ZZ Production at LEP

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Abstract
The process $e^+e^- \rightarrow ZZ$ is studied at LEP at center-of-mass energies near 183 and 189 GeV. Cross sections are measured and found to be in agreement with the Standard Model expectations. Limits on anomalous ZZZ and ZZγ couplings are set.

1. Introduction

Pair production of Z bosons became possible at LEP when the kinematic threshold for such a process was reached in 1997, for the first time in a e^+e^- collider. A good understanding of this process is important for several reasons. Namely, it allows for test of the Standard Model in a sector which had not been tested before, and opens a window for the study of triple neutral gauge boson couplings, forbidden at tree level in the Standard Model. Furthermore, it is one of the relevant backgrounds in the Higgs search.

In the following, the results on the cross section measurement of the Z pair production made at LEP collider are summarized. The studies on the anomalous neutral gauge bosons couplings are also reported.

2. Signal Definition

The production of Z boson pairs at LEP is described by the two conversion Feynman diagrams mediated by Z bosons depicted in Figure 1. This contribution is denoted as NC02. But what is measured in the detectors is a final state with four fermions, after the decay of the Z bosons. Then there are some other Feynman diagrams which contribute to the same final state, like the conversion diagrams of Figure 1 with some photon mediation or non-resonant contributions, one example of these can be seen in Figure 2.

So, the contribution of the non-resonant Feynman diagrams should be taken into account in the measurement procedure. The LEP experiments have different approaches to solve this problem.

ALEPH [1] quotes directly the NC02 cross section, and treats the rest of the contributions as background, neglecting the interferences. DELPHI [2] takes into account the non-resonant contributions and the interferences, and applies a correc-

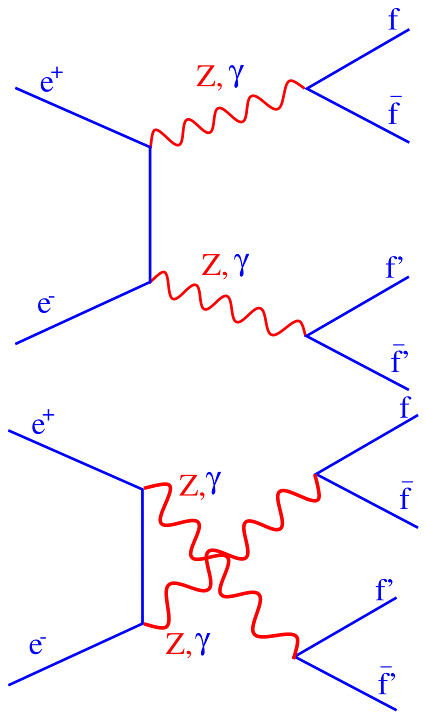

Figure 1. Feynman diagrams contributing at first order to the ZZ production (NC02).

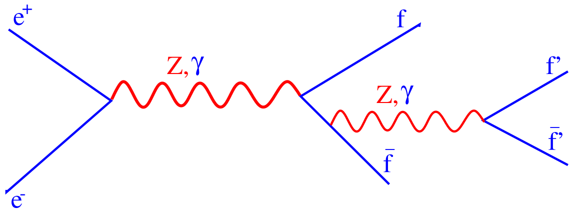

Figure 2. Example of non-resonant Feynman diagram contributing to the four-fermion final states.

tion factor to quote the final measurement as NC02. L3 [3] gives a signal definition , calling ZZ to a definite part of the phase space, including the non-resonant and interference contributions. To give a NC02 cross section, the results in this signal definition region are corrected. Finally, OPAL [4] takes the same approach than ALEPH. In order to combine results, all the LEP experiments quote a NC02 cross-section.

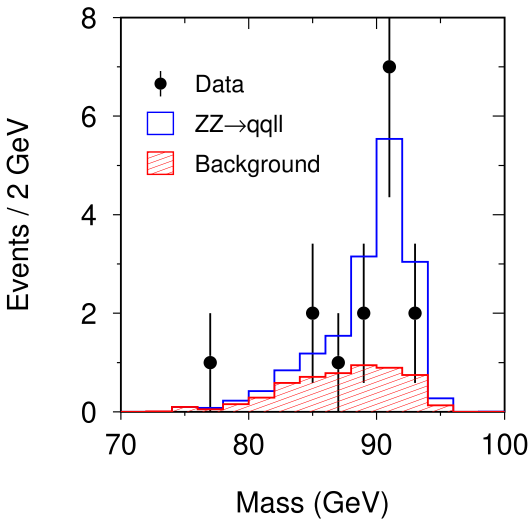

Figure 3. Z mass obtained after a kinematic fit imposing four-momentum conservation and equal masses for $q\bar{q}l^+l^-$ events from L3 at $\sqrt{s} = 189$ GeV. Dots are data, the open histogram is the SM prediction and the hatched histogram is the background.

3. Data Analysis

The possible final states that come from the ZZ production are listed in Table 1. The LEP experiments use all the visible final states for the measurements.

Channel	Experimental Signature
$q_1\bar{q}_1q_2\bar{q}_2$	4 hadronic jets
$q\bar{q}\nu\bar{\nu}$	2 jets + missing energy
$q\bar{q}l^+l^-$	2 jets + 2 leptons
$l^+l^-\nu\bar{\nu}$	2 leptons + missing energy
$l_1^+l_1^-l_2^+l_2^-$	4 leptons
$\nu_1\bar{\nu}_1\nu_2\bar{\nu}_2$	invisible!

Table 1. Possible final states in the ZZ production and their experimental signatures.

The channel with largest branching ratio is the $q_1\bar{q}_1q_2\bar{q}_2$. Its experimental signature are four hadronic jets. Two jet pairs should have invariant masses close to that of the Z boson. The background for this channel is very high, coming mainly from WW and QCD processes. Due to this high background, powerful signal identification techniques are necessary, so, usually neural networks or multidimensional analysis are used. The b-tagging is an important technique for this channel, as long as the b content of the ZZ events is much larger than the b content for the backgrounds.

The $q\bar{q}\nu\bar{\nu}$ suffers also from high background. The procedures used for the selection of this channel are similar to those used for the four jets. For these events, both the visible and the missing masses must be consistent with the Z mass.

The $q\bar{q}l^+l^-$ is the cleanest channel, but the statistics is not as high as it is for the channels described before. The invariant masses of the lepton pair and the jet pair must be close to the Z mass. The Z mass obtained for the selected $q\bar{q}l^+l^-$ events from L3 at $\sqrt{s} = 189$ GeV is shown in Figure 3.

The $l^+l^-\nu\bar{\nu}$ and $l_1^+l_1^-l_2^+l_2^-$ have clean signatures, but the statistics is very small. For the first one the lepton pair invariant mass and the missing mass should be close to the Z mass. For the second one, the two lepton pairs must be consistent with the ZZ production, both in masses and in flavours.

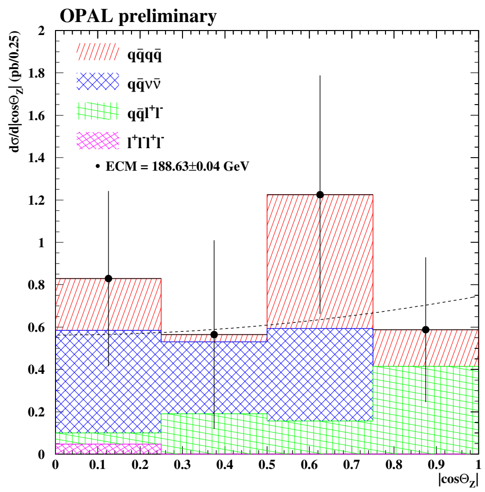

Figure 4. The $\cos\theta_Z$ distribution from OPAL. The Standard Model prediction is plotted as the dashed line.

These signatures have been analysed at $\sqrt{s} = 183$ and 189 GeV. The luminosity is around 55 pb^{-1}

per experiment for the first energy and around 175 pb^{-1} per experiment for the second. Nevertheless, the number of ZZ events is small, as can be seen in Figure 4, where the total differential cross section as a function of the cosine of the azimuthal angle of one Z measured by OPAL at $\sqrt{s} = 189$ GeV is shown. The background has been substracted and the Standard Model prediction is presented as the dashed line.

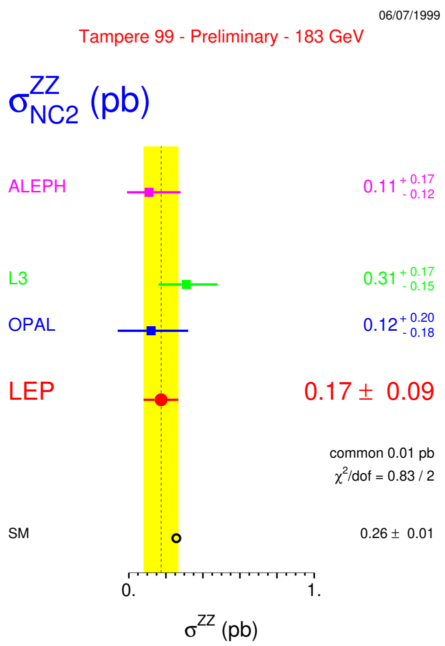

Figure 5. Cross sections measured by the LEP experiments at $\sqrt{s} = 183$ GeV and their combined value. The SM prediction is also plotted.

4. Cross Section Measurement

Each LEP experiment combines information of all the analyses described before to obtain a measurement of the ZZ cross section [1, 2, 3, 4]. The combinations are made using a maximum likelihood method, and taking into account the observed number of events, the expected number of events and the expected background.

The measurements done by the different experiments have been then combined to give LEP measurements, quoted in Figures 5 and 6 at $\sqrt{s} =$ 183 GeV and 189 GeV respectively. The errors contain the statistical and systematic contributions. The evolution of the measured cross sections with the center-of-mass energy is presented in Figure 7, compared with the Standard Model expectation. OPAL and ALEPH apply the same analysis done

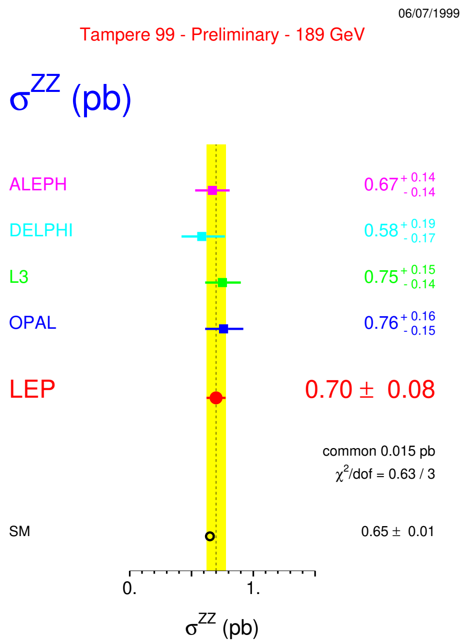

Figure 6. Cross sections measured by the LEP experiments at $\sqrt{s} = 189$ GeV and their combined value. The SM prediction is also plotted.

at $\sqrt{s} = 189$ GeV to the data at $\sqrt{s} = 183$ GeV

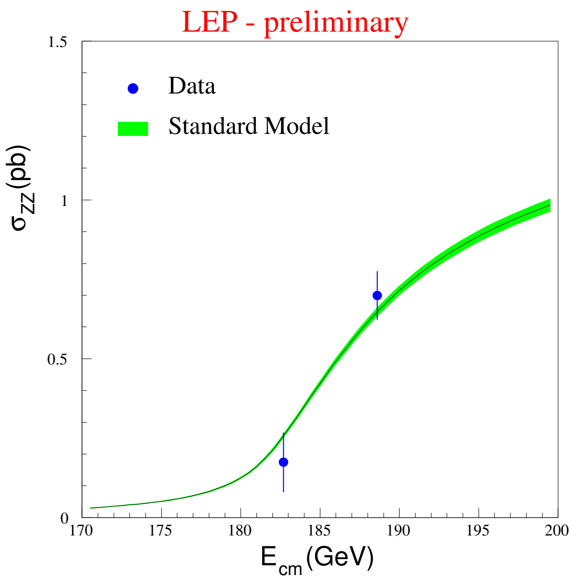

Figure 7. Evolution of the ZZ cross section with the center-of-mass energy. The curve is the SM prediction including a 2% theoretical error. Dots are LEP measurements.

to obtain these results. L3 performs a dedicated selection at $\sqrt{s} = 183$ GeV [5] in order to take into account the threshold effects. DELPHI does not present any measurement at $\sqrt{s} = 183$ GeV.

All the measured cross sections are in good agreement with the Standard Model predictions. They are largely dominated by the statistical errors.

5. Anomalous Couplings

The most general parametrization for couplings ZZZ and ZZγ [6] are used to look for deviations from the Standard Model in the neutral sector. If the Z bosons are considered on-shell, only four couplings exist, due to the Bose symmetry: f_4^V, f_5^V with $V = \mathrm{Z}, \gamma$. These couplings contribute through a diagram presented in Figure 8 and are expected to vanish in the Standard Model at tree leel. Some of the possible new physics effects that can originate anomalous couplings can be compositeness of the Z boson or new particles contributing in loops.

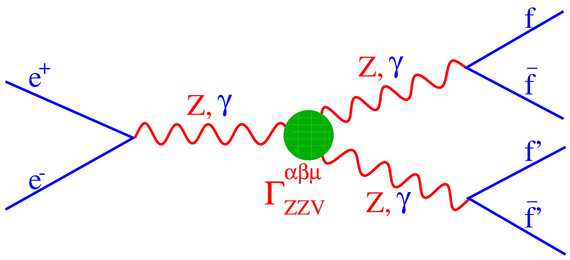

Figure 8. Feynman diagram for the neutral gauge boson anomalous couplings.

The experimental effects of the anomalous couplings are mainly three: a change in the total cross section, a change in the angular distributions and a change in the average polarization of the Z bosons. With the statistics available up to now, only the two first effects are experimentally accesible.

To obtain these anomalous couplings, a fit of the measurements to the expectations of the Standard Model plus the contribution of the diagram of the Figure 8 is done. No evidence of anomalous couplings is found, and then limits on them are set.

The limits set by the different experiments at 95 % C. L. are:

- DELPHI:
  $-1.6 \leq f_4^\gamma \leq 1.6$
  $-3.8 \leq f_5^\gamma \leq 3.8$
  $-2.6 \leq f_4^Z \leq 2.6$
  $-7.0 \leq f_5^Z \leq 5.7$
- L3:
  $-1.1 \leq f_4^\gamma \leq 1.1$
  $-3.0 \leq f_5^\gamma \leq 2.9$
  $-1.9 \leq f_4^Z \leq 1.9$
  $-4.9 \leq f_5^Z \leq 4.7$
- OPAL:
  $-1.2 \leq f_4^\gamma \leq 1.2$
  $-3.2 \leq f_5^\gamma \leq 3.0$
  $-2.0 \leq f_4^Z \leq 2.0$
  $-5.1 \leq f_5^Z \leq 3.6$

DELPHI and OPAL results are based on the statistics collected at $\sqrt{s} = 189$ GeV. L3 results take also into account the $\sqrt{s} = 183$ GeV sample. OPAL quote results both on the real and on the imaginary parts of the couplings. What is listed above are the real parts. ALEPH does not present any result on anomalous couplings.

6. Conclusions

The $e^+e^- \to \mathrm{ZZ}$ cross section has been measured at LEP at $\sqrt{s} = 183$ GeV and $\sqrt{s} = 189$ GeV for the first time. The results obtained are:

- $\sigma_{\mathrm{ZZ}}(\sqrt{s} = 183\ \ \mathrm{GeV}) = 0.17 \pm 0.09 \pm 0.03$ pb
- $\sigma_{\mathrm{ZZ}}(\sqrt{s} = 189\ \ \mathrm{GeV}) = 0.70 \pm 0.07 \pm 0.03$ pb

where the first error is statistical and the second is systematic.

The measurements are still dominated by the statistical error. They are in good agreement with the Standard Model expectations.

This process has been used to look for deviations from the Standard Model in the neutral gauge boson sector, parametrized in terms of anomalous couplings. No evidence for such couplings has been found and limits on their values have been set.

References

[1] ALEPH Collaboration, contributed paper #6-398 to this conference.
[2] DELPHI Collaboration, contributed paper #6-430 to this conference.
[3] L3 Collaboration, contributed paper #6-249 to this conference.
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[6] K. Hagiwara *et al.*, *Nucl. Phys.* **B282** (1987) 253.
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