Four fermion processes at LEP II

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In its second phase, LEP has given the unique opportunity to study four fermion processes never observed before. This papers deals with a preliminary study of WW, $We\nu$, ZZ and $Z\gamma^{\star}$ production in e^+e^- collisions. Measurement results on WW cross section, W branching fractions, WWV ($V = Z/\gamma$) anomalous couplings and W average polarization in WW events are presented. Moreover cross section measurements for $We\nu$, ZZ and $Z\gamma^{\star}$ production and limits on ZZZ and $ZZ\gamma$ anomalous couplings are reported. All the results are in good agreement with the Standard Model expectations.

Talk presented in
XXXVI Recontres de Moriond Electroweak Interactions and Unified Theories, 10-17 March 2001.

1 Introduction

In its second phase, LEP has been operated in years from 1996 to 2000 at centre-of-mass energies ($\sqrt{s}$) between 161 GeV and 208 GeV. This has allowed to each of the four experiments to collect nearly 700 pb^{-1} of data above the W-pair production threshold, as summarised in table 1.

Table 1: Approximated value of the integrated luminosity collected by the DELPHI experiment at LEP II.

$\sqrt{s}$ (GeV)	161	172	183	189	192	196	200	202	205	207
$\int Ldt$ (pb^{-1})	~10	~10	~55	~160	~25	~75	~85	~40	~85	~140
year	1996	1996	1997	1998	1999	1999	1999	1999	2000	2000

The high centre-of-mass energy achieved at LEP II has allowed to study several four fermion processes and hence to test the Standard Model (SM) of electroweak interactions in sectors only poorly known before. The most important process is the WW production because it allows to measure the W mass [1] and the triple gauge boson couplings WWV ($V = Z/\gamma$) (TGC) which appear at the tree level. Other four fermion final state are attained with the production of a pair of neutral gauge bosons ZZ and $Z\gamma^\star$. These processes may receive New Physics contributions from triple neutral gauge boson couplings ZZZ, $ZZ\gamma$ and $Z\gamma\gamma$ which are expected to be unobservably small in the SM. The remaining four fermion processes involve the production of a single gauge boson: $We\nu_e$ and Zee. Particularly important is $We\nu_e$ because it allows to further constrain the $WW\gamma$ vertex [2].

This paper presents the results on four fermion processes with particular attention to the preliminary measurements obtained with the data collected in the year 2000. The second section deals with WW and $We\nu$ processes while the third deals with ZZ and $Z\gamma^\star$ production. No new preliminary results on Zee process have been presented and the old ones are described elsewhere [3].

2 WW and $We\nu$ production

With the full luminosity available at LEP, about 11000 WW events are expected to be produced in each of the four experiments. According to the W decay modes, one has three different topologies in WW events: fully hadronic ($WW \to qqqq$), semileptonic ($WW \to qql\nu_l$) and fully leptonic ($WW \to l\nu_l l\nu_l$) events respectively with branching fraction of 46%, 43% and 11%. These events can be selected with high efficiencies and high purities.

The four experiments have measured the WW cross section at all energies above 161 GeV [4]. The combined results are shown in figure 1, compared with the theoretical predictions of RacoonWW [5] and YFSWW [6] programs that treat the $\mathcal{O}(\alpha)$ radiative corrections in "Double Pole Approximation" (DPA). The theoretical error for DPA is $\leq 0.5\%$ and it is small compared to the error of 2% wich characterize the calculation of $\mathcal{O}(\alpha)$ corrections in "Improved Born Approximation" (IBA) [2].

The W decay branching fractions $Br(W \to ff)$ have been determined from the cross section for the individual $WW \to 4f$ decay channels, and the results are shown in figure 1. The measurement of $B(W \to qq)$ allows an indirect determination [7] of the Cabibbo-Kobayashy-Maskawa matrix element $|V_{cs}|$: $|V_{cs}|_{LEP} = 0.996 \pm 0.013$.

The most general Lorentz invariant Lagrangian for WWV ($V = Z/\gamma$) vertex interactions, under some reasonable requirements [2], can be described by three independent couplings $\{\Delta g_1^Z, \Delta k_\gamma, \lambda_\gamma\}$ [a] (TGC) and another two constrained couplings, $\Delta k_Z = \Delta g_1^Z + \Delta k_\gamma \tan^2\theta_W$ and $\lambda_Z = \lambda_\gamma$.

The TGCs are measured using the information from the total cross section and from the shape of the distributions for physical observables. Due to the high precision achieved by LEP experiments, these distributions should be predicted including the $\mathcal{O}(\alpha)$ corrections in DPA. However, the generator programs used by the LEP experiments, wich include the description of the detectors, treat the $\mathcal{O}(\alpha)$ corrections using the IBA. Only the ALEPH collaboration [9] has estimated the systematic effect due to the missing DPA, showing that it contributes in a sizeable way to the total systematic error for the couplings Δg_1^Z and λ_γ. ALEPH is the only collaboration that has updated the results [9] on TGCs

[a] $\Delta c = c - 1$ indicates the deviation from the SM expectation for c that is 1 while in SM $\lambda_\gamma = 0$.

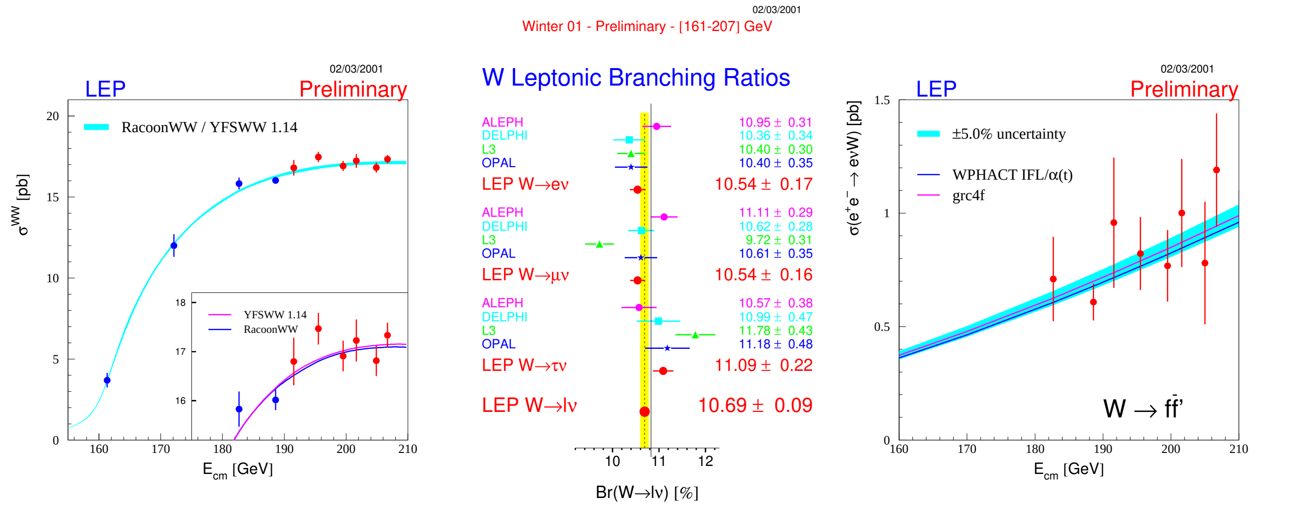

Figure 1: LEP combined results[7] on WW cross section (on the left), on W branching fractions (central figure) and on $We\nu$ cross section (on the right). The leptonic branching fraction, $Br(W \to l\nu) = (10.69 \pm 0.09)\%$, is measured assuming the lepton universality, and one can derive the hadronic branching fraction, $Br(W \to qq) = 1 - 3Br(W \to l\nu) = (67.92 \pm 0.27)\%$, in agreement with the SM value $Br(W \to qq)|_{SM} = 67.51\%$.

including the data collected in 2000 obtaining the following 95% confidence intervals: $[-0.048, +0.080]$ for Δg_1^Z, $[-0.164, +0.134]$ for Δk_γ and $[-0.059, +0.065]$ for λ_γ. No new LEP combined values have been produced after the 2000 summer conferences. It's wortwhile to note that the missing DPA should not change drammatically the LEP combined results [10] because for Δg_1^Z and λ_γ the statistical error dominates.

A model independent way to test the SM in the WW production consists in comparing the measured average W polarization f_λ (λ indicates the W polarization) with the theoretical expectations. The L3 collaboration has done this measurement in the semi-leptonic channel [11]. Using the data collected in 2000, they have measured $f_0 = (21.6 \pm 5.3)\%$, $f_{-1} = (64.7 \pm 6.6)\%$ and $f_{+1} = (13.7 \pm 3.4)\%$ that are in agreement with the SM values: $f_0^{SM} = 22.0\%$, $f_{-1}^{SM} = 62.3\%$ and $f_{+1}^{SM} = 15.7\%$.

The LEP combined measurements results for $We\nu$ cross section are shown in figure 1. Since the 2000 winter conferences, the only new preliminary results have been presented by the ALEPH collaboration [12] which has analysed the data collected in the year 2000.

3 ZZ and $Z\gamma^\star$ production

According to the Z decay modes there are five visible decay channels. The dominant ones are the four jets channel ($ZZ \to qqqq$), the two jets plus missing energy channel ($ZZ \to qq\nu\nu$) and the two jets plus two leptons ($ZZ \to qqll$) channel with an expected branching ratio of 49%, 28% and 14% respectively.

While $qqll$ events can be selected with high purity, the $qqqq$ and $qq\nu\nu$ channels are affected by a large amount of background. In these two channels, multivariate analyses are usually used to discriminate the signal from the background. In the four jets channel the b tag techinque is used againts WW events. The contamination is than mainly due to QCD events. This is clear in figure 2 wich shows the output of the multivariate analysis developed by the DELPHI collaboration compared with the SM expectations for each process.

The four experiments have measured the ZZ cross section at all energies above 183 GeV. The combined LEP results are shown in figure 2 and they are compared with the theoretical predictions calculated with the YFSZZ [13] and ZZTO [14] programs.

The ZZ production is sensitive to possible anomalous vertex interactions ZZV ($V = Z/\gamma$). Following the parametrization suggested in [16] there are four independent couplings: f_i^V ($i = 1, 2$ and $V = Z/\gamma$) that for $i = 4$ are CP-odd and for $i = 5$ are CP-even. The LEP combined results [10] at the 95% of confidence level are $[-0.21, +0.23]$ for f_4^γ, $[-0.40, +0.33]$ for f_4^Z, $[-0.37, +0.49]$ for f_5^γ and $[-0.27, +0.29]$ for f_5^Z. They are in agreement with the SM predictions $f_i^V = 0$. These measurements benefit of the higher energy run of the year 2000, only through the analyses performed by the ALEPH

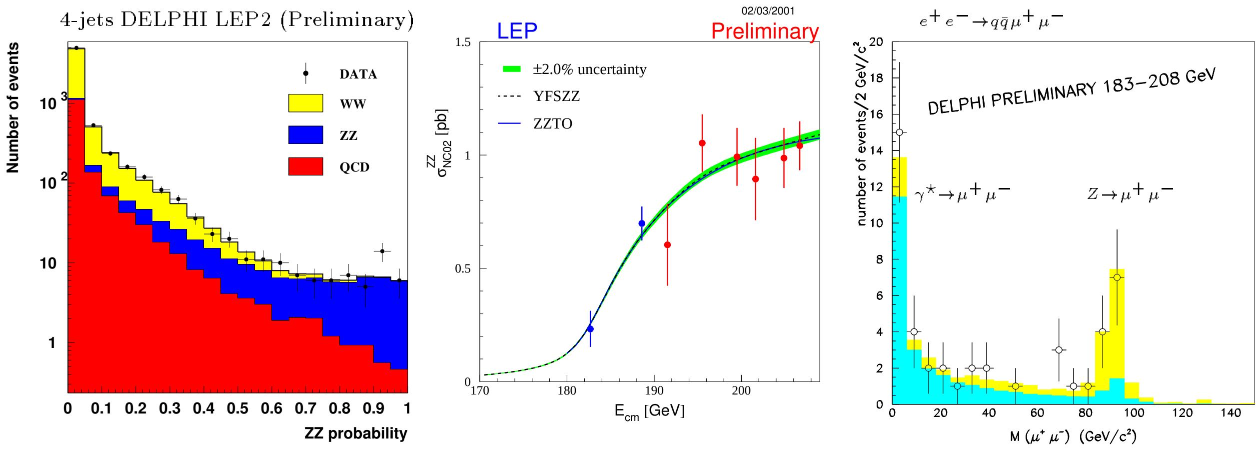

Figure 2: On the left: distributions of the ZZ probability in 4-jet channel for all the LEP2 data sample compared with the SM predictions. Central figure: LEP combined results[7] for ZZ cross section. On the right: invariant mass distribution for $\mu^+\mu^-$ pair in $q\bar{q}\mu^+\mu^-$ events.

and DELPHI collaborations [17].

In the $Z\gamma^\star$ production the virtual photon decays into a pair of fermions wich are separated by a small angle. The DELPHI collaboration [18] has presented the $Z\gamma^\star$ cross section for three different decay channels averaged over energies above 183 GeV: $\sigma_{Z\gamma^\star\rightarrow qq\mu\mu} = (0.123\pm0.025)$ pb, $\sigma_{Z\gamma^\star\rightarrow qq\nu\nu} = (0.129\pm 0.038)$ pb and $\sigma_{Z\gamma^\star\rightarrow qqqq} = (0.074\pm0.045)$ pb. They are in agreement with the SM expectations: 0.098 pb for $qq\mu\mu$, $(0.092 \div 0.084)$ pb for $qq\nu\nu$ and 0.082 pb for qqqq.

Acknowledgments

I thank my DELPHI colleagues working in these subjects for all the constructive discussions.

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