PHYSICAL REVIEW D **80,** 017301 (2009)

Probing the $ZZ\gamma$ and $Z\gamma\gamma$ couplings through the process $e^+e^- \to \nu\bar{\nu}\gamma$

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(Received 8 August 2008; revised manuscript received 6 April 2009; published 23 July 2009)

We study the sensitivity for testing the anomalous triple gauge couplings $ZZ\gamma$ and $Z\gamma\gamma$ via the process $e^+e^- \to \nu\bar{\nu}\gamma$ at high energy linear colliders. For integrated luminosities of 500 fb^{-1} and center of mass energies between 0.5 and 1.5 TeV, we find that this process can provide tests of the triple neutral gauge boson couplings of order 10^{-4}, 1 order of magnitude lower than the standard model prediction.

DOI: 10.1103/PhysRevD.80.017301 PACS numbers: 14.60.Lm, 12.15.Mm, 12.60.−i

I. INTRODUCTION

Triple gauge boson couplings constitute a sensitive probe of nonstandard interactions [1,2]. In particular, triple neutral gauge boson couplings (TNGBC) ZVV, with $V = Z, \gamma$, vanish when the three gauge bosons are on mass shell and Bose symmetry and Lorentz invariance are simultaneously satisfied [3,4]. Even though these vertices do not reflect directly the non-Abelian nature of the electroweak gauge group, since the Yang-Mills sector does not induce them at the tree or one-loop level, they constitute a window to new physics [1,2]. These vertices must be induced by loop effects in any renormalizable theory since they do not possess a renormalizable structure. At the one-loop level, they can be generated only by fermionic triangles [5,6]. In the standard model (SM), the minimal supersymmetric standard model, and the littlest Higgs models they are of order 10^{-3} [6–8], but new heavy quark generations may enhance them by about 1 order of magnitude [6].

Experimental measurements of possible TNGBC $ZZ\gamma$ and $Z\gamma\gamma$ have reached an accuracy at the few percent level at the Tevatron [9], even better than the accuracy obtained for nonstandard deviations of the $WWZ(\gamma)$ couplings [10]. Persuasive arguments within the effective Lagrangian approach indicate that TNGBC are not expected to be larger than 1% [1,2]. Indirect limits on these vertices have been obtained from the muon $g-2$ value, the known bound on the electron electric dipole moment [6], and the measurement of the rare decay mode $Z \to \nu\bar{\nu}\gamma$ obtained at LEP [11,12]. The process $e^+e^- \to Z\gamma$ has been studied also at the energies expected in future linear colliders in order to search for its sensitivity to the TNGBC through the effects of Z polarization and initial state radiation [13], as well as possible CP-violating effects in the decay mode $Z \to \mu^+\mu^-\gamma$ [14].

The process $e^+e^- \to \nu\bar{\nu}\gamma$ was first studied as a probe of anomalous weak neutral couplings [15]. It has been also studied in connection with the determination of the number of light neutrino species [16], its possible electric and magnetic moments [17], as well as in the search of extra neutral gauge bosons [18], supersymmetric neutralinos [19], and weakly interacting massive particles as possible dark matter candidates [20]. In the present paper we study the sensitivity to the TNGBC in the process $e^+e^- \to \nu\bar{\nu}\gamma$ at the next generation of linear colliders, namely, the international linear collider (ILC) [21] and the compact linear collider (CLIC) [22]. We expect to get better limits on the anomalous ZVV couplings through the $Z \to \nu\bar{\nu}$ channel because its larger branching ratio induces a cross section for $e^+e^- \to \nu\bar{\nu}\gamma$ about a factor 3 larger than the combined rates for $e^+e^- \to Z(\to e^+e^-, \mu^+\mu^-)\gamma$ [23]. The process $e^+e^- \to Z(\to \nu\bar{\nu})\gamma$ is also competitive with respect to $Z\gamma$ production at the LHC because the inclusive next to leading order QCD corrections to the $Z\gamma$ cross section are quite large at high photon transverse momenta in the SM and reduce the sensitivity to the TNGBC ZVV [24]. We will obtain in the present paper that the next generation of e^+e^- colliders may reach in fact sensitivities that are close to the SM predictions for the TNGBC if we impose a photon-energy cut $E_\gamma > 50$ GeV. Searches for such single-photon events in LEP could single out contributions to $e^+e^- \to \nu\bar{\nu}\gamma$ arising from the ZVV vertices [11]. In this respect, our study can be considered complementary to previous studies on the TNGBC [13,14].

This paper is organized as follows: In Sec. II we present the calculation of the cross section for the process with anomalous couplings $ZZ\gamma$ and $Z\gamma\gamma$ and, finally, we summarize our results and conclusions in Sec. III.

II. CROSS SECTIONS

The most general anomalous $Z(q_1)\gamma(q_2)Z(P)$ vertex function is given by [4]

$$\Gamma^{\alpha\beta\mu}_{Z\gamma Z}(q_1, q_2, P) = \frac{P^2 - q_1^2}{M_Z^2}\Big[h_1^Z(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \frac{h_2^Z}{M_Z^2}P^\alpha(P\cdot q_2 g^{\mu\beta} - q_2^\mu P^\beta) + h_3^Z\varepsilon^{\mu\alpha\beta\rho}q_{2\rho} + \frac{h_4^Z}{M_Z^2}P^\alpha\varepsilon^{\mu\beta\rho\sigma}P_\rho q_{2\sigma}\Big], \qquad (1)$$

where M_Z is the Z boson mass and the respective $Z\gamma\gamma$

general vertex function can be obtained from Eq. (1) by the following replacements:

$$\frac{P^2 - q_1^2}{M_Z^2} \rightarrow \frac{P^2}{M_Z^2}, \qquad h_i^Z \rightarrow h_i^\gamma, \qquad i = 1, 2, 3, 4. \quad (2)$$

The form factors h_i^V are dimensionless functions of the p_i^2 momenta and in order to avoid violation of partial wave unitarity, generalized dipole form factors will be considered [1]

$$h_i^V(s) = \frac{h_{i0}^V}{(1 + s/\Lambda^2)^3}; \qquad i = 1, 3, \quad (3)$$

$$h_i^V(s) = \frac{h_{i0}^V}{(1 + s/\Lambda^2)^4}; \qquad i = 2, 4. \quad (4)$$

It has been found that these dipole form factors satisfy the constraints imposed by partial-wave unitarity in the inelastic-vector-boson pair production amplitude involved in fermion-antifermion annihilation at an arbitrary center of mass energy [24]. These dipole form factors have been used mainly in hadronic processes [9,10,24] but recently they have been used also in electron-positron and electron-photon collisions [13]. We will assume that the new physics scale Λ is above the collision energy $\sqrt{s}$ and will also test this unitarization scheme by setting $\Lambda \rightarrow \infty$ in order to get the bare $ZZ\gamma$ and $Z\gamma\gamma$ couplings. Our study suggests that for high enough center of mass (c.m.) energies, of order 1.5 TeV, the limits obtained for these couplings do not depend on the unitarization prescription given in Eqs. (3) and (4). We will consider only the effect due to the anomalous $ZV^*\gamma$ vertices for various ILC/CLIC energies and luminosities. The SM contribution to this process would arise from initial state radiation coming from the e^+e^- beams and photons emitted from a virtual W boson exchanged in the t channel. In order to suppress the SM contribution we impose the cuts $E_\gamma > 50$ GeV and $45° < \theta_\gamma < 135°$, where θ_γ is the polar angle of the photon with respect to the beam direction [11,14].

The expression for the respective cross section with anomalous couplings $ZZ\gamma$ is given by

$$\sigma(e^+e^- \rightarrow \nu\bar{\nu}\gamma) = \int \frac{\alpha^2 e^2}{256\pi M_Z^4} C[x_W][(h_1^Z)^2 F_1(s, E_\gamma, \cos\theta_\gamma) + (h_3^Z)^2 F_2(s, E_\gamma, \cos\theta_\gamma)] E_\gamma dE_\gamma d\cos\theta_\gamma, \quad (5)$$

where E_γ and $\cos\theta_\gamma$ are the energy and scattering angle of the photon.

The kinematics is contained in the functions

$$F_1(s, E_\gamma, \cos\theta_\gamma) \equiv \frac{[\frac{1}{2}\sqrt{s}E_\gamma + \frac{1}{2}(s-2)E_\gamma^2 - \sqrt{s}E_\gamma^3 - sE_\gamma^2\sin^2\theta_\gamma + \sqrt{s}E_\gamma^3\sin^2\theta_\gamma]}{(s - M_Z^2)^2 + M_Z^2\Gamma_Z^2}, \quad (6)$$

$$F_2(s, E_\gamma, \cos\theta_\gamma) \equiv \frac{[-sE_\gamma^2 + 2\sqrt{s}E_\gamma^3 + \frac{3}{2}sE_\gamma^2\sin^2\theta_\gamma - \sqrt{s}E_\gamma^3\sin^2\theta_\gamma]}{(s - M_Z^2)^2 + M_Z^2\Gamma_Z^2}, \quad (7)$$

while the coefficient C is given by

$$C[x_W] \equiv \frac{[1 - 4x_W + 8x_W^2]}{x_W^2(1 - x_W)^2}, \quad (8)$$

where $x_W \equiv \sin^2\theta_W$.

In the case of the anomalous coupling $Z\gamma\gamma$, in order to get the respective expression for the cross section, we have to use the substitution given in Eqs. (2)–(4) and take the appropriated photon propagator into account. We do not reproduce the analytical expressions here because they are rather similar to the terms given in Eqs. (5)–(8).

III. RESULTS AND CONCLUSIONS

We expect that the contribution arising from the ZVV anomalous vertices is enhanced in the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ at high energies with respect to the SM contribution [14,24] when we use the photon-energy cut $E_\gamma > 50$ GeV, as it is shown in Fig. 1. In this section we derive those values of h_{i0}^V, $V = Z$, γ, which would give rise to a deviation from the SM prediction at the level of 2 standard deviations (95% C.L.). As it is shown in Eq. (5), the couplings $h_{2,4}^V$ do not contribute to the total cross section

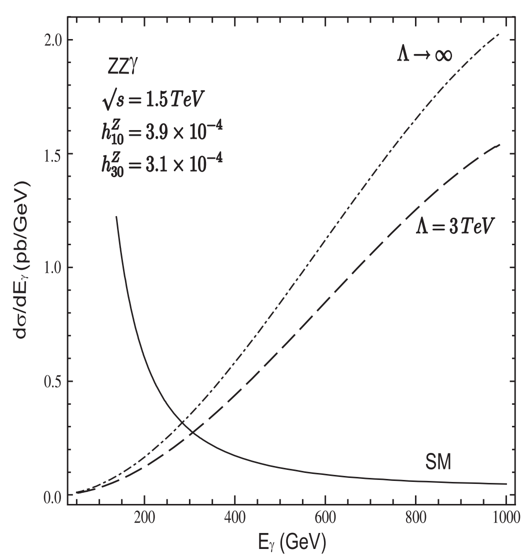

FIG. 1. Energy distribution of photons emitted in the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ with $\sqrt{s} = 1.5$ TeV, $\Lambda = 3$ TeV, and $\Lambda = \infty$ for the SM and one choice of the TNGBC $h_{1,3}^Z$. We have used the photon-energy cut $E_\gamma > 50$ GeV.

[6] and the calculation of the sensitivity bounds is facilitated by the fact that the CP-conserving and CP-violating couplings $h_{1,3}^V$ do not interfere. Even more, cross sections and sensitivities are nearly identical for equal values of these couplings [24]. For simplicity, we shall take then one of the vertex contributions at a time. In Fig. 2 we present the dependence of the sensitivity limits of the h_1^Z vertices with respect to the collider luminosity for three different values of the c.m. energy. A similar dependence is obtained for the sensitivity limits of the h_3^Z, $h_{1,3}^{\gamma}$ vertices with respect to the collider luminosity. In Fig. 3 we summarize the respective limit contours for these vertices at the 95% C.L. in the $h_{10}^V - h_{30}^V$ plane for a luminosity of 500 fb^{-1} and the c.m. energies 0.5–1.5 TeV. Finally, in Tables I, II, and III we include the 95% C.L. limits obtained for both vertices for three different values of the new physics scale energy $\Lambda = 3$, 5 TeV and $\Lambda = \infty$ and the collider luminosity of 500 fb^{-1}.

The process $e^+e^- \to XY \to XY\gamma$ has also been used to search for new neutral particles X and Y, where X is an hypothetical neutral particle that decays radiatively to Y, a stable weakly interacting neutral particle [25]. In some supersymmetry (SUSY) theories the lightest SUSY particle is either a gravitino or a neutralino, while in gauge-mediated SUSY breaking models the gravitino is the lightest SUSY particle with a mass less than few hundred eV/c^2 [19]. However, it is important to notice that while in the present paper we were interested in studying energetic single-photon events arising from a final state ZVV con-

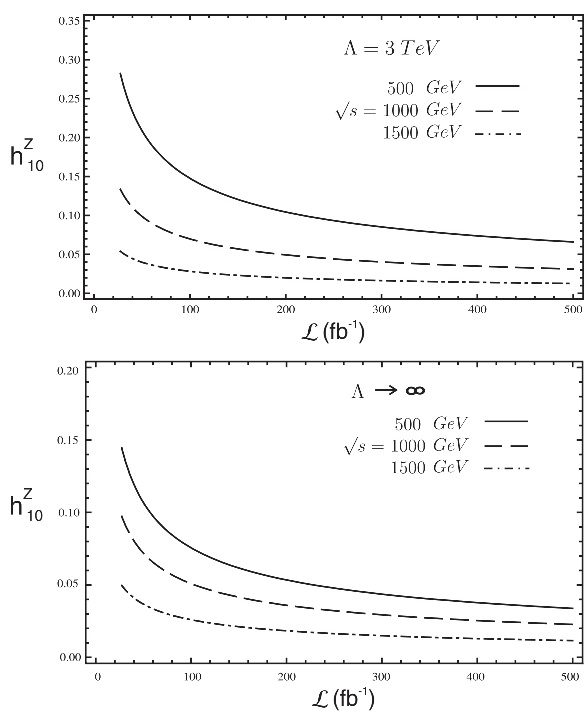

FIG. 2. Dependence of the sensitivity limits at 95% C.L. for the h_{10}^Z vertex for two values of the new physics energy scale Λ and three different values of the c.m. energy in the process $e^+e^- \to \nu\bar{\nu}\gamma$. We have used the photon-energy cut $E_\gamma > 50$ GeV.

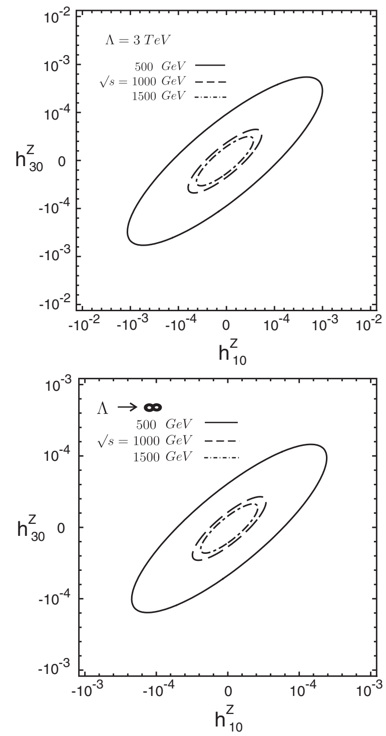

FIG. 3. Limits contours at the 95% C.L. in the h_{10}^Z–h_{30}^Z plane for $e^+e^- \to \nu\bar{\nu}\gamma$ with a luminosity of 500 fb^{-1} and c.m. energies of 1–1.5 TeV. We have used the photon-energy cut $E_\gamma > 50$ GeV.

TABLE I. Sensitivities achievable at the 95% C.L. for the $h_{1,3}^V$ vertices in the process $e^+e^- \to \nu\bar{\nu}\gamma$ for different c.m. energies with $\mathcal{L} = 500$ fb^{-1} and $\Lambda = 3$ TeV. We have used the photon-energy cut $E_\gamma > 50$ GeV.

	$\Lambda = 3$ TeV			
$\sqrt{s}$	h_{10}^Z	h_{30}^Z	h_{10}^{γ}	h_{30}^{γ}
500 GeV	0.0020	0.0016	0.0014	0.0011
1000 GeV	0.000 98	0.000 79	0.000 69	0.000 56
1500 GeV	0.000 39	0.000 31	0.000 28	0.000 22

TABLE II. Sensitivities achievable at the 95% C.L. for the $h_{1,3}^V$ vertices in the process $e^+e^- \to \nu\bar{\nu}\gamma$ for different c.m. energies with $\mathcal{L} = 500$ fb^{-1} and $\Lambda = 5$ TeV. We have used the photon-energy cut $E_\gamma > 50$ GeV.

	$\Lambda = 5$ TeV			
$\sqrt{s}$	h_{10}^Z	h_{30}^Z	h_{10}^{γ}	h_{30}^{γ}
500 GeV	0.0013	0.0011	0.000 97	0.000 79
1000 GeV	0.000 80	0.000 65	0.000 57	0.000 46
1500 GeV	0.000 37	0.000 29	0.000 26	0.000 21

TABLE III. Sensitivities achievable at the 95% C.L. for the $h^V_{1,3}$ vertices in the process $e^+e^- \to \nu\bar{\nu}\gamma$ for different c.m. energies with $\mathcal{L} = 500\ \text{fb}^{-1}$ and $\Lambda = \infty$. We have used the photon-energy cut $E_\gamma > 50$ GeV.

	$\Lambda = \infty$			
$\sqrt{s}$	h^Z_{10}	h^Z_{30}	h^γ_{10}	h^γ_{30}
500 GeV	0.0010	0.000 86	0.000 75	0.000 61
1000 GeV	0.000 71	0.000 57	0.000 50	0.000 40
1500 GeV	0.000 36	0.000 28	0.000 25	0.000 20

tribution, the search of the new neutral X and Y particles is tagged by a (low-energy) initial state radiation photon [25].

In conclusion, we have found that the process $e^+e^- \to \nu\bar{\nu}\gamma$ at the high energies and luminosities expected at the ILC/CLIC colliders can be used to probe for nonstandard ZVV vertices. In particular, we can appreciate that the 95% C.L. sensitivity limits expected for the $h^V_{1,3}$ vertices at 1–1.5 TeV c.m. energies already can provide tests of these vertices of order 10^{-4}, 1 order of magnitude lower than the SM, minimal supersymmetric standard model, and littlest Higgs models predictions [6–8]. These sensitivity limits are of the same order of magnitude that those expected in the process $e^+e^- \to Z(\to l^+l^-)\gamma$, also at future e^+e^- colliders, through the effects induced by the polarization of the Z gauge boson and initial state radiation [13]. These sensitivity limits are also better than those expected in the search of quartic gauge boson couplings at the ILC [26].

Finally, we would like to comment that our results indicate a rather weak dependence on the new physics scale Λ introduced in the unitarization scheme given by the generalized dipole form factors (3) and (4). On general grounds, we got smaller sensitivities for smaller cutoff scales Λ. In particular, the use of this parametrization scheme seems unnecessary at the ILC for c.m. energies as high as 1.5 TeV as it is show in Figs. 2 and 3 in Table III.

ACKNOWLEDGMENTS

We acknowledge support from CONACyT and SNI (México).

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