W,Z couplings and cross-sections at LEP2

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In 1998 the CERN electron positron Collider LEP has reached energies up to 94.5 GeV per beam and an integrated luminosity of about 170 pb^{-1} per experiment was collected. With this energy and luminosity a large statistics study of W pair production at LEP is allowed and a preliminary study of Z pair production is presented. Results are discussed concerning W pair production cross-section and branching ratios, single W cross-section and Z pair production. All the results are found in good agreement with the prediction of the Standard Model and limits are derived on anomalous Triple Boson Couplings at the ZWW, γWW, ZZγ and ZZZ vertices.

1 Introduction

In the first phase of the LEP electron-positron collider the Z boson properties were studied carefully and the bulk of the electroweak physics was in the two fermion events, resulting from the Z boson decays. The large statistics collected at the Z pole has allowed careful tests of the Standard Model [1]. Since 1996 LEP has entered the high energy phase, passing the threshold for W pairs and recently Z pairs events. These events are characterized by 4 fermions in the final state, each boson decaying into two fermions. Since 1996 the following center of mass energies have been scanned at LEP: 161, 172, 183 and 189 GeV. During the summer of 1998 about 170 pb^{-1} of integrated luminosity per each experiment were collected at this last energy point, increasing substantially the data sample available. Preliminary results are presented from these data.

2 W-pair Selection

W-pair events can be classified in hadronic, semileptonic or leptonic events depending on the 2 W decays. Because of the different topology each category requires dedicated selection criteria. The selections adopted by the 4 experiments are similar and are summarized in Table 1 where typical efficiencies and expected back-grounds are also indicated. Leptonic and semileptonic events are usually selected by means of a cut-based approach. Instead hadronic events are usually selected with a first set of cuts, then all the relevant variables are combined into a neural network: topological variables, jet reconstruction and kinematic information. The cross-section is then evaluated from a fit to the distribution of the Neural Network output.

Channel	Selection	Efficiency	Accepted BG
$\ell\nu\ell\nu$	2 acoplanar ℓ, E_{miss}, no γ	$\simeq$ 60%	$\simeq$100 fb
$qq\ell\nu_\ell$	1 isolated ℓ, 2 jets, E_{miss}	$\simeq$ 84,86,65% ($\ell = e, \mu, \tau$)	$\simeq$150,60,340 fb ($\ell = e, \mu, \tau$)
$qqqq$	Neural Network	$\simeq$ 87.5%.	$\simeq$1.46 pb

Table 1: Typical selection criteria, efficiency and accepted background for each WW channel.

3 W-Pair Cross-Section

Preliminary results for W pair cross-sections at $\sqrt{s}$ =189 GeV and final results for lower energies are available from each experiment [2]. Table 2 shows the results of the 4 LEP experiments if Standard Model branching ratios are assumed for the W decays. It can be noted that the 189 GeV cross-section is about two standard deviation lower than the SM prediction. However the theory estimate is probably affected by some uncertainty due to the incomplete calculations which are estimated to be 2%.

Figure 1 shows the evolution of the cross-section with center of mass energy. In the Standard Model the cross-section for W pairs results from the strong cancellation of the s-channel diagrams with a Z or γ exchange and the t-channel diagram with a neutrino exchange. The ZWW vertex, whose existence is predicted in the SM, is crucial in this cancellation, as it can be seen from Figure 1. The good agreement between the prediction and the data proves the existence of the ZWW and γWW vertices, in particular hypotheses without ZWW vertex or t-channel neutrino only are ruled out.

3.1 W-Pair versus 4-Fermion production

It is important to stress that some of the final states which are being selected for W pair production can be given not only by the 3 Feynman diagrams (usually called CC03) responsible for the on-shell W-pair production, but also by other diagrams, where the production of those fermions does not necessarily happen through the W production. A complete classification of all the 4 fermion processes and the

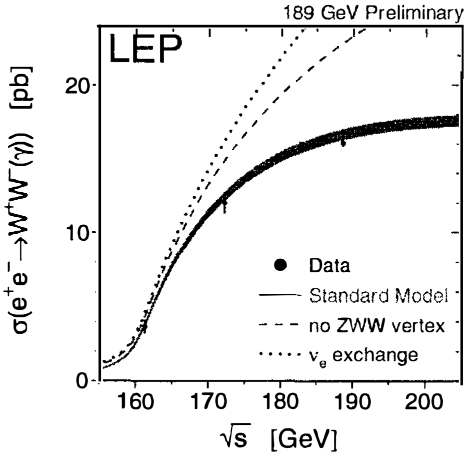

Figure 1: WW cross-section [2] measured at LEP as a function of the center of mass energy. The Figure also shows the preliminary measurement at 189 GeV. The Standard Model prediction is shown with a 2% error band.

Cross-section σ_{CC03} (pb)		
Experiment	$\sqrt{s}$ =183 GeV	$\sqrt{s}$ =189 GeV
ALEPH	15.57 ± 0.68	*15.64 ± 0.43*
DELPHI	15.86 ± 0.74	*15.79 ± 0.49*
L3	16.53 ± 0.72	*16.20 ± 0.46*
OPAL	15.43 ± 0.66	*16.55 ± 0.40*
LEP	15.83 ± 0.36	*16.07 ± 0.23*
SM	*15.70 ± 0.31*	*16.65 ± 0.33*

Table 2: WW cross-section measured at LEP at 183 and 189 GeV. The data are corrected for non-resonant processes, as explained in the text, giving a CC03 cross-section. The measurements written in *slanted* are preliminary.

corresponding Feynman diagrams can be found in [3]. The experiments usually give a CC03-equivalent cross-section, that is to say, the contribution of the non resonant 4-fermions diagrams is taken care of with a subtractive or multiplicative procedure.

3.2 Single W production

For some of the processes it is also interesting to quote the non-resonant production cross-section, as for the $We\nu_e$ cross-section (often referred as "single W"). The relevant diagrams for this process are 20. The signal definition makes use of some kinematic cuts to select a region of the phase space where the contribution of the single resonating diagrams is maximum with respect to the others. Figure 2 shows the cross-section as a function of $\sqrt{s}$ as measured by the L3 experiment, together with the prediction of two Monte Carlo calculations for the same set of kinematical cuts. The preliminary cross-section at 189 GeV is: $\sigma_{We\nu}$(189 GeV)=$(0.53^{+0.12}_{-0.11} \pm 0.03)$ pb, where the first error is statistical and the second systematic.

4 W Branching Ratios and Measurement of V_{cs}

The W decay branching ratios have been determined by each experiment from the cross-sections of the individual final states with and without the assumption of lepton universality. Figure 3 shows these measurements. The data are consistent with each other and with the hypothesis of lepton universality. Under this assumption, the average hadronic W Branching Ratio is: $B_h = (68.07 \pm 0.42)\%$.

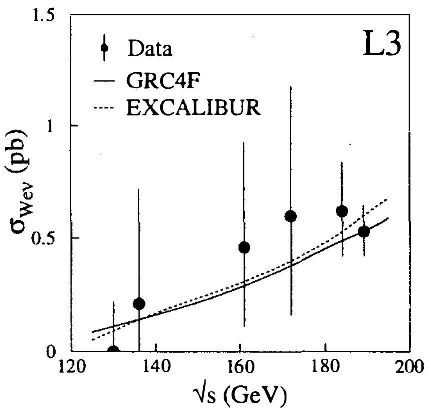

Figure 2: Single W cross-section as a function of the center of mass energy, as measured by the L3 experiment [4]. The point at 189 GeV is preliminary. The figure also shows the cross-section predicted by two Monte Carlo codes which calculate the full set of 20 diagrams: Grace4f[5] and Excalibur[6].

In the Standard Model B_h depends on the 6 elements of the CKM Matrix not involving the top quark according to the formula:

$$\frac{B_h}{1-B_h} = \sum_{i=u,c}\sum_{j=d,s,b} |V_{ij}|^2(1+\frac{\alpha_s}{\pi}). \qquad (1)$$

From the knowledge of B_h, α_s and 5 of the 6 V_{CKM} elements in the formula, it is thus possible to calculate the 6th. The diagonal elements are the most sensitive to this calculation, out of which V_{cs} is the worst measured until now. So from the above B_h measurement, assuming $\alpha_s(m_W^2)$=(0.121±0.002) and the 5 V_{CKM} elements from [7], one can deduce: $|V_{cs}| = (1.002 \pm 0.016_{stat} \pm 0.012_{syst})$. This determination is about 10 times more accurate than the current world average direct determination [7].

5 Trilinear Gauge Coupling

The parametrization of the anomalous TGC is described in [8]. The most general Lorentz-invariant Lagrangian which describes this coupling contains 14 parameters. Assuming C and P conservation and electromagnetic gauge-invariance, only 5 parameters remain. Other constraints on SU(2) invariance and on the boson propagators allow to reduce the model to 3 parameters: Δg_1^Z, $\Delta\kappa_\gamma$ and λ_γ, which are all zero in the Standard Model. (We follow the notation of Ref. [8]).

As already pointed out in Section 3, the measurement of the total WW cross-section is very sensitive to a possible anomalous behaviour of the couplings in the ZWW and γWW vertices. But these would also affect the production angles and the helicities of the W bosons, causing anomalous distributions for the decay products.

There are two different techniques to constrain the values of the trilinear gauge couplings from the WW events:

- from a fit to the distributions of the W production angle and the emission angle of the fermions in the W rest-frame,

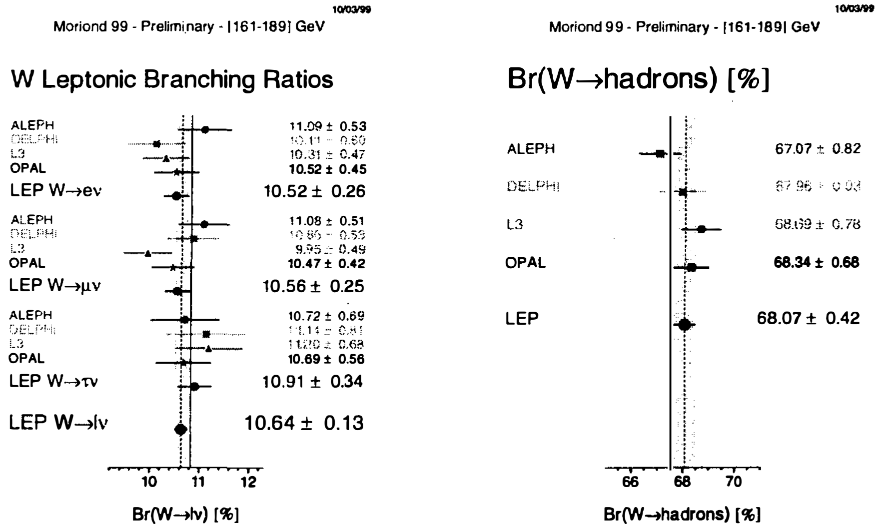

Figure 3: Leptonic and hadronic Branching Ratios measured by the 4 LEP experiments and combined LEP values. The data include the 189 GeV data sample, and thus are preliminary.

- or with the Optimal-Observable analysis, as described in[9]. This analysis projects the 5 observables of the events into 1 variable whose sensitivity to a given coupling α is optimal:

$$\mathcal{OO}_i^\alpha = \frac{1}{\sigma_i^{SM}} \left(\frac{d\sigma_i(\alpha)}{d\alpha} \right)_{\alpha=0} \quad \text{with} \quad \sigma_i(\alpha) = \left(\frac{d\sigma(\Omega,\alpha)}{d\Omega} \right)_{\Omega=\Omega_i} \tag{2}$$

The sensitivity and the adopted method depend on the different WW channels. Both one parameter fits and 2 dimensional fits are performed by each experiment and the results are expressed in terms of maximum likelihood curves, used in the LEP combination of the results.

Preliminary results[10] for the average values of the parameters and for the 95% CL limits are shown in Figure 4.

Furthermore there are other processes which are sensitive to these quantities: indeed both the Weν ("single W") and the $\nu\nu\gamma$ ("single photon") channels are sensitive to the γWW coupling[11,12], but the new 189 GeV results are not yet available.

6 Z-Pair Cross-Section

Since 1998 LEP is running at energies above the threshold for ZZ production. The Z physics has been thoroughly studied at LEP1, nevertheless the ZZ signal is important for several reasons:

- the ZZ signal is a process predicted by the Standard Model, and thus it is interesting to verify the correctness of the prediction,
- it is a background in the search of the Higgs signal in the Z mass range and a test of the selections for the Higgs search. Being at the current LEP energy the ZZ cross-section non-negligible, a good understanding of this signal has become mandatory for the Higgs search analyses.

Above the threshold for Z pair production, the most important Feynman diagrams for this process are the ones usually called NC02 (following the notation of[8]), where two Z bosons are produced by a t-channel electron exchange. The events are classified and selected depending on the decay channel

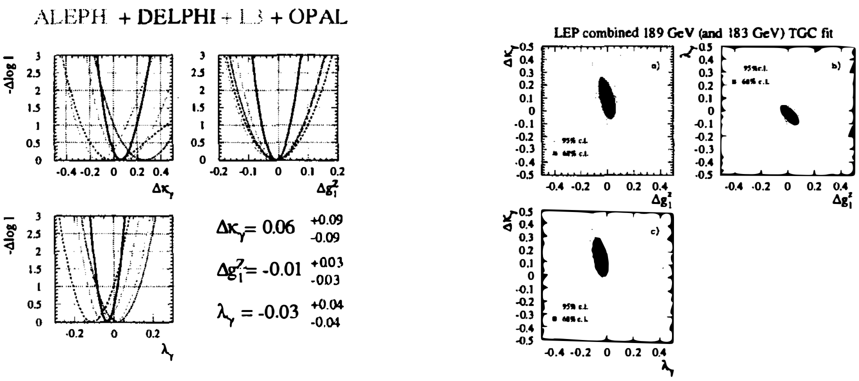

Figure 4: (left) Log-Likelihood curves used in the determination of the trilinear gauge coupling parameters (1-dimensional fit results). (right) 68% and 95% C.L. contours relative to the estimate of the trilinear gauge coupling parameters from the 2-dimensional fits.

of the 2 Z bosons. Table 3 shows the various topologies, the available statistics and qualitatively the amount of background for each channel.

Channel	Statistics	Signature	Background
$q\bar{q}q'\bar{q}'$	Large	4 jets	Large
$q\bar{q}\nu\bar{\nu}$	Large	2 jets + E_{miss}	Medium
$q\bar{q}\ell^+\ell^-$	Medium	2 jets + 2 ℓ	Low
$\ell^+\ell^-\nu\bar{\nu}$	Low	2 ℓ + E_{miss}	Medium
$\ell^+\ell^-\ell'^+\ell'^-$	Low	4 leptons	Medium
$\nu\bar{\nu}\nu'\bar{\nu}'$		*invisible*	

Table 3: For each type of ZZ events the Table shows qualitatively the statistics, the experimental signature and the amount of background.

As for the WW signal, there are more diagrams, other than NC02, which can give the same final state. For final states involving electrons or electron neutrinos, the number of diagrams to be considered in the calculation is very high. Furthermore, some of these diagrams are in common with the charged current calculations. So the cross-section is calculated for "on-shell ZZ" signal, defined through some kinematic cuts where the contribution of the NC02 diagram is higher, or eventually the data are corrected for the 4-fermions back-ground by multiplicative or subtractive method and the "NC02 cross-section" is evaluated. Indeed the data should be compared with the theoretical calculation taking care of the full set of Feynman diagrams, but the "NC02 cross-section" is important for comparison with simple theory calculations which do not involve kinematic cuts and for comparison between the 4 experiments.

Three of the LEP experiments have provided numbers for the NC02 cross-section, as shown in Table 4, while L3 also provides a "on-shell ZZ" cross-section, following the definition in [13]. A preliminary average of these numbers is: $\sigma_{NC02}(\sqrt{s} = 189\ GeV) = (0.64 \pm 0.08)$ pb, where only the statistical error has been considered. This value is in agreement with the Standard Model expectation of 0.61-0.63 pb.

7 ZZ Anomalous Coupling

Beside the NC02 diagrams, an anomalous ZZZ or ZZγ vertex could contribute to the ZZ cross-section, through an s-channel Z or γ exchange. Following the scheme described in [15], L3 has derived preliminary limits on the 4 parameters involved in this process:

Experiment	$\sigma(\sqrt{s}=189$ GeV) (pb)	
	NC02	"on-shell ZZ"
ALEPH	0.63±0.12±0.05	
DELPHI	0.58±0.17	
L3	$0.71^{+0.16}_{-0.17}$	$0.68^{+0.15}_{-0.14}$
Average	*0.64±0.08$_{stat}$*	
SM	$\simeq$ *0.61-0.63*	

Table 4: Preliminary ZZ Cross-section measurements at 189 GeV [14]. The first column shows the NC02 cross-section, the non-resonant 4-fermions events are taken care of by a subtractive or multiplicative procedure. The definition of the "on-shell ZZ" signal measured by L3 can be found in [13].

$$-1.7 \leq f_4^Z \leq 1.8 \quad -4.7 \leq f_5^Z \leq 4.7$$
$$-1.0 \leq f_4^\gamma \leq 1.1 \quad -2.8 \leq f_5^\gamma \leq 2.9$$
(L3 95% CL Preliminary)

These 4 parameters are compatible with zero, in agreement with the SM expextations.

8 Conclusions

Preliminary results for WW cross-sections at LEP at $\sqrt{s}$=189 GeV have been given. The successful high-statistic 1998 run has allowed new improved values for the W Branching Ratios, from which a V_{cs} measurement about 10 times more precise than the current world average is achieved.

Evidence for ZZ signal at LEP2 has been well established.

Good agreement with the SM predictions is found for the WW and ZZ cross-sections and distributions, thus limits on γWW, ZWW, ZZγ and ZZZ anomalous couplings are derived.

No deviation from the Standard Model is observed for what concerns the cross-sections, branching ratios and couplings.

The expected doubling of the statistics and the raise of the LEP energy in the coming next 2 years will allow improved tests of the Standard Model in the W and Z bosons studies: indeed the V_{cs} measurement is still dominated by the statistical error and the tests in the Triple Boson Coupling sector and ZZ production will both profit of the increase in energy.

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