

LEP II BOSON CROSS-SECTIONS AND COUPLINGS

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Measurements performed at LEP of W-pair, Z-pair and single W production cross-sections up to 202 GeV centre-of-mass energy are presented, together with measurements of the trilinear gauge boson couplings predicted by the Standard Model, namely the WWZ and $WW\gamma$ vertices. In addition, limits are set to possible anomalous couplings among three neutral gauge bosons as well as among four gauge bosons.

1 Introduction

The large electron-positron (LEP) collider has been running above the W-pair production threshold since 1996. In 1999 the centre-of-mass energy ranged from 192 to 202 GeV, yielding an integrated luminosity of about 220 pb^{-1} per experiment. Z-pair event production became possible in 1997, when the centre-of-mass energy reached 183 GeV. To date, each collaboration has collected about 6500 W-pair events and 200 Z-pair events. LEP will accomplish its program this summer, when the centre-of-mass energy is expected to reach 206 GeV. All results concerning the data collected in 1999 and presented in this report are preliminary.

2 Boson production cross-sections

2.1 W-pairs

At LEP, W-pair events can be classified into three different categories according to the decay channel of each W: fully leptonic events, characterised by two acoplanar charged leptons and missing momentum in the final state; semileptonic events, with two jets, one charged lepton and missing momentum in the final state; and fully hadronic events, characterised by four jets and no missing energy. High selection efficiencies and purities are achieved in each category. Assuming the Standard Model W decay branching fractions, the CC03^a production cross-section is measured by all four LEP collaborations¹. Figure 1 shows the combined results, compared with the predictions of the Gentle calculation and the RacoonWW and YFSWW3 Monte Carlo programs. The χ^2/dof for the data-Gentle comparison is about two, whereas it is about one for the data-RacoonWW comparison: preliminary combined results at high energy appear in favour of the most recent calculations. Also shown in the plot are the WW cross-section predictions for the case of either the s-channel Z boson exchange or both s-channel diagrams did not exist: the measured W-pair production cross-section provides strong evidence of the existence of the WWZ and WW γ vertices.

The W decay branching fractions are also measured directly, the results being in good agreement with both lepton universality and the Standard Model values: $\text{Br}(W \rightarrow \ell\nu) = (10.71 \pm 0.10)\%$, and $\text{Br}(W \rightarrow \text{had}) = (67.85 \pm 0.33)\%$. The measured W decay branching fraction into hadrons is used to extract the CKM matrix element $|V_{cs}| = .993 \pm .016$, without assuming the unitarity of V^{CKM} .

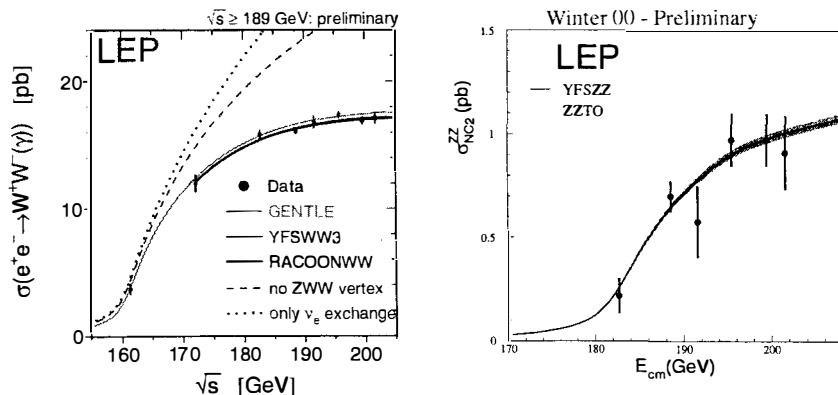


Figure 1: W-pair (left) and Z-pair (right) production cross-sections, as a function of the centre-of-mass energy, as measured at LEP. Results above 189 GeV are preliminary. Various theoretical predictions are also shown.

^aCC03 diagrams correspond to the t-channel ν exchange and the two s-channel Z and photon exchange

2.2 Z-pairs

Z-pair events can be classified according to the decay of each Z boson. Fully hadronic events have the larger statistics (46%), but suffer from a large irreducible background, mainly due to hadronically decaying W-pair events. In order to improve the signal to background ratio, *b*-tagging techniques are applied to all final states including hadrons. In this way the measured fraction of events containing b quarks can also be checked to be consistent with the hypothesis of Z-pair production. Z-pair events are the major background to Higgs searches in case $M_{Higgs} \simeq M_Z$. LEP combined results² for the Z-pair production cross-section are shown in figure 1 and are in good agreement with the prediction of the Standard Model.

2.3 Single W

At LEP II, single W production is possible through the diagrams shown in figure 2. Many other diagrams can lead to the same $e\nu f\bar{f}$ final states, both in the s- and t-channel. The four LEP collaborations recently came to an agreement about the definition of the single W signal. This is taken as the set of t-channel diagrams (which is gauge invariant) with the following kinematic cuts: $M_{q\bar{q}} > 45 \text{ GeV}/c^2$ for hadronic W decays, $E_\ell > 20 \text{ GeV}$ for leptonic W decays and, in addition, for $e^+\nu e^-\bar{\nu}$ final states, $\cos\theta_{e^+} < 0.95$ and $\cos\theta_{e^-} > 0.95$ or vice-versa. Combined LEP results³ are shown in figure 2. Not all collaborations have contributed results at all energies yet.

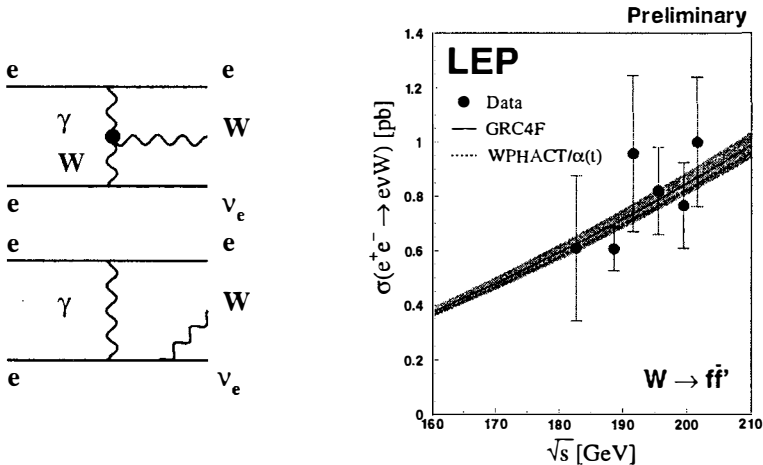


Figure 2: Left: Feynman diagrams for the single W production process. Right: Lep combined results for single W production cross-section, as a function of the centre-of-mass energy. Two different Monte Carlo predictions are also shown. The band corresponds to the theoretical uncertainty.

3 Boson couplings

The W-pair production process, $e^+e^- \rightarrow W^+W^-$, involves the triple gauge boson vertices between the W^+W^- and the Z or the photon. Both single W ($e\nu W$) and single photon ($\nu\bar{\nu}\gamma$) production are sensitive to the $WW\gamma$ vertex alone. Z-pair production events can be studied to search for possible triple gauge boson vertices involving only neutral gauge bosons. Such vertices might also occur in Z γ production. In contrast with triple gauge boson vertices with two charged bosons, purely neutral gauge boson vertices do not exist in the Standard Model.

3.1 Charged Triple Gauge Boson Couplings

Two main strategies are used at LEP II to measure the triple gauge boson couplings: a so-called “model dependent” analysis, to be defined in the following, and a model independent one, consisting in the direct study of the W helicity structure in W-pair events.

The most general Lorentz invariant Lagrangian⁴ describing the triple gauge boson vertices $WW\gamma$ and WWZ has fourteen independent terms, seven for each vertex. Such large parameter space is reduced to only 3 independent terms by assuming electromagnetic gauge invariance, C and P conservation and $SU(2)_L \times U(1)_Y$ gauge invariance. The independent parameters (TGCs) are usually taken as κ_γ , g_1^Z and λ_γ . In the analyses performed at LEP, results are presented in terms of deviations from their Standard Model values: $\Delta\kappa_\gamma = \kappa_\gamma - 1$, $\Delta g_1^Z = g_1^Z - 1$, and λ_γ .

In W-pair events, both the total and the differential cross-section have a quadratic dependence on the TGCs. Most of the information comes however from the angular distributions. Fixing the W boson mass and neglecting the Initial State Radiation (ISR), W-pair events are completely described by 5 angles, conventionally chosen as the production polar angle of the W^- boson ($\cos\theta_W$) and the polar and azimuthal angles of the W^- (W^+) decay fermion (antifermion) in its parent rest frame (θ_f^* , ϕ_f^*). The experimental accessibility of such angles depends on the W decay channel. In semileptonic events the W charge can be inferred from the lepton charge, the only ambiguity being in the quark flavour. Fully hadronic events suffer from imperfect jet pairing and partial W charge identification, inferred from the jet charges. As a result the sensitivity of the fully hadronic channel to the TGCs is about a factor of two worse than the semileptonic channel. Fully leptonic events suffer from a two-fold ambiguity in the W polar and fermion azimuthal angles, as well as from limited statistics.

Different techniques are applied by the four LEP experiments in order to extract the TGC parameters from the measured angular distributions⁵, e.g. unbinned maximum likelihood fits and Optimal Observable based fits. In general, measured distributions are compared to Monte Carlo predictions at detector level, in order to include all the effects of the detector resolution. One exception is represented by the maximum likelihood fit to $\mu\nu q\bar{q}$ and $e\nu q\bar{q}$ events performed by ALEPH, where the event-by-event probability density function is taken from the theory. The remaining W-pair event classes cannot be used due to the need to fold the theoretical angular distributions with complicated detector resolution functions. On the other side, all the 14 TGC parameters can be extracted, and the assumptions of the model dependent analysis can be tested.

Single W events and events with W fusion into one photon are statistically less sensitive to the TGCs than W-pair events, but allow a clean access to the $WW\gamma$ vertex alone, providing constraints to the κ_γ and λ_γ parameters. In single W events, most of the information comes from the measurement of the total production cross-section. The sensitivity to the κ_γ parameter is similar to that of W-pair events. In single photon events, the distributions of the polar angle and of the energy of the photon are very important, the majority of $\nu\bar{\nu}\gamma$ events coming from radiative return to the Z with subsequent decay of the Z boson into neutrinos, a process which does not involve any triple gauge boson vertices.

Combined LEP results⁶ for 1-parameter fits, including data up to 202 GeV, are shown in table 1. No deviations from the Standard Model is observed. Not all the LEP collaborations have provided preliminary results at high energy, nor all the final states have been analysed yet. Once all the data collected up to now are analysed, the precision of the one-parameter fits will be better than 0.02 for Δg_1^Z and λ_γ , and better than 0.05 for $\Delta\kappa_\gamma$. Such precision is already better than that expected before the LEP II program actually started. Combined two- and three-parameter fits are also performed, providing information about the correlations among the TGC parameters.

Model independent analyses have been performed by OPAL at 183 GeV with the Spin Density Matrix (SDM) method, and by L3 at 183-202 GeV with the Decay Angle method. The Spin Density

Parameter	68% C.L.	95% C.L.
Δg_1^z	$-0.024^{+0.024}_{-0.024}$	$[-0.071, 0.024]$
$\Delta \kappa_\gamma$	$+0.021^{+0.063}_{-0.059}$	$[-0.09, 0.15]$
λ_γ	$-0.016^{+0.026}_{-0.026}$	$[-0.066, 0.035]$

Table 1: The combined results 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 SM value. Both statistical and systematic errors are included.

Matrix elements are observables directly related to the polarisation of the W. From their measurement the relative production of all possible W helicity states can be extracted. The Decay Angle method consists in fitting the $\cos \theta_f^*$ distributions, as a function of the W^- production angle, to contributions from all W helicity states (see fig 3). Longitudinally polarised W bosons have been observed with both methods and their fraction has been found to be in agreement with the prediction of the Standard Model.

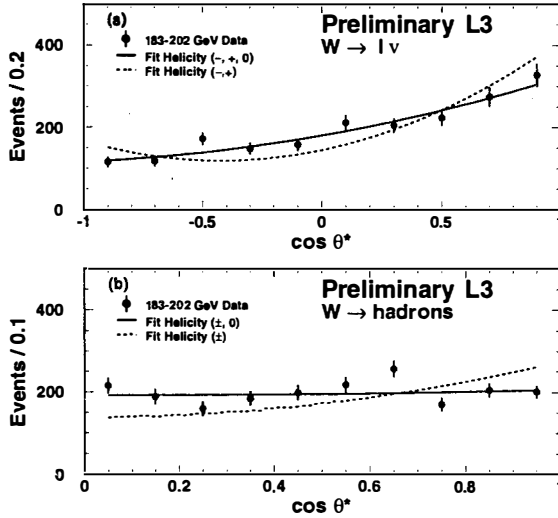


Figure 3: $\cos \theta^*$ distribution for (a) leptonic and (b) hadronic W decays at $\sqrt{s} = 183 - 202$ GeV. Fit results for different W helicity hypotheses are also shown.

3.2 Neutral Triple Gauge Boson Couplings

There are two possible anomalous vertices in the neutral sector, each parametrised by the most general Lorentz and $U(1)_{em}$ invariant Lagrangian plus Bose symmetry⁷.

One vertex refers to anomalous $Z\gamma\gamma$ and $ZZ\gamma$ couplings, accessible at LEP through the process $e^+e^- \rightarrow Z\gamma$. The parametrisation contains eight couplings: h_i^V with $i = 1, \dots, 4$ and $V = \gamma, Z$. The superscript γ refers to $Z\gamma\gamma$ couplings and superscript Z refers to $ZZ\gamma$ couplings. The photon and the Z boson in the final state are considered as on-shell particles. The invariant amplitudes associated to the h_1^V and h_2^V couplings are CP-odd, while those associated to h_3^V and h_4^V are CP-even.

The other vertex refers to anomalous $ZZ\gamma$ and ZZZ couplings, accessible at LEP through the process $e^+e^- \rightarrow ZZ$. It is parametrised in terms of four couplings: f_i^V with $i = 4, 5$ and $V = \gamma, Z$. The superscript γ refers to $ZZ\gamma$ couplings and the superscript Z refers to ZZZ couplings. Both Z bosons in the final state are assumed to be on-shell. The couplings f_4^V are CP-odd whereas f_5^V are CP-even.

The h_i^V and f_i^V couplings are in general independent of each other. For the results presented here they are considered as real, with the imaginary parts fixed to zero. At tree level they all vanish in the Standard Model, so that LEP results represent limits to possible anomalous couplings. Such limits are mainly based on the measurement of the $Z\gamma$ and ZZ total production cross-section. To date, only Delphi and L3 have set limits to the h_i^V couplings⁸, whereas all collaborations but ALEPH have provided limits to the f_i^V couplings². In both cases, only part of the available data sample has been analysed. Combined preliminary results⁶ are shown in table 2 and table 3.

Parameter	68% C.L.	95% C.L.
h_1^γ	$-0.098^{+0.062}_{-0.043}$	[-0.17, 0.08]
h_1^Z	$-0.13^{+0.10}_{-0.07}$	[-0.26, 0.09]
h_2^γ	$-0.05^{+0.12}_{-0.04}$	[-0.11, 0.10]
h_2^Z	$+0.071^{+0.053}_{-0.088}$	[-0.11, 0.16]
h_3^γ	$0.008^{+0.017}_{-0.018}$	[-0.027, 0.041]
h_3^Z	$+0.07^{+0.08}_{-0.16}$	[-0.29, 0.21]
h_4^γ	$-0.003^{+0.013}_{-0.012}$	[-0.026, 0.022]
h_4^Z	$0.08^{+0.08}_{-0.16}$	[-0.12, 0.20]

Table 2: The combined results and 95% C.L. intervals obtained combining the results from DELPHI and L3. In each case the parameter listed is varied while the others are fixed to their SM value. Both statistical and systematic errors are included.

Parameter	68% C.L.	95% C.L.
f_4^γ	$+0.29^{+0.11}_{-0.21}$	[-0.49, 0.49]
f_4^Z	$+0.49^{+0.19}_{-0.31}$	[-0.82, 0.82]
f_5^γ	$-0.6^{+1.4}_{-0.3}$	[-1.1, 1.1]
f_5^Z	$-0.01^{+0.56}_{-0.57}$	[-1.1, 1.1]

Table 3: The combined results and 95% confidence intervals obtained after combination of the results from DELPHI, L3 and OPAL. Only the parameter listed is varied while the other two are fixed to their SM value. Both statistical and systematic errors are included.

3.3 Limits to anomalous Quartic Gauge Boson Couplings

Quartic Gauge Boson couplings (QGCs) are also predicted in the Standard Model. In the few processes involving QGCs which are energetically accessible at LEP II, their contribution to any measurable cross-section is expected to be undetectable. Nevertheless, both OPAL and L3 have searched for possible large anomalous contributions⁹. Their results are summarised in table 4, where limits are set to genuine QGC parameters, not already constrained by TGC limits.

Final state	$a_0/\Lambda^2 \text{ GeV}^{-2}$	$a_c/\Lambda^2 \text{ GeV}^{-2}$	$a_n/\Lambda^2 \text{ GeV}^{-2}$
$WW\gamma^{(Opal)}$	[-.070, .070]	[-.13, .19]	[-0.61, 0.57]
$WW\gamma^{(L3)}$	[-.042, .045]	[-.072, .148]	[-.390, .378]
$\nu\nu\gamma\gamma^{(Opal)}$	[-.086, .086]	[-.23, .23]	-
$Z^0\gamma\gamma^{(L3)}$	[-.009, .008]	[-.007, .013]	-

Table 4: 95% C.L. limits on anomalous quartic couplings as measured by the L3 and OPAL collaborations. Λ represents the energy scale for new physics.

4 Conclusions

Preliminary analyses of data collected at LEP in 1999 show good agreement with the Standard Model in both W-pair, Z-pair and single W production cross-section. The precision in the measurement of the trilinear gauge boson couplings WWZ and WW γ has exceeded the expectations prior to the LEP II startup. Combined limits to possible anomalous couplings among three neutral gauge boson have been presented for the first time, as well as new limits on quartic gauge boson couplings. No deviations from the Standard Model has been observed.

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