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Preliminary Results on the Pair-Production of W Bosons in e^+e^- Interactions at $\sqrt{s} = 172$ GeV

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Abstract

We report preliminary results on the measurement of W-boson pair-production at 172.13 GeV centre-of-mass energy with the L3 detector at LEP. In a data sample corresponding to a total luminosity of 10.25 pb^{-1}, we select 113 four-fermion events with high invariant masses of pairs of hadronic jets or leptons. These data allow us to determine W-pair cross sections, W-decay branching fractions, the mass of the W boson and anomalous triple-vector-boson couplings.

1 Introduction

In the second half of the 1996 data taking period, the e^+e^- collider LEP at CERN was operated at centre-of-mass energies, $\sqrt{s}$, of 170.31 GeV and 172.32 GeV [1]. These centre-of-mass energies are above the kinematic threshold of W-pair production, $e^+e^- \rightarrow W^+W^-$, which was investigated earlier [2]. The higher centre-of-mass energy implies an increased cross section for the W-pair signal and a reduced cross section for the background, improving the signal-to-background ratio by a factor of about four.

During this run the L3 detector collected a total integrated luminosity of 1.00 pb^{-1} at 170.31 GeV and 9.25 pb^{-1} at 172.32 GeV. For the results presented in this note these two data samples are combined using a luminosity weighted centre-of-mass energy of 172.13 GeV. All final states mediated by W-pairs (CC03 [3–5]), $e^+e^- \rightarrow WW \rightarrow ffff$, are analysed:

1. $e^+e^- \rightarrow qqe\nu(\gamma)$ 2. $e^+e^- \rightarrow qq\mu\nu(\gamma)$ 3. $e^+e^- \rightarrow qq\tau\nu(\gamma)$

4. $e^+e^- \rightarrow \ell\nu\ell\nu(\gamma)$ 5. $e^+e^- \rightarrow qqqq(\gamma)$,

where (γ) indicates the possible presence of radiative photons.

Additional contributions to the production of these four-fermion final states arise from other neutral-current (NC) or charged-current (CC) Feynman diagrams. For high invariant masses of pairs of fermions and for the visible fermions all within the acceptance of the detector, the additional contributions are small. At the current level of statistical accuracy they need to be taken into account only for $e^+e^- \rightarrow qqe\nu(\gamma)$ (CC20) and $e^+e^- \rightarrow \ell\nu\ell\nu(\gamma)$ (CC56+NC56) [3–5].

All experimental results presented in the following are preliminary.

2 Cross Sections and W-Decay Branching Fractions

A $qqe\nu$ event selected in the 172 GeV data is shown in Figure 1. In total, 113 W-pair candidates are selected in a data sample corresponding to a total luminosity of 10.25 pb^{-1}.

Most event selections are similar to those at 161 GeV [2], adapted to the higher centre-of-mass energy. An exception is the $qqqq$ selection which is not using a neural network. An overview on selections is given in Table 1, summarising selection efficiencies, accepted background cross sections and systematic errors. These numbers enter the maximum likelihood fits described in [2] to determine cross sections and W-decay branching fractions. The results of these fits are listed in Tables 2 and 3.

For the $qqe\nu(\gamma)$ and $\ell\nu\ell\nu(\gamma)$ final state the measured cross sections contain significant contributions from processes not mediated by resonant W-pair production. For these two final states, the efficiency is determined within phase-space cuts ($E_e, E_\nu > 20$ GeV, $|\cos\theta_e|, |\cos\theta_\nu| < 0.95$, $M_{e\nu}, M_{qq} > 45$ GeV for $qqe\nu$; and $|\cos\theta_\ell| < 0.96$ for both charged leptons, with energies larger than 15 GeV and 5 GeV for $\ell\nu\ell\nu$). In order to determine W-pair cross sections also for these final states the measured cross sections are scaled by a multiplicative factor, f_i. These conversion factors are given by the ratio of the total CC03 cross section and the four-fermion cross section within cuts, and are calculated within the Standard Model using the EXCALIBUR [6] event generator. They are determined to be 1.10 for $qqe\nu(\gamma)$ and 1.03 for $\ell\nu\ell\nu(\gamma)$, where the dependence of the f_i on M_W is negligible. These cross sections for the $qqe\nu(\gamma)$ and $\ell\nu\ell\nu(\gamma)$ final states are also listed in Table 2.

The data collected at 161 GeV [2] and at 172 GeV are combined for the determination of the W-decay branching fractions. The W-decay branching fractions obtained for the individual leptonic decay modes are in agreement with each other. Assuming charged-current lepton universality, the branching fraction for the decay of the W boson to hadrons is found to be:

$$B(\mathrm{W} \rightarrow \mathrm{hadrons}) \quad = \quad 62.3^{+3.9}_{-4.0}\ (stat.) \pm 0.8\ (syst.)\ \%\,, \tag{1}$$

in good agreement with the Standard-Model expectation of 67.5 %. Assuming Standard-Model W-decay branching fractions, the total W-pair cross section at $\sqrt{s} = 172.13 \pm 0.06$ GeV [1] is measured to be:

$$\sigma_{\mathrm{WW}} \quad = \quad 12.93^{+1.50}_{-1.41}\ (stat.) \pm 0.38\ (syst.)\ \mathrm{pb}\,. \tag{2}$$

The cross sections for W-pair production measured at 161 GeV and at 172 GeV are compared to the Standard-Model expectations in Figure 2. Good agreement is observed.

3 Mass of the W Boson

Based on the events as selected above, the mass of the W boson, $\mathrm{M_W}$, is determined using the method of direct reconstruction [7]. Two W bosons are reconstructed in each event by grouping the four reconstructed final-state fermions in pairs. A kinematic fit imposing four-momentum conservation is applied to improve the determination of invariant masses.

Various methods to extract a value for the W boson mass, $\mathrm{M_W}$, from the distribution of the reconstructed average invariant masses, $\mathrm{M_{inv}}$, are studied, in particular the methods referred to as Monte Carlo calibration method, convolution method, and reweighting method in Section 3.3 of [7]. The results are in good agreement between all methods. In the following the results of unbinned maximum-likelihood fits to the data using the box method are quoted. The box method is a reweighting method where event weights are calculated summing over Monte Carlo events in small bins ("boxes") of reconstructed invariant mass centred around each data event.

The mass of the W boson is determined separately for the $qqqq$, $qqe\nu$ and $qq\mu\nu$ event samples, with the result:

$$\begin{aligned}
\mathrm{M_W}(qqqq) &= 80.79 \pm 0.50\ (stat.) \pm 0.07\ (exp.\ syst.) \pm 0.10\ (theo.\ syst.) \pm 0.03\ (\mathrm{LEP})\ \ \mathrm{GeV} \\
\mathrm{M_W}(qqe\nu) &= 80.88 \pm 0.54\ (stat.) \pm 0.07\ (exp.\ syst.) \pm 0.10\ (theo.\ syst.) \pm 0.03\ (\mathrm{LEP})\ \ \mathrm{GeV} \\
\mathrm{M_W}(qq\mu\nu) &= 80.12 \pm 0.86\ (stat.) \pm 0.07\ (exp.\ syst.) \pm 0.02\ (theo.\ syst.) \pm 0.03\ (\mathrm{LEP})\ \ \mathrm{GeV}
\end{aligned}$$

The first error is the *expected* statistical error for an event sample of the size selected in the data. It is determined from the spread of the fitted central values for $\mathrm{M_W}$ obtained by fitting several Monte Carlo samples the size of the data samples. The second error is the experimental systematic error derived from comparing different event reconstruction and fitting methods. The third error is a theoretical error concerning the functional form of the invariant-mass spectrum. Especially, it contains a contribution of 100 MeV for the $qqqq$ final state arising from colour-reconnection and Bose-Einstein effects [7], and of 100 MeV for the $qqe\nu$ final state due to single- and non-resonant contributions. The last error arises from the calibration of the LEP beam energy [1].

The results obtained for the different final states are in good agreement with each other. They are combined taking correlated systematic errors into account. The result on $\mathrm{M_W}$ thus obtained from the 172 GeV data is:

$$\mathrm{M_W} = 80.72 \pm 0.34\ (stat.) \pm 0.11\ (syst.) \pm 0.03\ (\mathrm{LEP})\ \ \mathrm{GeV}, \tag{3}$$

as shown in Figure 3. This result is in good agreement with our published result on $\mathrm{M_W}$ determined from the cross section at threshold (161 GeV), $\mathrm{M_W} = 80.80^{+0.48}_{-0.42} \pm 0.03$ (LEP) GeV [2]. Combining these results, the mass of the W boson is determined to be:

$$\mathrm{M_W} = 80.75 \pm 0.28\ (exp.) \pm 0.03\ (\mathrm{LEP})\ \ \mathrm{GeV}. \tag{4}$$

4 Triple-Vector-Boson Couplings

Alternatively, when the W mass is known, the total cross section can be interpreted in terms of triple-vector-boson couplings [8,9]. In particular, it is interesting to test if the coupling between the Z and a pair of W bosons exists [10].

For the results presented in the following, the differential cross section in the W^- polar angle for selected $qqe\nu$ and $qq\mu\nu$ events is used together with the total cross section measured at 161 GeV and at 172 GeV. The differential cross section is shown in Figure 4.

The deviation, δ_Z, of the ZWW coupling, g_ZWW, from its Standard Model value of $\cot\theta_\mathrm{W} = 1.9$ is found to be:

$$\begin{aligned}
\delta_\mathrm{Z} &= g_\mathrm{ZWW} - \cot\theta_\mathrm{W} && (5)\\
&= 0.0^{+1.1}_{-0.9}\ \ (68\%\ \mathrm{CL}) && (6)\\
&= 0.0^{+2.0}_{-1.6}\ \ (95\%\ \mathrm{CL}), && (7)
\end{aligned}$$

This confirms the existence of the ZWW coupling at more than 95% CL. In an alternative scenario [9], where more than one anomalous coupling is introduced, but depending on a single parameter, $\alpha_{\mathrm{W}\Phi}$, one finds:

$$\begin{aligned}
\alpha_{\mathrm{W}\Phi} &= 0.0^{+0.4}_{-0.4}\ \ (68\%\ \mathrm{CL}) && (8)\\
&= 0.0^{+0.7}_{-0.6}\ \ (95\%\ \mathrm{CL}) && (9)
\end{aligned}$$

With the increased statistics at 172 GeV it is also possible to determine two triple-vector-boson couplings simultaneously, for example, an anomalous contribution to the magnetic dipole-moment of the W boson, $\Delta\kappa_\gamma = \kappa_\gamma - 1$, in addition to δ_Z. The result of a two-parameter fit to the data is:

$$\begin{aligned}
\delta_\mathrm{Z} &= -0.4^{+1.1}_{-0.7}\ \ (68\%\ \mathrm{CL}) && (10)\\
\Delta\kappa_\gamma &= +0.4^{+1.9}_{-1.8}\ \ (68\%\ \mathrm{CL}), && (11)
\end{aligned}$$

as shown in Figure 5. The constraint $\Delta\kappa_\gamma = -\cot^2\theta_\mathrm{W}(\Delta\kappa_\mathrm{Z} - \delta_Z\tan\theta_\mathrm{W})$ [9] is imposed. In all scenarios good agreement with the Standard Model expectation of $\delta_\mathrm{Z} = \alpha_{\mathrm{W}\Phi} = \Delta\kappa_\gamma = 0$ is observed.

5 Summary and Conclusion

In a data sample corresponding to an integrated luminosity of 10.25 pb^{-1} collected at an average centre-of-mass energy of 172.13 GeV, we have measured W-pair production by selecting 113 four-fermion events with high invariant masses. All final states mediated by W-pair production are analysed. The experimental results presented in this note are preliminary.

The total cross section for W-pair production is found to be $\sigma_\mathrm{WW} = 12.93^{+1.50}_{-1.41}$ (*stat.*) $\pm$ 0.38 (*syst.*) pb. Combining the results on the W-boson mass obtained at 161 GeV and at

172 GeV, we find $\mathrm{M_W} = 80.75 \pm 0.28\ (exp.) \pm 0.03\ (\mathrm{LEP})$ GeV. The existence of the ZWW coupling is established at more than 95% CL. Limits on anomalous triple-vector-boson couplings are: $-1.6 < \delta_\mathrm{Z} < 2.0$ or $-0.6 < \alpha_{\mathrm{W}\Phi} < 0.7$ at 95% CL.

6 Acknowledgements

We wish to congratulate the CERN accelerator divisions for the successful upgrade of the LEP machine and to express our gratitude for its good performance. We acknowledge with appreciation the effort of all engineers, technicians and support staff who have participated in the construction and maintenance of this experiment. Those of us who are not from member states thank CERN for its hospitality and help.

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Process	Efficiencies [%]					Background	Systematic
	$qqqq$	$qqe\nu$	$qq\mu\nu$	$qq\tau\nu$	$\ell\nu\ell\nu$	[pb]	Error [%]
$\mathrm{e^+e^-} \to qqqq(\gamma)$	76.0	0.65	0.65	0.65	—	1.53	5
$\mathrm{e^+e^-} \to qqe\nu(\gamma)$	—	73.4	0.15	1.80	—	0.073	7
$\mathrm{e^+e^-} \to qq\mu\nu(\gamma)$	—	0.09	78.7	1.99	—	0.035	5
$\mathrm{e^+e^-} \to qq\tau\nu(\gamma)$	0.54	5.23	7.03	45.6	—	0.254	6
$\mathrm{e^+e^-} \to \ell\nu\ell\nu(\gamma)$	—	—	—	—	43.7	0.019	3

Table 1: Selection efficiencies, accepted background cross sections from non-W processes, and total systematic uncertainties for signal processes $\mathrm{e^+e^-} \to qqqq(\gamma)$, $\mathrm{e^+e^-} \to qqe\nu(\gamma)$, $\mathrm{e^+e^-} \to qq\mu\nu(\gamma)$, $\mathrm{e^+e^-} \to qq\tau\nu(\gamma)$, $\mathrm{e^+e^-} \to \ell\nu\ell\nu(\gamma)$. For the $qqe\nu$ ($\ell\nu\ell\nu$) signal, the signal efficiency is derived from a CC20 (CC56+NC56) Monte Carlo sample and contains the conversion factor f_i as explained in the text. The total systematic uncertainties are relative to the cross sections listed in Table 2.

Process	$\mathcal{L}$	N_{data}	N_{bg}	σ(cuts)	σ(CC03)	r_{SM}	σ_{SM}
	[pb^{-1}]			[pb]	[pb]	[%]	[pb]
$\mathrm{e^+e^-} \to qqqq(\gamma)$	10.25	59	15.7	—	$5.51^{+1.03}_{-0.94} \pm 0.28$	45.6	5.66
$\mathrm{e^+e^-} \to qqe\nu(\gamma)$	10.25	19	0.75	$2.16^{+0.57}_{-0.49} \pm 0.15$	$2.37^{+0.63}_{-0.54} \pm 0.17$	14.6	1.81
$\mathrm{e^+e^-} \to qq\mu\nu(\gamma)$	10.25	10	0.36	—	$1.14^{+0.44}_{-0.35} \pm 0.06$	14.6	1.81
$\mathrm{e^+e^-} \to qq\tau\nu(\gamma)$	10.25	15	2.60	—	$2.14^{+0.91}_{-0.77} \pm 0.13$	14.6	1.81
$\mathrm{e^+e^-} \to \ell\nu\ell\nu(\gamma)$	9.76	10	0.19	$2.24^{+0.80}_{-0.65} \pm 0.07$	$2.30^{+0.82}_{-0.67} \pm 0.07$	10.6	1.32

Table 2: Total luminosity used in the analyses, $\mathcal{L}$, number of selected data events, N_{data}, number of expected non-W background events, N_{bg}, and cross sections for the reactions $\mathrm{e^+e^-} \to qqqq(\gamma)$, $\mathrm{e^+e^-} \to qqe\nu(\gamma)$, $\mathrm{e^+e^-} \to qq\mu\nu(\gamma)$, $\mathrm{e^+e^-} \to qq\tau\nu(\gamma)$ and $\mathrm{e^+e^-} \to \ell\nu\ell\nu(\gamma)$. For the $qqe\nu$ and $\ell\nu\ell\nu$ signal, the cross sections within the phase-space cuts described in the text, σ(cuts), are given in addition to the CC03 cross sections, σ(CC03). The first error is statistical and the second systematic. Also shown are the CC03 branching fractions, r_{SM}, and the CC03 cross sections, σ_{SM}, as expected within the Standard Model. They are calculated using Standard-Model W-decay branching fractions [4] and the GENTLE [11] program for a W mass of 80.356 GeV [12].

Parameter	Lepton Non-Universality	Lepton Universality	Standard Model
$B(\mathrm{W} \to \mathrm{e}\nu)$ [%]	$15.6^{+3.6}_{-3.2} \pm 0.9$	—	
$B(\mathrm{W} \to \mu\nu)$ [%]	$8.5^{+2.7}_{-2.3} \pm 0.4$	—	
$B(\mathrm{W} \to \tau\nu)$ [%]	$13.9^{+4.3}_{-4.0} \pm 0.9$	—	
$B(\mathrm{W} \to \ell\nu)$ [%]	—	$12.6^{+1.3}_{-1.3} \pm 0.3$	10.8
$B(\mathrm{W} \to qq)$ [%]	$62.0^{+3.9}_{-4.0} \pm 0.8$	$62.3^{+3.9}_{-4.0} \pm 0.8$	67.5
σ_{WW} [pb]	$13.20^{+1.60}_{-1.50} \pm 0.38$	$12.98^{+1.53}_{-1.43} \pm 0.38$	12.41

Parameter	Using SM W-Decay Branching Fractions	Standard Model
σ_{WW} [pb]	$12.92^{+1.50}_{-1.41} \pm 0.38$	12.41

Table 3: W-decay branching fractions, B, and total W-pair cross section, σ_{WW}, derived with and without the assumption of charged-current lepton universality. In the bottom part of the table, the measured total W-pair cross section imposing Standard-Model W-decay branching fractions is given. The first error is statistical and the second systematic. Also shown are the W-decay branching fractions [4] and the total W-pair cross section as expected in the Standard Model. The latter is calculated for $\mathrm{M_W} = 80.356$ GeV [12] using the GENTLE [11] program.

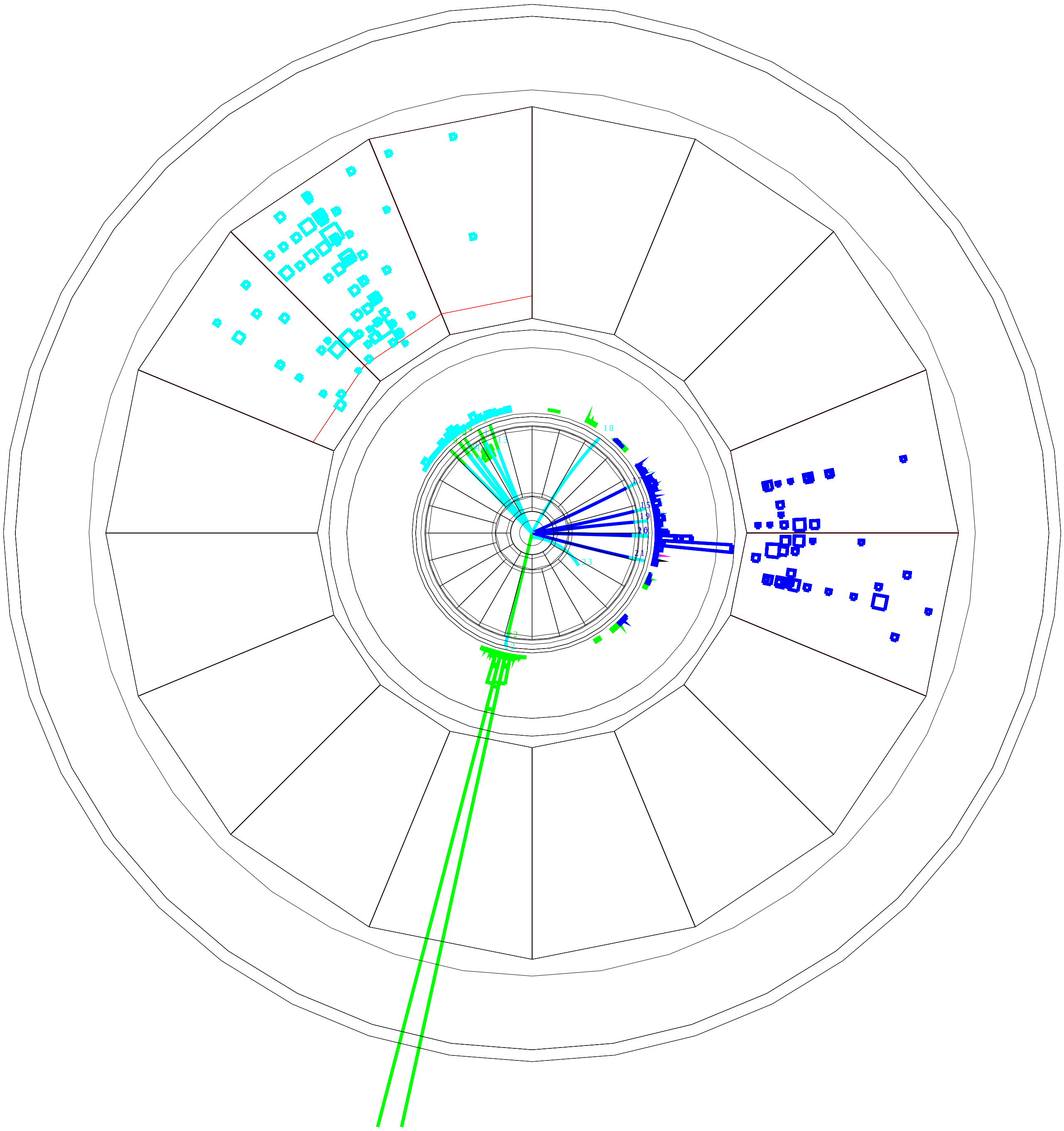

Figure 1: A $qqe\nu$ event selected in the data. Shown is the view in the plane perpendicular to the beam axis. The thick lines are the tracks reconstructed in the central tracking chamber. Energy depositions in the electromagnetic and hadron calorimeter are shown as squares with size proportional to the amount of energy deposited in the calorimeter cell. The large cluster in the lower part of the electromagnetic calorimeter with a track pointing to it is identified as the electron. The two hadronic jets correspond to the qq system.

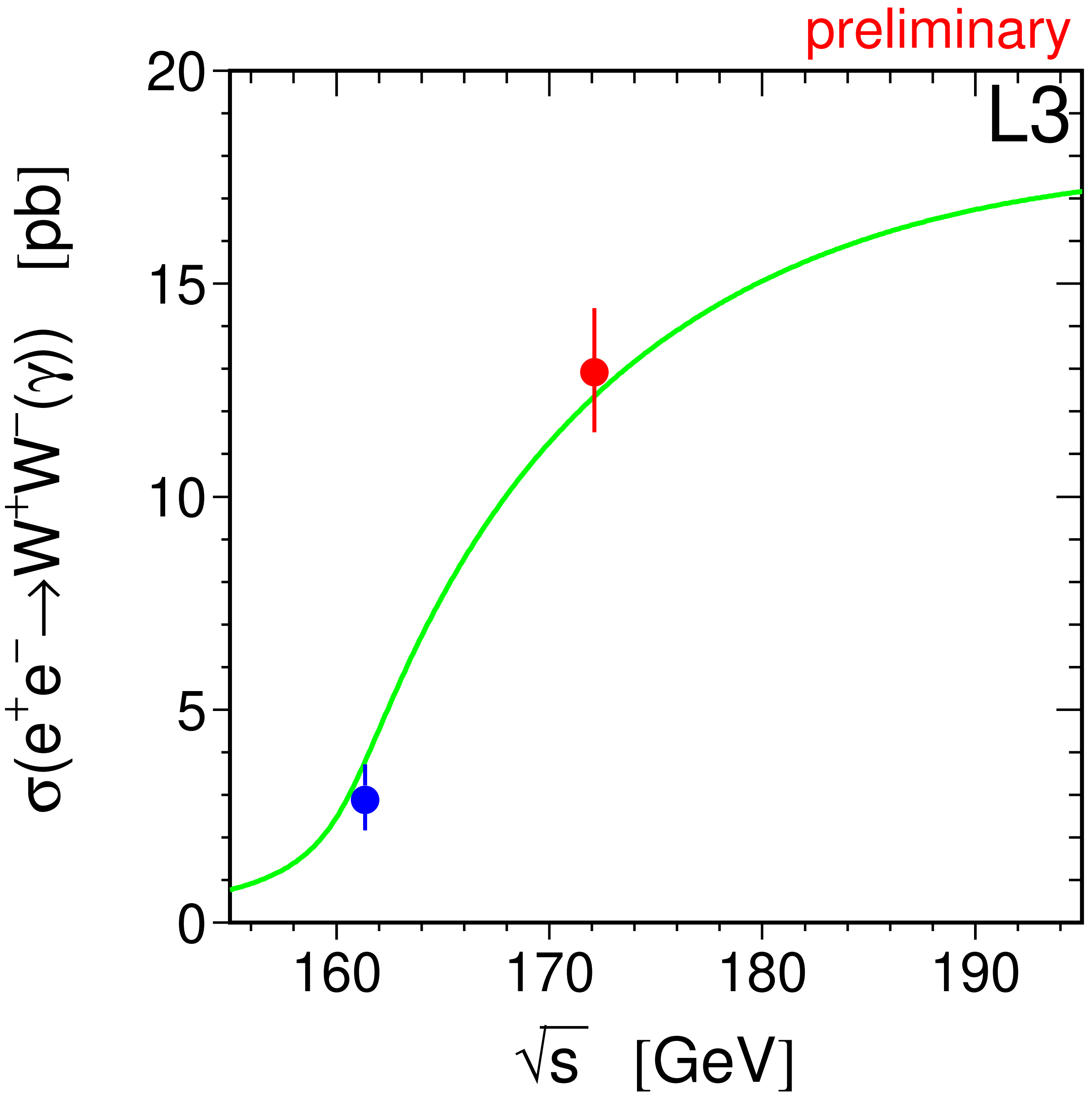

Figure 2: The W-pair cross section as a function of centre-of-mass energy. The curve shows the Standard Model expectation for a W mass of $M_W = 80.356$ GeV [12].

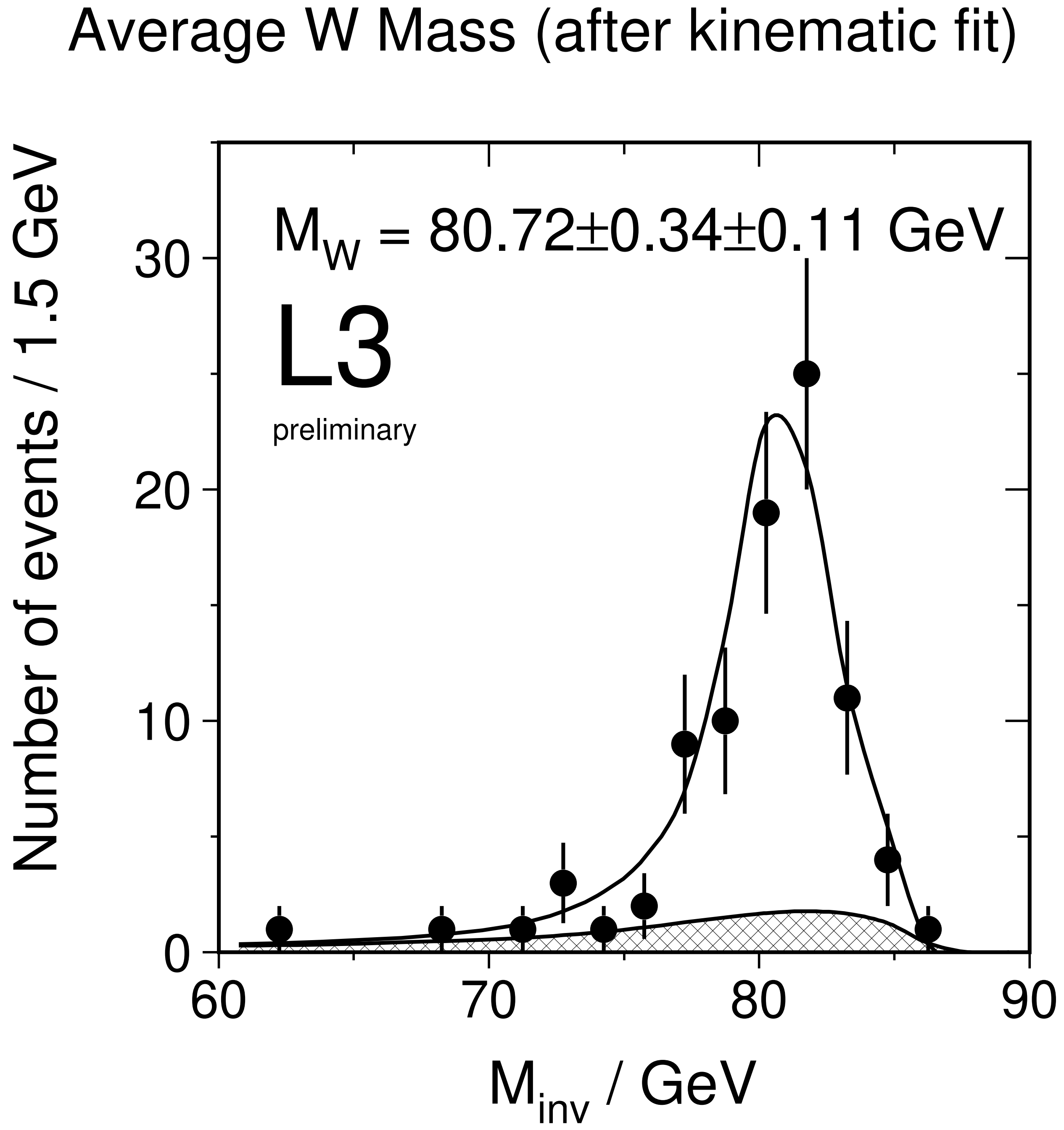

Figure 3: The distribution of the reconstructed invariant masses, $\mathrm{M_{inv}}$, for $qqqq$, $qqe\nu$ and $qq\mu\nu$ events. The curve is the result of the fit. The hatched region shows the combined background which is dominated by $q\bar{q}(\gamma)$ events accepted by the $qqqq$ selection.

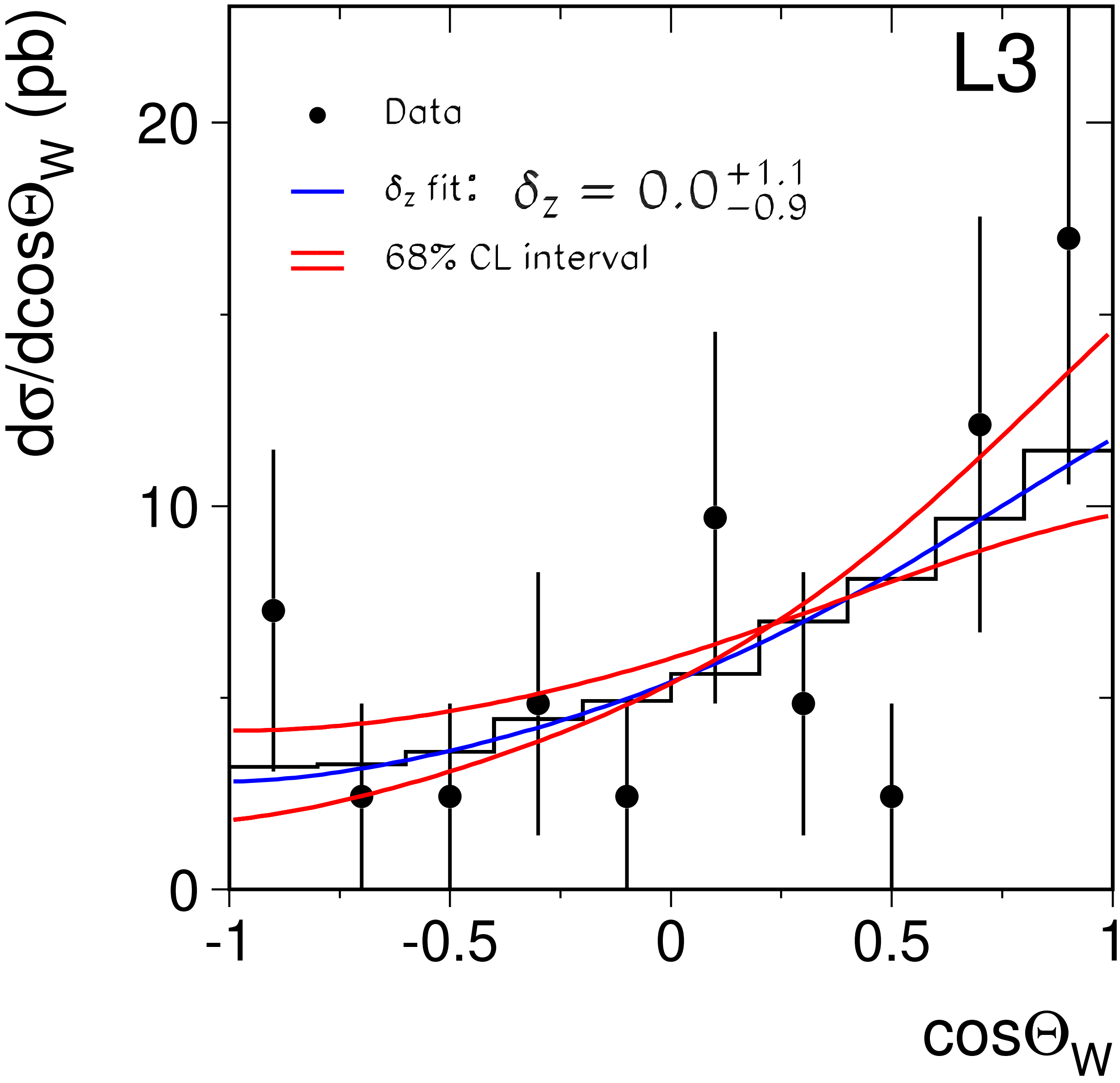

Figure 4: Differential cross section in W^- polar angle, $\cos\Theta_W$, of the selected $qqe\nu$ and $qq\mu\nu$ events. The solid histogram is the Monte-Carlo prediction for vanishing anomalous couplings. The lines show the fit result with 68% CL errors derived from this distribution and the measurements of the total cross section at 161 GeV [2] and at 172 GeV.

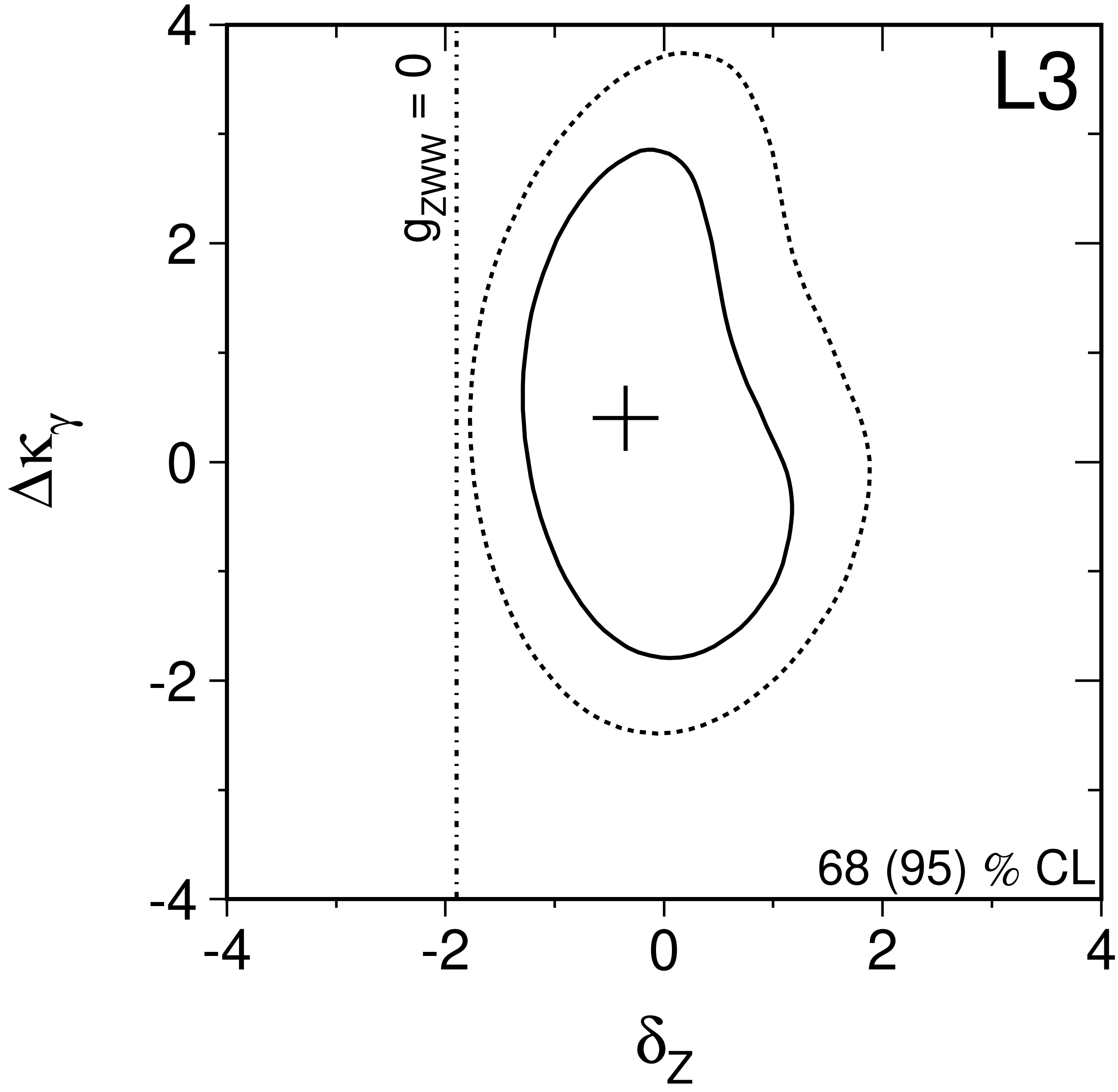

Figure 5: Contour curves of 68% and 95% confidence level for the two anomalous triple-vector-boson couplings $\Delta\kappa_\gamma$ and δ_Z.