Lepton flavor violating signals of gauge bosons $Z'$ at future $e^+e^-$ colliders

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Abstract

Many models, such as topcolor-assisted technicolor (TC2) models and flavor-universal TC2 models, predict the existence of extra $U(1)$ gauge bosons $Z'$, which couple preferentially to the third generation. The lepton flavor violating (LFV) signals of these new particles at the future $e^+e^-$ colliders (LCs) are discussed via calculating its contributions to the LFV process $e^+e^- \rightarrow \mu \tau$. We calculate the cross section of this process and discuss its dependence on the beam polarization. The ratio of signal over square root of the background ($S/\sqrt{B}$) is also calculated. The results show that the LFV signals of the gauge bosons $Z'$ may be detected at the future LC experiments.

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The high statistic results of the SuperKamiokande (SK) atmospheric neutrino experiment [1] and the solar neutrino experiment [2] have made one to believe that neutrinos are massive and oscillate in flavor. This phenomenon is lepton flavor violating (LFV). LFV processes are practically suppressed to zero in the standard model (SM), due to the unitarity of the leptonic analog of the CKM mixing matrix and the near masslessness of the three neutrinos. So the experimental result is the first convincing signature of new physics (NP) beyond the SM and make that one is of interest in the LFV processes.

There are many kinds of NP scenarios predicting new particle, 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 [3, 4]. 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 [5, 6].

Many kinds of models beyond the SM predict the presence of massive gauge bosons $Z'$ that couple preferentially to the third generation quarks and leptons. Examples are the topcolor-assisted technicolor (TC2) models [7] and flavor-universal TC2 models [8]. It has been shown that, to fit the electroweak measurement data, the $Z'$ mass must be larger than 1 TeV [9]. Some signals of this kind of extra gauge bosons have been studied in literature [5, 6, 10]. In this paper, we are interested in studying the contributions of $Z'$ to the LFV process $e^+e^- \rightarrow \mu\tau$, as a possible LFV signal of this kind of gauge bosons at the future high energy $e^+e^-$ linear collider (LC) experiments. We calculate the cross section of this process and discuss its dependence on the beam polarization. The main SM backgrounds of this process come from the Drell-Yan process $e^+e^- \rightarrow Z(\gamma) \rightarrow \tau^+\tau^- \rightarrow \mu\bar{\nu}_\mu\tau\nu_\tau$ and $W^+W^-$ pair production $e^+e^- \rightarrow W^+W^- \rightarrow \mu\bar{\nu}_\mu\tau\nu_\tau$. The ratio of signal over square root of the background ($S/\sqrt{B}$) is simply calculated. Our results show that there will be several tens and up to thousand events to be generated at a future LC experiment with the center-of-mass energy $\sqrt{s} = 800 GeV$ and a yearly integrated luminosity of $L = 580 fb^{-1}$.2
The LFV signals of the extra \( U(1) \) gauge bosons \( Z' \), which couple preferentially to the third generation, may be detected at the future LC experiments.

The key feature of TC2 models \([7]\) and flavor-universal TC2 models \([8]\) 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 couplings of the extra \( U(1) \) gauge bosons \( Z' \) to ordinary fermions, which are related to our calculation, can be written as \([7, 11]\):

\[
\mathcal{L} = \frac{1}{2} g_1 \left\{ \tan \theta' (\bar{e}_L \gamma \mu e_L + 2 \bar{e}_R \gamma \mu e_R) - k_{\tau \mu} (\bar{\tau}_L \gamma \mu \mu_L + 2 \bar{\tau}_R \gamma \mu \mu_R) \right\} \cdot Z'_\mu, \tag{1}
\]

where \( g_1 \) is the hypercharge gauge coupling constant, \( \theta' \) is the mixing angle with \( \tan \theta' = \frac{g_1}{2 \sqrt{\pi k_1}} \) and \( k_{\tau \mu} \) is flavor mixing factor. In the following estimation, we will take \( k_{\tau \mu} = \lambda \), where \( \lambda = 0.22 \) is the Wolfenstein parameter \([12]\).

Since the electroweak gauge bosons \( \gamma \) and \( Z \) can not couple to \( \mu\tau \) at tree-level, we need not consider the interference effects between the \( \gamma, Z \) and \( Z' \) on the cross section of the process \( e^+e^- \rightarrow \mu\tau \). Then the total unpolarized cross section \( \sigma \) can be written as (at tree-level):

\[
\sigma = \frac{25 \pi^2 \alpha^3 k_{\tau \mu}^2}{12 C_W^6 k_1} \cdot \frac{s}{(s - M_Z^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2}, \tag{2}
\]

where \( C_W = \cos \theta_W \), \( \theta_W \) is the Weinberg angle. \( \sqrt{s} \) is the center-of-mass energy of LC experiments. \( M_Z \) is the mass of the extra \( U(1) \) gauge boson \( Z' \) and \( \Gamma_{Z'} \) is its total decay width. \( \Gamma_{Z'} \) is dominated by \( t\bar{t} \) and \( b\bar{b} \), which can be written as \([13]\):

\[
\Gamma_{Z'} \approx \frac{k_1 M_Z}{3}
\]
To obtain proper 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. $k_1 \leq 1$. The limits on the $Z'$ mass $M_{Z'}$ can be obtained via studying its effects on experimental observable $\sqrt{s}$. Recently, Ref.[9] has shown that, to fit the current electroweak measurement data, the $Z'$ mass must be larger than $1 TeV$. As numerical estimation, we assume the center-of-mass energy $\sqrt{s} = 800 GeV$ and take $k_1$, $M_{Z'}$ as free parameters.

In Fig.1 we plot the production cross section $\sigma$ of the LFV process $e^+e^- \rightarrow \mu\tau$ as a function of $M_{Z'}$ for three values of the parameter $k_1$: $k_1 = 0.2$ (solid line), $0.6$ (dashed line), and $1.0$ (dotted line). We can see from Fig.1 that the production cross section $\sigma$ increases as $k_1$ decreasing and strongly suppressed by large $M_{Z'}$. For $k_1 \geq 0.6$, $M_{Z'} \geq 3 TeV$, the value of $\sigma$ is smaller than $5.8 \times 10^{-3} fb$, which is too small to be detected. However, for $k_1 = 0.2$, $1 TeV \leq M_{Z'} \leq 3 TeV$, the cross section $\sigma$ varies in the range of $1.8 \times 10^{-2} fb \sim 9.5 fb$. In our calculation, we have assumed $k_{\tau\mu} = \lambda = 0.22$. If we let the flavor mixing factor $k_{\tau\mu}$ increase, then the cross section $\sigma$ will be enhanced. For example, if we take $k_{\tau\mu} = \frac{1}{\sqrt{2}}$, the cross section $\sigma$ can reach $97 fb$ for $k_1 = 0.2$ and $M_{Z'} = 1 TeV$.

TESLA is a proposed $e^+e^-$ linear collider with a center-of-mass energy $\sqrt{s} = 500 GeV$ or $800 GeV$. It is a multi-purpose machine that will test various aspects of the SM and search for signals of NP beyond the SM. It has a design luminosity of $5.8 \times 10^{34} cm^{-2}s^{-1}$ at $\sqrt{s} = 800 GeV$, which corresponds to $L = 580 fb^{-1}$ per year [14]. Thus, for $k_1 = 0.2$, $1 TeV \leq M_{Z'} \leq 3 TeV$, there will be about 10 and up to 5533 events to be generated per year at this machine.

A strong longitudinal polarization program at TESLA with considerable polarization of the electron beam and the possibility of polarization of the positron beam is planned [15]. Beam polarization is not only useful for a possible reduction of the background, but might also serve as a possible tool to disentangle different contributions to the signal. Beam polarization of the electron and positron beams would lead to a substantial enhancement of cross section of some processes. Considering the polarization of electron and positron beams, the cross section $\sigma$ of the LFV process $e^+e^- \rightarrow \mu\tau$ can be written
\[
\sigma = (1 + P_e)(1 - P_e)(\sigma_{RR} + \sigma_{RL}) + (1 - P_e)(1 + P_e)(\sigma_{LL} + \sigma_{LR}),
\]

where \( P_e \) and \( P_\bar{e} \) are the degrees of longitudinal electron and positron polarization, respectively. \( \sigma_{ij} \) are the chiral cross section of this process, which can be easily given from Eq.(1). We calculate the cross section \( \sigma \) for different beam polarizations. We find that the value of \( \sigma \) for \( (P_e, P_\bar{e}) = (0.8, 0.6) \) is equal to that of \( (P_e, P_\bar{e}) = (-0.8, 0.6) \). For \( (P_e, P_\bar{e}) = (0.8, -0.6) \), the cross section \( \sigma \) is larger than that of \( (P_e, P_\bar{e}) = (0, 0) \) in all of the parameter space. In Fig.2 we plot \( \sigma \) as a function of \( M_Z \) for \( k_1 = 0.2 \) and different beam polarizations, in which the solid line, dashed line, dotted line and dotted-dashed line represent \( (P_e, P_\bar{e}) = (0, 0), (0.8, 0.6), (0.8, -0.6), \) and \( (-0.8, -0.6) \), respectively. From Fig.2 we can see that \( \sigma \) is indeed sensitive to the polarization of electron and positron beams. For \( (P_e, P_\bar{e}) = (0.8, -0.6) \) and \( k_1 = 0.2 \), the cross section \( \sigma \) varies in the range of \( 4.2 \times 10^{-2} fb \sim 22 fb \) for \( 1 TeV \leq M_Z \leq 3 TeV \).

To see the effect of center-of-mass energy \( \sqrt{s} \) on the cross section \( \sigma \), we show the dependence of \( \sigma \) on \( \sqrt{s} \) for \( k_1 = 0.2 \), \( M_Z = 1.5 TeV \) and different beam polarizations in Fig.3. We can see from Fig.3 that the cross section \( \sigma \) increases with \( \sqrt{s} \) increasing for \( \sqrt{s} \leq M_Z \). For \( \sqrt{s} = M_Z \), \( \sigma \) reach the maximum value. The maximum value of \( \sigma \) can reach 464 fb.

Although the LFV signal is quite spectacular, it is not background-free \cite{16}. The leading SM background of the LFV process \( e^+e^- \rightarrow \mu\tau \) come from the Drell-Yan process \( e^+e^- \rightarrow Z(\gamma) \rightarrow \tau^+\tau^- \rightarrow \mu\bar{\nu}_\mu\nu_\tau\tau \) and \( W^+W^- \) pair production process \( e^+e^- \rightarrow W^+W^- \rightarrow \mu\bar{\nu}_\mu\tau\bar{\nu}_\tau \). As numerical estimation, we only calculate the cross sections of the SM background at tree-level and do not apply cut on the final state. Certainly, cuts as applied in the study of lepton production will enhance the \( S/\sqrt{B} \), which is the ratio signal over square root of the background. In Fig.4 we plot \( S/\sqrt{B} \) as a function of the \( Z' \) mass \( M_Z \) for \( (P_e, P_\bar{e}) = (0, 0) \) and three values of the parameter \( k_1 \): \( k_1 = 0.2, 0.6 \) and \( 1.0 \). In Fig.4 we have taken the integrated luminosity \( L = 580 fb^{-1} \) for \( \sqrt{s} = 800 GeV \) and the branching ratios \( Br(\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau) = (17.4 \pm 0.06)\% \), \( Br(W \rightarrow \mu\bar{\nu}_\mu) = (10.54 \pm 0.16)\% \) and \( Br(W \rightarrow \tau\bar{\nu}_\tau) = (11.09 \pm 0.22)\% \) \cite{17}. From Fig.4 we can see that, with reasonable values
of the parameters, the LFV signals of extra $U(1)$ gauge bosons $Z'$ may be detected in the future LC experiments, even if any cuts are not applied and the electron beam and the positron beam are not polarized. If we apply appropriate cuts on the SM background, the cases where the ratio $S/\sqrt{B}$ is of order 1 or smaller should clearly improve. For example, a cut on the angular distribution of the final state leptons will strongly reduce the $WW$ background\cite{18}.

The results of the atmospheric neutrino experiment and the solar neutrino experiment imply that large mixing is expected between the second and third generation for leptons. In this paper, we assume that the large mixing between the third and second generation leptons is due to the new strong interactions and consider the LFV process $e^+e^- \rightarrow \mu\tau$. We find that the extra $U(1)$ gauge bosons $Z'$ predicted by TC2 models or flavor-universal TC2 models can give significant contributions to this process. Over a sizable region of the parameter space, the production cross section $\sigma$ of this process is large than $1.0 \times 10^{-2} \text{fb}$. Furthermore, the cross section $\sigma$ can be significantly enhanced by polarization of the electron beam and the positron beam. For example, the value of $\sigma$ can reach $22 \text{fb}$ for $(P_e, P_\bar{e}) = (0.8, -0.6)$. Thus we can conclude that the LFV signals of extra $U(1)$ gauge bosons $Z'$ may be detected via this LFV process $e^+e^- \rightarrow \mu\tau$ in the future LC experiments.
Figure captions

Fig.1: The cross section $\sigma$ of the LFV process $e^+e^- \rightarrow \mu\tau$ as a function of the gauge boson $Z'$ mass $M_{Z'}$ for $\sqrt{s} = 800 GeV$, $k_1 = 0.2$(solid line), 0.6(dashed line) and 1.0(dotted line).

Fig.2: The cross section $\sigma$ as a function of $M_Z$ for $\sqrt{s} = 800 GeV$, $k_1 = 0.2$ and different beam polarizations, in which the solid line, dashed line, dotted line and dotted-dashed line represent $(P_e, P_{\bar{e}}) = (0, 0), (0.8, 0.6), (0.8, -0.6)$ and $(-0.8, -0.6)$, respectively.

Fig.3: The dependence of $\sigma$ on $\sqrt{s}$ for $k_1 = 0.2$, $M_Z = 1.5 TeV$ and different beam polarizations, in which the solid line, dashed line, dotted line and dotted-dashed line represent $(P_e, P_{\bar{e}}) = (0, 0), (0.8, 0.6), (0.8, -0.6)$ and $(-0.8, -0.6)$, respectively.

Fig.4: The ratio of $S/\sqrt{B}$ as a function of $M_Z$ for $L = 580 fb^{-1}$. and $k_1 = 0.2$(solid line), 0.6(dashed line) and 1.0(dotted line).
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Fig. 1

Fig. 2
