W PHYSICS AT LEP

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Abstract

Production, decay and properties of W bosons measured in e^+e^- collisions at LEP are presented. W-pair and single-W cross-sections and W decay branching fractions are determined and agree well with theoretical predictions. Including the analysis of differential distributions, trilinear and quartic couplings of the W boson to the other gauge bosons are extracted. The trilinear, C and P conserving couplings are found to be $\kappa_\gamma = 0.896^{+0.058}_{-0.056}$, $\lambda_\gamma = -0.023^{+0.025}_{-0.023}$, and $g_1^Z = 0.990^{+0.023}_{-0.024}$, consistent with the Standard Model expectations. A precise measurement of the mass and width of the W boson yields $M_W = 80.450 \pm 0.039$ GeV and $\Gamma_W = 2.150 \pm 0.091$ GeV. The W mass is in good agreement with the one obtained indirectly from an analysis of other electroweak data measured at LEP and SLD. Many of the results presented in this article are preliminary.

1 Introduction

From 1989 until 2000, the e^+e^- collider LEP was operated at centre-of-mass energies, $\sqrt{s}$, close to the Z resonance and at higher energies above the threshold of W-pair production. The data collected by the four LEP experiments, ALEPH, DELPHI, L3, and OPAL, at $\sqrt{s} = 161 - 209$ GeV corresponds to an integrated luminosity of about 4×700 pb^{-1}. Each experiment registered about 10000 W-pair events. Their analysis allows a precise measurement of the properties of the W gauge boson and a thorough test of the Standard Model (SM) of electroweak interaction [1].

2 W-Pair and Single-W Production

At LEP W bosons are produced in pairs in the process $e^+e^- \rightarrow W^+W^-$, which is described in the SM by three charged current (CC03) Feynman diagrams, one t-channel diagram with neutrino exchange and two s-channel diagrams with γ and Z exchange. The W bosons subsequently decay into a pair of quarks, $q\overline{q'}$, or a lepton and a neutrino, $\ell\nu$, ℓ=e,μ,τ. The experimental W-pair signatures are therefore fully hadronic qqqq(γ), semi-leptonic qq$\ell\nu(\gamma)$, and fully leptonic $\ell\nu\ell\nu(\gamma)$ events, with a branching fraction of 45%, 44% and 11%, respectively. Possible photon radiation is indicated by (γ). The efficiency to select those events varies from about 80-85% in the qqqq(γ) channel, 50-85% in the qq$\ell\nu(\gamma)$ channel, to 20-60% in the $\ell\nu\ell\nu(\gamma)$ channel, depending on the lepton flavour.

The total production cross-section, σ_{WW}, measured at centre-of-mass energies between 161 and 209 GeV is shown in Figure 1a, together with the theoretical prediction calculated with the YFSWW and RacoonWW Monte Carlo programs [2]. Also shown is the evolution of σ_{WW} in case W couplings to the other gauge bosons are absent, or only the coupling to γ is present. The measurements exclude those scenarios and clearly prefer the $\mathrm{SU}(2) \times \mathrm{U}(1)$ gauge structure of the SM. Taking the ratio of the measured to predicted cross-section, as shown in Figure 1b, and combining all data, the value obtained for $\sigma_{\mathrm{WW}}/\sigma_{\mathrm{theo}}$ is $0.998 \pm 0.006(\mathrm{stat.}) \pm 0.007(\mathrm{syst.})$ [3], perfectly consistent with unity. To match the data precision, the SM predictions need to take into accound higher-order photonic and electroweak corrections, as it is done in RacoonWW and YFSWW, which reach a theoretical uncertainty of 0.5% on σ_{WW}.

Since the lepton flavours are separately identified in the LEP detectors the W branching fractions to leptons are derived from the measured cross-sections:

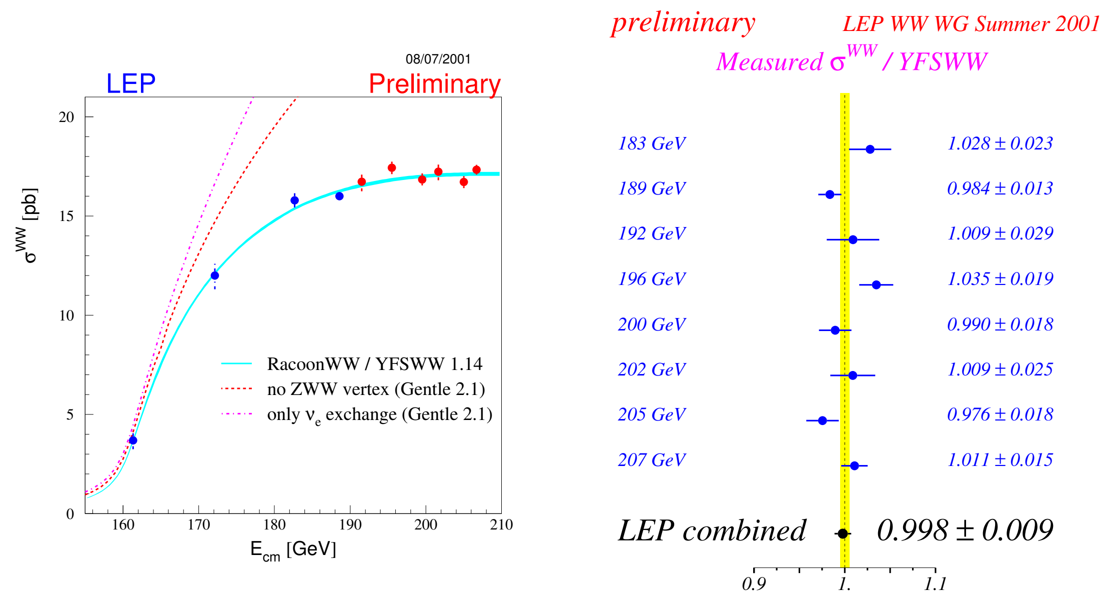

Figure 1: *(a) The cross-section, $\sigma_{\rm WW}$ (CC03), of the process* $\rm e^+e^- \to W^+W^- \to ffff(\gamma)$ *as a function of centre-of-mass energy,* $\sqrt{s}$*. The measurements are shown together with the SM predictions and two scenarios in which the couplings to the other gauge bosons are absent. (b) The ratio,* $\sigma_{\rm WW}/\sigma_{\rm theo}$*, measured at different* $\sqrt{s}$ *and their combined value.*

$$
\begin{aligned}
{\rm BR(W \to e\nu)} &= 10.54 \pm 0.17\% \\
{\rm BR(W \to \mu\nu)} &= 10.54 \pm 0.16\% \\
{\rm BR(W \to \tau\nu)} &= 11.09 \pm 0.22\%
\end{aligned}
$$

These results support lepton universality in the W decay and can be combined to $\rm BR(W \to \ell\nu) = 10.69 \pm 0.09\%$. The remaining W decays are into pairs of quarks with a branching fraction of $\rm BR(W \to q\overline{q'}) = 67.92 \pm 0.27\%$, in agreement with the SM expectation of 67.51%. The hadronic branching fraction is related to the CKM matrix elements, V_{ij}, through the relation

$$
{\rm BR(W \to q\overline{q'})/[1 - BR(W \to q\overline{q'})]} = (1 - \frac{\alpha_{\rm s}}{\pi}) \sum_{\rm i,j} |{\rm V_{ij}}|^2 \,, \qquad (1)
$$

where the sum extends over $i = \rm u, c$ and $j = \rm d, s, b$. Assuming unitarity of the CKM matrix and since five of the matrix elements are well measured or contribute negligibly to the sum of squares [4], one can derive a value for $|V_{cs}|$ of 0.996 ± 0.013 [3]. However, this is only an indirect measurement. By explicitly tagging c-quarks in W decays, ALEPH and DELPHI measure $|V_{cs}|$ directly to $0.97\pm0.09(\rm stat.)\pm0.07(\rm syst.)$ [4].

In $\rm e^+e^-$ collisions W bosons can not only be produced in pairs but also through Wγ-fusion in the t-channel or W-bremsstrahlung, leading to a $\rm e\nu_e W$ final

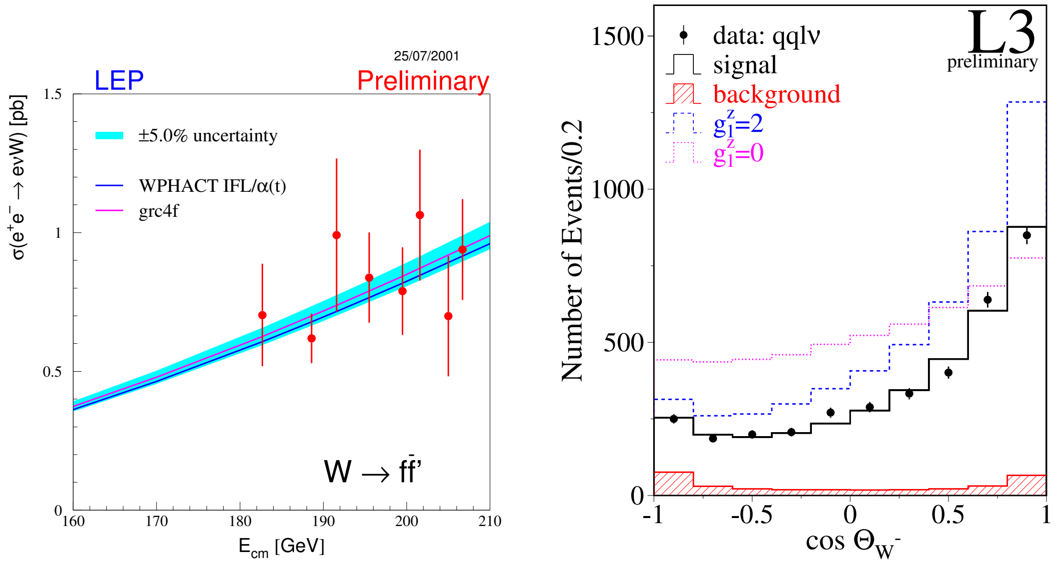

Figure 2: *(a) Measured cross-section of single-W production,* $\mathrm{e^+e^-} \to \mathrm{e}\nu_\mathrm{e}\mathrm{W}$*, as a function of centre-of-mass energy,* $\sqrt{s}$*, together with the SM prediction. (b) Distribution of the W production angle measured in* $\mathrm{qq}\ell\nu$ *events. Data are shown together with the SM expectation as well as the differential distribution in case of anomalous values of the* g_1^Z *coupling.*

state. This single-W production is characterized by an electron that is scattered at small angles to the beam direction and that escapes undetected. In the experiment the W decays are identified as single leptons or a pair of quark jets, with no other activity in the detector. To separate the single-W process from other processes leading to the same $\mathrm{e}\nu_\mathrm{e}\mathrm{ff'}$ final state, the signal phase space is restricted by kinematic cuts: $m_{\mathrm{q}\overline{\mathrm{q}'}} > 45$ GeV for the $\mathrm{e}\nu_\mathrm{e}\mathrm{qq}$ final states, $E_\ell > 20$ GeV for the $\mathrm{e}\nu_\mathrm{e}\mu\nu_\mu$ and $\mathrm{e}\nu_\mathrm{e}\tau\nu_\tau$ final states, and finally $|\cos\theta_{\mathrm{e}^-}| > 0.95, |\cos\theta_{\mathrm{e}^+}| < 0.95$ and $E_{\mathrm{e}^+} > 20$ GeV (or the charge conjugate cuts) for the $\mathrm{e}\nu_\mathrm{e}\mathrm{e}\nu_\mathrm{e}$ final states. Combining the data of the four LEP experiments the measured single-W cross-section is shown in Figure 2a as a function of $\sqrt{s}$. The results agree well with the theoretical predictions of WPHACT and grc4f [5].

3 Gauge Couplings

Couplings between three gauge bosons are probed at LEP in W-pair production, as can be seen in Figure 1a, in single-W and in single-γ production, $\mathrm{e^+e^-} \to \nu\nu\gamma$. The boson self-couplings arise due to the non-abelian gauge structure of the SM. In the most general case, the effective Lagrangian that describes the triple gauge boson couplings (TGC) has 14 coupling parameters [6]. Assuming C and P conservation reduces the number of couplings to six:

$$\frac{i\mathcal{L}_{\text{eff}}}{g_{\text{VWW}}} = g_1^{\text{V}}\text{V}^{\mu}(\text{W}^{-}_{\mu\nu}\text{W}^{+\,\nu}) + \kappa_{\text{V}}\text{W}^{+}_{\mu}\text{W}^{-}_{\nu}\text{V}^{\mu\nu} + \frac{\lambda_{\text{V}}}{\text{M}_{\text{W}}^2}\text{V}^{\mu\nu}\text{W}^{+}_{\nu}\text{W}^{-}_{\mu}\,, \tag{2}$$

with the coupling parameters g_1^{V}, κ_{V}, and λ_{V}, where V can be either γ or Z. The normalization is given by $g_{\gamma\text{WW}} = -e$ and $g_{\text{ZWW}} = -e\cot\theta_w$, with θ_w being the weak mixing angle. General $\text{SU}(2)\times\text{U}(1)$ gauge invariance fixes g_1^{γ} to 1 and adds the relations $\kappa_{\text{Z}} = g_1^{\text{Z}} - (\kappa_\gamma - 1)\tan^2\theta_w$ and $\lambda_{\text{Z}} = \lambda_\gamma$. Finally, κ_γ, λ_γ and g_1^{Z} remain as free parameters, whose SM values are 1, 0, and 1, respectively. The couplings are related to the static properties of the W boson, the magnetic dipole moment $\mu_{\text{W}} = \frac{e}{2M_{\text{W}}}(g_1^{\gamma}+\kappa_\gamma+\lambda_\gamma)$ and the electric quadrupole moment $Q_{\text{W}} = -\frac{e}{M_{\text{W}}^2}(\kappa_\gamma - \lambda_\gamma)$.

To increase sensitivity to the couplings, not only the total cross-sections of the processes are fitted, but also differential distributions, like in the case of W-pairs the decay angles of the W boson and the W^- production angle, which is shown in Figure 2 b. The measured multi-differential cross-section is compared to the theoretical expectation, for which it is as important as for the total cross-section to take higher-order corrections into account. The difference in the shape of the distributions between $\mathcal{O}(\alpha)$ and lowest order calculations manifests itself in a shift of the measured couplings by -0.015 for λ_γ and g_1^{Z}, and -0.04 for κ_γ [7].

The likelihood curves for g_1^{Z} and κ_γ, as extracted by the four LEP experiments, are shown in Figure 3. The combination of the measurements, taking systematic errors and their correlations properly into account, yields [7]:

$$\begin{aligned} \kappa_\gamma &= 0.896^{+0.058}_{-0.056} \\ \lambda_\gamma &= -0.023^{+0.025}_{-0.023} \\ g_1^{\text{Z}} &= 0.990^{+0.023}_{-0.024}\,. \end{aligned}$$

The value of κ_γ deviates slightly from the SM, while the others agree perfectly with the expectations. The largest correlated systematic uncertainty originates from $\mathcal{O}(\alpha)$ corrections, where the full difference to the lower order calculation is taken. Since a better understanding of the theoretical uncertainties is expected and because not all data are completely analysed by the LEP experiments, the final uncertainty on the TGCs may still improve by 10-20%.

An alternative test of the gauge structure of the SM is performed by analysing the elements, ρ_{ij}, of the Spin Density Matrix (SDM) in W pair production, where i and j indicate the W helicity states 0, + and -. The terms ρ_{ij} are measured

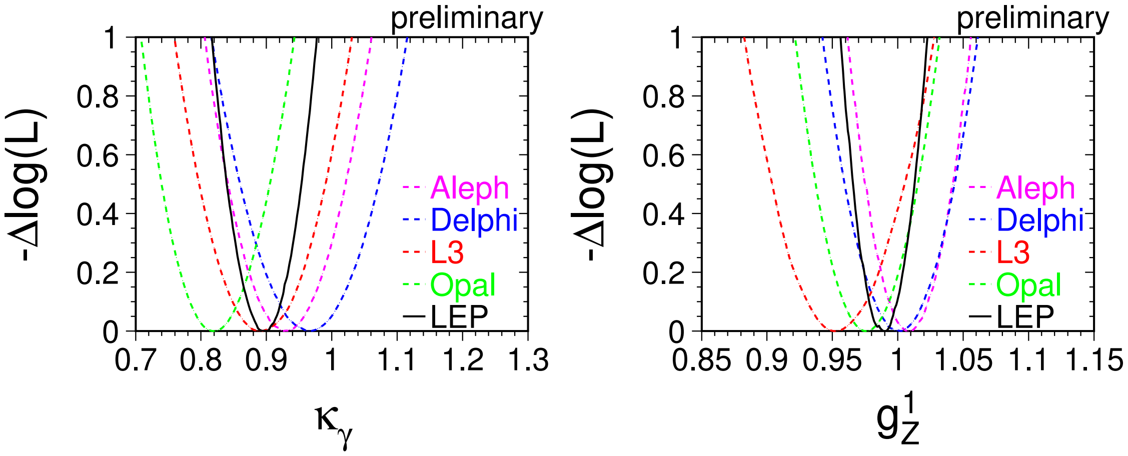

Figure 3: *Negative logarithm of the likelihood curves for the TGCs κ_γ and g_1^{Z} measured in the channels $\mathrm{W^+W^-}$, $\mathrm{e}\nu_{\mathrm{e}}\mathrm{W}$ and $\nu\nu\gamma$ by the four LEP experiments, and their combination. The curves include statistical and systematic uncertainties. The combined likelihood takes correlations properly into account. In each case the minimal value is subtracted.*

in bins of the polar production angle of the W^-, $\cos\theta_{\mathrm{W}}$, as shown in Figure 4. The imaginary parts of the off-diagonal elements are sensitive to CP and CPT violating contributions of the scattering amplitudes. However, no such anomalous behaviour is found [8]. From the diagonal elements the cross-sections for longitudinally and transverse polarized W bosons, σ_L and σ_T, are derived:

$$\sigma_L = \int \rho_{00} \frac{d\sigma}{d\cos\theta_{\mathrm{W}}} d\cos\theta_{\mathrm{W}} \tag{3}$$

$$\sigma_T = \int \{\rho_{++} + \rho_{--}\} \frac{d\sigma}{d\cos\theta_{\mathrm{W}}} d\cos\theta_{\mathrm{W}}\,. \tag{4}$$

An existance of the longitudinal polarization state is, in the SM, a consequence of the Higgs mechanism and an important test of the theory. A determination of the fraction σ_L/σ, derived from SDM elements by Opal and from a fit to decay angle distributions by L3, yields [9]:

$$\sigma_L/\sigma = 0.210 \pm 0.033 \pm 0.016 \qquad (\text{Opal},\ \sqrt{\mathrm{s}} = 189\ \text{GeV},\ \text{SM} = 0.257)$$

$$\sigma_L/\sigma = 0.234 \pm 0.027 \pm 0.012 \qquad (\text{L3},\ \langle\sqrt{\mathrm{s}}\rangle = 197\ \text{GeV},\ \text{SM} = 0.241)\,,$$

where the first error is statistical and the second systematic. Both measurements clearly show a longitudinal polarization of the W bosons as predicted in the SM.

Radiative W-pairs, $\mathrm{W^+W^-}\gamma$, and $\nu\nu\gamma\gamma$ events are used to extend the search for anomalous couplings to quartic terms, that are present if dimension-6

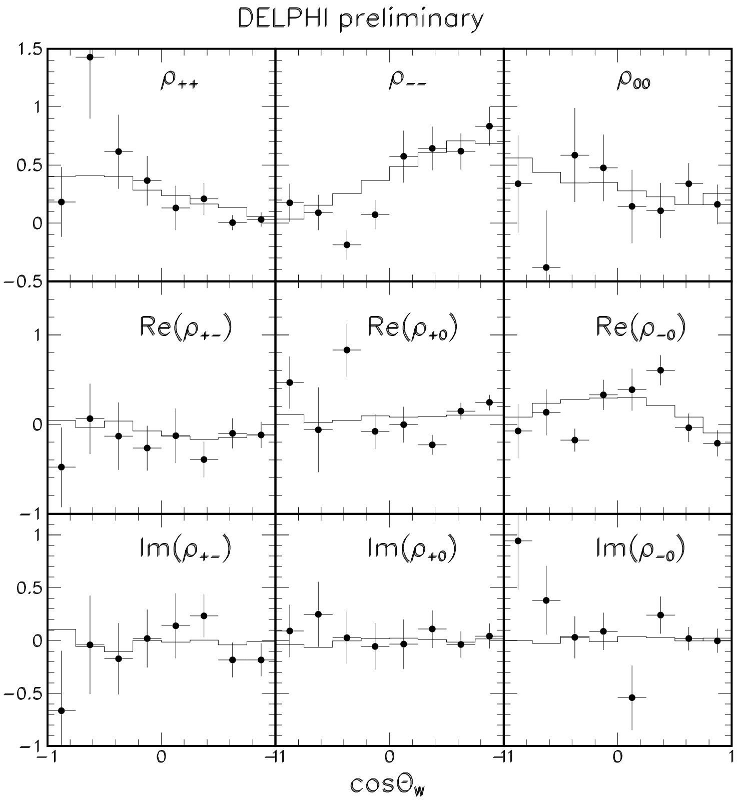

Figure 4: *Elements, ρ_{ij}, of the SDM as determined by the DELPHI collaboration at 189 GeV* [9]*. Data are marked with dots. The solid line shows the SM expectation.*

operators are included into the effective Lagrangian [10]:

$$\mathcal{L}_0 = -\frac{e^2}{16}\frac{a_0}{\Lambda^2}F^{\mu\nu}F_{\mu\nu}\vec{\mathrm{W}}^{\alpha}\cdot\vec{\mathrm{W}}_{\alpha} \tag{5}$$

$$\mathcal{L}_c = -\frac{e^2}{16}\frac{a_c}{\Lambda^2}F^{\mu\alpha}F_{\mu\beta}\vec{\mathrm{W}}^{\beta}\cdot\vec{\mathrm{W}}_{\alpha} \tag{6}$$

$$\mathcal{L}_n = -\frac{e^2}{16}\frac{a_n}{\Lambda^2}\epsilon_{ijk}\mathrm{W}^{(\mathrm{i})}_{\mu\alpha}\mathrm{W}^{(\mathrm{j})}_{\nu}\mathrm{W}^{(\mathrm{k})\alpha}\mathrm{F}^{\mu\nu} \tag{7}$$

The anomalous quartic gauge couplings (QGC) are a_0, a_c and a_n, where the latter one is CP violating. The scale of the new interaction is set by Λ. In general, there are three couplings for each of the heavy gauge bosons, W and Z. Here, only the W couplings are considered. Sensitive variables are the cross-sections $\sigma_{\mathrm{WW}\gamma}$, shown in Figure 5a, and $\sigma_{\nu\nu\gamma\gamma}$, as well as the measured photon spectra, displayed in Figure 5b. Limits on the anomalous QGCs are derived in a combined LEP analysis

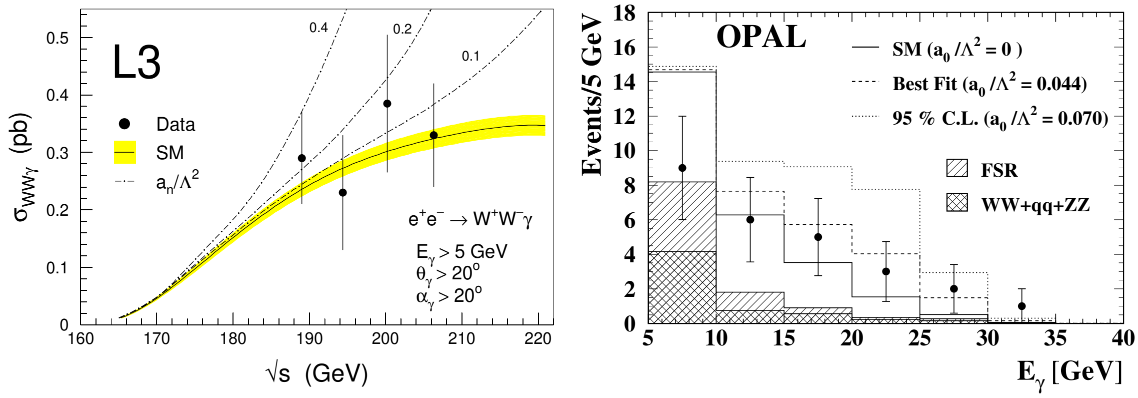

Figure 5: *(a) Measured cross-section of the process* $e^+e^- \rightarrow W^+W^-\gamma$ *compared to the SM prediction as a function of centre-of-mass energy,* $\sqrt{s}$*. The shaded band corresponds to the theoretical uncertainty on the prediction of* $\pm 5\%$*. The dash-dotted lines correspond to the cross-section for the indicated values of* a_n^W/Λ^2*. (b) Energy spectrum as determined in OPAL data and the SM prediction, together with the expected spectrum for the best fit and the 95% upper limit for the coupling* a_0^W*. Coupling values are given in* GeV^{-2} *units.*

at 95% confidence level [7]:

$$
\begin{aligned}
-0.02 \leq \ & a_0^W/\Lambda^2 \cdot \ \mathrm{GeV}^2 & \leq 0.02 \\
-0.03 \leq \ & a_c^W/\Lambda^2 \cdot \ \mathrm{GeV}^2 & \leq 0.05 \\
-0.17 \leq \ & a_n^W/\Lambda^2 \cdot \ \mathrm{GeV}^2 & \leq 0.15 \quad (\mathrm{WW}\gamma \text{ channel only})\,.
\end{aligned}
$$

No deviation of the anomalous couplings from zero is observed.

4 W Mass Measurement and Final State Interactions

A determination of the mass of the W boson is performed at LEP in two ways. At the threshold, $\sqrt{s} \approx 2 \times M_W$, the sensitivity of the W-pair cross-section to the W mass is used to measure M_W. From data at $\sqrt{s} = 161 - 172$ GeV a mass of $M_W = 80.40 \pm 0.22$ GeV is derived. There is, however, only little luminosity collected at threshold, so that the influence on the final result is small.

At higher energies, the WW $\rightarrow$ ffff final state is reconstructed and M_W and Γ_W are derived from the invariant mass spectra of the W decays products. The sensitivity of the event reconstruction method is improved by applying kinematic constraints to the measured fermion energies and angles. In a kinematic fit, these quantities are varied within their resolution imposing energy and momentum conservation. An additional constraint is applied in some analyses by requiring the two

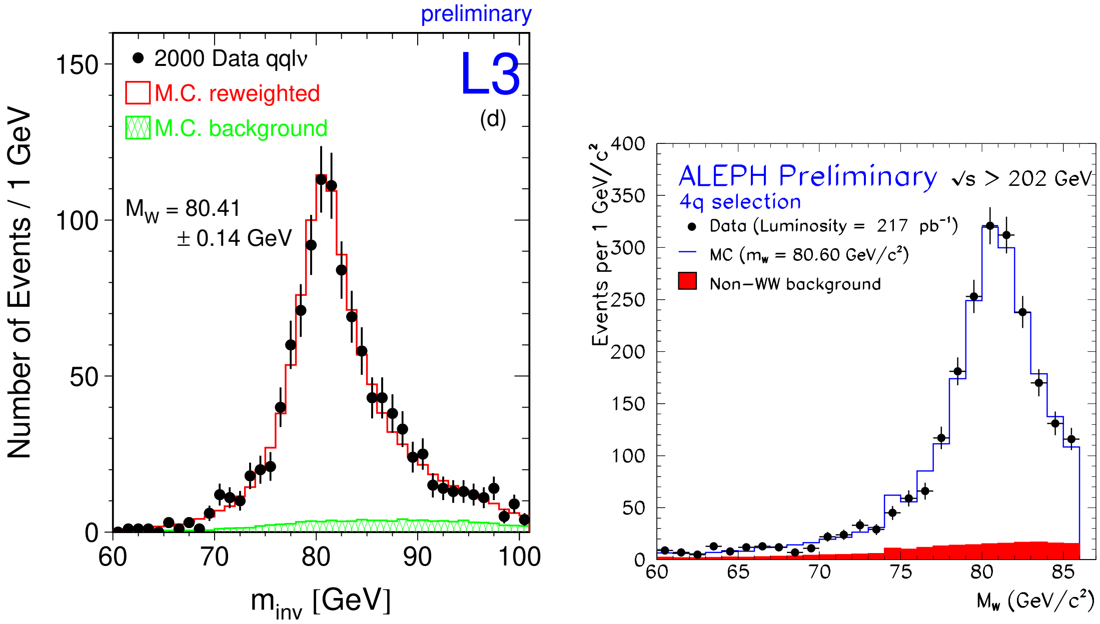

Figure 6: *Distributions of the invariant mass spectra measured in the* qq$\ell\nu$ *and the* qqqq *channel by L3 and ALEPH. Data are shown together with the SM predictions, using an underlying W mass value of* 80.41 GeV *and* 80.60 GeV, *respectively.*

reconstructed W masses to be equal. The kinematic fit is applied in the qqqq and qq$\ell\nu$ channel. It can not be used in the $\ell\nu\ell\nu$ channel because of the two unmeasured neutrinos in the final state. Therefore, the leptonic energy spectrum and the transverse masses of the leptons are analysed in $\ell\nu\ell\nu$ events.

After imposing the kinematic constraints, the invariant mass spectra measured in data are compared to Monte Carlo predictions with different underlying M_{W} values. ALEPH and L3 apply an event reweighting procedure to obtain Monte Carlo samples with varying W masses. Unbinned maximum likelihood fits are then performed to extract M_{W} in the qqqq and qq$\ell\nu$ channel. The reweighting method is free of any bias, as long as the Monte Carlo correctly describes the measured mass spectra. Figure 6 shows the invariant mass distributions after kinematic reconstruction.

The analysis method used by OPAL is based on a Breit-Wigner fit to the mass spectra. The extracted mass values are calibrated with Monte Carlo reference samples with known underlying W masses. DELPHI applies a convolution method, folding a Breit-Wigner function with a resolution curve and a radiator function to parametrize initial-state photon emission. In fully hadronic events also the event-

Source	Systematic Uncertainties on M_{W} in MeV		
	$\mathrm{qq}\ell\nu$	qqqq	combined
Detector Systematics	12	8	10
LEP Beam Energy	17	17	17
ISR/FSR	8	9	8
Hadronisation	19	17	17
Colour Reconnection	–	40	11
BE Correlations	–	25	7
Other	4	4	3
Total Systematic	29	54	30
Statistical	33	30	26
Total	44	62	40

Table 1: *Decomposition of systematic uncertainties in the LEP W mass measurement. The 'Other' category refers to errors due to simulation statistics, background estimation, four-fermion treatment, fitting method and event selection. The uncertainties in the* $\mathrm{qq}\ell\nu$ *and* qqqq *channel are determined from independent and separate fits to the data of the two channels.*

by-event probability density depending on the two invariant masses is included. A remaining mass bias is taken into account and corrected for.

With these refined extraction methods the current statistical uncertainty on M_{W} is 26 MeV combining the four LEP experiments. This error is expected to decrease because not all data are included in the combination[1], and the contribution of the fully hadronic channel is reduced because of systematic uncertainties that currently dominate the qqqq measurement. The weight of the qqqq channel in the LEP combination is only 0.27.

A list of systematic errors is given in Table 1. Detector systematics include uncertainties in the jet and lepton energy scale and in their energy and angular resolution. The knowledge of the LEP beam energy is of great importance because it sets the scale for the W mass measurement. The current preliminary uncertainties on the beam energy [11)] translate into an error on M_{W} of 17 MeV. This value can possibly be reduced to $10 - 15$ MeV [12)].

All mass extraction methods rely on a correct Monte Carlo description of radiative corrections (ISR/FSR) and of fragmentation of quarks. Both error sources are fully correlated between experiments and between different energy points. The fragmentation uncertainty therefore becomes one of the largest systematics in the

[1]OPAL did not yet include the 2000 data.

combined measurement and amounts to 17 MeV. It is determined from comparisons of different fragmentation models, like PYTHIA, HERWIG and ARIADNE [14]. The understanding of the model differences and a better estimation of the model parameters, that are determined from Z resonance data, will help to reduce this error source.

One uncertainty that is only present in the fully hadronic channel are possible interactions in the hadronic final state (FSI), like Bose-Einstein (BE) correlations [15] and Colour Reconnection (CR) [17]. They may lead to cross-talk between the two hadronically decaying W bosons, and the momentum transfer changes the reconstructed invariant masses. Quantitative comparisons show that a common change of the FSI modelling has the same effect on the measurements of the different LEP experiments [18]. BE and CR effects currently contribute with 25 MeV and 40 MeV to the qqqq error.

To probe the existance of FSI in fully hadronic events, dedicated studies are made. BE correlations lead to an enhancement of the production of identical bosons close in phase space. The BE measurements in W pairs mainly concentrate on charged pion production. Assuming a spherical and gaussian shaped source emitting the pions, the two-particle correlation function C can be written as:

$$C(Q_{\pi\pi}) = 1 - \lambda \exp(-R^2 Q_{\pi\pi}^2) \ , \tag{8}$$

where $Q_{\pi\pi}$ is the square of the four-momentum difference of the two pions, $-(p_{\pi,1} - p_{\pi,2})^2$. The parameter λ is the correlation strength and R is the inverse radius of the source. The correlation function is measured in a ratio of two-particle densities $R_2(Q) = \rho_{data}/\rho^{MC}_{noBE}$, where the numerator is measured from data and the denominator determined in a Monte Carlo that does not contain BE correlations. When analysing semi-hadronic W events, it is found that the BE correlations between pions coming from the same W boson agree very well with the correlations observed in Z decays, if Z $\rightarrow$ bb is suppressed. Important for the mass measurement are, however, the correlations between pions from different W bosons. If there are no such correlatations the two-particle density in fully hadronic events can be split into three terms:

$$\rho^{\mathrm{WW}}(1,2) = \rho^{\mathrm{W}+}(1,2) + \rho^{\mathrm{W}-}(1,2) + 2\rho^{\mathrm{W}^+}(1)\rho^{\mathrm{W}^-}(2) \ . \tag{9}$$

The first two terms on the right-hand side of the equation are the density functions for pions coming from the same W. They can be determined in semi-hadronic events. The last term describes the case when one pion comes from one W boson and the

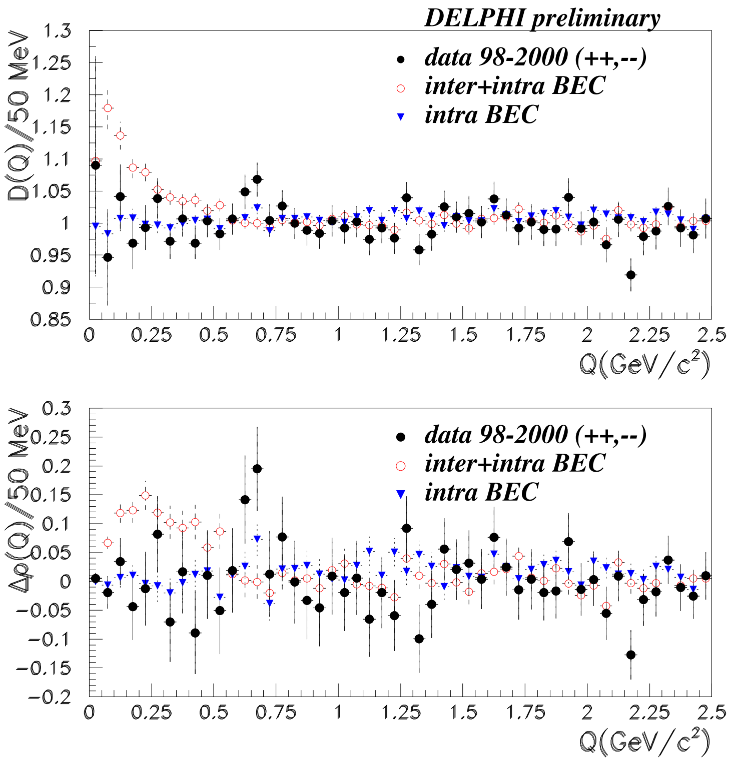

Figure 7: *Distribution of the ratio, D, and the difference, $\Delta\rho$, of the two-particle densities in fully hadronic and semi-hadronic W pair events measured by DELPHI. Data are marked with dots. The expectations in case of absence and existance of BE correlations between pions from different W bosons are marked with open triangles and circles, respectively. Data prefer the absence of those correlations. Similar distributions are obtained by the other LEP experiments* [16].

second from the other W boson. This part can be constructed from a sample of mixed semi-hadronic event: $\rho^{\mathrm{W}^+}(1)\rho^{\mathrm{W}^-}(2) = \rho^{\mathrm{W}^+\mathrm{W}^-}_{\mathrm{mix}}$. If the equation holds, i.e. in absence of BE correlations between two W's, the following ratio and difference of densities

$$D = \frac{\rho^{\mathrm{WW}}}{2\rho^{\mathrm{W}} + 2\rho^{\mathrm{W}^+\mathrm{W}^-}_{\mathrm{mix}}} \tag{10}$$

$$\Delta\rho = \rho^{\mathrm{WW}} - 2\rho^{\mathrm{W}} - 2\rho^{\mathrm{W}^+\mathrm{W}^-}_{\mathrm{mix}} \tag{11}$$

are equal to 1 and 0, respectively. Figure 7 shows the two quantities as a function of Q. The data are consistent with the absence of BE correlations between pions from different W's. Each of the LEP experiments exclude the existance of those

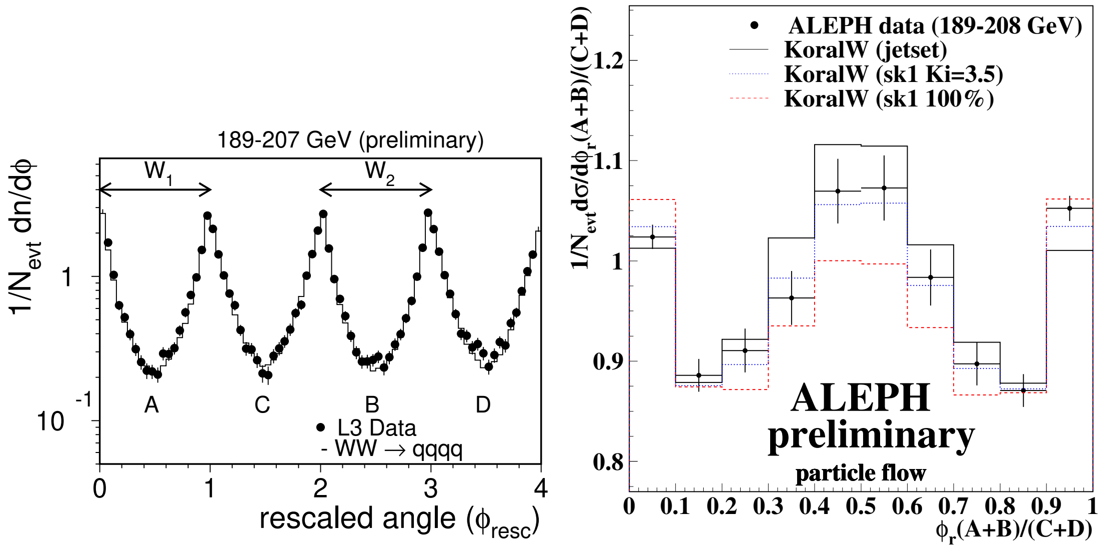

Figure 8: *a) Rescaled angle, $\phi_{\rm resc}$, of the particles measured in* qqqq *events at L3. The jet directions are at integer values of $\phi_{\rm resc}$ by construction. The regions A and B contain particles that point in the region between the two jets of the W bosons. The regions outside the two W bosons are marked with C and D. b) Ratio of the particle flow from regions A+B and C+D. In case of CR the ratio shows a depletion in the central part. ALEPH data are shown together with predictions for a standard Monte Carlo and two scenarios of the SK1 model, one with a reconnection probability of about 70% and one with full reconnnection.*

correlations with a significance of $2-3\sigma$ [16]. Currently, a combination of the BE measurements is in preparation to obtain an upper limit on the correlation strength λ. Preliminary studies show that the corresponding W mass shift is proportional to λ, so that the systematic uncertainty on $M_{\rm W}$ due to BE effects can be reduced.

A similar approach is made in the reduction of the CR uncertainty. CR changes the colour flow in qqqq events, such that not the quarks that originate from the same W form a colour singlet, but the quarks that come from two different W bosons. This obviously changes the development of the fragmentation process. There are many different models [17] that simulate CR, for example the Sjöstrand-Khose (SK) models 1 and 2, the Herwig model, or the Ariadne models 1-3.

CR mainly manifests in a distortion of the W mass distribution. Effects on particle multiplicities are too small to be detected in data [19]. The only other observable sensitive to CR is the particle flow in the regions between the quark jets. Figure 8a shows the angular distribution of particles in qqqq events, after rescaling the angle of the particle to the next jet in such a way that each of the four jets is positioned at an integer angular value. A ratio R is then calculated between the particle flow of the regions that connect two jets of one W and the region that connects two jets of different W's, as displayed in Figure 8b. The R distribution is integrated in the central interval $[0.2, 0.8]$, once for data and for two Monte Carlo sets, where one is generated without CR and the other with full CR according the model SK1. In this way the double ratio $D = (R_{\rm data} - R_{\rm noCR})/(R_{\rm CR} - R_{\rm noCR})$ is zero if no CR effect is seen in data and unity in case of SK1 CR. Since the CR effects increase with $\sqrt{s}$, data from different centre-of-mass energy are combined at a reference value at 189 GeV. The preliminary results of the LEP experiments are [19]

	D
ALEPH	0.52 ± 0.28
DELPHI	-0.01 ± 0.43
L3	0.06 ± 0.20
OPAL	0.68 ± 0.25 .

The data show no clear exclusion of the SK1 model and a combination of the measurements is in preparation to limit the internal parameters of the model. When assigning a systematic uncertainty to the W mass measurement, typically a reconnection probability of 30% is assumed in the CR models. This leads to a systematic error of 40 MeV in the qqqq channel. Eventually, FSI effects may also show up directly in the difference between the fully hadronic and semi-leptonic W mass

$$\Delta M_{\rm W} \;=\; M_{\rm W}({\rm qqqq}) - {\rm M_W}({\rm qq}\ell\nu) = +9 \pm 44 \ {\rm MeV} \ ,$$

where systematic errors due to possible FSI are removed. The observed value is compatible with zero.

With the current systematic errors and all correlations properly included, the LEP W mass measurement split into qq$\ell\nu$ and qqqq channel yields [18]:

$$\begin{aligned} M_{\rm W}({\rm qq}\ell\nu) &= 80.448 \pm 0.033({\rm stat.}) \pm 0.028({\rm syst.}) \ {\rm GeV} \\ M_{\rm W}({\rm qqqq}) &= 80.457 \pm 0.030({\rm stat.}) \pm 0.054({\rm syst.}) \ {\rm GeV} \ , \end{aligned}$$

with a correlation coefficient of 0.28. The combined mass value for all channels is

$$M_{\rm W}({\rm ffff}) \;=\; 80.450 \pm 0.026({\rm stat.}) \pm 0.030({\rm syst.}) \ {\rm GeV} \ ,$$

with a good χ^2/d.o.f of 31.1/35. Including the result derived from the cross-section measurement does not change numerically the above result:

$$M_{\rm W}^{\rm LEP} \;=\; 80.450 \pm 0.039 \ {\rm GeV} \ .$$

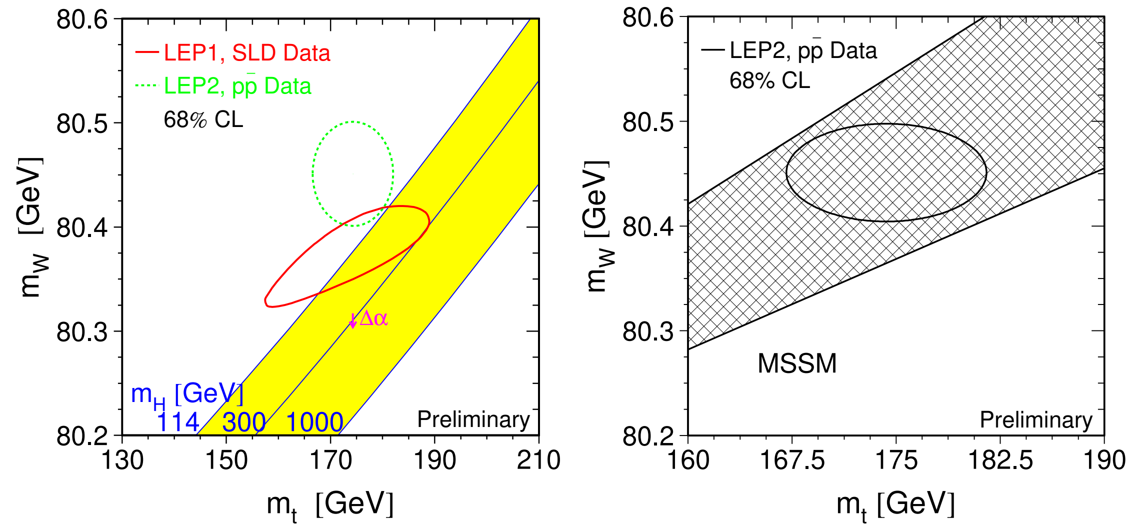

Figure 9: *a) Countour curves for the direct and indirect measurement of M_{W} and M_{t} compared to the SM prediction for different values of M_{H}. b) The direct M_{W} and M_{t} measurements compared to the MSSM prediction* [24]*. The upper boundary corresponds to a set of MSSM parameters with light supersymmetric particles, and the lower boundary corresponds to heavy supersymmetric particles. The exclusion limits from searches for new particles at LEP are taken into account in the calculation. The MSSM and SM areas overlap in the region where the mass of the SM Higgs boson is in the MSSM range, i.e. for $M_{\mathrm{H}} \lesssim 130$ GeV.*

The method of direct reconstruction is also well suited to measure the width of the W boson, Γ_{W}. A combined fit to the LEP data yields [18]:

$$\Gamma_{\mathrm{W}}^{\mathrm{LEP}} = 2.150 \pm 0.091 \text{ GeV} ,$$

and agrees well with the SM prediction of $\Gamma_{\mathrm{W}} = 2.102$ using the LEP W mass cited above.

Other direct W mass measurements performed at $\mathrm{p\bar{p}}$ colliders [20] are in good agreement with the LEP result. The combination of all direct W mass determinations results in [21]:

$$M_{\mathrm{W}}^{\mathrm{LEP+p\bar{p}}} = 80.451 \pm 0.033 \text{ GeV} .$$

This value is also very consistent with the indirect determination of the W mass from an analysis of the LEP and SLD electroweak data, which yields $M_{\mathrm{W}} = 80.372 \pm$

0.033 GeV [21]. The recent result obtained in νN scattering by NUTEV, $M_{\rm W} = 80.136 \pm 0.084$ GeV [22], which is derived from the measurement of the electroweak mixing angle, $\sin^2\theta_w$, deviates from the LEP result by 3.5 σ. However, there is no systematic effect found that may cause this difference.

The W mass is an important parameter in the SM. The precise measurement of $M_{\rm W}$ probes the SM at the level of its radiative corrections. A comparison of the direct and indirect W mass determinations is shown in Figure 9a in the plane of W mass and top quark mass, $M_{\rm t}$, that is measured at the Tevatron [23]. Good agreement between the two sets of measurements is observed. Also shown is the SM prediction for various values of the mass of the Higgs boson, $M_{\rm H}$. The measurements prefer small values of $M_{\rm H}$.

In a supersymmetric extension of the theory, the Minimal Supersymmetric Standard Model (MSSM), the preferred $M_{\rm W}$-$M_{\rm t}$ area differs slightly from the SM prediction. Additional radiative correction terms, involving supersymmetric particles, shift the $M_{\rm W}$-$M_{\rm t}$ band to larger values of $M_{\rm W}$. The MSSM prediction [24] is shown in Figure 9b. The current data tend to agree better with the MSSM area than with the SM, but the experimental precision is not accurate enough to be decisive. However, the electroweak data gives motivation to continue the search for the Higgs boson, as the last missing piece of the SM, and for supersymmetric particles at the Tevatron and at future LHC experiments.

5 Conclusion

At LEP many properties of the W boson are measured. W-pair and single-W production cross-sections as well as the W decay fractions are found to be in good agreement with the SM. Trilinear couplings of the W bosons to γ or Z are determined with an accuracy of ± 0.02 to ± 0.05. All gauge couplings are consistent with their SM expectation and no anomalous contribution is found. The mass and width of the W boson are measured precisely: $M_{\rm W}^{\rm LEP} = 80.450 \pm 0.039$ GeV and $\Gamma_{\rm W}^{\rm LEP} = 2.150 \pm 0.091$ GeV. Exploiting the results on FSI, the $M_{\rm W}$ measurement is expected to reach a final accuracy of $30 - 35$ MeV, completing the many precision tests of the SM performed at LEP.

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