Anomalous couplings in $e^+e^- \rightarrow W^+W^-\gamma$ at CERN LEP 2 and NLC

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We present sensitivity limits on the coefficients of a dimension-6 effective Lagrangian that parametrizes the possible effects of new physics beyond the standard model. Our results are based on the study of the process $e^+e^- \rightarrow W^+W^-\gamma$ at CERN LEP 2 and NLC energies. In our calculations, we include *all* the new anomalous interactions, involving vectors and Higgs bosons, and take into account the standard model irreducible background. We analyze the impact of these new interactions on the total cross section, including the effects of the initial electron and final W polarizations. We then focus on the operators that will not be constrained by the $e^+e^- \rightarrow W^+W^-$ process, obtaining limits based on the photon energy distribution. [S0556-2821(97)05019-4]

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I. INTRODUCTION

One of the main physics goals of the CERN e^+e^- collider LEP 2 and future e^+e^- colliders is to directly test the gauge nature of couplings among the electroweak gauge bosons. The process with a largest cross section at LEP 2 involving these couplings is the W -pair production $e^+e^- \rightarrow W^+W^-$, which is sensitive to the trilinear $WW\gamma$ and WWZ couplings. The measurement of these couplings and the sensitivity to possible deviations from the standard model (SM) predictions have been extensively studied in the recent years [1].

The most general phenomenological parametrization for these couplings [2] can be achieved by means of an effective Lagrangian [3] that involves operators with dimension higher than 4, containing the relevant fields at low energies and respecting the symmetries of the standard model. The effective Lagrangian approach is a model-independent way to describe new physics that can occur at an energy scale Λ much larger than the scale where the experiments are performed.

The effective Lagrangian depends on the particle content at low energies and since the Higgs boson has not yet been found, there are two logical possibilities to describe the new physics effect at low energies. In one of them, the Higgs boson can be light, being present in the higher dimensional operators, in addition to the electroweak gauge bosons, and the SM symmetries are linearly realized [4,5]. Alternatively, the Higgs boson can be very heavy and it must be integrated out at low energies. In this case, the relevant fields at low energies are only electroweak gauge bosons and the SM symmetries are realized nonlinearly [6]. Here we focus on a linearly realized $SU_L(2) \times U_Y(1)$ -invariant effective Lagrangian to describe the bosonic sector of the standard model, keeping the fermionic couplings unchanged.

The same effective Lagrangian used to describe anomalous trilinear gauge couplings can, in general, lead to anomalous quartic interaction among gauge bosons and also to anomalous couplings of these particles with the Higgs field. All these interactions should also be investigated at LEP 2 and at the Next Linear Colliders (NLC) in order to search for hints about the nature of the new physics described by these higher dimensional operators.

New quartic gauge boson couplings have been studied before in many different processes at future e^+e^- , $e\gamma$, $\gamma\gamma$, e^-e^- , and pp colliders [7]. However, most of these previous works have focused on the so-called genuinely quartic operators, i.e., operators that give rise only to quartic gauge boson interactions without altering the trilinear couplings [8]. Since these operators do not appear in a dimension-6 linearly realized $SU(2)_L \times U_Y(1)$ invariant effective Lagrangian [9], they will not be considered here. Anomalous Higgs boson couplings have also been studied before in Higgs and Z boson decays [10], in e^+e^- [11,12] and $\gamma\gamma$ colliders [13].

The process with largest cross section in e^+e^- colliders that also involves quartic couplings, and possibly anomalous Higgs couplings, besides the trilinear couplings, is $e^+e^- \rightarrow W^+W^-\gamma$. Therefore, it is the most promising channel to look for possible deviations from the standard model predictions. This process has been considered by Bélanger and Boudjema [8] and by Leil and Stirling [14] in the context of genuinely quartic operators, where the Higgs and trilinear couplings were set to the standard model values and 3σ deviations in the total cross section were used to determine the reach of this reaction. Grosse-Knetter and Schildknecht [15] have considered the effect of a *single* higher dimensional operator usually denoted by $\mathcal{O}_W$ (see below) in the above process, taking into account modifications on both trilinear and quartic couplings. However, they assumed that the Higgs boson mass lies above the energy region to be investigated and therefore they disregarded its contribution.

The purpose of this work is to study the sensitivity to these anomalous couplings of the process $e^+e^- \rightarrow W^+W^-\gamma$ at LEP 2 and the NLC. We consistently include in our calculations *all* new couplings introduced by the effective Lagrangian that has become widely adopted to describe new physics beyond the standard model. In particular, this process is sensitive to operators related to anomalous Higgs boson couplings that do *not* affect the self-coupling of gauge bosons and hence are not constrained by the LEP 2 measurements of $e^+e^- \rightarrow W^+W^-$. Therefore, the process $e^+e^- \rightarrow W^+W^-\gamma$ may provide important information about these operators at the NLC.

This paper is organized as follows. In Sec. II, we review

the framework of effective Lagrangians that we use to parametrize anomalous couplings and explain the methodology used to study the $W^+W^-\gamma$ production. In Sec. III, we analyze the sensitivity at LEP 2 based on the total cross section. In Sec. IV, we study the improvements arising from going to NLC energies, the effects of having a polarized electron beam, and the impact of being able to measure the W boson polarization. We then concentrate on the analysis of operators which will not be probed by the $e^+e^- \rightarrow W^+W^-\gamma$ process, obtaining limits based on the photon energy spectrum. We present our conclusions in Sec. V.

II. EFFECTIVE LAGRANGIAN AND THE PROCESS

$$e^+e^- \rightarrow W^+W^-\gamma$$

In order to write down the most general dimension-6 effective Lagrangian containing all SM bosonic fields, i.e., γ , $W^\pm$, Z^0 , and H , we adopt the notation of Hagiwara *et al.* [5]. This Lagrangian has eleven independent operators in the linear representation that are locally $SU_L(2) \times U_Y(1)$ invariant, C and P even. We discard the four operators which affect the gauge boson two-point functions at the tree level and therefore are strongly constrained by LEP 1 measurements. We also do not consider the two operators that modify only the Higgs boson self-interactions, since they are not relevant for our calculations. We are then left with five independent operators, and the Lagrangian is written as

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} (f_{WWW} \mathcal{O}_{WWW} + f_{WW} \mathcal{O}_{WW} + f_{BB} \mathcal{O}_{BB} + f_W \mathcal{O}_W + f_B \mathcal{O}_B), \quad (1)$$

with each operator $\mathcal{O}_i$ defined as

$$\mathcal{O}_{WWW} = \text{Tr}[\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^\mu], \quad (2)$$

$$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi, \quad (3)$$

$$\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi, \quad (4)$$

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi), \quad (5)$$

$$\mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi), \quad (6)$$

where Φ is the Higgs field doublet, which in the unitary gauge assumes the form

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

and

$$\hat{B}_{\mu\nu} = i \frac{g'}{2} B_{\mu\nu}, \quad \hat{W}_{\mu\nu} = i \frac{g}{2} \sigma^a W_{\mu\nu}^a, \quad (7)$$

with $B_{\mu\nu}$ and $W_{\mu\nu}^a$ being the field strength tensors of the $U(1)$ and $SU(2)$ gauge fields, respectively.

The operator $\mathcal{O}_{WWW}$ contributes only to anomalous gauge couplings, $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$ contribute only to anomalous Higgs couplings HZZ and $HZ\gamma$, whereas $\mathcal{O}_W$ and $\mathcal{O}_B$ give

FIG. 1. Feynman diagrams for the standard model process $e^+e^- \rightarrow W^+W^-\gamma$. Crossed diagrams are not shown.

rise to both types of new couplings. Therefore, the existence of anomalous trilinear gauge boson couplings could be related to the anomalous quartic gauge couplings and Higgs interaction, which are the subject of our investigation.

Studies of anomalous trilinear gauge boson couplings from W -pair production will significantly constrain combinations of the parameters f_{WWW} , f_W , and f_B . However they are “blind” with respect to f_{WW} and f_{BB} . We chose to study the reaction $e^+e^- \rightarrow W^+W^-\gamma$ since it is the process with the largest cross section involving triple, quartic gauge boson couplings and also anomalous Higgs-gauge boson couplings. Therefore, it is also sensitive to f_{WW} and f_{BB} , offering an excellent possibility for a detailed study of these couplings.

The standard model cross section for the process $e^+e^- \rightarrow W^+W^-\gamma$ was evaluated in Ref. [16]. When we neglect the electron mass, Higgs contributions for this reaction do not appear at tree level since the couplings $H\gamma\gamma$ and the $HZ\gamma$ are generated only at one loop [17,18]. Taking into account these contributions, there are 16 Feynman diagrams involved in the reaction $e^+e^- \rightarrow W^+W^-\gamma$, which are represented in Fig. 1 (the crossed diagrams are not shown) which yields

$$\sigma_{WW\gamma}^{\text{SM}} = 46(418) \text{ fb}, \quad \text{with } E_\gamma > 20(5) \text{ GeV} \\ \text{at } \sqrt{s} = 190 \text{ GeV}, \quad (8)$$

$$\sigma_{WW\gamma}^{\text{SM}} = 144 \text{ fb}, \quad \text{with } E_\gamma > 20 \text{ GeV at } \sqrt{s} = 500 \text{ eV},$$

where we have required that the angle between any two particles is larger than 15° . The cross section peaks at roughly $\sqrt{s} = 300 \text{ GeV}$ and is typically two orders of magnitude

FIG. 2. The vector bosons anomalous contributions to $e^+e^- \rightarrow W^+W^-\gamma$. Crossed diagrams are not shown.

smaller than the two-body process $e^+e^- \rightarrow W^+W^-$, used to constrain anomalous trilinear couplings.

In order to compute the contribution from all possible anomalous couplings, we have developed a MATHEMATICA code to automatically generate the Feynman rules for the Lagrangian (1) that were then incorporated in HELAS-type [19] subroutines. These new subroutines were used to extend a MADGRAPH [20] generated code to include all the anomalous contributions and to numerically evaluate the helicity amplitudes and the squared matrix element. In our calculations, we have taken into account the standard loop Higgs contributions besides all the relevant anomalous couplings, which give rise to the 42 contributions shown in Figs. 1, 2, and 3. We have checked that our code passed the nontrivial test of electromagnetic gauge invariance. We employed VEGAS [21] to perform the Monte Carlo phase space integration with the appropriate cuts to obtain the differential and total cross sections. Moreover, we have studied the angular variables in order to find optimal cuts to improve the anomalous contribution over the SM signal.

III. $WW\gamma$ PRODUCTION AT LEP 2

We studied the reaction $e^+e^- \rightarrow W^+W^-\gamma$ at LEP 2 assuming a center-of-mass energy of $\sqrt{s}=190$ GeV and an integrated luminosity of $\mathcal{L}=0.5 \text{ fb}^{-1}$. We applied a cut in the photon energy ($E_\gamma > 5$ GeV), and we required the angle between any two particles to be larger than $\theta_{ij} > 15^\circ$.

Our results for the sensitivity of LEP 2 to the operators appearing in the effective Lagrangian (1), from an analysis of the total cross section, are summarized in Fig. 4 for a fixed value of the Higgs boson mass $M_H=170$ GeV. We plot the

FIG. 3. The Higgs boson anomalous contributions to $e^+e^- \rightarrow W^+W^-\gamma$.

contributions of the five different operators separately, assuming that only one operator contributes each time. We also show the result for an extension of the so-called Hagiwara-Ishihara-Szalapski-Zeppenfeld (HISZ) scenario [5], where all the coefficients are considered equal, i.e., $f_{WWW}=f_{WW}=f_{BB}=f_W=f_B=f$, in order to reduce the number of free parameters to only one (f). The standard model cross section and its value with 1, 2, and 3 σ deviations are depicted as horizontal lines.

The most sensitive contribution comes from $\mathcal{O}_{WWW}$, $\mathcal{O}_W$, and $\mathcal{O}_B$. A 1σ deviation in the total cross section would be observed for the following ranges of the coefficients of these operators, for $\Lambda=1$ TeV,

FIG. 4. Total cross section (SM+anomalous) for the process $e^+e^- \rightarrow W^+W^-\gamma$, at LEP 2 as a function of different anomalous coefficients and also for the HISZ scenario (f_{all}). We assumed $m_H=170$ GeV and $\mathcal{L}=0.5 \text{ fb}^{-1}$. The results for the SM and for 1, 2, and 3 σ deviations are displayed (see text for energy and angular cuts).

FIG. 5. Normalized W^+e^+ angular distribution. The solid (dashed) line represents the SM (SM+anomalous) contribution for $f_{\text{all}}/\Lambda^2 = 150 \text{ TeV}^{-2}$ and $m_H = 170 \text{ GeV}$.

$$\begin{aligned} -75 < f_{WW} < 178, \quad -48 < f_W < 192, \\ -188 < f_B < 550, \quad -253 < f_{WW} < 110; \end{aligned} \quad (9)$$

whereas for the extended HISZ scenario, we have

$$-33 < f < 119. \quad (10)$$

Of course, the operators that also give rise to changes in the triple vector boson couplings can also be constrained at LEP 2 via the reaction $e^+e^- \rightarrow W^+W^-$. A recent analysis of W -boson pair production based on a log-likelihood fit to a fivefold differential cross section obtained the 1σ limits [22], $|f_{WWW}| < 10$, $|f_W| < 7.1$, and $|f_B| < 46$. However, one should keep in mind that this reaction is insensitive to f_{WW} and f_{BB} , and therefore the study of the process $e^+e^- \rightarrow W^+W^- \gamma$ can provide further information on these operators, as we show in this paper.

The contribution of the anomalous couplings involving only the Higgs boson, i.e., f_{WW} and f_{BB} (see Fig. 3), is dominated by on-mass-shell Higgs production with the subsequent $H \rightarrow W^+W^-$ decay:

$$\sigma(e^+e^- \rightarrow W^+W^- \gamma) \propto \sigma(e^+e^- \rightarrow H \gamma) \frac{\Gamma(H \rightarrow W^+W^-)}{\Gamma(H \rightarrow \text{all})}. \quad (11)$$

For large values of the operator coefficients, the total Higgs boson width is dominated by the anomalous decay $H \rightarrow \gamma\gamma$ [10], which is also proportional to f_{WW} and f_{BB} . On the other hand, the anomalous width $\Gamma(H \rightarrow W^+W^-)$ depends only on f_{WW} . Therefore, the contribution from the anomalous coupling f_{BB} is much less sensitive than the contributions from the other operators since $\sigma(e^+e^- \rightarrow W^+W^- \gamma)$ becomes almost independent of this coefficient. Fortunately, this is not the case if one is sensitive to small values of the coefficients, as will occur at the NLC study in the next section.

We have investigated various distributions to try to improve the LEP 2 sensitivity. The most promising distribution is the angular distribution of the W bosons with respect to the

FIG. 6. The same as Fig. 4 for NLC, with $\sqrt{s} = 500 \text{ GeV}$ and $\mathcal{L} = 50 \text{ fb}^{-1}$.

beam direction (see Fig. 5). We computed the total cross section with the extra cut $\cos\theta_{W^+e^+} > 0$, as suggested by this distribution, and found an increase in sensitivity from 2σ to 2.8σ . However, due to the small deviations in the shape of the kinematical distributions and small statistics, no further improvement seems to be possible.

IV. $WW\gamma$ PRODUCTION AT NLC

The effect of the anomalous operators becomes more evident with the increase of energy, and we are able to put tighter constraints on the coefficients by studying their contribution to different processes at the Next Linear Collider. We studied the sensitivity of NLC to the process $e^+e^- \rightarrow W^+W^- \gamma$ assuming $\sqrt{s} = 500 \text{ GeV}$ and an integrated luminosity $\mathcal{L} = 50 \text{ fb}^{-1}$. We adopted a cut in the photon energy of $E_\gamma > 20 \text{ GeV}$ and required the angle between any two particles to be larger than 15° . We have analyzed this process for different values of the Higgs boson mass.

In Fig. 6, we show the results for the total cross section, for $M_H = 170 \text{ GeV}$, including the effects of the anomalous operators. The values of the coefficients f 's for which a 2σ deviation is obtained are shown in Table I, being typically of

TABLE I. The minimum and maximum values (min,max) of the coefficients f_i/Λ^2 in units of TeV^{-2} for a 2σ deviation of the unpolarized total cross section.

Anomalous couplings	Unpolarized
f_{all}/Λ^2	(-2, 5)
f_B/Λ^2	(-5, 31)
f_{BB}/Λ^2	(-11, 7)
f_W/Λ^2	(-3, 23)
f_{WW}/Λ^2	(-8, 4)
f_{WWW}/Λ^2	(-5, 5)

FIG. 7. The same as Fig. 6 for a 90% right-handed polarized electron, with $\sqrt{s}=500$ GeV and $\mathcal{L}=50$ fb $^{-1}$.

the order of $1-10$ TeV $^{-2}$. As we could expect, the W pair production at NLC is able to put a limit that is one order of magnitude better for the coefficients $f_{B,W,WWW}$ [22]. However, this latter reaction is *not* able to constrain $f_{BB,WW}$.

In an attempt to increase the sensitivity, we looked at the effects of a 90% polarized electron beam in order to reduce the SM background, mainly the one coming from diagrams of Figs. 1(a) and 1(b) were just left-handed electrons are present. We have considered both left-handed (LH) and right-handed (RH) polarizations, expecting a larger anomalous sensitivity for RH electrons.

In Fig. 7, we show the results for the total cross section, for a 90% right-handed (RH) polarized electron, for $M_H=170$ GeV. Comparing Fig. 6 and Fig. 7, we notice that the effect of the anomalous contributions in the total cross section are larger for the polarized case. However, the small absolute value of the cross section for the polarized case reduces the statistics and leads to no improvement in the established limits, as shown in Table II.

Since we expect the new interactions to involve mainly longitudinally polarized gauge bosons, we studied the sensitivity for different combinations of the polarizations of the W

TABLE II. The minimum and maximum values (min,max) of the coefficients f_i/Λ^2 in units of TeV $^{-2}$ for a 2σ deviation of the total cross section with 90% polarized LH and RH electrons for a reduced luminosity of $\mathcal{L}=25$ fb $^{-1}$.

Anomalous couplings	e_{LH}^-	e_{RH}^-
f_{all}/Λ^2	(-2, 5)	(-3, 5)
f_B/Λ^2	(-11, 42)	(-2, 26)
f_{BB}/Λ^2	(-19, 17)	(-8, 3)
f_W/Λ^2	(-2, 26)	(-17, 9)
f_{WW}/Λ^2	(-7, 5)	(-15, 11)
f_{WWW}/Λ^2	(-5, 5)	(-12, 11)

FIG. 8. The same as Fig. 6 for longitudinal W bosons ($W_L W_L$), with $\sqrt{s}=500$ GeV and $\mathcal{L}=50$ fb $^{-1}$.

pair. In Fig. 8, we show the analogous of Fig. 6 for the $W_L W_L$ case. Again, the effect of the anomalous contributions to the total cross section is increased, but no further improvements are found due to the small statistics. The results for the bounds on the anomalous coefficients for the $W_L W_L$, $W_T W_T$, and $(W_L W_T + W_T W_L)$ cases can be seen in Table III. These bounds were obtained requiring a 2σ effect on the total cross section.

It is important to notice that the kinematical distributions of the longitudinally polarized W 's are quite different from the SM results. As we could expect, the new physics effects becomes more evident for longitudinal W 's since the decay $H \rightarrow W^+ W^-$ is dominated by this state of polarization. In Fig. 9, we present the angular distribution of the longitudinal W^+ boson with the initial positron and with the final photon, the energy and the transverse momentum distributions. We can see, for instance, that the W energy distribution is very different from the SM prediction. Its characteristic behavior for $100 < E_W < 175$ GeV is due to the presence of the Higgs boson, which decays into the W pair giving rise, at the same time, to a monochromatic photon.

We present in Fig. 10 the percent deviation of the SM

TABLE III. The minimum and maximum values (min,max) of the coefficients f_i/Λ^2 in units of TeV $^{-2}$ for a 2σ deviation of the total cross section for different combinations of the final state W -pair polarization.

Anomalous Couplings	$W_L W_L$	$W_T W_T$	$(W_L W_T + W_T W_L)$
f_{all}/Λ^2	(-1, 14)	(-5, 3)	(-2, 7)
f_B/Λ^2	(-2, 35)	(-29, 29)	(-9, 36)
f_{BB}/Λ^2	(-12, 9)	(-14, 10)	(-13, 8)
f_W/Λ^2	(-1, 25)	(-36, 22)	(-4, 23)
f_{WW}/Λ^2	(-8, 6)	(-9, 6)	(-8, 5)
f_{WWW}/Λ^2	(-51, 96)	(-6, 4)	(-5, 25)

FIG. 9. Kinematical distributions of the longitudinally polarized W^+ vector boson for the SM (solid histogram) and for the anomalous contribution (dotted histogram).

prediction in the photon transverse momentum distribution: i.e.,

$$\Delta = \left(\frac{d\sigma_{\text{ANO}}/dp_{T\gamma}}{d\sigma_{\text{SM}}/dp_{T\gamma}} - 1 \right) \times 100\%,$$

for the different polarization of the W 's. Once again the relevance of the $W_L W_L$ case is evident: $\Delta > 100\%$ for $p_{T\gamma} > 120$ GeV. When a cut of $p_{T\gamma} > 100$ GeV is implemented, the background is drastically reduced and the ratio of anomalous over SM events per year goes from 576/442 to 424/74, for $f_{\text{all}} = 15 \text{ TeV}^{-2}$.

Using the reaction $e^+e^- \rightarrow W^+W^-\gamma$, we are also able to establish bounds on the values of the coefficients f_{WW} and f_{BB} , for which the W -pair process is insensitive, since they

FIG. 10. Plot of deviation (Δ) in the photon $P_{T\gamma}$ distribution for the cases of $W_L W_L$ (solid line), $W_L W_T + W_T W_L$ (dashed line), and $W_T W_T$ (dotted line).

only affect the Higgs boson couplings. In Fig. 11, we present the results of a combined sensitivity analysis in the form of a contour plot for the two free parameter, f_{BB} and f_{WW} , for $M_H = 170$ GeV. These are the most relevant coefficients for the anomalous Higgs boson phenomenology and they are not constrained by the W -pair production. We should keep in mind that the $WW\gamma$ production at LEP 2 can put a 1σ bound on f_{WW} (9) while it is not possible to impose a limit on f_{BB} since the cross section is quite insensitive to this coefficient.

If the Higgs boson is found with a mass in the range from 170 to 300 GeV, one would have a large sensitivity for the

FIG. 11. Contour plot of $f_{BB} \times f_{WW}$, for $M_H = 170$ GeV. The curves show the one, two, and three σ deviations from the standard model value of the total cross section.

FIG. 12. Photon energy distribution for the SM (solid line) and for the SM+anomalous (dashed line), for $f_{WW}/\Lambda^2 = f_{BB}/\Lambda^2 = 5 \text{ TeV}^{-2}$, and $M_H = 170 \text{ GeV}$, with a 5 GeV bin.

anomalous Higgs couplings f_{WW} and f_{BB} in the photon energy distribution of the process $e^+e^- \rightarrow W^+W^-\gamma$. This increased sensitivity comes about because the existence of a peak in the photon energy spectrum due to the two-body nature of the dominant contribution, i.e., $e^+e^- \rightarrow H\gamma$ followed by the subsequent decay $H \rightarrow W^+W^-$ (see Fig. 3). In Fig. 12, we illustrate this effect with a typical photon energy distribution, for $f_{WW}/\Lambda^2 = f_{BB}/\Lambda^2 = 5 \text{ TeV}^{-2}$ and $M_H = 170 \text{ GeV}$, where the Higgs peak appears very clearly in the photon spectrum of the anomalous contribution.

In order to analyze the significance of the signal based on the photon energy spectrum, we took different energy bins of 1, 3, and 5 GeV. The reason is to roughly mimic the effects of a realistic simulation including the finite energy resolution of the detector and the small spread in the real center-of-mass energy due to initial state radiation. We have not considered the experimental efficiency ϵ_{eff} for W reconstruction. It can be easily incorporated by multiplying the obtained significances by $\sqrt{\epsilon_{\text{eff}}}$. Table IV shows the improvement on the sensitivity compared to the total cross section analysis for the $f_{WW}/\Lambda^2 = f_{BB}/\Lambda^2 = 5 \text{ TeV}^{-2}$ and $M_H = 170 \text{ GeV}$ cases.

In Table V, we present our results for the sensitivity on f_{BB}/Λ^2 and f_{WW}/Λ^2 , assuming $f_{BB} = f_{WW}$, for the three energy bins above. We obtained a sensitivity of the order of a TeV^{-2} for $M_H = 170 \text{ GeV}$, decreasing by a factor of roughly four for $M_H = 300 \text{ GeV}$, which does not depend in a significant way of the bin size. For larger Higgs boson masses, the cross section is reduced due to phase space suppression. For smaller Higgs boson masses, the cross section is reduced since the Higgs boson is off-mass shell, and in

TABLE IV. Number of standard deviations σ from the standard model from a sensitivity analysis based on the total cross section compared to a sensitivity analysis based on the peak of the photon energy distribution, considering a 1, 3, and 5 GeV bin for different values of the Higgs mass. We fixed $f_{WW}/\Lambda^2 = f_{BB}/\Lambda^2 = 5 \text{ TeV}^{-2}$.

M_H (GeV)	Total cross section	1 GeV bin	3 GeV bin	5 GeV bin
170	4.2	52.2	43.1	35.8
200	2.8	17.8	20.9	17.8
250	1.8	8.3	10.7	9.9
300	1.0	2.5	3.8	4.3

this case it would be better to study processes such as $e^+e^- \rightarrow b\bar{b}\gamma$ or $e^+e^- \rightarrow \gamma\gamma\gamma$ [12].

V. CONCLUSION

The search for the effect of higher dimensional operators that give rise to anomalous bosonic couplings should be pursued in all possible processes since the results may provide important information on physics beyond the standard model. We have studied here the production of a W pair plus a photon in e^+e^- colliders in order to analyze the contributions of anomalous couplings arising from dimension-6 operators of a linearly realized $\text{SU}_L(2) \times \text{U}_Y(1)$ invariant effective Lagrangian. We have included *all* the anomalous trilinear and quartic gauge couplings, as well as the anomalous Higgs couplings with gauge bosons.

We present the limits attainable at LEP 2 and at NLC, including the standard model irreducible background. Polarization of the electron beam and of the W pair are found to be insufficient to improve the limits obtained from the total cross section.

We also focused on the operators $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$, which cannot be tested in the W -pair production process. We showed, in particular, that for Higgs boson masses in the range $M_H = 170\text{--}300 \text{ GeV}$, the photon energy spectrum provides a sensitive signature for the anomalous Higgs couplings. Typical sensitivities of a few TeV^{-2} at the NLC are obtained for these coefficients, providing complementary information on different higher dimensional operators.

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TABLE V. The minimum and maximum values (min, max) of the coefficients f_i/Λ^2 (for $f_{BB} = f_{WW} = f$) in units of TeV^{-2} that generate a 95% C.L. signal for the total cross section analysis and for the photon energy spectrum analysis with 1, 3, and 5 GeV energy bins for different values of the Higgs mass.

M_H (GeV)	Total cross section	1 GeV bin	3 GeV bin	5 GeV bin
170	(−5.9, 2.8)	(−3.9, 0.3)	(−3.9, 0.4)	(−3.9, 0.5)
200	(−6.4, 3.6)	(−4.4, 0.9)	(−4.1, 0.8)	(−4.2, 0.9)
250	(−7.0, 4.9)	(−4.2, 1.8)	(−3.9, 1.6)	(−4.0, 1.6)
300	(−8.3, 6.9)	(−6.2, 4.3)	(−5.1, 3.2)	(−4.9, 3.0)

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