New Higgs Interactions in $ZZ\gamma$ and $Z\gamma\gamma$ Production

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Abstract

The effect of new operators that only modify the bosonic couplings of the Higgs boson, without altering the $WW\gamma$ or $WWZ$ three–point functions, are examined in the $e^+e^− \rightarrow ZZ\gamma$ and $Z\gamma\gamma$ processes. We analyse the constraints on these interactions that can be imposed by the LEP II collider at CERN and at the Next Linear Collider.
I. INTRODUCTION

The experiments which are taking place at the CERN LEP II electron–positron collider will be able to explore the gauge structure of $WW\gamma$ and $WWZ$ three–point functions in the $W$–pair production [1]. Deviations from the Standard Model (SM) predictions for this reaction would indicate the existence of new physics effects.

In general, such deviations can be parametrized in terms of effective Lagrangians by adding to the SM Lagrangian, high–dimension operators that describe the new phenomena [2]. This model–independent approach accounts for new physics that shows up at an energy scale $\Lambda$, larger than the electroweak scale. The effective Lagrangians are constructed with the light particle spectrum that exists at low energies, while the heavy degrees of freedom are integrated out. They are invariant under the $SU(2)_L \times U(1)_Y$ and, in the linearly realized version, they involve, in addition to the usual gauge–boson fields, also the light Higgs particle. The most general dimension–6 effective Lagrangian, containing all SM bosonic fields, that is $C$ and $P$ even, was constructed in Ref. [3].

In this letter, we explore the consequence of new operators that give rise to anomalous Higgs boson couplings, without affecting the self–interaction amongst the gauge bosons. These anomalous interactions can not be constraint by the LEP II results on $W$–pair production. In particular, we study the reactions $e^+e^- \rightarrow ZZ\gamma$ and $Z\gamma\gamma$. These processes do not involve any triple–vector–boson coupling, but only $HZ\gamma$ and $H\gamma\gamma$ anomalous Higgs interactions. In the SM, neglecting the Higgs–electron coupling, there are no Higgs contributions to these reactions at tree level since the $HZ\gamma$ and $H\gamma\gamma$ couplings are generated only at one–loop [4,5].

Out of the eleven independent operators constructed in Ref. [3], two of them describe new interactions between the Higgs particle and the vector bosons,

$$\mathcal{L}_{\text{eff}} = \frac{f_{WW}}{\Lambda^2} \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi + \frac{f_{BB}}{\Lambda^2} \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi,$$  \hspace{1cm} (1)

where, in the unitary gauge, the Higgs doublet becomes $\Phi = (1/\sqrt{2})[0, (v + H)]^T$, and $\hat{B}_{\mu\nu} = i(g' / 2) B_{\mu\nu}$, and $\hat{W}_{\mu\nu} = i(g / 2) \sigma^a W^a_{\mu\nu}$, with $B_{\mu\nu}$ and $W^a_{\mu\nu}$ being the field strength tensors of the $U(1)$ and $SU(2)$ gauge fields respectively.

We should notice that the operators (1) contribute only to the anomalous Higgs couplings, $HVV$, $V = W, Z, \gamma$, since their possible contribution to the self–gauge–boson couplings, $WW\gamma$ and $WWZ$, can be completely absorbed in the redefinition of the SM fields and gauge couplings [3]. Furthermore, no new $ZZ\gamma$ or $Z\gamma\gamma$ vertices, like the ones studied in Ref. [3], are generated via these operators. Therefore, studies of anomalous trilinear gauge boson couplings are insensitive to the coefficients $f_{WW}$ and $f_{BB}$. Anomalous Higgs boson couplings have already been studied in Higgs and Z boson decays [6], in $e^+e^-$ [7,9], $\gamma\gamma$ [10], and $p\bar{p}$ colliders [11]. Here, in order to impose limits on the dimension–6 operators (1) that generate the new Higgs interactions, we examine the total $ZZ\gamma$ and $Z\gamma\gamma$ yield and kinematical distributions of the final state particles at LEP II and at the Next Linear Collider, NLC.
II. RESULTS FOR THE ANOMALOUS ZZγ AND Zγγ PRODUCTION

In our analysis of the \( e^+e^- \rightarrow ZZ\gamma \) and \( Z\gamma\gamma \) reactions, we have taken into account the standard one loop Higgs contributions \([4,5]\) to these processes. In this way, the \( Z\gamma\gamma \) production involves seven (eight) standard (anomalous) Feynman contributions, while in the \( ZZ\gamma \) process there are ten (twelve) standard (anomalous) diagrams. In order to compute these contributions, we have incorporated all anomalous couplings in Helas–type \([12]\) Fortran subroutines. These new subroutines were used to adapt a Madgraph \([13]\) output to include all the anomalous contributions. We have checked that our code passed the non–trivial test of electromagnetic gauge invariance.

We investigate the \( Z\gamma\gamma \) and \( ZZ\gamma \) production both at LEP II and at NLC, assuming a center–of–mass energy of \( \sqrt{s} = 190 \) and \( 500 \) GeV and an integrated luminosity of \( L = 0.5 \) and \( 50 \) fb\(^{-1}\) respectively. We required that the photon energy, \( E_\gamma \), is larger than 5 GeV for LEP II and than 20 GeV for NLC. We applied an isolation cut by requiring that the angle between any two final state particles is larger than 15°. The same cut was applied to the angle of the bosons with the beam pipe.

Our results for the sensitivity of LEP II to the operators appearing in the effective Lagrangian \([1]\) indicate that the reaction \( e^+e^- \rightarrow Z\gamma\gamma \) can provide limits on both anomalous couplings since \( \sigma_{Z\gamma\gamma}^{SM} = 654 \) fb, and we can expect around 300 events per year. A 1σ deviation in the total cross section, assuming a Higgs boson with mass of 100 GeV, requires that,

\[
-296 < \frac{f_{BB}}{\Lambda^2} < 500 \text{ TeV}^{-2} , \quad -58 < \frac{f_{WW}}{\Lambda^2} < 92 \text{ TeV}^{-2} .
\]

These results are similar to those arising from the analysis of the reaction \( e^+e^- \rightarrow W^+W^-\gamma \) \([14]\), where a 1σ deviation implies \( |f_{WW}| \lesssim 150 \).

On the other hand, the reaction \( e^+e^- \rightarrow ZZ\gamma \) is almost insensitive to the anomalous coefficient \( f_{BB} \). For a Higgs boson mass of 100 GeV, a 1σ deviation can be observed for \( |f_{WW}/\Lambda^2| \sim 300 \text{ TeV}^{-2} \). The small SM cross section for this process, \( \sigma_{ZZ\gamma}^{SM} = 4.4 \) fb, leads to very few events per year at LEP II, and in consequence, the constraints from this reaction are limited by the poor statistics.

Due to the increase on the available phase space, we are able to establish tighter constraints on the coefficients \( f_{WW, BB} \) by studying the contribution of the operators \([1]\) to these same processes at NLC. For instance, at \( \sqrt{s} = 500 \) GeV, \( \sigma_{ZZ\gamma}^{SM} = 58 \) fb, which yields 2900 events per year assuming the expected luminosity for NLC (\( L = 50 \) fb\(^{-1}\)). Requiring a maximum deviation of 2σ in the total cross section, and assuming a Higgs boson of 200 GeV, we obtain the allowed ranges \(-39 < f_{BB}/\Lambda^2 < 35 \text{ TeV}^{-2} \) and \(-9.6 < f_{WW}/\Lambda^2 < 14 \text{ TeV}^{-2} \).

Unlike at LEP II, at NLC the best constraint on the anomalous couplings come from the reaction \( e^+e^- \rightarrow ZZ\gamma \), which gives rise to \( \sim 675 \) events per year at \( \sqrt{s} = 500 \) GeV. Figure \([1]\) shows the effect of the anomalous operators \([1]\) in the total cross section of this reaction. A 2σ deviation in the total cross section sets the bounds,

\[
-12.6 < \frac{f_{BB}}{\Lambda^2} < 8.5 \text{ TeV}^{-2} , \quad -6.6 < \frac{f_{WW}}{\Lambda^2} < 5.7 \text{ TeV}^{-2} ,
\]

also for a 200 GeV Higgs boson. Furthermore, we can expect the new interactions to affect most the longitudinally polarized gauge bosons production due to the presence of the scalar...
Higgs boson as intermediate state. We tried to take advantage of this fact by studying the longitudinal $Z$–pair production which brings on a slightly better result, $i.e.$ $-11.9 < f_{BB}/\Lambda^2 < 7.8 \ TeV^{-2}$ and $-6.4 < f_{WW}/\Lambda^2 < 5.2 \ TeV^{-2}$ for a $2\sigma$ effect. Unfortunately the improvement is very small because the requirement of polarized $Z$ reduces by two orders of magnitude the total yield.

We have also investigated different distributions of the final state particles in order to search for kinematical cuts that could improve the NLC sensitivity. The most promising variable is the photon transverse momentum which distribution is presented in Fig. 2 for the unpolarized case. We observe that the contribution of the anomalous couplings is larger in the high $p_T$ region. Therefore a cut of $p_T > 100$ GeV drastically reduces the background. The improvement on $f_{WW,BB}$ bounds can be clearly seen from Fig. 3 where a 1, 2, and $3\sigma$ deviations in the total cross section is shown before and after the above cut is applied.

The contribution of the anomalous couplings is dominated by on–mass–shell Higgs production with the subsequent $H \rightarrow ZZ$ decay. The peak around 210 GeV in the photon transverse momentum distribution is due to the monochromatic photon with $E_{\gamma}^{\text{mono}} = (s - M_Z^2)/(2\sqrt{s})$ which is emitted in association with the 200 GeV Higgs boson. Therefore the best constraints are obtained at NLC for Higgs boson masses in the range $2M_Z \leq M_H \leq (\sqrt{s} - E_{\gamma}^{\text{min}}) \ GeV$, where a on–shell production is allowed.

We present in Table I the limits on the coefficients $f_{BB}$ and $f_{WW}$ based on a $2\sigma$ deviation in the total cross section for a Higgs mass in the range $200 \leq M_H \leq 350$ GeV. Table II shows the same limits after the cut in the photon transverse momentum distribution of $p_T > 100$ GeV is implemented. These results are comparable to the limits for $f_{BB}$ and $f_{WW}$ obtained from the study of the reaction $e^+e^- \rightarrow W^+W^-\gamma$ presented in Ref. [14], suggesting that the processes considered here can be used as a complementary tool in the study of anomalous Higgs interactions.

In conclusion, the search for the effect of higher dimensional operators that give rise to anomalous Higgs boson couplings may provide important information on physics beyond the Standard Model and should be pursued in all possible reactions. We have studied here the triple vector boson production, $ZZ\gamma$ and $Z\gamma\gamma$, in $e^+e^-$ colliders focusing on the operators that generate only anomalous Higgs boson couplings and cannot be tested in the $W$–pair production. We established the limits that can be imposed at LEP II and NLC through the analysis of the deviations on the total cross section. Furthermore, we used the photon transverse momentum spectrum and polarization of the $Z$’s to improve these constraints to few TeV$^{-2}$ at the NLC.

ACKNOWLEDGMENTS

We would like to thank M. C. Gonzalez–Garcia for very useful discussions. This work was supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), and by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP).
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FIGURES

FIG. 1. Total cross section for the reaction $e^+e^- \rightarrow ZZ\gamma$ at NLC, for $M_H = 200$ GeV, as a function of $f_{BB}$ and $f_{WW}$.

FIG. 2. Photon transverse momentum distribution for $e^+e^- \rightarrow ZZ\gamma$ at NLC, assuming $M_H = 200$ GeV, for the Standard Model (solid line), and for $f_{BB}/\Lambda^2 = 10$ and $f_{WW}/\Lambda^2 = 0$ TeV$^{-2}$ (dashed line) and for $f_{WW}/\Lambda^2 = 10$ and $f_{BB}/\Lambda^2 = 0$ TeV$^{-2}$ (dotted line).

FIG. 3. Contour plot of $f_{BB} \times f_{WW}$, from $e^+e^- \rightarrow ZZ\gamma$ at NLC, for $M_H = 200$ GeV. The curves show the one, two, and three sigma deviations from the Standard Model total cross section: (a) No cut on $p_T\gamma$, and (b) with a cut of $p_T\gamma > 100$ GeV.
TABLES

| $M_H$(GeV) | $f_{BB}/\Lambda^2$ | $f_{WW}/\Lambda^2$ |
|------------|------------------|------------------|
| 200        | (−12.6 , 8.5)    | (−6.6 , 5.7)    |
| 250        | (−13.3 , 9.5)    | (−7.5 , 6.2)    |
| 300        | (−16.0 , 12.5)   | (−9.1 , 7.9)    |
| 350        | (−21.9 , 18.3)   | (−12.3 , 11.5)  |

TABLE I. Range of the allowed values of the coefficients $f_{BB}$ and $f_{WW}$, in TeV$^{-2}$, for a 2σ deviation in the total cross section of the process $e^+e^- \rightarrow ZZ\gamma$ at NLC.

| $M_H$(GeV) | $f_{BB}/\Lambda^2$ | $f_{WW}/\Lambda^2$ |
|------------|------------------|------------------|
| 200        | (−9.6 , 5.4)     | (−5.4 , 3.7)     |
| 250        | (−10.3 , 6.5)    | (−5.9 , 4.4)     |
| 300        | (−12.9 , 9.3)    | (−7.3 , 5.9)     |
| 350        | (−20.5 , 16.1)   | (−10.6 , 10.1)   |

TABLE II. The same as Table I after the implementation of the cut $p_{T\gamma} > 100$ GeV.
Fig. 1
