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Anomalous Higgs Couplings in Triple Gauge Boson Production at the NLC *

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Abstract

We present the sensitivity limits on the coefficients of a dimension–6 effective operators that parametrizes the possible effects of new physics beyond the Standard Model. Our results are based on the study of the processes $e^+e^- \to W^+W^-\gamma$, $ZZ\gamma$, and $Z\gamma\gamma$ at NLC energies. In our calculations, we include *all* the anomalous interactions involving vector and Higgs bosons, and take into account the Standard Model irreducible background. We analyse the impact of these new interactions on the total cross section and on some kinematical distributions of the final state particles.

I. INTRODUCTION

One of the main physics goals of LEP2 and future e^+e^- colliders is to directly test the gauge nature of couplings among the electroweak gauge bosons. Deviations from the

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Standard Model (SM) predictions for these couplings would indicate the existence of new physics effects. The most general phenomenological parametrization for these deviations can be achieved by means of an effective Lagrangian [1] that involves, apart from the SM Lagrangian, high–dimension operators that describe the new phenomena, 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 [2]. 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. 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.* [3]. 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 tree–level and therefore are strongly constrained by LEP1 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,

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

with each operator $\mathcal{O}_i$ defined as in ref. [3]. It is important to notice that this effective Lagrangian, often used to describe anomalous trilinear gauge couplings, can lead to anomalous quartic interaction among gauge bosons and also to anomalous couplings of these particles with the Higgs field. The operator $\mathcal{O}_{WWW}$ contributes only to anomalous gauge boson self couplings (VVV, $VVVV$), $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$ contribute only to anomalous Higgs couplings (HVV), whereas $\mathcal{O}_W$ and $\mathcal{O}_B$ give rise to both kinds of new couplings. All these interactions should be investigated at the NLC in order to search for hints about the nature of the new physics described by these higher dimensional operators.

In this contribution we present the results of our analyses constraining the coefficients

of the dimension–6 effective Lagrangian (1) via the processes $e^+e^- \to W^+W^-\gamma$ [4], $ZZ\gamma$, and $Z\gamma\gamma$ [5] at the Next Linear Collider (NLC). Some related works include the references [6, 7, 8, 9, 10, 11].

We chose to study the reaction $e^+e^- \to W^+W^-\gamma$ 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. It is important to notice that 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}.

Another way to test the anomalous Higgs couplings generated by the operators $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$ is through the analysis of the processes $e^+e^- \to ZZ\gamma$ and $Z\gamma\gamma$, that are only sensitive to $HZ\gamma$ and $H\gamma\gamma$ anomalous Higgs interactions which, in the SM, appear only at one–loop level [12, 13].

II. ANOMALOUS $WW\gamma$ PRODUCTION AT NLC

The Standard Model cross section for the process $e^+e^- \to W^+W^-\gamma$ was evaluated in Ref. [14]. Including the new contributions from (1), there are 16 standard and 26 anomalous Feynman diagrams involved in the reaction $e^+e^- \to W^+W^-\gamma$ [15]. In order to compute these contributions, we have incorporated all new couplings in a `Helas`–type [16] Fortran subroutines. These new subroutines were used to extend a `Madgraph` [17] generated code to include all the anomalous contributions and to numerically evaluate the helicity amplitudes and the squared matrix element. We have checked that our code passed the non–trivial test of electromagnetic gauge invariance. We employed `Vegas` [18] to perform the Monte Carlo phase space integration with the appropriate cuts to obtain the differential and total cross sections.

Our results were obtained assuming $\sqrt{s} = 500$ GeV and an integrated luminosity $\mathcal{L} =$

50 fb^{-1}. We adopted a cut in the photon energy of $E_\gamma > 20$ GeV and required the angle between any two particles to be larger than 15°. In these conditions, $\sigma^{SM}_{WW\gamma} \simeq 144$ fb and we can expect around 7200 events per year.

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 $f_{B,W,WWW}$ [19]. However this reaction is *not* able to constraint $f_{BB,WW}$. This can be accomplished using the reaction $e^+e^- \to W^+W^-\gamma$, which gives rise to bounds on the values of these coefficients.

M_H(GeV)	f_{BB}/Λ^2	f_{WW}/Λ^2
170	(−11.8 , 6.6)	(−6.4 , 4.7)
200	(−12.7 , 8.6)	(−7.4 , 5.8)
250	(−14.1 , 11.3)	(−8.5 , 7.7)
300	(−17.4 , 15.1)	(−10.2 , 9.6)
350	(−24.0 , 21.5)	(−15.5 , 13.7)

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 $e^+e^- \to W^+W^-\gamma$ at NLC.

The contribution of the anomalous couplings $f_{BB,WW}$ is dominated by on–mass–shell Higgs production with the subsequent $H \to W^+W^-$ decay. Therefore the best constraints are obtained at NLC for Higgs boson masses in the range $2M_W \leq M_H \leq (\sqrt{s} - E_\gamma^{\min})$ GeV, *i.e.* when on–shell production is allowed. We present in Table I the limits on the coefficients f_{BB} and f_{WW} based on a 2σ deviation in the total cross section for a Higgs mass in the range $170 \leq M_H \leq 350$ GeV. In Fig. 1 (a), 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.

In an attempt to increase the sensitivity of this reaction, we have considered the effect of electron beam polarization in reducing the SM background. Even assuming a 90% degree of polarization for right–handed (RH) electrons, no significant improvement was obtained.

Fig. 1

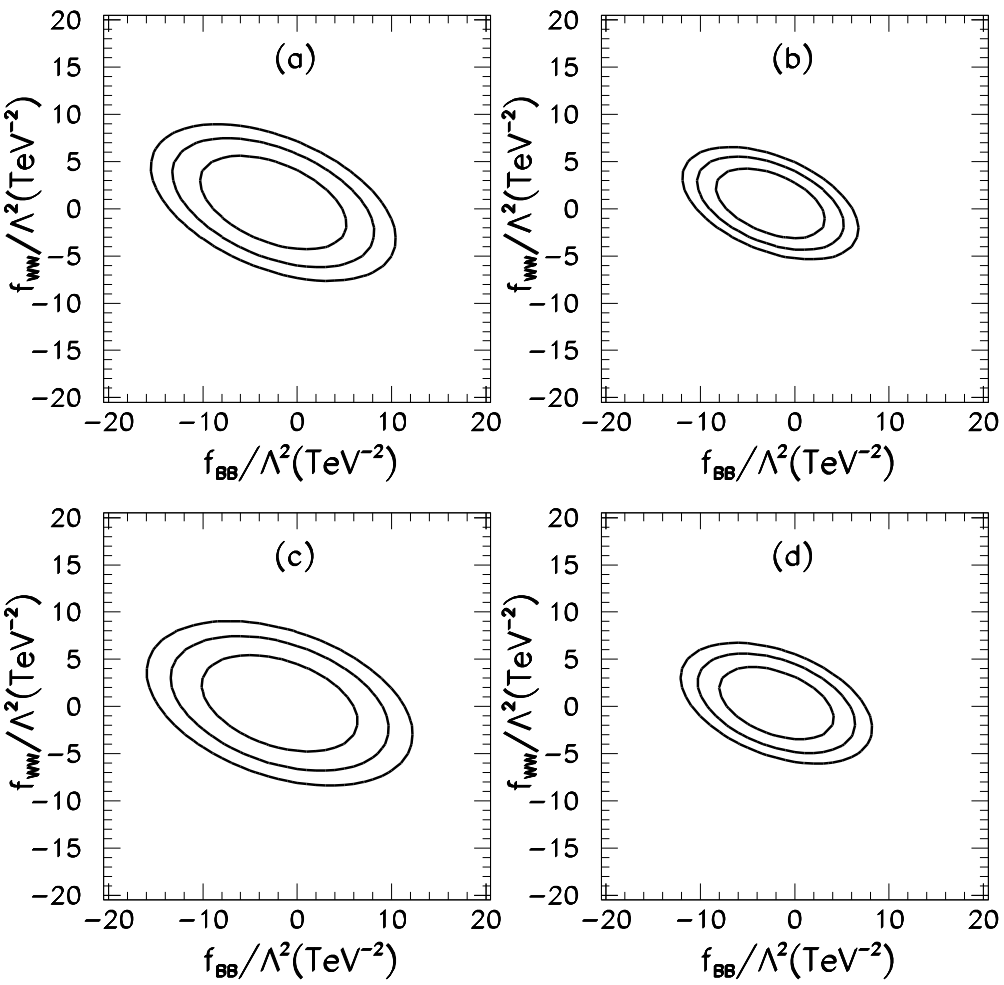

FIGURE 1. Contour plot of $f_{BB} \times f_{WW}$. The curves show the 1, 2, and 3 σ deviations from the SM total cross section, for $e^+e^- \to W^+W^-\gamma$ ($M_H = 170$ GeV), with (a) no cut on p_{T_γ}, and (b) cut of $p_{T_\gamma} > 100$ GeV, and for $e^+e^- \to ZZ\gamma$ ($M_H = 200$ GeV), with (c) no cut on p_{T_γ}, and (d) cut of $p_{T_\gamma} > 100$ GeV.

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's. An analysis of the photon transverse momentum distribution for the different polarizations of the W's shows the relevance of the W_LW_L production for the anomalous contributions [4]. However, the improvement is very small because the requirement of longitudinally polarized W bosons reduces drastically 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. In the photon transverse momentum we observe that the contribution of the anomalous couplings is larger in the high p_{T_γ} region. Therefore, a cut of $p_{T_\gamma} > 100$ GeV drastically reduces the background. The improvement on $f_{WW,BB}$ bounds can be clearly seen from Fig. 1(b) where a 1, 2, and 3σ deviations in the total cross section, for $M_H = 170$ GeV, is shown after the above cut is applied.

III. ANOMALOUS $ZZ\gamma$ AND $Z\gamma\gamma$ PRODUCTION AT NLC

Through the processes $e^+e^- \to ZZ\gamma$ and $e^+e^- \to Z\gamma\gamma$ we are also able to establish constraints on the coefficients $f_{WW,BB}$ at NLC. Now there are 7 (10) standard and 8 (12) anomalous Feynman diagrams involved in the $Z\gamma\gamma$ ($ZZ\gamma$) production. These reactions were computed in the same way as before, and assuming the same cuts *i.e.* $E_\gamma > 20$ GeV and the angle between any two particles larger than 15°.

The reaction $e^+e^- \to Z\gamma\gamma$ yields 2900 events per year, assuming the expected luminosity for NLC ($\mathcal{L} = 50$ 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 $-39 < f_{BB}/\Lambda^2 < 35$ TeV^{-2} and $-9.6 < f_{WW}/\Lambda^2 < 14$ TeV^{-2}.

The best constraint on the anomalous couplings come from the reaction $e^+e^- \to ZZ\gamma$, which gives rise to ~ 675 events per year at $\sqrt{s} = 500$ GeV. The contribution of the anomalous couplings is also dominated by on–mass–shell Higgs production with the subsequent $H \to ZZ$ decay. Therefore the best results are obtained at NLC for Higgs boson masses in the range $2M_Z \leq M_H \leq (\sqrt{s} - E_\gamma^{\min})$ GeV, where on–shell production is allowed. We present in Table II the limits on the coefficients f_{BB} and f_{WW} based on a 2σ deviation in the total cross section for a Higgs mass in the range $200 \leq M_H \leq 350$ GeV.

M_H(GeV)	f_{BB}/Λ^2	f_{WW}/Λ^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 II. 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 $e^+e^- \to ZZ\gamma$ at NLC.

We tried to take advantage of the fact that the new interactions affect mostly the longitudinally polarized gauge bosons by studying the polarized Z production. Unfortunately the improvement obtained is very small since this requirement 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 again the photon transverse momentum. Similarly to the $WW\gamma$ production, the contribution of the anomalous couplings is larger in the high p_{T_γ} region, and a cut of $p_{T_\gamma} > 100$ GeV is able to reduce in a significant way the background. The improvement on $f_{WW,BB}$ bounds can be clearly seen from Fig. 1 (c) and 1 (d) where the deviations in the total cross section, for $M_H = 200$ GeV, are shown before and after the above cut is applied.

The limits for f_{BB} and f_{WW} obtained from the study of the reactions $e^+e^- \to W^+W^-\gamma$ and $e^+e^- \to ZZ\gamma$, presented in Tables I and II, are comparable and both processes can be used as complementary tool in the study of anomalous Higgs interactions.

IV. CONCLUSION

The search for the effect of higher dimensional operators that give rise to anomalous bosonic couplings may provide important information on physics beyond the Standard Model. We have analysed the contributions of anomalous couplings arising from dimension–6

operators of a linearly realized $SU_L(2)\times U_Y(1)$ invariant effective Lagrangian in the processes $e^+e^- \to W^+W^-\gamma$, $e^+e^- \to ZZ\gamma$, and $e^+e^- \to Z\gamma\gamma$. We have included in our calculations, *all* the anomalous trilinear and quartic gauge couplings, the anomalous Higgs couplings with gauge bosons and we have taken into account the Standard Model irreducible background. The impact of the anomalous contributions in the total cross section of these processes were analysed at the NLC. Polarization of the final state bosons are found to be insufficient to improve the limits obtained from the total cross section of the three processes.

We mainly focused on the operators $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$, which cannot be tested in the $W-$pair production process. We showed that a photon transverse momentum cut, $p_{T_\gamma} > 100$ GeV, can improve the limits on f_{WW} and f_{BB} obtained through an analysis of the total cross section. Typical sensitivities of a few TeV^{-2} are obtained at the NLC for these coefficients.

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REFERENCES

[1] S. Weinberg, *Physica* **96A**, 327 (1979); see also H. Georgi, *Weak Interactions and Modern Particle Theory* (Benjamim/Cummings, Menlo Park, 1984) and J. F. Donoghue, E. Golowich and B. R. Holstein, *Dynamics of the Standard Model* (Cambridge University Press, 1992).

[2] K. Gaemers and G. Gounaris, Z. Phys. **1**, 259 (1979); K. Hagiwara, K. Hikasa, R. D. Peccei and D. Zeppenfeld, Nucl. Phys. **B282**, 253 (1987).

[3] K. Hagiwara, S. Ishihara, R. Szalapski and D. Zeppenfeld, Phys. Lett. **B283**, 353 (1992); *idem*, Phys. Rev. **D48**, 2182 (1993).

[4] F. de Campos, S. M. Lietti, S. F. Novaes and R. Rosenfeld, Phys. Rev. **D56**, 4384 (1997).

[5] S. M. Lietti and S. F. Novaes, preprint IFT-P.048/97, hep-ph/9708433, submitted for publication.

[6] S. Godfrey, contributed paper to the *International Symposium on Vector Boson Self-Interactions*, Los Angeles, CA, 1–3 February 1995, preprint OCIP/C-95-5, hep-ph/9505252 and references therein.

[7] G. Bélanger and F. Boudjema, Phys. Lett. **B288**, 201 (1992), Phys. Lett. **B288**, 210 (1992) ; O. J. P. Éboli, M. C. Gonzalez–Garcia and S. F. Novaes, Nucl. Phys. **B411**, 381 (1994); O. J. P. Éboli, M. B. Magro, P. G. Mercadante, and S. F. Novaes Phys. Rev. **D52**, 15 (1995).

[8] K. Hagiwara, R. Szalapski and D. Zeppenfeld, Phys. Lett. **B318**, 155 (1993).

[9] K. Hagiwara and M. L. Stong, Z. Phys. **62**, 99 (1994); B. Grzadowski and J. Wudka, Phys. Lett. **B364**, 49 (1995); G. J. Gounaris, F. M. Renard and N. D. Vlachos, Nucl. Phys. **B459**, 51 (1996); W. Killian, M. Krämer and P. M. Zerwas, Phys. Lett. **B381**, 243 (1996).

[10] S. M. Lietti, S. F. Novaes and R. Rosenfeld, Phys. Rev. **D54**, 3266 (1996); F. de Campos,

S. M. Lietti, S. F. Novaes and R. Rosenfeld, Phys. Lett. **B389**, 93 (1996).

[11] G. J. Gounaris, J. Layssac and F. M. Renard, Z. Phys. **69**, 505 (1996); G. J. Gounaris and F. M. Renard, Z. Phys. **69**, 513 (1996).

[12] J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. **B106**, 292 (1976); A. I. Vainshtein, M. B. Voloshin, V. I. Zakharov, and M. S. Shifman, Sov. J. Nucl. Phys. **30**, 711 (1979).

[13] L. Bergstrom ang G. Hulth, Nucl. Phys. **B259**, 137 (1985); A. Barroso, J. Pulido, J. C. Romão, Nucl. Phys. **B267**, 509 (1986)

[14] V. Barger, T. Han and R. J. N. Phillips, Phys. Rev. **D39**, 146 (1989).

[15] In our analysis, we have also taken into account the SM one–loop Higgs contributions to the couplings $H\gamma\gamma$ and $HZ\gamma$.

[16] H. Murayama, I. Watanabe and K. Hagiwara, KEK report 91–11 (unpublished).

[17] T. Stelzer and W. F. Long, Comput. Phys. Commun. **81**, 357 (1994).

[18] G. P. Lepage, J. Comp. Phys. **27**, 192 (1978).

[19] K. Hagiwara, T. Hatsukano, S. Ishihara and R. Szalapski, Nucl. Phys. **B496**, 66 (1997).