

W Physics and Testing the Standard Model at LEP

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Measurements of the Z^0 resonance parameters at LEP have established the validity of the Standard Model to high precision. The high energy operation of LEP2 in 1996 allowed W pair production in e^+e^- collisions for the first time providing a unique opportunity for detailed studies of W physics and stringent tests of the Standard Model,

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I. Introduction

One of the most important developments in particle physics in the past three decades is the establishment of the Standard Model of electroweak theory [1] and quantum chromodynamics. The experimental confirmation of the electroweak theory came first in the observation of the neutral current in neutrino scattering experiments [2] and then in the discovery of the intermediate vector bosons, W^\pm and Z^0 [3]. Precision measurements of the parameters in the electroweak theory can provide not only a stringent test of the validity of the theory but also a window to indications of new physics in an energy domain beyond the reach of the present generation of accelerators.

The operation of LEP at energies near the Z^0 mass during 1990-1995 has provided about 4 million events to each of the four LEP experiments. The high-statistics measurements of the Z^0 parameters have confirmed many of the predictions of the Standard Model to high precision. In 1996 the center-of-mass energy of LEP was increased in two steps to 161 GeV and 172 GeV, thus allowing the production of pairs of W bosons for the first time in an e^+e^- collider. The studies of W physics at LEP2 enable us to further extend our knowledge of the Standard Model.

In this report we review some of the measurements carried out at LEP2. Section 2 is devoted to the measurements of W pair production cross sections and W decay branching ratios. In Section 3 the measurements of the mass of the W boson are presented. The studies of the triple gauge boson couplings are given in Section 4.

II. Cross sections and branching ratios

The processes contributing to the reaction

$$e^+e^- \rightarrow W^+W^- \quad (1)$$

are depicted in Figure 1. The largest contribution comes from neutrino exchange. In the Standard Model, the triple gauge boson couplings (TGCs) for Z^0/γ exchange have the Yang-Mills form, and the presence of these couplings gives cancellations among the different amplitudes. The resultant cross section, as a consequence of this cancellation, has proper behavior at high energies. This is illustrated by the set of theoretical curves in Figure 2.

During the initial year of operation of LEP2 in 1996, the energy of the e^+e^- collider was increased in two steps with running at 161 GeV and 172 GeV in center-of-mass energy. Each of the four LEP experiments accumulated approximately 10 pb^{-1} of integrated luminosity at each of the two energies. In Table 1 the cross sections measured by the experiments for $e^+e^- \rightarrow W^+W^-$ are listed for both energies [4,5].

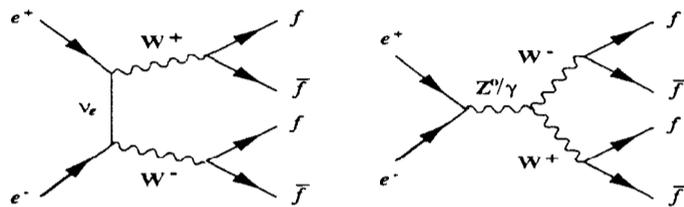


FIG. 1. The processes contributing to $e^+e^- \rightarrow W^+W^-$.

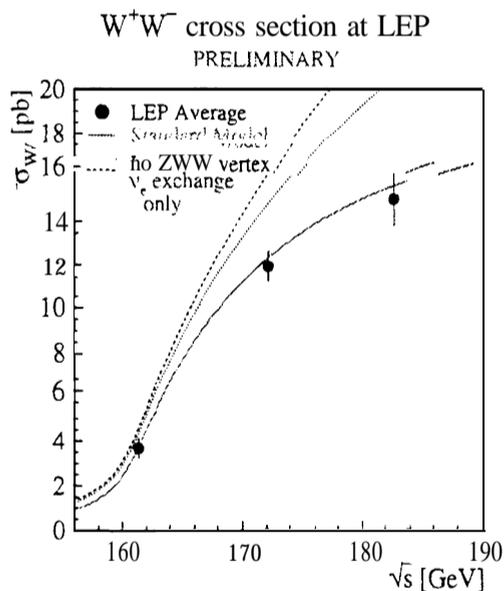


FIG. 2. The cross-section of $e^+e^- \rightarrow W^+W^-$ as a function of energy. The measurement at 183 GeV is highly preliminary.

TABLE I. W^+W^- cross sections measured by the LEP experiments. The measurements of DELPHI and OPAL at 172 GeV are preliminary.

Experiment	$\sigma_{W^+W^-}$ (pb) 161 GeV	$\sigma_{W^+W^-}$ (pb) 172 GeV
ALEPH	$4.23 \pm 0.73 \pm 0.19$	$11.71 \pm 1.23 \pm 0.28$
DELPHI	$3.67^{+0.97}_{-0.85} \pm 0.19$	$11.58^{+1.44}_{-1.35} \pm 0.32$
L3	$2.89^{+0.81}_{-0.70} \pm 0.14$	$12.27^{+1.41}_{-1.32} \pm 0.23$
OPAL	$3.62^{+0.93}_{-0.82} \pm 0.16$	$12.3 \pm 1.3 \pm 0.3$
LEP Average	3.69 ± 0.45	12.0 ± 0.7

TABLE II. Measured W decay branching ratios in percent by the LEP experiments. The measurements of DELPHI are preliminary.

Experiment	$\text{Br}(W \rightarrow e\nu)$	$\text{Br}(W \rightarrow \mu\nu)$	$\text{Br}(W \rightarrow \tau\nu)$	$\text{Br}(W \rightarrow q\bar{q})$
ALEPH	9.7 ± 2.2	11.2 ± 2.2	11.3 ± 2.9	67.7 ± 3.2
DELPHI	10.2 ± 3.8	10.7 ± 3.2	13.4 ± 5.0	66.0 ± 3.7
L3	16.5 ± 3.7	8.4 ± 2.8	10.9 ± 4.2	64.2 ± 3.7
OPAL	9.8 ± 2.1	7.3 ± 1.8	14.0 ± 2.9	69.8 ± 3.2
LEP Ave.	10.8 ± 1.3	9.2 ± 1.1	12.7 ± 1.7	67.2 ± 1.7

In Figure 2, the measured cross sections at 161 GeV and 172 GeV are compared with the theoretical calculations. A very preliminary cross section measurement for the 183 GeV data accumulated in 1997 is also shown. As can be seen, the dashed curve, corresponding to the theoretical cross section with neutrino exchange only is totally inconsistent with the data. The Standard Model, on the other hand, describes the data well over the energy range studied.

The four LEP experiments have also determined the branching ratios of the W decay. These results are summarized in Table II.

III. W mass measurements

Prior to LEP2 the mass of W was determined indirectly in the relation

$$C_F = \frac{\alpha\pi}{\sqrt{2}m_W^2(1 - m_W^2/m_Z^2)} \frac{1}{1 - \Delta\tau}, \quad (2)$$

where the Fermi constant G_F is accurately measured from muon decay and Δr deviates from 0 when m_t - and m_H - dependent loop corrections are included. At LEP2, m_W can be measured directly, and the relation (2) serves as a test of the Standard Model and as a constraint for the mass of the Higgs boson.

The data recorded at 161 GeV, which is just above the pair production threshold, and m_W can be determined by comparing the measured cross-section with the predicted behavior. At higher energies, m_W can be determined by reconstructing the decay products of the W boson. Thus the LEP collaborations were able to determine the W mass using two complementary methods with data collected in 1996.

In the first run, at 161 GeV, each experiment accumulated a total luminosity of approximately 10 pb^{-1} . The W pair cross-sections determined by the 4 experiments [4] are shown in Table I. The LEP average cross-section at 161 GeV is $3.69 \pm 0.45 \text{ pb}$. The LEP center-of-mass energy averaged over the 4 experiments has been determined to be $161.33 \pm 0.05 \text{ GeV}$. The predicted cross-section as a function of the W mass can be calculated using the Gentle [6] program. This is shown in Figure 3. From this, the W mass is determined to be:

$$m_W = 80.40_{-0.21}^{+0.22} \pm 0.03 \text{ GeV}, \quad (3)$$

where the first error is experimental, and the second error is due to the LEP energy calibration. Approximately 70 MeV of the experimental error is due to common systematics.

Each experiment also accumulated 10 pb^{-1} at the higher energy of 172 GeV [5]. The cross-section at 172 GeV is more than a factor 3 higher than at 161 GeV, and each experiment recorded approximately 100 W pair events at this energy. To determine the W mass, the experiments fit the reconstructed invariant mass distributions. As an illustration, the OPAL reconstructed mass distributions are shown in Figure 4. The results of the four LEP experiments are given in Table III. Combining the 172 GeV results yields:

$$m_W = 80.53 \pm 0.17 \pm 0.05 \text{ GeV}. \quad (4)$$

And combining this value from 172 GeV and the m_W value from 161 GeV yields the current LEP average of

$$m_W = 80.48 \pm 0.13 \pm 0.05 \text{ GeV} \quad (5)$$

for the mass of W.

IV. Triple gauge boson couplings

The W^+W^- production process involves the triple gauge boson vertices between the W^+W^- and the Z^0 or photon. The measurement of these triple gauge boson couplings (TGCs) and the search for possible anomalous values is one of the principal physics goals at LEP2. The parameterization of anomalous TGCs is described in References [7,8]. The

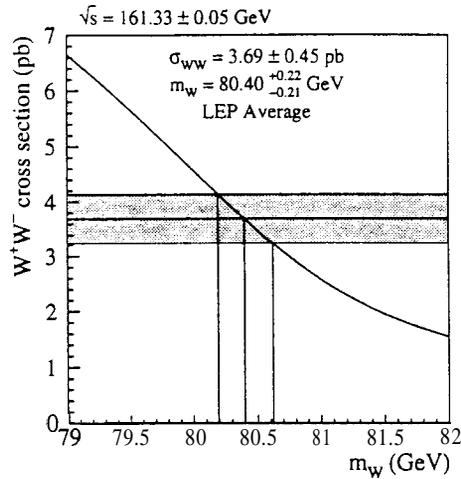


FIG. 3. The cross-section of the process $e^+e^- \rightarrow W^+W^-$ as a function of the W mass. The horizontal band shows the cross-section measurement with its error. The curve shows the Standard Model prediction.

TABLE III. The measurements of m_W at 172 GeV.

Experiment	$m_W(q\bar{q}\ell\nu)$ (GeV)	$m_W(q\bar{q}q\bar{q})$ (GeV)
ALEPH	$80.38 \pm 0.43 \pm 0.12$	$80.30 \pm 0.47 \pm 0.10$
DELPHI	$80.51 \pm 0.57 \pm 0.06$	$79.90 \pm 0.59 \pm 0.12$
L3	$80.42 \pm 0.54 \pm 0.08$	$80.91 \pm 0.42 \pm 0.13$
OPAL	$80.53 \pm 0.41 \pm 0.10$	$80.08 \pm 0.44 \pm 0.15$
LEP	80.46 ± 0.24	80.62 ± 0.26

most general Lorentz invariant Lagrangian which describes the triple gauge boson interaction has fourteen independent terms, seven describing the $WW\gamma$ vertex and seven describing the WWZ vertex. Assuming electromagnetic gauge invariance and C and P conservation the number of parameters reduces to five. One common set is $\{g_1^z, \kappa_z, \kappa_\gamma, \lambda_z, \lambda_\gamma\}$ where $g_1^z = \kappa_z = \kappa_\gamma = 1$ and $\lambda_z = \lambda_\gamma = 0$ in the Standard Model. Another such set is $\{\delta_z, \Delta\kappa_z, \Delta\kappa_\gamma, y_z, y_\gamma\}$ which are all zero in the Standard Model.

Different sets of parameters have also been proposed which are motivated by $SU(2) \times U(1)$ gauge invariance and constraints arising from precise measurements at LEP. One such set [8] is:

$$\alpha_{W\phi} \equiv \Delta g_1^z \cos^2 \theta_w \quad (6)$$

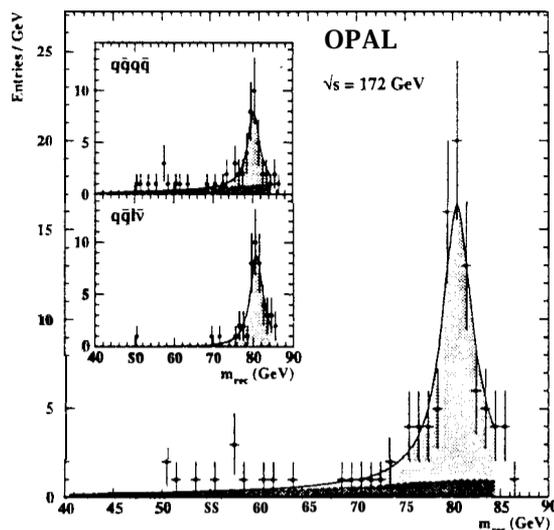


FIG. 4. OPAL Reconstructed mass distributions. The main plot show the combined of the two samples in the insets. The solid curves are the maximum likelihood fits.

$$\alpha_W \equiv \lambda_\gamma \quad (7)$$

$$\alpha_{B\phi} \equiv \Delta\kappa, -\Delta g_1^z \cos^2 \theta_w \quad (8)$$

with the constraints that $\Delta\kappa, = -\Delta\kappa_\gamma \tan^2 \theta_w + \Delta g_1^z$ and $\lambda_z = \lambda_\gamma$. The Δ indicates the deviation of the respective quantity from its Standard Model value and θ_w is the weak mixing angle. Each of the α parameters has the value zero in the Standard Model.

Each of the LEP experiments has measured several of the many possible TGC parameters analyzing the 1996 data set [9]. The measurements result from approximately 25 and 100 events per experiment at 161 GeV and 172 GeV respectively. The common overlap of all experiments are the measurements of $\alpha_{W\phi}, \alpha_W$ and $\alpha_{B\phi}$.

Anomalous TGCs can affect both the total production cross-section and the shape of the differential cross-section as a function of the W^- production angle. The relative contributions of each helicity state of the W bosons are also changed, which in turn affects the distributions of their decay products. The analyses presented by each experiment make use of different combinations of each of these quantities, and of different decay modes of the WW system. The results from each experiment are shown in Table IV, where the errors include both statistical and systematic effects.

Each of the experiments has provided the full negative log likelihood curves, $\log \mathcal{L}$, as a function of each of the measured TGC parameters. The $\log \mathcal{L}$ curves from each experiment include both statistical and systematic effects. It is necessary to use the $\log \mathcal{L}$ curves directly for the combination as they are not parabolic. Common correlated systematic and statistical errors are small and neglected.

The individual $\log \mathcal{L}$ curves for each parameter are added together. The results of this procedure are shown in Figure 4, where each is plotted relative to its minimum value.

TABLE IV. The measured central values and one standard deviation errors obtained by the four LEP experiments for the anomalous TGC parameters. Both statistical and systematic errors are included.

Parameter	ALEPH	DELPHI	L3	OPAL
$\alpha_{W\phi}$	$-0.14^{+0.29}_{-0.28}$	$0.24^{+0.26}_{-0.27}$	$0.04^{+0.43}_{-0.35}$	$-0.08^{+0.30}_{-0.27}$
α_W	$0.06^{+0.59}_{-0.55}$	$0.14^{+0.46}_{-0.47}$	$0.22^{+0.59}_{-0.61}$	$0.18^{+0.54}_{-0.52}$
$\alpha_{B\phi}$	$1.01^{+0.91}_{-0.87}$	$0.40^{+0.71}_{-0.68}$	$0.07^{+1.77}_{-1.16}$	$0.35^{+1.34}_{-1.14}$

TABLE V. The combined one standard deviation and 95% confidence intervals obtained after combination of the results from the four LEP experiments for the anomalous TGC parameters. Both statistical and systematic errors are included.

Parameter	1 S.D.	95% C.L. interval
$\alpha_{W\phi}$	$0.02^{+0.16}_{-0.15}$	$[-0.28, 0.33]$
α_W	$0.15^{+0.27}_{-0.27}$	$[-0.37, 0.68]$
$\alpha_{B\phi}$	$0.45^{+0.56}_{-0.67}$	$[-0.81, 1.50]$

The one standard deviation limits (S.D.) are obtained directly from the curves by taking the values of each TGC parameter where $\Delta \log \mathcal{L} = 0.5$ from the minimum. The 95% confidence level (C.L.) limit is given by the values of each TGC parameter where $\Delta \log \mathcal{L} = 1.92$. The results obtained are given in Table IV [10]. The value of each TGC parameter given in the table is consistent with the expectation of the Standard Model.

V. Summary

The reaction $e^+e^- \rightarrow W^+W^-$ has been studied for the first time at LEP2 using data collected by the four LEP experiments at 161 GeV and 172 GeV in center-of-mass energy. The W pair production cross sections and W decay branching ratios are presented. The mass of the W boson has been determined to be $80.48 \pm 0.13 \pm 0.05$ GeV for the LEP average. The study of the structure of triple gauge boson couplings has been carried out through the measurements of the anomalous coupling constants. All measurements agree well with the predictions of the standard Model.

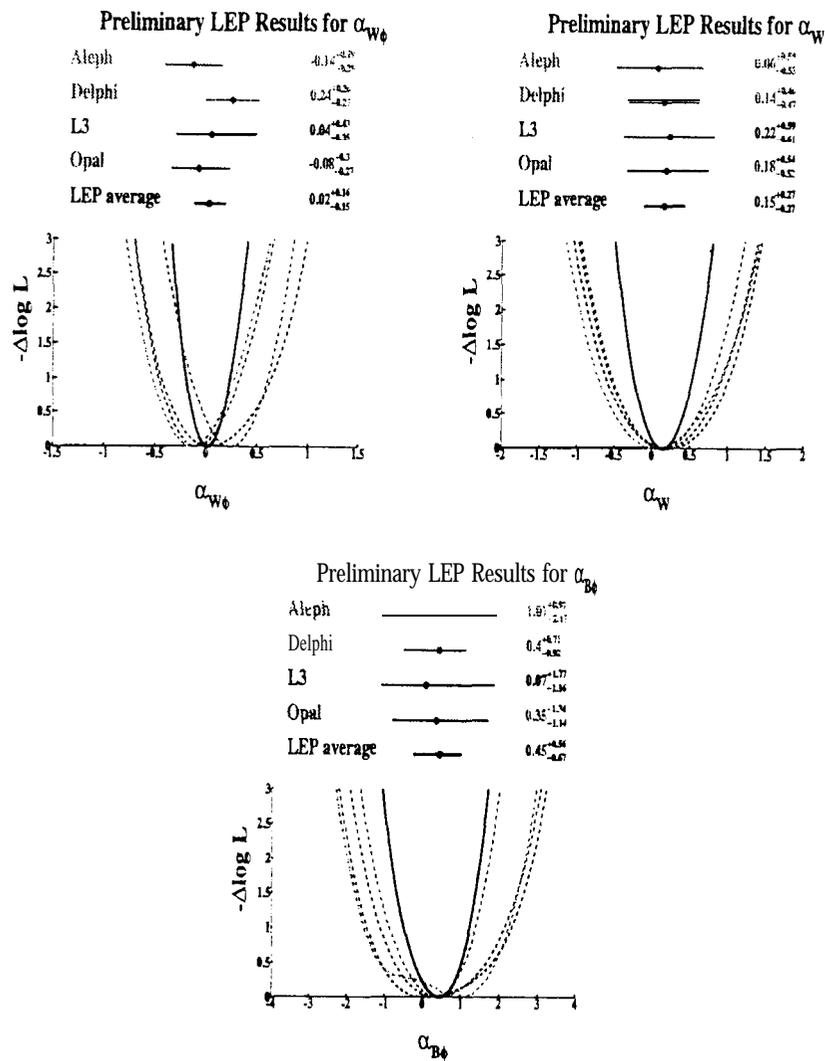


FIG. 5. The LEP combined $\log \mathcal{L}$ curves for the parameters $\alpha_{W\phi}$, α_W , and $\alpha_{B\phi}$. This is obtained from the combination of the curves from the individual LEP experiments which are shown as dotted lines. The minimum value has been subtracted in all cases. The measurements and 1 standard deviation errors are also listed.

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