Probing topcolor-assisted technicolor models from like-sign $\tau$ pair production in $e\gamma$ collisions

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Abstract

We consider the contributions of the extra gauge boson $Z'$ to the like sign $\tau$ production process $e^-\gamma \rightarrow e^+ (\mu^+)\tau^-\tau^-$, induced by the tree-level flavor changing interactions. Since these rare production are far below the observable level in the Standard Model and other popular new physics models such as the minimal supersymmetric model, we find that $Z'$ can give significant contributions to this process, and with reasonable values of the parameters in TC2 models, the cross section $\sigma$ can reach several tens of fb and may be detected at the $e\gamma$ collisions.

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The mechanism of electroweak symmetry breaking (EWSB) remains the most prominent mystery in elementary particle physics. Probing EWSB will be one of the most important tasks in the future high energy colliders. Dynamical electroweak symmetry breaking (EWSB), such as technicolor (TC) theory [1], is an attractive idea that it avoids the shortcomings of triviality and unnaturalness arising from the elementary Higgs field. TC2 theory is an attractive scheme in which there is an explicit dynamical mechanism for breaking electroweak symmetry and generating the fermion masses including the heavy top quark mass. It is one of the important promising candidates for the mechanism of EWSB.

In TC2 theory [2], EWSB is driven mainly by TC interactions, the extended technicolor (ETC) interactions give contributions to all ordinary quark and lepton masses including a very small portion of the top quark mass, namely \( m_t' = \epsilon m_t \) with a model-dependent parameter \( \epsilon (\epsilon \ll 1) \). The topcolor interactions also make small contributions to EWSB and give rise to the main part of the top quark mass \( m_t - m_t' = (1 - \epsilon) m_t \) similar to the constituent masses of the light quarks in QCD. This means that the associated \( Z' \) is the physically observable objects. Thus \( Z' \) can be seen as the characteristic feature of TC2 theory. Studying the possible signatures of \( Z' \) at future high energy colliders can be used to test TC2 theory and further probe the EWSB mechanism.

The third generation is treated differently, which is the characteristic feature of the TC2 theory. As the heaviest lepton, the properties of the \( \tau \) lepton are distinctive –it may have larger tree-level flavor changing couplings, such as \( \tau - \mu \) and \( \tau - e \) transformation. At the same time, there are many kinds of new physics scenarios predicting new particles, which can lead to significant LFC signals. For example, in the minimal supersymmetric standard model (SM), a large \( \nu_\mu - \nu_\tau \) mixing leads to clear LFC signals in slepton and lepton collider [3]. 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 LFC processes [4].

The international linear collider (ILC) offers excellent new opportunities for the study of high energy particle collisions. The idea to convert the electron beams of a ILC into photon beams, by laser backscattering, and thus create a photon collider, was first discussed almost 30 years ago in [5], and then studied sufficiently in the coming years [6]. With the luminosity and energy of such colliders being comparable to those of the basic \( e^+e^- \) collider, one may now consider the process such as \( e^-\gamma \rightarrow e^+(\mu^+)\tau^-\tau^- \).
Some leptonic flavor violations in the presence of an extra Z’ has been studied in the literature\cite{7}. In this note, we calculate the contributions of the extra $U(1)$ gauge boson $Z'$ to the flavor violating process $e^-\gamma \rightarrow e^+(\mu^+)\tau^-\tau^-$ and see whether $Z'$ can be detected via this process at high-energy linear $e\gamma$ collision experiments. We find that this process is important in probing the gauge boson $Z'$. With reasonable values of the parameters in TC2 models, the signal rates can be fairly large, which may be detected at the $e\gamma$ colliders based on the ILC experiments.

For TC2 models \cite{2}, the underlying interactions, topcolor interactions, are non-universal and therefore do not posses a GIM mechanism. This is an essential feature of this kind of models due to the need to single out the top quark for condensation. This non-universal gauge interactions result in the FC coupling vertices when one writes the interactions in the quark mass eigenbasis. Thus the extra gauge boson predicted by this kind of models have large couplings to the third generation and can induce the FC couplings.

The couplings of the extra $U(1)$ gauge bosons $Z'$ to the ordinary fermions can be written as \cite{8}:

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

where $g_1$ is the ordinary hypercharge gauge coupling constant and $k_{\mu e}$, $k_{\tau e}$ 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 $e\gamma \rightarrow \bar{e}(\bar{\mu})\tau\tau$.

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 $\mu$ and $e$ leptons. Since the non-universal gauge 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 $e\gamma \rightarrow \bar{e}\tau\tau$ and $e\gamma \rightarrow \bar{\mu}\tau\tau$ is only the masses the final state particles. Considering the large mass of the $Z'$, $M_{Z'} > 1 TeV$, for simplicity, We will take $m_{\mu} = m_e = 0$ in the following discussion, i.e., assuming the cross sections of the two channels $e\gamma \rightarrow \bar{e}\tau\tau$ and $e\gamma \rightarrow \bar{\mu}\tau\tau$ are equal to each other and take the former as an example in the following discussion.
The TC2 parameters concerned in this process are $K_{\tau e}$, $K_{\tau \mu}$, $K_{\epsilon \mu}$, $K_1$ and the mass of the extra gauge boson $M'_Z$. $K_{\epsilon \mu}$ is very small, about $10^{-3}$, we will not consider the process induced by the coupling with it. In our calculation, we have assumed $K_{\tau \mu} = K_{\tau e} = K_{\tau l}$ ($l = e, \mu$) [8, 9]. In fact, for the TC2 models, the extended gauge groups are broken at the TeV scale, which proposes that $K_{\tau l}$ is an $O(1)$ free parameter. Its value can be generally constrained by the current experimental upper limits on the LFV processes $l_i \to l_j \gamma$ and $l_i \to l_j l_k l_l$. However, from the numerical results of Ref. [10], we can see that the LFV processes $l_i \to l_j \gamma$ and $l_i \to l_j l_k l_l$ can not give severe constraints on the mixing factor $K_{\tau l}$. Thus, in our calculation, we choose $K_{\tau l}$ in the range of $0 - 1$, which is expected consistent with theoretically-allowed parameter regions and also with current experimental data.

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]. We choose $K_1 = 0.2$ since the $K_1$ occurs only in the decay width of $Z'$ and affects the cross section slightly.

The lower limits on the mass $M'_Z$ of the new gauge boson $Z'$ predicted by topcolor $Z'$ scenario can be obtained via studying its effects on various observable, which has been extensively studied [8]. For example, Ref. [12] has shown that, to fit the electroweak precision measurement data, the $Z'$ mass $M'_Z$ must be larger than 1 TeV. The lower $Z'$ bounds on $M'_Z$ can also be obtained from dijet and dilepton production at the Tevatron $Z'$ experiments [13], or from $B \bar{B}$ mixing [14]. However, these bounds are significantly weaker than those from precisely electroweak data. Furthermore, Refs. [15] have shown that, for the coupling parameter $K_1 < 1$, the $Z'$ mass $M'_Z$ can be explored up to several TeV at the ILC experiment with $\sqrt{S} = 500$ GeV and the integrated luminosity $L_{int} = 100$ fb$^{-1}$. As numerical estimation, we will take $M'_Z$ as a free parameter and assume that $M'_Z$ is in the range of 1TeV - 2.5TeV throughout this paper. Finally, Note that the charge conjugate $\bar{\tau} \bar{\tau} \mu(e)$ production channel are also included in our numerical study.

The total decay width of the extra gauge boson $Z'$ is dominated, since the topcolor scenarios treat the third generation differently, by the third generation, i.e., the $t\bar{t}$, $b\bar{b}$, $\tau\bar{\tau}$ and the $\nu_\tau \bar{\nu}_\tau$ channels, which can be approximately calculated as:

$$\Gamma'_Z \sim \frac{g^2 \cot \theta}{4\pi} M'_Z \left( \frac{5}{4} + \frac{1}{3} \right) \sim K_1 M'_Z$$

Where the former factor in the bracket is from the lepton contribution, while the quarks
give the latter result.

\[
\begin{align*}
\mathcal{M} &= \frac{1}{4} i e g K_{\tau\mu}^2 \left[ a_1 \bar{u}_{\tau,2} \gamma_{\mu} (P_L + 2P_R) v_{e2} \cdot \bar{u}_{\tau,1} \gamma_{\mu} (P_L + 2P_R) (p_{e1} + p_\gamma) \gamma_{\mu} u_e \epsilon_{\mu} \\
&\quad + a_2 \bar{u}_{\tau,2} \gamma_{\nu} (P_L + 2P_R) v_{e2} \cdot \bar{u}_{\tau,1} \gamma_{\nu} (p_{\tau,2} - p_\gamma) \gamma_{\nu} (P_L + 2P_R) u_e \epsilon_{\mu} \\
&\quad + a_3 \bar{u}_{\tau,2} \gamma_{\nu} (P_L + 2P_R) p_\gamma \gamma_{\mu} v_{e2} \cdot \bar{u}_{\tau,1} \gamma_{\mu} (P_L + 2P_R) u_e \epsilon_{\mu} \\
&\quad + a_4 \bar{u}_{\tau,2} \gamma_{\mu} (p_{\tau,2} - p_\gamma) \gamma_{\mu} v_{e2} \cdot \bar{u}_{\tau,1} \gamma_{\mu} (P_L + 2P_R) u_e \epsilon_{\mu} \right]
\end{align*}
\]

The expressions \( a_1, a_2, a_3 \) and \( a_4 \) in equation (3) are given as,

\[
\begin{align*}
a_1 &= \frac{1}{(p_e + p_\gamma)^2 - M_{Z'}^2}, \\
a_2 &= \frac{1}{(p_{\tau 1} - p_\gamma)^2 - M_{Z'}^2}, \\
a_3 &= \frac{1}{(p_\gamma - p_e)^2 - M_{Z'}^2}, \\
a_4 &= \frac{1}{(p_{\tau 2} - p_\gamma)^2 - M_{Z'}^2}.
\end{align*}
\]
Where \( p_e(p_{\bar{e}}) \) denotes the momentum of the initial \( e \) (the final state \( \bar{e} \)), \( p_{\tau_1} \) and \( p_{\tau_2} \) denotes the momenta of the final two like-sign \( \tau \) particles and \( p_\gamma \), the initial photon momentum; \( P_{R,L} = (1 \pm \gamma^5)/2 \) are the chiral operator.

The hard photon beam of the \( e^-\gamma \) colliders can be obtained from laser backscattering at the ILC\[16\]. We define that \( \sqrt{\hat{s}} \) and \( \sqrt{s} \) are the center-of-mass energies of the \( e^-\gamma \) and \( e^+e^- \) colliders, respectively. After calculating the cross section \( \sigma(\hat{s}) \) for the subprocess \( e^-\gamma \rightarrow e^+(\mu^+)\tau\tau \), the total cross section \( \sqrt{s} \) at the ILC experiments can be obtained by folding \( \sigma(\hat{s}) \) with the backscattered laser photon spectrum \( f_\gamma(x)(\hat{s} = x^2s) \)

\[
\sigma = \int_{2m_e/\sqrt{s}}^{x_{max}} dx \hat{\sigma}(\hat{s}) f_\gamma(x). \tag{5}
\]

The backscattered laser photon spectrum \( f_\gamma(x) \) is given in Ref.[16]. Beyond a certain laser energy \( e^+e^- \) pairs are produced, which significantly degrades the photon beam. This leads to a maximum \( e\gamma \) centre of mass energy of \( \sim 0.91 \times \sqrt{s} \).

In our calculation, we restrict the angles of the observed particles relative to the beam, \( \theta_{e^-} \) and \( \theta_{e^+} \) to the range \( 10^\circ \leq \theta_{e^-}, \theta_{e^+} \leq 170^\circ \). We further restrict the particle energy \( E_e \geq 10 \text{ GeV} \). For simplicity, we have ignored the possible polarization for the electron and photon beams. To obtain numerical results, we take \( m_\tau = 1.777 \text{ GeV} \), \( m_\mu = 0.12 \text{ GeV} \) and \( \alpha_e = 1/128 \)\[17\]. For estimating the number of the \( e^+\tau\tau \) event, we consider the \( e^+e^- \) centre-of-mass energy \( \sqrt{s} \) in the range of 300GeV-1500GeV appropriate to the TESLA/NLC/JLC high energy colliders and assume an integrated luminosity of \( L = 500 fb^{-1} \).

In Fig.2, we show the cross section \( \sigma \) of the process \( e^-\gamma \rightarrow e^+(\mu^+)\tau^-\tau^- \) as a function of the mass of the \( Z' \) for three values of the center-of-mass energy \( \sqrt{s} \). One can see that \( Z' \) can give significant contributions to the process \( e^-\gamma \rightarrow e^+\tau\tau \), and the cross section \( \sigma \) is sensitive to the parameter space. The \( Z' \) contribution increases with the increasing \( \sqrt{s} \).

The signature of \( e\gamma \rightarrow e(\mu)\tau\tau \) can be chosen as two like-sign leptons, one light antilepton, plus missing energy, i.e., \( \mu\mu\ell + E(\ell = e, \mu) \) with the two \( \tau \) leptons decaying into the like-sign \( \mu \) leptons. The background is negligible though the signal is hurt by a factor about 1/36, the product of the leptonic decay branching ratios of the \( \tau \) lepton.

From Fig.2, we can see the optimum value of the cross section can reach several tens fb, so there could be hundreds of events after the signal depressed with the designated integrated luminosity above, i.e, \( L = 500 fb^{-1} \), which may be detected in the future ILC experiments.

To see the effect of flavor violating \( K_{\tau l} \) on the \( \sigma \), we plot the sigma varying as \( K_{\tau l} \) for
three values of the $M_Z'$. We can see from Fig.3 that the cross section $\sigma$ is larger than $0.1 \, fb$ for $K_{\tau l} \geq 0.4$. Increasing $K_{\tau l}$, the maximum value can reach several $fb$. In this case, there are about several hundred like-sign $\tau\tau$ production events to be generated in the future ILC experiments. Considering the rare clear background of the leptons production, we can still obtain several events even with small sample of the leptonic decay of the like-sign $\tau$ leptons.

![Graph](image1.png)

**FIG. 2:** The contribution from top-pion scalars $\pi_t^0$ the process $e\gamma \rightarrow e^+ (\mu^+) \tau\bar{\tau}$ in TC2 models.

![Graph](image2.png)

**FIG. 3:** The dependence of the cross section $\sigma$ of the LFV process $e\gamma \rightarrow \tau\tau\bar{e}(\bar{\mu})$ on the mixing parameter $K_{\tau l}$ for $M_{Z'} = 1, 1.5,$ and $2.5$ TeV with (a) $\sqrt{s} = 500$ GeV, (b) $\sqrt{s} = 800$ GeV.

The TC2 models also predict the existence of the neutral state, top-pion boson $\pi_t^0$, which
can also induce the LFV processes with the couplings:

\[
\frac{m_\tau}{\nu} K_{\tau i} \bar{\tau}^\gamma_5 l_i \pi^0_t ,
\]  

(6)

Where \( \nu = \nu_W/\sqrt{2} \approx 174 \text{GeV} \), \( l = \tau, \mu \) or \( e \), \( l_i (i=1,2) \) is the first(second)generation lepton \( e(\mu) \), and \( k_{\tau i} \) is the flavor mixing factor between the third-and the first-or second- generation leptons. There certainly is also the FC scalar coupling \( \pi^0_t \mu \bar{e} \). However, Similarly, the topcolor interactions only contact with the third-generation fermions, and thus, the flavor mixing between the first- and second-generation fermions is very small, which can be safely ignored. We can see from Fig.4 that the cross section \( \sigma \) is smaller than \( 4 \times 10^{-3} \text{fb} \) for \( \sqrt{s} \geq 500 \text{GeV} \). The contribution of \( \pi^0_t \) is negligible, which is understandable from the LFV couplings in eqn(6) since the strengths are depressed by factor \( \frac{m_\tau}{\nu} \).

Before ending the discussion, we want to point out that the like-sign \( \tau \) pair productions may be quite unique in probing the TC2 model at the ILC. To enhance the like-sign \( \tau \) pair production rate to the accessible level at the ILC, the LFV \( \tau \) lepton couplings \( \tau \bar{e}Z' \) cannot be too small. The TC2 model predict sizable tree-level \( \tau \bar{e}Z' \) coupling and thus may enhance the like-sign \( \tau \) pair production rate to the accessible level at the ILC. In many other popular extensions of the SM, there are no tree-level \( \tau \) lepton LFV couplings and the couplings \( \tau \bar{e}\phi \) ( \( \phi \) is any scalar field) or \( \tau \bar{e}V \) (\( V = \gamma, Z, g \) or any new gauge boson) are induced at loop-level, which are usually too small to make the like-sign \( \tau \) pair productions observable at
the ILC. For example, the \( \tau \) lepton LFV couplings are induced at loop-level in the \( R \)-parity violating MSSM \([19]\). Although they can be much larger than in the SM, we found that their contribution to the cross sections of \( e\gamma \to \bar{\epsilon}(\bar{\mu})\tau\tau \) at the ILC is smaller than \( 10^{-5} \text{ fb} \).

The search for LFV processes is one of the most interesting possibilities to test the SM, with the potential for either discovering or putting stringent bounds on new physics. In the SM, there are no FC coupling at tree-level and at one-loop level they are GIM suppressed. In models beyond SM, however, new particles may appear and have significant contributions to the LFV processes. Therefore, the processes can give an ideal place to search the signals of the new particles. In this paper, we calculated the contributions of the gauge boson \( Z' \) to the LFV process \( e^-\gamma \to e^+(\mu^+)\tau\tau \) in the framework of TC2 models and discussed the possibility of detecting this new particle in the future ILC experiments. Our numerical results show that the cross section \( \sigma \) induced by the extra gauge boson \( Z' \) is in the range of the \( 10^{-1} - 1 \) fb. In quite a large space of the parameters, the cross section \( \sigma \) can reach several fb. So it is possible to detect the signals of the extra gauge boson \( Z' \) via the process \( e^-\gamma \to e^+(\mu^+)\tau\tau \) at the \( e\gamma \) colliders based on the ILC experiments.

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