Bounds on the anomalous $H Z \gamma$ vertex arising from the process $e^+ e^- \rightarrow \tau^+ \tau^- \gamma$

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Abstract

We obtain limits on the anomalous coupling $H Z \gamma$ 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 $115 < M_H < 145$ GeV, two orders of magnitude above the Standard Model prediction.

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I. INTRODUCTION

In the Standard Model (SM) of electroweak interactions there are no couplings at the tree level among three neutral bosons involving photons, such as $HZ\gamma$. These couplings only appear at the one-loop level through fermion and charged vector bosons [1–3]. In the SM it is dominated by $W$ gauge boson and top quark loops and the branching ratio for the decay mode $H \rightarrow Z\gamma$ reaches its maximum value of order $10^{-3}$ for an intermediate-mass Higgs boson ($115 < M_H < 140$ GeV) [3]. The study of this vertex has attracted much attention because its strength can be sensitive to scales beyond the SM. The interest in this type of couplings thus lies in the additional contributions that may appear in extensions of the SM. This is the case, for example, for contributions coming from new charged scalar and vector bosons in Left-Right (L-R) symmetric gauge models [4], or Two Higgs Doublet Models (THDM) [5, 6], as well as charginos and neutralinos in the Minimal Supersymmetric Standard Model (MSSM) [5, 6]. The SM and L-R symmetric models predict an anomalous $HZ\gamma$ vertex of order $10^{-4}$ [1–3], the MSSM may induce a suppression effect [3, 6] but an effective Lagrangian approach leaves room for an enhancement effect [3, 7]. It has been found also that the QCD corrections in the SM are well under control [8]. A measurement of this vertex thus may be used to distinguish among theories beyond the SM.

The sensitivity to the $HZ\gamma$ vertex has been studied in processes like $e^-\gamma \rightarrow e^-H$ and $e^+e^- \rightarrow H\gamma$ [3, 9, 10], rare $Z$ and $H$ decays [11, 13], $pp$ collisions via the basic interaction $qq \rightarrow qqH$ [13] and the annihilation process $e^+e^- \rightarrow HZ$ [10, 14, 15]. It has been found that the latter reaction with polarized beams may lead to the best sensitivity to the $HZ\gamma$ vertex [14] 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 [13].

The general aim of the present paper is to obtain limits on the $HZ\gamma$ vertex coming from the LEP-I data on the reaction $e^+e^- \rightarrow \tau^+\tau^-\gamma$ [16, 17]. 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 [13], but still two orders of magnitude above the SM prediction [3, 5]. The L3 collaboration has obtained also limits on the $HZ\gamma$ vertex using now LEP-II data for events with photons and a $Z$ vector boson in the final state [18]. 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 $H \gamma$ 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 $H \gamma$ vertex when the $Z$ vector boson is produced on mass-shell. We do not include the contribution coming from initial photon bremsstrahlung because the L3 data considered the appropriate energy cuts to reduce this contribution.

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

II. CROSS SECTIONS

The anomalous $V_1^\mu (p_1) - V_2^\nu (p_2) - H(p_H)$ vertex function is given by [7, 10]

$$\Gamma_{\mu \nu}^{H V_1 V_2} (p_H, p_1, p_2) = g_Z M_Z^2 \left[ h_{1 V_1 V_2} g_{\mu \nu} + \frac{h_{2 V_1 V_2}}{M_Z^2} p_{2 \mu} p_{1 \nu} \right], \tag{1}$$

where $M_Z$ is the $Z$ boson mass, $g_Z = e / \sin \theta_W \cos \theta_W$ and $V_1, V_2$ can be $(V_1 V_2) = (ZZ), (Z\gamma), (\gamma Z), (\gamma \gamma), (W^+ W^-)$ or $(W^+ W^-)$. The coefficients $h_{1 V_1 V_2}$ are

$$h_{1 Z \gamma}^Z (p_1, p_2) = \frac{p_1^2 + p_2^2 - m_H^2}{m_Z^2} c_{2 Z \gamma} - \frac{p_1^2 - p_2^2 - m_H^2}{m_Z^2} c_{3 Z \gamma}, \tag{2}$$

$$h_{2 Z \gamma}^Z (p_1, p_2) = 2 (c_{2 Z \gamma} - c_{3 Z \gamma}), \tag{3}$$

for the $H \gamma$ couplings. The coefficients $c_{2 Z \gamma}$ and $c_{3 Z \gamma}$ are given explicitly in Eqs. (12d) and (12h) of Ref. [10].

In the present study we have considered only CP-conserving $H \gamma$ couplings but our results can be applied also for the CP-violating coupling. Since the L3 Collaboration [18] has used the $H \rightarrow Z \gamma$ decay rate in order to get its limits on the $H \gamma$ coupling, we present below the expression for its decay width

$$\Gamma (H \rightarrow Z \gamma) = \frac{g_Z^2 m_Z^2 (m_H^2 - m_Z^2)}{8 \pi m_H^3} (h_{1 Z \gamma}^Z)^2, \tag{4}$$

where we have used the fact that for on-shell particles, only one of the form factors given in Eq. (1) contribute to the decay width [5].

The expression for the respective cross section, that includes the SM and the $H \gamma$ vertex contributions shown in Fig. 1, is given by
$$\sigma(e^+e^- \rightarrow \tau\bar{\tau}\gamma) = \int \frac{\alpha^3}{96} \left[ 3m_\gamma^2 C_1(x_W) \left[ F_1(s, E_\gamma, \cos \theta_\gamma)(h_1^Z)^2 + F_2(s, E_\gamma, \cos \theta_\gamma)(h_2^Z)^2 \right] ight. \\
+ m_\gamma^2 C_2(x_W) \left[ F_3(s, E_\gamma, \cos \theta_\gamma)h_1^Z + F_4(s, E_\gamma, \cos \theta_\gamma)h_2^Z \right] \\
+ C_3(x_W) F_5(s, E_\gamma, \cos \theta_\gamma) \left] E_\gamma dE_\gamma d\cos \theta_\gamma, \right)$$

where $\alpha = e^2/4\pi$ is the electromagnetic coupling, $E_\gamma$ and $\cos \theta_\gamma$ are the energy and scattering angle of the photon and the $C_{1,2,3}$ coefficients label the contributions arising from the $HZ\gamma$, interference, and SM amplitudes, respectively. The kinematics is contained in the functions

$$F_1(s, E_\gamma, \cos \theta_\gamma) \equiv \left( \frac{4}{s} - \sqrt{s}E_\gamma - 2m_\gamma^2 \right) \left[ (s - M_Z^2)^2 + M_Z^4 \Gamma_Z^2 \right] (s + 2\sqrt{s}E_\gamma - M_H^2)^2,$$

$$F_2(s, E_\gamma, \cos \theta_\gamma) \equiv \left( \frac{4}{s} - \sqrt{s}E_\gamma - 2m_\gamma^2 \right) \left[ (s - M_Z^2)^2 + M_Z^4 \Gamma_Z^2 \right] (s + 2\sqrt{s}E_\gamma - M_H^2)^2,$$

$$F_3(s, E_\gamma, \cos \theta_\gamma) \equiv \left( -1 - \frac{4}{\sin^2 \theta_\gamma} + \frac{2\sqrt{s}}{E_\gamma \sin^2 \theta_\gamma} + \frac{2E_\gamma}{M_Z^2} - \frac{6m_\gamma^2}{\sqrt{s}E_\gamma \sin^2 \theta_\gamma} \right),$$

$$F_4(s, E_\gamma, \cos \theta_\gamma) \equiv \left( -1 - \frac{2}{\sin^2 \theta_\gamma} - \frac{2\sqrt{s}E_\gamma}{M_Z^2} + \frac{4\sqrt{s}E_\gamma}{M_Z^2 \sin^2 \theta_\gamma} + \frac{2E_\gamma^2}{M_Z^2} \right) \left[ (s - M_Z^2)^2 + M_Z^4 \Gamma_Z^2 \right] (s + 2\sqrt{s}E_\gamma - M_H^2)^2,$$

$$F_5(s, E_\gamma, \cos \theta_\gamma) \equiv \left[ (4 - \sin^2 \theta_\gamma)\sqrt{s} - 2E_\gamma \sin^2 \theta_\gamma \right] \left[ (s - M_Z^2)^2 + M_Z^4 \Gamma_Z^2 \right] (\sqrt{s} \sin^2 \theta_\gamma),$$

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

$$C_1(x_W) \equiv \frac{(1 - 4x_W + 8x_W^2)}{x_W^3 (1 - x_W)^3},$$

$$C_2(x_W) \equiv \frac{(1 + 4x_W)}{x_W^5 (1 - x_W)^3},$$

$$C_3(x_W) \equiv \frac{(1 + 4x_W + 8x_W^2)}{x_W^3 (1 - x_W)^3},$$

where $x_W \equiv \sin^2 \theta_W$. We have used the SM prediction for the $H\tau^+\tau^-$ vertex $\frac{iem}{2\sin \theta_W M_W}$ in order to get the cross section given in Eq (5). The coefficients $C_{1,2,3}$ come from the expressions for $g_Z$ and the leptonic couplings to the $Z$ and $H$ bosons. The functions $F_{1,2}$ come from the anomalous vertex diagrams of Fig. 1(a), while $F_5$ comes from the Feynman diagrams shown in Fig. 1(b,c) and $F_{3,4}$ arise from the respective interference contribution.
III. 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 $5 GeV$ to $45.5 GeV$ for various fixed values of the mass $M_H$. These cuts on the photon energy and polar angle were used by the L3 Collaboration in order to reduce the contribution coming from initial-state radiation (ISR). Accordingly, we did not include in our calculation of the cross section the contribution due to ISR. Using the numerical values $\alpha = 1/137.03$, $\sin^2 \theta_W = 0.2314$, $M_{Z_1} = 91.18 GeV$, $\Gamma_{Z_1} = 2.49 GeV$ and $m_\tau = 1.776 GeV$, we obtain the cross section $\sigma = \sigma(h_1^{Z\gamma}, h_2^{Z\gamma}, M_H)$. As was discussed in Ref. [16], $N \approx \sigma(h_1^{Z\gamma}, h_2^{Z\gamma}, M_H)$, and using Poisson statistics [16, 19], we require that $N \approx \sigma(h_1^{Z\gamma}, h_2^{Z\gamma}, M_H)$ be less than 1559, with $\mathcal{L} = 100 pb^{-1}$, according to the data reported by the L3 collaboration [16]. A similar number of events was obtained for the same process by the OPAL Collaboration [17]. The experimental value obtained by the L3 Collaboration for the cross section and the respective branching ratio of the $H \rightarrow Z\gamma$ decay are given by $\sigma(e^+e^- \rightarrow \tau^+\tau^-\gamma) = (1.472\pm0.006\pm0.02) nb$ [16, 20] and $Br(H \rightarrow Z\gamma) < 10^{-3}$ [21]. Taking this into consideration, we get limits on $h_1^{Z\gamma}$ and $h_2^{Z\gamma}$ as a function of $M_H$. For example, for a Higgs boson mass $M_H = 130 GeV$ we get the limits [22]

$$|h_1^{Z\gamma}| < 0.047,$$
$$|h_2^{Z\gamma}| < 0.081,$$ (8)

while for $M_H = 145 GeV$ we get

$$|h_1^{Z\gamma}| < 0.11,$$
$$|h_2^{Z\gamma}| < 0.19.$$ (9)

We plot the total cross section in Fig. 2 as a function of the Higgs boson mass $M_H$ for the values $h_1^{Z\gamma} = 0.047$, $h_2^{Z\gamma} = 0.081$ and $h_1^{Z\gamma} = 0.042$, $h_2^{Z\gamma} = 0.045$ given in Eqs. (8) and
We observe in this figure that the cross section of the process $e^+e^- \rightarrow \tau^+\tau^-\gamma$ decreases with the increase of the Higgs boson mass $M_H$. In Fig. 3 we show the region excluded at 95% C. L. for the branching ratio BR($H \rightarrow Z\gamma$) using Eq. (4) and our limits obtained for the coupling $h_1^{Z\gamma}$. We notice an improvement of about an order of magnitude with respect the results obtained by the L3 Collaboration from the process $e^+e^- \rightarrow H\gamma$ [18].

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 [16]. We have made similar analysis using LEP data in order to improve previous limits on the $ZZ\gamma$ and $Z\gamma\gamma$ vertices [23, 24], the magnetic and electric dipole moments of tau neutrinos [25] and the tau lepton [26], as well as some of the parameters involved in L-R symmetric and $E_6$ superstring model [27]. In the present case, our bounds shown in Eqs. (8, 9) are close to the limits expected in the annihilation process $e^+e^- \rightarrow HZ$ with polarized beams [14], and an order of magnitude better than the limits obtained for the same process by the L3 Collaboration [18]. 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. [18].

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FIG. 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. Diagrams for initial-state radiation are not considered in the calculation.
FIG. 2: Cross-section for the process $e^+e^- \rightarrow \tau^+\tau^-\gamma$ as a function of $M_H$ with $h_1^{Z\gamma} = 0.047$, $h_2^{Z\gamma} = 0.081$ (continuous line) and $h_1^{Z\gamma} = 0.042$, $h_2^{Z\gamma} = 0.045$ (dashed line).

FIG. 3: The region above the line is excluded for the branching ratio $BR(H \rightarrow Z\gamma)$ at 95% C. L. for a Higgs mass of $M_H = 130$ GeV (continuous line) and $M_H = 115$ GeV (dashed line).