Non-universal gauge bosons $Z'$ and rare top decays

Chongxing Yue $^a$, Hongjie Zong $^b$, Lanjun Liu $^b$

$^a$ 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

We study a new method for detecting non-universal gauge bosons $Z'$ via considering their effects on rare top decays. We calculate the contributions of the non-universal gauge bosons $Z'$ predicted by topcolor-assisted technicolor (TC2) models and flavor-universal TC2 models on the rare top decays $t \rightarrow eV (V=g, \gamma, Z)$ and $t \rightarrow cl_i l_j (l_i, l_j = \tau, \mu, or e)$. We show that the branching ratios of these processes can be significantly enhanced. Over a sizable region of the parameter space, we have $Br(t \rightarrow cg) \sim 10^{-5}$ and $Br(t \rightarrow c\tau\tau) \sim 10^{-7}$, which may approach the observable threshold of near future experiments. Non-universal gauge bosons $Z'$ may be detected via the rare top decay processes at the top-quark factories such as the CERN LHC.

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*E-mail: cxyue@lnnu.edu.cn
There are many models beyond the standard model (SM) predicting the existence of extra $U(1)$ gauge bosons $Z'$. If discovered they would represent irrefutable proof of new physics, most likely that the SM gauge groups must be extended. If these extensions are associated with flavor symmetry breaking, the gauge interactions will not be flavor-universal, which predict the existence of non-universal gauge bosons $Z'$. After the mass diagonalization from the flavor eigenbasis into the mass eigenbasis, the non-universal gauge interactions result in the tree-level flavor-changing neutral current (FCNC) vertices of the non-universal gauge bosons $Z'$. Hence, $Z'$ may have significant contributions to some FCNC processes. If these effects are indeed detected at LHC, LC or other experiments, it will be helpful to identify the gauge bosons $Z'$, and therefore unravel underlying theory.

In the SM, due to the GIM mechanism, rare top decays induced by FCNC are absent at tree-level and extremely small at loop levels. In some new physics models beyond the SM, rare top decays may be significantly enhanced. Thus, rare top decays provide a very sensitive probe of physics beyond the SM. Detection of rare top decays at visible levels by any of the future colliders would be instant evidence of new physics. Searching for rare top decays is one of the major goals of the next generation of high energy collider experiments, such as the Tevatron Run II and the CERN LHC.

The rare top decays have been extensively studied in the context of the SM and beyond. It has been shown that the SM predictions for rare top decays are far below the feasible experimental possibilities at present or future collider experiments and some models beyond the SM can enhance them by several orders to make them approach the observable threshold of near-future experiments. The aim of this paper is to show that the non-universal gauge bosons $Z'$ predicted by topcolor-assisted technicolor (TC2) models and flavor-universal TC2 models can give significant contributions to the rare top decays $t \rightarrow cV (V = g, \gamma$ or $Z)$ and $t \rightarrow c\ell_i \ell_j (\ell_i, \ell_j = \tau, \mu$, or $e)$. With reasonable values of the parameters, the value of $Br(t \rightarrow cg)$ can reach $5.1 \times 10^{-5}$. For the branching ratio $Br(t \rightarrow c\tau\tau)$, it is possible to reach $6.4 \times 10^{-6}$. Thus, rare top decays may be used to detect non-universal gauge bosons $Z'$ in near future experiments.
A common feature of TC2 models \[9\] and flavor-universal TC2 models \[10\] is that a large part of the top quark mass is dynamically generated by topcolor interactions at a scale of order $1T_{eV}$. To ensure that the top quark condenses and receives a large mass while the bottom quark does not, a non-universal extended hypercharge gauge group $U(1)$ is often invoked, so that the topcolor gauge group is usually taken to be a strong coupled $SU(3) \times U(1)$. Breaking of the extended gauge groups to their diagonal subgroups produces non-universal massive gauge bosons. Thus, TC2 models and flavor-universal TC2 models all predict the existence of the non-universal gauge bosons $Z'$. These new particles treat the third generation fermions differently from those in the first and second generations. So, they can lead to FC couplings.

The flavor-diagonal couplings of $Z'$ to ordinary fermions, which are related to our calculations, can be written as \[11\]:

$$\mathcal{L}_{Z'}^{FD} = g_1 \cot \theta' Z'_\mu [(\frac{1}{6} \bar{t}_L \gamma^\mu t_L + \frac{2}{3} \bar{t}_R \gamma^\mu t_R)$$

$$- (\frac{1}{2} \bar{t}_L \gamma^\mu \tau_L + \bar{t}_R \gamma^\mu \tau_R)$$

$$- \tan^2 \theta' (\frac{1}{2} \bar{\mu}_L \gamma^\mu \mu_L + \bar{\mu}_R \gamma^\mu \mu_R)$$

$$- \tan^2 \theta' (\frac{1}{2} \bar{\tau}_L \gamma^\mu \tau_L + \bar{\tau}_R \gamma^\mu \tau_R)]$$

(1)

where $g_1$ is the hypercharge gauge coupling constant, $\theta'$ is the mixing angle with $\tan \theta' = g_1/\sqrt{4\pi k_1}$. To obtain the top quark coupling and not form a $b\bar{b}$ condensation, there must be $\tan \theta' \ll 1$ \[9\] \[10\]. The FC couplings of $Z'$ to ordinary fermions, which are related to rare top decays, can be written as:

$$\mathcal{L}_{Z'}^{FC} = - \frac{1}{6} g_1 K_{tc} Z'_\mu (\bar{t}_L \gamma^\mu c_L + 4 \bar{t}_R \gamma^\mu c_R)$$

$$- \frac{1}{2} g_1 Z'_\mu [K_{\tau e}(\bar{\tau}_L \gamma^\mu e_L + 2 \bar{\tau}_R \gamma^\mu e_R)$$

$$+ K_{\mu e}(\bar{\tau}_L \gamma^\mu \mu_L + 2 \bar{\mu}_R \gamma^\mu \mu_R)]$$

(2)

where $K_{tc}$ and $K_{ij}$ are the flavor mixing factors.
From Eq. (1) and Eq. (2) we can see that the rare top decays $t \rightarrow cV$ and $t \rightarrow cl_{ij}$ can be generated via $Z'$ exchange in TC2 models and flavor-universal TC2 models. We first consider the rare top decay processes $t \rightarrow cV (V = g, \gamma, \text{or} \ Z)$. These processes are induced by penguin diagrams. The calculations are straightforward but tedious. Similarly, Feynman diagrams for contributions of the neutral scalars to $t \rightarrow cV$ and $t \rightarrow ch$ have been calculated in Ref. [6]. Here we do not present the lengthy formulas which are expressed in terms of two- and three-point standard Feynman integrals.

Figure 1: Branching ratios $Br(t \rightarrow cV)$ as functions of the gauge bosons $Z'$ mass $M_{Z'}$ for the flavor mixing factor $K_{tc} = \lambda = 0.22$.

Our numerical results are summarized in Fig.1 and Fig.2. In Fig.1, we have assumed $K_{tc} = \lambda$, which $\lambda = 0.22$ is the Wolfenstein parameter [12]. The limits on the mass of the extra $U(1)$ gauge bosons $Z'$ can be obtained via studying their effects on various experimental observables [11]. For example, Ref. [2] studied the bound placed by the electroweak measurement data on the $Z'$ mass $M_{Z'}$. They find that $Z'$ predicted by TC2 models and flavor-universal TC2 models must be heavier than about 1 TeV. As estimation the contributions of $Z'$ to the rare top decays, we have taken the $Z'$ mass $M_{Z'}$ as a free parameter in Fig.1 and Fig.2. One can see from Fig.1 that the branching ratio is sensitive to the $Z'$ mass $M_{Z'}$ and suppressed by large $M_{Z'}$. For $1 TeV \leq M_{Z'} \leq 2 TeV$, the values of the branching ratios $Br(t \rightarrow cg)$, $Br(t \rightarrow c\gamma)$, and $Br(t \rightarrow cZ)$ vary in the ranges of $1.6 \times 10^{-6} \sim 1.2 \times 10^{-5}$, $1.7 \times 10^{-7} \sim 1.3 \times 10^{-6}$, and $8.5 \times 10^{-7} \sim 6.7 \times 10^{-6}$, respectively.
To see the effects of the flavor mixing factor $K_{tc}$ on the branching ratios $Br(t \rightarrow cV)$, we plot $Br(t \rightarrow cV)$ as functions of $K_{tc}$ for $M_{Z'} = 1.5 TeV$ in Fig.2. One can see from Fig.2 that the values of $Br(t \rightarrow cg)[Br(t \rightarrow c\gamma)]$ can reach $5.1 \times 10^{-5}$ [$5.3 \times 10^{-6}$] for $M_{Z'} = 1.5 TeV$ and $K_{tc} = 0.8$. 

The LHC sensitivity to the top quark anomalous couplings $K_{tg}$ and $K_{\gamma g}$, which come from the effects of new physics, can be obtained by studying quark-gluon fusion, single top quark production, $t+\gamma (Z)$ production, and like-sign top-pair final states, separately. The relevant results are summarized in Ref. [13]. If we assume that the anomalous coupling vertexes $\bar{t}cV$ come from the non-universal gauge bosons $Z'$, the contributions of $Z'$ to the branching ratios $Br(t \rightarrow cV)$ can be transposed to those of $Z'$ to the top quark anomalous couplings $K_{tg}^{Z'}$ and $K_{\gamma g}^{Z'}$. For example, the value of the anomalous coupling $K_{tg}^{Z'}$ can reach $6.8 \times 10^{-3}$ for $M_{Z'} = 1.5 TeV$ and $K_{tc} = 0.8$. Hence, we can conclude that, if non-universal gauge bosons $Z'$ are not too heavy and can induce large FC couplings, the possible signals of these new particles may be detected via the FCNC processes $t \rightarrow cV$ at the top quark factories such as the CERN LHC.

The non-universal gauge bosons $Z'$ can induce the tree-level FC couplings at quark and lepton sector. Thus, the rare top decays $t \rightarrow cl_{i}l_{j}$ can be generated at tree-level or at one-loop only for $i = j$. However, the contributions of $Z'$ to the processes $t \rightarrow cl_{i}l_{j}$ via the off-shell photon pengiun and $Z$ pengiun diagrams are only at the order of the
magnitude of 1% of the tree-level result and therefore can be ignored. The conclusion is similar to that of the lepton flavor-violation tau decays $\tau \rightarrow l_i l_j l_k$ [14].

In the context of TC2 models and flavor-universal TC2 models, the non-universal gauge bosons $Z'$ only treat the fermions in the third generation differently from those in the first and second generation and treat the fermions in the first generation same as those in the second generation. Thus, there must be $Br(t \rightarrow c\mu\mu) = Br(t \rightarrow cee)$ and $Br(t \rightarrow c\tau\mu) = Br(t \rightarrow c\tau e)$ for assuming $K_{\tau\mu} = K_{\tau e}$. Compared with the couplings of $Z'$ to the third family fermions, the couplings of $Z'$ to the first and second family fermions are suppressed by the factor $tan^2\theta'$. It has been shown that the choice $k_1 = 1$ corresponds to $tan^2\theta' \approx 0.01$ [11]. Thus, the branching ratio $Br(t \rightarrow c\tau\tau)$ is about four orders of magnitude larger than those of the processes $t \rightarrow c\mu\mu$ and $t \rightarrow cee$.

In Fig.3 and Fig.4 we plot branching ratios $Br(t \rightarrow c\tau\tau)$ and $Br(t \rightarrow c\tau\mu)$ as functions of the flavor mixing factor $K$. We have assumed in Fig.3 and Fig.4 that the flavor mixing factor in quark sector is equal to that in lepton sector i.e. $K_{tc} = K_{\tau\mu} = K$.

One can see that the value of $Br(t \rightarrow c\tau\tau)$ is larger than that of $Br(t \rightarrow c\tau\mu)$ in all of
Figure 4: Same as Fig.3 but for $Br(t \to c\tau\mu)$.

the parameter space. For $M_{Z'} = 1.5 TeV$ and $0.1 \leq K \leq \frac{1}{\sqrt{2}}$, there are $2 \times 10^{-8} \leq Br(t \to c\tau\tau) \leq 9.7 \times 10^{-7}$ and $2 \times 10^{-12} \leq Br(t \to c\tau\mu) \leq 4.8 \times 10^{-9}$. For $M_{Z'} = 1.0 TeV$ and $K = 0.8$, it is possible to have $Br(t \to c\tau\tau) = 6.4 \times 10^{-6}$ and $Br(t \to c\tau\mu) = 4.2 \times 10^{-8}$.

Certainly, the values of branching ratios $Br(t \to cl_{i}l_{j})$ are strongly dependent on the value of the flavor mixing factor $K$. We expect that this physical parameter can be measured in the future experiments and it can give a strong clue about the new physics beyond the SM.

If the top anomalous couplings are present and large enough, the new particles can give significantly contributions to single production of top quarks. These have been extensively studied at lepton colliders [15] and at hadron colliders [16]. Thus the non-universal gauge bosons $Z'$ predicted by TC2 models and flavor-universal TC2 models might give large contributions to single production of top quarks.

To summarize, we have studied the contributions of the non-universal gauge bosons $Z'$ predicted by TC2 models and flavor-universal TC2 models to the rare top decays $t \to cV$ and $t \to cl_{i}l_{j}$. We have shown that the branching ratios of these processes can be significantly enhanced. With reasonable values of the parameters, the branching ratio
$Br(t \rightarrow cg) [Br(t \rightarrow c\tau\tau)]$ can reach $5.1 \times 10^{-5}$ [$6.4 \times 10^{-6}$], which might approach the observable threshold of near future experiments. For the branching ratio $Br(t \rightarrow c\tau\mu)$, it is possible to reach $4.1 \times 10^{-8}$. The production of $10^7 \sim 10^8$ top quark pairs per year at the CERN LHC will allow to probe the top couplings to both known and new particles involved in possible top decay channels different from the main $t \rightarrow Wb$. On a purely statistical basis, one should be able to detect a particular decay channel whenever its branching ratio is larger than about $10^{-6} \sim 10^{-7}$ \[1, 17\]. Hence, the non-universal gauge bosons $Z'$ may be detected via rare top decays at the top-quark factories, the CERN LHC, as long as their masses are not too heavy.

Except TC2 models and flavor-universal TC2 models, there are many models beyond the SM, such as non-commuting ETC models\[18\] and top flavor seesaw models\[19\], predicting the existence of non-universal gauge bosons $Z'$, which have similar property considered in this paper. Therefore, we believe that our conclusion is quite model-independent.

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