STUDY OF ZZ PRODUCTION IN e^+e^- COLLISIONS AT $\sqrt{s} = 189$ GeV WITH THE L3 DETECTOR AT LEP

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A study of ZZ production using the 176 pb^{-1} of integrated luminosity collected by the L3 detector at LEP at the centre-of-mass energy of 188.66 GeV is performed. The ZZ production cross section is measured to be $\sigma_{ZZ} = 0.54^{+0.16}_{-0.14}$ pb, in agreement with the Standard Model expectation. No evidence for the existence of anomalous triple gauge boson ZZZ and ZZγ couplings is found and limits on these couplings are set. All the presented results are preliminary.

1 Introduction

In e^+e^- collisions at centre of mass energies above $2 * M_Z \simeq 182$ GeV the production of a pair of on-shell Z bosons as intermediate state contributes to four-fermion final states. The study of these events is a new test of the Standard Model, as cross sections and distributions different from its predictions could signal the existence of new physics. Moreover, ZZ events are and important background for Higgs searches, and therefore must be well understood.

Although the ZZ production rate is low and there are large backgrounds, it is being measured at LEP since 1997, and deviations from the Standard Model are being searched for.

Some of the Feynman Diagrams involved in four-fermion production are shown in Figure 1. WW production is one of the dominant processes at LEP2 energies; its cross section is 25 times greater than the ZZ cross section, and gives rise to a large and partially irreducible background for some final states. On-shell ZZ production proceeds through the ZZ conversion diagram shown in Figure 1. Multiperipheral diagrams give a large contribution to final states with electrons at low angle. Many other diagrams contribute to four-fermion final states [1].

In order to be highly sensitive to the on-shell ZZ production diagram, and have a small contribution from the others, we define our ZZ signal in four-fermion final states, in terms of the following criteria:

- Two fermion-antifermion pairs with invariant masses in the range (70,105) GeV
- In final states with electrons, these electrons must verify $|\cos\theta_{\rm e}| < 0.95$, $\theta_{\rm e}$ being their angle with respect to the beam axis
- In final states with WW contribution, namely $\rm u\bar{u}d\bar{d}$, $\rm c\bar{c}s\bar{s}$ and $\rm l^+l^-\nu\bar{\nu}$, the masses of the fermion pairs susceptible to come from W decay must be outside (75,85) GeV

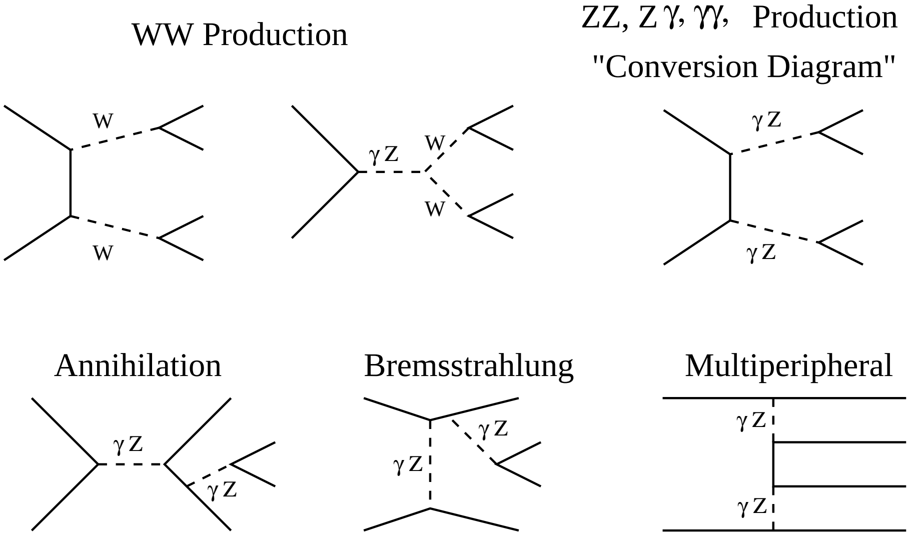

Figure 1: A few four-fermion Feynman Diagrams.

The ZZ cross section within our signal definition is shown in Figure 2 as a function of the centre of mass energy. The Excalibur [2] four-fermion Monte Carlo generator has been used for this calculation. There is a threshold at $\sqrt{\rm s} \sim 2 * \rm M_Z$ and the maximum is reached slightly above the LEP2 energies.

In Table 1 the cross sections for the different ZZ final states at $\sqrt{\rm s} =$ 188.66 GeV are shown. The small differences between the actual fractions and those calculated naively from the Z branching ratios are due to the contribution of non resonant Feynman Diagrams to the signal, and to the cuts applied in the signal definition to minimize this non resonant contribution.

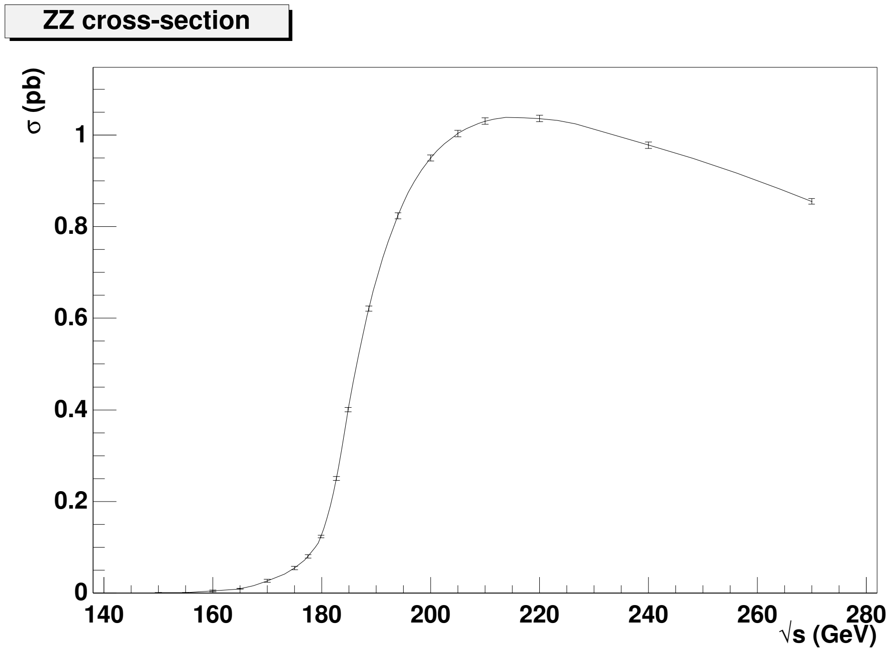

Figure 2: ZZ cross-section calculated with Excalibur.

Table 1: ZZ cross sections calculated with Excalibur. The first column refers to the ZZ decay channel. The second column contains the cross sections. The third column gives the fraction of the total that the channel represents. The fourth column are the fractions calculated from the branching ratio of the Z boson, taken from the Particle Data Group.

ZZ $\rightarrow$	σ (pb)	Fraction	'Naive' (B.R.)
$q_1\bar{q}_1 q_2\bar{q}_2$	$0.2895 \pm 0.2\%$	46.8 %	48.9 %
$q\bar{q}\nu\bar{\nu}$	$0.1702 \pm 0.2\%$	27.4 %	28.0 %
$q\bar{q}l^+l^-$	$0.0973 \pm 0.2\%$	15.6 %	14.1 %
$l^+l^-\nu\bar{\nu}$	$0.0271 \pm 0.3\%$	4.4 %	4.0 %
$l_1^+l_1^-l_2^+l_2^-$	$0.0111 \pm 2.2\%$	1.8 %	1.0 %
$\nu_1\bar{\nu}_1\nu_2\bar{\nu}_2$	$0.0248 \pm 0.2\%$	4.0 %	4.0 %
ZZ	$0.6200 \pm 0.1\%$	100.0 %	100.0 %

2 Data and Monte Carlo samples

The analysis presented here corresponds to a luminosity of 176 pb^{-1} collected by the L3 experiment at $\sqrt{s} \simeq 188.66$ GeV during 1998.

The EXCALIBUR Monte Carlo is used to simulate the four-fermion events. KORALW 1.21 [3] is also used for on–shell W^+W^- production. Backgrounds from fermion–pair production are simulated with PYTHIA 5.72 [4] ($e^+e^- \rightarrow q\overline{q}(\gamma)$), KORALZ 4.02 [5] ($e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ and $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$) and BHWIDE 3 [6] ($e^+e^- \rightarrow e^+e^-(\gamma)$).

The L3 detector response is simulated using the GEANT 3.15 program [7], which takes into account the effects of energy loss, multiple scattering and showering in the detector. The GEISHA program [8] is used to simulate hadronic interactions in the detector.

3 ZZ Selection

ZZ events are characterized experimentally by two pairs of visible fermions, (leptons or hadronic jets), with high invariant masses, or a single pair of fermions with large visible and recoil masses.

Different cut based selections as well as artificial neural networks are used to select the ZZ events, rejecting a large amount of the background. The results are sumarized in table 2.

Table 2: ZZ selection results. The first column refers to the ZZ decay channel. The second one contains the experimental signatures. In the third column the number of observed events in data. In the fourth one the number of expected events from background. In the fifth column, the signal efficiencies are shown.

Channel	Experimental Signature	DATA	BKG	Eff.
$q_1\bar{q}_1q_2\bar{q}_2$	4 hadronic jets	211	207.5 ± 9.0	34 %
$q\bar{q}\nu\bar{\nu}$	2 jets + missing energy	36	22.7 ± 0.1	35 %
$q\bar{q}l^+l^-$	2 jets + 2 leptons	12	3.8 ± 0.5	77 % (qqee) 61 % (qq$\mu\mu$) 32 % (qq$\tau\tau$)
$\nu_1\bar{\nu}_1\nu_2\bar{\nu}_2$	invisible!	0	0.0	0 %

The qqqq selection is based on the following criteria:

- A preselection of events is done requiring high multiplicity, large visible energy, small missing energy, no energetic leptons and at least four jets ($Y_{34} > .007$)

- Then a neural network is used to distinguish among ZZ, WW and qq. The inputs are variables related to the multiplicity, the energy and direction of the jets, and kinematic variables as invariant masses of pairs of jets

In Figure 3(a) the output of the neural network is shown.
The qqnn selection is based on the following criteria:

- High multiplicity events
- $\sin\theta_{\mathrm{Pmiss}} > 0.7$
- 2 acoplanar, ($> 2.38^o$), and acollinear, ($> 2.35^o$), hadronic jets.
- $\mathrm{P_T}/\sqrt{\mathrm{s}} > 0.06$
- Visible Energy $\in (0.42, 0.56)\sqrt{s}$
- Large visible and recoil masses

In Figure 3(b) the visible invariant mass is shown.

For the qqll selection three selections, qqee, qq$\mu\mu$ and qq$\tau\tau$, are combined with a logical 'or'. The criteria are:

- qqee selection: 2 electrons and 2 jets with invariant masses above 50 GeV. Opening angle of the Z bosons above 130^o. Large visible energy and small missing momentum.
- qq$\mu\mu$ selection: 2 muons and 2 jets with invariant masses above 50 GeV. Opening angle of the Z bosons above 130^o.
- qq$\tau\tau$ selection: 2 low multiplicity jets and 2 high multiplicity jets with invariant masses in the range (70,120) GeV. Visible mass slightly below $\sqrt{\mathrm{s}}$.

In Figure 3(c) the invariant mass of the two leptons is shown.

4 Cross Section results

Combining the results from the qqqq, qq$\nu\nu$ and qqll selections, the ZZ cross section is measured. From the three experimental distributions shown previously, a Log Likelihood with one free parameter, the ZZ cross section, is maximized, Figure 3(d). The measured cross section is $0.54^{+0.16}_{-0.14}$ pb which can be compared to the Standard Model prediction, 0.62 pb. The error is statistical only. Our previous published result at $\sqrt{\mathrm{s}} = 183$ GeV [9], $0.30^{+0.22}_{-0.16}\,^{+0.07}_{-0.03}$ pb, was also compatible with the Standard Model prediction 0.25 pb.

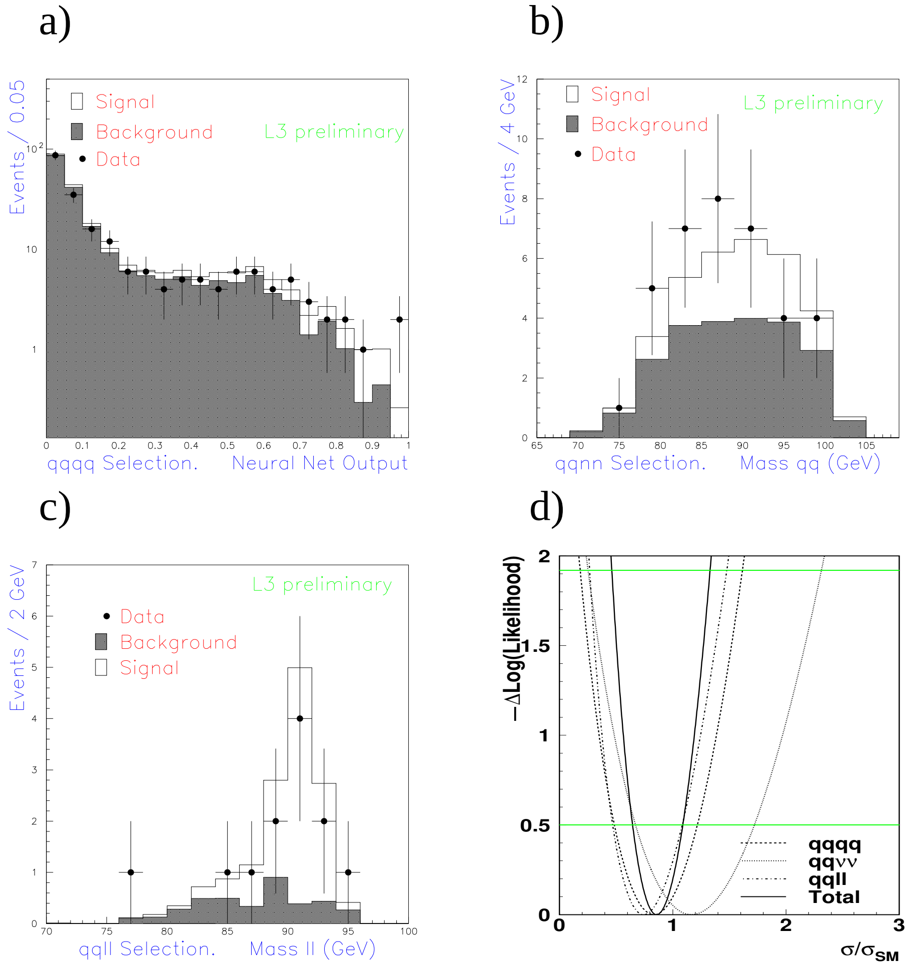

Figure 3: A few experimental distributions for the selected ZZ events in three different selections: NN output for the qqqq selected events (a). Visible invariant mass for the qqnn selected events (b). Invariant mass of leptons for the qqll selected events (c). Minus log-likelihood of the distributions as a function of the ratio of the measured cross section and the Standard Model prediction (d).

5 ZZZ and ZZγ Anomalous Couplings

The study of ZZ production allows us to look for deviations from the SM in triple gauge boson couplings. Standard ZZ production is mainly due to the conversion diagram, (see Figure 1). The existence of ZZZ or ZZγ anomalous couplings would give rise to the new diagrams shown in Figure 4.

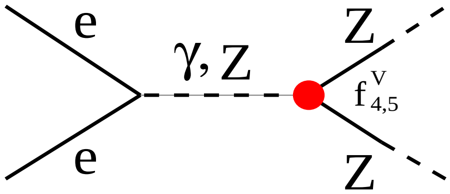

Figure 4: ZZ production diagrams with Anomalous Couplings.

Four possible couplings[10] are associated to this diagram: f_4^Z, f_4^γ, f_5^Z and f_5^γ, all of them vanish in the Standard Model at tree level. f_4^Z and f_4^γ are CP-violating whereas f_5^Z and f_5^γ are P-violating.

The signatures of these anomalous couplings would be:

- Change in the total cross section $e^+e^- \rightarrow ZZ$
- Modification of the angular distributions of the Z bosons
- Change in the average polarization of the Z's, and therefore change in the angular distributions of the decay fermions from the Z's.

The amplitude for the anomalous coupling diagram has been calculated analytically, and the result has been added to the full set of amplitudes used by the Excalibur program[11].

Therefore, for any four-fermion Monte Carlo event, knowing the four four-momenta, the corresponding amplitude squared is calculated as a function of the anomalous couplings. Then to obtain distributions with anomalous couplings, the SM distributions are reweighted, event by event, according to the ratio of matrix elements represented in Figure 5.

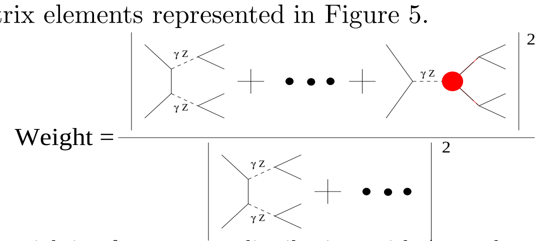

Figure 5: Reweighting factor to get distributions with Anomalous Couplings.

The histograms of the experimental variables shown previously are used to compare the measured data with the Monte Carlo expectations, (which include background and ZZ signal). The value of anomalous couplings is varied, reweighting in the Monte Carlo histogram,the four-fermion events susceptible to come from the decay of two Z's, in order to maximize a binned likelihood:

$$\mathcal{L} = \prod_{\mathrm{i=1}}^{\mathrm{N_{BIN}}} \left[\frac{\mathrm{N_{MC}(i)^{N_{DATA}(i)}}}{\mathrm{N_{DATA}(i)!}} \mathrm{e}^{-\mathrm{N_{MC}(i)}} \right]$$

where

$$\mathrm{N_{MC}(f_4^V, f_5^V) = N_{BKG} + N_{SIGNAL}(f_4^V, f_5^V)}$$

From the qqll selection at $\sqrt{\mathrm{s}} \simeq 189$ GeV, the measured values of the four possible anomalous couplings are compatible with zero, the Standard Model prediction. Limits at the 95 % confidence level are shown in Table 3. This new limits improve notably our previous published result at $\sqrt{\mathrm{s}} = 183$ GeV [9].

Table 3: 95 % confidence level limits to ZZZ and ZZγ anomalous couplings, from the qqll selection at 189 GeV (first column), compared to our previous published result, from the combination of all the selections performed at 183 GeV (second column).

Limits with $\sqrt{\mathrm{s}} \simeq 189$ GeV Data	Limits with $\sqrt{\mathrm{s}} \simeq 183$ GeV Data
$-1.8 < f_4^Z < 1.8$	$-3.6 < f_4^Z < 3.4$
$-5.5 < f_5^Z < 5.4$	$-8.4 < f_5^Z < 7.9$
$-1.1 < f_4^\gamma < 1.0$	$-2.1 < f_4^\gamma < 2.1$
$-3.3 < f_5^\gamma < 3.2$	$-4.9 < f_5^\gamma < 4.8$

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