STUDY OF ZZ PRODUCTION AT LEP AT $\sqrt{s} = 183 - 209$ GeV

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A study of Z boson pair production in e^+e^- annihilation using the OPAL detector at LEP is reported. The ZZ production cross-section is measured, limits on anomalous ZZ γ and ZZZ couplings are derived, and constraints on models of low scale quantum gravity in extra spatial dimensions are set.

1. Introduction

In the Standard Model (SM), the process $e^+e^- \rightarrow ZZ$ occurs via the NC2 diagrams. No tree level ZZZ and ZZ γ couplings are expected, however, physics beyond the SM could lead to effective couplings which could then contribute to the ZZ production cross-section. Deviations from the SM may arise, for example, in models with low scale quantum gravity in extra spatial dimensions (LSG),¹ due to s -channel graviton exchange.^{2,3}

In this paper we report on measurements of the NC2 ZZ cross-section, including the extrapolation to final states where one or both Z bosons have invariant masses far from m_Z . These measurements, together with the angular distribution of the observed events, are then used to extract limits on ZZZ and ZZ γ anomalous couplings and constraints on the fundamental scale of LSG models.

2. ZZ Selections

Since 1997 the amount of data collected by the OPAL detector⁴ above the ZZ production threshold has reached an integrated luminosity of 650 pb⁻¹, divided between eight center-of-mass energies as listed in Table 1.

All ZZ topologies but $\tau^+\tau^-\nu\bar{\nu}$ and $\nu\bar{\nu}\nu\bar{\nu}$ are covered by five separate analyses which address the final states $\ell^+\ell^-\ell^+\ell^-$, $\ell^+\ell^-\nu\bar{\nu}$, $q\bar{q}\ell^+\ell^-$, $q\bar{q}\nu\bar{\nu}$ and $q\bar{q}q\bar{q}$. In addition, in those channels where at least one of the Z bosons decays hadronically, a b-tagging algorithm is used to identify $b\bar{b}\ell^+\ell^-$, $b\bar{b}\nu\bar{\nu}$ and $b\bar{b}q\bar{q}$ final states. The selections are described in detail elsewhere.^{5,6,7,8}

All selections are designed to measure pairs of on-shell Z bosons in order to avoid background from $Z\gamma^*$ production. The ZZ cross-section is defined as the contribution from NC2 diagrams to the total four-fermion cross-section. Contributions from

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Table 1. Luminosity weighted center-of-mass energies, luminosities and measured ZZ cross-sections in the different datasets collected by July 2000. The last two lines show a new update based on the data collected by October 2000. On the measured cross section the first error is statistical, the second one is systematic. The error on the luminosity measurement varies slightly from energy to energy, and it amounts approximately to 0.3%. The precise value of the luminosity may vary slightly from channel to channel.

$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb $^{-1}$)	σ_{ZZ} (pb)
182.62 $\pm$ 0.05	55	0.12 $^{+0.20}_{-0.18}$ $^{+0.03}_{-0.02}$
188.63 $\pm$ 0.04	178	0.80 $^{+0.14}_{-0.13}$ $^{+0.06}_{-0.05}$
191.59 $\pm$ 0.02	29	1.13 $^{+0.46}_{-0.39}$ $^{+0.13}_{-0.09}$
195.53 $\pm$ 0.02	73	1.28 $^{+0.27}_{-0.25}$ $^{+0.11}_{-0.08}$
199.52 $\pm$ 0.02	74	1.01 $^{+0.25}_{-0.22}$ $^{+0.08}_{-0.06}$
201.63 $\pm$ 0.02	37	1.09 $^{+0.39}_{-0.34}$ $^{+0.11}_{-0.08}$
204.8 $\pm$ 0.1	58	1.41 $^{+0.34}_{-0.30}$ $^{+0.12}_{-0.09}$
206.6 $\pm$ 0.1	28	0.30 $^{+0.37}_{-0.28}$ $^{+0.07}_{-0.04}$
204.9 $\pm$ 0.1	80	1.09 $^{+0.27}_{-0.24}$ $^{+0.10}_{-0.08}$
206.7 $\pm$ 0.1	125	1.05 $^{+0.21}_{-0.19}$ $^{+0.09}_{-0.07}$

all other four-fermion final states, including their interference with NC2 diagrams, are considered background, and estimated using the grc4f Monte Carlo program.⁹

In the case of the $\ell^+\ell^-\ell^+\ell^-$ and $q\bar{q}\ell^+\ell^-$ channels, the Z boson masses can be reconstructed relatively cleanly with no difficult WW background present, therefore a simple final cut on the reconstructed Z masses is sufficient. However, the $\ell^+\ell^-\nu\bar{\nu}$, $q\bar{q}\nu\bar{\nu}$ and $q\bar{q}q\bar{q}$ final states compete with backgrounds that have event topologies with invariant masses close to the signal region, requiring likelihood selections to exploit the differences between the ZZ signal and the mainly WW background. In the $q\bar{q}\nu\bar{\nu}$ channel the $W\nu$ and the $Z(n\gamma)$ backgrounds are also sizable.

3. Results

To obtain the total ZZ cross-sections and the limits on anomalous couplings and low scale gravity, maximum log-likelihood fits are used with Poisson probability density convoluted with Gaussians to describe uncertainties. The expected number of SM events (μ_i) in a selection is given by $\mu_i = \sigma_{ZZ} B_i \mathcal{L}_i \epsilon_i + b_i$, where B_i is the branching ratio of ZZ to the final state, $\mathcal{L}_i$ is the integrated luminosity, b_i is the expected background, ϵ_i is the ZZ efficiency estimated primarily by the YFSZZ Monte Carlo program¹⁰ and σ_{ZZ} is the ZZ production cross-section. The overlap between the b-tag and non-b-tag analyses is taken into account.

The fits are dominated by the large statistical errors associated with the small number of ZZ events. Even so, systematic errors^{5,6,7} are included in the analyses, and conservatively it is assumed that the bulk of these are common between channels and center-of-mass energies.

The results of the total cross-section measurements^{5,6,7,8} summarized in Table 1 are in agreement with the SM predictions¹¹ as shown in Figure 1(a). In order to

Fig. 1. (a) Measured ZZ production cross-section together with the theoretical prediction. (b) Determination of $BR(Z \rightarrow b\bar{b})$ from ZZ events together with the measured value at LEP1. On (a) both the statistical and systematic errors, while on (b) only the statistical errors are shown. The common systematic error on $BR(Z \rightarrow b\bar{b})$ is 5%.

further check the consistency with the SM, we have allowed the branching ratio $BR(Z \rightarrow b\bar{b})$ to be a free parameter in the fit at each center-of-mass energy. The fitted values are plotted in Figure 1(b). Combining all energies the average value⁸ is 0.200 ± 0.033 , which is 1.5 standard deviations above the LEP1 measurement¹² of 0.151 ± 0.001 .

To derive limits on new physics we have compared the SM expectation in four bins of $|\cos \theta|$, where θ is the polar angle of the produced Z boson, with our data (except at 183 GeV, where, due to the small number of produced ZZ events, only the total rate is used). In total 327 points are used in these fits. Additional systematic errors on the efficiency estimate are included. To obtain these results only the datasets collected until July 2000 are used.

Limits at the 95% confidence level (CL) on the CP- and C-violating f_4^{VZZ} and the CP-conserving, P-violating f_5^{VZZ} couplings, with V standing for Z or γ , are summarized in Table 2⁷. These are computed by fixing all other anomalous couplings to zero and using the parametrization of Hagiwara et al.¹³ The limits only slightly depend on the sign and the complex phase of couplings with the exception of f_5^{ZZZ} . Two-dimensional limit contours are also derived and are shown in Figure 2.

Table 2. Limits on anomalous ZZZ and ZZ γ couplings.

coupling	lower limit	upper limit
$Re(f_4^{ZZZ})$	-0.7	0.8
$Re(f_5^{ZZZ})$	-1.0	0.5
$Re(f_4^{ZZ\gamma})$	-0.4	0.4
$Re(f_5^{ZZ\gamma})$	-0.9	0.8

The Born-level matrix element in LSG models for s-channel graviton exchange^{2,3} is proportional to λ/M_S^4 . M_S is an ultraviolet cut-off parameter and is chosen to

Fig. 2. Two-dimensional limit contours for anomalous couplings if they are constrained to the (a) $f_4^{ZZZ} - f_4^{ZZ\gamma}$ and (b) $f_5^{ZZZ} - f_5^{ZZ\gamma}$ planes. In (a) the likelihood has no unique minimum, therefore a dashed line shows the location of the minimum values of the likelihood function. In (b) the location of the unique minimum is denoted by a star.

agree with the notation of Hewett². The factor λ incorporates any model dependence. The analyses of the ZZ data¹⁴ gives $\lambda/M_S^4 = -2.96^{+2.77}_{-2.76} 1/\text{TeV}^4$, which translates to 95% CL lower limits on M_S of 0.59 (0.83) TeV for $\lambda = -1$ (+1). After the combination¹⁴ with OPAL studies^{15,16,17,7} of $e^+e^- \rightarrow \gamma\gamma$, $\mu^+\mu^-$ and $\tau^+\tau^-$ production, the lower limits on M_S become 0.80 (0.90) TeV for $\lambda = -1$ (+1).

References

1. N. Arkani-Hamed, S. Dimopoulos, G. Dvali, *Phys. Rev.* **D59** (1999) 086004.
2. J.L. Hewett, *Phys. Rev. Lett.* **82** (1999) 4765.
3. K. Agashe, N.G. Deshpande, *Phys. Lett.* **B456** (1999) 60.
4. The OPAL Collaboration, K. Ahmet *et al.*, *Nucl. Instr. Meth.* **A305** (1991) 275.
5. The OPAL Collaboration, G. Abbiendi *et al.*, *Phys. Lett.* **B476** (2000) 256.
6. The OPAL Collaboration, *Z Boson Pair Production in e^+e^- Collisions at $\sqrt{s} > 190$ GeV*, OPAL Physics Note 423, 3 March 2000.
7. The OPAL Collaboration, *Measurement of Standard Model Processes in e^+e^- Collisions at $\sqrt{s} > 202$ GeV*, OPAL Physics Note 437, 18 July 2000.
8. The OPAL Collaboration, *Measurement of Standard Model Processes in e^+e^- Collisions at $\sqrt{s} > 202$ GeV*, OPAL Physics Note 467, 1 November 2000.
9. J. Fujimoto *et al.*, *Comput. Phys. Commun.* **B100** (1997) 128.
10. S. Jadach, W. Placzek, B.F.L. Ward, *Phys. Rev.* **D56** (1997) 6939.
11. M.W. Grnwald, G. Passarino *et al.*, *Four-fermion production in electron-positron collisions*, hep-ph 0005309, 30 May 2000.
12. Particle Data Group, D.E. Groom *et al.*, *Eur. Phys. J.* **C15** (2000) 567.
13. K. Hagiwara, R.D. Peccei, D. Zeppenfeld and K. Hikasa, *Nucl. Phys.* **B282** (1987) 253.
14. The OPAL Collaboration, *Search for Low Scale Gravity in Extra Spatial Dimensions in $Z^0 Z^0$ Production at LEP*, OPAL Physics Note 440, 19 July 2000.
15. The OPAL Collaboration, G. Abbiendi *et al.*, *Eur. Phys. J.* **C13** (2000) 553.
16. The OPAL Collaboration, G. Abbiendi *et al.*, *Phys. Lett.* **B465** (1999) 303.
17. The OPAL Collaboration, *Multi-photon Production in e^+e^- Collisions at $\sqrt{s} = 192 - 202$ GeV*, OPAL Physics Note 433, 12 July 2000.