The process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ in topcolor-assisted technicolor models

Chongxing Yue$^a$, Hongjie Zong$^b$, Wei Wang$^a$

$^a$ Department of Physics, Liaoning Normal University, Dalian 116029, China

$^b$ College of Physics and Information Engineering, Henan Normal University, Henan 453002, China

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Abstract

In the context of topcolor-assisted technicolor (TC2) models, we consider the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ and calculate the cross section of this process at leading order. It is shown that the extra $U(1)$ gauge boson $Z'$ predicted by TC2 models can give significant contributions to the process $e^+e^- \rightarrow \nu_\tau\bar{\nu}_\tau\gamma$, which may be detected in the future high energy linear $e^+e^-$ collider (LC) experiments.

*E-mail:cxyue@lnnu.edu.cn
The cause of electroweak symmetry breaking (EWSB) and the origin of fermion masses are important problems of current particle physics. The present and next generation of colliders will help explain the nature of EWSB and the origin of fermion masses. The LHC is expected to directly probe possible new physics (NP) beyond the standard model (SM) up to a scale of a few TeV, while the high energy linear $e^+e^-$ collider (LC) is required to complement the probe of the new particles with detailed measurements. Furthermore, some kinds of NP predict the existence of new particles that would be manifested as rather spectacular resonance in the LC experiments, if the achievable centre-of-mass energy is sufficient. Even their masses exceed the centre-of-mass energy, it also retains an indirect sensitivity through a precision study the virtual corrections to the electroweak observables. A LC represents an ideal laboratory for studying this kind of NP [1].

The production of one or more photons and missing energy in high energy $e^+e^-$ collisions is a process of great interest for the LEP and future LC experiments. The process $e^+e^-\rightarrow\nu\bar{\nu}\gamma$ in the SM has been successfully used for giving the number of light neutrino species. The events with single- and multi-photon final states plus missing energy play an important role in the search for the new phenomena of NP beyond the SM [2].

In the context of the SM, the process $e^+e^-\rightarrow\nu\bar{\nu}\gamma$ has been extensively studied in leading order, one-loop QED, and three-loop QCD corrections [2, 3, 4]. Recently, Ref.[5] has examined the sensitivity of this process to extra gauge bosons $W'$, which arise in the left-right symmetric model (LRM) [6], un-unified model (UUM) [7], and the $KK$ model [8]. They find that the process $e^+e^-\rightarrow\nu\bar{\nu}\gamma$ can be used to detected these new particles up to several TeV, which depends on the model, the centre-of-mass energy, and the assumed integrated luminosity. Furthermore, if these new particles are discovered at LHC or other experiments, this process can also be used to measure the couplings of $W'$ to neutrinos.

In this note, we consider the process $e^+e^-\rightarrow\nu\bar{\nu}\gamma$ in the framework of topcolor-assisted technicolor (TC2) models [9] and calculate the contributions of the extra $U(1)$ gauge boson $Z'$ to this process. We find that the gauge boson $Z'$ can only give significant contributes to the process $e^+e^-\rightarrow\nu\tau\bar{\nu}_\tau\gamma$. When the centre-of-mass $\sqrt{s}$ is slightly larger the extra gauge boson $Z'$ mass $M_{Z'}$, the peak of each curve emerges. With reasonable
values of the parameters in TC2 models, the cross section $\sigma$ of the process $e^+e^- \rightarrow \nu_\tau \bar{\nu}_\tau \gamma$ can reach 2.4pb. Thus, this process may be used to detect the extra $U(1)$ gauge boson $Z'$ and further test TC2 models in the future LC experiments.

It is believed that there may be a common origin for EWSB and top quark mass generation. Much theoretical work has been carried out in connection to the top quark and EWSB. TC2 models [9] and flavor-universal TC2 models [10] are two of such examples. A common feature of such type of models is that the existence of extra $U(1)$ gauge bosons $Z'$ is predicted. These new particles treat the third generation fermions differently from those in the first and second generations. The couplings of the gauge boson $Z'$ relevant to our calculation can be written as [11, 12]:

$$L_{Z'} = -\frac{g_1}{2} \left[ \cot \theta' (\bar{\tau}_L \gamma^\mu \tau_L + 2 \bar{\tau}_R \gamma^\mu \tau_R + \bar{\nu}_\tau L \gamma^\mu \nu_\tau L) - \tan \theta' (\bar{e}_L \gamma^\mu e_L + 2 \bar{e}_R \gamma^\mu e_R + \bar{\nu}_e L \gamma^\mu \nu_e L + 2 \bar{\mu}_L \gamma^\mu \mu_L + \bar{\nu}_\mu L \gamma^\mu \nu_\mu L) \right] \cdot Z_\mu,$$

(1)

where $g_1$ is the ordinary hypercharge gauge coupling constant, $\theta'$ is the mixing angle. To obtain the top quark condensation and not form the bottom quark condensation, there must be $\tan \theta' \ll 1$ [9, 11].

We can see from Eq.(1) that the extra gauge boson $Z'$ exchange can indeed contribute to the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. However, compared to the process $e^+e^- \rightarrow \nu_\tau \bar{\nu}_\tau \gamma$, the cross sections of the processes $e^+e^- \rightarrow \nu_e \bar{\nu}_e \gamma$ and $e^+e^- \rightarrow \nu_\mu \bar{\nu}_\mu \gamma$ are suppressed by the factor $\tan^4 \theta'$. Thus, we can ignore the corrections of $Z'$ to the processes $e^+e^- \rightarrow \nu_\mu \bar{\nu}_\mu \gamma$, $\nu_e \bar{\nu}_e \gamma$ and only consider the contributions of $Z'$ to the process $e^+e^- \rightarrow \nu_\tau \bar{\nu}_\tau \gamma$.

In the SM, the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ proceeds at tree-level through s-channel Z exchange and t-channel W exchange with a photon being radiated from every possible charged particle. The relevant Feynman diagrams are shown in Fig.1 of Ref.[2]. In our calculation, we must consider the interference effects between the electroweak gauge bosons $W$, $Z$ and extra $U(1)$ gauge boson $Z'$ on the cross section of the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. However, since the $Z'$ has significant contributions to the process $e^+e^- \rightarrow \nu_\tau \bar{\nu}_\tau \gamma$ only, the interference term relative only to the couplings $Z\nu_\tau \bar{\nu}_\tau$ and $Z'\nu_\tau \bar{\nu}_\tau$. The Feynman diagrams for the process $e^+e^- \rightarrow \nu_\tau \bar{\nu}_\tau \gamma$ are depicted in Fig.1 at leading order. The main aim of
this paper is to calculate the contributions of TC2 models to the process \( e^+e^- \rightarrow \nu\bar{\nu}\gamma \) and see whether the \( Z' \) can be detected in the future LC experiments via this process. If the extra \( U(1) \) gauge boson \( Z' \) is indeed observed, it will be important to study high order effects.

Figure 1: The Feynman diagrams contribute to the process \( e^+e^- \rightarrow \nu\bar{\nu}\gamma \) at leading order.

Let \( M \) denote the sum of the amplitudes shown in Fig.1. Using Eq.(1) and other relevant Feynman rules, squaring the helicity amplitudes and summing over the final state helicities, the spin-averaged unpolarized \( |M|^2 \) for the process \( e^+(p_+) + e^-(p_-) \rightarrow \nu(q_-) + \bar{\nu}(q_+) + \gamma(k) \) can be written as:

\[
|M|^2 = \frac{(4\pi)^3\alpha^3}{2S_W^4C_W^4 k_+k_-} \left\{ \left[ \frac{(S_W^2 - \frac{1}{2})^2 + \frac{S_W^4}{4Z^2} + \frac{(S_W^2 - \frac{1}{2})S_W^2}{Z \cdot Z'}}{Z^2} \right](u^2 + u'^2) \right.
\]
\[
+ \left[ \frac{1}{Z^2} + \frac{1}{Z'^2} + \frac{2}{Z \cdot Z'} \right] S_W^4(t^2 + t'^2) \right\},
\]

with

\[
s' = (q_+ + q_-)^2, \quad u = (p_+ - q_-)^2, \quad u' = (p_- - q_+)^2,
\]
\[
t = (p_+ - q_+)^2, \quad t' = (p_- - q_-)^2, \quad k_\pm = 2p_{\pm}k,
\]
\[
Z = s' - M_Z^2 + iM_Z\Gamma_Z, \quad Z' = s' - M_{Z'}^2 + iM_{Z'}\Gamma_{Z'}.
\]

Where \( \alpha \) is the electromagnetic coupling constant, \( S_W = \sin \theta_W \) which \( \theta_W \) is the Weinberg angle. \( \Gamma_Z \) and \( \Gamma_{Z'} \) are the total decay widths of the gauge bosons \( Z \) and \( Z' \), respectively.
The decay width $\Gamma_{Z'}$ is dominated by the decay models $t\bar{t}, b\bar{b}$. In the following numerical estimation, we will take [11]:

$$\Gamma_{Z'} \approx \frac{g_1^2 \cot^2 \theta'}{12\pi} M_{Z'} = \frac{1}{3} M_{Z'},$$

which corresponds to $\tan^2 \theta' = 0.01$.

The limits on the masses of the extra $U(1)$ gauge bosons $Z'$ can be obtained via studying their effects on various experimental observables [12,13]. For example, Ref.[14] has shown that $B\bar{B}$ mixing provides stronger lower bounds on the mass of $Z'$ predicted by TC2 models, one must has $M_{Z'} > 6.8 \text{ TeV}(9.6 \text{ TeV})$ if ETC does(does not) contribute to the $cp$–violation parameter $\varepsilon$. Recently, Ref.[15] has restudied the bound placed by the electroweak measurement data on the $Z'$ mass. They find that $Z'$ predicted by TC2 models must be heavier than 1 TeV. As numerical estimation, we will take $M_{Z'}$ as a free parameter and assume it in the range of $1 \sim 3 \text{ TeV}$.

For the process $e^+e^- \rightarrow \nu_\tau \bar{\nu}_\tau \gamma$, the signal is a detected, energetic photon. The kinematic variable of interest are the photon’s energy $E_\gamma$ and its angle relative to the incident electron, $\theta_\gamma$, which are both defined in the $e^+e^-$ centre-of-mass frame [5]. The doubly differential cross section of this process can be written as :

$$\frac{d\sigma}{dE_\gamma d\cos \theta_\gamma} = \frac{E_\gamma}{2s} \frac{1}{(4\pi)^4} \int_0^\pi d\theta \sin \theta \int_0^{2\pi} d\varphi |M|^2,$$

where $\sqrt{s}$ is the centre-of-mass energy of LC experiments, $\theta$ and $\varphi$ are the polar and azimuthal angles of $q_+$, in a frame where $q_+$ and $q_-$ are back-to-back.

To obtain numerical results, we take the SM parameters as $S_{W}^2 = 0.2315$, $\alpha = \frac{1}{128}$, $M_{Z} = 91.2 \text{ GeV}$, and $\Gamma_{Z} = 2.495 \text{ GeV}[16]$. Kinematically, the maximum allowed value for $E_\gamma$ is $\frac{\sqrt{s}}{2}$. In our numerical integral, we take the kinematic variables in the ranges : $10 \text{ GeV} \leq E_\gamma \leq \frac{\sqrt{s}}{2}$ and $10^0 \leq \theta_\gamma \leq 170^0$ [5].

The cross section $\sigma$ of the process $e^+e^- \rightarrow \nu_\tau \bar{\nu}_\tau \gamma$ is plotted in Fig.2 as a function of $\sqrt{s}$ for three values of $M_{Z'}$: $M_{Z'} = 1 \text{ TeV}, 2 \text{ TeV}$ and $3 \text{ TeV}$. From Fig.2 we can see that the cross section $\sigma$ increases as $M_{Z'}$ and $\sqrt{s}$ decreasing in most of the parameter space. However, the resonance peak emerges for $\sqrt{s}$ slightly above the $Z'$ mass $M_{Z'}$. For
Figure 2: The cross section $\sigma$ of the process $e^+e^- \rightarrow \nu_\tau \bar{\nu}_\tau \gamma$ versus $\sqrt{s}$ for $M_{Z'} = 1$ TeV, 2 TeV, and 3 TeV.

$\sqrt{s} = 1100$ GeV and $M_{Z'} = 1000$ GeV, the value of the cross section $\sigma$ is 2.41 pb. As long as $\sqrt{s} \leq 2$ TeV and $M_{Z'} \leq 3$ TeV, $\sigma$ is larger than 0.19 pb.

To see the effect of the extra $U(1)$ gauge boson $Z'$ mass $M_{Z'}$ on the cross section $\sigma$, we plot $\sigma$ versus $M_{Z'}$ for $\sqrt{s} = 800$ GeV, 1500 GeV and 2500 GeV in Fig.3. From Fig.3 we can see that the cross section $\sigma$ is suppressed by large $Z'$ mass $M_{Z'}$. For $\sqrt{s} = 1500$ GeV, $M_{Z'} = 1300$ GeV, the value of $\sigma$ can reach 1.48 pb. If we assume $M_{Z'} = 700$ GeV, then we have $\sigma = 4.43 \text{pb}$ for $\sqrt{s} = 800$ GeV.

The process $e^+e^- \rightarrow \nu_\tau \bar{\nu}_\tau \gamma$, which has a detected, energetic photon final state and missing energy plays an important role in the search for NP. It has been extensively studied in the SM and some specific models, such as LRM, UUM and $KK$ models. However, it is very little to study this process in the context of dynamical models of EWSB. In this note, we discuss this process in the framework of TC2 models. We find that, since the extra gauge boson $Z'$ treats the third generation fermions differently to those of the first and second generation fermions and couples preferentially to the third generation fermions,
Figure 3: The cross section $\sigma$ as a function of $M_{Z'}$ for $\sqrt{s} = 800 \text{ GeV}$, 1500 GeV and 2500 GeV.

The cross section $\sigma$ of the process $e^+e^- \rightarrow \nu_\tau \bar{\nu}_\tau \gamma$ can be significantly enhanced. With reasonable values of the parameters in TC2 models, $\sigma$ can reach 2.4 pb, which may be detected in the future LC experiments. Thus, the process $e^+e^- \rightarrow \nu_\tau \bar{\nu}_\tau \gamma$ can be used to probe the possible signals of $Z'$ and further unravel the TC2 models.

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