Anomalous Higgs Boson Contribution to $e^+e^- \rightarrow b\bar{b}\gamma$ at LEP2.

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Abstract

We study the effect of anomalous $H\gamma\gamma$ and $HZ\gamma$ couplings, described by a general effective Lagrangian, on the process $e^+e^- \rightarrow b\bar{b}\gamma$ at LEP2 energies. We include the relevant irreducible standard model background to this process, and from the photon energy spectrum, we determine the reach of LEP2 to unravel the anomalous couplings by analyzing the significance of the signal for Higgs boson with mass up to 150 GeV.

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I. INTRODUCTION

The Standard Model (SM) has been tested to an unprecedented degree of accuracy of 0.1% in some of the physical observables at LEP1, with many implications to physics beyond the SM \[1\]. However, the $Z$-pole experiments are able to probe with great precision just the fermionic couplings to the vector bosons while furnishing very little information about the interaction between the gauge bosons and the Higgs sector of the SM. In principle, it is conceivable that the interactions of the Higgs boson, which is responsible for the spontaneous breaking of the electroweak symmetry and for generating fermion masses, are different from those prescribed by the SM. In this case, an effective Lagrangian formalism can be used to describe possible anomalous interactions between the Higgs boson and the vector bosons.

The effective Lagrangian approach is a convenient model-independent parametrization of the low-energy effects of new physics beyond the SM that may show up at higher energies \[2\]. Effective Lagrangians, employed to study processes at a typical energy scale $E$, can be written as a power series in $1/\Lambda$, where the scale $\Lambda$ is associated with the new particle masses belonging to the underlying theory. The coefficients of the different terms in the effective Lagrangian arise from integrating out the heavy degrees of freedom that are characteristic of a particular model for new physics. Invariant amplitudes, generated by such Lagrangians, will be an expansion in $E/\Lambda$, and in practice one can only consider the first few terms of the effective Lagrangian, e.g. dimension six operators, which are dominant for $E \ll \Lambda$.

The anomalous $H\gamma\gamma$ and $HZ\gamma$ couplings have already been considered in $Z$ and Higgs decays \[3\], in $e^+e^-$ collisions \[3,4\] and at $\gamma\gamma$ colliders \[5\]. In this paper, we concentrate our analyses on the effect of anomalous $H\gamma\gamma$ and $HZ\gamma$ couplings, described by a general effective Lagrangian, on the process $e^+e^- \rightarrow b\bar{b}\gamma$. This is a very interesting reaction since the SM contribution to $e^+e^- \rightarrow H(\rightarrow b\bar{b})\gamma$, being a one loop process, is extremely small, and the observation of any $H\gamma$ event at LEP2 will be a clear signal of new physics. It may also be the only possibility of detecting a Higgs boson with mass larger than 80 GeV at LEP2, provided that the anomalous couplings are sufficiently large. In our calculation, we
include the dominant decay of the Higgs boson into a pair of bottom and anti-bottom quarks in the framework of a complete tree-level calculation of the process $e^+e^- \rightarrow b\bar{b}\gamma$ involving both the SM and the anomalous Higgs boson couplings. In this way, the irreducible SM background to the new physics is taken into account. Furthermore, we employ the photon energy spectrum to identify the existence of the anomalous Higgs boson or at least impose further bounds on its effective couplings.

This paper is organized as follows: in Sec. II, we review the use of effective Lagrangians to study anomalous Higgs boson couplings, including limits on these couplings arising from precision measurements. In Sec. III, we study the process $e^+e^- \rightarrow b\bar{b}\gamma$, and we present our results and trace our conclusions in Sec. IV.

II. EFFECTIVE LAGRANGIANS AND THE ANOMALOUS $H\gamma\gamma$ AND $HZ\gamma$ COUPLINGS

In order to define an effective Lagrangian, it is necessary to specify the symmetry and the particle content of the low-energy theory. In our case, we require the effective Lagrangian to be CP-conserving, invariant under the SM symmetry $SU(2)_L \times U(1)_Y$ and to have as fundamental fields the same ones appearing in the SM spectrum. In particular, the Higgs field will be manifest and the symmetry is realized linearly. There are eleven independent dimension-six operators [9] of which only five are relevant for our discussions. Following the notation of reference [9], we can write,

$$\mathcal{L}_{eff} = \frac{1}{\Lambda^2} \left[ f_{BW} \Phi \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi + f_W (D_\mu \Phi) \hat{W}^{\mu\nu} (D_\nu \Phi) + f_B (D_\mu \Phi) \hat{B}^{\mu\nu} (D_\nu \Phi) + f_{WW} \Phi \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi + f_{BB} \Phi \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi \right],$$

(1)

where $\Phi$ is the Higgs field doublet, which in the unitary gauge assumes the form,

$$\Phi = \begin{pmatrix} 0 \\ (v + H)/\sqrt{2} \end{pmatrix},$$

and

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and
\[ \hat{B}_{\mu\nu} = \frac{g}{2} B_{\mu\nu} , \quad \hat{W}_{\mu\nu} = \frac{g}{2} g^a W^a_{\mu\nu} , \]  

(2)

with \( B_{\mu\nu} \) and \( W^a_{\mu\nu} \) being the field strength tensors of the respective \( U(1) \) and \( SU(2) \) gauge fields.

This Lagrangian gives rise to the following anomalous \( H\gamma\gamma \) and \( HZ\gamma \) couplings, in the unitary gauge [3],

\[ L_{\text{eff}}^{H\gamma\gamma,HZ\gamma} = g_{H\gamma\gamma} H A_{\mu\nu} A^{\mu\nu} + g^{(1)}_{HZ\gamma} A_{\mu\nu} Z^{\mu} \partial^\nu H + g^{(2)}_{HZ\gamma} H A_{\mu\nu} Z^{\mu\nu} , \]  

(3)

where \( A(Z)_{\mu\nu} = \partial^\mu A(Z)^\nu - \partial^\nu A(Z)^\mu \), and the coupling constants \( g_{H\gamma\gamma} \), and \( g^{(1,2)}_{HZ\gamma} \) are related to the coefficients of the operators appearing in (3) through,

\[ g_{H\gamma\gamma} = - \left( \frac{g M_W}{\Lambda^2} \right) \frac{s^2(f_{BB} + f_{WW} - f_{BW})}{2} , \]

\[ g^{(1)}_{HZ\gamma} = \left( \frac{g M_W}{\Lambda^2} \right) \frac{s(f_W - f_B)}{2c} , \]

\[ g^{(2)}_{HZ\gamma} = \left( \frac{g M_W}{\Lambda^2} \right) \frac{s(2s^2f_{BB} - 2c^2f_{WW} + (c^2 - s^2)f_{BW})}{2c} , \]  

(4)

with \( g \) being the electroweak coupling constant, and \( s(c) \equiv \sin(\cos)\theta_W \).

The coefficients \( f_B \) and \( f_W \) can be related to triple vector boson anomalous couplings and are bounded, for instance, by the direct measurement of \( WW\gamma \) vertex at hadron colliders. However, more stringent bounds on the coefficients of the effective Lagrangian (3) come from the precision measurements of the electroweak parameters obtained at LEP1 [4]. Typically one has that \( |f_{W,B,WW,BB}/\Lambda^2| \) can be as large as 100 TeV\(^{-2} \), whereas \( |f_{BW}/\Lambda^2| \) should be at most \( \sim 1 \) TeV\(^{-2} \).

### III. ANOMALOUS COUPLINGS AND HIGGS BOSON CONTRIBUTION TO \( e^+e^- \to b\bar{b}\gamma \)

An interesting option to test the couplings described by (3) at LEP2 is via the reaction \( e^+e^- \to H\gamma \), with the subsequent decay of the Higgs boson into a \( b\bar{b} \) pair. In the SM, at tree-level, there are eight Feynman diagrams that contribute to the process \( e^+e^- \to b\bar{b}\gamma \) (see Fig. II\((a) - (d))\).
A SM Higgs boson contribution to this process appears only at one–loop level, and is extremely small. For instance, the total cross section for the process $e^+e^- \to H\gamma$ [8], at $\sqrt{s} \simeq 175$ GeV, varies from $0.2$ fb to $0.02$ fb, for the Higgs mass in the range $70 < M_H < 150$ GeV. Therefore, with the expected LEP2 luminosity, no such events should be seen. Even in the Minimal Supersymmetric Standard Model, one cannot expect an enhancement larger than a factor of 3 with respect to the SM result [9]. In this way, we neglect this loop contribution in our calculation.

The bulk of the SM cross section comes from the $Z$ boson contribution to the diagrams (a) – (b) when the $Z$ boson is on-mass-shell, and the process is effectively a 2-body one. This implies that the majority of the photons emitted are monochromatic, with energy given by $E^Z_\gamma = (s - M_Z^2)/(2\sqrt{s})$.

When we take into account the anomalous Higgs boson couplings described above, two additional diagrams should be considered (see Fig. 1(e)). Their contributions are dominated by the on–mass–shell $H\gamma$ production, with $H \to b\bar{b}$. Therefore, we can anticipate the existence of a a secondary peak in the photon energy spectrum, generated at an energy

$$E^H_\gamma = \frac{s - M_H^2}{2\sqrt{s}}$$

which would be a very clear signal for the Higgs boson.

In order to evaluate the total cross section and kinematical distributions for the process $e^+e^- \to b\bar{b}\gamma$, we have used the package MadGraph [10] coupled to DHELAS, the double precision version of HELAS [11], for generating the tree–level SM amplitudes. We have written the relevant subroutines for the Higgs anomalous couplings, and included in the MadGraph generated file the two additional anomalous amplitudes. In this way, all interference effects between the SM and the anomalous amplitudes were taken into account. We checked for electromagnetic gauge invariance of the whole invariant amplitude, and incorporated a three–body phase space code, based on [12]. Since the Higgs boson resonance is very narrow, $\Gamma(H \to b\bar{b}) \sim 5$ MeV, for $M_H \sim 100$ GeV, we make sure to use appropriate variables to take care of the Higgs events close to the resonance peak. Finally, we used VEGAS [13] to
perform the phase space integration.

In our analyses we have assumed a center–of–mass energy of $\sqrt{s} = 175$ GeV for the LEP2 collider, with a luminosity of 0.5 fb$^{-1}$. Our results were obtained using the following energy and angular cuts,

$$E_{\gamma} \geq 20 \text{ GeV}, \quad (6)$$

$$|\cos \theta_{e-(e+)^{\gamma}}| \leq 0.87, \quad (7)$$

$$|\cos \theta_{b(\bar{b})^{\gamma}}| \leq 0.94. \quad (8)$$

The photon energy cut (6) is intended to reject the background from unresolved pair of photons from $\pi^0$ decays and assures, in principle, a sensitivity to $M_H$ up to 150 GeV. The cuts in $\cos \theta_{e-(e+)^{\gamma}}$ and $\cos \theta_{b(\bar{b})^{\gamma}}$ were introduced to reduce initial and final state radiation, respectively.

IV. RESULTS AND CONCLUSIONS

Our purpose is to determine the range of anomalous $H\gamma\gamma$ and $HZ\gamma$ couplings that could be probed at LEP2 by searching for a signal of the Higgs boson in the process $e^+e^- \rightarrow b\bar{b}\gamma$. We assume that the Higgs couplings to fermions are the standard ones, which makes the $BR(H \rightarrow b\bar{b})$ dominant in the range $70 < M_H < 150$ GeV, for $|f_i/\Lambda^2| \sim \text{TeV}^{-2}$.

Figure 2 shows our typical results for the photon energy distribution presented as a 1 GeV bin histogram. We have taken $g_{H\gamma\gamma} = 10^{-3}$ GeV$^{-1}$, $g_{HZ\gamma}^{(1,2)} = 0$ and varied the Higgs mass between 70 and 120 GeV. We should point out that the general behavior of the energy distribution remains the same when we consider the other couplings, $g_{HZ\gamma}^{(1,2)}$, different from zero. We can identify the $Z$–boson peak around $E_{\gamma} \simeq 64$ GeV and also the various secondary peaks due to the Higgs boson at the energies given by (5). We can notice that the smaller the Higgs mass, the larger is its effect in the $E_{\gamma}$ distribution. Its detectability should rely on a careful analyses of the tail (in the case where $M_H \neq M_Z$) of the SM contribution to the photon energy spectrum in the process $e^+e^- \rightarrow b\bar{b}\gamma$. 

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In Fig. 3, for the sake of comparison between the signal \((H)\) and background \((Z)\) behavior, we present separately the normalized angular distribution for SM and anomalous contributions, for \(g_{H\gamma\gamma} = 10^{-3}\) \(\text{GeV}^{-1}\), and \(M_H = 110\) GeV. We consider the angles between the electron beam and the final particles \((\theta_{\gamma e}, \text{and} \theta_{be})\), and also the ones between the final particles \((\theta_{\gamma b}, \text{and} \theta_{bb})\). We can see that the signal has a very small contribution at \(\theta_{\gamma e} \sim \pi/2\), due to the scalar nature of the Higgs, whereas the events from the background yields some events from transversal \(Z\)’s in the central region. The \(\theta_{bb}\) angular distribution shows that the produced quarks have a minimum angle between themselves, which depends on the mass and energy of the parent particle, \(i.e. \theta_{bb} > \theta_{\text{min}}^{Z(H)} = 2 \arcsin(M_{Z(H)}/E_{Z(H)})\). This variable could be used to further increase the signal over background ratio. For instance, for \(M_H > M_Z\), the cut \(\theta_{bb} > \theta_{\text{min}}^{H}\) is able to get rid of most of the \(b\bar{b}\) events coming from the \(Z\). In fact, at the \(Z\) peak, the number of events is reduced by a factor of 3 when this cut is implemented for a Higgs boson of 110 GeV. On the other hand, for \(M_H < M_Z\), a cut \(\theta_{bb} < \theta_{\text{min}}^{Z}\) plays the same role. We should point out that there is no difference among the distributions coming from the three anomalous couplings \((5)\). Therefore, it will be very difficult to make a distinction among these couplings based only on these kinematical distributions \((4)\).

In order to estimate the reach of LEP2 to disentangle the anomalous Higgs boson couplings, we have evaluated the significance \((S = \text{Signal}/\sqrt{\text{Background}})\) of the signal based on the Higgs boson peaks in the \(E_\gamma\) distribution, assuming a Poisson distribution for both signal and background. We have scanned the parameter space for the three anomalous couplings keeping only one non–zero coupling in each run, for different values of the Higgs boson mass. We took the coupling constants \(g_{H\gamma\gamma}, g_{HZ\gamma}^{(1,2)}\) in the range \(10^{-4} - 10^{-2}\) \(\text{GeV}^{-1}\) \((4)\), and we assumed a \(b\)-tagging efficiency of 68\% \((5)\). In Fig. 4 we present the significance for each of these couplings, assuming four different values of the Higgs boson mass \(M_H = 70, 90, 110,\) and 130 GeV. We should notice that for \(M_H = 90\) GeV the significance is reduced due to the presence of the \(Z\) boson peak.

In Table I, we show the values of the coupling constants \(g_{H\gamma\gamma}, g_{HZ\gamma}^{(1,2)}\) that corresponds to a 5 \(\sigma\) effect in the 1 GeV bin of the \(E_\gamma\) distribution around the Higgs peaks, for different
Higgs boson masses. We also present the total number of signal and background events in these bins. For $M_H = 90$ GeV, a large numbers of events is needed due to the $Z$ boson peak. Since the signal increases with the square of the anomalous couplings, for some values of the coupling constants, we could expect to have a reliable signal for the anomalous Higgs boson in less than one year of LEP2 run.

In this study, we have not taken into account initial state radiation, which would result in an energy degradation of the original $e^+e^-$ beams, and we have not included a realistic simulation of the electromagnetic energy resolution. It is important to notice that an increase in the $b$-tagging efficiency, and a good resolution of the electromagnetic calorimeter can help to select the $b\bar{b}$ events, increasing the signal over background ratio and improving the resolution of the Higgs boson peak in the photon energy distribution.

In conclusion, searching for the anomalous Higgs at LEP2 provides a complementary way to the indirect precision measurements at LEP1 in probing effective Lagrangians that are the low–energy limit of physics beyond the SM. We have shown that the study of the process $e^+e^- \rightarrow b\bar{b}\gamma$ can be a very important tool in the search of these particles at LEP2. We found that anomalous couplings $g_{H\gamma\gamma}, g_{HZ\gamma}^{(1,2)} \sim 10^{-2}$ GeV$^{-1}$ are necessary for identifying an anomalous Higgs of 150 GeV. However, for a lighter Higgs boson, couplings as small as $4 \times 10^{-4}$ GeV$^{-1}$ should suffice.

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FIGURES

FIG. 1. Feynman diagrams for $e^+e^- \rightarrow b\bar{b}\gamma$ in the standard model at tree–level (a, b, c, d) and the anomalous Higgs boson contribution (e).

FIG. 2. Photon energy distribution ($d\sigma/dE_\gamma$) of the process $e^+e^- \rightarrow b\bar{b}\gamma$, for the standard model contribution (dashed histogram). We also show the Higgs boson peaks (solid histogram) for different values of its mass, and $g_{H\gamma\gamma} = 10^{-3}$ GeV$^{-1}$.

FIG. 3. Normalized angular distribution $(1/\sigma)d\sigma/d\cos\theta_i$, for $\theta_i = \theta_{\gamma e}$, $\theta_{\gamma b}$, $\theta_{b\bar{b}}$. The solid (dotted) lines represent the anomalous (standard model) contributions, for $g_{H\gamma\gamma} = 10^{-3}$ GeV$^{-1}$.

FIG. 4. Significance of anomalous events as a function of the coupling constants $g_{H\gamma\gamma}$, and $g_{HZ\gamma}^{(1,2)}$, and different Higgs masses: 70 GeV (dot–dashed), 90 GeV (dashed), 110 GeV (solid), 130 GeV (dotted).
| $M_H$ (GeV) | $|g_{H\gamma\gamma}|$ (GeV$^{-1}$) | $|g_{HZ\gamma}^{(1)}| (\text{GeV}^{-1})$ | $|g_{HZ\gamma}^{(2)}| (\text{GeV}^{-1})$ | Signal / Background |
|------------|---------------------------------|---------------------------------|---------------------------------|-------------------|
| 70         | $3.89 \times 10^{-4}$           | $1.93 \times 10^{-3}$           | $9.62 \times 10^{-4}$           | 4.69/0.88         |
| 80         | $5.63 \times 10^{-4}$           | $2.66 \times 10^{-3}$           | $1.37 \times 10^{-3}$           | 7.32/2.14         |
| 90         | $1.52 \times 10^{-3}$           | $7.47 \times 10^{-3}$           | $3.74 \times 10^{-3}$           | 43.09/74.26       |
| 100        | $1.04 \times 10^{-3}$           | $4.98 \times 10^{-3}$           | $2.49 \times 10^{-3}$           | 13.61/7.41        |
| 110        | $8.90 \times 10^{-4}$           | $4.30 \times 10^{-3}$           | $2.14 \times 10^{-3}$           | 7.16/2.05         |
| 120        | $1.02 \times 10^{-3}$           | $4.91 \times 10^{-3}$           | $2.43 \times 10^{-3}$           | 5.81/1.35         |
| 130        | $1.36 \times 10^{-3}$           | $6.44 \times 10^{-3}$           | $3.24 \times 10^{-3}$           | 4.77/0.91         |
| 140        | $2.70 \times 10^{-3}$           | $1.09 \times 10^{-2}$           | $5.45 \times 10^{-3}$           | 4.72/0.89         |
| 150        | $5.16 \times 10^{-3}$           | $2.65 \times 10^{-2}$           | $1.24 \times 10^{-2}$           | 4.92/0.97         |

**TABLE I.** Values of the anomalous couplings $g_{H\gamma\gamma}$, $g_{HZ\gamma}^{(1)}$, and $g_{HZ\gamma}^{(2)}$ corresponding to a significance of 5 $\sigma$, and the ratio of the total number of signal and background events.
Fig. 1
Fig. 2
Fig. 3
