Research Article

Sensitivity on the Dipole Moments of the τ -Neutrino at e^+e^- Colliders: ILC and CLIC

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Received 7 October 2013; Accepted 3 January 2014; Published 26 February 2014

Academic Editor: P. Bussey

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We study the sensitivity on the anomalous magnetic and electric dipole moments of the τ -neutrino at a high-energy and high-luminosity linear electron positron collider, such as the ILC or CLIC, through the reaction $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. We obtain limits on the dipole moments at the future linear colliders energies. For integrated luminosities of 500 fb^{-1} and center of mass energies between 0.5 and 3 TeV, the future e^+e^- colliders may improve the existing limits by two or three orders of magnitude.

1. Introduction

In the standard model (SM) [1–3] extended to contain right-handed neutrinos, the neutrino magnetic moment induced by radiative corrections is unobservably small, $\mu_\nu \approx 3.1 \times 10^{-19} (m_\nu/1 \text{ eV})\mu_B$ [4]. Current limits on these magnetic moments are several orders of magnitude larger, so that a magnetic moment close to these limits would indicate a window for probing effects induced by new physics beyond the SM [5]. Similarly, a neutrino electric dipole moment will also point to new physics and will be of relevance in astrophysics and cosmology, as well as terrestrial neutrino experiments [6]. Some bounds on the neutrino magnetic moment are shown in Table 1.

Gould and Rothstein [7] reported in 1994 a bound on μ_{ν_τ} obtained through the analysis of the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$, near the Z -resonance, with a massive neutrino and the SM Ze^+e^- and $Z\nu\bar{\nu}$ couplings.

At higher s , near the Z pole $s \approx M_Z^2$, the dominant contribution involves the exchange of a Z boson. The dependence on the magnetic moment (μ_{ν_τ}) and the electric dipole moment (d_{ν_τ}) comes from the radiation of the photon observed by the neutrino or antineutrino in the final state. However, in order to improve the limits on the magnetic moment and the electric dipole moment of

the tau-neutrino, in our calculation of the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ we consider the contribution that involves the exchange of a virtual photon. In this case, the dependence on the magnetic moment comes from a direct coupling to the virtual photon, and the observed photon is a result of initial-state Bremsstrahlung. The Feynman diagrams which give the most important contribution to the cross section are shown in Figure 1.

Our aim in the present paper is to analyze the reaction $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ in the framework of the standard model minimally extended to include massive Dirac neutrinos and we attribute an anomalous magnetic moment (MM) and an electric dipole moment (EDM) to a massive tau-neutrino. This process sets limits on the tau-neutrino MM and EDM. In this paper, we take advantage of this fact to set limits on μ_{ν_τ} and d_{ν_τ} for integrated luminosities of 500 fb^{-1} and center of mass energies between 0.5 and 3 TeV, that is to say, in the next generation of linear colliders, namely, the International Linear Collider (ILC) [8] and the Compact Linear Collider (CLIC) [9].

The L3 Collaboration [10] evaluated the selection efficiency using detector-simulated $e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$ events, random trigger events, and large-angle $e^+e^- \rightarrow e^+e^-$ events. From Figure 1 of [10] the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ with γ emitted in the initial state is the sole background in the $[44.5^\circ, 135.5^\circ]$

TABLE 1: Bounds on the neutrino magnetic moment.

Laboratory experiment TEXONO [14]	$\mu_\nu < 2.9 \times 10^{-11} \mu_B$
Cooling rates of white dwarfs [15]	$\mu_\nu \lesssim 10^{-11} \mu_B$
Cooling rates of red giants [16]	$\mu_\nu \lesssim 3 \times 10^{-12} \mu_B$
Supernova energy loss [17]	$\mu_\nu \lesssim (1.1-2.7) \times 10^{-12} \mu_B$
Absence of high-energy events in the SN1987A neutrino signal [18]	$\mu_\nu \lesssim 10^{-12} \mu_B$
Standard model (Dirac mass) [4]	$\mu_\nu \lesssim 3.1 \times 10^{-19} (m_\nu/1 \text{ eV}) \mu_B$

FIGURE 1: The Feynman diagrams contributing to the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ (1, 2) when the Z vector boson is produced on mass-shell and (3, 4) contributions from anomalous neutrino electromagnetic couplings with initial-state radiation.

angular range (white histogram). From the same figure in this angular interval, that is, $-0.7 < \cos\theta_\gamma < 0.7$, we see that only 6 events were found; this is the real background, not 14 events. In this case a simple method [11–13] is that at 1σ level (68% C.L.) for a null signal the number of observed events should not exceed the fluctuation of the estimated background events: $N = N_B + \sqrt{N_B}$. Of course, this method is good only when N_B is sufficiently large (i.e., when the Poisson distribution can be approximated with a gaussian [11–13]) but for $N_B > 10$ it is a good approximation. This means that at 1σ , 2σ , and 3σ level (68%, 90%, and 95% C.L.) the limits on the nonstandard parameters are found replacing the equation for the total number of events expected $N = N_B + \sqrt{N_B}$ in the expression $N = \sigma(\mu_\nu, d_{\nu\tau})\mathcal{L}$. The distributions of the photon energy and the cosine of its polar angle are consistent with SM predictions.

This paper is organized as follows. In Section 2 we present the calculation of the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ in the context of the standard model minimally extended to include massive Dirac neutrinos. Finally, we present our results and conclusions in Section 3.

2. The Total Cross Section

In this section we calculate the total cross section for the reaction $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. The respective transition amplitudes are thus given by

$$\begin{aligned}
 \mathcal{M}_1 &= \frac{-g^2}{4\cos^2\theta_W(l^2 - m_\nu^2)} [\bar{u}(p_3) \Gamma^\alpha(l + m_\nu) \gamma^\beta v(p_4)] \\
 &\quad \times \frac{(g_{\alpha\beta} - p_\alpha p_\beta / M_Z^2)}{[(p_1 + p_2)^2 - M_Z^2 - iM_Z \Gamma_Z]} \\
 &\quad \times [\bar{u}(p_2) \gamma^\alpha (g_v - g_A \gamma_5) v(p_1)] \epsilon_\alpha^\lambda, \\
 \mathcal{M}_2 &= \frac{-g^2}{4\cos^2\theta_W(l'^2 - m_\nu^2)} [\bar{u}(p_3) \gamma^\beta (\not{l}' + m_\nu) \Gamma^\alpha v(p_4)] \\
 &\quad \times \frac{(g_{\alpha\beta} - p_\alpha p_\beta / M_Z^2)}{[(p_1 + p_2)^2 - M_Z^2 - iM_Z \Gamma_Z]} \\
 &\quad \times [\bar{u}(p_2) \gamma^\alpha (g_v - g_A \gamma_5) v(p_1)] \epsilon_\alpha^\lambda, \\
 \mathcal{M}_3 &= \frac{e^2}{(k^2 - m_e^2)} [\bar{u}(p_3) \Gamma^\alpha v(p_4)] \\
 &\quad \times \frac{g_{\alpha\beta}}{(p_1 + p_2)^2} [\bar{u}(p_2) \gamma^\alpha (\not{k} + m_e) \gamma^\beta v(p_1)] \epsilon_\alpha^\lambda, \\
 \mathcal{M}_4 &= \frac{e^2}{(k'^2 - m_e^2)} [\bar{u}(p_3) \Gamma^\alpha v(p_4)] \frac{g_{\alpha\beta}}{(p_1 + p_2)^2} \\
 &\quad \times [\bar{u}(p_2) \gamma^\beta (\not{k}' + m_e) \gamma^\alpha v(p_1)] \epsilon_\alpha^\lambda,
 \end{aligned} \tag{1}$$

where

$$\Gamma^\alpha = eF_1(q^2) \gamma^\alpha + \frac{ie}{2m_\nu} F_2(q^2) \sigma^{\alpha\mu} q_\mu + eF_3(q^2) \gamma_5 \sigma^{\alpha\mu} q_\mu \tag{2}$$

is the neutrino electromagnetic vertex, e is the charge of the electron, q^μ is the photon momentum, and $F_{1,2,3}(q^2)$ are the electromagnetic form factors of the neutrino, corresponding to charge radius, MM, and EDM, respectively, at $q^2 = 0$ [19, 20], while ϵ_α^λ is the polarization vector of the photon. $l(k)$ and $l'(k')$ stand for the momentum of the virtual neutrino (electron) and antineutrino (positron), respectively.

The MM and EDM give a contribution to the total cross section for the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ of the following form:

$$\begin{aligned}
 \sigma(e^+e^- \rightarrow \nu\bar{\nu}\gamma) &= \int \frac{\alpha^2}{96\pi} (\kappa^2 \mu_B^2 + d_{\nu\tau}^2) \\
 &\quad \times \left\{ \left[\frac{s - 2\sqrt{s}E_\gamma + (1/2)E_\gamma^2 \sin^2\theta_\gamma}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \right] \left[\frac{1 - 4x_W + 8x_W^2}{x_W^2(1 - x_W)^2} \right] \right.
 \end{aligned}$$

$$+32 \left[\frac{s - 2\sqrt{s}E_\gamma + 2E_\gamma^2 - E_\gamma^2 \sin^2 \theta_\gamma}{sE_\gamma^2 \sin^2 \theta_\gamma} \right] \} \\ \times E_\gamma dE_\gamma d\cos\theta_\gamma, \quad (3)$$

where $x_W \equiv \sin^2 \theta_W$ and $E_\gamma, \cos \theta_\gamma$ are the energy and the opening angle of the emitted photon.

The expression given for the first term of (3) corresponds to the cross section previously reported by Gould and Rothstein [7], while the second term comes from the contribution that involves the exchange of a virtual photon and the observed photon is radiated to the initial electron or positron.

3. Results and Conclusions

In order to evaluate the integral of the total cross section as a function of the parameters of the model, that is to say, μ_{ν_τ} and d_{ν_τ} , we require cuts on the photon angle and energy to avoid divergences when the integral is evaluated at the important intervals of each experiment. We integrate over θ_γ from 44.5° to 135.5° and E_γ from 15 GeV to 100 GeV. Using the following numerical values: $\sin^2 \theta_W = 0.2314$, $M_Z = 91.18$ GeV, and $\Gamma_Z = 2.49$ GeV, we obtain the cross section $\sigma = \sigma(\mu_{\nu_\tau}, d_{\nu_\tau})$.

As was discussed in [7, 10, 21, 22], $N \approx \sigma(\mu_{\nu_\tau}, d_{\nu_\tau}) \mathcal{L}$, where $N = N_B + \sqrt{N_B}$ is the total number of $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ events expected at 1σ , 2σ , and 3σ level as is mentioned in the introduction and $\mathcal{L} = 500 \text{ fb}^{-1}$ according to the data reported by the ILC and CLIC [8, 9]. Taking this into consideration, we can obtain a limit for the tau-neutrino magnetic moment with $d_{\nu_\tau} = 0$.

The bounds obtained on the μ_{ν_τ} magnetic moment and d_{ν_τ} electric dipole moment for $\sqrt{s} = 0.5, 1, 1.5, 3$ TeV and $\mathcal{L} = 500 \text{ fb}^{-1}$ at 1σ , 2σ , and 3σ are shown in Table 2. We observed that the results obtained in Table 2 are better than those reported in the literature [7, 10, 19, 23–39].

The previous analysis and comments can readily be translated to the EDM of the τ -neutrino with $\mu_{\nu_\tau} = 0$. The resulting limits for the EDM as a function of the center of mass energy are shown in Table 2.

In order to see the sensitivity of the photon energy and the magnetic moment to new physics, in Figure 2 we plot the differential cross section versus $(E_\gamma, \mu_{\nu_\tau})$ for the limits of the magnetic moment given in Table 2. We see that the differential cross section strongly depends on both the photon energy E_γ and the magnetic moment μ_{ν_τ} .

Figure 3 shows the total cross section for $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ as a function of the center of mass energy $\sqrt{s}$ and different values representative of the magnetic moment, which are reported in the literature, that is to say, $\mu_{\nu_\tau} = 3.3 \times 10^{-6} \mu_B$ (L3), $5.4 \times 10^{-7} \mu_B$ (BEBC (CERN)), $1.68 \times 10^{-8} \mu_B$ (Table 2). Starting from a center of mass energy just greater than the Z mass, a minimum around $\sqrt{s} \approx 200$ GeV occurs due to the SM Z -boson resonance tail on the high energies. For different values of the parameter μ_{ν_τ} the shape of the curves does not change and there is only a shift of these depending on the value

FIGURE 2: The differential cross section for $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ as a function of E_γ and μ_{ν_τ} .

FIGURE 3: The curves show the shape for $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ as a function of center of mass energy and different values of the μ_{ν_τ} magnetic moment.

of the magnetic moment. Finally, in Figure 4 we present the dependence of the sensitivity limits of the magnetic moment μ_{ν_τ} with respect to the collider luminosity $\mathcal{L}$ for three different values of the center of mass energy, $\sqrt{s} = 0.5, 1, 1.5$ TeV.

In conclusion, we have found that the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ in the context of the standard model minimally extended to include massive Dirac neutrino at the high energies and luminosities expected at the ILC/CLIC colliders can be used to probe for bounds on the magnetic moment μ_{ν_τ} and electric dipole moment d_{ν_τ} . In particular, we can appreciate that the 95% C.L. sensitivity limits expected for the magnetic moment at 0.5–1.5 TeV center of mass energies already can provide

TABLE 2: Bounds on the μ_{ν_τ} magnetic moment and d_{ν_τ} electric dipole moment for $\sqrt{s} = 0.5, 1, 1.5, 3$ TeV and $\mathcal{L} = 500 \text{ fb}^{-1}$ at $1\sigma, 2\sigma$, and 3σ .

C. L.	$\sqrt{s} = 0.5, 1, 1.5, 3 \text{ TeV } \mathcal{L} = 500 \text{ fb}^{-1}$	
	$ \mu_{\nu_\tau} (\mu_B) $	$ d_{\nu_\tau} (\text{ecm}) $
1σ	$1.48 \times 10^{-8}, (7.03, 4.60, 2.25) \times 10^{-9}$	$(2.86, 1.35) \times 10^{-19}, (8.88, 4.35) \times 10^{-20}$
2σ	$1.68 \times 10^{-8}, (7.99, 5.22, 2.56) \times 10^{-9}$	$(3.25, 1.54, 1.00) \times 10^{-19}, 4.94 \times 10^{-20}$
3σ	$1.86 \times 10^{-8}, (8.84, 5.78, 2.83) \times 10^{-9}$	$(3.60, 1.70, 1.11) \times 10^{-19}, 5.47 \times 10^{-20}$

FIGURE 4: Dependence of the sensitivity limits at 95% C.L. for the anomalous magnetic moment for three different values of the center of mass energy in the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$.

proof of these bounds of order 10^{-8} – 10^{-9} , that is to say, 2–3 orders of magnitude better than those reported in the literature: $\mu_{\nu_\tau} < 3.3 \times 10^{-6} \mu_B$ (90% C.L.) from a sample of e^+e^- annihilation events collected with the L3 detector at the Z resonance corresponding to an integrated luminosity of 137 pb^{-1} [10]; $\mu_{\nu_\tau} \leq 2.7 \times 10^{-6} \mu_B$ (95% C.L.) at $q^2 = M_Z^2$ from measurements of the Z invisible width at LEP [19]; $\mu_{\nu_\tau} \leq 2.62 \times 10^{-6}$ in the effective Lagrangian approach at the Z pole [36]; $\mu_{\nu_\tau} < 1.83 \times 10^{-6} \mu_B$ (90% C.L.) from the analysis of $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ at the Z -pole, in a class of E_6 inspired models with a light additional neutral vector boson [37]; from the order of $\mu_{\nu_\tau} < O(1.1 \times 10^{-6} \mu_B)$ Akama et al. derive and apply model-independent limits on the anomalous magnetic moments and the electric dipole moments of leptons and quarks due to new physics [38]. However, the limits obtained in [38] are for the tau-neutrino with an upper bound of $m_\tau < 18.2 \text{ MeV}$ which is the current experimental limit. It was pointed out in [38], however, that the upper limit on the mass of the electron neutrino and data from various neutrino oscillation experiments together imply that none of the active neutrino mass eigenstates is heavier than approximately 3 eV. In this case, the limits given in [38] are improved by seven orders of magnitude. The limit $\mu_{\nu_\tau} < 5.4 \times 10^{-7} \mu_B$ (90% C.L.) is obtained at $q^2 = 0$ from a beam-dump experiment

with assumptions on the D_s production cross section and its branching ratio into $\tau\nu_\tau$ [39], thus severely restricting the cosmological annihilation scenario [40]. Our results in Table 2 compare favorably with the limits obtained by the L3 Collaboration [10], and with other limits reported in the literature [7, 10, 19, 23–39].

In the case of the electric dipole moment the 95% C.L. sensitivity limits at 0.5–1.5 TeV center of mass energies and integrated luminosities of 500 fb^{-1} can provide proof of these bounds of order 10^{-19} – 10^{-20} , that is to say, are improved by 2–3 orders of magnitude than those reported in the literature: $|d(\nu_\tau)| \leq 5.2 \times 10^{-17} \text{ ecm}$, 95% C.L. [19] and $|d(\nu_\tau)| < O(2 \times 10^{-17} \text{ ecm})$ [38].

Finally, it seems that in order to improve these limits it might be necessary to study direct CP-violating effects [41]. In addition, the analytical and numerical results for the cross section could be of relevance for the scientific community.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The author acknowledges support from CONACyT, SNI, PROMEP, and PIFI (Mexico).

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