

# Bounding the Anomalous $HZ\gamma$ Coupling via the Process $e^+e^- \rightarrow \tau^+\tau^-\gamma$

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**Abstract.** We obtain bounds on the anomalous coupling  $HZ\gamma$  through data published by the L3 Collaboration on the process  $e^+e^- \rightarrow \tau^+\tau^-\gamma$ . Our analysis leads to bounds on this coupling of order  $10^{-2}$ , for an intermediate mass Higgs boson  $115 < M_H < 145 \text{ GeV}$ , two orders of magnitude above the Standard Model prediction.

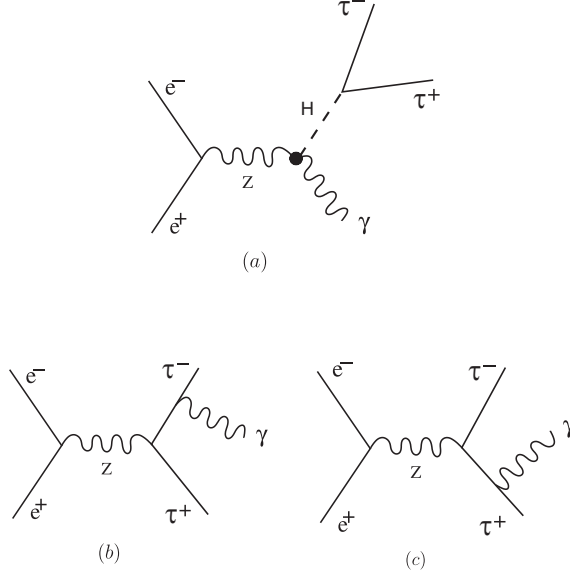
## 1. Introduction

The sensitivity to the  $HZ\gamma$  vertex has been studied in processes like  $e^-\gamma \rightarrow e^-H$  and  $e^+e^- \rightarrow H\gamma$  [1, 2, 3], rare  $Z$  and  $H$  decays [4, 5, 6],  $pp$  collisions via the basic interaction  $qq \rightarrow qqH$  [6] and the annihilation process  $e^+e^- \rightarrow HZ$  [3, 7, 8]. It has been found that the latter reaction with polarized beams may lead to the best sensitivity to the  $HZ\gamma$  vertex [7] while an anomalous  $HZ\gamma$  coupling may enhance partial Higgs decays widths by several orders of magnitude that would lead to measurable effects in Higgs signals at the LHC [6].

The general aim of the present paper is to obtain limits on the  $HZ\gamma$  vertex coming from the LEP data on the reaction  $e^+e^- \rightarrow \tau^+\tau^-\gamma$  [9]. We will find limits of order  $10^{-2}$ , which are better by an order of magnitude than the bounds obtained from the known limits on the partial decay widths of the  $Z$  boson [6], but still two orders of magnitude above the SM prediction [1, 10]. The L3 collaboration has obtained also limits on the  $HZ\gamma$  vertex using events with photons and a  $Z$  vector boson in the final state [11]. In this case they have used an analysis that involves the Higgs boson decay modes  $H \rightarrow \gamma\gamma, Z\gamma$ . We have found that our analysis with a tau-lepton pair in the final state induces more stringent limits on the  $HZ\gamma$  vertex.

In Fig. 1, we show the Feynman diagrams which give rise to the process  $e^+e^- \rightarrow \tau^+\tau^-\gamma$  in the SM at tree level and with the anomalous  $HZ\gamma$  vertex when the  $Z$  vector boson is produced on mass-shell. We do not include the contribution coming from initial photon bremsstrahlung because the LEP data considered the appropriated energy cuts to eliminate this contribution.

The paper is organized as follows. In Section 2 we present the calculation of the respective cross section and in Section 3 we presented our results and conclusions.



**Figure 1.** Feynman diagrams for the process  $e^+e^- \rightarrow \tau^+\tau^-\gamma$  induced by the anomalous vertex  $HZ\gamma$  (a) and the SM (b, c) when the  $Z$  vector boson is produced on mass-shell.

## 2. Cross-Section of the Process $e^+e^- \rightarrow \tau^+\tau^-\gamma$

The anomalous  $V_1^\mu(p_1) - V_2^\nu(p_2) - H(p_H)$  vertex function is given by [3, 12]

$$\Gamma_{\mu\nu}^{HV_1V_2}(p_H, p_1, p_2) = g_Z M_Z^2 [h_1^{V_1V_2} g_{\mu\nu} + \frac{h_2^{V_1V_2}}{M_Z^2} p_{2\mu} p_{1\nu}], \quad (1)$$

where  $M_Z$  is the  $Z$  boson mass and  $V_1, V_2$  can be  $(V_1V_2) = (ZZ), (Z\gamma), (\gamma Z), (\gamma\gamma), (W^+W^-)$  or  $(W^+W^-)$ .

In the present study we have considered only CP-conserving  $HZ\gamma$  couplings but our results can be applied also for the CP-violating coupling.

The expression for the respective cross section, that includes the SM and the  $HZ\gamma$  vertex contributions shown in Fig. 1, is given by

$$\begin{aligned} \sigma(e^+e^- \rightarrow \tau^+\tau^-\gamma) &= \int \frac{\alpha^3}{96} [3m_\tau^2 C_1(x_W) [F_1(s, E_\gamma, \cos \theta_\gamma) (h_1^{Z\gamma})^2 + F_2(s, E_\gamma, \cos \theta_\gamma) (h_2^{Z\gamma})^2] \\ &+ m_\tau^2 C_2(x_W) [F_3(s, E_\gamma, \cos \theta_\gamma) h_1^{Z\gamma} + F_4(s, E_\gamma, \cos \theta_\gamma) h_2^{Z\gamma}] \\ &+ C_3(x_W) F_5(s, E_\gamma, \cos \theta_\gamma)] E_\gamma dE_\gamma d\cos \theta_\gamma, \end{aligned} \quad (2)$$

where  $E_\gamma$  and  $\cos \theta_\gamma$  are the energy and scattering angle of the photon and the  $C_{1,2,3}$  coefficients label the respective contributions arising from the  $HZ\gamma$ , SM and interference amplitudes, respectively. The kinematics is contained in the functions

$$\begin{aligned} F_1(s, E_\gamma, \cos \theta_\gamma) &\equiv \frac{(\frac{1}{2}s - \sqrt{s}E_\gamma - 2m_\tau^2)}{[(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2](s + 2\sqrt{s}E_\gamma - M_H^2)^2}, \\ F_2(s, E_\gamma, \cos \theta_\gamma) &\equiv \frac{(\frac{1}{6}E_\gamma^2 - \frac{1}{3}\frac{E_\gamma^3}{\sqrt{s}} - \frac{2}{3}\frac{m_\tau^2 E_\gamma^2}{s})}{[(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2](s + 2\sqrt{s}E_\gamma - M_H^2)^2}, \end{aligned}$$

$$\begin{aligned}
F_3(s, E_\gamma, \cos \theta_\gamma) &\equiv \frac{(-1 - \frac{4}{\sin^2 \theta_\gamma} + \frac{2\sqrt{s}}{E_\gamma \sin^2 \theta_\gamma} + \frac{2\sqrt{s}E_\gamma}{M_Z^2} - \frac{6m_\tau^2}{\sqrt{s}E_\gamma \sin^2 \theta_\gamma})}{[(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2](s + 2\sqrt{s}E_\gamma - M_H^2)}, \\
F_4(s, E_\gamma, \cos \theta_\gamma) &\equiv \frac{(-1 - \frac{2}{\sin^2 \theta_\gamma} - \frac{2\sqrt{s}E_\gamma}{M_Z^2} + \frac{4\sqrt{s}E_\gamma}{M_Z^2 \sin^2 \theta_\gamma} + \frac{2sE_\gamma^2}{M_Z^4})}{[(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2](s + 2\sqrt{s}E_\gamma - M_H^2)}, \\
F_5(s, E_\gamma, \cos \theta_\gamma) &\equiv \frac{[(4 - \sin^2 \theta_\gamma)\sqrt{s} - 2E_\gamma \sin^2 \theta_\gamma]}{[(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2](\sqrt{s} \sin^2 \theta_\gamma)},
\end{aligned} \tag{3}$$

while the coefficients  $C_{1,2,3}$  are given by

$$\begin{aligned}
C_1(x_W) &\equiv \frac{(1 - 4x_W + 8x_W^2)}{x_W^3(1 - x_W)^3}, \\
C_2(x_W) &\equiv \frac{(1 - 4x_W)(1 - 4x_W + 8x_W^2)}{x_W^{5/2}(1 - x_W)^{5/2}}, \\
C_3(x_W) &\equiv \frac{(1 - 4x_W + 8x_W^2)^2}{x_W^2(1 - x_W)^2},
\end{aligned} \tag{4}$$

where  $x_W \equiv \sin^2 \theta_W$ .

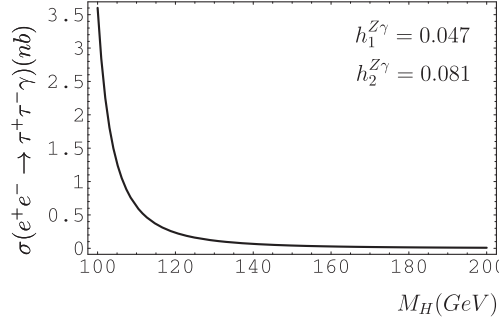
### 3. Results and Conclusions

In practice, detector geometry imposes a cut on the photon polar angle with respect to the electron direction, and further cuts must be applied on the photon energy and minimum opening angle between the photon and tau in order to suppress the background from tau decay products. In order to evaluate the integral of the total cross section as a function of the parameters  $h_1^{Z\gamma}$  and  $h_2^{Z\gamma}$ , we require cuts on the photon angle and energy to avoid divergences when the integral is evaluated at the important intervals of each experiment. We integrate over  $\cos \theta_\gamma$  from  $-0.74$  to  $0.74$  and  $E_\gamma$  from  $5 \text{ GeV}$  to  $45.5 \text{ GeV}$  for various fixed values of the Higgs boson mass  $M_H$ . For simplicity we have set the effective coupling  $g_Z$  equal to unity; using the numerical values  $\sin^2 \theta_W = 0.2314$ ,  $M_{Z_1} = 91.18 \text{ GeV}$ ,  $\Gamma_{Z_1} = 2.49 \text{ GeV}$  and  $m_\tau = 1.776 \text{ GeV}$ , we obtain the cross section  $\sigma = \sigma(h_1^{Z\gamma}, h_2^{Z\gamma}, M_H)$ . As was discussed in Ref. [9],  $N \approx \sigma(h_1^{Z\gamma}, h_2^{Z\gamma}, M_H)$ , and using Poisson statistics [9, 13], we require that  $N \approx \sigma(h_1^{Z\gamma}, h_2^{Z\gamma}, M_H)$  be less than 1559, with  $\mathcal{L} = 100 \text{ pb}^{-1}$ , according to the data reported by the L3 collaboration [9]. Taking this into consideration, we get limits on  $h_1^{Z\gamma}$  and  $h_2^{Z\gamma}$  as a function of  $M_H$ . The values obtained for these limits for several values of  $M_H$  are included in Table 1.

**Table 1.** Sensitivities achievable at the 95% C.L. for the  $h_{1,2}^{Z\gamma}$  vertices in the process  $e^+e^- \rightarrow \tau^+\tau^-\gamma$  with a luminosity of  $100 \text{ pb}^{-1}$ . We have applied the cuts used by L3 for the photon angle and energy.

$M_H$	$h_1^{Z\gamma}$	$h_2^{Z\gamma}$
115 GeV	[-0.042, 0.042]	[-0.045, 0.045]
130 GeV	[-0.047, 0.047]	[-0.081, 0.081]
145 GeV	[-0.11, 0.11]	[-0.19, 0.19]

We plot the total cross section in Fig. 2 as a function of the Higgs boson mass  $M_H$  for the values  $h_1^{Z\gamma} = 0.047$  and  $h_2^{Z\gamma} = 0.081$  given in Table 1. We observe in this figure that the cross



**Figure 2.** Cross-section for the process  $e^+e^- \rightarrow \tau^+\tau^-\gamma$  as a function of  $M_H$  with  $h_1^{Z\gamma} = 0.047$  and  $h_2^{Z\gamma} = 0.081$ .

section of the process  $e^+e^- \rightarrow \tau^+\tau^-\gamma$  decreases with the increases of the Higgs bosons mass  $M_H$ .

In conclusion, we have analyzed the constraints imposed on the  $HZ\gamma$  coupling from the known data for the process  $e^+e^- \rightarrow \tau^+\tau^-\gamma$  obtained by the L3 Collaboration [9]. We have made similar analysis using LEP data in order to improve previous limits on the  $ZZ\gamma$  and  $Z\gamma\gamma$  vertices [14, 15], the magnetic and electric dipole moments of tau neutrinos [16] and the tau lepton [17], as well as some of the parameters involved in L-R symmetric and  $E_6$  superstring model [18]. In the present case, our bounds shown in Table 1 are close to the limits expected in the annihilation process  $e^+e^- \rightarrow HZ$  with polarized beams [7], and an order of magnitude better [19] than the limits obtained for the same process by the L3 Collaboration [11]. In particular, we were able to improve the bounds on the  $HZ\gamma$  vertex because we did not need to use in our analysis the partial decay rates of the Higgs boson used in Ref. [11].

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