Eur Phys J C **33**, s01, s706–s708 (2004)
Digital Object Identifier (DOI) 10.1140/epjcd/s2004-03-1624-3

EPJ C direct
electronic only

W and Z pair production at LEP2

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Received: 1 November 2003 / Accepted: 14 January 2004 /
Published Online: 3 February 2004 –

Abstract. The measurements of W-pair, WWγ and ZZ cross sections performed by the four experiments at the LEP collider are herein reported. The statistics collected in the period 1996-2000 amounts to about 40000 WW, 400 WWγ and 1000 ZZ events distributed over a large center-of-mass energy range of 161-209 GeV. From the WW cross section measurements, also the W branching fractions in leptons and hadrons are derived with a percent precision: BR(W→ qq) = $67.77 \pm 0.18 \pm 0.22\%$ and BR(W→ $\ell\nu$) = $10.74 \pm 0.06 \pm 0.07\%$.

PACS. 12.15.Hh Determination of Kobayashi-Maskawa matrix elements – 12.15.Mm Neutral currents – 12.15.Lk Electroweak radiative corrections – 13.38.Be Decays of W bosons – 13.38.Dg Decays of Z bosons – 13.66.Fg Gauge and Higgs boson production in e-e+ interactions – 14.70.Fm W bosons – 14.70.Hp Z bosons

1 Introduction

The statistics used for the results presented in this report has been collected by the four LEP experiments [1, 2,3,4] during the years 1996-2000. It amounts to a total integrated luminosity of about 685 pb^{-1} corresponding to about 40000 selected W-pair events, 400 WWγ and 1000 ZZ. Concerning WW and WWγ selections, the results have to be considered final for all data collected until year 1998 included and preliminary for the following years. ZZ results, obtained considering the full statistics, are final and published.

2 WW production

W–pairs at e$^+$e$^-$ colliders are produced via three main diagrams, defined as CC03 (Charged Current 03), involving the Z/γ s–channel exchange and the neutrino t–channel exchange (Fig. 1). The current accuracy on the theoretical calculation for σ_{WW}, which include radiative corrections up to $\mathcal{O}(\alpha_{em})$, is about 0.5 % [5,6].
In order to compare directly the measurements between different channels and experiments it has been conventionally chosen to quote CC03–level cross sections. It means that the actually measured cross sections have to be corrected. The correction factors may be as high as ~ 10 %.
The selection of W-pair events is performed by the logical OR of ten different selections, corresponding to the related final states: $1 \times qqqq(\gamma)$, $3 \times qq\ell\nu(\gamma)$ and $6 \times \ell\nu\ell\nu(\gamma)$ where (γ) indicates the possible presence of radiative photons.
The $qqqq$ selection exploits the presence of four high multiplicity hadronic jets with very little missing energy. A neural network is used in order to discriminate the signal against the main background: $qq(\gamma)$ events with hard gluon radiation. The cross section is eventually derived from a fit to the neural network output distribution. For each experiment, a total of ~ 6000 events are selected. The selection efficiency is $\sim 85\%$ with an accepted background cross section around 1.5 pb. The $qqe(\mu)\nu$ selections are based on the identification of the lepton. Two hadronic jets and the presence of missing energy/momentum induced by the neutrino(s) are also required. For each experiment, a total of ~ 1500 events are selected. The selection efficiencies are around 80%, depending on the final state, with an accepted background cross section around 150 fb mainly coming from $qq(\gamma)$ events. The $qq\tau\nu$ selections is based on the identification of a low multiplicity jet or a lepton (e,μ). Two hadronic jets and the presence of missing energy/momentum induced by the neutrino(s) are also required. For each experiment, a total of ~ 1500 events are selected. The selection efficiency is around 60% with an accepted background cross section around 250 fb mainly coming from $qq(\gamma)$ events. The $\ell\nu\ell\nu$ selections look for very low multiplicity events containing two reconstructed leptons with non–zero acoplanarity in order to reject most of the $e^+e^- \rightarrow e^+e^-\ell^+\ell^-(\gamma)$ $e^+e^- \rightarrow \ell^+\ell^-(\gamma)$ back-

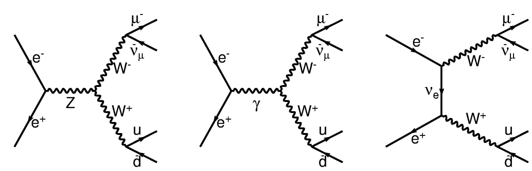

Fig. 1. CC03 diagrams for the production of W–pair events

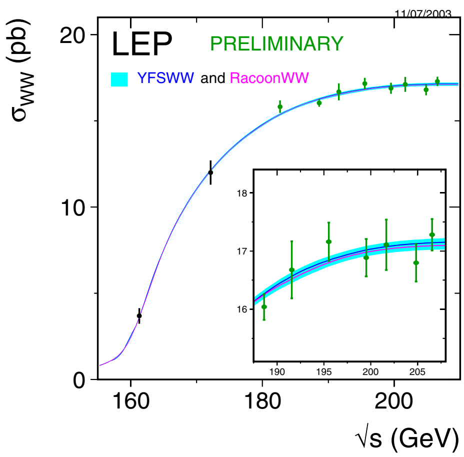

Fig. 2. Total $e^+e^- \to WW$ cross section from LEP at $\sqrt{s} = 161 - 208$ GeV compared with theoretical predictions

grounds. For each experiment, a total of ∼ 800 events are selected. The typical efficiency of this selection, along the different center-of-mass energies, goes from 60% up to 80% with an accepted background cross section around 150 fb.

2.1 Cross sections and branching fractions determination

Once the selections have been applied and their performances are known, each experiment performs a fit, properly taking into account the correlations among channels, in order to get the single channel cross section. The same approach is used to get the total WW cross sections which are then combined among the four LEP collaborations.

The detailed description of the combination procedure can be found in [7]. It takes into account correlated systematic errors, among which the hadronization modeling plays a leading role (Fig. 2). The ratio R between the measured values and the predictions as calculated with YFSWW [5] is

$$R = 0.997 \pm 0.010$$

showing a very good agreement with the Standard Model at the 1 % level. The uncertainty on the ratio R is dominated by the common systematic effect amounting to 0.015.

The leptonic and hadronic branching fractions, $\mathrm{BR}(W \to \mathrm{qq})$ and $\mathrm{BR}(W \to \ell\nu)$ are directly derived from the single channel cross sections. The LEP combined values, using the whole statistics and assuming unitary sum and lepton universality, are:

$$\mathrm{BR}(W \to \mathrm{qq}) = 67.77 \pm 0.28\%$$

$$\mathrm{BR}(W \to \ell\nu) = 10.74 \pm 0.09\%$$

These measured branching ratios allow also to extract a value for the least known Cabibbo–Kobayashi–Maskawa matrix [8] element not involving the top quark, $|V_{cs}|$, in fact:

$$\frac{1}{\mathrm{BR}(W \to \ell\nu_\ell)} = 3 + 3\left[1 + \frac{\alpha_s(\mathrm{M_W})}{\pi}\right] V^2$$

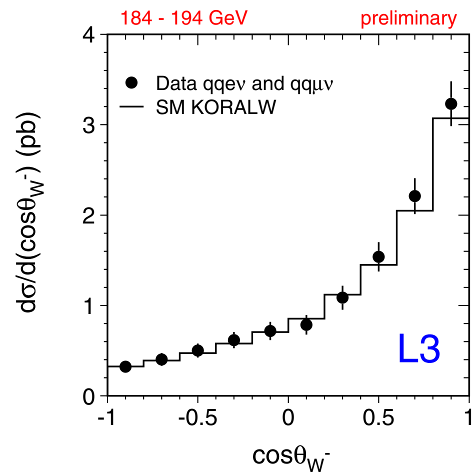

Fig. 3. Differential cross section as a function of the W boson polar scattering angle as measured by L3

where α_s is the strong coupling constant and

$$V^2 = \sum_{i=u,c;j=d,s,b} |V_{ij}|^2$$

Using the current world–average values [9] and errors of the other matrix elements, not assuming the unitarity of V_{CKM}, the result is:

$$|\mathrm{V_{cs}}| = 0.989 \pm 0.014$$

whose error includes both statistical and systematic uncertainties.

Inside the LEP community there are also plans to combine differential cross section measurements as a function of the polar scattering angle of the W^- boson: $\mathrm{d}\sigma/\mathrm{d}\cos\theta_W$. This distribution contains more information than the total cross section and hence represents a powerful test of the Standard Model [10] expectations. In Fig. 3, as an example, the differential cross section as obtained by the L3 experiment is shown averaged on the energy range $184 - 194$ GeV.

3 WWγ production

The presence of a detectable photon in the final state is also looked at in the LEP collaborations, due to its peculiar signature in case of the presence of an Anomalous Quartic Gauge Coupling in the $WW\gamma\gamma$ or $WWZ\gamma$ vertices. The quartic vertices have a negligible contribution at LEP2 energies, even if predicted in the Standard Model. A number of events in excess of the expected yield from radiation off the initial or final state particles, would directly point to new physics. An agreed signal definition has been chosen such to enhance anomalous effects:
1) $E_\gamma > 5$GeV, where E_γ is the photon energy;
2) $|\cos(\theta_\gamma)| < 0.95$, where θ_γ is the polar angle of the photon;
3) $\cos(\alpha_\gamma) < 0.90$, where α_γ is the minimal angle between the photon and the charged fermions;
4) $|M_{ff'} - M_W| < 2\Gamma_W$, where $M_{ff'}$ is the invariant mass between the fermions coming from a W boson.

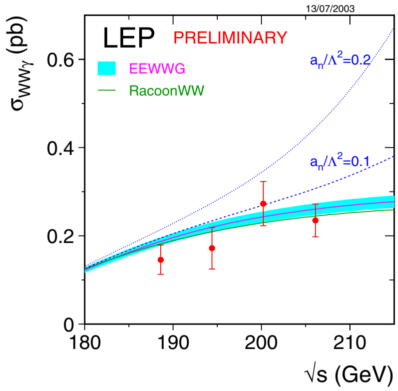

Fig. 4. Combined $WW\gamma$ cross section as a function of the center-of-mass energy. Only L3 and DELPHI results are used

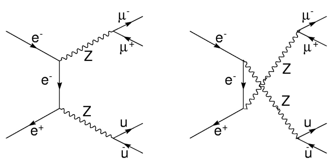

Fig. 5. NC02 diagrams for the production of Z–pair events

The results obtained by the DELPHI, L3 and OPAL collaborations have been combined and they are shown in Fig. 4. No statistically significant deviation is observed.

4 ZZ production

At LEP, the Z-pair final state is produced by means of two main born level diagrams referred to as NC02 (Neutral Current) and shown in Fig. 5. The signal definition for the LEP combination is based on the NC02 set of diagrams, including ISR corrections.

4.1 Selections and results

The experimental investigations of Z-pair production is made difficult by its rather low cross section, compared with competing processes that constitute large and sometimes irreducible backgrounds. All 12 visible Z-pair decay combinations are analysed. In all cases multi-variate techniques are used, to enhance the separation power against the most important backgrounds, namely W-pair production. The combination of the Z-pair cross sections as a function of the center-of-mass energy is shown in Fig. 6. The ratio R, described in the previous section, obtained using YFSZZ [11] as theoretical prediction, is $R = 0.962 \pm 0.055$. Good agreement with the Standard Model is observed.

5 Conclusions

The amount of data collected by the LEP experiments in the high energy running period is beeing extensively

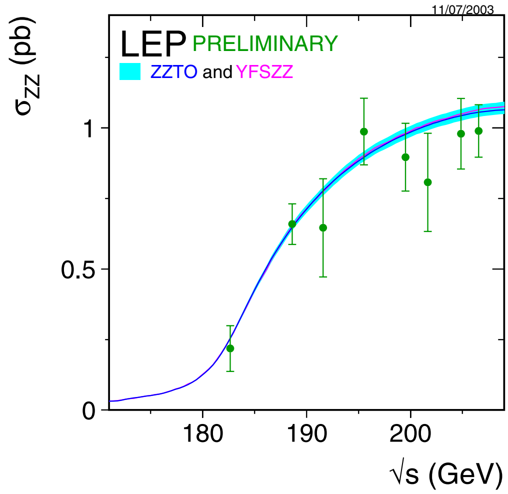

Fig. 6. Combined Z-pair cross sections compared to predicted values using the YFSZZ Montecarlo program

analysed and provides a powerful tool to test the Standard Model. In many cases, as for the W-pair cross section, the level of accuracy has reached the sensitivity threshold for radiative corrections. Although not yet final, the results herein presented are based on the full available statistics and don't show deviations from the Standard Model.

Acknowledgements. Let me thank the organisers of EPS03 Conference for their professionalism and warm hospitality.
I have also to thank my colleagues from the four LEP experiments and the members of the LEP Electroweak Working Group for providing the data which were presented in this report.

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