W physics at LEP

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A review of the measurements on the production and decay of the W bosons created in e^+e^-collisions at LEP is presented. Properties such as the branching ratios into quarks and leptons, and couplings to other neutral gauge couplings are reported. Also the W-pair and single-W cross-sections are determined and a precise measurement of the W mass and width at LEP is presented.

1 Introduction

The success of the Standard Model (SM) of particle physics in describing all interactions of quarks and leptons at the Z resonance (LEPI) confirmed that quantum radiative corrections at the one-loop level are required [1]. There are two classes of interesting loop corrections: the first associated with the running of α, the electromagnetic coupling constant and the second including heavy bosonic loops (W,Z). A stringent test of the existence of the latter requires a precise direct measurement of the mass of the W, (M_{W}) which is of fundamental importance in this model. At LEP1, M_{W} is inferred indirectly from the following relation using the precisely known Fermi constant, G_μ, derived from the muon lifetime:

$$M_{\mathrm{W}}{}^2(1-\frac{M_{\mathrm{W}}{}^2}{M_{\mathrm{Z}}{}^2})=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r_w+\Delta\alpha)$$

where M_{Z} is the Z mass. The terms $\Delta\alpha$ and Δr_w represent the electromagnetic (due mainly to light fermion loops) and the bosonic corrections respectively, amounting overall to a correction of $\sim -3\%$. The latter depends on the top mass (m_{t}) squared and to a smaller extent logarithmically on the Higgs boson mass ($\ln(m_{\mathrm{H}})$). From the measured value of m_{t} and all measurements performed at the Z resonance, the predicted value of M_{W} is 80.379 ± 0.023 GeV. One of the primary aims of LEP2 is to perform a direct measurement of M_{W} comparable or better in precision than this SM prediction. This can be used to set new constraints on m_{H}. Any significant deviation of M_{W} towards higher mass value than predicted might point to new physics.

A second important test of the SM is the structure of the triple gauge couplings (TGC's:WWγ and WWZ). They play a direct role at the tree level in the W-pair cross

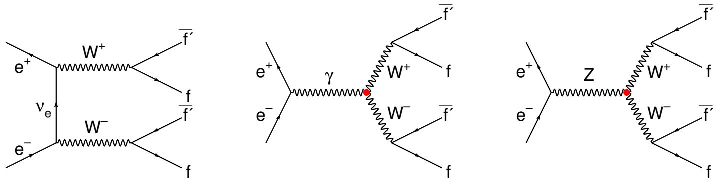


Fig. 1: Lowest order processes contributing to a WW final state in e^+e^- annihilations.

section in contrast to the Z resonance where they enter only through loops. The non-Abelian (Yang-Mills) nature of the TGCs can be established by studying the differential cross sections and topology of the W-pair events in detail.

LEP2 ran just above the WW production threshold in 1996 at a centre-of-mass (CM) collision energy of 161 GeV and this increased every year to reach 207 GeV in 2000. The data collected by the four LEP experiments, ALEPH, DELPHI, L3, and OPAL, in this energy range corresponds to an integrated luminosity of about $4 \times 700\mathrm{pb}^{-1}$. Each experiment registered about 10000 W-pair events. Their analysis allows a precise measurement of the properties of the W boson and a vital test of the SM.

2 W-pair and single-W production

W bosons are predominantly produced, at LEP, in pairs through the reaction $e^+e^- \to WW$, which is described in the SM by the three charged current (CC03) Feynman diagrams shown in figure 1. Each of the W's subsequently decays either hadronically ($q_1\bar{q}_2$), or leptonically ($\ell^-\bar{\nu_\ell}, \ell = e, \mu, \tau$). This yields three possible four-fermion final states (figure 2), hadronic ($q_1\bar{q}_2 q_3\bar{q}_4$), semi-leptonic ($q_1\bar{q}_2\ell\bar{\nu_\ell}$) and leptonic ($\ell^+\nu_\ell\ell'^-\bar{\nu_{\ell'}}$), with branching fractions of 45%, 44% and 11% respectively.

The LEP collaborations use separate selections to identify the three topologies [2]. The main characteristics of $q\overline{q}q\overline{q}$ events are the large visible energy and high multiplicity. A neural network is used to separate these events from the $q\overline{q}$ background yielding efficiencies of around 90%. The semileptonic selection, $q\overline{q}\ell\overline{\nu}_\ell$ is based on the identification of a high momentum lepton, two hadronic jets and missing energy in the event. The efficiencies for this channel are between $50-85\%$ depending on the lepton flavour. In the fully leptonic channel the identification is done by requiring two acoplanar and acollinear high momentum leptons, and missing energy in the event. In this case the efficiencies range from $20-60\%$ being the lowest for the cases in which one (or the two leptons) is a τ.

From these channels the W branching ratios are extracted (table 1). The results agree with the hypothesis of lepton universality, within the statistical error, and can be combined to $\mathrm{Br}(W\to l\nu)=10.69 \pm 0.09\%$. The hadronic branching ratio is determined assuming lepton universality and it is in agreement with the SM expectation of 67.51%.

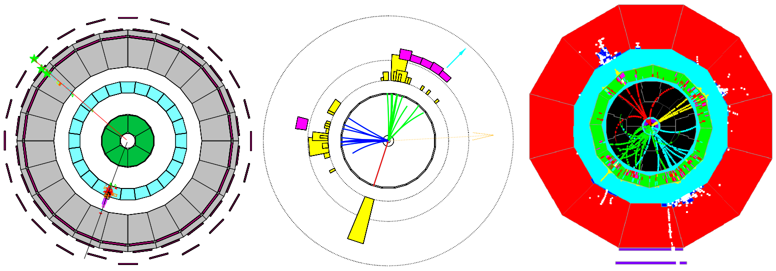


Fig. 2: Event displays corresponding to the three topologies of the final states: $\ell\nu\ell\nu$ (**left**), $\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ (**center**) and $\mathrm{q\overline{q}q\overline{q}}$ (**right**), collected by the DELPHI, ALEPH and OPAL experiments respectively.

Channel	$\mathrm{W} \to \mathrm{e}\nu_\mathrm{e}$	$\mathrm{W} \to \mu\nu_\mu$	$\mathrm{W} \to \tau\nu_\tau$	$\mathrm{W} \to \mathrm{q_1\bar{q}_2}$
Branching ratio (%)	10.54 ± 0.17	10.54 ± 0.16	11.09 ± 0.22	67.92 ± 0.27

Table 1 W branching ratio measurements at LEP2.

The hadronic branching fraction is related to the CKM matrix elements, V_{ij}, through the relation

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

where the sum extends over $i = \mathrm{u, c}$ and $j = \mathrm{d, s, b}$. Assuming unitarity of the CKM matrix and since five of the matrix elements are well measured or contribute negligibly to the sum of squares [3], one can derive a value for $|V_{cs}|$ of 0.996 ± 0.013 [4].

The total production cross section, σ_{WW}, measured at each CM energy is shown in figure 3 together with the theoretical prediction calculated with the YFSWW and RacoonWW Monte Carlo programs [5]. Figure 3 a also shows 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 $\mathrm{SU(2) \times U(1)}$ gauge structure of the SM. Taking the ratio of the measured to predicted cross-section, as shown in Figure 3 b, and combining all data, the value obtained for $\sigma_{\mathrm{WW}}/\sigma_{\mathrm{theo}}$ is 0.997 ± 0.011[4], perfectly consistent with unity. To match the data precision, the SM predictions need to take into account higher-order photonic and electroweak corrections, as it is done in RacoonWW and YFSWW, with a theoretical uncertainty of 0.5% on σ_{WW}.

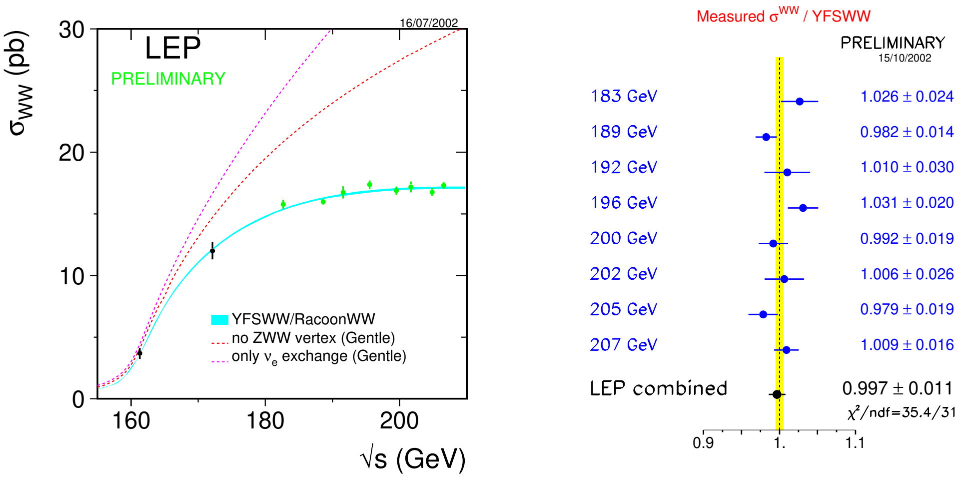


Fig. 3: (a) Total WW production cros-section, σ_{WW}, compared to the SM prediction and the scenarios where the couplings to the other gauge bosons are absent. (b) The ratio, $\sigma_{\mathrm{WW}}/\sigma_{\mathrm{theo}}$, measured at different $\sqrt{s}$ and their combined value.

WW production with an additional photon detected, $\mathrm{e}^+\mathrm{e}^-\to\mathrm{WW}\gamma$, inside a defined phase space region has also been studied at LEP. This kind of events provides a tool to test the implementation of radiative corrections and it is also used for anomalous $\mathrm{WW}\gamma\gamma$ and $\mathrm{WW}\gamma\mathrm{Z}$ couplings (figure 6a).

3 Other 4-fermion processes

In $\mathrm{e}^+\mathrm{e}^-$collisions W bosons can not only be produced in pairs but also through $\mathrm{W}\gamma$ fusion in the t-channel or W-bremsstrahlung, leading to a $\mathrm{e}\nu_{\mathrm{e}}\mathrm{W}$ final state. Single-W production is characterized by an electron scattered at small angles with respect to the beam direction. Combining the data of the four LEP experiments the measured single-W cross-section is shown in figure 4a as a function of $\sqrt{s}$. The results are in good agreement with the theoretical predictions of WPHACT and grc4f [6].

At CM energies exeeding twice the Z boson mass, pair production of Z bosons is kinematically allowed and in fact represents one of the main backgrounds in the direct search of the Higgs boson. Figure 4b shows the measurement of the ZZ cross-section as

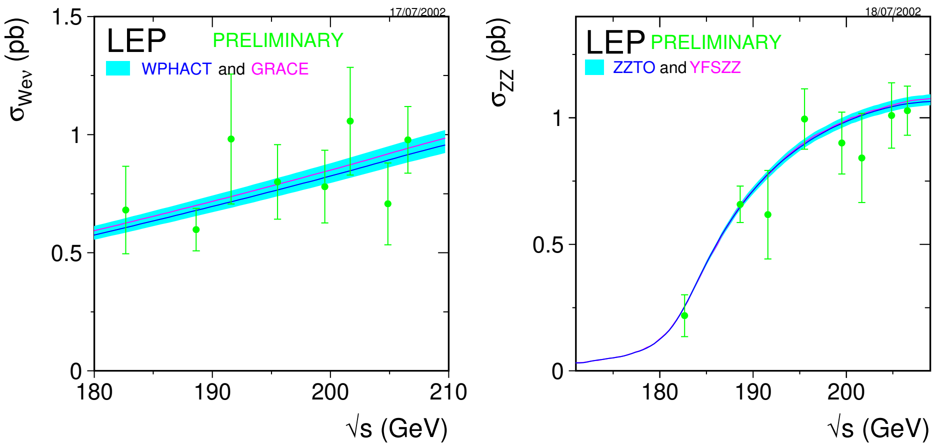


Fig. 4: (a) Measurement of the single-W production cross-section and (b) ZZ pair production cross section, as a function of the CM energy together withe the SM prediction. The shaded areas represent the uncertainties on the predictions.

a function of the CM energy, where they are compared to the theoretical predictions [7].

4 Gauge Couplings

One of the fundamental predictions of the electroweak theory is the self-coupling of the gauge bosons W, Z and γ due to the non-Abelian nature of the gauge fields. In general, there are seven unique Lorentz invariant couplings for each of the WWV vertex, where V denotes the neutral vector bosons γ and Z. Assuming electromagnetic gauge invariance, charge conjugation and parity conservation and using also constraints from low energy data reduces the number of couplings from 14 in the most general case to three $\{g_1^{\mathrm{Z}}, \kappa_\gamma, \lambda_\gamma\}$ [8]. In the SM they are predicted to be $g_1^{\mathrm{Z}} = \kappa_\gamma = 1, \lambda_\gamma = 0$.

The photonic couplings λ_γ and κ_γ are related to the magnetic and electric properties of the W-boson. One can write the lowest order terms for a multipole expansion describing the W-γ interaction as a function of λ_γ and κ_γ. For the magnetic dipole moment μ_W and the electric quadrupole moment q_W one obtains:

$$\mu_W = \frac{e}{2M_{\mathrm{W}}}\left(1 + \kappa_\gamma + \lambda_\gamma\right),$$

$$q_W = -\frac{e}{M_{\mathrm{W}}{}^2}\left(\kappa_\gamma - \lambda_\gamma\right).$$

Deviations of κ_γ and λ_γ from their SM values would therefore prove the existence of anomalous electromagnetic moments of the W boson and thus indicate the presence of new physics.

At LEP2 these coupling parameters can be probed in W-pair production, single-W and single-γ production and in $\mathrm{e^+e^-} \rightarrow \nu\nu\gamma$. To increase the sensitivity to the couplings, not only the total cross-sections of the processes are used, but also differential distributions, like in the case of W-pairs the decay angles of the W boson and the W^- production angle (figure 5a). 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 likelihood curves obtained by the four LEP experiments are shown in Figure 5b. The combination of the measurements, taking systematic errors and their correlations properly into account, yields[9]:

Parameter	68% C.L.	95% C.L.
g_1^{Z}	$0.998^{+0.023}_{-0.025}$	[0.951, 1.043]
κ_γ	0.943 ± 0.055	[0.835, 1.052]
λ_γ	-0.020 ± 0.024	[−0.067, 0.028]

Table 2 The combined 68% C.L. errors and 95% C.L. intervals obtained combining the results from the four LEP experiments. In each case the parameter listed is varied while the other two are fixed to their Standard Model values. Both statistical and systematic errors are included.

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 -0.039 for κ_γ[9].

Radiative W-pairs, $\mathrm{WW}\gamma$, and $\nu\nu\gamma\gamma$ events are used to extend the search for anomalous couplings to quartic terms. At LEP2 CM energies the contribution of four-boson vertex diagrams, predicted by the SM are negligible with respect to other competing diagrams, mainly initial state radiation. The study of the $\mathrm{WW}\gamma$ process is thus sens itive to anomalous quartic gauge couplings in both the $\mathrm{WWZ}\gamma$ and $\mathrm{WW}\gamma\gamma$ vertices. The SM Lagrangian can be extended to include 6-dimensional operators proportional to the three anomalous quartic gauge couplings [10], a_0/Λ^2, a_c/Λ^2 and a_n/Λ^2, where Λ^2 represents the energy scale for new physics.

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

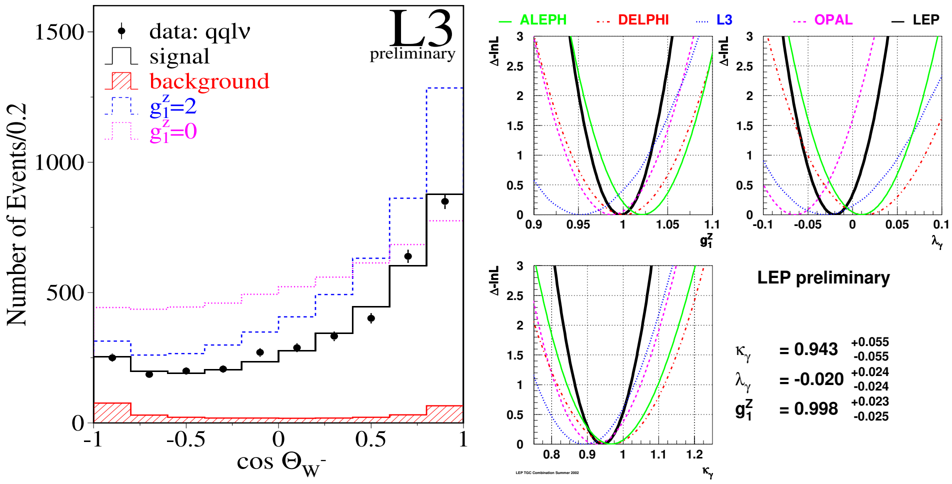


Fig. 5: (a) Distribution of the W^- production angle measured in $qq\ell\nu$ events. Data are shown together with the SM expectation as well as the differential distribution in case of anomalous values of the g_1^Z coupling. (b) Log($\mathcal{L}$) curves for the TGCs.

$$\mathcal{L}_c = -\frac{e^2}{16}\frac{a_c}{\Lambda^2}F^{\mu\alpha}F_{\mu\beta}\vec{\mathrm{W}}^{\beta}\cdot\vec{\mathrm{W}}_{\alpha} \tag{3}$$

$$\mathcal{L}_n = -\frac{e^2}{16}\frac{a_n}{\Lambda^2}\epsilon_{ijk}\mathrm{W}^{(\mathrm{i})}_{\mu\alpha}\mathrm{W}^{(\mathrm{j})}_{\nu}\mathrm{W}^{(\mathrm{k})\alpha}\mathrm{F}^{\mu\nu} \tag{4}$$

Sensitive variables to the anomalous quartic gauge couplings are the WWγ cross section (figure 6a) and the measured photon spectra in $\nu\nu\gamma\gamma$ events. The limits obtained combining L3 and OPAL results, at 95% CL, are:

$$-0.009 \leq \quad a_0^{\mathrm{W}}/\Lambda^2\cdot\mathrm{GeV}^2 \quad \leq 0.026$$
$$-0.033 \leq \quad a_c^{\mathrm{W}}/\Lambda^2\cdot\mathrm{GeV}^2 \quad \leq 0.046$$

In the SM the existence of all three W helicity states, +1, -1 and 0, is directly related to the mechanism of electroweak symmetry breaking. The measurement of the fraction of longitudinally polarized W bosons is therefore a crucial test of the SM. The different helicity states results in different angular distributions of the W decay products. Figure 6 b shows the angle between the lepton from the W decay and the W in the W rest frame. The result of a fit to the $\cos\theta^*$ distribution is also shown.

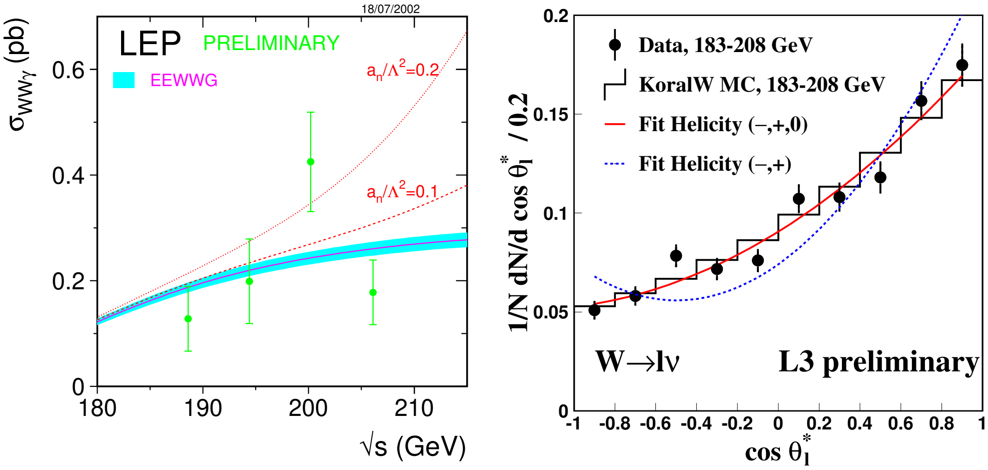


Fig. 6: (a) Measured cross-section of the process $e^+e^- \to WW\gamma$ compared to the SM prediction as a function of centre-of-mass energy, $\sqrt{s}$. The shaded band corresponds to the theoretical uncertainty on the prediction of $\pm 5\%$. The dash-dotted lines correspond to the cross-section for the indicated values of $a_n^{\mathrm{W}}/\Lambda^2$. (b) Angle between the lepton and the W in the W rest frame in $W \to l\nu$ decays.

The data is well described by the fit only if all three helicity states are used. The fraction of longitudinally polarized W bosons is shown in table 3 for L3 and OPAL experiments [11].

	σ_L/σ	SM
L3	$0.228 \pm 0.027 \pm 0.012$	0.241 at $<\sqrt{s}>= 197$ GeV
OPAL	$0.210 \pm 0.033 \pm 0.016$	0.257 at $\sqrt{s} = 189$ GeV

Table 3 Measured fraction of longitudinally polarized W

5 W-boson Mass and width

Two main methods have been employed to measure M_{W} at LEP2. The first exploits the sensitivity of the WW production cross section to M_{W} for CM energies close to threshold. In 1996, each of the four LEP experiments collected about 10 pb^{-1} of data at 161 GeV, resulting in a combined determination of the W mass of $M_{\mathrm{W}} = 80.40 \pm 0.20$ (exp.) $\pm\, 0.03$ (LEP)GeV. The quoted uncertainties are the total experimental and LEP beam energy errors respectively.

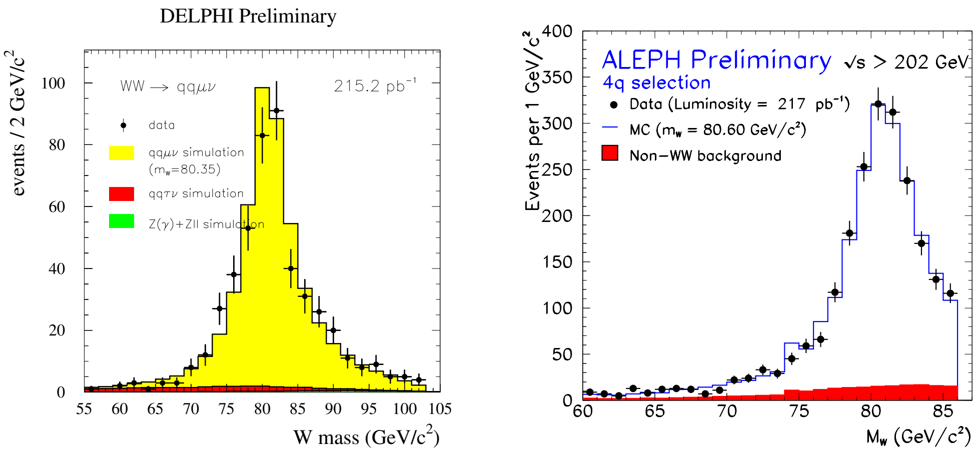


Fig. 7: Reconstructed invariant mass distribution for the (a) $\mathrm{q\overline{q}q\overline{q}}$ channel and (b) $\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ channel.

The second method measures M_{W} by direct reconstruction of the invariant mass of the W decay products. This method has taken over above threshold where the cross section is much larger (~ 16 pb) and no longer sensitive to M_{W}. Since most of the LEP2 data have been collected at CM energies well above threshold, the mass and width measurements are derived almost entirely from the direct reconstruction method. Using a kinematic fit to force the events to fulfill the energy and momentum conservation leads to a significant improvement in the resolution of the W mass. An additional constraint is applied in some analysis by requiring the two reconstructed W masses to be equal. The kinematic fit is applied in the $\mathrm{q\overline{q}q\overline{q}}$ and $\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ channel. It cannot be used in the $\ell\overline{\nu}_\ell\ell\overline{\nu}_\ell$ channel because of the two unmeasured neutrinos in the final state. Therefore, the leptonic energy spectrum and the transverse masses of the leptons are analyzed in $\ell\overline{\nu}_\ell\ell\overline{\nu}_\ell$ events.

After imposing the kinematic constraints, the invariant mass spectra measured in data are compared to Monte Carlo (MC) predictions with different underlying M_{W} and Γ_{W} values. ALEPH and L3 apply an event re-weighting procedure to obtain MC samples with varying W masses. Unbinned maximum likelihood fits are then performed to extract M_{W} in the $\mathrm{q\overline{q}q\overline{q}}$ and $\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ channel. The re-weighting method is free of any bias, as long as the MC correctly describes the measured mass spectra. Figure 7 shows the invariant mass distributions after kinematic reconstruction OPAL analysis method

Source	Systematic Error on M_W (MeV)		
	$q\overline{q}\ell\overline{\nu}_\ell$	$q\overline{q}q\overline{q}$	Combined
ISR/FSR	8	8	8
Hadronisation	19	18	18
Detector Systematics	12	8	11
LEP Beam Energy	17	17	17
Colour Reconnection	–	90	9
Bose-Einstein Correlations	–	35	3
Other	4	5	4
Total Systematic	29	101	30
Statistical	33	36	30
Total	44	107	42
Statistical in absence of Systematics	32	29	22

Table 4 Error decomposition for the combined LEP W mass results. Detector systematics include uncertainties in the jet and lepton energy scales and resolution. The 'Other' category refers to errors, all of which are uncorrelated between experiments, arising from: simulation statistics, background estimation, four-fermion treatment, fitting method and event selection. The error decomposition in the $q\overline{q}\ell\overline{\nu}_\ell$ and $q\overline{q}q\overline{q}$ channels refers to the independent fits to the results from the two channels separately.

is based on a Breit-Wigner fit to the invariant mass spectra. The extracted mass values are calibrated using MC reference samples with known W mass. DELPHI applies a convolution method, folding a Breit-Wigner function with a resolution curve and a function to parametrize initial-state photon emission.

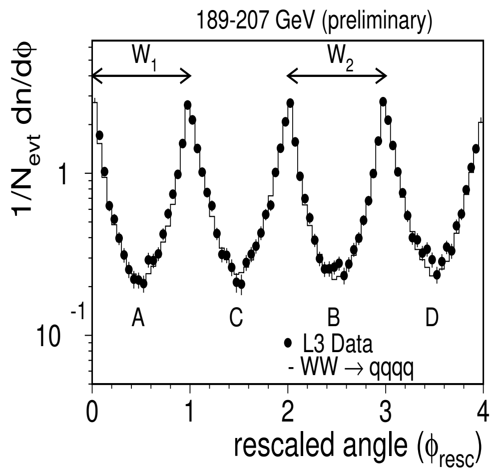
The LEP combined result for the W mass from direct reconstruction [12] is:

$$M_{\mathrm{W}} = 80.447 \pm 0.030(\mathrm{stat}) \pm 0.030(\mathrm{syst})\,\mathrm{GeV}$$

The weight of the hadronic channel in the combined fit is only 0.09. This is a consequence of the relatively large size of the current estimates of the uncertainty coming from the Final State Interactions in this channel. Table 4 shows the contribution of the various sources of systematic errors on the W mass. The hadronization uncertainty is determined by comparing different fragmentation models like PYTHIA, HERWIG and ARIADNE [13].

The width of the W boson measured at LEP is:

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



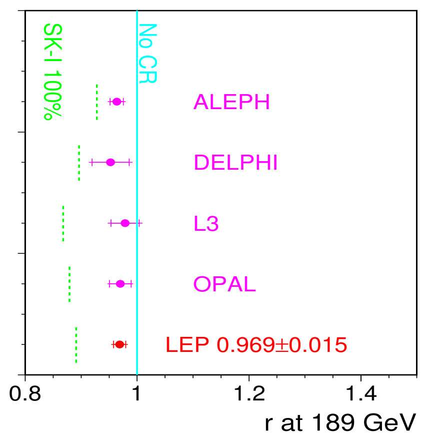


Fig. 8: (a) Particle flow distribution as a function of the rescaled angle for data and KORALW prediction. (b) Average value of r compared to the SKI model 100

6 Final State Interactions

Due to the relatively short distance separating the decay vertices of the W bosons produced in e^+e^- annihilations (~ 0.1 fm) compared to the typical hadronisation scale (1 fm) it is possible that partially overlapping hadronic systems from different W bosons are interacting. These so-called Final State Interactions (FSI) would undermine the hypothesis of two independent W bosons decays and lead to a change of the kinematic properties of the event. There are two different types of FSI to be considered.

The first one is Colour Reconnection (CR). The original colour singlets $W \rightarrow \mathrm{q}_1\bar{\mathrm{q}}_2$ and $\mathrm{W} \rightarrow \mathrm{q}_3\bar{\mathrm{q}}_4$ could rearrange in alternative $\mathrm{q}_1\bar{\mathrm{q}}_4$ and $\mathrm{q}_3\bar{\mathrm{q}}_2$ colour singlets via hard gluon exchange. This rearrangement probability is proportional to $(\alpha_s^2\Gamma_{\mathrm{W}})/(N_c^2 M_{\mathrm{W}})$, where α_s is the coupling constant of the strong interaction, Γ_{W} the width of the W and N_c the number of colours, it is less than 10^{-3}; hence very unlikely. However, CR might occur at the non-perturbative stage of the hadronisation cascade. In this cascade, colour fluxes between quark and gluons from the two fragmenting W systems may overlap. If so, there is some probability for CR to occur in this overlap region. Only phenomenological models [14] are able to simulate this non-perturbative reconnection effect. According to these models, CR results in some depletion and/or enhancement of soft particles in specific phase space regions leading to a bias in the reconstruction of the W decay products. Depending on the model used to simulate the CR effect the bias in W mass extracted in the $\mathrm{q\bar{q}q\bar{q}}$ channel may vary between 0 and 90 MeV.

A sensitive variable to CR is the particle flow in the regions between the quark jets.

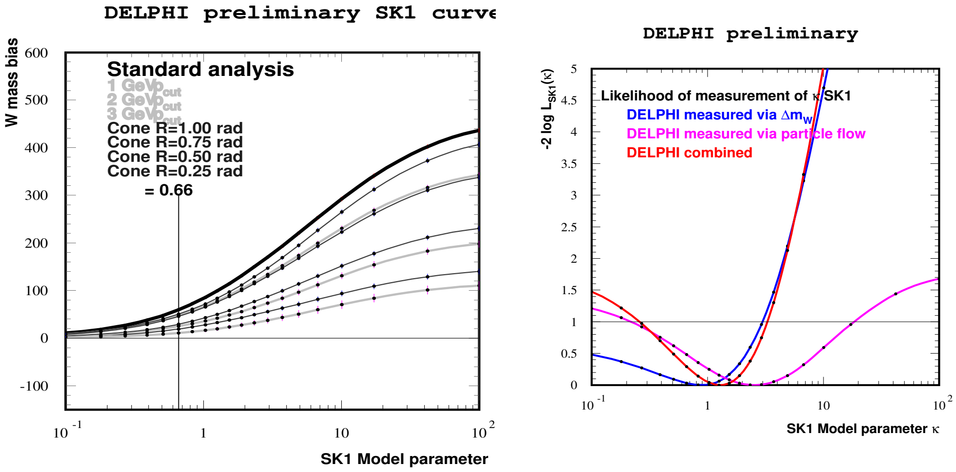


Fig. 9: (a) $M_{\rm W}(\kappa=0)$-$M_{\rm W}(\kappa)$ as a function of κ for different vaules of the p_{cut} and the cone radii. (b) The red curve shows the inferred likelihood function $\mathcal{L}(\kappa)$ from the combined measurement via $\Delta M_{\rm W}(std, R_{cone}=0.5rad)$ and the particle flow method.

Figure 8a shows the angular distribution of particles in $\rm q\overline{q}q\overline{q}$ events, after rescaling the angle of the particle to the next jet in such a way th at each of the four jets is positioned at an integer angular value.

In order to quantify the CR effect the ratio, R_N, between the particle flow in regions A+B and C+D is calculated in a restricted interval of the rescaled angle [15]. To compare the values obtained by the four LEP experiments R_N is normalized to a MC sample without CR, $r = R_N^{data}/R_N^{MCnoCR}$ (figure 8 b). The data disagree with the extreme scenario of the model SKI at a level of 5.2σ of the total error. The data are consistent with an intermediate CR scenario.

A new study on CR shows that different $M_{\rm W}$ estimators have different sensitivity to the model parameters used to describe the CR effect [16]. It has been observed that the $M_{\rm W}$ observable inferred from direct reconstruction is influenced when changing the value of κ[1] for the SKI model [17]. Alternative observables can be designed to have different sensitivity to κ. DELPHI has studied two new observables: $M_{\rm W}$ calculated when removing low momentum particles from the event (p_{cut} analysis), and $M_{\rm W}$ excluding particles at large angles with respect to the jet direction (cone analysis). Figure 9a shows the difference $M_{\rm W}(\kappa=0)$-$M_{\rm W}(\kappa)$ as a function of κ for different values of the p_{cut} and cone size. The influence of CR is decreased when removing low momentum particles, or when using the cone algorithm. On the other hand when neglecting part of the information of the event the statistical uncertainty on the value of the $M_{\rm W}$ estimator

[1] κ is the free strength parameter that controls the reconnection probability for the SKI model.

is increased. Taking into account statistical and systematic uncertainties DELPHI's largest sensitivity to CR is obtained using the cone analysis for a cone cut of 0.5 rad. By comparing the observed value of $\Delta M_{\mathrm{W}}(std, R_{cone} = 0.5_{rad}) = 36 \pm 36 \pm 25$ MeV with the MC expected value for different hypothesis of κ a measurement of κ is done using the log−likelihood function shown in figure 9 b . The measured value of κ using the ΔM_{W} method and the particle flow method is 1.3 and the 68% CL is $0.3 < \kappa < 3.3$

The second type of interaction is Bose-Einstein correlations (BEC). This effect is quantum mechanical in origin and manifests itself as an enhancement of the production of identical bosons close in phase space. BEC effects are usually studied in terms of two-particle correlation function $\rho(Q)$ where Q is the 4-momentum difference between two particles : $Q^2 = -(p_1 - p_2)^2$. To remove the existence of other correlations the correlation function is defined as $R_2 = \rho_{data}/\rho_{MCnoBE}$, which should be equal to one in the absence of BE correlations. BEC have been observed for two or more identical bosons ($\pi\pi$, KK, etc...) produced in Z decays and single W (intra-W BEC) decays (figure 10 a). They are in very good agreement when b decays of the Z are suppressed. Additional correlations between particles coming from different Ws (inter-WW BEC) might exist inducing a possible shift in the reconstructed W mass. In the absence of such correlations the two-particle density in fully hadronic events can be written as [18]:

$$\rho^{\mathrm{WW}}(1,2) = \rho^{\mathrm{W+}}(1,2) + \rho^{\mathrm{W-}}(1,2) + 2\rho^{\mathrm{W}^+}(1)\rho^{\mathrm{W}^-}(2)\ . \tag{5}$$

where $\rho^{\mathrm{W+}}(1,2)$ and $\rho^{\mathrm{W-}}(1,2)$ are the density functions for pions coming from the same W and $\rho^{\mathrm{W}^+}(1)\rho^{\mathrm{W}^-}(2)$ is the two particle density when the pions come from different W's. The first two terms can be measured in the hadronic decay of a semileptonic W event and the last one is measured in a sample of mixed events $\rho^{\mathrm{W}^+}(1)\rho^{\mathrm{W}^-}(2) = \rho^{\mathrm{W}^+\mathrm{W}^-}_{\mathrm{mix}}$ [18]. Using equation 5 one can define the ratio and difference of densities as:

$$D = \frac{\rho^{\mathrm{WW}}}{2\rho^{\mathrm{W}} + 2\rho^{\mathrm{W}^+\mathrm{W}^-}_{\mathrm{mix}}} \tag{6}$$

$$\Delta\rho = \rho^{\mathrm{WW}} - 2\rho^{\mathrm{W}} - 2\rho^{\mathrm{W}^+\mathrm{W}^-}_{\mathrm{mix}} \tag{7}$$

In the absence of BEC between the two W's D is equal to 1 and $\Delta\rho = 0$. Figure 10 b shows the average value of the fraction of the model, as implemented in LUBOEI [19] to simulate inter-W BEC, seen by the ALEPH and L3 experiments. Data are compatible with $3\% \pm 18\%$ full BEC which would transform into 10 MeV uncertainty in the W mass (this is not yet taken into account).

Eventually, FSI effects may show directly in the difference between the fully hadronic mass and the semi-leptonic W mass:

$$\Delta M_{\mathrm{W}} = M_{\mathrm{W}}(\mathrm{q\overline{q}q\overline{q}}) - M_{\mathrm{W}}(\mathrm{q\overline{q}}\ell\overline{\nu}_\ell) = -9 \pm 44 \mathrm{MeV}$$

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

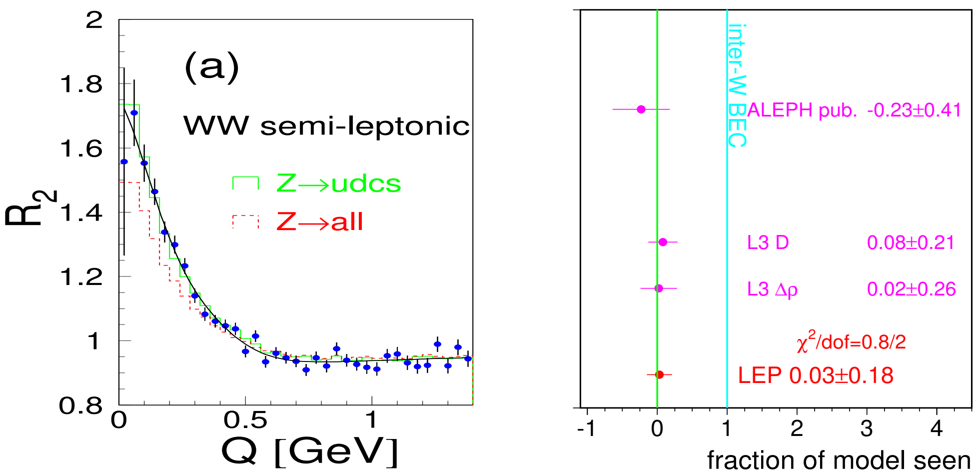


Fig. 10: (a) Correlation function in semi-leptonic events. The full histogram corresponds to light quark Z decays and the dashed histogram contains all hadronic Z decays. (b) Fraction of the LUBOEI model, used to simulate inter-W correlationd, seen by the LEP experiments.

7 Conclusions

High precision tests of the SM have been performed at LEP, in particular many properties of the W boson have been measured. W pair and single-W cross sections as well as the W decay branching fractions are found to be in very good agreement with their SM expectation. Trilinear couplings of the W boson to γ or Z have been determined with a precision of $1-5\%$. They are consistent with their SM value and no anomalous contribution has been found. The existence of longitudinally polarized W bosons has been established. The W mass is determined with an accuracy of 4×10^{-4} and recent studies on FSI point to the possible reduction of the uncertainty on M_{W} in the fully hadronic channel.

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