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W Boson Properties at LEP

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Abstract

The determination of the properties of the W boson provide a key precision test of the Standard Model. This article reviews the significant measurements made by the four LEP experiments using approximately 40,000 W-pair events collected at e^+e^- centre-of-mass energies from 161 to 209 GeV. These results include the measurement of the W^+W^- cross-section with a 1% accuracy, the determination of gauge boson self-couplings and the measurement of the W Mass with a 42 MeV/c^2 precision.

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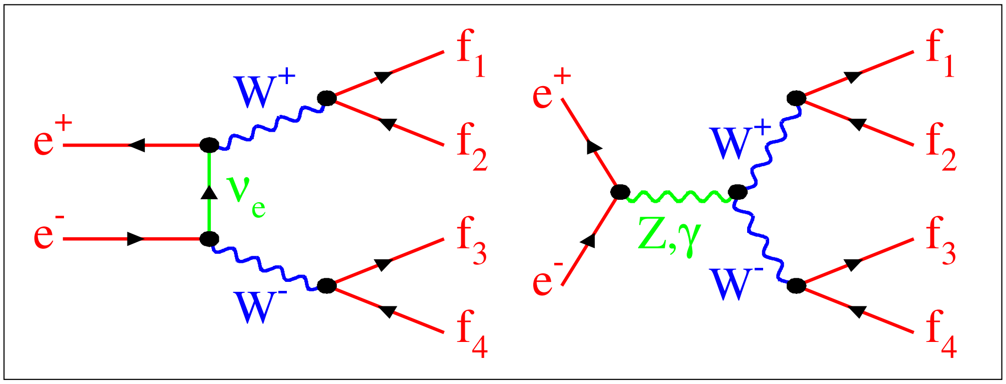

Figure 1: The leading order Feynman diagrams relevant to W^+W^- production at LEP2

1 Introduction

The primary aim of the LEP2 measurement programme was the study of the properties of the W boson, including the estimation of the W mass to a precision of better than 50 MeV/c^2 and the observation and study of triple gauge boson vertices. The LEP experiments achieved these aims using the data sample of approximately 700 pb^{-1} per experiment delivered during five years of operation (1996-2000) of the LEP2 accelerator at centre-of-mass energies from 161 to 209 GeV.

This article presents the principal W physics measurements made at LEP. Section 2 starts by describing the production processes for W bosons at LEP. The following sections then provide results on the cross-section for W-pair and single W production, the W hadronic branching ratio and the interpretation of this in terms of the CKM matrix element $|Vcs|$. The W Mass and width measurements are discussed in section 3. The electroweak systematics discussed in section 3.2.2 are relevant to the cross-section, mass and couplings. Cross-talk effects between the two Ws in an event are discussed in section 3.2.3. Measurements of triple and quartic gauge couplings and the fraction of longitudinally polarised Ws are discussed in section 4. Some of the results presented here are preliminary, further details are available in [1].

2 W production and Cross-sections

2.1 W Boson Production

W bosons were primarily produced at LEP through the process $e^+e^- \rightarrow W^+W^-$. The leading order Feynman diagrams relevant to W^+W^- production at LEP2 are given in Figure 1. Close to the W-pair production threshold, where the initial LEP2 data samples were recorded, the production cross-section is dominated by the t-channel neutrino exchange diagram. At higher energies the s-channel diagrams, containing a triple gauge boson vertex, play a more significant role. The s and t channel interference terms contribute negatively to the total cross-section and the well-behaved nature of the W^+W^- cross-section at higher energies is a consequence of these cancellations, and thus of the specific forms of the gauge boson couplings in the Standard Model (SM).

In addition, single W boson production is also possible at LEP and occurs through t-channel diagrams with an electron and neutrino in the final state.

2.2 Cross-section Measurements

The W boson sample can be divided into Ws decaying leptonically and hadronically. Hence, the W-pair sample is divided into three distinct experimentally observed topologies. Fully hadronic $W^+W^-\rightarrow q\bar{q}'\bar{q}q'$ events constitute 46% of the total W^+W^- cross-section and have an experimental signature of four (or more) high energy jets resulting from the primary quarks (and additional hard gluon radiation). Semi-leptonic $W^+W^-\rightarrow \ell\overline{\nu}_\ell q\bar{q}'$ have a similar (44%) branching ratio and are characterised by two (or more) jets, a high momentum electron, muon or decay products of a tau and missing momentum due to the unobserved neutrino. The fully-leptonic events $W^+W^-\rightarrow \ell\overline{\nu}_\ell\overline{\ell}\nu_\ell$ have a smaller (10%) branching ratio and contain two charged leptons and at least two unobserved neutrinos. The event selections are based on these characteristics and commonly use neural network and discriminant techniques to obtain the best efficiencies and purities. The principal backgrounds are from $Z(\gamma)$ decays, with ZZ events also becoming significant at the higher LEP energies.

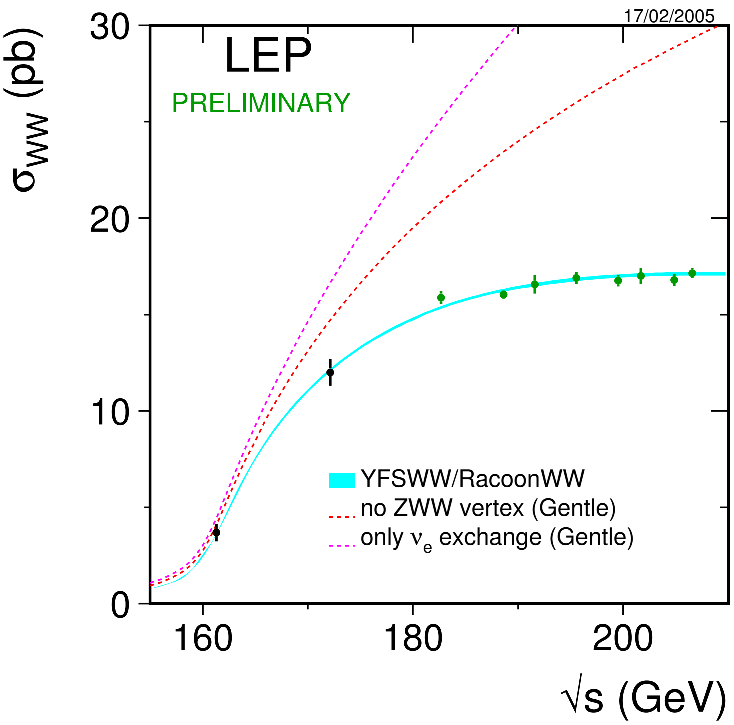

Figure 2: The data points and error bars show the combined measurements from the LEP experiments of the WW cross-section shown as a function of the centre-of-mass energy. Excellent agreement is obtained with the full theoretical prediction curves.

The measurement of the W^+W^- cross-section and theoretical predictions are shown in Figure 2. The measurements have been corrected for interference from other processes that can produce the same final state (e.g. $e^+e^-\to ZZ\to u\bar{u}d\bar{d}$) and represent the cross-section for the graphs shown in Figure 1. The average of the ratio of the observed cross-sections at all LEP2 energies to the predictions from the `YFSWW` Monte-Carlo routine [2], known as the R_{WW} value, is 0.994 ± 0.009. The `YFSWW` Monte-Carlo calculation includes the effect of $\mathcal{O}(\alpha)$ corrections which are discussed in section 3.2.2.

At LEP2 energies the single W production cross-section is more that an order of magnitude smaller than that for W-pair production. However, the rate is still measurable at LEP2 to better than 10%, the $R_{\mathrm{We}\nu_e}$ value for the combined LEP2 results to the expectation from WPHACT [3] is 1.002 ± 0.075.

2.3 Branching Ratio and $|V_{cs}|$

2.3.1 W Branching Ratio

As described above the W^+W^- event selection proceeds through the separate identification of semi-leptonic, fully-leptonic and fully-hadronic events (with further splittings by charged lepton species). Hence, the branching ratio of the W boson may be extracted. Assuming lepton universality, the hadronic branching ratio of the W boson is measured to be 67.48 $\pm$ 0.28 % to compare with the Standard Model value of 67.51 %. However, there is a 3.0 sigma discrepancy in the branching ratios (BR) of the tau lepton species:

$$2 \times BR(W\to\tau\overline{\nu}_\tau)/(BR(W\to e\overline{\nu}_e) + BR(W\to\mu\overline{\nu}_\mu)) = 1.077 \pm 0.026 \quad (1)$$

2.3.2 $|V_{cs}|$

The CKM matrix elements express the strength of the W coupling to the quark species. Hence, the hadronic branching ratio of the W can be interpreted as a measurement of the sum of the squares of the magnitudes of the six CKM matrix elements that do not involve the heavy top quark. The least well known of these elements is V_{cs}. Combining the LEP hadronic W branching ratio measurement with the existing measurements of the other elements provides the best determination of the magnitude of this element.

$$|V_{cs}| = 0.976 \pm 0.014 \tag{2}$$

where unitarity constraints have not been applied.

3 W Mass and Width

3.1 Method

The W boson invariant mass is reconstructed from fully hadronic and semi-leptonic W-pair events using the observed jet and lepton four-momenta and their estimated errors. Fully leptonic final states have a relatively low mass sensitivity as a result of the presence of at least two neutrinos in the event.

In the $q\bar{q}'\bar{q}q'$ final state the reconstructed jets must be appropriately paired to correspond to their parent Ws. The more sophisticated analyses make use of all possible pairings, weighting them when performing the final M_W fit.

The mass resolution due to detector reconstruction effects is larger than the intrinsic width of the W boson. This experimental mass resolution is improved by imposing energy and momentum constraints upon the event in a constrained fit. Two highly correlated masses may be extracted for each event, or more commonly the additional constraint of equal masses is imposed.

The W mass and width are then evaluated by performing a maximum likelihood fit to the data using either reweighted simulation events or a semi-analytic function calibrated by simulation.

3.2 Systematics

The LEP2 determination of the W Mass is dominated by the systematic error. Three contributions to the systematic error of particular interest are discussed in this section.

3.2.1 Beam Energy Determination

The LEP beam energy is applied as a constraint in the kinematic fits used in the mass reconstruction. Hence, the fractional error on the beam energy translates directly as a fractional error on the M_W determination.

At beam energies of up to 60 GeV polarised electron and positron beams could be produced and the beam energy determined extremely accurately ($\approx$ 200 KeV) through the study of the e+ or e- spin precession frequency; this method is used to calibrate the methods used at higher energies. These methods include: measurements of the magnetic field in the LEP dipole magnets; measurement of the LEP beam bend angle in a specially constructed steel dipole of accurately known magnetic field; and measurements of the accelerator's synchrotron tune variation with RF voltage.

The LEP energy working group has recently published the final energy determination [4], once this is incorporated in the final analyses the eventual error on the W mass resulting from the beam energy uncertainty will be approximately 10 MeV/c^2.

3.2.2 Electroweak Corrections

During the LEP2 programme $\mathcal{O}(\alpha)$ corrections to the four-fermion W^+W^- process have become available in event generators. These calculations include the effect of real (4f + γ) corrections and both factorisable and non-factorisable (e.g. γ exchange between decay products of different Ws) virtual corrections. All LEP collaborations are now using these corrections.

The LEP2 W^+W^- cross-section measurements, discussed above, provide evidence for the importance of these corrections. The ratio of the measurements to the `GENTLE` calculation [5], that neglects these corrections gives 0.969 ± 0.009, a 3.4 sigma deviation from unity.

The effect of electroweak corrections on differential distributions has also been studied. The effect of neglecting these corrections on the estimation of triple gauge boson vertices is significant [1]. The effect on the W Mass is less important and the systematic error for analyses using these corrections has recently been investigated and shown to be less than 10MeV/c^2 [6].

3.2.3 *Final State Interactions*

The statistical sensitivity of the fully-hadronic and semi-leptonic events is comparable, yet the fully-hadronic events have a weight of only 10% in the combined LEP W Mass average. This is due to the additional systematics applied in the fully-hadronic channel to account for final state interactions.

The decay distance of the W bosons produced at LEP2 ($\approx$ 0.1 fm) is significantly less than the typical hadronisation scale ($\approx$ 1 fm). Thus, cross-talk can occur between the final state particles from the two W bosons. Two effects are considered, Bose-Einstein Correlations and Colour Reconnection.

Bose-Einstein Correlations (BEC) give rise to the enhanced production of identical bosons (pions) close in momentum space. While BEC inside individual bosons are well established, the effect between the two different Ws is not. By comparing fully-hadronic and semi-leptonic events all LEP experiments have reported results compatible with inter-W BEC significantly reduced from the preferred `LUBOEI` model implemented in `JETSET` [7]. DELPHI do however report 2.4 sigma evidence for the existence of BEC between Ws [8]. The systematic error on the W Mass (and that on other measurements) is assessed using `LUBOEI` and hence is highly conservative.

Several phenomenological models of the potentially significant non perturbative phase reconnection effects exist. The `JETSET SK-I`, `ARIADNE-II` and `HERWIG` models are the most widely studied by the LEP collaborations. The LEP experiments have conservatively chosen the SK-I model, that predicts some of the largest shifts, to assign the M_W systematic. Measurements of the effect have also been made by the LEP collaborations [1] by studying particle production in the inter-jet regions inside a W and between Ws. Removing the particles in the inter-jet regions and studying the W mass variation provides another technique of measuring the effect or reducing its effect on the W Mass analysis. However, the statistical sensitivity is limited and work is continuing in this area.

3.3 Results

The preliminary LEP2 average value of the W Mass is

$$M_W = 80.412 \pm 0.29(\text{stat.}) \pm 0.031(\text{syst.})\ \text{GeV/c}^2,$$

when combined with the measurements made at the TeVatron a value of

$$M_W = 80.425 \pm 0.034\ \text{GeV/c}^2$$

is obtained. The preliminary LEP2 average direct W Width measurement is

$$\Gamma_W = 2.150 \pm 0.068(\text{stat.}) \pm 0.060(\text{syst.})\ \text{GeV/c}^2.$$

4 Angular distributions, Couplings and Spin-States

The existence of the SM triple gauge coupling (TGC) γWW and $ZWWW$ vertices is confirmed by the W^+W^- cross-section results presented above. The dashed lines in Figure 2 show the result that would be obtained in the absence of these vertices, as discussed in section 2.2.

In addition to the cross-section, TGCs affect the differential cross-sections as a function of the five W production and decay angles. A combined measurement has been made of the variation of the differential W^+W^- cross-section with the most important angle, the W- polar production angle with respect to the e- beam direction, for the $e\overline{\nu}_e q\bar{q}'$, $\mu\overline{\nu}_\mu q\bar{q}'$ decay channels. The charged lepton is required to be more than 20 degrees from the beam axis. This distribution, using measurements made by the ALEPH, DELPHI and L3 collaborations, is shown in Figure 3 for the data collected at the highest centre-of-mass energies in the year 2000.

The three coupling parameters which describe the TGC vertices and conserve C and P and SU(2) symmetry are denoted κ_γ, λ_γ and g_1^Z. Measurements of these parameters have been made by all LEP collaborations utilising cross-section and angular decay information. Single W production also carries TGC information, particularly on κ_γ, and hence is also included in the analyses of some experiments. Single parameter and two parameter fits have been performed and the results are compatible with the SM, with g_1^Z being determined to 2% accuracy.

Quartic Gauge couplings are also predicted by the SM but are below the sensitivity of the LEP experiments. However, limits have been placed on the existence of large anomalous QGCs and the cross-section for W^+W^- and a hard photon determined.

The existence of longitudinal polarised Ws is generated in the SM through the electroweak symmetry breaking process. By exploiting the angular distribution of the W decay products or by using the Spin Density

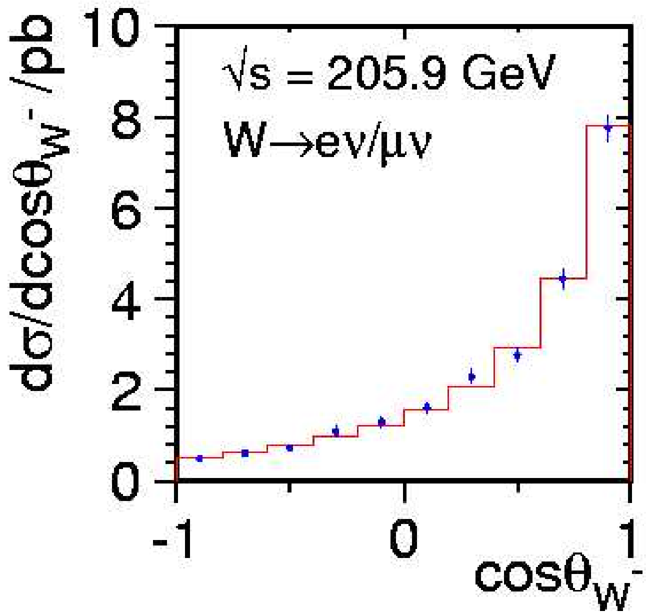

Figure 3: The W-pair differential cross-section as a function of the W- polar production angle for data collected at centre of mass energies above 204 GeV.

Method the fractions of longitudinal and transverse Ws have been determined by the DELPHI, L3 and OPAL collaborations. An experimental result of 23.6 $\pm$ 1.6% of longitudinal Ws is obtained at the average centre-of-mass energy in agreement with the SM prediction of 24.0%.

5 Summary

The principal W boson measurements of the LEP collaborations have been presented: including the determination of the WW cross-section to 1% accuracy, the W Mass to 42 MeV/c^2 and the observation and determination of triple gauge couplings. The mass of the W boson makes a particularly important contribution to tests of the standard model, particularly when combined with the top quark mass measurements from the TeVatron. The combined fit to electroweak data inside the standard model prefers a relatively light SM Higgs and yields a preferred Higgs mass of 126^{+73}_{-48}GeV/c^2 [1).

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