.10	13k	⁵⁵ ABACHI	95D D0	$E_{cm}^{p\bar{p}} = 1.8$ TeV
1.02 ± 0.08	1216	⁵⁶ ABE	92I CDF	$E_{cm}^{p\bar{p}} = 1.8$ TeV
1.00 ± 0.14 ± 0.08	67	ALBAJAR	89 UA1	$E_{cm}^{p\bar{p}} = 546,630$ GeV

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

1.24 ^{+0.6} / _{-0.4}	14	ARNISON	84D UA1	Repl. by ALBAJAR 89
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⁵⁵ ABACHI 95D obtain this result from the measured $\sigma_W B(W \rightarrow \mu\nu) = 2.09 \pm 0.23 \pm 0.11$ nb and $\sigma_W B(W \rightarrow e\nu) = 2.36 \pm 0.07 \pm 0.13$ nb in which the first error is the combined statistical and systematic uncertainty, the second reflects the uncertainty in the luminosity.

⁵⁶ ABE 92I obtain $\sigma_W B(W \rightarrow \mu\nu) = 2.21 \pm 0.07 \pm 0.21$ 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.

$\Gamma(\tau^+ \nu)/\Gamma(e^+ \nu)$ Γ_4/Γ_2

<u>VALUE</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
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1.002 ± 0.029 OUR FIT

0.961 ± 0.061	980	⁵⁷ ABBOTT	00D D0	$E_{cm}^{p\bar{p}} = 1.8$ TeV
0.94 ± 0.14	179	⁵⁸ ABE	92E CDF	$E_{cm}^{p\bar{p}} = 1.8$ TeV
1.04 ± 0.08 ± 0.08	754	⁵⁹ ALITTI	92F UA2	$E_{cm}^{p\bar{p}} = 630$ GeV
1.02 ± 0.20 ± 0.12	32	ALBAJAR	89 UA1	$E_{cm}^{p\bar{p}} = 546,630$ 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

⁵⁷ ABBOTT 00D measure $\sigma_W \times B(W \rightarrow \tau\nu_\tau) = 2.22 \pm 0.09 \pm 0.10 \pm 0.10$ nb. Using the ABBOTT 00B result $\sigma_W \times B(W \rightarrow e\nu_e) = 2.31 \pm 0.01 \pm 0.05 \pm 0.10$ nb, they quote the ratio of the couplings from which we derive this measurement.

⁵⁸ ABE 92E use two procedures for selecting $W \rightarrow \tau\nu_\tau$ events. The missing E_τ trigger leads to $132 \pm 14 \pm 8$ events and the τ trigger to $47 \pm 9 \pm 4$ events. Proper statistical and systematic correlations are taken into account to arrive at $\sigma B(W \rightarrow \tau\nu) = 2.05 \pm 0.27$ 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.

⁵⁹ This measurement is derived by us from the ratio of the couplings of ALITTI 92F.

$\Gamma(\pi^+ \gamma)/\Gamma(e^+ \nu)$ Γ_6/Γ_2

<u>VALUE</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
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$< 7 \times 10^{-4}$	95	ABE	98H CDF	$E_{cm}^{p\bar{p}} = 1.8$ TeV
$< 4.9 \times 10^{-3}$	95	⁶⁰ ALITTI	92D UA2	$E_{cm}^{p\bar{p}} = 630$ GeV
$< 58 \times 10^{-3}$	95	⁶¹ ALBAJAR	90 UA1	$E_{cm}^{p\bar{p}} = 546, 630$ GeV

⁶⁰ ALITTI 92D limit is 3.8×10^{-3} at 90%CL.

⁶¹ ALBAJAR 90 obtain < 0.048 at 90%CL.

$\Gamma(D_s^+ \gamma)/\Gamma(e^+ \nu)$ Γ_7/Γ_2

<u>VALUE</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
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$< 1.2 \times 10^{-2}$	95	ABE	98P CDF	$E_{cm}^{p\bar{p}} = 1.8$ TeV
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$\Gamma(cX)/\Gamma(\text{hadrons})$				Γ_8/Γ_5	
<u>VALUE</u>	<u>EVT5</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>	
0.49 ± 0.04	OUR AVERAGE				
0.481 ± 0.042 ± 0.032	3005	⁶² ABBIENDI	00V OPAL	$E_{\text{cm}}^{ee} = 183 + 189 \text{ GeV}$	
0.51 ± 0.05 ± 0.03	746	⁶³ BARATE	99M ALEP	$E_{\text{cm}}^{ee} = 172 + 183 \text{ GeV}$	

⁶² 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 $B(W \rightarrow \text{hadrons})$, $|V_{cs}|$ is determined to be $0.969 \pm 0.045 \pm 0.036$.

⁶³ BARATE 99M tag c jets using a neural network algorithm. From this measurement $|V_{cs}|$ is determined to be $1.00 \pm 0.11 \pm 0.07$.

$R_{cs} = \Gamma(c\bar{s})/\Gamma(\text{hadrons})$				Γ_9/Γ_5	
<u>VALUE</u>		<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>	
0.46^{+0.18}_{-0.14} ± 0.07		⁶⁴ ABREU	98N DLPH	$E_{\text{cm}}^{ee} = 161+172 \text{ GeV}$	

⁶⁴ 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.

$\langle N_{\pi^\pm} \rangle$				
<u>VALUE</u>		<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
15.70 ± 0.35		⁶⁵ ABREU,P	00F DLPH	$E_{\text{cm}}^{ee} = 189 \text{ GeV}$

⁶⁵ ABREU,P 00F measure $\langle N_{\pi^\pm} \rangle = 31.65 \pm 0.48 \pm 0.76$ and $15.51 \pm 0.38 \pm 0.40$ in the fully hadronic and semileptonic final states respectively. The value quoted is a weighted average without assuming any correlations.

$\langle N_{K^\pm} \rangle$				
<u>VALUE</u>		<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
2.20 ± 0.19		⁶⁶ ABREU,P	00F DLPH	$E_{\text{cm}}^{ee} = 189 \text{ GeV}$

⁶⁶ ABREU,P 00F measure $\langle N_{K^\pm} \rangle = 4.38 \pm 0.42 \pm 0.12$ and $2.23 \pm 0.32 \pm 0.17$ in the fully hadronic and semileptonic final states respectively. The value quoted is a weighted average without assuming any correlations.

$\langle N_p \rangle$				
<u>VALUE</u>		<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
0.92 ± 0.14		⁶⁷ ABREU,P	00F DLPH	$E_{\text{cm}}^{ee} = 189 \text{ GeV}$

⁶⁷ ABREU,P 00F measure $\langle N_p \rangle = 1.82 \pm 0.29 \pm 0.16$ and $0.94 \pm 0.23 \pm 0.06$ in the fully hadronic and semileptonic final states respectively. The value quoted is a weighted average without assuming any correlations.

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

<u>VALUE</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
19.41 ± 0.15 OUR AVERAGE			
19.44 ± 0.17	⁶⁸ ABREU,P	00F DLPH	$E_{\text{cm}}^{ee} = 183+189$ GeV
19.3 ± 0.3 ± 0.3	⁶⁹ ABBIENDI	99N OPAL	$E_{\text{cm}}^{ee} = 183$ GeV
19.23 ± 0.74	⁷⁰ ABREU	98C DLPH	$E_{\text{cm}}^{ee} = 172$ GeV

⁶⁸ ABREU,P 00F measure $\langle N_{\text{charged}} \rangle = 39.12 \pm 0.33 \pm 0.36$ and $38.11 \pm 0.57 \pm 0.44$ in the fully hadronic final states at 189 and 183 GeV respectively, and $\langle N_{\text{charged}} \rangle = 19.49 \pm 0.31 \pm 0.27$ and $19.78 \pm 0.49 \pm 0.43$ in the semileptonic final states. The value quoted is a weighted average without assuming any correlations.

⁶⁹ ABBIENDI 99N use the final states $W^+ W^- \rightarrow q\bar{q}\ell\bar{\nu}_\ell$ to derive this value.

⁷⁰ ABREU 98C combine results from both the fully hadronic as well semileptonic $W W$ final states after demonstrating that the W decay charged multiplicity is independent of the topology within errors.

TRIPLE GAUGE COUPLINGS (TGC'S)

Revised February 2002 by C. Caso (University of Genova) and A. Gurtu (Tata Institute).

Fourteen independent couplings, 7 each for ZWW and γWW , 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 [1,2] is $(\Delta\kappa_\gamma, \Delta\kappa_Z, \lambda_\gamma, \lambda_Z, \Delta g_1^Z)$, where $\Delta\kappa_\gamma = \Delta\kappa_Z = \Delta g_1^Z = 0$ and $\lambda_\gamma = \lambda_Z = 0$ in the Standard Model at the tree level. The W magnetic dipole moment, μ_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. For LEP2 data, the LEP Collaborations have agreed to express their results in terms of the parameters Δg_1^Z , $\Delta\kappa_\gamma$ and λ_γ (λ_Z and $\Delta\kappa_Z$ are related to these by gauge invariance).

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 bremsstrahlung 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. G. Gounaris *et al.*, CERN 96-01 525.

Δg_1^Z

We do not average since the measurements are highly correlated and obtained with different assumptions. Because of the current interest, we mention here the following preliminary result but do not include it in the Listings or Tables. Combining published and unpublished preliminary LEP results (as of October 2002), a single-parameter fit yields $\Delta g_1^Z = -0.002^{+0.023}_{-0.025}$, where the other two parameters, $\Delta\kappa_\gamma$ and λ_γ , were kept fixed to their Standard Model values.

(see http://lepewwg.web.cern.ch/LEPEWWG/lepww/tgc/summer02/gc_main.ps)

<u>VALUE</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$-0.009^{+0.060}_{-0.057}$	3455	⁷¹ ABBIENDI	01M OPAL	$E_{\text{cm}}^{ee} = 161\text{--}189$ GeV
$-0.02 \pm 0.07 \pm 0.01$	2114	⁷² ABREU	01l DLPH	$E_{\text{cm}}^{ee} = 183\text{+}189$ GeV
$0.023^{+0.059}_{-0.055}$	3586	⁷³ HEISTER	01c ALEP	$E_{\text{cm}}^{ee} = 161\text{--}189$ GeV
	331	⁷⁴ ABBOTT	99i D0	$E_{\text{cm}}^{p\bar{p}} = 1.8$ TeV
$0.11^{+0.19}_{-0.18} \pm 0.10$	1154	⁷⁵ ACCIARRI	99Q L3	$E_{\text{cm}}^{ee} = 161\text{+}172\text{+} 183$ GeV

⁷¹ ABBIENDI 01M combine results from $W^+ W^-$ in all decay channels. The 95% confidence interval is $-0.12 < \Delta g_1^Z < 0.11$. When all three couplings Δg_1^Z , $\Delta\kappa_\gamma$, and λ_γ are floated freely in the fit, one obtains $\Delta g_1^Z = 0.120^{+0.077}_{-0.083}$.

⁷² ABREU 01l combine results from $e^+ e^-$ interactions at 189 GeV leading to $W^+ W^-$ and $W e \nu_e$ final states with results from ABREU 99l at 183 GeV. The 95% confidence interval is $-0.16 < \Delta g_1^Z < 0.13$.

⁷³ HEISTER 01c study W -pair, single- W , and single photon events and combine with earlier results from BARATE,R 98, BARATE 98Y, and BARATE 99l to obtain the quoted value, fixing $\Delta\kappa_\gamma$ and λ_γ to their Standard Model values. The 95% confidence interval is $-0.087 < \Delta g_1^Z < 0.141$. When all three couplings Δg_1^Z , $\Delta\kappa_\gamma$, and λ_γ are floated freely in the fit, one obtains $\Delta g_1^Z = 0.013^{+0.066}_{-0.068}$.

⁷⁴ 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.

⁷⁵ ACCIARRI 99Q study W -pair, single- W , and single photon events.

$\Delta\kappa_\gamma$

We do not average since the measurements are highly correlated and obtained with different assumptions. Because of the current interest, we mention here the following preliminary result but do not include it in the Listings or Tables. Combining published and unpublished preliminary LEP results (as of October 2002), a single-parameter fit yields $\Delta\kappa_\gamma = -0.057 \pm 0.055$, where the other two parameters, Δg_1^Z and λ_γ , were kept fixed to their Standard Model values.

(see http://lepewwg.web.cern.ch/LEPEWWG/lepww/tgc/summer02/gc_main.ps)

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
$0.116^{+0.082}_{-0.086} \pm 0.068$	315	⁷⁶ ACHARD	02I L3	$E_{cm}^{ee} = 161\text{--}209$ GeV
$-0.03^{+0.20}_{-0.16}$	3455	⁷⁷ ABBIENDI	01M OPAL	$E_{cm}^{ee} = 161\text{--}189$ GeV
$0.25^{+0.21}_{-0.20} \pm 0.06$	2298	⁷⁸ ABREU	01I DLPH	$E_{cm}^{ee} = 183\text{+}189$ GeV
$0.022^{+0.119}_{-0.115}$	3586	⁷⁹ HEISTER	01C ALEP	$E_{cm}^{ee} = 161\text{--}189$ GeV
		⁸⁰ BREITWEG	00 ZEUS	$e^+ p \rightarrow e^+ W^\pm X$, $\sqrt{s} \approx 300$ GeV
-0.08 ± 0.34	331	⁸¹ ABBOTT	99I D0	$E_{cm}^{pp} = 1.8$ TeV
$0.11 \pm 0.25 \pm 0.17$	1154	⁸² ACCIARRI	99Q L3	$E_{cm}^{ee} = 161\text{+}172\text{+}183$ GeV

⁷⁶ ACHARD 02I study single W production in e^+e^- interactions from 192 to 209 GeV. The result quoted here is obtained including data from 161 to 189 GeV, ACCIARRI 00N. The 95% C.L. limits are $-0.10 < \Delta\kappa_\gamma < 0.32$ (for $\lambda_\gamma = 0$). When both couplings λ_γ and κ_γ are floated freely in the fit one obtains $\Delta\kappa_\gamma = 0.07 \pm 0.10 \pm 0.07$.

⁷⁷ ABBIENDI 01M combine results from W^+W^- in all decay channels. The 95% confidence interval is $-0.32 < \Delta\kappa_\gamma < 0.45$. When all three couplings Δg_1^Z , $\Delta\kappa_\gamma$, and λ_γ are floated freely in the fit, one obtains $\Delta\kappa_\gamma = 0.02^{+0.20}_{-0.15}$.

⁷⁸ ABREU 01I combine results from e^+e^- interactions at 189 GeV leading to W^+W^- , $W e \nu_e$, and $\nu \bar{\nu} \gamma$ final states with results from ABREU 99L at 183 GeV. The 95% confidence interval is $-0.13 < \Delta\kappa_\gamma < 0.68$.

⁷⁹ HEISTER 01C study W -pair, single- W , and single photon events and combine with earlier results from BARATE,R 98, BARATE 98Y, and BARATE 99L to obtain the quoted value, fixing Δg_1^Z and λ_γ to their Standard Model values. The 95% confidence interval is $-0.200 < \Delta\kappa_\gamma < 0.258$. When all three couplings Δg_1^Z , $\Delta\kappa_\gamma$, and λ_γ are floated freely in the fit, one obtains $\Delta\kappa_\gamma = 0.043 \pm 0.110$.

⁸⁰ 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 $\lambda_\gamma = 0$).

⁸¹ 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 $-0.25 < \Delta\kappa_\gamma < 0.39$.

⁸² ACCIARRI 99Q study W -pair, single- W , and single photon events.

λ_γ

We do not average since the measurements are highly correlated and obtained with different assumptions. Because of the current interest, we mention here the following preliminary result but do not include it in the Listings or Tables. Combining published and unpublished preliminary LEP results (as of October 2002), a single-parameter fit yields $\lambda_\gamma = -0.020 \pm 0.024$, where the other two parameters, Δg_1^Z and $\Delta \kappa_\gamma$, were kept fixed to their Standard Model values.

(see http://lepewwg.web.cern.ch/LEPEWWG/lepww/tgc/summer02/gc_main.ps)

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
$0.35^{+0.10}_{-0.13} \pm 0.08$	315	83 ACHARD	02l L3	$E_{cm}^{ee} = 161\text{--}209$ GeV
$-0.110^{+0.058}_{-0.055}$	3455	84 ABBIENDI	01M OPAL	$E_{cm}^{ee} = 161\text{--}189$ GeV
$0.05 \pm 0.09 \pm 0.01$	2298	85 ABREU	01l DLPH	$E_{cm}^{ee} = 183\text{+}189$ GeV
$0.040^{+0.054}_{-0.052}$	3586	86 HEISTER	01C ALEP	$E_{cm}^{ee} = 161\text{--}189$ GeV
		87 BREITWEG	00 ZEUS	$e^+ p \rightarrow e^+ W^\pm X$, $\sqrt{s} \approx 300$ GeV
$0.00^{+0.10}_{-0.09}$	331	88 ABBOTT	99l D0	$E_{cm}^{pp} = 1.8$ TeV
$0.10^{+0.22}_{-0.20} \pm 0.10$	1154	89 ACCIARRI	99Q L3	$E_{cm}^{ee} = 161\text{+}172\text{+}183$ GeV

⁸³ ACHARD 02l study single W production in e^+e^- interactions from 192 to 209 GeV. The result quoted here is obtained including data from 161 to 189 GeV, ACCIARRI 00N. The 95% C.L. limits are $-0.37 < \lambda_\gamma < 0.61$ (for $\kappa_\gamma=1$). When both couplings λ_γ and κ_γ are floated freely in the fit one obtains $\lambda_\gamma = 0.31^{+0.12}_{-0.20} \pm 0.07$.

⁸⁴ ABBIENDI 01M combine results from W^+W^- in all decay channels. The 95% confidence interval is $-0.22 < \lambda_\gamma < 0.01$. When all three couplings Δg_1^Z , $\Delta \kappa_\gamma$, and λ_γ are floated freely in the fit, one obtains $\lambda_\gamma = -0.190^{+0.087}_{-0.082}$.

⁸⁵ ABREU 01l combine results from e^+e^- interactions at 189 GeV leading to W^+W^- , $W e \nu_e$, and $\nu \bar{\nu} \gamma$ final states with results from ABREU 99L at 183 GeV. The 95% confidence interval is $-0.11 < \lambda_\gamma < 0.23$.

⁸⁶ HEISTER 01C study W -pair, single- W , and single photon events and combine with earlier results from BARATE,R 98, BARATE 98Y, and BARATE 99L to obtain the quoted value, fixing Δg_1^Z and $\Delta \kappa_\gamma$ to their Standard Model values. The 95% confidence interval is $-0.062 < \lambda_\gamma < 0.147$. When all three couplings Δg_1^Z , $\Delta \kappa_\gamma$, and λ_γ are floated freely in the fit, one obtains $\lambda_\gamma = 0.023^{+0.074}_{-0.077}$.

⁸⁷ 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 $\Delta \kappa_\gamma=0$).

⁸⁸ ABBOTT 99l 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 $-0.18 < \lambda_\gamma < 0.19$.

⁸⁹ ACCIARRI 99Q study W -pair, single- W , and single photon events.

Δg_5^Z

This coupling is *CP*-conserving but *C*- and *P*-violating.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$-0.44^{+0.23}_{-0.22} \pm 0.12$	1154	⁹⁰ ACCIARRI	99Q L3	$E_{cm}^{ee} = 161+172+183$ GeV

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

-0.16 ± 0.23 ⁹¹ EBOLI 00 THEO LEP1, SLC+ Tevatron

⁹⁰ ACCIARRI 99Q study *W*-pair, single-*W*, and single photon events.

⁹¹ EBOLI 00 extract this indirect value of the coupling studying the non-universal one-loop contributions to the experimental value of the $Z \rightarrow b\bar{b}$ width ($\Lambda=1$ TeV is assumed).

g_4^Z

This coupling is *CP*-violating (*C*-violating and *P*-conserving).

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$-0.02^{+0.32}_{-0.33}$	1065	⁹² ABBIENDI	01H OPAL	$E_{cm}^{ee} = 189$ GeV

⁹² ABBIENDI 01H study *W*-pair events, with one leptonically and one hadronically decaying *W*. The coupling is extracted using information from the *W* production angle together with decay angles from the leptonically decaying *W*.

$\tilde{\kappa}_Z$

This coupling is *CP*-violating (*C*-conserving and *P*-violating).

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$-0.20^{+0.10}_{-0.07}$	1065	⁹³ ABBIENDI	01H OPAL	$E_{cm}^{ee} = 189$ GeV

⁹³ ABBIENDI 01H study *W*-pair events, with one leptonically and one hadronically decaying *W*. The coupling is extracted using information from the *W* production angle together with decay angles from the leptonically decaying *W*.

$\tilde{\lambda}_Z$

This coupling is *CP*-violating (*C*-conserving and *P*-violating).

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$-0.18^{+0.24}_{-0.16}$	1065	⁹⁴ ABBIENDI	01H OPAL	$E_{cm}^{ee} = 189$ GeV

⁹⁴ ABBIENDI 01H study *W*-pair events, with one leptonically and one hadronically decaying *W*. The coupling is extracted using information from the *W* production angle together with decay angles from the leptonically decaying *W*.

W ANOMALOUS MAGNETIC MOMENT

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 Λ appearing in the theoretical limits below is a regularization cutoff which roughly corresponds to the energy scale where the structure of the *W* boson becomes manifest.

VALUE ($e/2m_W$)	EVTS	DOCUMENT ID	TECN	COMMENT
$2.22^{+0.20}_{-0.19}$	2298	⁹⁵ ABREU	01l DLPH	$E_{cm}^{ee} = 183+189$ GeV

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

96	ABE	95G	CDF
97	ALITTI	92C	UA2
98	SAMUEL	92	THEO
99	SAMUEL	91	THEO
100	GRIFOLS	88	THEO
101	GROTCH	87	THEO
102	VANDERBIJ	87	THEO
103	GRAU	85	THEO
104	SUZUKI	85	THEO
105	HERZOG	84	THEO

- ⁹⁵ ABREU 01l combine results from e^+e^- interactions at 189 GeV leading to W^+W^- , $W e \nu_e$, and $\nu \bar{\nu} \gamma$ final states with results from ABREU 99L at 183 GeV to determine Δg_1^Z , $\Delta \kappa_\gamma$, and λ_γ . $\Delta \kappa_\gamma$ and λ_γ are simultaneously floated in the fit to determine μ_W .
- ⁹⁶ ABE 95G report $-1.3 < \kappa < 3.2$ for $\lambda=0$ and $-0.7 < \lambda < 0.7$ for $\kappa=1$ in $p\bar{p} \rightarrow e\nu_e\gamma X$ and $\mu\nu_\mu\gamma X$ at $\sqrt{s} = 1.8$ TeV.
- ⁹⁷ ALITTI 92C measure $\kappa = 1_{-2.2}^{+2.6}$ and $\lambda = 0_{-1.8}^{+1.7}$ in $p\bar{p} \rightarrow e\nu\gamma + X$ at $\sqrt{s} = 630$ GeV. At 95%CL they report $-3.5 < \kappa < 5.9$ and $-3.6 < \lambda < 3.5$.
- ⁹⁸ 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.
- ⁹⁹ SAMUEL 91 use preliminary CDF data for $p\bar{p} \rightarrow W\gamma X$ to obtain $-11.3 \leq \Delta\kappa \leq 10.9$. Note that their $\kappa = 1 - \Delta\kappa$.
- ¹⁰⁰ GRIFOLS 88 uses deviation from ρ parameter to set limit $\Delta\kappa \lesssim 65 (M_W^2/\Lambda^2)$.
- ¹⁰¹ GROTCH 87 finds the limit $-37 < \Delta\kappa < 73.5$ (90% CL) from the experimental limits on $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ assuming three neutrino generations and $-19.5 < \Delta\kappa < 56$ for four generations. Note their $\Delta\kappa$ has the opposite sign as our definition.
- ¹⁰² VANDERBIJ 87 uses existing limits to the photon structure to obtain $|\Delta\kappa| < 33 (m_W/\Lambda)$. In addition VANDERBIJ 87 discusses problems with using the ρ parameter of the Standard Model to determine $\Delta\kappa$.
- ¹⁰³ GRAU 85 uses the muon anomaly to derive a coupled limit on the anomalous magnetic dipole and electric quadrupole (λ) moments $1.05 > \Delta\kappa \ln(\Lambda/m_W) + \lambda/2 > -2.77$. In the Standard Model $\lambda = 0$.
- ¹⁰⁴ SUZUKI 85 uses partial-wave unitarity at high energies to obtain $|\Delta\kappa| \lesssim 190 (m_W/\Lambda)^2$. From the anomalous magnetic moment of the muon, SUZUKI 85 obtains $|\Delta\kappa| \lesssim 2.2/\ln(\Lambda/m_W)$. Finally SUZUKI 85 uses deviations from the ρ parameter and obtains a very qualitative, order-of-magnitude limit $|\Delta\kappa| \lesssim 150 (m_W/\Lambda)^4$ if $|\Delta\kappa| \ll 1$.
- ¹⁰⁵ 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

Revised February 2002 by C. Caso (University of Genova) and A. Gurtu (Tata Institute).

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];

$$\begin{aligned} L_6^0 &= -\frac{e^2}{16\Lambda^2} a_0 F^{\mu\nu} F_{\mu\nu} \vec{W}^\alpha \cdot \vec{W}_\alpha \\ L_6^c &= -\frac{e^2}{16\Lambda^2} a_c F^{\mu\alpha} F_{\mu\beta} \vec{W}^\beta \cdot \vec{W}_\alpha \\ L_6^n &= -i\frac{e^2}{16\Lambda^2} a_n \epsilon_{ijk} W_{\mu\alpha}^{(i)} W_\nu^{(j)} W^{(k)\alpha} F^{\mu\nu} \end{aligned}$$

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 Λ is a scale for new physics. For the $ZZ\gamma\gamma$ coupling the CP -violating term represented by L_6^n does not contribute. These couplings are assumed to be real and to vanish at tree level in the Standard Model.

Within the same framework as above, a more recent description of the quartic couplings [3] treats the anomalous parts of the $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings separately leading to two sets parameterized as a_0^V/Λ^2 and a_c^V/Λ^2 , where $V = W$ or Z .

At LEP the processes studied in search of these quartic couplings are $e^+e^- \rightarrow WW\gamma$, $e^+e^- \rightarrow \gamma\gamma\nu\bar{\nu}$, and $e^+e^- \rightarrow Z\gamma\gamma$ and limits are set on the quantities $a_0^W/\Lambda^2, a_c^W/\Lambda^2, a_n/\Lambda^2$. The characteristics of the first process depend on all the three couplings whereas those of the latter two depend only on the two CP -conserving couplings. 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.

Different Monte Carlo descriptions of these couplings, *e.g.*, Ref. 2 and Ref. 4, do not agree, in particular for the $Z\gamma\gamma$ final state. Therefore, for the purpose of combining LEP results, only the measurements on $WW\gamma$ and $\gamma\gamma\nu\bar{\nu}$ final states are used and the 95% CL limits [5] are:

$$\begin{aligned}
 -0.018 < a_0^W/\Lambda^2 < 0.018, \\
 -0.033 < a_c^W/\Lambda^2 < 0.047, \\
 -0.17 < a_n/\Lambda^2 < 0.15.
 \end{aligned}$$

References

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2. J.W. Stirling and A. Werthenbach, Eur. Phys. J. **C14**, 103 (2000);
J.W. Stirling and A. Werthenbach, Phys. Lett. **B466**, 369 (1999).
3. G. Belanger *et al.*, Eur. Phys. J. **C13**, 103 (2000).
4. G. Montagna *et al.*, Phys. Lett. **B515**, 197 (2001).
5. The LEP Collaborations: ALEPH, DELPHI, L3, OPAL, the LEP Electroweak Working Group, and the SLD Heavy Flavour Group: CERN-EP/2001-098 (2001).

a_0/Λ^2 , a_c/Λ^2 , a_n/Λ^2

VALUE	DOCUMENT ID	TECN
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• • • We do not use the following data for averages, fits, limits, etc. • • •

106	ACHARD	02F L3
107	ABBIENDI	99U OPAL

¹⁰⁶ ACHARD 02F select 86 $e^+e^- \rightarrow W^+W^-\gamma$ events at 192–207 GeV, where $E_\gamma > 5$ GeV and the photon is well isolated. They also select 43 acoplanar $e^+e^- \rightarrow \nu\bar{\nu}\gamma\gamma$ events in this energy range, where the photon energies are >5 GeV and >1 GeV and the photon polar angles are between 14° and 166° . All these 43 events are in the recoil mass region corresponding to the Z (75–110 GeV). Using the shape and normalization of the photon spectra in the $W^+W^-\gamma$ events, and combining with the 42 event sample from 189 GeV data (ACCIARRI 00T), they obtain: $a_0/\Lambda^2 = 0.000 \pm 0.010$ GeV⁻², $a_c/\Lambda^2 = -0.013 \pm 0.023$ GeV⁻², and $a_n/\Lambda^2 = -0.002 \pm 0.076$ GeV⁻². Further combining the analyses of $W^+W^-\gamma$ events with the low recoil mass region of $\nu\bar{\nu}\gamma\gamma$ events (including samples collected at 183 + 189 GeV), they obtain the following one-parameter 95% CL limits: -0.015 GeV⁻² $< a_0/\Lambda^2 < 0.015$ GeV⁻², -0.048 GeV⁻² $< a_c/\Lambda^2 < 0.026$ GeV⁻², and -0.14 GeV⁻² $< a_n/\Lambda^2 < 0.13$ GeV⁻².

¹⁰⁷ 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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ACHARD	02F	PL B527 29	P. Achard <i>et al.</i>	(L3 Collab.)
ACHARD	02I	PL B547 151	P. Achard <i>et al.</i>	(L3 Collab.)
CHEKANOV	02C	PL B539 197	S. Chekanov <i>et al.</i>	(ZEUS Collab.)
KOTWAL	02	FERMILAB-FN-0716	A. Kotwal <i>et al.</i>	
ABBIENDI	01F	PL B507 29	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	01H	EPJ C19 229	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	01M	EPJ C19 1	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABREU	01I	PL B502 9	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ABREU	01K	PL B511 159	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ADLOFF	01A	EPJ C19 269	C. Adloff <i>et al.</i>	(H1 Collab.)
AFFOLDER	01E	PR D64 052001	T. Affolder <i>et al.</i>	(CDF Collab.)
HEISTER	01C	EPJ C21 423	A. Heister <i>et al.</i>	(ALEPH Collab.)
ABBIENDI	00V	PL B490 71	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI,G	00	PL B493 249	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBOTT	00	PRL 84 222	B. Abbott <i>et al.</i>	(D0 Collab.)
ABBOTT	00B	PR D61 072001	B. Abbott <i>et al.</i>	(D0 Collab.)
ABBOTT	00D	PRL 84 5710	B. Abbott <i>et al.</i>	(D0 Collab.)
ABREU	00K	PL B479 89	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ABREU,P	00F	EPJ C18 203	P. Abreu <i>et al.</i>	(DELPHI Collab.)
Also	02	EPJ C25 493 (erratum)	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ACCIARRI	00N	PL B487 229	M. Acciarri <i>et al.</i>	(L3 Collab.)
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AFFOLDER	00M	PRL 85 3347	T. Affolder <i>et al.</i>	(CDF Collab.)
BARATE	00J	PL B484 205	R. Barate <i>et al.</i>	(ALEPH Collab.)
BARATE	00T	EPJ C17 241	R. Barate <i>et al.</i>	(ALEPH Collab.)
BREITWEG	00	PL B471 411	J. Breitweg <i>et al.</i>	(ZEUS Collab.)
BREITWEG	00D	EPJ C12 411	J. Breitweg <i>et al.</i>	(ZEUS Collab.)
EBOLI	00	MPL A15 1	O. Eboli, M. Gonzalez-Garcia, S. Novaes	
ABBIENDI	99C	PL B453 138	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	99D	EPJ C8 191	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	99N	PL B453 153	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	99U	PL B471 293	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBOTT	99H	PR D60 052003	B. Abbott <i>et al.</i>	(D0 Collab.)
ABBOTT	99I	PR D60 072002	B. Abbott <i>et al.</i>	(D0 Collab.)
ABREU	99K	PL B456 310	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ABREU	99L	PL B459 382	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ABREU	99T	PL B462 410	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ACCIARRI	99	PL B454 386	M. Acciarri <i>et al.</i>	(L3 Collab.)
ACCIARRI	99Q	PL B467 171	M. Acciarri <i>et al.</i>	(L3 Collab.)
BARATE	99	PL B453 121	R. Barate <i>et al.</i>	(ALEPH Collab.)
BARATE	99I	PL B453 107	R. Barate <i>et al.</i>	(ALEPH Collab.)
BARATE	99L	PL B462 389	R. Barate <i>et al.</i>	(ALEPH Collab.)
BARATE	99M	PL B465 349	R. Barate <i>et al.</i>	(ALEPH Collab.)
ABBOTT	98N	PR D58 092003	B. Abbott <i>et al.</i>	(D0 Collab.)
ABBOTT	98P	PR D58 012002	B. Abbott <i>et al.</i>	(D0 Collab.)
ABE	98H	PR D58 031101	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	98P	PR D58 091101	F. Abe <i>et al.</i>	(CDF Collab.)
ABREU	98C	PL B416 233	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ABREU	98N	PL B439 209	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ACCIARRI	98P	PL B436 437	M. Acciarri <i>et al.</i>	(L3 Collab.)
BARATE	98Y	PL B422 369	R. Barate <i>et al.</i>	(ALEPH Collab.)
BARATE,R	98	PL B445 239	R. Barate <i>et al.</i>	(ALEPH Collab.)
ACCIARRI	97	PL B398 223	M. Acciarri <i>et al.</i>	(L3 Collab.)
ACCIARRI	97M	PL B407 419	M. Acciarri <i>et al.</i>	(L3 Collab.)
ACCIARRI	97S	PL B413 176	M. Acciarri <i>et al.</i>	(L3 Collab.)
ABACHI	95D	PRL 75 1456	S. Abachi <i>et al.</i>	(D0 Collab.)
ABE	95C	PRL 74 341	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	95G	PRL 74 1936	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	95P	PRL 75 11	F. Abe <i>et al.</i>	(CDF Collab.)
Also	95Q	PR D52 4784	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	95W	PR D52 2624	F. Abe <i>et al.</i>	(CDF Collab.)
Also	94B	PRL 73 220	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	92E	PRL 68 3398	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	92I	PRL 69 28	F. Abe <i>et al.</i>	(CDF Collab.)
ALITTI	92	PL B276 365	J. Alitti <i>et al.</i>	(UA2 Collab.)

ALITTI	92B	PL B276 354	J. Alitti <i>et al.</i>	(UA2 Collab.)
ALITTI	92C	PL B277 194	J. Alitti <i>et al.</i>	(UA2 Collab.)
ALITTI	92D	PL B277 203	J. Alitti <i>et al.</i>	(UA2 Collab.)
ALITTI	92F	PL B280 137	J. Alitti <i>et al.</i>	(UA2 Collab.)
SAMUEL	92	PL B280 124	M.A. Samuel <i>et al.</i>	(OKSU, CARL)
ABE	91C	PR D44 29	F. Abe <i>et al.</i>	(CDF Collab.)
ALBAJAR	91	PL B253 503	C. Albajar <i>et al.</i>	(UA1 Collab.)
ALITTI	91C	ZPHY C52 209	J. Alitti <i>et al.</i>	(UA2 Collab.)
SAMUEL	91	PRL 67 9	M.A. Samuel <i>et al.</i>	(OKSU, CARL)
Also	91C	PRL 67 2920 erratum	M.A. Samuel <i>et al.</i>	
ABE	90	PRL 64 152	F. Abe <i>et al.</i>	(CDF Collab.)
Also	91C	PR D44 29	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	90G	PRL 65 2243	F. Abe <i>et al.</i>	(CDF Collab.)
Also	91B	PR D43 2070	F. Abe <i>et al.</i>	(CDF Collab.)
ALBAJAR	90	PL B241 283	C. Albajar <i>et al.</i>	(UA1 Collab.)
ALITTI	90B	PL B241 150	J. Alitti <i>et al.</i>	(UA2 Collab.)
ALITTI	90C	ZPHY C47 11	J. Alitti <i>et al.</i>	(UA2 Collab.)
ABE	89I	PRL 62 1005	F. Abe <i>et al.</i>	(CDF Collab.)
ALBAJAR	89	ZPHY C44 15	C. Albajar <i>et al.</i>	(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 <i>et al.</i>	(UA1 Collab.)
ANSARI	87	PL B186 440	R. Ansari <i>et al.</i>	(UA2 Collab.)
ANSARI	87C	PL B194 158	R. Ansari <i>et al.</i>	(UA2 Collab.)
GROTCH	87	PR D36 2153	H. Grotch, R.W. Robinett	(PSU)
HAGIWARA	87	NP B282 253	K. Hagiwara <i>et al.</i>	(KEK, UCLA, FSU)
VANDEBBIJ	87	PR D35 1088	J.J. van der Bij	(FNAL)
APPEL	86	ZPHY C30 1	J.A. Appel <i>et al.</i>	(UA2 Collab.)
ARNISON	86	PL 166B 484	G.T.J. Arnison <i>et al.</i>	(UA1 Collab.)
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 <i>et al.</i>	(UA1 Collab.)
HERZOG	84	PL 148B 355	F. Herzog	(WISC)
Also	84B	PL 155B 468 erratum	F. Herzog	(WISC)
ARNISON	83	PL 122B 103	G.T.J. Arnison <i>et al.</i>	(UA1 Collab.)
BANNER	83B	PL 122B 476	M. Banner <i>et al.</i>	(UA2 Collab.)