Probing the topcolor-assisted technicolor model via the single t-quark production at the CERN LHC

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(Received 6 March 2008; published 11 June 2008)

The single t-quark production in proton-proton collisions can proceed through three distinct processes: tq, $t\bar{b}$, tW productions. With the running of the Large Hadron Collider (LHC) at CERN, it has good potential to measure each single t-quark production mode. The topcolor-assisted technicolor (TC2) model, one of the promising dynamical theories, predicts some new particles at the several hundred GeV scale: three top-pion bosons ($\Pi_t^{\pm}$, Π_t^0) and one top-Higgs boson (h_t). These particles are regarded as the typical feature of the TC2 model and can contribute to some processes. In this paper, we systematically study the contribution of the TC2 model to the single t-quark production at the Hadron colliders, especially at the LHC. The TC2 model can contribute to the cross section of the single t-quark production in two different ways. First, the existence of the top pions and top Higgs can modify the Wtb coupling via their loop contributions, and such modification can cause the correction to the cross sections of all three production modes. Our study shows that this kind of correction is negative and very small in all cases. Thus it is difficult to observe such a correction even at the LHC. On the other hand, there exist the tree-level flavor-changing (FC) couplings in the TC2 model which can also contribute to the cross sections of the tq and $t\bar{b}$ production processes. The resonant effect can greatly enhance the cross sections of the tq and $t\bar{b}$ productions. The first evidence of the single t-quark production has been reported by the D0 collaboration and the measured cross section for the single t-quark production of $\sigma(p\bar{p} \to tb + X, tqb + X)$ is compatible at the 10% level with the standard model prediction. Because the light top pion can make a great contribution to the $t\bar{b}$ production, the top-pion mass should be very large in order to make the predicted cross section in the TC2 model be consistent with the Tevatron experiments. More detailed information about the top-pion mass and the FC couplings in the TC2 model should be obtained with the running of the LHC.

DOI: 10.1103/PhysRevD.77.115006 PACS numbers: 12.60.Nz, 12.15.Lk, 14.80.Mz

I. INTRODUCTION

The t-quark, as the most massive object in the standard model (SM), is that which felt the symmetry breaking the most profoundly. The t-quark physics has become a very active research area since the existence of the t-quark was established in t-quark pair events produced via the strong interaction [1], where quark-antiquark annihilation or gluon-gluon fusion leads to top-antitop pairs. In addition to the top pair production via the strong interaction at hadron colliders, they can also be produced singly in electroweak (EW) interactions, and there are three single t-quark production modes in the SM: The t-channel tq production, the s-channel $t\bar{b}$ production and the associated tW production. Studying these single t-quark production modes at hadron colliders is important for a number of reasons. First, a measurement of the production cross section provides the only direct measurement of the total t-quark decay width and the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{tb}|^2$, without having to assume three quark generations or CKM matrix unitarity. Second, the measurement of the spin polarization of single t-quarks can be used to test the V-A structure of the t-quark EW charged current interaction. Third, the presence of various new SM and non-SM phenomena may be inferred by observing deviations from the predicted rate of the single t-quark signal and by comparing different production modes. Fourth, the single t-quark final states present an irreducible background to several searches for SM or non-SM signals, for example, Higgs boson searches in the associated production channel.

Here, we should emphasize that the single t-quark production is interesting beyond the SM. The single t-quark production as a window to probe new physics has been systematically studied [2,3] and the study shows that three single-top production modes can be used to distinguish several new physics models. New physics can influence the single t-quark production by inducing nonstandard weak interactions [3–5], via loop effects [6,7], or by providing new sources of single t-quark events [3,5,7,8]. Three single t-quark production modes respond quite differently to different realizations of physics beyond the SM [3]. In general, the tq production mode is insensitive to heavy charged bosons. The reason for this is that the t-channel exchanged results in a spacelike momentum, which never can go on shell, and thus the amplitude for the heavy particle is always suppressed by the mass of the heavy boson, $1/M_B^2$. However, the flavor-changing neutral-

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current (FCNC) processes can have a drastic effect on the tq production mode. Because they involve new FC interactions between the t-quark and a light quark (c or u), the tq production mode can be enhanced significantly. The $t\bar{b}$ production mode is very sensitive to an exotic charged boson which couples to t-quark and b-quark. Because the exchanged particle is timelike, there is the possibility (if it is heavier than the t-quark) that it can be produced on shell, resulting in a large enhancement of the cross section. Specific theories which predict an enhancement of the cross section of the $t\bar{b}$ production are theories with a W' [9] or charged Higgs, both of which can result in the cross section of the $t\bar{b}$ production different from the SM by factors of few at either the Tevatron or the LHC [3,10]. For the tW mode, the cross section is more or less insensitive to new bosons, because the W is manifest in the final state. Furthermore, the tq and $t\bar{b}$ modes are sensitive to different new physics models and hence can be used to distinguish between various exotic models. From this line of thinking, we see that all three modes are really complimentary views of the t-quark and new physics, and thus measured separately they provide more information than would be obtained by lumping them together into a singular single-top process.

On the experimental aspect, twelve years after the discovery of the t-quark via strong pair production at the Tevatron, the first evidence of the single t-quark production has been reported by the D0 collaboration [11,12] at the Tevatron. The events were selected from a 0.9 fb^{-1} data set that have an electron or muon and missing transverse energy from the decay of a W boson from the top quark decay, and two, three, or four jets with one or two of the jets identified as originating from a b hadron decay. A binned likelihood fit of the signal cross section plus background to the data from the combination of the results from the three analysis methods gives a cross section for single t-quark production of $\sigma(p\bar{p} \to tb + X, tqb + X) = 4.7 \pm 1.3$ pb [11]. Such a value is compatible at the 10% level with the standard model prediction. The LHC will accelerate proton beams and bring them to collision at a center of mass (c.m.) energy of $\sqrt{s} = 14$ TeV and at luminosities between $(1 - 2) \times 10^{33}\ \text{cm}^{-2}\,\text{s}^{-1}$ (initial low-luminosity phase) and $10^{34}\ \text{cm}^{-2}\,\text{s}^{-1}$ (high luminosity). The single t-quark production can be discovered at the Tevatron but the Tevatron has little ability to observe three modes individually. The study of the single t-quark production is a very important part of research programs at future LHC experiments. Such a study allows to investigate the t-quark properties with high enough accuracy and to measure a Wtb coupling structure with high precision. It may shed a light on the underlying theory which probably stands beyond the SM. At the LHC, it is expected that three different single t-quark production modes can be observed individually. The three single t-quark processes result in quite distinct final states and topologies, leading to the definition of specific analyses in each case. The discrimination between them makes use of the difference in jet multiplicity, number of b-tagged jets required. Besides, important difference subsists in the level of backgrounds that are faced in the various analyses, leading to the development of tools dedicated to the rejection of specific backgrounds. With more than 2.0×10^6 single t-quark events produced every year during a low-luminosity run at the LHC, a precise determination of all contributions to the total single t-quark cross section seems achievable. These measurements will constitute the first direct measurement of V_{tb} at the few percent level of precision, and also constitute a powerful probe for new physics, via the search for evidence of anomalous couplings to the t-quark, or the measurement of additional bosonic contributions to the single t-quark production.

In the transition from the Tevatron to the LHC, several aspects of single t-quark physics change. At the Tevatron, the main goal is to observe the EW mode of t-quark production for the first time, and that will be followed by initial measurements. Hence, the emphasis is on extracting the signal from the backgrounds, using optimized methods. By contrast, by the time that the LHC analyses are starting, the single t-quark production should already have been discovered, and the focus shifts to precision measurement. Thus, the single t-quark production can be used as tools to probe the EW sector and to look for new physics.

Among the various new physics models, the topcolor-assisted technicolor (TC2) model [13–16] is a most promising candidate of dynamical theories. The TC2 model gives a reasonable explanation of the electroweak symmetry breaking (EWSB) and heavy t-quark mass. In the TC2 model, the topcolor interaction makes a small contribution to the EWSB, and gives rise to the main part of the t-quark mass $(1 - \varepsilon)m_t$ with a model dependant parameter $0.03 \leq \varepsilon \leq 0.1$ [16]. The technicolor interaction plays a main role in the breaking of EW gauge symmetry. To account for the explicit breaking of quark and lepton flavor symmetries, the extended technicolor (ETC) was invented. The ETC interaction gives rise to the masses of the ordinary fermions including a very small portion of the t-quark mass εm_t. This kind of model predicts three CP odd top pions (Π_t^0, $\Pi_t^{\pm}$) and one CP even top Higgs (h_t^0) with large Yukawa couplings to the third family. As we know, the topcolor interaction is nonuniversal and such a nonuniversal feature can result in the new tree-level flavor-changing (FC) couplings when one writes the interaction in the quark mass eigenbasis. The TC2 model can contribute to the single t-quark production in two different ways. One is that the top pions and top Higgs can make the loop contribution to the vertex Wtb, and such a contribution can influence the production rates of all three single t-quark production modes. Another is that the existence of the FC couplings in the TC2 model can make a significant tree-level contribution to the FC t-quark production processes and some studies have been done [17]. The running of the LHC will open an ideal window to probe the effect of the TC2 model via the single t-quark production. In this paper, we will calculate these two kinds of contributions and study the potential to probe the TC2 model via the single t-quark production at hadron colliders, especially at the LHC.

The rest of this paper is organized as follows. In Sec. II, we will give a detailed calculation of the contributions of the TC2 model to each single t-quark production mode at hadron colliders and discuss the numerical results. The summary and conclusion are represented in Sec. III.

II. THE CONTRIBUTION OF THE TC2 MODEL TO EACH SINGLE t-QUARK PRODUCTION MODE AT HADRON COLLIDERS

A. One-loop correction of the TC2 model to the Wtb coupling

As it is known, the top pions and top Higgs are predicted by the TC2 model. The couplings of the top pions and top Higgs to the three family fermions are nonuniversal, and the top pions and top Higgs have large Yukawa couplings to the third family. Such a feature can result in the significant tree-level FC couplings of the top pions and top Higgs to the quarks when one writes the interaction in the quark mass eigenbasis. The couplings of the top pions and top Higgs to a pair of quarks are proportional to the masses of the quarks and the explicit form can be written as [18]

$$\begin{aligned}\mathcal{L} = \frac{m_t}{v_w}\tan\beta[&iK_{UR}^{tt}K_{UL}^{tt*}\bar{t}_L t_R \Pi_t^0 + \sqrt{2}K_{UR}^{tt*}K_{DL}^{bb}\bar{t}_R b_L \Pi_t^+ \\ &+ \sqrt{2}K_{UR}^{tc*}K_{DL}^{bb}\bar{c}_R b_L \Pi_t^+ + i\frac{m_b^*}{m_t}\bar{b}_L b_R \Pi_t^0 \\ &+ K_{UR}^{tt}K_{UL}^{tt*}\bar{t}_L t_R h_t^0 + iK_{UR}^{tc}K_{UL}^{tt*}\bar{t}_L c_R \Pi_t^0 \\ &+ K_{UR}^{tc}K_{UL}^{tt*}\bar{t}_L c_R h_t^0 + \text{H.c.}],\end{aligned} \qquad (1)$$

where $\tan\beta = \sqrt{(v_w/v_t)^2 - 1}$, $v_t = 60$–100 GeV is the top-pion decay constant, $v_w = 246$ GeV is the EWSB scale, $K_{U,D}^{i,j}$ are the matrix elements of the unitary matrix $K_{U,D}$, from which the CKM matrix can be derived as $V = K_{UL}^{-1}K_{DL}$. Their values can be written as

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

Here $\varepsilon = 0.03$–0.1, the mass m_b^* is a part of b-quark mass which is induced by the instanton, and can be estimated as [13,14]

$$m_b^* = \frac{3m_t\kappa}{8\pi^2} \sim 6.6\kappa \text{ GeV},$$

which we generally expect $\kappa \sim 1$ to 10^{-1} as in QCD.

The existence of the top pions and top Higgs can make the loop contribution to the Wtb coupling. The leading-order (LO) contribution arises from the terms including t-quark mass m_t. Considering the LO contribution, we only need to calculate the diagrams shown in Fig. 1.

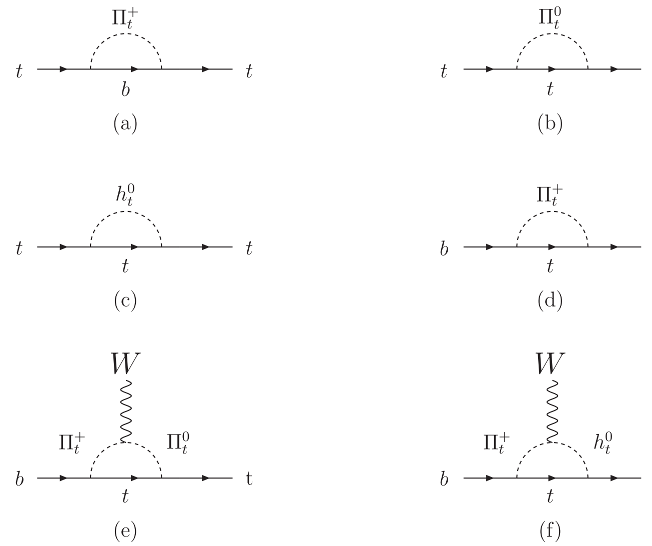

FIG. 1. The one-loop contribution of the TC2 model to the Wtb coupling.

The renormalized effective Wtb coupling can be written as

$$\begin{aligned}\Gamma^\mu(p_t, p_b) = -i\frac{g}{\sqrt{2}}\Big\{&\gamma^\mu P_L\Big[1 + F_L + \frac{1}{2}\delta\mathbf{Z}_b^L + \frac{1}{2}\delta\mathbf{Z}_t^L\Big] \\ &+ \gamma^\mu P_R F_R + p_t^\mu[P_L\tilde{F}_L + P_R\tilde{F}_R] \\ &+ p_b^\mu[P_L\hat{F}_L + P_R\hat{F}_R]\Big\}.\end{aligned} \qquad (2)$$

Here $P_L = \frac{1}{2}(1-\gamma_5)$ and $P_R = \frac{1}{2}(1+\gamma_5)$ are the chirality projectors. p_t^μ and p_b^μ are the momenta of outgoing t-quark and incoming t-quark. The form factors $F_{L,R}$, $\tilde{F}_{L,R}$, and $\hat{F}_{L,R}$ represent the contributions from the irreducible vertex loops. $\delta\mathbf{Z}_b^L$ and $\delta\mathbf{Z}_t^L$ denote the field renormalization constants for b-quark and t-quark, respectively. In the calculation of the renormalized effective Wtb coupling, we take dimensional regularization and the on-shell renormalization scheme. The explicit expressions of the form factors are given by (we have neglected b-quark mass)

$$F_L = \frac{1}{16\pi^2}\frac{m_t^2\tan^2\beta}{v_w^2}(1-\varepsilon)^2(2C_{24}^e + 2C_{24}^f), \qquad (3)$$

$$F_R = 0, \qquad (4)$$

$$\delta\mathbf{Z}_b^L = \frac{1}{8\pi^2}\frac{m_t^2\tan^2\beta}{v_w^2}(1-\varepsilon)^2 B_1^d, \qquad (5)$$

$$\delta \mathbf{Z}_t^L = \frac{1}{16\pi^2}\frac{m_t^2 \tan^2\beta}{v_w^2}(1-\varepsilon)^2 \times [B_1^b + B_1^c + 2m_t^2(B_1^{b'} + B_1^{c'} + B_1^{a'} + B_0^{b'} + B_0^{c'})], \tag{6}$$

$$\tilde{F}_L = \frac{1}{16\pi^2}\frac{m_t^3 \tan^2\beta}{v_w^2}(1-\varepsilon)^2 \times (3C_{11}^e + C_0^e + 2C_{21}^e + 2C_{22}^e - 3C_{12}^e - 4C_{23}^e + C_{12}^f - C_{11}^f - C_0^f + 2C_{21}^f + 2C_{22}^f - 4C_{23}^f), \tag{7}$$

$$\tilde{F}_R = 0, \tag{8}$$

$$\hat{F}_L = \frac{1}{16\pi^2}\frac{m_t^3 \tan^2\beta}{v_w^2}(1-\varepsilon)^2(C_{12}^e + C_{11}^e + C_0^e - 2C_{22}^e + 2C_{23}^e - 3C_{12}^f + C_{11}^f - C_0^f - 2C_{22}^f + 2C_{23}^f), \tag{9}$$

$$\hat{F}_R = 0. \tag{10}$$

$B_{0,1}$ and $C_{0,ij}$ are, respectively, two-point and three-point standard functions given in Ref. [19] and $B'_{0,1}$ denotes $\partial B_{0,1}/\partial p^2$. Their functional dependences are

$$C_{0,ij}^e = C_{0,ij}(-p_t, p_t - p_b, m_t, M_{\Pi_t}, M_{\Pi_t}),$$
$$C_{0,ij}^f = C_{0,ij}(-p_t, p_t - p_b, m_t, M_{h_t}, M_{\Pi_t}),$$
$$B_{0,1}^a = B_{0,1}(-p_t, m_b, M_{\Pi_t}),$$
$$B_{0,1}^b = B_{0,1}(-p_t, m_t, M_{\Pi_t}),$$
$$B_{0,1}^c = B_{0,1}(-p_t, m_t, M_{h_t}),$$
$$B_{0,1}^d = B_{0,1}(-p_b, m_t, m_{\Pi_t}).$$

Here we have ignored the mass difference between the neutral top pion and charged top pions.

The correction of the TC2 model to the Wtb coupling can influence all three single t-quark production modes.

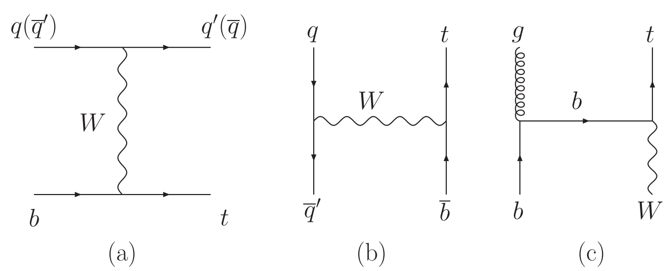

FIG. 2. The leading-order Feynman diagrams for the single t-quark production in the SM. (a) For the tq process, (b) for the $t\bar{b}$ process, and (c) for the associated tW process.

B. The tq production mode

In the SM, the tree-level tq production mode ($q = \bar{u}$, d, $\bar{c}$, s, here q also represent antiquarks for simplicity. In the following, we will name this process as tq production mode instead of t-channel mode called in the SM because the tree-level FC couplings in the TC2 model can also make a s-channel contribution to the tq production.) involves a spacelike W boson ($Q^2 \leq 0$), as shown in Fig. 2(a), and the virtual W boson strikes a b-quark in the proton sea, promoting it to a t-quark. Of the single t-quark production modes, the tq production mode has the largest cross section both at the Tevatron and the LHC and such a mode has been studied extensively [20]. Its cross section has been calculated at next-to-leading-order (NLO) in QCD, and the QCD NLO total cross section is 1.98 pb, 246 pb for the Tevatron and the LHC, respectively [21–23]. Significant sources of uncertainties affect the theoretical predictions of the cross section and the theoretical uncertainty of the tq production cross section is the largest one in all single t-quark production modes. At the LHC, the cross section is so large that it should be possible to collect large samples of single t-quark events via the tq production which can be used to study the t-quark EW coupling in detail.

The modification of the Wtb coupling can influence the cross section of the tq production in the way shown in Fig. 3.

The corresponding production amplitudes can be written as

$$M_1 = -\frac{g}{\sqrt{2}}G(p_4 - p_2, M_W)\bar{u}_t(p_4)\Gamma^\mu(p_4, p_2)u_b(p_2) \times \bar{u}_{q'}(p_3)\gamma_\mu P_L u_q(p_1), \tag{11}$$

$$M_2 = -\frac{g}{\sqrt{2}}G(p_4 - p_2, M_W)\bar{u}_t(p_4)\Gamma^\mu(p_4, p_2)u_b(p_2) \times \bar{v}_{\bar{q}'}(p_1)\gamma_\mu P_L v_{\bar{q}}(p_3), \tag{12}$$

where

$$G(p, m) = \frac{1}{p^2 - m^2}.$$

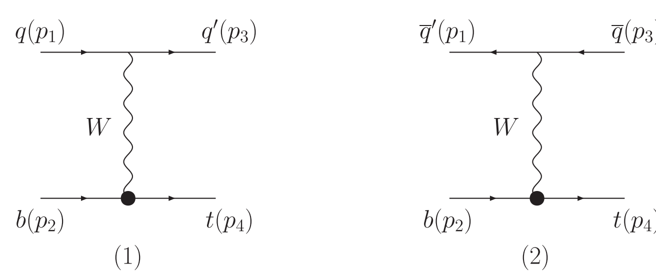

FIG. 3. The contribution to the tq production induced by the modification of the Wtb coupling in the TC2 model.

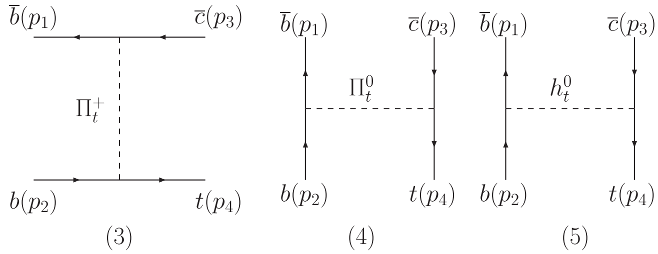

FIG. 4. The tree-level contribution of the FC couplings in the TC2 model to the $t\bar{c}$ production.

On the other hand, as we can see from Eq. (1), there exist the tree-level FC couplings $\Pi_t^0 t\bar{c}$, $h_t^0 t\bar{c}$, $\Pi_t^+ c\bar{b}$ in the TC2 model. Via $b\bar{b}$ collision, these FC couplings can induce the tree-level contribution to the $t\bar{c}$ production via the t-channel and s-channel exchange of Π_t^0, h_t^0, Π_t^+. The corresponding Feynman diagrams are shown in Fig. 4. We should note that the cross section of the $t\bar{c}$ production via the t-channel in the SM is very small and can be ignored. The tree-level FC contribution of the TC2 model, especially the resonant effect in the s-channel of Fig. 4, can greatly enhance the cross section of the $t\bar{c}$ production. The FC contribution of the TC2 model does not have interference with the SM amplitudes, because the FC contribution only comes from $b\bar{b}$ collision. Although such a FC contribution arises from both the t-channel and s-channel, we combine all the cross sections of $tq(q = \bar{u}, d, \bar{c}, s)$ productions together due to the difficulty to distinguish these light quarks.

The production amplitudes related to Fig. 4 can be written as

$$M_3 = -i\frac{2m_t^2\tan^2\beta}{v_w^2}(1-\varepsilon)\sqrt{2\varepsilon-\varepsilon^2}\frac{1}{(p_4-p_2)^2-M_{\Pi_t}^2} \times \bar{u}_t(p_4)P_L u_b(p_2)\bar{v}_{\bar{b}}(p_1)P_R v_{\bar{c}}(p_3), \tag{13}$$

$$M_4 = i\frac{m_t m_b^*\tan^2\beta}{v_w^2}\sqrt{2\varepsilon-\varepsilon^2} \times \frac{1}{(p_3+p_4)^2-M_{\Pi_t}^2+iM_{\Pi_t}\Gamma_{\Pi_t^0}} \times \bar{u}_t(p_4)P_R v_{\bar{c}}(p_3)\bar{v}_{\bar{b}}(p_1)\gamma_5 u_b(p_2), \tag{14}$$

$$M_5 = -i\frac{m_t m_b^*\tan^2\beta}{v_w^2}\sqrt{2\varepsilon-\varepsilon^2} \times \frac{1}{(p_3+p_4)^2-M_{h_t^0}^2+iM_{h_t^0}\Gamma_{h_t^0}} \times \bar{u}_t(p_4)P_R v_{\bar{c}}(p_3)\bar{v}_{\bar{b}}(p_1)u_b(p_2). \tag{15}$$

We can see that the timelike momentum may hit the top-pion (top-Higgs) pole in the top-pion (top-Higgs) propagator of the s-channel in Fig. 4. So we should take into account the effect of the width of the top pions (top Higgs) in the amplitudes M_4, M_5, i.e., we should take the complex mass term $M_{\Pi_t}^2 - iM_{\Pi_t}\Gamma_{\Pi_t^0}(M_{h_t}^2 - iM_{h_t}\Gamma_{h_t^0})$ instead of the simple top-pions (top-Higgs) mass term $M_{\Pi_t}^2(M_{h_t}^2)$ in the top-pions (top-Higgs) propagator. The term $M_{\Pi_t}^2 - iM_{\Pi_t}\Gamma_{\Pi_t^0}(M_{h_t}^2 - iM_{h_t}\Gamma_{h_t^0})$ is important in the vicinity of the resonance. The decay widths of Π_t^0 and h_t^0 have been calculated in Ref. [24].

With the above production amplitudes, we can directly obtain the cross sections of subprocesses. The hadronic cross sections at the hadron colliders can be obtained by folding the cross sections of subprocesses with the parton distribution. In the calculation of the cross section, instead of calculating the square of the production amplitudes analytically, we calculate the amplitudes numerically by using the method of Ref. [25]. This greatly simplifies our calculations.

To obtain numerical results of the contribution of the TC2 model to the tq production, we need to specify the relevant parameters in the SM. These parameters are $m_t = 174.2$ GeV, $m_b = 4.7$ GeV, $m_c = 1.25$ GeV, $m_u = 0.002$ GeV, $m_d = 0.005$ GeV, $m_s = 0.095$ GeV, $\alpha_s = 0.118$, $s_W^2 = 0.23$, and $M_W = 80.4$ GeV [26]. Except for these parameters, the production amplitudes are also dependent on some free parameters in the TC2 model: v_t, ε, M_{Π_t}, M_{h_t}. Here we choose $v_t = 60$ GeV and $\tan\beta$ can also be fixed. To see the influences of these parameters on the cross sections, we take $\varepsilon = 0.03, 0.06, 0.1$ and $M_{h_t} = 200$, 400 GeV as examples, and vary M_{Π_t} from 200 GeV to 400 GeV. For the parton distributions, we use CTEQ6L PDF [27]. On the other hand, the conjugated $\bar{t}$ production is also considered in the calculation.

To see the effect of the varying M_{Π_t}, in Fig. 5, we plot the relative correction $(\sigma_{\text{total}}^{tq} - \sigma_{\text{SM}}^{tq})/\sigma_{\text{SM}}^{tq}$ at the LHC as a function of M_{Π_t} for three values of $\varepsilon(0.03, 0.06, 0.1)$ and two values of $M_{h_t}(200, 400\text{ GeV})$. $\sigma_{\text{total}}^{tq}$ is the total cross section of tq production at the LHC which is defined as $\sigma_{\text{total}}^{tq} = \sigma_{\text{SM}}^{tq} + \delta\sigma_{Wtb}^{tq} + \sigma_{\text{FC}}^{tq}$, with σ_{SM}^{tq} being the tree-level SM cross section of the tq production and $\delta\sigma_{Wtb}^{tq}$ being the correction to the cross section induced by the modification of the Wtb coupling in the TC2 model and σ_{FC}^{tq} being the cross section of the $t\bar{c}$ production induced by the tree-level FC couplings in the TC2 model. From Fig. 5, we can see that the total correction of the TC2 model is positive in most cases and it becomes negative when M_{Π_t} is large. This is because $\delta\sigma_{Wtb}^{tq}$ is negative and σ_{FC}^{tq} is positive. The resonant effect of the s-channel enhances the σ_{FC}^{tq} significantly and it drops sharply when M_{Π_t} becomes large. As we will discuss in the next section, the light top-pion is not allowed by the Tevatron experiments due to the large contribution of the light top pion to the $t\bar{b}$ production. For the heavy top pion, the contribution of the TC2 model to the tq production at the LHC is not large. Comparing two diagrams in Fig. 5, we can conclude that large M_{h_t} can also

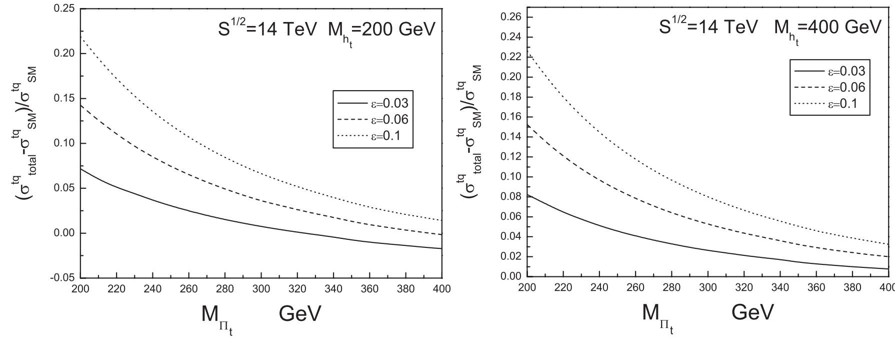

FIG. 5. The relative correction of the TC2 model to the tq production at the LHC, $(\sigma^{tq}_{\rm total} - \sigma^{tq}_{\rm SM})/\sigma^{tq}_{\rm SM}$, as a function of M_{Π_t} with ε being 0.03, 0.06, 0.1 and M_{h_t} being 200, 400 GeV.

depress the correction. The dependence of ε on the relative correction is clear, and the relative correction increases with ε increasing.

To provide more information, we show each contribution of the TC2 model to the tq production at the LHC in Table I. We can see that the main correction of the TC2 model to the tq production comes from the tree-level FC coupling and such a correction is positive. The correction induced by the modification of the Wtb coupling in the TC2 model is negative and the maximal value of the relative correction is only about -4%.

The ability to detect the correction of the TC2 model via the single t-quark production at the LHC is determined by the precision to measure the tq process. The precision on the cross section is related to the statistical sensitivity, systematic uncertainties, theoretical background uncertainties, and the luminosity uncertainties. So the final state signature and the backgrounds should be analyzed in detail.

The final state signature of the tq production is characterized by a high energy isolated lepton and missing transverse energy from the decay of the W from the t-quark into $l\nu$, and two or three jets. One of the jets originates from a b-quark from the t-quark decay and is usually central (low pseudorapidities) and energetic. There usually are, apart from the b jet from t-quark decay, a moderately energetic light flavor jet and a high pseudorapidity low energy b-quark jet from gluon splitting. This very forward or backward b jet is a unique feature of this signal, but it is rarely reconstructed and even more difficult to tag. Among the two or three jets, at least one jet must be b tagged in the central pseudorapidity region. The other b jet in the final state is usually emitted towards the very forward region, outside the tracker acceptance and thus out of reach of the b-tagging algorithm in most cases.

The main processes that can mimic the final state topology of tq production are: (i) $W +$ jets events, where the W boson decays semileptonically and two or more associated jets are produced; (ii) $t\bar{t}$ events, where one or both t-quarks decay leptonically; and (iii) QCD or multijet events. Contrary to the situation at the Tevatron, the main background comes from the t-quark pair production at the LHC,

TABLE I. Each contribution of the TC2 model to the tq production at the LHC.

ϵ	M_{h_t} (GeV)	M_{Π_t} (GeV)	$\sigma^{tq}_{\rm SM}$ (pb)	$\delta\sigma^{tq}_{Wtb}$ (pb)	$\sigma^{tq}_{\rm FC}$ (pb)	$\sigma^{tq}_{\rm total}$ (pb)
		200		−7.24	23.26	239.42
		250		−7.65	14.44	230.19
0.03	200	300	223.40	−8.21	9.87	225.06
		350		−8.83	7.12	221.69
		400		−9.47	5.64	219.56
		200		−6.80	38.64	255.24
		250		−7.19	23.78	239.98
0.06	200	300	223.40	−7.71	15.78	231.46
		350		−8.30	11.22	226.33
		400		−8.90	8.53	223.03
		200		−6.24	55.16	272.32
		250		−6.60	33.45	250.25
0.1	200	300	223.40	−7.08	21.87	238.19
		350		−7.61	15.18	230.97
		400		−8.17	11.32	226.55

well above the W + jets and WQQ (here Q are the light quarks) events. The t-quark pair production has a cross section larger than the single t-quark production. But the average energy in the event is larger, due to the presence of two t-quarks, and events tend to be more spherical and have more jet multiplicity than single t-quark events. Two t-quarks produce two W bosons and two b-quark jets, the latter with very similar kinematics to the signal and therefore likely to be b tagged as well. The same final state signature as in the single t-quark processes is obtained if only one of the W bosons decays leptonically and the other hadronically, or if both do, but only one lepton is reconstructed. This background can be properly simulated using ALPGEN or PYTHIA. The W + jets background is by far the most problematic to get rid of. It consists of a leptonically decaying W boson and at least two associated quarks or gluons. W + jets events contain less energy in the event than the single t-quark signals since they do not contain a heavy object like the t-quark. But the cross section is very large in comparison to the single t-quark production, and the flavor composition of the associated jets is sufficiently complex, to make this background hard to model and even harder to get rid of as one applies b tagging techniques, since they tend to shift distributions to be more signal-like and wash away any low energy feature. This background has been estimated using simulated events, by ALPGEN, for example, and is usually scaled to data to get the overall normalization right. The QCD background typically enters as misreconstructed events, where a jet is wrongly identified as an electron, or a muon from a heavy flavor jet appears isolated in the detector. Multijet events may also contain heavy flavor jets or just light jets that are misidentified by the b tagging algorithma. The transverse energy of QCD events is much less than signal events, and the mass of the system of the b-tagged jet, the lepton, and the neutrino does not peak at m_t, but the cross section is overwhelmingly large. This background is usually obtained directly from data, and after some initial basic criteria can be reduced in size to the same level as the signal.

With a large cross section, the tq production will be the first single t-quark production accessible with the early data at the LHC. The cross section measurement of such a mode benefits from a significantly higher statistics compared to the other single t-quark production modes. The final topology is also significantly different from that of the other modes, and leads to a specific selection. The precision on the cross section is related to the statistical sensitivity, systematic uncertainties, theoretical background uncertainties, and the luminosity uncertainties. With a simple selection, the precision is expected to be [28]

$$\frac{\Delta\sigma}{\sigma} = 1.02\%_{\text{stat}} \pm 11\%_{\text{exp}} \pm 6\%_{\text{bckgdtheo}} \pm 5\%_{\text{lumi}} \quad (16)$$

at ATLAS for $L = 30\ \text{fb}^{-1}$, and

$$\frac{\Delta\sigma}{\sigma} = 2.7\%_{\text{stat}} \pm 8.1\%_{\text{exp}} \pm 3\%_{\text{lumi}} \quad (17)$$

at CMS for $L = 10\ \text{fb}^{-1}$ [29].

We can see that the statistical sensitivity is very small with the large cross section at the LHC and the main uncertainties come from systematic uncertainties. Based on our calculation, we can conclude that the LHC should have the ability to detect the contribution induced by the FC coupling in the TC2 model via the tq production, but higher sensitivity is needed if one wants to obtain the information about the modification of the Wtb coupling in the TC2 model.

C. The $t\bar{b}$ production mode

Another process in the SM that produces a single t-quark is the s-channel $t\bar{b}$ production via the timelike W boson, as shown in Fig. 2(b) [30]. The cross section of such a production in the SM is much less than that of the tq production because it scales like $1/s$ rather than $1/M_W^2$. However, the $t\bar{b}$ process has the advantage of little theoretical uncertainty [22,23,31]. This is because the quark and antiquark distribution functions are relatively well known, so the uncertainty from the parton distribution functions is small. Furthermore, the parton luminosity can be constrained by measuring the Drell-Yan process $q\bar{q} \to W^* \to l\bar{\nu}$, which has the identical initial state. The next-to-leading order (NLO) cross section of the $t\bar{b}$ production in the SM is 0.88 pb, 10.6 pb for the Tevatron and the LHC, respectively [22,23,31]. The total cross section is even known to next-to-next-to-leading order [32].

Because of the existence of the Wtb coupling, the modification of the Wtb coupling in the TC2 model also affects the $t\bar{b}$ production as shown in Fig. 6(6).

Including the modification of the Wtb coupling in the TC2 model, we can write the production amplitude of the $t\bar{b}$ process as

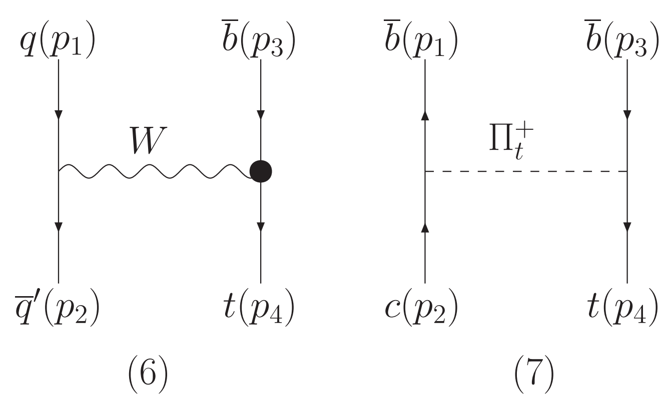

FIG. 6. The contribution of the TC2 model to the $t\bar{b}$ production.

$$M_6 = -\frac{g}{\sqrt{2}} G(p_3 + p_4, M_W)\bar{u}_t(p_4)\Gamma^\mu(p_4, -p_3)v_{\bar{b}}(p_3) \times \bar{v}_{\bar{q}'}(p_2)\gamma_\mu P_L u_q(p_1). \quad (18)$$

On the other hand, due to the existence of the tree-level FC coupling $\Pi^+ c\bar{b}$, Π_t^+ can contribute to the $t\bar{b}$ production through the s-channel virtual exchange of a Π_t^+ as shown in Fig. 6(7).

As in the tq production, the s-channel contribution of Π_t^+ to the $t\bar{b}$ production can also allow a large resonant contribution. The distribution of the invariant mass of the $t\bar{b}$ system could show the resonant effect around the mass of Π_t^+, which serves to identify this type of particles. However, if the mass of Π_t^+ is very large and its width is broad, the resonant shape can be washed out.

The production amplitude of the $t\bar{b}$ process induced by the FC coupling $\Pi^+ c\bar{b}$ is

$$M_7 = -i\frac{2m_t^2 \tan^2\beta}{v_w^2}(1-\varepsilon)\sqrt{2\varepsilon - \varepsilon^2} \times \frac{1}{(p_3+p_4)^2 - M_{\Pi_t}^2 + iM_{\Pi_t}\Gamma_{\Pi_t^+}} \times \bar{u}_t(p_4)P_L v_{\bar{b}}(p_3)\bar{v}_{\bar{b}}(p_1)P_R u_c(p_2). \quad (19)$$

Here we also take into account the effect of the width of the charged top pions in the amplitude M_7 due to the existence of the resonant effect. The decay width of the charged top pions has been given in Ref. [33].

The amplitude M_7 does not have a significant interference with the SM amplitudes because the SM contribution is mostly from light quarks (u and $\bar{d}$). So, in the TC2 model, the total cross section of the $t\bar{b}$ production can been written as

$$\sigma_{\text{total}}^{t\bar{b}} = \sigma_{\text{SM}}^{t\bar{b}} + \delta\sigma_{Wtb}^{t\bar{b}} + \sigma_{\text{FC}}^{t\bar{b}}. \quad (20)$$

Here $\sigma_{\text{SM}}^{t\bar{b}}$ is the SM tree-level cross section of $t\bar{b}$ production, $\delta\sigma_{Wtb}^{t\bar{b}}$ is the correction induced by the modification of the Wtb coupling in the TC2 model, and $\sigma_{\text{FC}}^{t\bar{b}}$ is the cross section of the $t\bar{b}$ production induced by the tree-level FC coupling in the TC2 model.

In Fig. 7, we plot the total relative correction at the LHC, $(\sigma_{\text{total}}^{t\bar{b}} - \sigma_{\text{SM}}^{t\bar{b}})/\sigma_{\text{SM}}^{t\bar{b}}$, as a function of M_{Π_t}, here the $\bar{t}$ production is also considered as in the tq production. The relative correction drops sharply with M_{Π_t}. It is shown that even with large M_{Π_t}, the contribution of the TC2 model can also enhance the SM cross section significantly. To represent each contribution of the TC2 model, we show $\sigma_{\text{SM}}^{t\bar{b}}$, $\delta\sigma_{Wtb}^{t\bar{b}}$, $\sigma_{\text{FC}}^{t\bar{b}}$, $\sigma_{\text{total}}^{t\bar{b}}$ in Table II. Similar to the tq production, the correction induced by the Wtb coupling is negative and below 4% in the parameter space considered. The total contribution is dominated by the contribution induced by the tree-level FC coupling $\Pi_t^+ c\bar{b}$.

Like the tq production, there is the final state signature $l\nu$ and a b-quark jet in the $t\bar{b}$ production. The other energetic jet is also from a b-quark, and shares similar kinematics with the b-quark from the t-quark decay. Thus b-quark identification, or b tagging, in the $t\bar{b}$ production is equally likely between the b-quark from the t-quark decay and the b-quark from the original interaction. From a phenomenological standpoint, the most important distinction of the final states between $t\bar{b}$ and tq productions is the presence of a second high-p_T b-jet in the $t\bar{b}$ process. In the tq production, the second b-jet tends to be at low p_T and is often not seen. Therefore, the requirement of two b-jets with high p_T will eliminate most of the background coming from the tq production. On the other hand, the requirement of two b-tagged jets is also crucial to reduce the contamination of W + jets events that have a cross section several orders of magnitude that of the signal. Furthermore, it is also necessary, as in other single t-quark production modes, to design cuts to reduce the W + jets and $t\bar{t}$ backgrounds. In order to reduce contamination by W + jets events, the reconstructed t-quark mass in each event must fall within a window about the known t-quark mass, and the events must have a total transverse jet momentum above 175 GeV. Only events containing exactly two jets (both tagged as b's) are kept in order to reduce the $t\bar{t}$ background. The study indicates that, despite the large anticipated background rate, it should be possible to perform a good statistical measurement of the cross section for the $t\bar{b}$ production. The resulting S/B ratio is about 11%

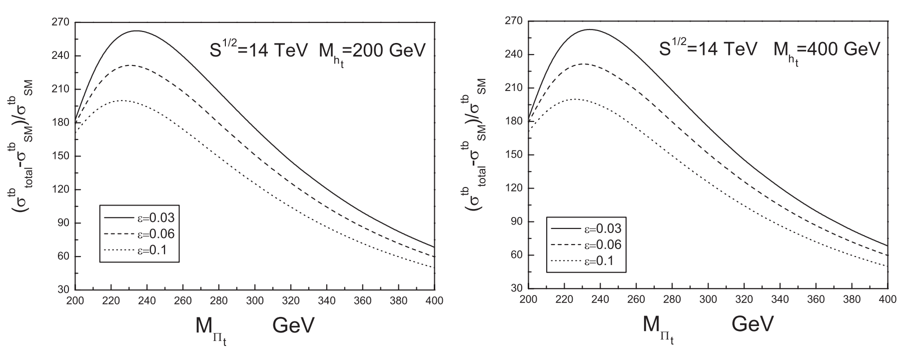

FIG. 7. The relative correction of the TC2 model to the $t\bar{b}$ production at the LHC, $(\sigma_{\text{total}}^{t\bar{b}} - \sigma_{\text{SM}}^{t\bar{b}})/\sigma_{\text{SM}}^{t\bar{b}}$, as a function of M_{Π_t} with ε being 0.03, 0.06, 0.1 and M_{h_t} being 200, 400 GeV.

TABLE II. Each contribution of the TC2 model to the $t\bar{b}$ production at the LHC.

ϵ	M_{h_t} (GeV)	M_{Π_t} (GeV)	$\sigma^{tq}_{\rm SM}$ (pb)	$\delta\sigma^{tq}_{Wtb}$ (pb)	$\sigma^{tq}_{\rm FC}$ (pb)	$\sigma^{tq}_{\rm total}$ (pb)
		200		−0.07	1315.66	1322.81
		250		−0.14	1827.92	1834.99
0.03	200	300	7.21	−0.19	1261.03	1268.05
		350		−0.24	789.16	796.14
		400		−0.28	492.08	499.01
		200		−0.06	1289.54	1296.68
		250		−0.13	1582.34	1589.42
0.06	200	300	7.21	−0.18	1087.66	1094.68
		350		−0.22	683.81	690.79
		400		−0.26	430.73	437.68
		200		−0.06	1231.46	1238.61
		250		−0.12	1341.44	1348.53
0.1	200	300	7.21	−0.17	903.13	910.17
		350		−0.21	567.59	574.60
		400		−0.24	359.65	366.62

(9%) in the $t\bar{b}(\bar{t}b)$ final state. It is obvious that the combination of both final states is required to improve the sensitivity. The precision on the cross section has been assessed at the LHC for an integrated luminosity of 30 fb^{-1} at different stages of the analysis. After the simple preselection stage, results show a good statistical sensitivity but higher level of systematic uncertainties. The precision at ATLAS for $L = 30$ fb^{-1} is shown as [28]

$$\frac{\Delta\sigma}{\sigma} = 7\%_{\rm stat} \pm 13.8\%_{\rm exp} \pm 11\%_{\rm bckgdtheo} \pm 5\%_{\rm lumi}. \quad (21)$$

Using both the H_T (the total transverse energy) and reconstructed t-quark mass results in a significantly reduced level of systematics at the price of loss in statistical sensitivity

$$\frac{\Delta\sigma}{\sigma} = 12\%_{\rm stat} \pm 12\%_{\rm exp} \pm 11\%_{\rm bckgdtheo} \pm 5\%_{\rm lumi}. \quad (22)$$

At CMS for $L = 10$ fb^{-1}, the precision is [29]

$$\frac{\Delta\sigma}{\sigma} = 18\%_{\rm stat} \pm 31\%_{\rm exp} \pm 3\%_{\rm lumi}. \quad (23)$$

In all cases, systematic errors are expected to dominate the cross section determination.

As we have discussed above, the measurement of the $t\bar{b}$ production may appear as the most delicate of the main three single t-quark processes because of its relatively low cross section compared to the others at the LHC. It is, however, one of the most interesting because the final state events of the $t\bar{b}$ production is directly sensitive to contributions from extra particles predicted in new physics models. Our results show that the correction to the $t\bar{b}$ production induced by the Wtb coupling is still small as in the tq production which is embedded in the large contribution coming from the tree-level FC coupling in the TC2 model. Certainly, the LHC has the ability to detect such a FC effect. On the other hand, the LHC experiments about the $t\bar{b}$ production should provide a severe limit on the FC coupling $\Pi_t^+ c\bar{b}$ if the cross section of the $t\bar{b}$ production is measured precisely at the LHC. Therefore

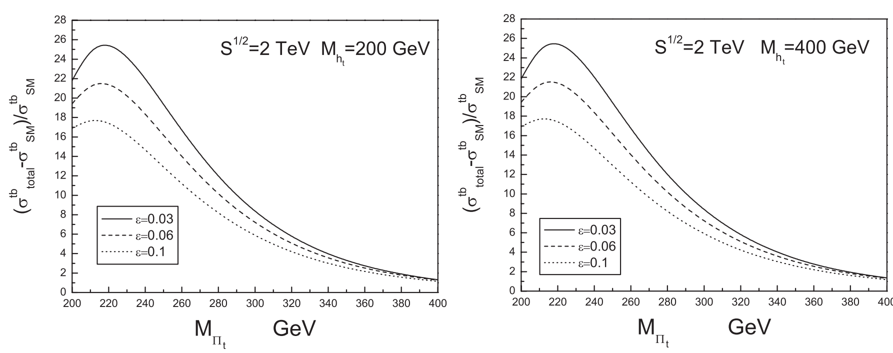

FIG. 8. The relative correction of the TC2 model to the $t\bar{b}$ production at the Tevatron, $(\sigma^{t\bar{b}}_{\rm total} - \sigma^{t\bar{b}}_{\rm SM})/\sigma^{t\bar{b}}_{\rm SM}$, as a function of M_{Π_t} with ε being 0.03, 0.06, 0.1 and M_{h_t} being 200, 400 GeV.

TABLE III. Each contribution of the TC2 model to the $t\bar{b}$ production at the Tevatron

ϵ	M_{h_t} (GeV)	M_{Π_t} (GeV)	$\sigma^{tq}_{\rm SM}$ (pb)	$\delta\sigma^{tq}_{Wtb}$ (pb)	$\sigma^{tq}_{\rm FC}$ (pb)	$\sigma^{tq}_{\rm total}$ (pb)
		200		−0.004	5.61	5.86
		250		−0.007	4.98	5.23
0.03	200	300	0.26	−0.008	2.15	2.40
		350		−0.010	0.86	1.10
		400		−0.010	0.35	0.59
		200		−0.004	5.00	5.24
		250		−0.006	4.16	4.41
0.06	200	300	0.26	−0.008	1.85	2.10
		350		−0.009	0.77	1.02
		400		−0.010	0.34	0.58
			200		−0.004	4.34
4.60						
		250		−0.006	3.32	3.57
0.1	200	300	0.26	−0.007	1.51	1.76
		350		−0.008	0.66	0.91
		400		−0.009	0.30	0.55

$t\bar{b}$ production provides a unique chance to study the properties of the FC coupling $\Pi_t^+ c\bar{b}$ at the LHC.

Although the Tevatron cannot measure three single t-quark production modes separately, the measured cross section $\sigma(p\bar{p} \to tb + X, tqb + X)$ has been given by the Tevatron experiments which can also provide rude information about $t\bar{b}$ production. The experimental value of the cross section of $t\bar{b}$ production is almost consistent with the SM value. So it is necessary to calculate the contribution of the TC2 model to the $t\bar{b}$ production at the Tevatron due to the large contribution of the TC2 model to the $t\bar{b}$ production. We plot the total relative correction of the TC2 model to the $t\bar{b}$ production at the Tevatron in Fig. 8 and represent each contribution in Table III. Clearly there should exist a large down-limit on the top-pion mass if the predicted cross section in the TC2 model is consistent with the Tevatron experiments.

D. The associated production tW

A single t-quark may also be produced via the weak interaction in association with a real W boson ($q^2 = M_W^2$), as shown in Fig. 2(c) [34,35]. Like the tq production, one of the initial partons is a b-quark. However, unlike the tq production, this associated production scales like $1/s$. This, combined with the higher values of x needed to produce both a t-quark and a W boson, leads to a cross section which is significantly less than that of the tq process, despite the fact that it is order $\alpha_s \alpha_e$ rather than α_e^2. The tW process is also known at NLO, and the total NLO cross section is 0.14 pb at the Tevatron which is negligible, while it is 68 pb at the LHC [23,35,36].

If the t-quark has indeed a special role in the generation of masses, it is crucial that its interactions should be carefully studied in order to learn what properties the underlying theory at high energies must possess. The deviations of Wtb coupling from the SM predictions may represent the best clues on the nature of the EWSB. As we know, each single t-quark production mode is sensitive to different types of new physics, with the tW mode distinct in that it is sensitive only to physics which directly modifies the Wtb coupling from its SM structure. This distinction is a result of the fact that in this mode both the t-quark and the W are directly observable, whereas in the other two modes the W bosons are virtual, and thus those processes may receive contributions from exotic types of charged bosons or FCNC interactions. On the other hand, tW mode can also provide complimentary information about the Wtb coupling by probing it in a region of momentum different from other single t-quark production modes. Similar to the tq production, the cross section for this associated production increases by more than 2 orders of magnitude from the Tevatron to the LHC, it is sufficiently large at the LHC to not only observe this mode of single t-quark production but also to study the Wtb coupling in detail.

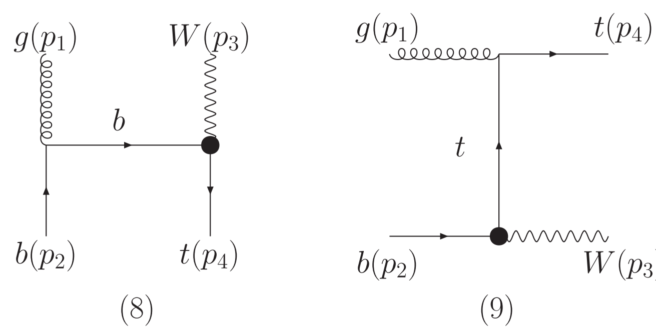

FIG. 9. The contribution to the associated tW production induced by the modification of the Wtb coupling in the TC2 model.

Unlike the other two single t-quark production modes, there only exists the contribution from Wtb coupling for the tW production in the TC2 model, shown as Fig. 9. The production amplitudes including such a contribution are

$$M_8 = -g_s T^a_{ij} \bar{u}_{ti}(p_4)\Gamma^\mu(p_4, p_3 + p_4)\varepsilon_\mu(p_3) \times \frac{\not{p}_3 + \not{p}_4 + m_b}{(p_3 + p_4)^2 - m_b^2} \not{\varepsilon}^a(p_1) u_{bj}(p_2), \tag{24}$$

$$M_9 = -g_s T^a_{ij} \bar{u}_{ti}(p_4) \not{\varepsilon}^a(p_1) \frac{\not{p}_2 - \not{p}_3 + m_t}{(p_2 - p_3)^2 - m_t^2} \times \varepsilon_\mu(p_3)\Gamma^\mu(p_2 - p_3, p_2) u_{bj}(p_2). \tag{25}$$

The total cross section of the tW production is defined as $\sigma^{tW}_{\rm total} = \sigma^{tW}_{\rm SM} + \delta\sigma^{tW}_{Wtb}$. Here we only consider the tree-level SM cross section $\sigma^{tW}_{\rm SM}$, and $\delta\sigma^{tW}_{Wtb}$ represents the correction from the Wtb coupling. In the calculation, we take the same parameter values as in the other two single t-quark production modes, and also consider the $\bar{t}$ production. Here we focus on studying the tW production mode at the LHC. The numerical results of relative correction at the LHC, $(\sigma^{tW}_{\rm total} - \sigma^{tW}_{\rm SM})/\sigma^{tW}_{\rm SM}$, are shown in Fig. 10. Because the correction to the tW production only comes from the modification of the Wtb coupling in the TC2 model the relative correction to the tW production is small and negative.

As for the other two single t-quark production modes, we select tW events by requiring a single high P_T lepton and a high missing transverse energy. Such a selection criterion implies that one W boson decays leptonically and that the second W boson must decay into two jets. Therefore, the selected events have exactly three jets with one of them tagged as a b-jet. This allows to reject part of the $t\bar{t}$ background. In addition, by requiring a 2-jet invariant mass within a window around the W mass, it is possible to eliminate most events that do not contain a second W, i.e. all backgrounds other than $t\bar{t}$.

The strategy for measuring the cross section of the tW production is similar to that for the tq production, as they share the same backgrounds. However, the nature of the associated production makes it relatively easy to separate the signal from the W + jets background and difficult to separate from the $t\bar{t}$ background. Therefore, the dominant background arises from $t\bar{t}$ production. From the point of view of signal identification, the region with small tW invariant mass, near the $t\bar{t}$ threshold, has possibly a chance to be optimal. The tW process analysis benefits from the relative high cross section. However, due to high similarities with top pair events, the selection is hampered by a high level of background contamination. These characteristics make the tW cross section very difficult to measure with the early data at the LHC. Two studies designed to separate signal from background have been performed using two different final states. The first is a study which attempts to isolate tW signal events in which one W decays to jets and the other decays to leptons [37]. The second study attempts to isolate signal events in which both W's decay leptonically [38]. Based on the SM prediction, the S/B ratio is well below 10%. Because the main background comes from the top pair production, the prior precise determination of the top pair production cross section is needed. Combining both electron and muon channels as well as all two and three jet final states leads to a statistical precision slightly below 6% for an integrated luminosity of 1 fb^{-1}. As we have discussed above, the relative correction of the TC2 model to the tW production is only a few percent even in the optimal parameter space. Based on the precision on the cross section of the tW production, it is difficult to observe such a correction at the LHC. Therefore, tW production is not an ideal process to test the TC2 model.

III. THE SUMMARY AND CONCLUSION

The single t-quark production plays an important role in probing the properties of the Wtb coupling and new physics model. With the running of the LHC, it is possible to measure each single t-quark production mode separately and the cross section can be measured precisely. So the LHC opens an ideal window to probe the new physics via the single t-quark production. In this paper, we systemati-

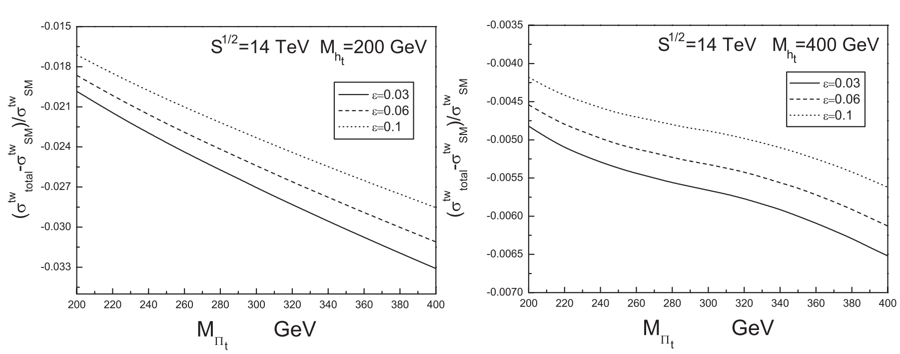

FIG. 10. The relative correction of the TC2 model to the tW production at the LHC, $(\sigma^{tW}_{\rm total} - \sigma^{tW}_{\rm SM})/\sigma^{tW}_{\rm SM}$, as a function of M_{Π_t} with ε being 0.03, 0.06, 0.1 and M_{h_t} being 200, 400 GeV.

cally study the contribution of the TC2 model to each single t-quark production mode at the LHC and also study the $t\bar{b}$ at the Tevatron. Because of the existence of the top pions and top Higgs, the TC2 model can contribute to the single t-quark production in two different ways. One is that the TC2 model can make the loop-level contribution to the cross sections which is induced by the modification of the Wtb coupling in the TC2 model. Such a contribution exists in all three single t-quark production modes, but it is very small. Even at the LHC, it is difficult to observe this kind of loop-level contribution. Another kind of contribution comes from the tree-level FC couplings in the TC2 model. Such a contribution only exists in the tq and $t\bar{b}$ production modes and the resonant effect can greatly enhance the cross sections. The recent Tevatron experiments have given a cross section for single t-quark production of $\sigma(p\bar{p} \to tb + X, tqb + X)$ which is consistent with the SM value. So there should exist down-limit on the top-pion mass. With the precise measurement of the cross section for each single t-quark production mode at the LHC, detailed information about the parameters and the FC couplings in the TC2 model can be obtained.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China under Grant Nos. 10775039, 10575029, and 10505007.

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