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Seeking $\mathcal{CP}$ Violating Couplings in ZZ Production at LEP2

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Abstract

The effects of $\mathcal{CP}$ violating anomalous ZZZ and γZZ vertices in ZZ production are determined. We present the differential cross-section for $e^+e^- \to ZZ$ with dependence on the spins of the Z bosons. It is shown that from the different spin combinations those with one longitudinally and one transversally polarized Z in the final state are the most sensitive to $\mathcal{CP}$ violating anomalous couplings.

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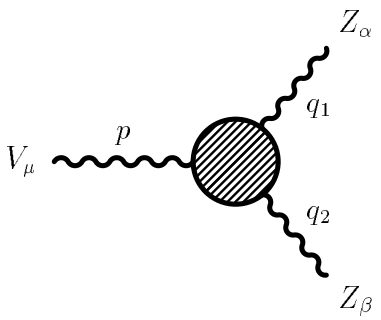

Figure 1: *The VZZ vertex with $V = \gamma, Z$. Two Z bosons with momenta q_i are on-shell, $q_i^2 = m_Z^2$.*

1 Introduction

LEP2 runs now at energies above the ZZ production threshold and the first Z pairs are observed. During the run of LEP2 some several hundred events will be collected. This might be enough to provide limits for ZZZ and γZZ vertices, which are absent in the Standard Model of electroweak interactions at tree-level. However, physics beyond the Standard Model might give strong contributions to neutral gauge boson vertices [1].

Requiring only invariance under Lorentz transformations the most general VZZ vertex, see figure 1, with two on-shell Z bosons is given by [2,3]:

$$\Gamma^{\alpha\beta\mu}_{VZZ} = \frac{p^2 - m_V^2}{m_Z^2}\left[if_4^V(p^\alpha g^{\mu\beta} + p^\beta g^{\mu\alpha}) + if_5^V\epsilon^{\mu\alpha\beta\rho}(q_1 - q_2)_\rho\right]. \qquad (1)$$

In contrast to the VW^+W^- vertex, with seven possible anomalous couplings [2,3], Bose symmetry forbids more couplings in (1)[1]. The anomalous parameter f_5^V in (1) leads to violation of $\mathcal{C}$ and $\mathcal{P}$ symmetry, but maintains invariance under $\mathcal{CP}$ transformations, while f_4^V would introduce $\mathcal{CP}$ violation in (1).

The differential Standard Model cross-section for ZZ production in e^+e^- annihilation is known for almost 20 years [2,4]. Also, the effects of anomalous neutral gauge boson couplings in the production of γZ, ZZ, and γ bosons have been studied, see e.g. [5]. In $Z\gamma$ production processes at the Tevatron [6] and LEP [7], limits to the vertex $Z\gamma Z$ were obtained. However, they cannot be transferred to Z pair production, since the anomalous couplings in equation (1) are independent of couplings in $Z\gamma$ production.

2 The Differential Cross-Section

The differential cross-section for ZZ production is presented in this section. It is obtained for the various spin combinations of final state Z bosons. This allows to determine their sensitivity to the anomalous couplings.

The finite width effects of the produced Z bosons are considered by convoluting the cross-section for ZZ production with two Breit-Wigner functions. The differential

[1]More anomalous couplings are allowed in (1), if one additional Z boson is off-shell, but their contributions are suppressed by a factor $(q_1^2 - q_2^2)$.

cross-section is then expressed by the sum:

$$\frac{d\sigma}{d\cos\theta} = \sum_{\sigma\sigma'} \frac{d\sigma^{\sigma\sigma'}}{d\cos\theta}, \tag{2}$$

with

$$\frac{d\sigma^{\sigma\sigma'}}{d\cos\theta} = \int \mathrm{d}s_1 \int \mathrm{d}s_2 \, \frac{\sqrt{\lambda}}{64\pi s^2} \left|\mathcal{M}^{\sigma\sigma'}\right|^2 \rho(s_1)\rho(s_2), \tag{3}$$

where σ and σ' stand for the possible Z boson helicities $+$, $-$, and 0, which are defined by the vectors:

$$\epsilon_{1\pm} = \epsilon_{2\mp} = \frac{1}{\sqrt{2}}\,(0, \mp 1, -i, 0)\,, \tag{4}$$

$$\epsilon_{10} = \frac{1}{2\sqrt{s s_1}}\left(\sqrt{\lambda}, 0, 0, (s + s_1 - s_2)\right), \tag{5}$$

$$\epsilon_{20} = \frac{1}{2\sqrt{s s_2}}\left(\sqrt{\lambda}, 0, 0, -(s - s_1 + s_2)\right). \tag{6}$$

The Källén function λ, the Breit-Wigner factors $\rho(s_i)$ and other notations may be inferred from [8]. The squared matrix element $\left|\mathcal{M}^{\sigma\sigma'}\right|^2$ in (3) can be expressed by the Standard Model part $\left|\mathcal{M}^{\sigma\sigma'}_{\mathrm{SM}}\right|^2$ and the anomalous contributions $A^{\sigma\sigma'}$:

$$\left|\mathcal{M}^{\sigma\sigma'}\right|^2 = \left|\mathcal{M}^{\sigma\sigma'}_{\mathrm{SM}}\right|^2 + A^{\sigma\sigma'}. \tag{7}$$

The squared amplitude in the Standard Model is:

$$\left|\mathcal{M}^{\sigma\sigma'}_{\mathrm{SM}}\right|^2 = \left(L_Z^4 + R_Z^4\right) \mathcal{G}^{\sigma\sigma'}_{\mathrm{SM}}(s_1, s_2), \tag{8}$$

where the Zee couplings L_Z and R_Z can again be taken from [8]. The functions $\mathcal{G}^{\sigma\sigma'}_{\mathrm{SM}}$ are:

$$\mathcal{G}^{00}_{\mathrm{SM}}(s_1, s_2) = \frac{16 s^2 s_1 s_2}{u^2 t^2} \cos^2\theta \sin^2\theta, \tag{9}$$

$$\mathcal{G}^{\pm\pm}_{\mathrm{SM}}(s_1, s_2) = \frac{\mathcal{G}^{00}}{4} + 2(s_1 - s_2)^2 \sin^2\theta \left(\frac{1}{u^2} + \frac{1}{t^2}\right), \tag{10}$$

$$\mathcal{G}^{\pm\mp}_{\mathrm{SM}}(s_1, s_2) = \frac{s^2(u+t)^2}{u^2 t^2}(1 - \cos^4\theta), \tag{11}$$

$$\mathcal{G}^{0\pm}_{\mathrm{SM}}(s_1, s_2) = \frac{2 s s_1}{u^2 t^2}\left\{8 s_2^2 \cos^2\theta + 4 s_2 \sin^2\theta \left(s_1 - s\cos^2\theta\right) + \lambda \sin^4\theta\right\}, \tag{12}$$

$$\mathcal{G}^{\pm 0}_{\mathrm{SM}}(s_1, s_2) = \mathcal{G}^{0\mp}_{\mathrm{SM}}(s_2, s_1), \tag{13}$$

with the Mandelstam variables:

$$t = -\frac{1}{2}\left(s - s_1 - s_2 - \sqrt{\lambda}\cos\theta\right), \tag{14}$$

$$u = -\frac{1}{2}\left(s - s_1 - s_2 + \sqrt{\lambda}\cos\theta\right). \tag{15}$$

It is noteworthy that the coupling constant combination $(L_Z^4 - R_Z^4)$ gives additional contributions to equation (8). However, these terms cancel each other for all measurable cross-sections and are therefore not reproduced[2].

The contributions from the anomalous diagrams are:

$$\begin{aligned} A^{\sigma\sigma'} &= \sum_{V_k,V_l=\gamma,Z} \frac{1}{m_Z^4} \left(L_{V_k} L_{V_l} + R_{V_k} R_{V_l}\right) \mathcal{G}_s^{\sigma\sigma'}(s_1, s_2; V_k, V_l) \\ &\quad + \sum_{V=\gamma,Z} \frac{f_5^V}{m_Z^2} \left(L_V L_Z^2 - R_V R_Z^2\right) \mathcal{G}_i^{\sigma\sigma'}(s_1, s_2), \end{aligned} \tag{16}$$

with the coupling constants $L_\gamma = R_\gamma = -e/2$ for the γee coupling. The denominators of the s-channel propagators $1/(s - m_V^2)$ cancel with the corresponding factors in the anomalous vertex function (1). Photon and Z exchange have the same s-dependence in (16). Again, as in equation (8) terms with additional coupling constant combinations appear for the various spin combinations, but they do not contribute to physical observables.

The functions $\mathcal{G}_s^{\sigma\sigma'}$ for the s-channel diagrams squared are:

$$\mathcal{G}_s^{00}(s_1, s_2) = \frac{\lambda \sin^2\theta}{4 s_1 s_2} (s_1 - s_2)^2 f_4^{V_k} f_4^{V_l}, \tag{17}$$

$$\mathcal{G}_s^{0\pm}(s_1, s_2) = \frac{(1 + \cos^2\theta)\, s}{8 s_1} \left\{ \lambda f_4^{V_k} f_4^{V_l} + (\lambda - 4 s_1 [s - 2(s_1 + s_2)]) f_5^{V_k} f_5^{V_l} \right\}, \tag{18}$$

$$\mathcal{G}_s^{\pm\pm}(s_1, s_2) = (s_1 - s_2)^2 \sin^2\theta f_5^{V_k} f_5^{V_l}, \tag{19}$$

$$\mathcal{G}_s^{\pm 0}(s_1, s_2) = \mathcal{G}_s^{0-}(s_2, s_1), \tag{20}$$

$$\mathcal{G}_s^{\pm\mp}(s_1, s_2) = 0. \tag{21}$$

Similarly, the interferences $\mathcal{G}_i^{\sigma\sigma'}$ between t and u-channel diagram and the s-channel diagram can be expressed by:

$$\mathcal{G}_i^{0\pm}(s_1, s_2) = \frac{s(3s_1 + s_2 - s)}{ut} \left\{ 4 s_2 - (3 s_2 - s_1 + s) \sin^2\theta \right\}, \tag{22}$$

$$\mathcal{G}_i^{\pm\pm}(s_1, s_2) = \frac{2(s_1 - s_2)^2 (u + t)}{ut} \sin^2\theta, \tag{23}$$

$$\mathcal{G}_i^{\pm 0}(s_1, s_2) = \mathcal{G}_i^{0-}(s_2, s_1), \tag{24}$$

$$\mathcal{G}_i^{00}(s_1, s_2) = \mathcal{G}_s^{\pm\mp}(s_1, s_2) = 0. \tag{25}$$

As expected there are no contributions of anomalous couplings to the spin combinations $(+-)$ and $(-+)$. These are spin 2 states and cannot be produced by the s-channel diagrams.

Equations (17) – (25) exhibit that the $\mathcal{CP}$ violating couplings proportional to f_4^V do neither interfere with the Standard Model terms nor with terms proportional to f_5^V. A further conclusion is that it is impossible to separate out the effects of the parameters

[2]Since the produced Z bosons are identical, not all of the various spin combinations are observable by themselves. As an example, the contribution of $\mathcal{G}^{+-}(s_1, s_2)$ cannot be distinguished from $\mathcal{G}^{-+}(s_2, s_1)$ and only their sum can be measured.

f_4^Z and f_4^γ on the differential cross-section of the process $e^+e^- \to ZZ$. However, both parameters imply $\mathcal{CP}$ violation in a VZZ vertex.

In the limit of on-shell Z pair production only the combination with one longitudinally and one transversally polarized Z receives contributions from anomalous couplings.

With the given expressions for the various spin combinations, the differential cross-section (2) is obtained:

$$\frac{d\sigma}{d\cos\theta} = \int \mathrm{d}s_1 \int \mathrm{d}s_2 \, \frac{\sqrt{\lambda}}{64\pi s^2} \rho(s_1)\rho(s_2) \left\{ S + A_i + A_s \right\}, \tag{26}$$

with the functions

$$S = 2\frac{L_Z^4 + R_Z^4}{u^2 t^2} \left\{ 4\lambda \sin^2\theta (s\sigma + s_1 s_2) + \lambda^2 (1 - \cos^4\theta) + 16 s s_1 s_2 \sigma \right\}, \tag{27}$$

$$A_i = -\frac{4}{m_Z^2} \sum_{V=\gamma,Z} \frac{L_V L_Z^2 - R_V R_Z^2}{ut} f_5^V \left\{ 2s[(s-\sigma)\sigma - 4s_1 s_2] - \lambda(s+\sigma)\sin^2\theta \right\}, \tag{28}$$

$$A_s = \sum_{V_k, V_l = \gamma, Z} \frac{L_{V_k} L_{V_l} + R_{V_k} R_{V_l}}{4 s_1 s_2 m_Z^4} \left\{ \lambda(1+\cos^2\theta) \left[s\sigma f_4^{V_k} f_4^{V_l} + (s\sigma - 8 s_1 s_2) f_5^{V_k} f_5^{V_l} \right] \right. \tag{29}$$
$$\left. + (s_1 - s_2)^2 \left[\lambda \sin^2\theta f_4^{V_k} f_4^{V_l} + 16 s_1 s_2 f_5^{V_k} f_5^{V_l} \right] \right\},$$

where the abbreviation $\sigma = s_1 + s_2$ is used. The Standard Model part is described by S while the anomalous contributions are contained in A_i and A_s.

In the Standard Model limit the differential cross-section in (26) is in agreement with the result presented in [9]. Radiative corrections to (26) due to initial state radiation, see e.g. [10], can be applied in the structure function approach including a Lorentz boost of the scattering angle as described similarly in W pair production [8].

3 Conclusions

The presented analytical results demonstrate how potential anomalous couplings change the differential ZZ production cross-section. Anomalous couplings will have their main effect in the production of a longitudinally and a transversally polarized Z boson. For on-shell ZZ production, these are the only spin combinations which are sensitive to an anomalous signal. Effects of non-vanishing f_4^V and f_5^V on the final states with two transversally or two longitudinally polarized Z bosons are zero or are suppressed by a factor $(s_1 - s_2)^2$.

Therefore, a measurement of the final state spins might be used to increase the ratio of the anomalous signal over the Standard Model background. But, since only one type of spin combinations is sensitive to anomalous couplings, a spin analysis cannot be used to disentangle the signals from f_4^V and f_5^V. However, due to the interference contribution of f_5^V in (22) and (24), the anomalous parameters f_4^V and f_5^V show different angular distributions and it might be possible to separate out their effects at LEP2.

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