Physics Letters B 705 (2011) 222–227

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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, PR China

ARTICLE INFO

Article history:
Received 2 July 2011
Received in revised form 17 September 2011
Accepted 30 September 2011
Available online 6 October 2011
Editor: M. Cvetič

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 (*TC*2) 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 $pp \to \bar{t}W^+ + X$ are significant large, which might be detected at the *LHC*.

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 cannot be detected 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 (*TC*2) model [11,12], the littlest Higgs model with T-parity (called *LHT* model) [13], etc. In this Letter, we will focus our attention on the anomalous top couplings induced by the *TC*2 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 *TC*2 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 $pp \to tW^- + X$ and $pp \to \bar{t}W^+ + X$ are in the ranges of 14–32% and 11–24%, 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 *TC*2 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.

* Corresponding author.
E-mail address: cxyue@lnnu.edu.cn (C.-X. Yue).

0370-2693 © 2011 Elsevier B.V. Open access under CC BY license.
doi:10.1016/j.physletb.2011.09.118

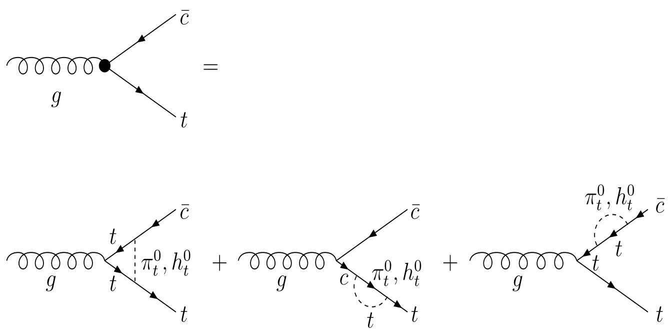


Fig. 1. Feynman diagrams for the effective vertex $t\bar{c}g$ in the *TC*2 model.

2. The *TC*2 model and *tW* production at the *LHC*

The *TC*2 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 εm_t with the parameter $\varepsilon \ll 1$. The topcolor interaction generates the bulk of m_t through condensation of top pairs $\langle t\bar{t}\rangle$, but makes only a small contribution to *EWSB*.

The *TC*2 model predicts the existence of a number of new scalar states at the electroweak scale: three top-pions ($\pi_t^{\pm}, \pi_t^0$), a top-Higgs (h_t^0), and a techni-Higgs (h_{tc}^0), which are bound-states of the top quark, the bottom quark and of the technifermions. 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 ($\pi_t^0, \pi_t^{\pm}$) to ordinary fermions, which are related to our calculation, can be written as [11,12,14]

$$\frac{m_t}{\sqrt{2}F_t}\frac{\sqrt{\nu_W^2 - F_t^2}}{\nu_W}\big(iK_{UL}^{tt*}K_{UR}^{tt}\bar{t}_L t_R \pi_t^0 + \sqrt{2}K_{UR}^{tt*}K_{DL}^{bb}\bar{t}_R b_L \pi_t^+ + iK_{UL}^{tt*}K_{UR}^{tc}\bar{t}_L c_R \pi_t^0 + \sqrt{2}K_{UR}^{tc*}K_{DL}^{bb}\bar{c}_R b_L \pi_t^+ + \text{h.c.}\big), \quad (1)$$

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]

$$K_{UL}^{tt} \approx K_{DL}^{bb} \approx 1, \qquad K_{UR}^{tt} \approx 1 - \varepsilon, \qquad K_{UR}^{tc} \leqslant \sqrt{2\varepsilon - \varepsilon^2}. \quad (2)$$

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

The relevant couplings for the top-Higgs h_t^0 are similar with those of the neutral top-pion π_t^0 [14]. However, the coupling $h_{tc}^0 t\bar{t}$ 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 π_t^0 and the top-Higgs h_t^0 can generate the anomalous top coupling vertex $t\bar{c}g$, which are shown in Fig. 1. It is obvious that the effective vertex *tcg* can generate additional contributions to the *tW* production channel at the *LHC*. The relevant Feynman diagrams are shown in Fig. 2.

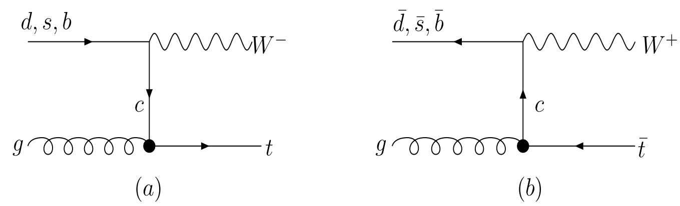


Fig. 2. Feynman diagrams for the *tW* production process at the *LHC* contributed by the anomalous top coupling *tcg*.

Certainly, the neutral scalars π_t^0 and h_t^0 can also generate the anomalous top coupling vertex $t\bar{u}g$ via the *FC* couplings $\pi_t^0(h_t^0)t\bar{u}$. However, it has been argued that the maximum *FC* mixing occurs between the third and second generation fermions, and the *FC* couplings $\pi_t^0(h_t^0)t\bar{u}$ is very small which can be neglected [14]. Similar to π_t^0, 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 π_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.

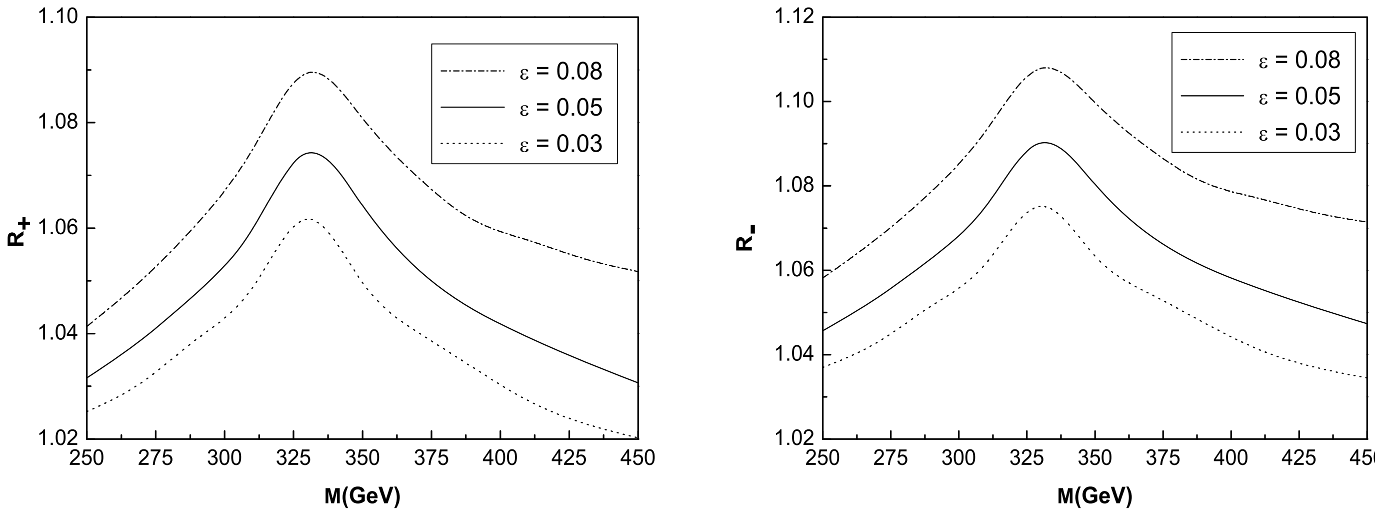
One of the authors for this Letter has discussed the anomalous top coupling *tcg* induced by the *TC*2 model in Ref. [16]. The explicit expressions for the effective vertex $t\bar{c}g$ has been given in Ref. [16]. In this Letter, we will use *Loop Tools* [17] and the *CTEQ6L* parton distribution functions (*PDFs*) [18] to calculate the contributions of the *TC*2 model to the *tW* production process. The renormalization and factorization scales (μ_R and μ_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 $pp \to tW^- + X$ and $pp \to \bar{t}W^+ + X$ are dependent on the free parameter ε and the masses of the top-pion and top-Higgs boson. From the theoretical point of view, ε with value from 0.01 to 0.1 is favored [11]. In this Letter we will assume that its value is in the range of 0.03–0.08. 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 $m_{\pi_t^0} = m_{h_t^0} = M$ and assume that the value of M is in the range of 200–500 GeV.

To see whether the contributions of the anomalous top coupling *tcg* induced by the *TC*2 model to the *tW* production channel can be detected at the *LHC*, we define the relative correction parameters as

$$R_+ = \frac{\sigma(\bar{t}W^+)}{\sigma^{SM}(\bar{t}W^+)}, \qquad R_- = \frac{\sigma(tW^-)}{\sigma^{SM}(tW^-)}, \quad (3)$$

where $\sigma(\bar{t}W^+)$ and $\sigma(tW^-)$ denote the total production cross sections including the contributions from the *SM* and the *TC*2 model for the processes $pp \to \bar{t}W^+ + X$ and $pp \to tW^- + X$, 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 Figs. 3 and 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 ε. 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 *TC*2 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 a charge asymmetry for the *tW* production process. For



(a) (b)

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

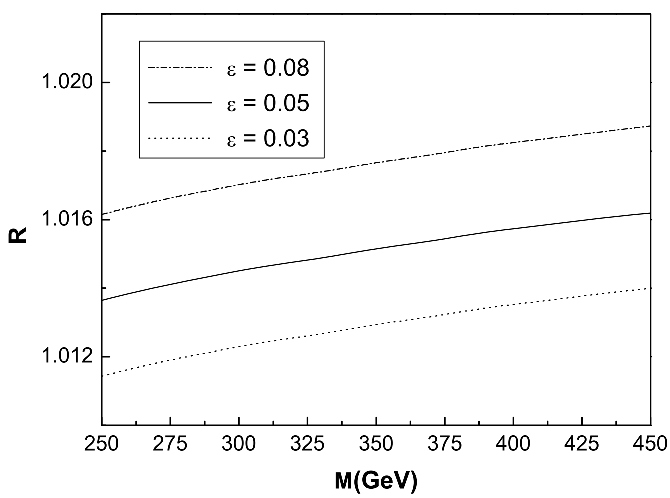


Fig. 4. The charge asymmetry parameter R as a function of M for the parameter $\varepsilon = 0.03$, 0.05 and 0.08.

$0.03 \leqslant \varepsilon \leqslant 0.08$ and 200 GeV $\leqslant M \leqslant$ 500 GeV, the corrections to the production cross sections of the processes $pp \to \bar{t}W^+ + X$ and $pp \to tW^- + X$ are in the ranges of 2.5–5.2% and 3.7–7.2%, respectively. The value of the charge asymmetry parameter R is in the range of 1.011–1.018. 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 *TC*2 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_μ and A_μ. 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

$$M_{A_H} = \frac{g_1 f}{\sqrt{5}}\left[1 - \frac{5v^2}{f^2}\right],$$

$$M_{Z_H} \approx M_{W_H} = g_2 f\left[1 - \frac{v^2}{8f^2}\right], \tag{4}$$

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 coupling constants, respectively.

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

$$M_{F_i} = \sqrt{2}k_i f, \tag{5}$$

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

$$V^+_{Hu} V_{Hd} = V_{CKM}, \qquad V^+_{H\nu} V_{Hl} = V_{PMNS}. \tag{6}$$

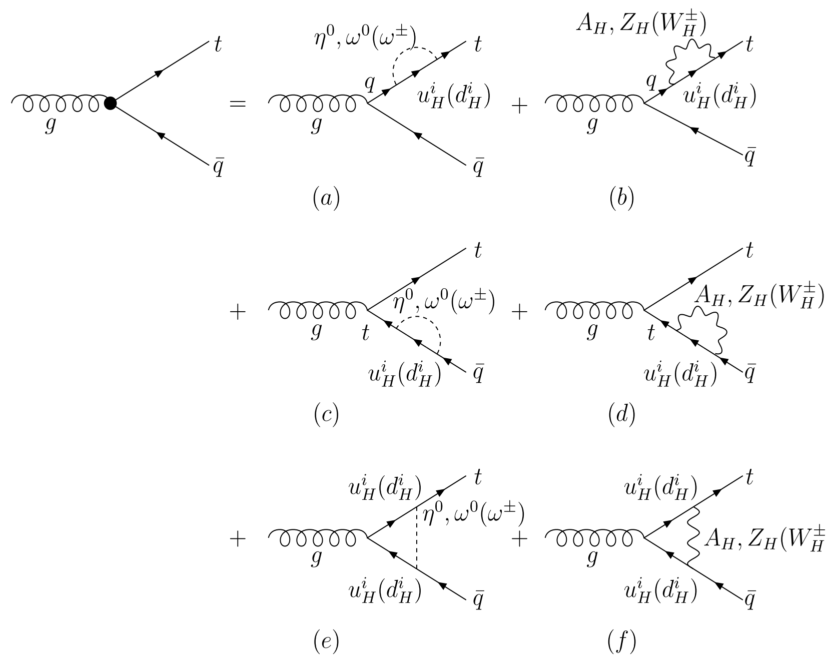
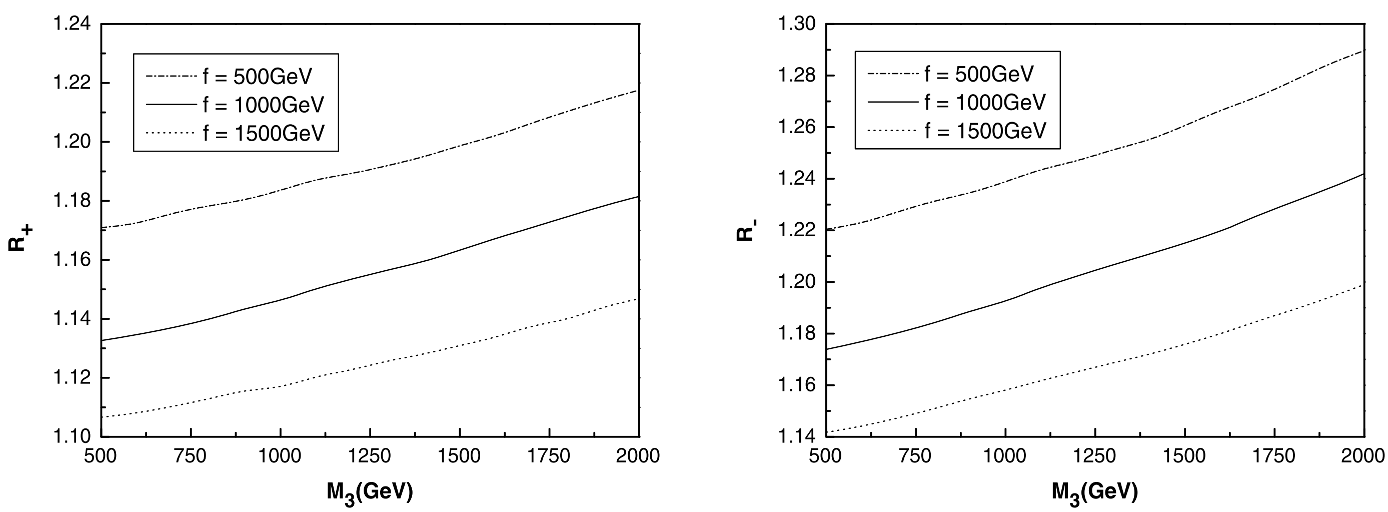


Fig. 5. Feynman diagrams for the effective vertex $t\bar{q}g$ in the *LHT* model.



(a)

(b)

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

Here 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.

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 Letter, 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, $W_H^{\pm}$, and Z_H) and Goldstone bosons (η_0, ω_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 Letter, we do not give the analytical expressions of the effective vertexes $t\bar{c}g$ 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 *Loop Tools* [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 ν^2/f^2 terms and neglect the terms proportioning to m_c/m_t or m_u/m_t.

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 0–1. Since X_L contributes the coupling tqg at least at order of

v^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 $M_{U_H^i} = M_{D_H^i} = M_i$ at $O(v/f)$. The mixing matrix V_{Hd} can be parameterized by three mixing angles θ_{12}^d, θ_{23}^d, θ_{13}^d and three irreducible phases δ_{12}^d, δ_{23}^d, δ_{13}^d [26]. The mixing matrix V_{Hu} can be determined by $V_{Hu}^{+} V_{Hd} = V_{CKM}$.

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 Letter, 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 $M_1 = M_2 =$ 300 GeV and the mass M_3 of the third generation mirror quarks in the range of 500–2000 GeV. For the scale parameter f, we take its typical values, i.e. 500–2000 GeV.

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 Figs. 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 *TC*2 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 *TC*2 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 1.042–1.056 and 1.045–1.061 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 tqg 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 *TC*2 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.

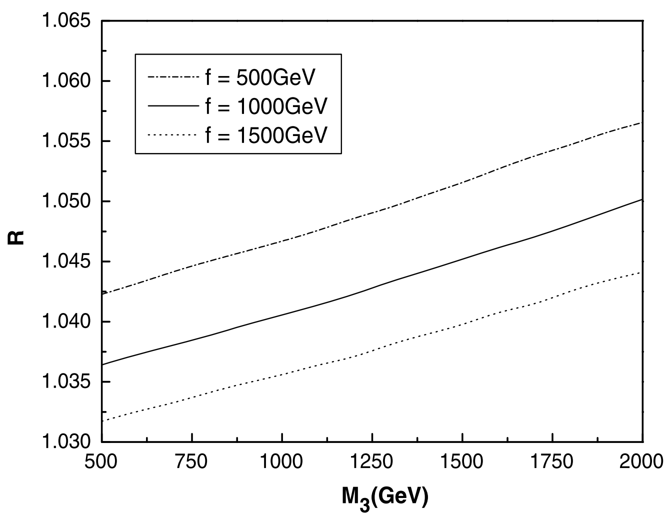
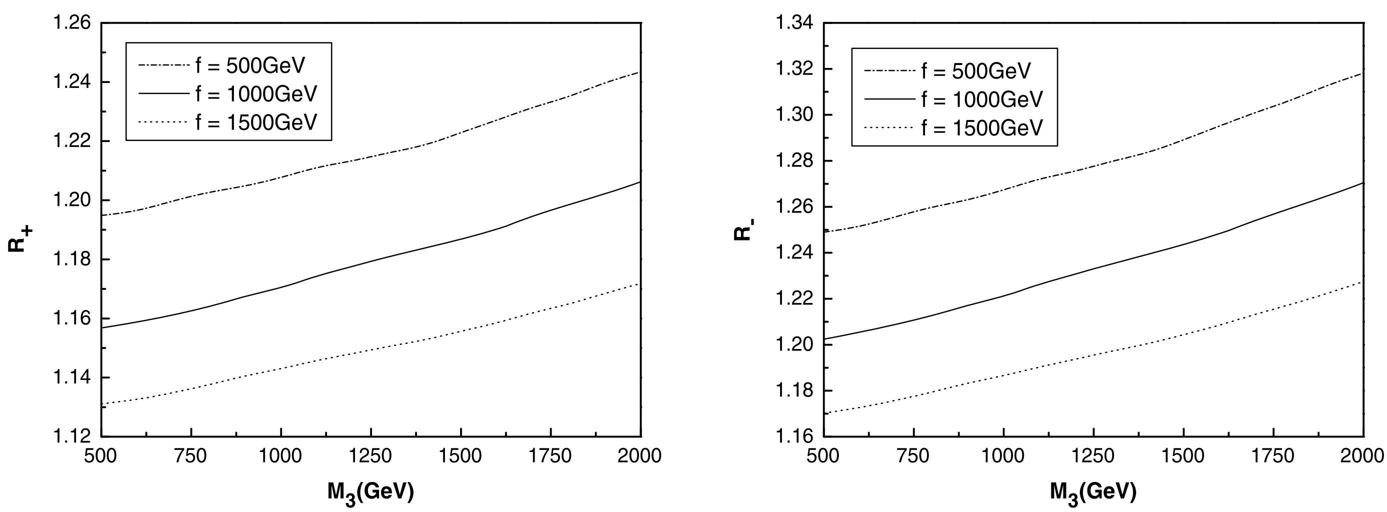


Fig. 7. In case I, the charge asymmetry parameter R as a function of the mass parameter M_3 for $M_1 = M_2 = 300$ GeV and three values of the scale parameter f.

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. $R = \sigma(tW^-)/\sigma(\bar{t}W^+) = 1$. However, the anomalous top coupling tqg can generate contributions to the cross sections $\sigma(tW^-)$ and $\sigma(\bar{t}W^+)$, and further give rise to the charge asymmetry. If the correction effects of the new coupling tqg



(a) (b)

Fig. 8. The same as Fig. 6 but for case II.

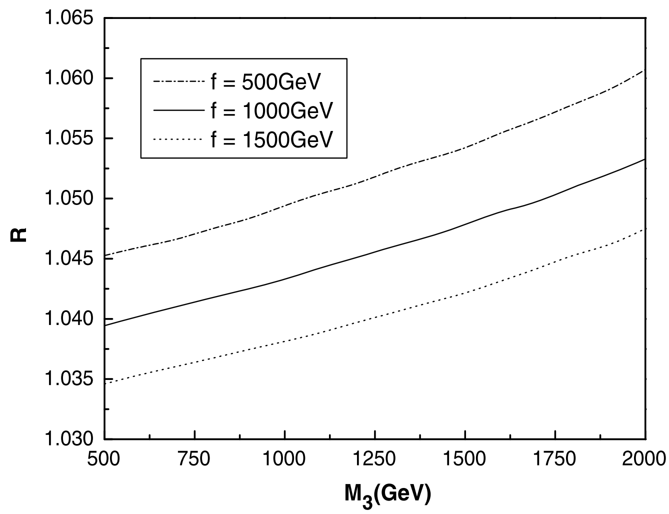


Fig. 9. The same as Fig. 7 but for case II.

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 *TC*2 model and the *LHT* model are two kinds of popular new physics models, which can generate the anomalous top coupling tqg. In the context of the *TC*2 and *LHT* models, we consider the correction effects of the new coupling tqg 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 tqg induced by the *TC*2 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 $pp \to tW^- + X$ and $pp \to \bar{t}W^+ + X$ can reach 32% and 24%, respectively. The value of the charge asymmetry parameter $R = \sigma(tW^-)/\sigma(\bar{t}W^+)$ can reach 1.06.

The *TC*2 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 $pp \to tW^- + X$ are equal to those for the production cross section of the process $pp \to \bar{t}W^+ + X$. Thus, such modification about the Wtb coupling cannot cause the charge asymmetry in the tW production process at the *LHC*.

Acknowledgements

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).

References

[1] G. Weiglein, et al., LHC/LC Study Group, Phys. Rep. 426 (2006) 47.
[2] For recent reviews, see W. Bernreuther, J. Phys. G 35 (2008) 083001;
J.R. Incandela, A. Quadt, W. Wagner, D. Wicke, Prog. Part. Nucl. Phys. 63 (2009) 239.
[3] G. Ladinsky, C.-P. Yuan, Phys. Rev. D 43 (1991) 789;
S. Moretti, Phys. Rev. D 56 (1997) 7427;
T.M.P. Tait, Phys. Rev. D 61 (2000) 034001;
T.M.P. Tait, C.-P. Yuan, Phys. Rev. D 63 (2000) 014018;
A. Belyaev, E. Boos, Phys. Rev. D 63 (2001) 034012;
S. Zhu, Phys. Lett. B 524 (2004) 283;
J. Campbell, F. Tramontano, Nucl. Phys. B 726 (2005) 109;
N. Kidonakis, Phys. Rev. D 74 (2006) 114012;
Q.H. Cao, arXiv:0801.1539 [hep-ph];
S. Frixione, E. Laenen, P. Motylinski, B.R. Webber, C.D. White, JHEP 0807 (2008) 029;
C.D. White, S. Frixione, E. Laenen, F. Maltoni, JHEP 0911 (2009) 074;
E. Re, Eur. Phys. J. C 71 (2011) 1547.
[4] M. Beccaria, G. Macorini, F.M. Renard, C. Verzegnassi, Phys. Rev. D 73 (2006) 093001;
M. Beccaria, et al., Eur. Phys. J. C 53 (2008) 257.
[5] M.M. Najafabadi, JHEP 0803 (2008) 024;
J.A. Aguilar-Saavedra, Nucl. Phys. B 804 (2008) 160.
[6] G.L. Bayatian, et al., CMS Collaboration, J. Phys. G 34 (2007) 995.
[7] ATLAS Collaboration, ATLAS Physics TDR, vol. 2, CERN/LHCC/99-15.
[8] J.A. Aguilar-Saavedra, A. Onofre, Phys. Rev. D 83 (2011) 073003.
[9] S.M. Etesami, M.M. Najafabadi, Phys. Rev. D 81 (2010) 117502.
[10] G. Eilam, J.L. Hewett, A. Soni, Phys. Rev. D 44 (1991) 1473;
B. Mele, S. Petrarca, A. Soddu, Phys. Lett. B 435 (1998) 401;
G. Eilam, M. Frank, I. Turan, Phys. Rev. D 73 (2006) 053011;
A. Cordero-Cid, J.M. Hernandez, G. Tavares-Velasco, J.J. Toscano, Phys. Rev. D 73 (2006) 094005;
F. Larios, R. Martinez, M.A. Perez, Int. J. Mod. Phys. A 21 (2006) 3473.
[11] C.T. Hill, Phys. Lett. B 345 (1995) 483;
K.D. Lane, E. Eichten, Phys. Lett. B 433 (1998) 96.
[12] G. Cvetic, Rev. Mod. Phys. 71 (1999) 513;
C.T. Hill, E.H. Simmons, Phys. Rep. 381 (2003) 235;
C.T. Hill, E.H. Simmons, Phys. Rep. 390 (2004) 553, Erratum.
[13] H.C. Cheng, I. Low, JHEP 0309 (2003) 051;
H.C. Cheng, I. Low, JHEP 0408 (2004) 061;
I. Low, JHEP 0410 (2004) 067.
[14] H.J. He, C.P. Yuan, Phys. Rev. Lett. 83 (1999) 28;
G. Burdman, Phys. Rev. Lett. 83 (1999) 2888;
H.J. He, S. Kanemura, C.P. Yuan, Phys. Rev. Lett. 89 (2002) 101803.
[15] A.K. Leibovich, D.L. Rainwater, Phys. Rev. D 65 (2002) 055012.
[16] Chong-Xing Yue, Gong-Ru Lu, Guo-Li Liu, Qing-Jun Xu, Phys. Rev. D 64 (2001) 095004;
Chong-Xing Yue, Zheng-Jun Zong, Li-Li Xu, Jian-Xing Chen, Phys. Rev. D 73 (2006) 015006.
[17] T. Hahn, M. Perez-Victoria, Comput. Phys. Comm. 118 (1999) 153;
T. Hahn, Nucl. Phys. B Proc. Suppl. 135 (2004) 333.
[18] J. Pumplin, et al., CTEQ Collaboration, JHEP 0602 (2006) 032.
[19] W.M. Yao, et al., Particle Data Group, J. Phys. G 33 (2006) 1, and partial update for the 2008 edition.
[20] M. Schmaltz, D. Tucker-Smith, Ann. Rev. Nucl. Part. Sci. 55 (2005) 229;
M. Perelstein, Prog. Part. Nucl. Phys. 58 (2007) 247.
[21] J. Hubisz, P. Meade, Phys. Rev. D 71 (2005) 035016;
A. Belyaev, Chuan-Ren Chen, K. Tobe, C.P. Yuan, Phys. Rev. D 74 (2006) 115020;
J. Hubisz, P. Meade, A. Noble, M. Perelstein, JHEP 0601 (2006) 135;
J. Hubisz, S.J. Lee, G. Paz, JHEP 0606 (2006) 041;
M. Blanke, et al., JHEP 0612 (2006) 003.
[22] M. Blanke, et al., JHEP 0701 (2007) 066.
[23] T. Goto, Y. Okada, Y. Yamamoto, Phys. Lett. B 670 (2009) 378.
[24] F. del Aguila, J.I. Illana, M.D. Jenkins, JHEP 0901 (2009) 080;
M. Blanke, et al., Acta Phys. Polon. B 41 (2010) 657.
[25] H.-S. Hou, Phys. Rev. D 75 (2007) 094010;
Hui-Di Yang, Chong-Xing Yue, Jia Wen, Yong-Zhi Wang, Mod. Phys. Lett. A 24 (2009) 1943;
X.L. Wang, Y.J. Zhang, H.L. Jin, Y.H. Xi, Nucl. Phys. B 810 (2009) 226;
J.Z. Han, B.Z. Li, X.L. Wang, Phys. Rev. D 83 (2011) 034032.
[26] M. Blanke, et al., Phys. Lett. B 646 (2007) 253.
[27] I.I. Bigi, et al., JHEP 0907 (2009) 097;
A. Paul, I.I. Bigi, S. Recksiegel, Phys. Rev. D 82 (2010) 094006.
[28] X.L. Wang, Y.H. Xi, Y.J. Zhang, H.L. Jin, Phys. Rev. D 77 (2008) 115006.
[29] Q.-H. Cao, C.-S. Li, C.-P. Yuan, Phys. Lett. B 668 (2008) 24;
F. Penunuri, F. Larios, Phys. Rev. D 79 (2009) 015013.