Probing topcolor-assisted technicolor from lepton flavor violating processes in photon-photon collision at ILC

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Abstract

In topcolor-assisted technicolor models (TC2) the hitherto unconstrained lepton flavor mixing induced by the new gauge boson $Z'$ will lead to the lepton flavor violating productions of $\tau\bar{\mu}$, $\tau\bar{e}$ and $\mu\bar{e}$ in photon-photon collision at the proposed International Linear Collider (ILC). Through a comparative analysis of these processes, we find that the better channels to probe the TC2 is the production of $\tau\bar{\mu}$ or $\tau\bar{e}$ which occurs at a much higher rate than $\mu\bar{e}$ production due to the large mixing angle and the large flavor changing coupling, and may reach the detectable level of the ILC for a large part of the parameter space. Since the rates predicted by the Standard Model are far below the detectable level, these processes may serve as a sensitive probe for the TC2 model.

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I. INTRODUCTION

Since in the Standard Model (SM) the lepton flavor violating (LFV) interactions are extremely suppressed, any observation of the LFV processes would serve as a robust evidence for new physics beyond the SM. These LFV processes, which have been searched in various experiments \cite{1-3}, can be greatly enhanced in new physics models like supersymmetry \cite{4, 5} and the topcolor-assisted models (TC2) \cite{6-8}. Such enhancement can be several orders to make them potentially accessible at future collider experiments.

Due to its rather clean environment, the proposed International Linear Collider (ILC) will be an ideal machine to probe new physics. In such a collider, in addition to $e^+e^-$ collision, we can also realize $\gamma\gamma$ collision with the photon beams generated by the backward Compton scattering of incident electron- and laser-beams. The LFV interactions in TC2 model will induce various processes at the ILC, such as the productions of $\tau\bar{\mu}$, $\tau\bar{e}$ and $\mu\bar{e}$ via $e^+e^-$. It is noticeable that the productions of $\tau\bar{\mu}$, $\tau\bar{e}$ and $\mu\bar{e}$ in $\gamma\gamma$ collision have not been studied in the framework of the TC2. Such LFV productions in $\gamma\gamma$ collision may be more important than in $e^+e^-$ collision \cite{8} collision since these productions are a good probe for new physics because it is essentially free of any SM irreducible background. It is also noticeable that all these LFV processes at the ILC involve the same part of the parameter space of the TC2. Therefore, it is necessary to comparatively study all these processes to find out which process is best to probe the TC2 model.

We in this work will study the LFV processes $\gamma\gamma \rightarrow \ell_i\bar{\ell}_j \ (i \neq j \text{ and } \ell_i = e, \mu, \tau)$ induced by the extra $U(1)$ gauge boson $Z'$ in TC2 models. We calculate the production rates to figure out if they can reach the sensitivity of the photon-photon collision of the ILC.

The work is organized as follows. We will briefly discuss the TC2 model in Section II, giving the new couplings which will be involved in our calculation. In Section III and IV we give the calculation results and compare with the results in the SUSY. Finally, the conclusion is given in Section V.

II. ABOUT TC2 MODEL

There are many kinds of new physics scenarios predicting new particles, which can lead to significant LFV signals. For example, in the minimal supersymmetric SM, a large $\nu_{\mu} - \nu_\tau$
mixing leads to clear LFV signals in slepton and sneutrino production and in the decays of neutralinos and charginos into sleptons and sneutrinos at hadron colliders and lepton colliders \[9\]. The non-universal U(1) gauge bosons $Z'$, which are predicted by various specific models beyond the SM, can lead to the large tree-level flavor changing (FC) couplings. Thus, these new particles may have significant contributions to some LFV processes \[10\].

The key feature of TC2 models \[6\] and flavor-universal TC2 models \[11\] is that the large top quark mass is mainly generated by topcolor interactions at a scale of order 1 TeV. The topcolor interactions may be flavor non-universal (as in TC2 models) or flavor-universal (as in flavor-universal TC2 models). However, to tilt the chiral condensation in the $t\bar{t}$ direction and not form a $b\bar{b}$ condensation, all of these models need a non-universal extended hypercharge group $U(1)$. Thus, the existence of the extra $U(1)$ gauge bosons $Z'$ is predicted. These new particles treat the third generation fermions (quarks and leptons) differently from those in the first and second generations, namely, couple preferentially to the third generation fermions. After the mass diagonalization from the flavor eigenbasis into the mass eigenbasis, these new particles lead to tree-level FC couplings. The flavor-diagonal couplings of the extra $U(1)$ gauge bosons $Z'$ to ordinary fermions, which are related to our calculation, can be written as \[6, 12\]:

$$L = -\frac{1}{2} g_1 \tan \theta' \left\{ \bar{e}_L \gamma^\mu e_L + 2 \bar{e}_R \gamma^\mu e_R + \bar{\mu}_L \gamma^\mu \mu_L + 2 \bar{\mu}_R \gamma^\mu \mu_R \right\} \cdot Z'_\mu,$$

(1)

where $g_1$ is the ordinary hypercharge gauge coupling constant, $\theta'$ is the mixing angle and $\tan \theta' = \frac{g_1}{2\sqrt{\pi} K_1}$ where $K_1$ is the coupling constant.

The flavor-changing couplings of the extra $U(1)$ gauge bosons $Z'$ to ordinary fermions, which are related to our calculation, are given in the followings: \[6, 12\]:

$$L = -\frac{1}{2} g_1 \{ K_{\mu e} (\bar{e}_L \gamma^\mu \mu_L + 2 \bar{e}_R \gamma^\mu \mu_R) + k_{\tau e} (\bar{\tau}_L \gamma^\mu \tau_L + 2 \bar{\tau}_R \gamma^\mu \tau_R) \} \cdot Z'_\mu,$$

(2)

where $k_{\mu e}$, $k_{\tau e}$ and $k_{\tau \mu}$ are the flavor mixing factors. Since the new gauge boson $Z'$ couples preferentially to the third generation, the factor $K_{\mu e}$ are negligibly small, so in the following estimation, we will neglect the $\mu - e$ mixing, and consider only the flavor changing coupling processes $\gamma \gamma \rightarrow \tau \mu$ and $\gamma \gamma \rightarrow \tau e$.

Note that the difference between the $Z' \tau \bar{\mu}$ and $Z' \tau \bar{e}$ couplings lies only in the flavor mixing factor $K_{\tau \mu}$ and $K_{\tau e}$ and the masses of the final state leptons. Since the non-universal gauge
The boson $Z'$ treats the fermions in the third generation differently from those in the first and second generations and treats the fermions in the first same as those in the second generation, so in the following calculation, we will assume $K_{\tau\mu} = K_{\tau e}$. Then what makes the discrepancy of the cross sections of the two channels $\gamma \gamma \rightarrow \tau \bar{\mu}$ and $\gamma \gamma \rightarrow \tau \bar{e}$ is only the masses of the final state particles. Considering the large mass $M_{Z'} > 1$ TeV, for simplicity, we will take $M_{\tau} = M_{\mu} = M_{e} = 0$ in the following discussion, i.e., assuming the cross sections of the two channels $\gamma \gamma \rightarrow \tau \bar{\mu}$ and $\gamma \gamma \rightarrow \tau \bar{e}$ are equal to each other.

### III. CALCULATION

The Feynman diagram of the LFV processes $\gamma \gamma \rightarrow \ell_i \ell_j$ ($i \neq j$ and $\ell_i = e, \mu, \tau$) induced by the extra U(1) $Z'$ is shown in Fig. 1. There are only t- and u- channel contributions, the latter not shown in Fig. 1 but we can calculate them by exchanging the two photons.

![Feynman diagrams contributing to the process $\gamma \gamma \rightarrow \ell_i \ell_j$ in TC2 models.](image)

Note that there is no s-channel contribution to the LFV processes. As we know, in the SM production of on-shell $Z$ boson at a photon-photon collider (or $Z$ decays into $\gamma \gamma$) is strictly forbidden by angular momentum conservation and Bose statistics, which is the predict of the famous Laudau-Yang Theorem. This theorem is still effective to our case, since that the two real photons cannot be in a state with angular momentum $J = 1$ regardless of on-shell or off-shell bosons, so the s-channel contribution with two real photons to an extra $Z'$ vanishes automatically.

The electroweak gauge bosons $\gamma$ and $Z$ can not couple to $\tau \bar{e}$, $\mu \bar{e}$ and $\tau \bar{\mu}$, so we need not consider the interference effects between the $\gamma$, $Z$ and $Z'$ on the cross section of the
process $\gamma\gamma \rightarrow \ell_i\bar{\ell}_j (i \neq j \text{ and } \ell_i = e, \mu, \tau)$. In TC2 models the gauge invariant amplitude of $\gamma\gamma \rightarrow \tau\bar{\mu}(\bar{e})$ induced by the extra boson $Z'$ is given by

$$M = \frac{1}{2} \bar{u}_\tau \Gamma^{\mu\nu} P_L v_\mu \epsilon_\mu(\lambda_1) \epsilon_\nu(\lambda_2)$$

(3)

where the $\Gamma^{\mu\nu}$ is defined same as that in [14]. These amplitudes contain the Passarino-Veltman one-loop functions, which are calculated by using LoopTools [15].

Since the photon beams in $\gamma\gamma$ collision are generated by the backward Compton scattering of the incident electron- and the laser-beam, the events number is obtained by convoluting the cross section of $\gamma\gamma$ collision with the photon beam luminosity distribution:

$$N_{\gamma\gamma \rightarrow \ell_i\bar{\ell}_j} = \int d\sqrt{s_{\gamma\gamma}} dL_{\gamma\gamma} \hat{\sigma}_{\gamma\gamma \rightarrow \ell_i\bar{\ell}_j}(s) \equiv L_{e^+e^-} \sigma_{\gamma\gamma \rightarrow \ell_i\bar{\ell}_j}(s)$$

(4)

where $dL_{\gamma\gamma}/d\sqrt{s_{\gamma\gamma}}$ is the photon-beam luminosity distribution and $\sigma_{\gamma\gamma \rightarrow \ell_i\bar{\ell}_j}(s)$ ( $s$ is the squared center-of-mass energy of $e^+e^-$ collision) is defined as the effective cross section of $\gamma\gamma \rightarrow \ell_i\bar{\ell}_j$. In optimum case, it can be written as [16]

$$\sigma_{\gamma\gamma \rightarrow \ell_i\bar{\ell}_j}(s) = \int_{\sqrt{s_{\gamma\gamma}}}^{x_{\max}} 2zd\zeta \hat{\sigma}_{\gamma\gamma \rightarrow \ell_i\bar{\ell}_j}(s_{\gamma\gamma} = z^2) \int_{x_{\max}/x_{\gamma}}^{x_{\max}} \frac{dx}{x} F_{\gamma/e}(x) F_{\gamma/e}(z^2/x)$$

(5)

where $F_{\gamma/e}$ denotes the energy spectrum of the back-scattered photon for the unpolarized initial electron and laser photon beams given by

$$F_{\gamma/e}(x) = \frac{1}{D(\xi)} \left[ 1 - x + \frac{1}{1 - x} - \frac{4x}{\xi(1 - x)} + \frac{4x^2}{\xi^2(1 - x)^2} \right]$$

(6)

with

$$D(\xi) = (1 - \frac{4}{\xi} - \frac{8}{\xi^2}) \ln(1 + \xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1 + \xi)^2}.$$  

(7)

Here $\xi = 4E_e E_0/m_e^2$ ($E_e$ is the incident electron energy and $E_0$ is the initial laser photon energy) and $x = E/E_E$ with $E$ being the energy of the scattered photon moving along the initial electron direction. The definitions of parameters $\xi$, $D(\xi)$ and $x_{\max}$ can be found in Ref. [16]. In our numerical calculation, we choose $\xi = 4.8$, $D(\xi) = 1.83$ and $x_{\max} = 0.83$.

IV. NUMERICAL RESULTS AND DISCUSSIONS

As for the involved SM parameter, we take

$$m_\mu = 0.106 \text{ GeV}, m_\tau = 1.777 \text{ GeV}, m_b = 4.2 \text{ GeV}, \alpha = 1/137, \sin^2 \theta_W = 0.223$$  

(8)
The TC2 parameters concerned in this process are $K_{\tau e}$, $K_{\tau \mu}$, $K_{e\mu}$, $K_1$ and the mass of the extra gauge boson $M'_Z$. $K_{e\mu}$ is very small, about $10^{-3}$, we will not consider the $e - \mu$ conversion processes. In our calculation, we have assumed $K_{\tau \mu} = K_{\tau e} \simeq \lambda \simeq 0.22$ [12, 19], which $\lambda$ is the Wolfenstein parameter [18]. It has been shown that the vacuum tilting (the topcolor interactions only condense the top quark but not the bottom quark), the coupling constant $K_1$ should satisfy certain constraint, i.e. $K_1 \leq 1$ [11]. The limits on the $Z'$ mass $M'_Z$ can be obtained via studying its effects on various experimental observables [12]. Ref. [20], for example, has been shown that to fit the electroweak measurement data, the $Z'$ mass $M'_Z$ must be larger than 1 TeV. As numerical estimation, we choose the center-of-mass energy $\sqrt{s} = 500$ and 1000 GeV, to observe the different behavior in the two energy area, and take the $M'_Z$ and $K_1$ as free parameters. Finally, Note that the charge conjugate $\bar{\tau}\mu(e)$ production channel are also included in our numerical study.

In Fig. 2 we plot the production cross section $\sigma$ of the LFV process $\gamma\gamma \rightarrow \ell_i\ell_j$ as a function of $M_Z$ for $K_1 = 0.2, 0.6$ and 1.0 with (a) $\sqrt{s} = 500$ GeV (b) $\sqrt{s} = 1000$ GeV.

![Figure 2](image_url)
third generation is singled out from the former two ones, so that it always shows distinct features.

The background for $\gamma\gamma \to e\bar{\tau}$ comes from $\gamma\gamma \to \tau^+\tau^- \to \tau^-\nu_e\bar{\nu}_e e^+$, $\gamma\gamma \to W^+W^- \to \tau^-\nu_e\bar{\nu}_e e^+$ and $\gamma\gamma \to e^+e^-\tau^+\tau^-$, and we make kinematical cuts $|\cos \theta_\ell| < 0.9$ and $p_T^\ell > 20$ GeV ($\ell = e, \mu$), to enhance the ratio of signal to background. With these cuts, the background cross sections from $\gamma\gamma \to \tau^+\tau^- \to \tau^-\nu_e\bar{\nu}_e e^+$, $\gamma\gamma \to W^+W^- \to \tau^-\nu_e\bar{\nu}_e e^+$ and $\gamma\gamma \to e^+e^-\tau^+\tau^-$ at $\sqrt{s} = 500$ GeV are suppressed respectively to $9.7 \times 10^{-4}$ fb, $1.0 \times 10^{-1}$ fb and $2.4 \times 10^{-2}$ fb (see Table I of [21]). To get the 3$\sigma$ observing sensitivity with $3.45 \times 10^2$ fb$^{-1}$ integrated luminosity [22], the production rates of $\gamma\gamma \to \tau\bar{\ell}, \tau\bar{\mu}$ after the cuts must be larger than $2.5 \times 10^{-2}$ fb [21]. We see from Fig.2 that under the current bounds from $\ell_i \to \ell_j \gamma$ [3] and $\mu \to 3e$ [10], the LFV couplings in TC2 models can still large enough to enhance the productions $\gamma\gamma \to e\bar{\tau}, \mu\bar{\tau}$ to the 3$\sigma$ sensitivity and may be detected in the future ILC colliders. Finally note that we in Fig.2 only show the results of the channels with the $\tau$ lepton in the final states, i.e., $\gamma\gamma \to \tau\bar{\mu}, \tau\bar{e}$.

Fig.3 shows that the cross section of the LFV processes as a function of $K_1$ for $M'_{Z} = 1, 1.5, 2.5$ TeV. We can see more clearly that the cross section is increasing as the $K_1$ increasing.

We also show the cross sections of $\gamma\gamma \to \ell_i\bar{\ell}_j$ as a function of center-of-mass energy $\sqrt{s}$ of the ILC in Fig.4. We see that with the increasing of the center-of-mass energy, the cross sections of these processes are not compressed, instead of becoming larger. This is
FIG. 4: The dependence of the cross section $\sigma$ of the LFV process $\gamma\gamma \rightarrow \tau \bar{\mu}(\bar{e})$ on the center-of-mass energy $\sqrt{s}$ for $M_{Z'} = 1, 1.5,$ and $2.5$ TeV with (a) $k_1 = 0.2$, (b) $k_1 = 0.6$.

different with the results in [8], since, as mentioned above, the contribution of the $\gamma\gamma \rightarrow \ell_i \bar{\ell}_j$ are the the results of $t$- and $u$-channels, while in the processes $e^+e^- \rightarrow \ell_i \bar{\ell}_j$, the $s$-channel contribution decreases with the increasing $\sqrt{s}$ when the center-of-mass energy of the processes arrives at the critical value[8]. Actually, we can also feel the larger cross section with larger center of mass from Fig.2 and Fig.3.

Table I: Theoretical predictions for the $\ell_i \bar{\ell}_j$ ($i \neq j$) productions at $\gamma\gamma$ collision at the ILC. SUSY and TC2 predictions are the optimum values. The collider energy is 500 GeV.

|                  | SUSY         | TC2  |
|------------------|--------------|------|
| $\sigma(\gamma\gamma \rightarrow \tau \bar{\mu})$ | $\mathcal{O}(10^{-2})$ fb | 1 fb |
| $\sigma(\gamma\gamma \rightarrow \tau \bar{e})$ | $\mathcal{O}(< 10^{-1})$ fb | 1 fb |
| $\sigma(\gamma\gamma \rightarrow \mu \bar{e})$ | $\mathcal{O}(< 10^{-3})$ fb | $10^{-3}$ fb |

As discussed in the former sections, motivated by the fact that any process that is forbidden or strongly suppressed within the SM constitutes a natural laboratory to search for any new physics effects, LFV processes have been the subject of considerable interest in the literature. It turns out that they may have large cross sections, much larger than the SM ones, within some extended theories such as the R-parity violating MSSM [5] and the TC2 models. However, in the R-parity violating MSSM, as discussed in [5], the LFV coupling by the exchange of the squark is $\lambda_{ijk} \sim 10^{-2}$, much smaller than that of the TC2 models ($K_{\tau \mu(e)} \sim 0.2$). Therefore we can evaluate that in the SUSY models the sigma of the LFV
process \( \gamma\gamma \rightarrow \ell_i\ell_j \) is about 2 – 3 order smaller than that in the TC2 models, as shown in table. I.

V. CONCLUSION

We have performed an analysis for the TC2-induced LFV productions of \( \tau\bar{\mu} \) and \( \tau\bar{e} \) via \( \gamma\gamma \) collision at the ILC. We found that in the optimum part of the parameter space, the production rate of \( \gamma\gamma \rightarrow \tau\bar{\mu}(\bar{e}) \) can reach 1 fb. This means that we may have 100 events each year for the designed luminosity of 100 fb\(^{-1}\)/year at the ILC. Since the SM value of the production rate is completely negligible, the observation of such \( \tau\bar{\mu}(\bar{e}) \) events would be a robust evidence of TC2. Therefore, these LFV processes may serve as a sensitive probe of TC2.

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