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^- 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, $\sigma(e^+e^- \to W^+W^-)$, 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 209 GeV) at which LEP has run during 1996–2000. In the second method, which is used at the higher energies, the W mass has been determined by directly reconstructing the W from its decay products.

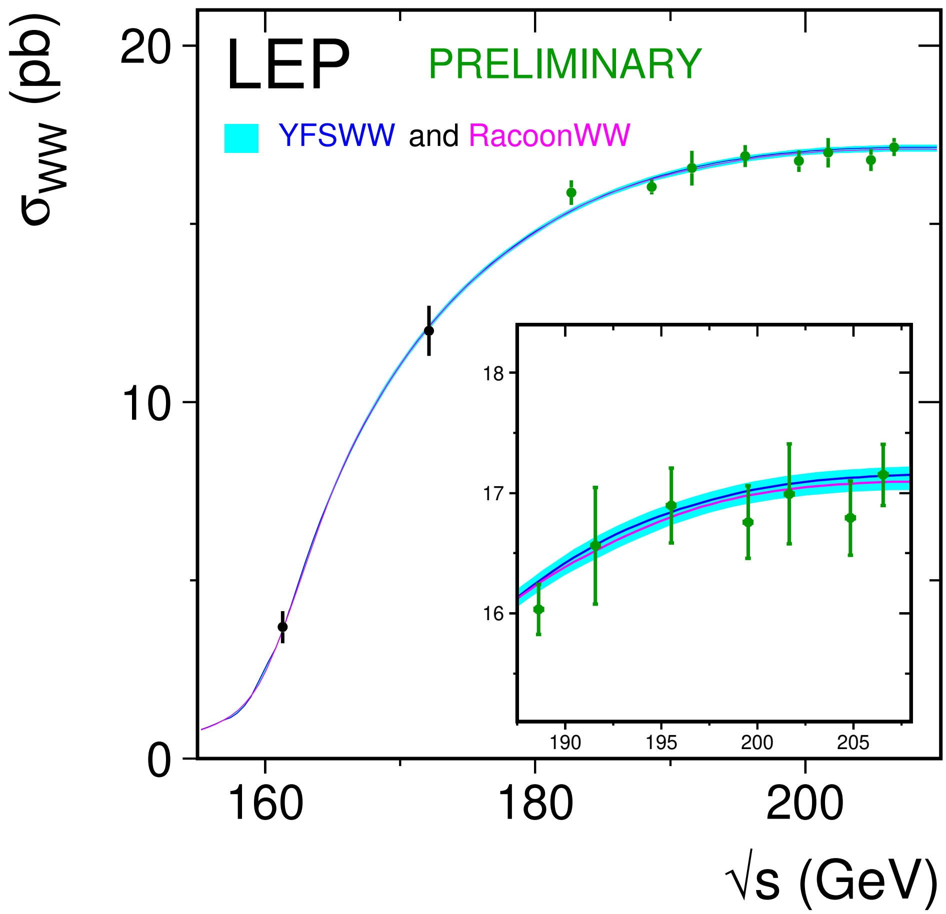

Figure 1: Measurement of the W-pair production cross section as a function of the center–of–mass energy [1], compared to the predictions of RACOONWW [3] and YFSWW [4]. The shaded area represents the uncertainty on the theoretical predictions, estimated to be $\pm 2\%$ for $\sqrt{s} < 170$ GeV and ranging from 0.7 to 0.4% above 170 GeV. See full-color version on color pages at end of book.

Each LEP experiment has combined their own mass values properly taking into account the common systematic errors.

In order to compute the LEP average W mass each experiment has provided its measured W mass for the $q\overline{q}q\overline{q}$ and $q\overline{q}\ell\overline{\nu_\ell}$ 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 $= 80.388 \pm 0.035$ GeV [2], which includes W mass determination from W-pair producton cross section variation at threshold. Errors due to uncertainties in LEP energy (9 MeV) and possible effect of color reconnection (CR) and Bose–Einstein correlations (BEC) between quarks from different W's (7 MeV) are included. The mass difference between $q\overline{q}q\overline{q}$ and $q\overline{q}\ell\overline{\nu_\ell}$ final states (due to possible CR and BEC effects) is -4 ± 44 MeV.

For completeness we give here also the *preliminary* LEP value for the W width: $\Gamma(W) = 2.134 \pm 0.079$ GeV [2].

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 [5]= 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 a *preliminary* average W mass of 80.405 ± 0.030 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 80.406 ± 0.029 GeV.

The Standard Model prediction from the electroweak fit, using Z-pole data plus $m_{\rm top}$ measurement, gives a W–boson mass of 80.364 ± 0.021 GeV [1,2].

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, the LEP Electroweak Working Group, CERN-PH-EP/2005-051, `hep-ex/0511027` (9 November 2005).
2. A. Venturi, "New (almost final) W mass and width results from LEP", talk given at "Les Rencontres de Physique de la Vallée d'Aoste", La Thuile (Italy), 5–11 March 2006.
3. A. Denner *et al.*, Nucl. Phys. **B587** 67, (2000).
4. S. Jadach *et al.*, Comput. Phys. Comm. **140**, 432 (2001).
5. V.M. Abazov *et al.*, Phys. Rev. **D70**, 092008 (2004).

W MASS

To obtain the world average, common systematics between experiments are properly taken into account. The LEP average *W* mass based on published results is 80.383 ± 0.035 GeV. The combined $p\overline{p}$ collider data yields an average *W* mass of 80.454 ± 0.059 GeV (ABAZOV 04D).

OUR FIT uses these average LEP and $p\overline{p}$ collider *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*
80.403± 0.029 OUR FIT					
80.415± 0.042±0.031	11830	[1] ABBIENDI	06	OPAL	$E^{ee}_{\rm cm}$ = 170–209 GeV
80.270± 0.046±0.031	9909	[2] ACHARD	06	L3	$E^{ee}_{\rm cm}$ = 161–209 GeV
80.440± 0.043±0.027	8692	[3] SCHAEL	06	ALEP	$E^{ee}_{\rm cm}$ = 161–209 GeV
80.483± 0.084	49247	[4] ABAZOV	02D	D0	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV
80.359± 0.074±0.049	3077	[5] ABREU	01K	DLPH	$E^{ee}_{\rm cm}$= 161+172+183 +189 GeV
80.433± 0.079	53841	[6] AFFOLDER	01E	CDF	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
82.87 ± 1.82 $^{+0.30}_{-0.16}$	1500	[7] AKTAS	06	H1	$e^{\pm} p \rightarrow \overline{\nu}_e(\nu_e)X$, $\sqrt{s} \approx 300$ GeV
80.41 ± 0.41 ±0.13	1101	[8] ABBIENDI	03C	OPAL	Repl. by ABBIENDI 06
80.3 ± 2.1 ± 1.2 ± 1.0	645	[9] CHEKANOV	02C	ZEUS	$e^- p \rightarrow \nu_e$X, $\sqrt{s}$= 318 GeV
80.432± 0.066±0.045	2789	[10] ABBIENDI	01F	OPAL	Repl. by ABBIENDI 06
80.482± 0.091	45394	[11] ABBOTT	00	D0	Repl. by ABAZOV 02D
80.418± 0.061±0.047	2977	[12] BARATE	00T	ALEP	Repl. by SCHAEL 06

$81.4^{+2.7}_{-2.6} \pm 2.0^{+3.3}_{-3.0}$	1086	[13] BREITWEG	00D	ZEUS	$e^+ p \to \overline{\nu}_e X$, $\sqrt{s} \approx$ 300 GeV
$80.270 \pm 0.137 \pm 0.048$	809	[14] ABREU	99T	DLPH	Repl. by ABREU 01K
80.61 ± 0.15	801	[15] ACCIARRI	99	L3	Repl. by ACHARD 06
80.41 ± 0.18	8986	[16] ABE	95P	CDF	Repl. by AFFOLDER 01E
$80.84 \pm 0.22 \pm 0.83$	2065	[17] ALITTI	92B	UA2	See W/Z ratio below
$80.79 \pm 0.31 \pm 0.84$		[18] ALITTI	90B	UA2	$E^{p\overline{p}}_{\text{cm}}$= 546,630 GeV
$80.0 \pm 3.3 \pm 2.4$	22	[19] ABE	89I	CDF	$E^{p\overline{p}}_{\text{cm}}$= 1.8 TeV
$82.7 \pm 1.0 \pm 2.7$	149	[20] ALBAJAR	89	UA1	$E^{p\overline{p}}_{\text{cm}}$= 546,630 GeV
$81.8 {}^{+6.0}_{-5.3} \pm 2.6$	46	[21] ALBAJAR	89	UA1	$E^{p\overline{p}}_{\text{cm}}$= 546,630 GeV
$89 \pm 3 \pm 6$	32	[22] ALBAJAR	89	UA1	$E^{p\overline{p}}_{\text{cm}}$= 546,630 GeV
$81. \pm 5.$	6	ARNISON	83	UA1	E^{ee}_{cm}= 546 GeV
$80. {}^{+10.}_{-6.}$	4	BANNER	83B	UA2	Repl. by ALITTI 90B

[1] ABBIENDI 06 use direct reconstruction of the kinematics of $W^+W^- \to q\overline{q}\ell\nu_\ell$ and $W^+W^- \to q\overline{q}q\overline{q}$ events. The result quoted here is obtained combining this mass value with the results using $W^+W^- \to \ell\nu_\ell\ell'\nu_{\ell'}$ events in the energy range 183–207 GeV (ABBIENDI 03C) and the dependence of the WW production cross-section on m_W at threshold. The systematic error includes $\pm$0.009 GeV due to the uncertainty on the LEP beam energy.

[2] ACHARD 06 use direct reconstruction of the kinematics of $W^+W^- \to q\overline{q}\ell\nu_\ell$ and $W^+W^- \to q\overline{q}q\overline{q}$ events in the C.M. energy range 189–209 GeV. The result quoted here is obtained combining this mass value with the results obtained from a direct W mass reconstruction at 172 and 183 GeV and with those from the dependence of the WW production cross-section on m_W at 161 and 172 GeV (ACCIARRI 99).

[3] SCHAEL 06 use direct reconstruction of the kinematics of $W^+W^- \to q\overline{q}\ell\nu_\ell$ and $W^+W^- \to q\overline{q}q\overline{q}$ events in the C.M. energy range 183–209 GeV. The result quoted here is obtained combining this mass value with those obtained from the dependence of the W pair production cross-section on m_W at 161 and 172 GeV (BARATE 97 and BARATE 97S respectively). The systematic error includes $\pm$0.009 GeV due to possible effects of final state interactions in the $q\overline{q}q\overline{q}$ channel and $\pm$0.009 GeV due to the uncertainty on the LEP beam energy.

[4] ABAZOV 02D improve the measurement of the W-boson mass including $W \to e\nu_e$ 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 GeV. The value reported here is a combination of this measurement with all previous DØ W-boson mass measurements.

[5] 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 GeV due to the beam energy uncertainty and $\pm$0.033 GeV due to possible color reconnection and Bose-Einstein effects in the purely hadronic final state.

[6] AFFOLDER 01E fit the transverse mass spectrum of 30115 $W \to e\nu_e$ events (M_W= $80.473 \pm 0.065 \pm 0.092$ GeV) and of 14740 $W \to \mu\nu_\mu$ 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.

[7] AKTAS 06 fit the Q^2 dependence (300 < Q^2 < 30,000 GeV^2) of the charged-current differential cross section with a propagator mass. The first error is experimental and the second corresponds to uncertainties due to input parameters and model assumptions.

[8] ABBIENDI 03C determine the mass of the W boson using fully leptonic decays $W^+ W^- \rightarrow \ell \nu_\ell \ell' \nu_{\ell'}$. They use the measured energies of the charged leptons and an approximate kinematic reconstruction of the event (both neutrinos are assumed in the same plane as the charged leptons) to get a W pseudo-mass. All these variables are combined in a simultaneous maximum likelihood fit. The systematic error is dominated by the uncertainty on the lepton energy.

[9] CHEKANOV 02C fit the Q^2 dependence ($200 < Q^2 < 60000$ 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 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.

[11] 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 $p_T(\nu)$.

[12] 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.

[13] 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.

[14] 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.

[15] 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.

[16] 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.

[17] 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.

[18] 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.

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

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

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

[22] 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
0.88173±0.00032 OUR FIT				
0.8821 ±0.0011 ±0.0008	28323	[23] ABBOTT 98N	D0	$E_{\rm cm}^{p\overline{p}}$= 1.8 TeV
0.88114±0.00154±0.00252	5982	[24] ABBOTT 98P	D0	$E_{\rm cm}^{p\overline{p}}$= 1.8 TeV
0.8813 ±0.0036 ±0.0019	156	[25] ALITTI 92B	UA2	$E_{\rm cm}^{p\overline{p}}$= 630 GeV

[23] 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.

[24] 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.

[25] 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
10.785±0.029 OUR FIT			
10.4 ±1.4 ±0.8	ALBAJAR 89	UA1	$E_{\rm cm}^{p\overline{p}}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
11.3 ±1.3 ±0.9	ANSARI 87	UA2	$E_{\rm cm}^{p\overline{p}}$= 546,630 GeV

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

Test of CPT invariance.

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

W WIDTH

The CDF and DØ widths labelled "extracted value" are obtained by measuring $R = [\sigma(W)/\sigma(Z)]\,[\Gamma(W \rightarrow \ell\nu_\ell)]/(\mathrm{B}(Z \rightarrow \ell\ell)\Gamma(W))$ where the bracketed quantities can be calculated with plausible reliability. $\Gamma(W)$ is then extracted by using a value of $\mathrm{B}(Z \rightarrow \ell\ell)$ 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 2.0910 ± 0.0015 GeV (see Review on "Electroweak model and constraints on new physics" in this Edition).

To obtain OUR FIT, the correlation between systematics within LEP experiments and within Tevatron experiments is properly taken into account as given in the LEP note accessible at http://lepewwg.web.cern.ch/LEPEWWG/lepww/mw/pdg_2006/ and in the combined Tevatron paper of ABAZOV 04D. The respective average values (2.164 ± 0.085 GeV from LEP and 2.115 ± 0.105 GeV from Tevatron) yield an average W width of 2.145 ± 0.066 GeV coming from direct measurements. ABAZOV 04D also determine the average extracted W width using CDF and DØ data to obtain a value of 2.141 ± 0.057 GeV.

They further combine the Tevatron direct and extracted W widths to obtain an average Tevatron width of 2.135 ± 0.050 GeV. Finally combining this with the LEP W width and the extracted W width values from UA1 and UA2 one obtains the quoted value.

VALUE (GeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
2.141±0.041 OUR FIT						
1.996±0.096±0.102		10729	[26] ABBIENDI	06	OPAL	E^{ee}_{cm}= 170–209 GeV
2.18 ±0.11 ±0.09		9795	[27] ACHARD	06	L3	E^{ee}_{cm}= 172–209 GeV
2.14 ±0.09 ±0.06		8717	[28] SCHAEL	06	ALEP	E^{ee}_{cm}= 183–209 GeV
2.23 $^{+0.15}_{-0.14}$ ±0.10		294	[29] ABAZOV	02E	D0	Direct meas.
2.266±0.176±0.076		3005	[30] ABREU	01K	DLPH	E^{ee}_{cm}= 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.
2.064±0.060±0.059			[33] ABE	95W	CDF	Extracted value
2.10 $^{+0.14}_{-0.13}$ ±0.09		3559	[34] ALITTI	92	UA2	Extracted value
2.18 $^{+0.26}_{-0.24}$ ±0.04			[35] ALBAJAR	91	UA1	Extracted value
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2.04 ±0.16 ±0.09		2756	[36] ABBIENDI	01F	OPAL	Repl. by ABBIENDI 06
2.24 ±0.20 ±0.13		1711	[37] BARATE	00T	ALEP	Repl. by SCHAEL 06
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
1.97 ±0.34 ±0.17		687	[40] ACCIARRI	99	L3	Repl. by ACHARD 06
2.11 ±0.28 ±0.16		58	[41] ABE	95C	CDF	Repl. by AFFOLDER 00M
2.30 ±0.19 ±0.06			[42] ALITTI	90C	UA2	Extracted value
2.8 $^{+1.4}_{-1.5}$ ±1.3		149	[43] 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	[44] ARNISON	86	UA1	$E^{p\overline{p}}_{cm}$= 546,630 GeV

[26] ABBIENDI 06 use direct reconstruction of the kinematics of $W^+W^- \rightarrow q\overline{q}\ell\nu_\ell$ and $W^+W^- \rightarrow q\overline{q}q\overline{q}$ events. The systematic error includes ±0.003 GeV due to the uncertainty on the LEP beam energy.

[27] ACHARD 06 use direct reconstruction of the kinematics of $W^+W^- \rightarrow q\overline{q}\ell\nu_\ell$ and $W^+W^- \rightarrow q\overline{q}q\overline{q}$ events in the C.M. energy range 189–209 GeV. The result quoted here is obtained combining this value of the width with the result obtained from a direct W mass reconstruction at 172 and 183 GeV (ACCIARRI 99).

[28] SCHAEL 06 use direct reconstruction of the kinematics of $W^+W^- \rightarrow q\overline{q}\ell\nu_\ell$ and $W^+W^- \rightarrow q\overline{q}q\overline{q}$ events. The systematic error includes ±0.05 GeV due to possible effects of final state interactions in the $q\overline{q}q\overline{q}$ channel and ±0.01 GeV due to the uncertainty on the LEP beam energy.

[29] 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.

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

[31] ABBOTT 00B measure $R = 10.43 \pm 0.27$ for the $W \to e\nu_e$ decay channel. They use the SM theoretical predictions for $\sigma(W)/\sigma(Z)$ and $\Gamma(W \to e\nu_e)$ and the world average for $\mathrm{B}(Z \to ee)$. 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) $W \to e\nu_e$ and $W \to \mu\nu_\mu$ events to obtain $\Gamma(W)= 2.04 \pm 0.11(\text{stat}) \pm 0.09(\text{syst})$ GeV. This is combined with the earlier CDF measurement (ABE 95C) to obtain the quoted result.

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

[34] 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.

[35] 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.

[36] 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.

[37] BARATE 00T obtain this value using $WW \to q\overline{q}q\overline{q}$, $WW \to e\nu_e q\overline{q}$, and $WW \to \mu\nu_\mu q\overline{q}$ decays. The systematic error includes ± 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.

[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 $\sigma(W)/\sigma(Z)$, $\mathrm{B}(Z \to \ell\ell)$, and $\Gamma(W \to \ell\nu_\ell)$.

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

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

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

[42] 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.

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

[44] 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] ($10.80\pm\ 0.09$) %	
Γ_2	$e^+\nu$	($10.75\pm\ 0.13$) %	
Γ_3	$\mu^+\nu$	($10.57\pm\ 0.15$) %	
Γ_4	$\tau^+\nu$	($11.25\pm\ 0.20$) %	
Γ_5	hadrons	($67.60\pm\ 0.27$) %	
Γ_6	$\pi^+\gamma$	$< 8 \times 10^{-5}$	95%
Γ_7	$D_s^+\gamma$	$< 1.3 \times 10^{-3}$	95%
Γ_8	cX	($33.4\ \pm\ 2.6$) %	
Γ_9	$c\overline{s}$	($31\ {}^{+13}_{-11}$) %	
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

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*
$30^{+52}_{-48}\pm 33$	[45] BARATE	99I	ALEP	$E^{ee}_{\rm cm}$= 161+172+183 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[46] BARATE	99L	ALEP	$E^{ee}_{\rm cm}$= 161+172+183 GeV

[45] 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.

[46] 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. LEP averages on $W \rightarrow e\nu_e$, $W \rightarrow \mu\nu_\mu$, and $W \rightarrow \tau\nu_\tau$, and their correlations are first obtained by combining results from the four experiments taking properly into account the common systematics. The procedure is described in the note LEPEWWG/XSEC/2001-02, 30 March 2001, at http://lepewwg.web.cern.ch/LEPEWWG/lepww/4f/PDG01. The LEP average values so obtained, using published data, are given in the note LEPEWWG/XSEC/2005-01 accessible at http://lepewwg.web.cern.ch/

LEPEWWG/lepww/4f/PDG05/. These results, together with results from the $p\overline{p}$ colliders are then used in fits to obtain the world average W branching ratios. 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 = 4.7 for 10 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=11.3 for 12 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.

$\Gamma(\ell^+\nu)/\Gamma_{total}$ — Γ_1/Γ

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

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.1080±0.0009 OUR FIT				
0.1085±0.0014±0.0008	13600	ABDALLAH 04G	DLPH	E^{ee}_{cm} = 161–209 GeV
0.1083±0.0014±0.0010	11246	ACHARD 04J	L3	E^{ee}_{cm} = 161–209 GeV
0.1096±0.0012±0.0005	16116	SCHAEL 04A	ALEP	E^{ee}_{cm}= 183–209 GeV
0.1056±0.0020±0.0009	5778	ABBIENDI,G 00	OPAL	E^{ee}_{cm}= 161+172+183 +189 GeV
0.1102±0.0052	11858	[47] ABBOTT 99H	D0	$E^{p\overline{p}}_{cm}$= 1.8 TeV
0.104 ±0.008	3642	[48] ABE 92I	CDF	$E^{p\overline{p}}_{cm}$= 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.1071±0.0024±0.0014	4843	ABREU 00K	DLPH	Repl. by ABDALLAH 04G
0.1060±0.0023±0.0011	5328	ACCIARRI 00V	L3	Repl. by ACHARD 04J
0.1101±0.0022±0.0011	5258	BARATE 00J	ALEP	Repl. by SCHAEL 04A
0.107 ±0.004 ±0.002	1440	ABBIENDI 99D	OPAL	Repl. by ABBIENDI,G 00

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

[48] $1216 \pm 38^{+27}_{-31}$ $W \rightarrow \mu\nu$ 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
0.1075±0.0013 OUR FIT				
0.1061±0.0028		[49] ABAZOV 04D	TEVA	$E^{p\overline{p}}_{cm}$= 1.8 TeV
0.1055±0.0031±0.0014	1804	ABDALLAH 04G	DLPH	E^{ee}_{cm} = 161–209 GeV
0.1078±0.0029±0.0013	1576	ACHARD 04J	L3	E^{ee}_{cm} = 161–209 GeV
0.1078±0.0027±0.0010	2142	SCHAEL 04A	ALEP	E^{ee}_{cm}= 183–209 GeV
0.1046±0.0042±0.0014	801	ABBIENDI,G 00	OPAL	E^{ee}_{cm}= 161+172+183 +189 GeV
0.10 ±0.014 $^{+0.02}_{-0.03}$	248	[50] ANSARI 87C	UA2	$E^{p\overline{p}}_{cm}$= 546,630 GeV

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

$0.1044 \pm 0.0015 \pm 0.0028$	67318	[51] ABBOTT	00B	D0	Repl. by ABAZOV 04D
$0.1018 \pm 0.0054 \pm 0.0026$	527	ABREU	00K	DLPH	Repl. by ABDALLAH 04G
$0.1077 \pm 0.0045 \pm 0.0016$	715	ACCIARRI	00V	L3	Repl. by ACHARD 04J
$0.1135 \pm 0.0046 \pm 0.0017$	720	BARATE	00J	ALEP	Repl. by SCHAEL 04A
$0.117 \pm 0.009 \pm 0.002$	224	ABBIENDI	99D	OPAL	Repl. by ABBIENDI,G 00
$0.1094 \pm 0.0033 \pm 0.0031$		[52] ABE	95W	CDF	Repl. by ABAZOV 04D
seen	119	APPEL	86	UA2	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
seen	172	ARNISON	86	UA1	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV

[49] ABAZOV 04D take into account all correlations to properly combine the CDF (ABE 95W) and DØ (ABBOTT 00B) measurements of the ratio R in the electron channel. The ratio R is defined as $[\sigma_W \cdot \mathrm{B}(W \to e\nu_e)]$ / $[\sigma_Z \cdot \mathrm{B}(Z \to ee)]$. The combination gives $\mathrm{R}^{Tevatron} = 10.59 \pm 0.23$. σ_W / σ_Z is calculated at next–to–next–to–leading order (3.360 ± 0.051). The branching fraction B($Z \to ee$) is taken from this *Review* as (3.363 ± 0.004)%.

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

[51] ABBOTT 00B measure $R \equiv [\sigma_W \mathrm{B}(W \to e\nu_e)]/[\sigma_Z \mathrm{B}(Z \to ee)] = 10.43 \pm 0.27$ 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($Z \to ee$).

[52] ABE 95W result is from a measurement of $\sigma\mathrm{B}(W \to e\nu)/\sigma\mathrm{B}(Z \to e^+e^-) = 10.90 \pm 0.32 \pm 0.29$, 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.

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

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.1057±0.0015 OUR FIT					
$0.1065 \pm 0.0026 \pm 0.0008$	1998	ABDALLAH	04G	DLPH	$E^{ee}_{\rm cm}$ = 161–209 GeV
$0.1003 \pm 0.0029 \pm 0.0012$	1423	ACHARD	04J	L3	$E^{ee}_{\rm cm}$ = 161–209 GeV
$0.1087 \pm 0.0025 \pm 0.0008$	2216	SCHAEL	04A	ALEP	$E^{ee}_{\rm cm}$= 183–209 GeV
$0.1050 \pm 0.0041 \pm 0.0012$	803	ABBIENDI,G	00	OPAL	$E^{ee}_{\rm cm}$= 161+172+183+189 GeV
0.10 ± 0.01	1216	[53] ABE	92I	CDF	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV

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

$0.1092 \pm 0.0048 \pm 0.0012$	649	ABREU	00K	DLPH	Repl. by ABDALLAH 04G
$0.0990 \pm 0.0046 \pm 0.0015$	617	ACCIARRI	00V	L3	Repl. by ACHARD 04J
$0.1110 \pm 0.0044 \pm 0.0016$	710	BARATE	00J	ALEP	Repl. by SCHAEL 04A
$0.102 \pm 0.008 \pm 0.002$	193	ABBIENDI	99D	OPAL	Repl. by ABBIENDI,G 00

[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
0.1125±0.0020 OUR FIT					
0.1146±0.0039±0.0019	2034	ABDALLAH	04G	DLPH	E^{ee}_{cm} = 161–209 GeV
0.1189±0.0040±0.0020	1375	ACHARD	04J	L3	E^{ee}_{cm} = 161–209 GeV
0.1125±0.0032±0.0020	2070	SCHAEL	04A	ALEP	E^{ee}_{cm}= 183–209 GeV
0.1075±0.0052±0.0021	794	ABBIENDI,G	00	OPAL	E^{ee}_{cm}= 161+172+183 +189 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.1105±0.0075±0.0032	579	ABREU	00K	DLPH	Repl. by ABDALLAH 04G
0.1124±0.0062±0.0022	536	ACCIARRI	00V	L3	Repl. by ACHARD 04J
0.1051±0.0055±0.0022	607	BARATE	00J	ALEP	Repl. by SCHAEL 04A
0.101 ±0.010 ±0.003	183	ABBIENDI	99D	OPAL	Repl. by ABBIENDI,G 00

$\Gamma(\text{hadrons})/\Gamma_{total}$ 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
0.6760±0.0027 OUR FIT					
0.6745±0.0041±0.0024	13600	ABDALLAH	04G	DLPH	E^{ee}_{cm} = 161–209 GeV
0.6750±0.0042±0.0030	11246	ACHARD	04J	L3	E^{ee}_{cm} = 161–209 GeV
0.6713±0.0037±0.0015	16116	SCHAEL	04A	ALEP	E^{ee}_{cm}= 183–209 GeV
0.6832±0.0061±0.0028	5778	ABBIENDI,G	00	OPAL	E^{ee}_{cm}= 161+172+183 +189 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.6789±0.0073±0.0043	4843	ABREU	00K	DLPH	Repl. by ABDALLAH 04G
0.6820±0.0068±0.0033	5328	ACCIARRI	00V	L3	Repl. by ACHARD 04J
0.6697±0.0065±0.0032	5258	BARATE	00J	ALEP	Repl. by SCHAEL 04A
0.679 ±0.012 ±0.005	1440	ABBIENDI	99D	OPAL	Repl. by ABBIENDI,G 00

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

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.983±0.018 OUR FIT					
0.89 ±0.10	13k	[54] ABACHI	95D	D0	$E^{p\overline{p}}_{cm}$= 1.8 TeV
1.02 ±0.08	1216	[55] ABE	92I	CDF	$E^{p\overline{p}}_{cm}$= 1.8 TeV
1.00 ±0.14 ±0.08	67	ALBAJAR	89	UA1	$E^{p\overline{p}}_{cm}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.24 $^{+0.6}_{-0.4}$	14	ARNISON	84D	UA1	Repl. by ALBAJAR 89

[54] ABACHI 95D obtain this result from the measured 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
1.046±0.023 OUR FIT					
0.961±0.061	980	[56] ABBOTT	00D	D0	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV
0.94 ±0.14	179	[57] ABE	92E	CDF	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV
1.04 ±0.08 ±0.08	754	[58] ALITTI	92F	UA2	$E^{p\overline{p}}_{\rm cm}$= 630 GeV
1.02 ±0.20 ±0.12	32	ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$= 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	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV
< 4.9 × 10^{-3}	95	[59] ALITTI	92D	UA2	$E^{p\overline{p}}_{\rm cm}$= 630 GeV
<58 × 10^{-3}	95	[60] ALBAJAR	90	UA1	$E^{p\overline{p}}_{\rm cm}$= 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	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV

$\Gamma(c\mathrm{X})/\Gamma(\mathrm{hadrons})$ — 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 $W \rightarrow c$X 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 ± 0.045 ± 0.036.

[62] BARATE 99M tag c jets using a neural network algorithm. From this measurement $|V_{cs}|$ is determined to be 1.00 ± 0.11 ± 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}_{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}_{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}_{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}_{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 $\langle N_{\text{charged}} \rangle = 39.12 \pm 0.33 \pm 0.36$ 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.

[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 $W W$ final states after demonstrating that the W decay charged multiplicity is independent of the topology within errors.

TRIPLE GAUGE COUPLINGS (TGC'S)

Revised March 2006 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 $(\kappa_\gamma, \kappa_Z, \lambda_\gamma, \lambda_Z, g_1^Z)$, where $\kappa_\gamma = \kappa_Z = g_1^Z = 1$ and $\lambda_\gamma = \lambda_Z = 0$ in the Standard Model at the tree level. The parameters κ_Z and λ_Z are related to the other three due to constraints of gauge invariance as follows: $\kappa_Z = g_1^Z - (\kappa_\gamma - 1)\tan^2\theta_W$ and $\lambda_Z = \lambda_\gamma$, where θ_W is the weak mixing angle. 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. 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 p. 525.

g_1^Z

OUR FIT below is obtained by combining the measurements taking into account properly the common systematic errors (see LEPEWWG/TGC/2005-01 at http://lepewwg.web.cern.ch/LEPEWWG/lepww/tgc).

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.984^{+0.022}_{-0.019}$ OUR FIT					
$1.001\pm0.027\pm0.013$	9310	[70] SCHAEL	05A	ALEP	E^{ee}_{cm}= 183–209 GeV
$0.987^{+0.034}_{-0.033}$	9800	[71] ABBIENDI	04D	OPAL	E^{ee}_{cm}= 183–209 GeV
$0.966^{+0.034}_{-0.032}\pm0.015$	8325	[72] ACHARD	04D	L3	E^{ee}_{cm} = 161–209 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
	2.3	[73] ABAZOV	05S	D0	$E^{p\overline{p}}_{cm}$ = 1.96 TeV
$0.98\ \pm0.07\ \pm0.01$	2114	[74] ABREU	01I	DLPH	E^{ee}_{cm}= 183+189 GeV
	331	[75] ABBOTT	99I	D0	$E^{p\overline{p}}_{cm}$= 1.8 TeV

[70] SCHAEL 05A study single–photon, single–W, and WW–pair production from 183 to 209 GeV. The result quoted here is derived from the WW–pair production sample. Each parameter is determined from a single–parameter fit in which the other parameters assume their Standard Model values.

[71] ABBIENDI 04D combine results from W^+W^- in all decay channels. Only CP-conserving couplings are considered and each parameter is determined from a single-parameter fit in which the other parameters assume their Standard Model values. The 95% confidence interval is $0.923 < g_1^Z < 1.054$.

[72] ACHARD 04D study WW–pair production, single–W production and single–photon production with missing energy from 189 to 209 GeV. The result quoted here is obtained from the WW–pair production sample including data from 161 to 183 GeV, ACCIARRI 99Q. Each parameter is determined from a single–parameter fit in which the other parameters assume their Standard Model values.

[73] ABAZOV 05S study $\overline{p}p \rightarrow WZ$ production with a subsequent trilepton decay to $\ell\nu\ell'\overline{\ell}'$ (ℓ and ℓ' = e or μ). Three events (estimated background 0.71 ± 0.08 events) with WZ decay characteristics are observed from which they derive limits on the anomalous WWZ couplings. The 95% CL limit for a form factor scale $\Lambda = 1.5$ TeV is $0.51 < g_1^Z < 1.66$, fixing λ_Z and κ_Z to their Standard Model values.

[74] 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 $0.84 < g_1^Z < 1.13$.

[75] 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 $0.63 < g_1^Z < 1.57$, fixing λ_Z and κ_Z to their Standard Model values, and assuming Standard Model values for the $WW\gamma$ couplings.

κ_γ

OUR FIT below is obtained by combining the measurements taking into account properly the common systematic errors (see LEPEWWG/TGC/2005-01 at http://lepewwg.web.cern.ch/LEPEWWG/lepww/tgc).

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.973^{+0.044}_{-0.045}$ OUR FIT					
$0.971 \pm 0.055 \pm 0.030$	10689	[76] SCHAEL	05A	ALEP	$E^{ee}_{cm} = 183$–209 GeV
$0.88\ ^{+0.09}_{-0.08}$	9800	[77] ABBIENDI	04D	OPAL	$E^{ee}_{cm} = 183$–209 GeV
$1.013^{+0.067}_{-0.064} \pm 0.026$	10575	[78] ACHARD	04D	L3	$E^{ee}_{cm} = 161$–209 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
	141	[79] ABAZOV	05J	D0	$E^{p\overline{p}}_{cm} = 1.96$ TeV
$1.25\ ^{+0.21}_{-0.20} \pm 0.06$	2298	[80] ABREU	01I	DLPH	$E^{ee}_{cm} = 183+189$ GeV
		[81] BREITWEG	00	ZEUS	$e^+ p \rightarrow e^+ W^{\pm} X$, $\sqrt{s} \approx 300$ GeV
0.92 ± 0.34	331	[82] ABBOTT	99I	D0	$E^{p\overline{p}}_{cm} = 1.8$ TeV

[76] SCHAEL 05A study single–photon, single–W, and WW–pair production from 183 to 209 GeV. Each parameter is determined from a single–parameter fit in which the other parameters assume their Standard Model values.

[77] ABBIENDI 04D combine results from $W^+ W^-$ in all decay channels. Only CP-conserving couplings are considered and each parameter is determined from a single-parameter fit in which the other parameters assume their Standard Model values. The 95% confidence interval is $0.73 < \kappa_\gamma < 1.07$.

[78] ACHARD 04D study WW–pair production, single–W production and single–photon production with missing energy from 189 to 209 GeV. The result quoted here is obtained including data from 161 to 183 GeV, ACCIARRI 99Q. Each parameter is determined from a single–parameter fit in which the other parameters assume their Standard Model values.

[79] ABAZOV 05J perform a likelihood fit to the photon E_T spectrum of $W\gamma$ + X events, where the W decays to an electron or muon which is required to be well separated from the photon. For $\Lambda = 2.0$ TeV the 95% CL limits are $0.12 < \kappa_\gamma < 1.96$. In the fit λ_γ is kept fixed to its Standard Model value.

[80] ABREU 01I combine results from $e^+ e^-$ interactions at 189 GeV leading to $W^+ W^-$, $W e \nu_e$, and $\nu \overline{\nu} \gamma$ final states with results from ABREU 99L at 183 GeV. The 95% confidence interval is $0.87 < \kappa_\gamma < 1.68$.

[81] 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 $-3.7 < \kappa_\gamma < 2.5$ (for $\lambda_\gamma = 0$).

[82] 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 $0.75 < \kappa_\gamma < 1.39$.

λ_γ

OUR FIT below is obtained by combining the measurements taking into account properly the common systematic errors (see LEPEWWG/TGC/2005-01 at http://lepewwg.web.cern.ch/LEPEWWG/lepww/tgc).

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$-0.028^{+0.020}_{-0.021}$ OUR FIT					
$-0.012 \pm 0.027 \pm 0.011$	10689	[83] SCHAEL	05A	ALEP	$E^{ee}_{cm} = 183$–209 GeV
$-0.060^{+0.034}_{-0.033}$	9800	[84] ABBIENDI	04D	OPAL	$E^{ee}_{cm} = 183$–209 GeV
$-0.021^{+0.035}_{-0.034} \pm 0.017$	10575	[85] ACHARD	04D	L3	$E^{ee}_{cm} = 161$–209 GeV

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

	141	[86] ABAZOV	05J D0	$E^{p\overline{p}}_{\rm cm}$ = 1.96 TeV
$0.05 \pm 0.09 \pm 0.01$	2298	[87] ABREU	01I DLPH	$E^{ee}_{\rm cm}$ = 183+189 GeV
		[88] BREITWEG	00 ZEUS	$e^+ p \to e^+ W^\pm X$, $\sqrt{s} \approx$ 300 GeV
$0.00 \, ^{+0.10}_{-0.09}$	331	[89] ABBOTT	99I D0	$E^{p\overline{p}}_{\rm cm}$ = 1.8 TeV

[83] SCHAEL 05A study single–photon, single–W, and WW–pair production from 183 to 209 GeV. Each parameter is determined from a single–parameter fit in which the other parameters assume their Standard Model values.

[84] ABBIENDI 04D combine results from $W^+ W^-$ in all decay channels. Only CP-conserving couplings are considered and each parameter is determined from a single-parameter fit in which the other parameters assume their Standard Model values. The 95% confidence interval is $-0.13 < \lambda_\gamma < 0.01$.

[85] ACHARD 04D study WW–pair production, single–W production and single–photon production with missing energy from 189 to 209 GeV. The result quoted here is obtained including data from 161 to 183 GeV, ACCIARRI 99Q. Each parameter is determined from a single–parameter fit in which the other parameters assume their Standard Model values.

[86] ABAZOV 05J perform a likelihood fit to the photon E_T spectrum of $W\gamma$ + X events, where the W decays to an electron or muon which is required to be well separated from the photon. For Λ = 2.0 TeV the 95% CL limits are $-0.20 < \lambda_\gamma < 0.20$. In the fit κ_γ is kept fixed to its Standard Model value.

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

[88] BREITWEG 00 search for W production in events with large hadronic p_T. For p_T >20 GeV, the upper limit on the cross section gives the 95%CL limit $-3.2 < \lambda_\gamma < 3.2$ for κ_γ fixed to its Standard Model value.

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

κ_Z

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

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.924^{+0.059}_{-0.056} \pm 0.024$	7171	[90] ACHARD	04D L3	$E^{ee}_{\rm cm}$ = 189–209 GeV

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

	2.3	[91] ABAZOV	05S D0	$E^{p\overline{p}}_{\rm cm}$ = 1.96 TeV

[90] ACHARD 04D study WW–pair production, single–W production and single–photon production with missing energy from 189 to 209 GeV. The result quoted here is obtained using the WW–pair production sample. Each parameter is determined from a single–parameter fit in which the other parameters assume their Standard Model values.

[91] ABAZOV 05S study $\overline{p}p \to WZ$ production with a subsequent trilepton decay to $\ell\nu\ell'\overline{\ell}'$ (ℓ and ℓ' = e or μ). Three events (estimated background 0.71 ± 0.08 events) with WZ decay characteristics are observed from which they derive limits on the anomalous WWZ couplings. The 95% CL limit for a form factor scale Λ = 1 TeV is $-1.0 < \kappa_Z < 3.4$, fixing λ_Z and g^Z_1 to their Standard Model values.

λ_Z

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

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{-0.088^{+0.060}_{-0.057}\pm0.023}$	7171	[92] ACHARD 04D	L3	$E^{ee}_{\rm cm}$ = 189–209 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	2.3	[93] ABAZOV 05S	D0	$E^{p\overline{p}}_{\rm cm}$ = 1.96 TeV

[92] ACHARD 04D study WW–pair production, single–W production and single–photon production with missing energy from 189 to 209 GeV. The result quoted here is obtained using the WW–pair production sample. Each parameter is determined from a single–parameter fit in which the other parameters assume their Standard Model values.

[93] ABAZOV 05S study $\overline{p}p \rightarrow WZ$ production with a subsequent trilepton decay to $\ell\nu\ell'\overline{\ell}'$ (ℓ and ℓ' = e or μ). Three events (estimated background 0.71 ± 0.08 events) with WZ decay characteristics are observed from which they derive limits on the anomalous WWZ couplings. The 95% CL limit for a form factor scale Λ = 1.5 TeV is $-0.48 < \lambda_Z < 0.48$, fixing g^Z_1 and κ_Z to their Standard Model values.

g^Z_5

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

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.93±0.09 OUR AVERAGE Error includes scale factor of 1.1.				
$0.96^{+0.13}_{-0.12}$	9800	[94] ABBIENDI 04D	OPAL	$E^{ee}_{\rm cm}$= 183–209 GeV
1.00±0.13±0.05	7171	[95] ACHARD 04D	L3	$E^{ee}_{\rm cm}$ = 189–209 GeV
$0.56^{+0.23}_{-0.22}\pm0.12$	1154	[96] ACCIARRI 99Q	L3	$E^{ee}_{\rm cm}$= 161+172+ 183 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.84±0.23		[97] EBOLI 00	THEO	LEP1, SLC+ Tevatron

[94] ABBIENDI 04D combine results from W^+W^- in all decay channels. Only *CP*-conserving couplings are considered and each parameter is determined from a single-parameter fit in which the other parameters assume their Standard Model values. The 95% confidence interval is $0.72 < g^Z_5 < 1.21$.

[95] ACHARD 04D study WW–pair production, single–W production and single–photon production with missing energy from 189 to 209 GeV. The result quoted here is obtained using the WW–pair production sample. Each parameter is determined from a single–parameter fit in which the other parameters assume their Standard Model values.

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

[97] 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).

g^Z_4

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

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{-0.02^{+0.32}_{-0.33}}$	1065	[98] ABBIENDI 01H	OPAL	$E^{ee}_{\rm cm}$= 189 GeV

[98] 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	[99] ABBIENDI 01H	OPAL	$E^{ee}_{\rm cm}$= 189 GeV

[99] 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	[100] ABBIENDI 01H	OPAL	$E^{ee}_{\rm cm}$= 189 GeV

[100] 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 $-e(\kappa-\lambda)/m^2_W$. A description of the parameterization of these moments and additional references can be found in HAGIWARA 87 and BAUR 88. The parameter Λ appearing in the theoretical limits below is a regularization cutoff which roughly corresponds to the energy scale where the structure of the W boson becomes manifest.

VALUE ($e/2m_W$)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$\mathbf{2.22^{+0.20}_{-0.19}}$	2298	[101] ABREU 01I	DLPH	$E^{ee}_{\rm cm}$= 183+189 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[102] ABE 95G	CDF	
		[103] ALITTI 92C	UA2	
		[104] SAMUEL 92	THEO	
		[105] SAMUEL 91	THEO	
		[106] GRIFOLS 88	THEO	
		[107] GROTCH 87	THEO	
		[108] VANDERBIJ 87	THEO	
		[109] GRAU 85	THEO	
		[110] SUZUKI 85	THEO	
		[111] HERZOG 84	THEO	

[101] 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^Z_1, $\Delta\kappa_\gamma$, and λ_γ. $\Delta\kappa_\gamma$ and λ_γ are simultaneously floated in the fit to determine μ_W.

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

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

[104] 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.

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

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

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

[108] 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 $\Delta\kappa$.

[109] 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 $\lambda = 0$.

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

[111] 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 March 2006 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];

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

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

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

$$\widetilde{L}_6^0 = -\frac{e^2}{16\Lambda^2}\ \widetilde{a}_0\ F^{\mu\nu}\ \widetilde{F}_{\mu\nu}\vec{W}^\alpha \cdot \vec{W}_\alpha$$

$$\widetilde{L}_6^n = -i\frac{e^2}{16\Lambda^2}\ \widetilde{a}_n\epsilon_{ijk}\ W_{\mu\alpha}^{(i)}\ W_\nu^{(j)}\ W^{(k)\alpha}\widetilde{F}^{\mu\nu}$$

where F, W are photon and W fields, L_6^0 and L_6^c conserve C, P separately ($\widetilde{L}_6^0$ conserves only C) and generate anomalous

$W^+W^-\gamma\gamma$ and $ZZ\gamma\gamma$ couplings, L_6^n violates CP ($\widetilde{L}_6^n$ violates both C and P) and generates an anomalous $W^+W^-Z\gamma$ coupling, and Λ is an energy 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.

References

1. G. Belanger and F. Boudjema, Phys. Lett. **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);
   A. Denner *et al.*, Eur. Phys. J. **C20**, 201 (2001);
   G. Montagna *et al.*, Phys. Lett. **B515**, 197 (2001).
3. G. Belanger *et al.*, Eur. Phys. J. **C13**, 103 (2000).

a_0/Λ^2, a_c/Λ^2, a_n/Λ^2

Using the $WW\gamma$ final state, the LEP combined 95% CL limits on the anomalous contributions to the $WW\gamma\gamma$ and $WWZ\gamma$ vertices (as of summer 2003) are given below:

(See P. Wells, "Experimental Tests of the Standard Model," Int. Europhysics Conference on High-Energy Physics, Aachen, Germany, 17–23 July 2003)

$$-0.02 < a_0^W/\Lambda^2 < 0.02 \text{ GeV}^{-2},$$
$$-0.05 < a_c^W/\Lambda^2 < 0.03 \text{ GeV}^{-2},$$
$$-0.15 < a_n/\Lambda^2 < 0.15 \text{ GeV}^{-2}.$$

VALUE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[112] ABBIENDI	04B	OPAL
	[113] ABBIENDI	04L	OPAL
	[114] HEISTER	04A	ALEP
	[115] ABDALLAH	03I	DLPH
	[116] ACHARD	02F	L3

[112] ABBIENDI 04B select 187 $e^+e^- \rightarrow W^+W^-\gamma$ events in the C.M. energy range 180–209 GeV, where E_γ >2.5 GeV, the photon has a polar angle $|\cos\theta_\gamma| < 0.975$ and is well isolated from the nearest jet and charged lepton, and the effective masses of both fermion-antifermion systems agree with the W mass within 3 Γ_W. The measured differential cross section as a function of the photon energy and photon polar angle is used to extract the 95% CL limits: -0.020 GeV^{-2} $<a_0/\Lambda^2 < 0.020$ GeV^{-2}, -0.053 GeV^{-2} $<a_c/\Lambda^2 < 0.037$ GeV^{-2} and -0.16 GeV^{-2} $<a_n/\Lambda^2 < 0.15$ GeV^{-2}.

[113] ABBIENDI 04L select 20 $e^+e^- \rightarrow \nu\overline{\nu}\gamma\gamma$ acoplanar events in the energy range 180–209 GeV and 176 $e^+e^- \rightarrow q\overline{q}\gamma\gamma$ events in the energy range 130–209 GeV. These samples are used to constrain possible anomalous $W^+W^-\gamma\gamma$ and $ZZ\gamma\gamma$ quartic couplings. Further combining with the $W^+W^-\gamma$ sample of ABBIENDI 04B the following one–parameter 95% CL limits are obtained: -0.007 $< a_0^Z/\Lambda^2 <$ 0.023 GeV^{-2}, -0.029 $< a_c^Z/\Lambda^2 <$ 0.029 GeV^{-2}, -0.020 $< a_0^W/\Lambda^2 <$ 0.020 GeV^{-2}, -0.052 $< a_c^W/\Lambda^2 <$ 0.037 GeV^{-2}.

[114] In the CM energy range 183 to 209 GeV HEISTER 04A select 30 $e^+e^- \rightarrow \nu\overline{\nu}\gamma\gamma$ events with two acoplanar, high energy and high transverse momentum photons. The photon–photon acoplanarity is required to be $> 5^\circ$, $E_\gamma/\sqrt{s} > 0.025$ (the more energetic photon having energy $> 0.2\sqrt{s}$), $p_{T_\gamma}/E_{beam} > 0.05$ and $|\cos\theta_\gamma| < 0.94$. A likelihood fit to the photon energy and recoil missing mass yields the following one–parameter 95% CL limits: -0.012 $< a_0^Z/\Lambda^2 <$ 0.019 GeV^{-2}, -0.041 $< a_c^Z/\Lambda^2 <$ 0.044 GeV^{-2}, -0.060 $< a_0^W/\Lambda^2 <$ 0.055 GeV^{-2}, -0.099 $< a_c^W/\Lambda^2 <$ 0.093 GeV^{-2}.

[115] ABDALLAH 03I select 122 $e^+e^- \rightarrow W^+W^-\gamma$ events in the C.M. energy range 189–209 GeV, where E_γ >5 GeV, the photon has a polar angle $|\cos\theta_\gamma| < 0.95$ and is well isolated from the nearest charged fermion. A fit to the photon energy spectra yields $a_c/\Lambda^2 = 0.000^{+0.019}_{-0.040}$ GeV^{-2}, $a_0/\Lambda^2 = -0.004^{+0.018}_{-0.010}$ GeV^{-2}, $\tilde{a}_0/\Lambda^2 = -0.007^{+0.019}_{-0.008}$ GeV^{-2}, $a_n/\Lambda^2 = -0.09^{+0.16}_{-0.05}$ GeV^{-2}, and $\tilde{a}_n/\Lambda^2 = +0.05^{+0.07}_{-0.15}$ GeV^{-2}, keeping the other parameters fixed to their Standard Model values (0). The 95% CL limits are: -0.063 GeV^{-2} $<a_c/\Lambda^2 < +0.032$ GeV^{-2}, -0.020 GeV^{-2} $<a_0/\Lambda^2 < +0.020$ GeV^{-2}, -0.020 GeV^{-2} $< \tilde{a}_0/\Lambda^2 < +0.020$ GeV^{-2}, -0.18 GeV^{-2} $<a_n/\Lambda^2 < +0.14$ GeV^{-2}, -0.16 GeV^{-2} $< \tilde{a}_n/\Lambda^2 < +0.17$ GeV^{-2}.

[116] ACHARD 02F select 86 $e^+e^- \rightarrow W^+W^-\gamma$ events at 192–207 GeV, where E_γ >5 GeV and the photon is well isolated. They also select 43 acoplanar $e^+e^- \rightarrow \nu\overline{\nu}\gamma\gamma$ 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/Λ^2= 0.000 $\pm$ 0.010 GeV^{-2}, a_c/Λ^2= $-$0.013 $\pm$ 0.023 GeV^{-2}, and a_n/Λ^2= $-$0.002 $\pm$ 0.076 GeV^{-2}. Further combining the analyses of $W^+W^-\gamma$ events with the low recoil mass region of $\nu\overline{\nu}\gamma\gamma$ 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}.

W REFERENCES

ABBIENDI	06	EPJ C45 307	G. Abbiendi et al.	(OPAL Collab.)
ACHARD	06	EPJ C45 569	P. Achard et al.	(L3 Collab.)
AKTAS	06	PL B632 35	A. Aktas et al.	(H1 Collab.)
SCHAEL	06	CERN-PH-EP/2006-004	S. Schael et al.	(ALEPH Collab.)
To appear in EPJ C.				
ABAZOV	05J	PR D71 091108R	V.M. Abazov et al.	(D0 Collab.)
ABAZOV	05S	PRL 95 141802	V.M. Abazov et al.	(D0 Collab.)
SCHAEL	05A	PL B614 7	S. Schael et al.	(ALEPH Collab.)
ABAZOV	04D	PR D70 092008	V.M. Abazov et al.	(CDF, D0 Collab.)
ABBIENDI	04B	PL B580 17	G. Abbiendi et al.	(OPAL Collab.)
ABBIENDI	04D	EPJ C33 463	G. Abbiendi et al.	(OPAL Collab.)
ABBIENDI	04L	PR D70 032005	G. Abbiendi et al.	(OPAL Collab.)
ABDALLAH	04G	EPJ C34 127	J. Abdallah et al.	(DELPHI Collab.)
ACHARD	04D	PL B586 151	P. Achard et al.	(L3 Collab.)
ACHARD	04J	PL B600 22	P. Achard et al.	(L3 Collab.)
HEISTER	04A	PL B602 31	A. Heister et al.	(ALEPH Collab.)
SCHAEL	04A	EPJ C38 147	S. Schael et al.	(ALEPH Collab.)
ABBIENDI	03C	EPJ C26 321	G. Abbiendi et al.	(OPAL Collab.)
ABDALLAH	03I	EPJ C31 139	J. Abdallah et al.	(DELPHI Collab.)
ABAZOV	02D	PR D66 012001	V.M. Abazov et al.	(D0 Collab.)
ABAZOV	02E	PR D66 032008	V.M. Abazov et al.	(D0 Collab.)
ACHARD	02F	PL B527 29	P. Achard et al.	(L3 Collab.)
CHEKANOV	02C	PL B539 197	S. Chekanov et al.	(ZEUS Collab.)
ABBIENDI	01F	PL B507 29	G. Abbiendi et al.	(OPAL Collab.)
ABBIENDI	01H	EPJ C19 229	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.)
AFFOLDER	01E	PR D64 052001	T. Affolder et al.	(CDF 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.)
Also		EPJ C25 493 (erratum)	P. Abreu et al.	(DELPHI Collab.)
ACCIARRI	00T	PL B490 187	M. Acciarri et al.	(L3 Collab.)
ACCIARRI	00V	PL B496 19	M. Acciarri et al.	(L3 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.)
BREITWEG	00D	EPJ C12 411	J. Breitweg et al.	(ZEUS Collab.)
EBOLI	00	MPL A15 1	O. Eboli, M. Gonzalez-Garcia, S. Novaes	
ABBIENDI	99D	EPJ C8 191	G. Abbiendi et al.	(OPAL Collab.)
ABBIENDI	99N	PL B453 153	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	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	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.)

ABBOTT	98N	PR D58 092003	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.)
BARATE	97	PL B401 347	R. Barate *et al.*	(ALEPH Collab.)
BARATE	97S	PL B415 435	R. Barate *et al.*	(ALEPH Collab.)
ABACHI	95D	PRL 75 1456	S. Abachi *et al.*	(D0 Collab.)
ABE	95C	PRL 74 341	F. Abe *et al.*	(CDF Collab.)
ABE	95G	PRL 74 1936	F. Abe *et al.*	(CDF Collab.)
ABE	95P	PRL 75 11	F. Abe *et al.*	(CDF Collab.)
Also		PR D52 4784	F. Abe *et al.*	(CDF Collab.)
ABE	95W	PR D52 2624	F. Abe *et al.*	(CDF Collab.)
Also		PRL 73 220	F. Abe *et al.*	(CDF Collab.)
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		PRL 67 2920 (erratum)	M.A. Samuel *et al.*	
ABE	90	PRL 64 152	F. Abe *et al.*	(CDF Collab.)
Also		PR D44 29	F. Abe *et al.*	(CDF Collab.)
ABE	90G	PRL 65 2243	F. Abe *et al.*	(CDF Collab.)
Also		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		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		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.)