The anomalous top quark coupling $tqg$ and $tW$ production at the $LHC$

Chong-Xing Yue, Jue Wang, You Yu, Ting-Ting Zhang

Department of Physics, Liaoning Normal University, Dalian 116029, P. R. China

January 25, 2013

Abstract

Many new physics models beyond the standard model ($SM$) can give rise to the large anomalous top couplings $tqg$ ($q = u$ and $c$). We focus our attention on these couplings induced by the topcolor-assisted technicolor ($TC2$) model and the littlest Higgs model with $T$-parity (called $LHT$ model), and consider their contributions to the production cross section and the charge asymmetry for $tW$ production at the $LHC$. We find that the anomalous top coupling $tqg$ induced by these two kinds of new physics models can indeed generate sizable charge asymmetry. The correction effects of the $LHT$ model on the production cross sections of the processes $pp \to tW^- + X$ and $pp \to tW^+ + X$ are significant large, which might be detected at the $LHC$.

PACS numbers: 14.65.Ha, 12.60.Cn, 12.15.Lk

*E-mail:cxyue@lnnu.edu.cn
1. Introduction

One of the main goals of the current or future high energy experiments, such as the LHC and ILC, is to search for new physics beyond the standard model (SM) [1]. Because of the largest mass of the top quark among all observed particles within the SM, it may be more sensitive to new physics than other fermions and it may serve as a window to probe new physics. Thus, studying the correction effects of new physics on observables about top quark is a good way to test the SM flavor structure and to learn more about the nature of electroweak symmetry breaking (EWSB) [2].

In the SM, top quark can be produced singly via electroweak interaction at hadron colliders. At leading order, there are three kinds of the partonic processes: the s-channel process ($q'\bar{q} \to tb$) involving the exchange of a time-like W boson, the t-channel process ($bq \to tq'$) involving the exchange of a space-like W boson, and the $tW$ production process ($gb \to tW^-$) involving an on-shell W boson. These processes have completely different kinematics and can be observed separately [2]. Furthermore, the t-channel process is the main source of single top production, both at the Tevatron and the LHC. At the Tevatron, the contributions of the $tW$ production process are very small, while the contributions from the s-channel production process are very small at the LHC. Thus, an accurate description of all the three production processes is important.

tW production at hadron colliders has been calculated at next leading order (NLO) in the SM [3] and been extensively studied in Refs.[4, 5]. It has been shown that this process is observable at the LHC using the fully simulated data at the CMS and ATLAS detectors [6, 7]. In the SM, the $tW$ production channel is charge symmetric, which means that the production cross section for the process $pp \to tW^- + X$ is equal to that for the process $pp \to \bar{t}W^+ + X$. However, the charge asymmetry in the $tW$ production process can be generated by non-SM values of $V_{td}$ and $V_{ts}$ of CKM matrix [8] and by the anomalous top coupling $tqg$ ($q = u$ or $c$) [9].

In the SM, the anomalous top quark coupling $tqg$ is absent at tree level and is extremely suppressed at one loop due to the GIM mechanism [10], which can not be de-
tected in current or future high-energy experiments. However, it may be large in some new physics models beyond the SM, such as the topcolor-assisted technicolor (TC2) model [11, 12], the littlest Higgs model with T-parity (called LHT model) [13], etc. In this paper, we will focus our attention on the anomalous top couplings induced by the TC2 model and the LHT model, and calculate their contributions to the production cross section and the charge asymmetry for tW production at the LHC with the center-of-mass (c.m.) energy $\sqrt{s} = 14$ TeV. Our numerical results show that the contributions of the anomalous top coupling $tqg$ induced by the TC2 model to the $tW$ process are generally smaller than those for the LHT model. With reasonable values of the free parameters of the LHT model, its corrections to the production cross sections of the processes $pp \rightarrow tW^- + X$ and $pp \rightarrow \bar{t}W^+ + X$ are in the ranges of $14\% \sim 32\%$ and $11\% \sim 24\%$, respectively. The value of the charge asymmetry parameter $R = \sigma(tW^-)/\sigma(\bar{t}W^+)$ can reach 1.05.

After discussing the anomalous top couplings $tqg$ induced by the TC2 model and the LHT model, we calculate the additional contributions of these anomalous top couplings to the $tW$ production channel at the LHC in sections 2 and 3. Our conclusions are given in section 4.

2. The TC2 model and tW production at the LHC

The TC2 model [11] is one of the phenomenologically viable models, which has almost all essential features of the topcolor scenario [12]. This model has two separate strongly interacting sectors in order to explain EWSB and the large top mass. Technicolor interaction is responsible for most of EWSB via the condensation of technifermions, but contributes very little to the top mass $\varepsilon m_t$ with the parameter $\varepsilon \ll 1$. The topcolor interaction generates the bulk of $m_t$ through condensation of top pairs $< t\bar{t} >$, but makes only a small contribution to EWSB.

The TC2 model predicts the existence of a number of new scalar states at the electroweak scale: three top-pions ($\pi^\pm_t$, $\pi^0_t$), a top-Higgs ($h^0_t$), and a techni-Higgs ($h^0_{tc}$), which are bound-states of the top quark, the bottom quark and of the techni-fermions. Since
the topcolor interaction is not flavor-universal and mainly couples to the third generation fermions, the couplings of top-pions or top-Higgs to the three family fermions are non-universal, and they have large Yukawa couplings to the third generation and can induce flavor changing (FC) couplings. The couplings of the top-pions ($\pi^0_t$, $\pi^+_t$) to ordinary fermions, which are related to our calculation, can be written as [11, 12, 14]

$$\frac{m_t}{\sqrt{2}F_t} \nu_W (iK_{UL}^{tt} K_{UR}^{tt} \bar{t}_L t_R \pi^0_t + \sqrt{2}K_{UR}^{bb} K_{DL}^{bb} \bar{b}_R b_L \pi^+_t + \text{h.c.}),$$

(1)

$$iK_{UL}^{tt} K_{UR}^{tc} \bar{c}_L c_R \pi^0_t + \sqrt{2}K_{UR}^{bb} K_{DL}^{bb} \bar{c}_R c_L \pi^+_t + \text{h.c.}),$$

(2)

where $\nu_W = \nu/\sqrt{2} \approx 174$ GeV, $F_t \approx 50$ GeV is the physical top-pion decay constant, which can be estimated from the Pagels-Stokar formula. To yield a realistic form of the CKM matrix $V_{CKM}$, it has been shown that the values of the matrix elements $K_{UL(R)}^{ij}$ can be taken as [14]

$$K_{UL}^{tt} \approx K_{DL}^{bb} \approx 1, \ K_{UR}^{tt} \approx 1 - \varepsilon, \ K_{UR}^{tc} \leq \sqrt{2} \varepsilon - \varepsilon^2.$$

(3)

In the following numerical estimation, we will assume $K_{UR}^{tc} = \sqrt{2} \varepsilon - \varepsilon^2$ and take $\varepsilon$ as free parameter.

The relevant couplings for the top-Higgs $h^0_t$ are similar with those of the neutral top-pion $\pi^0_t$ [14]. However, the coupling $h^0_t t \bar{t}$ is very small, which is proportionate to a factor of $\varepsilon/\sqrt{2}$ [15]. Furthermore, the mass of the techni-Higgs $h_{tc}$ is at the order of 1 TeV. Thus, the contributions of $h_{tc}$ to the $tW$ production process can be safely neglected.

From the above discussions we can see that the neutral top-pion $\pi^0_t$ and the top-Higgs $h^0_t$ can generate the anomalous top coupling vertex $t \bar{c} g$, which are shown in Fig.1. It is obvious that the effective vertex $t cg$ can generate additional contributions to the $tW$ production channel at the LHC. The relevant Feynman diagrams are shown in Fig.2.

Certainly, the neutral scalars $\pi^0_t$ and $h^0_t$ can also generate the anomalous top coupling vertex $t \bar{u} g$ via the FC couplings $\pi^0_t (h^0_t) t \bar{u}$ . However, it has been argued that the maximum FC mixing occurs between the third and second generation fermions, and the FC couplings $\pi^0_t (h^0_t) t \bar{u}$ is very small which can be neglected [14]. Similar to $\pi^0_t$, the charged
top-pions $\pi_{t}^{\pm}$ can also give rise to the anomalous top coupling $tcg$ via the $FC$ couplings $\pi_{t}^{\pm}bc$. However, compared with those of $\pi_{t}^{0}$, the contributions of $\pi_{t}^{\pm}$ to the $tcg$ coupling are approximately suppressed by the factor $m_{b}^{2}/m_{t}^{2}$, which can be safely neglected. Hence, in the following numerical estimation, we will ignore the contributions of $\pi_{t}^{\pm}$ to the $tW$ production process.

One of the authors for this paper has discussed the anomalous top coupling $tcg$ induced by the $TC2$ model in Ref.[16]. The explicit expressions for the effective vertex $t\bar{c}g$ has
been given in Ref.[16]. In this paper, we will use LoopTools [17] and the CTEQ6L parton distribution functions (PDFs) [18] to calculate the contributions of the TC2 model to the tW production process. The renormalization and factorization scales ($\mu_R$ and $\mu_F$) have been taken equal to $\mu_F = \mu_R = m_t + m_W$. The masses of the top quark and the gauge boson W are taken as $m_t = 170.9\, GeV$ and $m_W = 80.42\, GeV$ [19]. It is obvious that the cross sections for the processes $pp \rightarrow tW^- + X$ and $pp \rightarrow \bar{t}W^+ + X$ are dependent on the free parameter $\varepsilon$ and the masses of the top-pion and top-Higgs boson. From the theoretical point of view, $\varepsilon$ with value from 0.01 to 0.1 is favored [11]. In this paper we will assume that its value is in the range of $0.03 \sim 0.08$. The masses of the neutral top-pion and top-Higgs boson are model-dependent and are usually of a few hundred GeV [12]. In our numerical estimation, we will take $m_{\pi^0_t} = m_{h^0_t} = M$ and assume that the value of $M$ is in the range of $200 GeV \sim 500 GeV$.

Figure 3: The relative correction parameters $R_+(a)$ and $R_-(b)$ as function of the mass parameter $M$ for three values of the parameter $\varepsilon$.

To see whether the contributions of the anomalous top coupling $tcg$ induced by the TC2 model to the tW production channel can be detected at the LHC, we define the relative correction parameters as

$$R_+ = \frac{\sigma(tW^+)}{\sigma^{SM}(tW^+)}$$

$$R_- = \frac{\sigma(tW^-)}{\sigma^{SM}(tW^-)}$$

(4)
where $\sigma(\bar{t}W^+)$ and $\sigma(tW^-)$ denote the total production cross sections including the contributions from the SM and the TC2 model for the processes $pp \rightarrow \bar{t}W^+ + X$ and $pp \rightarrow tW^- + X$, respectively. The charge asymmetry parameter $R$ is defined as $R = \sigma(tW^-)/\sigma(\bar{t}W^+)$. Since the PDF for the bottom quark in proton is same as that for the anti-bottom quark, there is $R = 1$ in the SM.

Our numerical results are summarized in Fig.3 and Fig.4, in which we plot the parameter $R_i$ as function of the mass parameter $M$ for the c.m. energy $\sqrt{s} = 14 TeV$ and three values of the free parameter $\varepsilon$. One can see from Fig.3 that there is a peak at $M \sim 330 GeV$, which is due to the effect of the $t\bar{t}$ in the loop going on-shell and the anomalous top coupling $tcg$ increasing. In all of the parameter space of the TC2 model, the value of $R_+$ is smaller than that of $R_-$ and the value of the parameter $R$ is larger than 1, which leads to an charge asymmetry for the $tW$ production process. For $0.03 \leq \varepsilon \leq 0.08$ and $200 GeV \leq M \leq 500 GeV$, the corrections to the production cross sections of the
processes \( pp \to tW^+ + X \) and \( pp \to tW^- + X \) are in the ranges of 2.5% \( \sim \) 5.2% and 3.7% \( \sim \) 7.2%, respectively. The value of the charge asymmetry parameter \( R \) is in the range of 1.011 \( \sim \) 1.018. It has been shown [6, 7] that the production cross section of \( tW \) production at the LHC can be measured with precision of about 9.9% and 2.8% for 10 fb\(^{-1} \) and 30 fb\(^{-1} \) of integrated luminosity of data, respectively. Thus, it is impossible to detect the charge asymmetry induced by the TC2 model for the \( tW \) production process at the LHC even for the c.m. energy \( \sqrt{s} = 14 TeV \).

3. The LHT model and \( tW \) production at the LHC

Little Higgs theory [20] was proposed as an alternative solution to the hierarchy problem of the SM, which provides a possible kind of EWSB mechanism accomplished by a naturally light Higgs boson. In order to make the littlest Higgs model consistent with electroweak precision tests and simultaneously having the new particles of this model at the reach of the LHC, a discrete symmetry, \( T \)-parity, has been introduced, which forms the LHT model. The detailed description of the LHT model can be found for instance in Refs.[13, 21, 22], and here we just want to briefly review its essential features, which are related to our calculation.

The LHT model is based on an \( SU(5)/SO(5) \) global symmetry breaking pattern. A subgroup \( [SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2 \) of the \( SU(5) \) global symmetry is gauged, and at the scale \( f \) it is broken into the SM electroweak symmetry \( SU(2)_L \times U(1)_Y \). \( T \)-parity exchanges the \( [SU(2) \times U(1)]_1 \) and \( [SU(2) \times U(1)]_2 \) gauge symmetries. The \( T \)-even combinations of the gauge fields are the SM electroweak gauge bosons \( W^a_\mu \) and \( A_\mu \). The \( T \)-odd combinations are \( T \)-parity partners of the SM electroweak gauge bosons.

After taking into account EWSB, at the order of \( v^2/f^2 \), the masses of the \( T \)-odd set of the \( SU(2) \times U(1) \) gauge bosons are given as

\[
M_{A_H} = g_1 f \frac{1}{\sqrt{5}} [1 - \frac{5v^2}{f^2}], \quad M_{Z_H} \approx M_{W_H} = g_2 f [1 - \frac{v^2}{8f^2}],
\]

where \( v = 246 GeV \) is the electroweak scale and \( f \) is the scale parameter of the gauge symmetry breaking of the LHT model. \( g_1 \) and \( g_2 \) are the SM \( U(1)_Y \) and \( SU(2)_L \) gauge
A consistent implementation of $T$-parity also requires the introduction of mirror fermions — one for each quark and lepton species. The masses of the $T$-odd (mirror) fermions can be written in a unified manner

$$M_{F_i} = \sqrt{2} k_i f,$$

where $k_i$ are the eigenvalues of the mass matrix $k$ and their values are generally dependent on the fermion species $i$. These new fermions ($T$-odd quarks and $T$-odd leptons) have new FC interactions with the SM fermions. These interactions are governed by new mixing matrices $V_{Hd}$ and $V_{Hl}$ for down-type quarks and charged leptons, respectively. The corresponding matrices in the up-type quarks ($V_{Hu}$) and neutrino ($V_{H\nu}$) sectors are obtained by means of the relations

$$V_{Hu}^+ V_{Hd} = V_{CKM}, \quad V_{H\nu}^+ V_{Hl} = V_{PMNS}.$$
Where the $CKM$ matrix $V_{CKM}$ is defined through flavor mixing in the down-type quark sector, while the $PMNS$ matrix $V_{PMNS}$ is defined through neutrino mixing.

Figure 6: In case I, the parameters $R_+(a)$ and $R_-(b)$ dependence on the mass parameter $M_3$ for $M_1 = M_2 = 300\,\text{GeV}$ and three values of the scale parameter $f$.

The Feynman rules of the $LHT$ model have been studied in Ref.[22] and the corrected Feynman rules of Ref.[22] are given in Refs.[23, 24]. To simplify our paper, we do not list them here.

From the above discussions, we can see that the flavor structure of the $LHT$ model is much richer than the one of the $SM$, mainly due to the presence of three doublets of mirror quarks and leptons and their interactions with the ordinary quarks and leptons, which are mediated by the $T$-odd gauge bosons ($A_H, W^+_H,$ and $Z_H$) and Goldstone bosons ($\eta_0, \omega_0,$ and $\omega^\pm$). Such new $FC$ interactions can induce the anomalous top coupling $tqg$ ($q = c$ and $u$) in quark sector. The relevant Feynman diagrams for the effective vertex $t\bar{q}g$ are shown in Fig.5. To simplify our paper, we do not give the analytical expressions of the effective vertexes $t\bar{e}g$ and $t\bar{u}g$ here. The new coupling $tqg$ can generate significant contributions to the $FC$ top decays $t \to cg$, $t \to cqg$ and the $FC$ single top production processes $pp \to \bar{t}c + X$, $pp \to t + X$, and $pp \to tg + X$ [25]. In this section, we will
consider its contributions to $tW$ production at the LHC. Similar with section 2, we use the LoopTools [17] to give our numerical results in the ‘t Hooft-Feynman gauge. In our calculation, we use the corrected Feynman rules including the high order $\nu^2/f^2$ terms and neglect the terms proportioning to $m_c/m_t$ or $m_u/m_t$.

![Figure 7: In case I, the charge asymmetry parameter $R$ as a function of the mass parameter $M_3$ for $M_1 = M_2 = 300 GeV$ and three values of the scale parameter $f$.](image)

The new parameters in the LHT model are the scale parameter $f$, the mixing parameter $X_L$, the mirror fermion masses, and the mixing matrices $V_{Hd}$ and $V_{Hl}$. The masses of the $T$-odd gauge bosons $W_{H}^{\pm}, Z_{H}$, and $A_{H}$ can be fixed by the scale parameter $f$. The parameter $X_L$ describes the mixing between the $T$-even heavy top quark $T_{+}$ and the top quark $t$, and its value is in the range of $0 \sim 1$. Since $X_L$ contributes the coupling $tqg$ at least at order of $\nu^2/f^2$, we fix its value as 0.5. The masses of the mirror leptons and the mixing matrix $V_{Hl}$ are not related our calculation. For the masses of the mirror quarks,
there is \( M_{U_H} = M_{D_H} = M_i \) at \( O(\nu/f) \). The mixing matrix \( V_{Hd} \) can be parameterized by three mixing angles \( \theta_{12}^d, \theta_{23}^d, \theta_{13}^d \) and three irreducible phases \( \delta_{12}^d, \delta_{23}^d, \delta_{13}^d \) [26]. The mixing matrix \( V_{Hu} \) can be determined by \( V_{Hu} V_{Hd} = V_{CKM} \).

![Graphs showing \( R_+ \) and \( R_- \) as functions of \( M_3 \) for different scale parameters.](image)

Figure 8: Same as Fig.6 but for case II.

Refs.[21, 22, 26, 27] have studied the impact of the LHT dynamics on the \( K, B, \) and \( D \) systems in considerable detail. They have shown that the LHT model can produce potentially sizable effects on the relative observables and its free parameters should be constrained. To simplify our calculation, in this paper, we only consider two scenarios for the structure of \( V_{Hd} \), which can easily escape these constraints,

Case I: \( V_{Hd} = I, V_{Hu} = V_{CKM}^+ \),

Case II: \( S_{23}^d = 1/\sqrt{2}, S_{12}^d = S_{13}^d = 0, \delta_{12}^d = \delta_{23}^d = \delta_{13}^d = 0 \).

In both above cases, the constraints on the mass spectrum of the mirror quarks are very relaxed. So we assume \( M_1 = M_2 = 300GeV \) and the mass \( M_3 \) of the third generation mirror quarks in the range of \( 500GeV \sim 2000GeV \). For the scale parameter \( f \), we take its typical values, i.e. \( 500GeV \sim 2000GeV \).

The parameters \( R_+, R_- \), and \( R \) contributed by the anomalous top couplings \( tcg \) and \( tug \) in the LHT model are plotted as functions of the mass parameter \( M_3 \) for the c.m.
energy $\sqrt{s} = 14$ TeV and three values of the scale parameter $f$, which are shown in figures 6 ~ 9. From these figures one can see that the contributions of the anomalous top coupling $tqg$ induced by the $LHT$ model to the $tW$ production process are generally larger than those for the $TC2$ model. This is partly because the contributions of the $LHT$ model from the anomalous top couplings $tcg$ and $tug$, while only from the anomalous top coupling $tcg$ for the $TC2$ model. The values of the parameters $R_+, R_-$, and the deviation $\delta R = R_- - R_+$ increase as the mass parameter $M_3$ increases, which is because the couplings between the mirror quarks and the $SM$ quarks are proportion to the mirror quark masses. So the parameter $R$ also increases as $M_3$ increases. Certainly, compared to the parameters $R_+$ and $R_-$, $R$ is insensitive to the mass parameter $M_3$ and its values are only in the ranges of $1.042 \sim 1.056$ and $1.045 \sim 1.061$ for case I and case II, respectively. These parameters also depend on the parameterization scenarios of the matrix $V_{Hd}$. Their values for case II are generally larger than those for case I. In most of the parameter space of the $LHT$ model, the values of the relative correction parameters $R_+$ and $R_-$ are larger than 1.1.
Thus, the correction effects of the anomalous top coupling $tqq$ induced by the $LHT$ model on the $tW$ production cross section might be detected at the $LHC$. Although the value of the charge asymmetry parameter $R$ induced by the $LHT$ model is larger than that for the $TC2$ model, its value is smaller than 1.06. So, observing the charge asymmetry of $tW$ production at the $LHC$ induced by the $LHT$ model is much challenge.

4. Conclusions

The $tW$ production process is one of important single top production channels at the $LHC$. In the $SM$, the production cross sections of single top quark and single anti-top quark in the $tW$ channel are equal, i.e. $R = \sigma(tW^-)/\sigma(tW^+) = 1$. However, the anomalous top coupling $tqq$ can generate contributions to the cross sections $\sigma(tW^-)$ and $\sigma(tW^+)$, and further give rise to the charge asymmetry. If the correction effects of the new coupling $tqq$ on the $tW$ production channel are observed at the $LHC$, it will be helpful to test the flavor structure of the $SM$ and further to probe new physics beyond the $SM$.

The $TC2$ model and the $LHT$ model are two kinds of popular new physics models, which can generate the anomalous top coupling $tqq$. In the context of the $TC2$ and $LHT$ models, we consider the correction effects of the new coupling $tqq$ on the $tW$ production channel at the $LHC$ with the c.m. energy $\sqrt{s} = 14 TeV$. Our numerical results show that they can indeed generate significant contributions to the $tW$ production process. The contributions of the anomalous top coupling $tqq$ induced by the $TC2$ model to the $tW$ production process are generally smaller than those for the $LHT$ model. With reasonable values of the free parameters for the $LHT$ model, its corrections to the production cross sections of the processes $pp \rightarrow tW^- + X$ and $pp \rightarrow tW^+ + X$ can reach 32% and 24%, respectively. The value of the charge asymmetry parameter $R = \sigma(tW^-)/\sigma(tW^+)$ can reach 1.06.

The $TC2$ model and the $LHT$ model can modify the $Wtb$ coupling and further produce correction effects on the $tW$ production cross section [28, 29]. However, their contributions to the production cross section of the process $pp \rightarrow tW^- + X$ are equal to those for the
production cross section of the process $pp \to t\bar{t}W + X$. Thus, such modification about the $Wtb$ coupling can not cause the charge asymmetry in the $t\bar{t}W$ production process at the LHC.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China under Grants No.10975067, the Specialized Research Fund for the Doctoral Program of Higher Education (SRFDP) (No.200801650002).

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