MEASUREMENT OF MASS AND COUPLINGS OF THE W BOSON AT LEP

A. STRAESSNER
III. Phys. Institut, RWTH Aachen, 52056 Aachen, Germany
E-mail: Arno.Straessner@cern.ch

This article summarizes the results of the four LEP experiments ALEPH, DELPHI, L3, and OPAL on the mass and couplings of the W boson. These properties of the W boson are studied at LEP at centre-of-mass energies between 161 GeV and 189 GeV. The measurements yield important knowledge on the Standard Model of electroweak interactions, testing the basic relations of the theory and its non-abelian character.

1 W Boson Production at LEP

Since 1996 the e^+e^--collider LEP has been operated at centre-of-mass energies above the threshold for W-pair production, $e^+e^- \rightarrow W^+W^-$, at energies between 161 GeV and 189 GeV. The production of W-pairs leads to four-fermion final states qqqq, $qq\ell\nu$, and $\ell\nu\ell\nu$ which are selected according to their characteristic signals in the detectors. Each of the four LEP experiments collected about 3500 W-pair events [1] in a total luminosity of 230 – 260 pb^{-1} per experiment.

At energies above 130 GeV the production of single W bosons, $e^+e^- \rightarrow W\, e\nu$, is measured and each experiment detects about 100 events of that type. In this reaction the electron or the positron is scattered predominately at small angles to the beam axis, so that only the W decay products are seen in the detector. Both the single-W and the W-pair data yield information on the values of the trilinear gauge couplings. For the measurement of the W mass only W-pair events are analysed.

2 Measurement of the Mass of the W Boson

The measurement of the W mass can be performed in two ways: by determining the cross-section of W-pair production, σ_{WW}, at the threshold, and by reconstructing the decay products of the W bosons. In the first method the Standard Model relation between m_W and σ_{WW} [2] is exploited. The data at 161 GeV is most sensitive to m_W and a value of $m_W = 80.40 \pm 0.22$ GeV is derived [3].

Since the cross-section dependence on m_W gets weaker with increasing centre-of-mass energy [2] the direct reconstruction method is applied at energies above the threshold. The visible final-state fermions, electrons, muons, hadronic τ jets, and the hadronic jets corresponding to quarks are reconstructed and possible neutrinos are identified as the missing momentum of an event. The lepton and the neutrino, and the pairs of jets are combined to form the two W's produced in each event.

Kinematic constraints are imposed to improve the resolution of the measured fermion energies and angles. In a kinematic fit these quantities are varied within their experimental resolution to satisfy energy and momentum conservation. As an additional constraint the two reconstructed W masses are forced to be equal.

The W mass is obtained from the reconstructed invariant mass spectrum in an unbinned maximum likelihood fit. In the $\ell\nu\ell\nu$ channel the energy spectrum of the leptons is used. The theoretical prediction of the differential cross-section is calculated using Monte-Carlo events distributed in phase-space around each measured W-pair event. The dependency of the differential cross-section on the parameter m_W is introduced by a reweighting procedure.

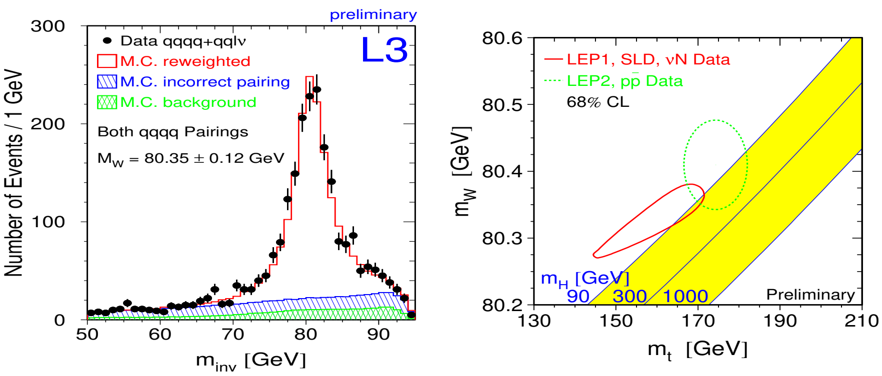

Figure 1. (a) Distribution of reconstructed invariant mass, m_{inv}, for all W-pairs selected in the 189 GeV data used by L3 for the mass analysis. The solid line shows the result of the fit of m_W. The quoted error combines statistical and systematic errors in quadrature. (b) Results for direct and indirect measurement of m_W and m_t measured by LEP, SLD, NuTeV and at pp-colliders. Both pair of measurements agree well with each other. The Standard Model predictions for different masses of the Higgs boson, m_H, are indicated by the grey band.

Figure 1a shows an example of the mass spectrum measured with the L3 detector at 189 GeV and the theoretical prediction for the best fitting value of m_W. The results of the four LEP collaborations [1] combining the data from

161 GeV to 189 GeV are given in Table 1, showing the mass values for $qq\ell\nu$ and qqqq events alone and their combination.

In qqqq events strong final state interactions (FSI) between the hadronic systems of the two decaying W bosons can lead to shifts in the reconstructed invariant masses due to effects of colour-reconnection or Bose-Einstein correlations. This affects the W boson mass determined from those events. Therefore, a systematic error of 65 MeV is assigned to the combined qqqq mass estimated by studying different Monte-Carlo models. FSI effects may show up in the mass difference between $qq\ell\nu$ and qqqq events which is determined to be 0.196 ± 0.091 GeV, not significantly different from zero. Using all LEP data the mass of the W boson is determined to be 80.370 ± 0.063 GeV.

The combined LEP W mass is in very good agreement with the mass value determined at $p\overline{p}$-colliders [4]. All direct measurements combined yield $m_W = 80.410 \pm 0.044$ GeV. This value agrees very well with the indirect determination of $m_W = 80.364 \pm 0.029$ GeV [3], using LEP1 and SLD data, and the top quark mass as it is measured at TeVatron. The W measurements, and the direct and indirect determination of the mass of the top quark are shown in Figure 1b together with the Standard Model predictions for different Higgs boson masses. Both the direct and indirect measurements favour values of the Higgs mass below 300 GeV.

	Mass of the W Boson		
	$m_W(qq\ell\nu)$[GeV]	$m_W(qqqq)$[GeV]	$m_W(ffff)$[GeV]
ALEPH	80.343 ± 0.098	80.561 ± 0.121	80.425 ± 0.081
DELPHI	80.540 ± 0.247	80.103 ± 0.192	80.265 ± 0.152
L3	80.224 ± 0.135	80.656 ± 0.156	80.404 ± 0.109
OPAL	80.354 ± 0.165	80.434 ± 0.221	80.382 ± 0.134
LEP	80.318 ± 0.073	80.485 ± 0.103	80.368 ± 0.065

Table 1. Results of fits to m_W in the semi-leptonic and the fully hadronic channel and their combination determined by the LEP experiments using 172 – 183 GeV data. The ALEPH and L3 results include the 189 GeV data set. The quoted errors combine statistical and systematic errors in quadrature. The systematic error coming from possible strong final state interactions is 23 MeV on the combined mass value and the systematic error due to the LEP energy measurement is 18 MeV.

3 Measurement of W Boson Couplings

An interesting test of the Standard Model is the measurement of the couplings of the W boson to the other gauge bosons, γ and Z. These couplings arise due to the non-abelian gauge structure of the theory. The corresponding effective

Lagrangian contains in general 14 coupling parameters, but usually just the C and P conserving terms are taken into account reducing its number to six [2]:

$$\frac{i\mathcal{L}_{\rm eff}}{\rm g_{VWW}} = {\rm g}_1^{\rm V}{\rm V}^\mu \left({\rm W}^-_{\mu\nu}{\rm W}^{+\ \nu}\right) + \kappa_{\rm V}{\rm W}^+_\mu {\rm W}^-_\nu {\rm V}^{\mu\nu} + \frac{\lambda_{\rm V}}{\rm m_W^2}{\rm V}^{\mu\nu}{\rm W}^{+\ \rho}_\nu {\rm W}^-_{\rho\mu}\,,$$

where V can be either γ or Z. The normalization is given by $\rm g_{\gamma WW} = -e$, and $\rm g_{ZWW} = -e\cot\theta_W$. General $SU(2)\times U(1)$ gauge invariance fixes $\rm g_1^\gamma$ to 1 and adds the relations $\Delta\kappa_{\rm Z} = \Delta {\rm g}_1^{\rm Z} - \Delta\kappa_\gamma \tan^2\theta_{\rm W}$, and $\lambda_{\rm Z} = \lambda_\gamma$, where the Δ indicates the deviation of the parameters from their Standard Model values of 1. Finally, λ_γ, $\Delta\kappa_\gamma$, and $\Delta{\rm g}_1^{\rm Z}$ remain as free parameters.

The values of the couplings are determined from the measured cross-sections and the phase space distributions of the W decay products in W-pair and single W production. In the case of W-pair events, the polar angle of the $\rm W^-$ and the decay angles of the fermions in the W rest frame are analysed, and in the case of single-W events the output of the neural-net for the hadronic decay mode and the lepton energy spectra. Also the single photon channel, $\rm e^+e^- \rightarrow \gamma\nu_e\nu_e$, can be explored for the measurement of the γWW couplings because the WW $\rightarrow \gamma$ fusion in the t-channel involves a triple gauge boson vertex. Here, the energy spectrum of the photon and its polar angle distribution are used as input to the measurement.

The same Monte-Carlo based fitting method as for the mass determination is applied, extended by a term accounting for the measured cross-section. Another method makes use of optimal observables [2] defined as $\rm O(\delta) = c_1/c_0$, where $\rm c_1$ and $\rm c_0$ are coefficents in the expansion of the differential cross section with respect to the couplings $\rm d\sigma/d\Omega(\delta) = c_0 + c_1\cdot\delta + c_2\cdot\delta^2$, and where δ is one of the three couplings to be measured.

The results of the four LEP experiments [1] for λ_γ, $\Delta\kappa_\gamma$ and $\Delta{\rm g}_1^{\rm Z}$ at $\sqrt{\rm s} \leq$ 189 GeV are shown in Table 2. All measurements agree well with each other and no deviations from the Standard Model values are found.

	Results of 1-Parameter Couplings Fits		
	λ_γ	$\Delta\kappa_\gamma$	$\Delta{\rm g}_1^{\rm Z}$
ALEPH	-0.05±0.07	0.09 ±0.16	0.00 ±0.06
DELPHI	0.02 ±0.08	0.25 ±0.19	-0.01±0.07
L3	0.00 ±0.07	-0.12±0.15	-0.02±0.07
OPAL	-0.11±0.08	0.00 ±0.23	-0.01±0.08
LEP	-0.03±0.04	0.06 ±0.09	-0.01±0.03

Table 2. Results of couplings fits using W-pair, single-W, and single γ events selected at centre-of-mass energies up to 189 GeV. The quoted errors combine statistical and systematic errors in quadrature.

4 Conclusion

The mass of the W boson is measured by the LEP experiments and the combination of all data yields a value of $m_W = 80.368 \pm 0.065$ GeV. This is in good agreement with the mass measurement at $p\overline{p}$-colliders and with the indirect determination of the W-mass. The trilinear gauge couplings are determined with good precision limiting deviations from the Standard Model values to typically ± 0.03 to ± 0.09 which confirms the non-abelian gauge structure of the theory.

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