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.

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

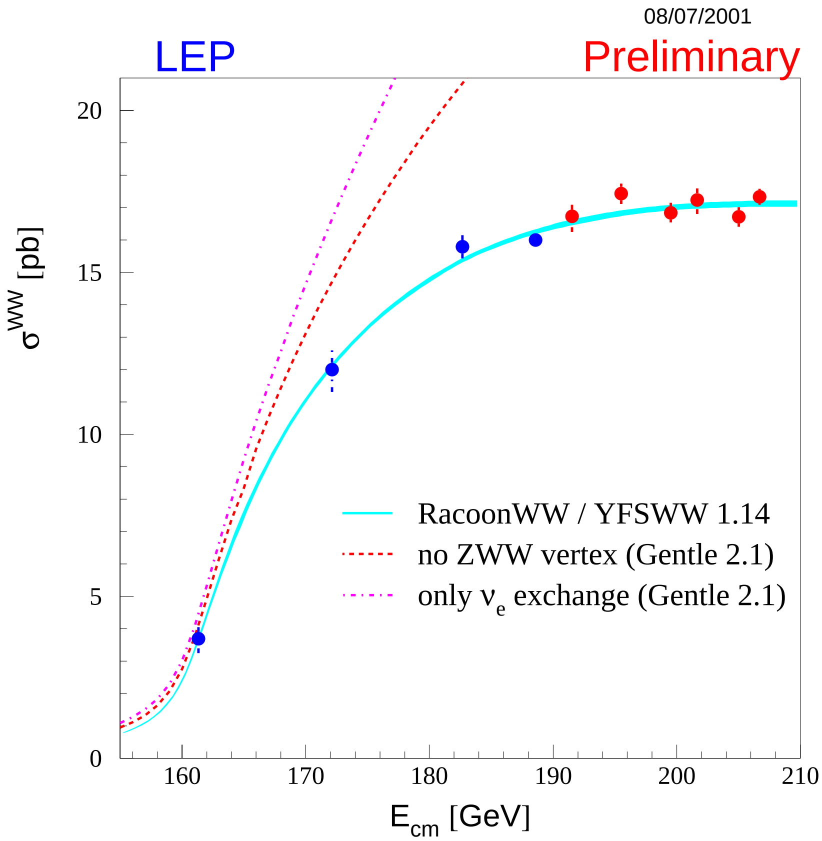

Figure 1: The W–pair cross section as a function of the center–of–mass energy. The data points are the LEP averages. The solid lines are predictions from different models of WW production. For comparison the figure contains also the cross section if the ZWW coupling did not exist (dashed line), or if only the t–channel ν_e exchange diagram existed (dotted-dashed line). (Figure from `http://lepewwg.web.cern.ch/LEPEWWG/lepww/4f/summer01/s01_sww_no_tgc.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 = 80.450±0.039 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 $+9 \pm 44$ MeV.

The two Tevatron experiments have also carried out the exercise of identifying common systematic errors (25 MeV) and averaging with CERN UA2 data obtain an average W mass [2]= 80.454±0.060 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 80.451 ± 0.033 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 80.448 ± 0.031 GeV.

The Standard Model prediction from the electroweak fit, excluding the direct W mass measurements from LEP and Tevatron, gives a W–boson mass of 80.373 ± 0.023 GeV [3].

OUR FIT 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, and the LEP W Working Group, LEPEWWG/MASS/2001-02, July 11, 2001, accessible at `http://lepewwg.web.cern.ch/LEPEWWG/lepww/mw/Summer01/`).

2. D. Charlton, "Experimental Tests of the Standard Model," Int. Europhysics Conference on High Energy Physics, July 12–18, 2001 (Budapest, Hungary).
3. The LEP Collaborations: ALEPH, DELPHI, L3, OPAL, the LEP Electroweak Working Group, and the SLD Heavy Flavour and Electroweak Groups, CERN-EP-2001-098, hep-ex/0112021 (December 2001).

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. In order to average the Tevatron data a common systematic error of 25 MeV is taken which leads to a Tevatron average *W* mass value of 80.454 ± 0.062 GeV.

OUR FIT uses these average LEP and Tevatron *W* mass values together with the *Z* mass, the *W* to *Z* mass ratio, and mass difference measurements.

VALUE (GeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
80.423± 0.039 OUR FIT					
80.432± 0.066±0.045	2789	[1] ABBIENDI	01F	OPAL	E^{ee}_{cm}= 161+172+183 +189 GeV
80.359± 0.074±0.049	3077	[2] ABREU	01K	DLPH	E^{ee}_{cm}= 161+172+183 +189 GeV
80.433± 0.079	53841	[3] AFFOLDER	01E	CDF	$E^{p\overline{p}}_{cm}$= 1.8 TeV
80.482± 0.091	45394	[4] ABBOTT	00	D0	$E^{p\overline{p}}_{cm}$= 1.8 TeV
80.418± 0.061±0.047	2977	[5] BARATE	00T	ALEP	E^{ee}_{cm}= 161+172+183 +189 GeV
80.61 ± 0.15	801	[6] ACCIARRI	99	L3	E^{ee}_{cm}= 161+172+ 183 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
79.9 ± 2.2 ±2.3	700	[7] ADLOFF	01A	H1	$e^- p \to \nu_e X$, $\sqrt{s} \approx$ 320 GeV
80.9 ± 3.7 ±3.7	700	[8] 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	[9] BREITWEG	00D	ZEUS	$e^+ p \to \overline{\nu}_e X$, $\sqrt{s} \approx$ 300 GeV
80.38 ± 0.12 ±0.05	701	[10] ABBIENDI	99C	OPAL	Repl. by ABBIENDI 01F
80.270± 0.137±0.048	809	[11] ABREU	99T	DLPH	Repl. by ABREU 01K
80.423± 0.112±0.054	812	[12] BARATE	99	ALEP	Repl. by BARATE 00T
80.44 ± 0.10 ±0.07	28323	[13] ABBOTT	98O	D0	Repl. by ABBOTT 00
$80.80 ^{+0.48}_{-0.42} \pm 0.03$	20	[14] ACCIARRI	97	L3	Repl. by ACCIARRI 99
$80.5 ^{+1.4}_{-2.4} \pm 0.3$	94	[15] ACCIARRI	97M	L3	Repl. by ACCIARRI 99
$80.71 ^{+0.34}_{-0.35} \pm 0.09$	101	[16] ACCIARRI	97S	L3	Repl. by ACCIARRI 99

80.35	± 0.14	±0.23	5982	[17] ABACHI	96E	D0	Repl. by ABBOTT 00
80.41	± 0.18		8986	[18] ABE	95P	CDF	Repl. by AFFOLDER 01E
80.84	± 0.22	±0.83	2065	[19] ALITTI	92B	UA2	See W/Z ratio below
80.79	± 0.31	±0.84		[20] ALITTI	90B	UA2	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
80.0	± 3.3	±2.4	22	[21] ABE	89I	CDF	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV
82.7	± 1.0	±2.7	149	[22] ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
81.8	$^{+6.0}_{-5.3}$	±2.6	46	[23] ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
89	± 3	±6	32	[24] ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
81.	± 5.		6	ARNISON	83	UA1	$E^{ee}_{\rm cm}$= 546 GeV
80.	$^{+10.}_{-6.}$		4	BANNER	83B	UA2	Repl. by ALITTI 90B

[1] 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 ±0.017 GeV due to LEP energy uncertainty and ±0.028 GeV due to possible color reconnection and Bose-Einstein effects in the purely hadronic final state.

[2] 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 ±0.017 GeV due to the beam energy uncertainty and ±0.033 GeV due to possible color reconnection and Bose-Einstein effects in the purely hadronic final state.

[3] AFFOLDER 01E fit the transverse mass spectrum of 30115 $W \rightarrow e\nu_e$ events (M_W= $80.473 \pm 0.065 \pm 0.092$ GeV) and of 14740 $W \rightarrow \mu\nu_\mu$ events (M_W= $80.465 \pm 0.100 \pm 0.103$ GeV) obtained in the run IB (1994-95). Combining the electron and muon results, accounting for correlated uncertainties, yields M_W= 80.470 ± 0.089 GeV. They combine this value with their measurement of ABE 95P reported in run IA (1992-93) to obtain the quoted value.

[4] 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 $p_T(\nu)$.

[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 ± 0.14 ± 0.08 GeV.

[7] 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.

[8] 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.

[9] 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.

[10] 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.

[11] 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.

[12] 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.

[13] 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.

[14] 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 σ_{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.

[15] 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 σ_{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.

[16] 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.

[17] 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.

[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 ($\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.

[20] 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.

[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.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.88196±0.00043 OUR FIT					
0.8821 ±0.0011 ±0.0008	28323	[25] ABBOTT	98N	D0	$E_{cm}^{p\overline{p}}$= 1.8 TeV
0.88114±0.00154±0.00252	5982	[26] ABBOTT	98P	D0	$E_{cm}^{p\overline{p}}$= 1.8 TeV
0.8813 ±0.0036 ±0.0019	156	[27] ALITTI	92B	UA2	$E_{cm}^{p\overline{p}}$= 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.

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.764±0.039 OUR FIT				
10.4 ±1.4 ±0.8	ALBAJAR	89	UA1	$E_{cm}^{p\overline{p}}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
11.3 ±1.3 ±0.9	ANSARI	87	UA2	$E_{cm}^{p\overline{p}}$= 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	$E_{cm}^{p\overline{p}}$= 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 ± 0.021 (ROSNER 94).

To obtain OUR FIT,the correlation between systematics is properly taken into account for the LEP experiments (note LEPEWWG/MASS/2002-01 dated March 11, 2002, accessible at http://lepewwg.web.cern.ch/LEPEWWG/lepww/mw/pdg_2002/).

VALUE (GeV)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.118±0.042 OUR FIT						
2.12 ±0.04 OUR AVERAGE						
2.04 ±0.16 ±0.09		2756	[28] ABBIENDI	01F	OPAL	E^{ee}_{cm}= 172+183 +189 GeV
2.266±0.176±0.076		3005	[29] ABREU	01K	DLPH	E^{ee}_{cm}= 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
1.97 ±0.34 ±0.17		687	[33] ACCIARRI	99	L3	E^{ee}_{cm}= 172+183 GeV
2.064±0.060±0.059			[34] ABE	95W	CDF	Extracted value
2.10 $^{+0.14}_{-0.13}$ ±0.09		3559	[35] ALITTI	92	UA2	Extracted value
2.18 $^{+0.26}_{-0.24}$ ±0.04			[36] ALBAJAR	91	UA1	Extracted value
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.84 ±0.32 ±0.20		674	[37] ABBIENDI	99C	OPAL	Repl. by ABBIENDI 01F
2.044±0.097		11858	[38] ABBOTT	99H	D0	Repl. by ABBOTT 00B
2.48 ±0.40 ±0.10		737	[39] ABREU	99T	DLPH	Repl. by ABREU 01K
2.126$^{+0.052}_{-0.048}$±0.035			[40] BARATE	99I	ALEP	E^{ee}_{cm}= 161+172+183 GeV
1.74 $^{+0.88}_{-0.78}$ ±0.25		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 $^{+1.4}_{-1.5}$ ±1.3		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

[28] 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.

[29] ABREU 01K obtain this value properly combining results obtained at 183 and 189 GeV using $WW \rightarrow \ell\overline{\nu}_\ell q\overline{q}$ and $WW \rightarrow q\overline{q}q\overline{q}$ 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.

[30] 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.

[31] 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.

[32] BARATE 00T obtain this value using $WW \rightarrow q\overline{q}q\overline{q}$, $WW \rightarrow e\nu_e q\overline{q}$, and $WW \rightarrow \mu\nu_\mu q\overline{q}$ 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.

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

[34] 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.

[35] 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.

[36] 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.

[37] 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.

[38] 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 $\Gamma(W \rightarrow \ell\nu_\ell)$.

[39] ABREU 99T obtain this value using $WW \rightarrow \ell\overline{\nu}_\ell q\overline{q}$ and $WW \rightarrow q\overline{q}q\overline{q}$ 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.

[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 $W \rightarrow e\nu_e$ 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 $W \rightarrow e\nu$ 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 (Γ_i/Γ)	Confidence level
Γ_1	$\ell^+\nu$	[a]	(10.68 ± 0.12) %	
Γ_2	$e^+\nu$		(10.72 ± 0.16) %	
Γ_3	$\mu^+\nu$		(10.57 ± 0.22) %	
Γ_4	$\tau^+\nu$		(10.74 ± 0.27) %	
Γ_5	hadrons		(67.96 ± 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 ± 2.7) %	
Γ_9	$c\overline{s}$		$(31 {}^{+13}_{-11})$ %	
Γ_{10}	invisible	[b]	(1.4 ± 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

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

[46] 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.

[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, 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 χ^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($W \rightarrow$ hadrons) = 1–3 B($W \rightarrow \ell\nu$). This fit has a χ^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.

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

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

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	11858	[48] ABBOTT	99H	D0	$E^{p\overline{p}}_{\text{cm}}$= 1.8 TeV
0.104 ±0.008	3642	[49] ABE	92I	CDF	$E^{p\overline{p}}_{\text{cm}}$= 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 $R \equiv [\sigma_W\, \text{B}(W \rightarrow \ell\nu_\ell)]/[\sigma_Z\, \text{B}(Z \rightarrow \ell\ell)] = 10.90 \pm 0.52$ 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($Z \rightarrow \ell\ell$).

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

$\Gamma(e^+\nu)/\Gamma_{total}$ Γ_2/Γ

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.

$\Gamma(\mu^+\nu)/\Gamma_{total}$ Γ_3/Γ

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.

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

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

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

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±0.0068±0.0033	5328	ACCIARRI	00V	L3	E^{ee}_{cm}= 161+172+183+189 GeV
0.6697±0.0065±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 ±0.012 ±0.005	1440	ABBIENDI	99D	OPAL	Repl. by ABBIENDI,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 ACCIARRI 00V

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

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.986±0.024 OUR FIT				
0.89 ±0.10	13k	[54] ABACHI 95D	D0	$E_{cm}^{p\overline{p}}$= 1.8 TeV
1.02 ±0.08	1216	[55] ABE 92I	CDF	$E_{cm}^{p\overline{p}}$= 1.8 TeV
1.00 ±0.14 ±0.08	67	ALBAJAR 89	UA1	$E_{cm}^{p\overline{p}}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.24 $^{+0.6}_{-0.4}$	14	ARNISON 84D	UA1	Repl. by ALBAJAR 89

[54] ABACHI 95D obtain this result from the measured σ_WB($W \rightarrow \mu\nu$)= 2.09 ± 0.23 ± 0.11 nb and σ_WB($W \rightarrow e\nu$)= 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 σ_WB($W \rightarrow \mu\nu$)= 2.21 ± 0.07 ± 0.21 and combine with ABE 91C σ_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

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

[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 τ trigger to 47 ± 9 ± 4 events. Proper statistical and systematic correlations are taken into account to arrive at σB($W \rightarrow \tau\nu$) = 2.05 ± 0.27 nb. Combined with ABE 91C result on σB($W \rightarrow e\nu$), 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.

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

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 7 × 10^{-4}	95	ABE 98H	CDF	$E_{cm}^{p\overline{p}}$= 1.8 TeV
< 4.9 × 10^{-3}	95	[59] ALITTI 92D	UA2	$E_{cm}^{p\overline{p}}$= 630 GeV
<58 × 10^{-3}	95	[60] ALBAJAR 90	UA1	$E_{cm}^{p\overline{p}}$= 546, 630 GeV

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

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

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

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.2 × 10^{-2}	95	ABE 98P	CDF	$E_{cm}^{p\overline{p}}$= 1.8 TeV

$\Gamma(cX)/\Gamma(\text{hadrons})$ Γ_8/Γ_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 $1.00 \pm 0.11 \pm 0.07$.

$R_{cs} = \Gamma(c\overline{s})/\Gamma(\text{hadrons})$ Γ_9/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.46^{+0.18}_{-0.14}\pm0.07}$	[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.

$\langle N_{\pi^\pm} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
15.70±0.35	[64] ABREU,P	00F	DLPH	$E^{ee}_{\rm cm}$= 189 GeV

[64] 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.

$\langle N_{K^\pm} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
2.20±0.19	[65] ABREU,P	00F	DLPH	$E^{ee}_{\rm cm}$= 189 GeV

[65] 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.

$\langle N_p \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.92±0.14	[66] ABREU,P	00F	DLPH	$E^{ee}_{\rm cm}$= 189 GeV

[66] 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.

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

VALUE	DOCUMENT ID		TECN	COMMENT
19.41±0.15 OUR AVERAGE				
19.44±0.17	[67] ABREU,P	00F	DLPH	E^{ee}_{cm}= 183+189 GeV
19.3 ±0.3 ±0.3	[68] ABBIENDI	99N	OPAL	E^{ee}_{cm}= 183 GeV
19.23±0.74	[69] ABREU	98C	DLPH	E^{ee}_{cm}= 172 GeV

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

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

[69] 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 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 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. G. Gounaris *et al.*, CERN 96-01 525.

Δg_1^Z

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.004±0.035 OUR AVERAGE					
$-0.009^{+0.060}_{-0.057}$	3455	[70] ABBIENDI	01M	OPAL	E^{ee}_{cm}= 161–189 GeV
$-0.02 \pm 0.07 \pm 0.01$	2114	[71] ABREU	01I	DLPH	E^{ee}_{cm}= 183+189 GeV
$0.023^{+0.059}_{-0.055}$	3586	[72] HEISTER	01C	ALEP	E^{ee}_{cm}= 161–189 GeV
$0.11\ ^{+0.19}_{-0.18} \pm 0.10$	1154	[73] ACCIARRI	99Q	L3	E^{ee}_{cm}= 161+172+ 183 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
-0.018 ± 0.026		[74] EBOLI	00	THEO	LEP1, SLC+ Tevatron
$0.01\ ^{+0.13}_{-0.12}$	853	[75] ABBIENDI	99D	OPAL	Repl. by ABBIENDI 01M
	331	[76] ABBOTT	99I	D0	$E^{p\overline{p}}_{cm}$= 1.8 TeV
$-0.04\ ^{+0.14}_{-0.12}$	547	[77] ABREU	99L	DLPH	Repl. by ABREU 01I
$-0.017\pm0.018^{+0.018}_{-0.003}$		[78] MOLNAR	99	THEO	LEP1, SLAC+Tevatron

[70] 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 $\Delta g_1^Z = 0.120^{+0.077}_{-0.083}$.

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

[72] 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 $\Delta g_1^Z = 0.013^{+0.066}_{-0.068}$.

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

[74] 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 (Λ=1 TeV is assumed).

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

[76] 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 λ_Z=$\Delta\kappa_Z$ =0 and assuming Standard Model values for the $WW\gamma$ couplings.

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

[78] 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
0.03 ±0.08 OUR AVERAGE					
$-0.03\ ^{+0.20}_{-0.16}$	3455	[79] ABBIENDI	01M	OPAL	E^{ee}_{cm}= 161–189 GeV
$0.25\ ^{+0.21}_{-0.20}\ \pm0.06$	2298	[80] ABREU	01I	DLPH	E^{ee}_{cm}= 183+189 GeV
$0.022\ ^{+0.119}_{-0.115}$	3586	[81] HEISTER	01C	ALEP	E^{ee}_{cm}= 161–189 GeV
$-0.04\ ^{+0.15}_{-0.17}\ \pm0.09$	137	[82] ACCIARRI	00N	L3	E^{ee}_{cm}= 130–189 GeV
$-0.08\ \pm0.34$	331	[83] ABBOTT	99I	D0	$E^{p\overline{p}}_{cm}$= 1.8 TeV
$0.11\ \pm0.25\ \pm0.17$	1154	[84] ACCIARRI	99Q	L3	E^{ee}_{cm}= 161+172+ 183 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[85] BREITWEG	00	ZEUS	$e^+p \rightarrow e^+W^\pm X$, $\sqrt{s} \approx$ 300 GeV
$0.11\ ^{+0.52}_{-0.37}$	853	[86] ABBIENDI	99D	OPAL	Repl. by ABBIENDI 01M
$0.19\ ^{+0.32}_{-0.34}$	586	[87] ABREU	99L	DLPH	Repl. by ABREU 01I
	15	[88] BARATE	99L	ALEP	Repl. by HEISTER 01C
$0.016\pm0.019\ ^{+0.009}_{-0.013}$		[89] MOLNAR	99	THEO	LEP1, SLAC+Tevatron
$0.06\ ^{+0.27}_{-0.26}$	86	[90] ACCIARRI	98N	L3	Repl. by ACCIARRI 00N
$0.05\ ^{+1.15}_{-1.10}\ \pm0.25$	207	[91] BARATE,R	98	ALEP	Repl. by HEISTER 01C

[79] 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 $\Delta\kappa_\gamma = 0.02^{+0.20}_{-0.15}$.

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

[81] 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 $\Delta\kappa_\gamma = 0.043 \pm 0.110$.

[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 $-0.44 < \Delta\kappa_\gamma < 0.29$ (for λ_γ=0). When both couplings λ_γ and κ_γ are floated freely in the fit, one obtains $\Delta\kappa_\gamma = -0.07 \pm 0.16 \pm 0.09$.

[83] 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 $-0.25 < \Delta\kappa_\gamma < 0.39$.

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

[85] 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 λ_γ=0).

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

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

[88] 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 λ_γ=0.

[89] 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.

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

[91] 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 $-2.2 < \Delta\kappa_\gamma < 2.3$.

λ_γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
-0.012 ± 0.035 OUR AVERAGE	Error includes scale factor of 1.1.				
$-0.110^{+0.058}_{-0.055}$	3455	[92] ABBIENDI	01M	OPAL	E^{ee}_{cm}= 161–189 GeV
$0.05 \pm 0.09 \pm 0.01$	2298	[93] ABREU	01I	DLPH	E^{ee}_{cm}= 183+189 GeV
$0.040^{+0.054}_{-0.052}$	3586	[94] HEISTER	01C	ALEP	E^{ee}_{cm}= 161–189 GeV
$-0.26\ ^{+0.53}_{-0.19} \pm 0.13$	137	[95] ACCIARRI	00N	L3	E^{ee}_{cm}= 130–189 GeV
$0.00\ ^{+0.10}_{-0.09}$	331	[96] ABBOTT	99I	D0	$E^{p\overline{p}}_{cm}$= 1.8 TeV
$0.10\ ^{+0.22}_{-0.20} \pm 0.10$	1154	[97] ACCIARRI	99Q	L3	E^{ee}_{cm}= 161+172+ 183 GeV

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

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
		[98] BREITWEG	00	ZEUS	$e^+p \rightarrow e^+W^\pm X$, $\sqrt{s} \approx$ 300 GeV

-0.50 ± 0.73		[99] EBOLI	00	THEO	LEP1, SLC+ Tevatron
$-0.10 {}^{+0.13}_{-0.12}$	853	[100] ABBIENDI	99D	OPAL	Repl. by ABBIENDI 01M
$-0.15 {}^{+0.19}_{-0.15}$	586	[101] ABREU	99L	DLPH	Repl. by ABREU 01I
	15	[102] BARATE	99L	ALEP	Repl. by HEISTER 01C
$-0.48 {}^{+0.44}_{-0.21}$	86	[103] ACCIARRI	98N	L3	Repl. by ACCIARRI 00N
$-0.05 {}^{+1.55}_{-1.45} \pm 0.30$	207	[104] BARATE,R	98	ALEP	Repl. by HEISTER 01C

[92] 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 $\lambda_\gamma = -0.190^{+0.087}_{-0.082}$.

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

[94] 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 $\lambda_\gamma = 0.023^{+0.074}_{-0.077}$.

[95] 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 κ_γ=1). When both couplings λ_γ and κ_γ are floated freely in the fit, one obtains $\lambda_\gamma = -0.31^{+0.68}_{-0.19} \pm 0.13$.

[96] 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 $-0.18 < \lambda_\gamma < 0.19$.

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

[98] 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).

[99] 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 (Λ=1 TeV is assumed).

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

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

[102] 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.

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

[104] 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 $-3.1 < \lambda_\gamma < 3.2$.

Δg_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	[105] ACCIARRI	99Q	L3	$E^{ee}_{\rm cm}$= 161+172+ 183 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
-0.16 ± 0.23		[106] EBOLI	00	THEO	LEP1, SLC+ Tevatron

[105] ACCIARRI 99Q study W-pair, single-W, and single photon events.
[106] 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 (Λ=1 TeV is assumed).

g_4^Z

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

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{-0.02^{+0.32}_{-0.33}}$	1065	[107] ABBIENDI	01H	OPAL	$E^{ee}_{\rm cm}$= 189 GeV

[107] 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.

$\widetilde{\kappa}_Z$

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

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{-0.20^{+0.10}_{-0.07}}$	1065	[108] ABBIENDI	01H	OPAL	$E^{ee}_{\rm cm}$= 189 GeV

[108] 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.

$\widetilde{\lambda}_Z$

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

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{-0.18^{+0.24}_{-0.16}}$	1065	[109] ABBIENDI	01H	OPAL	$E^{ee}_{\rm cm}$= 189 GeV

[109] 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*
$\mathbf{2.22^{+0.20}_{-0.19}}$	2298	[110] ABREU	01I	DLPH	E^{ee}_{cm}= 183+189 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[111] ABE	95G	CDF	
		[112] ALITTI	92C	UA2	
		[113] SAMUEL	92	THEO	
		[114] SAMUEL	91	THEO	
		[115] GRIFOLS	88	THEO	
		[116] GROTCH	87	THEO	
		[117] VANDERBIJ	87	THEO	
		[118] GRAU	85	THEO	
		[119] SUZUKI	85	THEO	
		[120] HERZOG	84	THEO	

[110] ABREU 01I combine results from e^+e^- interactions at 189 GeV leading to W^+W^-, $We\nu_e$, and $\nu\overline{\nu}\gamma$ 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.

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

[112] ALITTI 92C measure $\kappa = 1^{+2.6}_{-2.2}$ and $\lambda = 0^{+1.7}_{-1.8}$ in $p\overline{p} \to e\nu\gamma + X$ at $\sqrt{s}$ = 630 GeV. At 95%CL they report $-3.5 < \kappa < 5.9$ and $-3.6 < \lambda < 3.5$.

[113] 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.

[114] SAMUEL 91 use preliminary CDF data for $p\overline{p} \to W\gamma X$ to obtain $-11.3 \le \Delta\kappa \le 10.9$. Note that their $\kappa = 1-\Delta\kappa$.

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

[116] GROTCH 87 finds the limit $-37 < \Delta\kappa < 73.5$ (90% CL) from the experimental limits on $e^+e^- \to \nu\overline{\nu}\gamma$ assuming three neutrino generations and $-19.5 < \Delta\kappa < 56$ for four generations. Note their $\Delta\kappa$ has the opposite sign as our definition.

[117] 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 $\Delta\kappa$.

[118] 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 $\lambda = 0$.

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

120 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];

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

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

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

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 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 $e^+e^- \to WW\gamma$, $e^+e^- \to \gamma\gamma\nu\overline{\nu}$, and $e^+e^- \to Z\gamma\gamma$ 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 $\gamma\gamma\nu\overline{\nu}$ final states are used and the 95% CL limits [5] are:

$$-0.018 < a_0^W/\Lambda^2 < 0.018,$$
$$-0.033 < a_c^W/\Lambda^2 < 0.047,$$
$$-0.17 < a_n/\Lambda^2 < 0.15.$$

References

1. G. Belanger and F. Boudjema, Nucl. Phys. **B288**, 201 (1992).
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
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[121] ACCIARRI	00T	L3
	[122] ABBIENDI	99U	OPAL

[121] 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}, $-0.08\ \mathrm{GeV}^{-2} < a_c/\Lambda^2 < 0.13\ \mathrm{GeV}^{-2}$, $-0.41\ \mathrm{GeV}^{-2} < a_n/\Lambda^2 < 0.37\ \mathrm{GeV}^{-2}$.

[122] 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 $-0.070\ \mathrm{GeV}^{-2} < a_0/\Lambda^2 < 0.070\ \mathrm{GeV}^{-2}$, $-0.13\ \mathrm{GeV}^{-2} < a_c/\Lambda^2 < 0.19\ \mathrm{GeV}^{-2}$, $-0.61\ \mathrm{GeV}^{-2} < a_n/\Lambda^2 < 0.57\ \mathrm{GeV}^{-2}$.

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ABBIENDI	01F	PL B507 29	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	01H	EPJ C19 229	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	01M	EPJ C19 1	G. Abbiendi *et al.*	(OPAL Collab.)
ABREU	01I	PL B502 9	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	01K	PL B511 159	P. Abreu *et al.*	(DELPHI Collab.)
ADLOFF	01A	EPJ C19 269	C. Adloff *et al.*	(H1 Collab.)
AFFOLDER	01E	PR D64 052001	T. Affolder *et al.*	(CDF Collab.)
HEISTER	01C	EPJ C21 423	A. Heister *et al.*	(ALEPH Collab.)
ABBIENDI	00V	PL B490 71	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI,G	00	PL B493 249	G. Abbiendi *et al.*	(OPAL Collab.)
ABBOTT	00	PRL 84 222	B. Abbott *et al.*	(D0 Collab.)
ABBOTT	00B	PR D61 072001	B. Abbott *et al.*	(D0 Collab.)
ABBOTT	00D	PRL 84 5710	B. Abbott *et al.*	(D0 Collab.)
ABREU	00K	PL B479 89	P. Abreu *et al.*	(DELPHI Collab.)
ABREU,P	00F	EPJ C18 203	P. Abreu *et al.*	(DELPHI Collab.)
ACCIARRI	00N	PL B487 229	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	00T	PL B490 187	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	00V	PL B496 19	M. Acciarri *et al.*	(L3 Collab.)
ADLOFF	00B	EPJ C13 609	C. Adloff *et al.*	(H1 Collab.)
AFFOLDER	00M	PRL 85 3347	T. Affolder *et al.*	(CDF Collab.)
BARATE	00J	PL B484 205	R. Barate *et al.*	(ALEPH Collab.)
BARATE	00T	EPJ C17 241	R. Barate *et al.*	(ALEPH Collab.)
BREITWEG	00	PL B471 411	J. Breitweg *et al.*	(ZEUS Collab.)
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EBOLI	00	MPL A15 1	O. Eboli, M. Gonzalez-Garcia, S. Novaes	
ABBIENDI	99C	PL B453 138	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	99D	EPJ C8 191	G. Abbiendi *et al.*	(OPAL Collab.)
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ABBIENDI	99U	PL B471 293	G. Abbiendi *et al.*	(OPAL Collab.)
ABBOTT	99H	PR D60 052003	B. Abbott *et al.*	(D0 Collab.)
ABBOTT	99I	PR D60 072002	B. Abbott *et al.*	(D0 Collab.)
ABREU	99K	PL B456 310	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	99L	PL B459 382	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	99T	PL B462 410	P. Abreu *et al.*	(DELPHI Collab.)
ACCIARRI	99	PL B454 386	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	99Q	PL B467 171	M. Acciarri *et al.*	(L3 Collab.)
BARATE	99	PL B453 121	R. Barate *et al.*	(ALEPH Collab.)
BARATE	99I	PL B453 107	R. Barate *et al.*	(ALEPH Collab.)
BARATE	99L	PL B462 389	R. Barate *et al.*	(ALEPH Collab.)
BARATE	99M	PL B465 349	R. Barate *et al.*	(ALEPH Collab.)
MOLNAR	99	PL B461 149	P. Molnar, M. Grunewald	
ABBOTT	98N	PR D58 092003	B. Abbott *et al.*	(D0 Collab.)
ABBOTT	98O	PRL 80 3008	B. Abbott *et al.*	(D0 Collab.)
ABBOTT	98P	PR D58 012002	B. Abbott *et al.*	(D0 Collab.)
ABE	98H	PR D58 031101	F. Abe *et al.*	(CDF Collab.)
ABE	98P	PR D58 091101	F. Abe *et al.*	(CDF Collab.)
ABREU	98C	PL B416 233	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	98N	PL B439 209	P. Abreu *et al.*	(DELPHI Collab.)
ACCIARRI	98N	PL B436 417	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	98P	PL B436 437	M. Acciarri *et al.*	(L3 Collab.)
BARATE	98Y	PL B422 369	R. Barate *et al.*	(ALEPH Collab.)
BARATE,R	98	PL B445 239	R. Barate *et al.*	(ALEPH Collab.)
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.)
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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.)
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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)
ARNISON	83	PL 122B 103	G.T.J. Arnison *et al.*	(UA1 Collab.)
BANNER	83B	PL 122B 476	M. Banner *et al.*	(UA2 Collab.)