Charged top-pion production associated with the bottom quark pair as a probe of the topcolor-assisted technicolor model at the LHC

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The topcolor-assisted technicolor (TC2) model predicts the existence of the charged top-pions ($\pi_t^{\pm}$), whose large couplings with the third generation fermions will induce the charged top-pion production associated with the bottom and antibottom quark pair at the CERN Large Hadron Collider (LHC) through the parton processes $c\bar{b} \rightarrow \pi_t^+ b\bar{b}$ and $u\bar{d}(c\bar{s}) \rightarrow \pi_t^+ b\bar{b}$. In this report, we examine these productions and find that, due to the small standard model backgrounds, their production rates can exceed the 3σ sensitivity of the LHC in a large part of parameter space, so these processes may serve as a good probe of the TC2 model.

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I. INTRODUCTION

The mechanism of electroweak symmetry breaking (EWSB) remains the most prominent mystery in elementary particle physics. Probing EWSB will be one of the most important tasks in the high energy colliders. Dynamical EWSB, such as technicolor (TC) theory [1], is an attractive idea that avoids the shortcomings of triviality and unnaturalness arising from the elementary Higgs field.

Among various kinds of technicolor theories, the topcolor scenario [2] is attractive because it can explain the large top quark mass and provides a possible EWSB mechanism. TC2 model [3] is one of the phenomenologically viable models, which has all essential features of the topcolor scenario. This model predicts three *CP*-odd toppions π_t^0, $\pi_t^{\pm}$ and one *CP*-even top-higgs h_t^0 with large couplings to the third family, which may make these new scalar particles have a distinct experimental signature [4]. Thus, discovery of the scalar particles in future high energy colliders would be a definite signal of new physics beyond the standard model (SM), which would help us to understand the scalar sector and more importantly what lies beyond the SM.

LHC has already started its operation, and it will have considerably capability to discover and measure almost all the quantum properties of a SM higgs boson of any mass [5]. However, from the theoretical view point, it would be expected that the SM is replaced by a more fundamental theory at the TeV scale. If hadron colliders find evidence for a new scalar state, it may not necessarily be the SM Higgs boson. Many alternative new physics theories, such as supersymmetry, technicolor and little Higgs, predict the existence of new scalars or pseudoscalar particles. These new particles may have so large cross sections and branching fractions as to be observable at the high energy colliders. Thus, studying the production of the new scalars at the LHC will serve as a powerful tool of the new physics models.

In this report, we study how the technicolor models affect the charged top-pion production associated with the bottom quark pair processes $c\bar{b} \rightarrow \pi_t^+ b\bar{b}$ and $u\bar{d}(c\bar{s}) \rightarrow \pi_t^+ b\bar{b}$ via the new couplings in the TC2 model. In Sec. II, the technicolor model relative to our calculations is briefly reviewed. Sec. III shows the the numerical results for the different processes, respectively, and analyzes simply the SM backgrounds and the detectable probability. Summary and discussions are given in Sec. IV.

II. ABOUT THE TC2 MODEL

The TC2 model predicts a number of charged bosons like the top-pions at the weak scale [3]. These scalars have large Yukawa couplings to the quarks at tree-level, among which the top-bottom and the charm-bottom couplings to the charged top-pion $\pi_t^{\pm}$ are most significant. Such couplings will induce bottom antibottom pair productions associated with a charged scalar at the LHC through the parton processes $c\bar{b} \rightarrow \pi_t^+ b\bar{b}$ and $u\bar{d}(c\bar{s}) \rightarrow \pi_t^+ b\bar{b}$. In this report, we will examine these productions and figure out if their rates can exceed the 3σ sensitivity of the LHC. Since in the SM, such signals of the productions have unobservably small backgrounds at the LHC, these processes will serve as a probe for the TC2 model if their TC2 predictions can be above the 3σ sensitivity.

Before our calculations, we recapitulate the basics of TC2 model. The TC2 model [3] combines technicolor interaction with topcolor interaction, with the former being responsible for electroweak symmetry breaking and the latter for generating large top quark mass. The top quark mass is generated from two sources: one is from the extended technicolor (proportional to ϵ) and the other from the topcolor (proportional to $1 - \epsilon$). So, the mass matrix of up-type quarks is composed of both extended technicolor and topcolor contributions. The diagonalization of this mass matrix will induce flavor-changing top quark interactions in the Yukawa couplings, which involve the composite scalars from topcolor and technicolor condensations, respectively.

The relevant couplings with the top-pion and the fermions can be written as [6]

$$\mathcal{L}_Y = \frac{(1-\epsilon)m_t}{\sqrt{2}F_t}\frac{\sqrt{v_w^2 - F_t^2}}{v_w}(\sqrt{2}K_{UR}^{tt*}K_{DL}^{bb}\bar{t}_R b_L \pi_t^- + \sqrt{2}K_{UR}^{tc*}K_{DL}^{bb}\bar{c}_R b_L \pi_t^-), \quad (1)$$

where K_{DL} and K_{UR} are the rotation matrices that transform the weak eigenstates of left-handed down-type and right-handed up-type quarks to their mass eigenstates, respectively. According to the analysis of [6], their favored values are given by

$$K_{DL}^{bb} \simeq 1, \qquad K_{UR}^{tt} \simeq \frac{m_t'}{m_t} = 1-\epsilon, \qquad K_{UR}^{tc} \leq \sqrt{1-(K_{UR}^{tt})^2} = \sqrt{2\epsilon - \epsilon^2}. \quad (2)$$

In Eq. (2), we neglected the mixing between up quark and top quark. The factor $\sqrt{v_w^2 - F_t^2}/v_w$ ($v_w \simeq 174$ GeV) reflects the effect of the mixing between the top-pions and the would-be Goldstone bosons [7].

The total hadronic cross section for $pp \to \pi_t^+ b\bar{b} + X$ can be obtained by folding the subprocess cross section $\hat{\sigma}$ with the parton luminosity

$$\sigma(s) = \int_{\tau_0}^1 d\tau \frac{dL}{d\tau}\hat{\sigma}(\hat{s} = s\tau), \quad (3)$$

where $\tau_0 = (2m_b + m_\pi)^2/s$, and s is the pp center-of-mass energy squared. $dL/d\tau$ is the parton luminosity given by

$$\frac{dL}{d\tau} = \int_\tau^1 \frac{dx}{x}[f_{p_1}^p(x,Q)f_{p_2}^p(\tau/x,Q) + (p_1 \leftrightarrow p_2)], \quad (4)$$

where $f_{p_1}^p$ and $f_{p_2}^p$ are the parton p_1 and p_2 distribution functions in a proton, respectively. For our case, they could be u, d, c, s and b quark.

In our numerical calculation, the hadronic cross section at the LHC is obtained by convoluting the parton cross section with the parton distribution functions. In our calculations we use CTEQ6L [8] to generate the parton distributions with the renormalization scale μ_R and the factorization scale μ_F chosen to be $\mu_R = \mu_F = 2m_b + m_\pi$.

III. CALCULATIONS AND RESULTS

At the LHC, the cross sections of the charged top-pion production comes mainly from the quark collision processes $c\bar{b}$, $u\bar{d}$, $c\bar{s} \to \pi_t^+ b\bar{b}$, as shown in Fig. 1. In our numerical calculation, we use FormCalc for the three phase space integration [9].

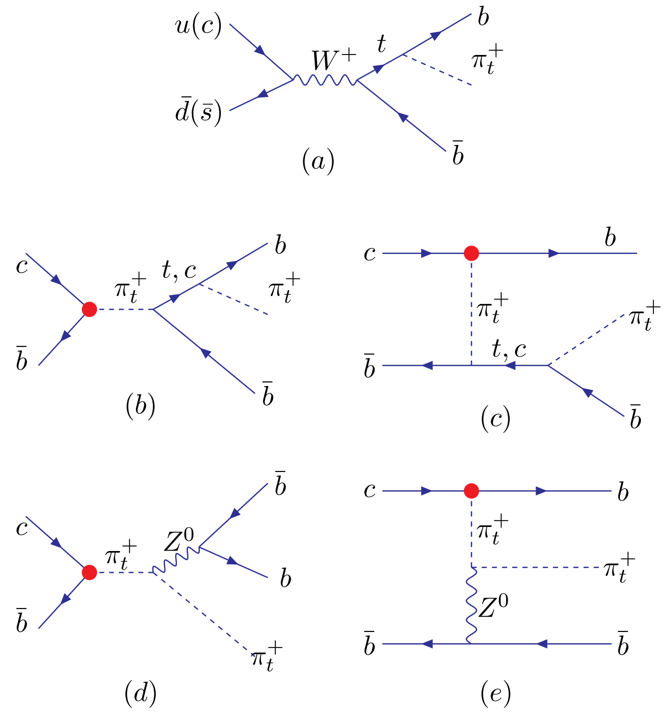

FIG. 1 (color online). Feynman diagrams for parton-level process $u\bar{d}(c\bar{s}) \to \pi_t^+ b\bar{b}$ and $c\bar{b} \to \pi_t^+ b\bar{b}$.

For the SM parameters, we will take $m_u = 2$ MeV, $m_d = 3$ MeV, $m_s = 100$ MeV, $m_c = 1.27$ GeV, $m_b = 4.5$ GeV, $m_t = 172.0$ GeV, $m_Z = 91.2$ GeV, $m_W = 80.399$ GeV [10].

The TC2 parameters involved in our calculations are the masses of the top-pions, the parameter K_{UR}^{tc}, the top-pion decay constant F_t and the parameter ϵ which parametrizes the portion of the extended-technicolor contribution to the top quark mass. The masses of the charged top-pion mass are constrained from the absence of $t \to \pi_t^+ b$, which gives a lower bound of 165 GeV [11], and also from R_b data, which yields a lower bound of about 220 GeV [12].

In the TC2 model, ϵ parameterizes the portion of the extended-technicolor (ETC) contribution to the top quark mass. The bare value of ϵ is generated at the ETC scale, and subject to very large radiative enhancement from the topcolor and $U(1)_{Y_1}$ by a factor of order 10 when evolving down to the weak scale [3]. This ϵ can induce a nonzero top-pion mass (proportional to $\sqrt{\epsilon}$) [13] and thus ameliorate the problem of having dangerously light scalars. Numerical analysis shows that, with reasonable choice of other input parameters, ϵ of order 10^{-2}–10^{-1} may induce top-pions as massive as the top quark [3]. Indirect phenomenological constraints on ϵ come from low energy flavor-changing processes such as $b \to s\gamma$ [14]. However, these constraints are very weak. From the theoretical point of view, ϵ with value from 0.01 to 0.1 is favored. Since a large ϵ can slightly suppress the FCNC Yukawa couplings, we fix conservatively $\epsilon = 0.1$ throughout this report. About the top-pion decay constant F_t, the Pagels-Stokar formula [15] gives a rough guide, and F_t may be in the range 40–70 GeV [16].

In our numerical results, we will take $F_t = 50$ GeV, $\epsilon = 0.1$, $K_{UL}^{tt} = 1$, $K_{UR}^{tt} = 0.9$ and retain m_π and K_{UR}^{tc} as free parameters with $200 \le m_\pi \le 600$ GeV and $K_{UR}^{tc} \le \sqrt{2\epsilon - \epsilon^2} = 0.43$.

In the following, we present the results for the hadronic production cross sections $c\bar{b} \to \pi_t^+ b\bar{b}$ and $u\bar{d}(c\bar{s}) \to \pi_t^+ b\bar{b}$, respectively.

A. The parton-level process $c\bar{b} \to \pi_t^+ b\bar{b}$

The process is carried through out as Fig. 1(b)–1(e), containing one or more $\pi_t^+ c\bar{b}$ vertexes, which is proportional to the TC2 parameter K_{UR}^{tc}.

Figure 2 shows that the hadronic cross section versus top-pion mass for different values of K_{UR}^{tc}. The cross section, which is about several hundreds fb in most of the parameter space, decreases with the increasing top-pion mass.

We see that the cross section increases with the increasing K_{UR}^{tc} since the cross section is mainly proportional to $(K_{UR}^{tc})^2$, with the vertex $\pi_t^+ c\bar{b}$, $\sim K_{UR}^{tc}$.

B. The processes $u\bar{d} \to \pi_t^+ b\bar{b}$ and $c\bar{s} \to \pi_t^+ b\bar{b}$

Figure 3 shows the dependence of the cross sections of the two processes on the top-pion masses, from which we can see that the production rates is at the order of 1000 fb in a large parameter space.

We can see from Fig. 3 that the production rate of $u\bar{d} \to \pi_t^+ b\bar{b}$ are larger than that of the $c\bar{s} \to \pi_t^+ b\bar{b}$, which is easy to understand since what makes the difference is only the parton distribution functions when we neglect the light quark masses.

Comparing Figs. 2 and 3, we can arrive at the conclusion that the cross section of the $c\bar{b}$ collision is smaller than that of the $u\bar{d}$, which is also determined mainly by the parton distribution functions since the couplings in the two processes are almost in the same order of the two processes, i.e, the coupling $W^+ u\bar{d} \sim e/(\sqrt{2}\sin\theta_W)$ is approximately equal to that of the $\pi_t^+ c\bar{b} \sim m_t/(\sqrt{2}F_t)K_{UR}^{tc}$, where θ_W is the Weinberg angle. As to the process $c\bar{s} \to \pi_t^+ b\bar{b}$, with the similar parton distribution functions as that of $c\bar{b} \to \pi_t^+ b\bar{b}$, the cross sections of them are almost equivalent.

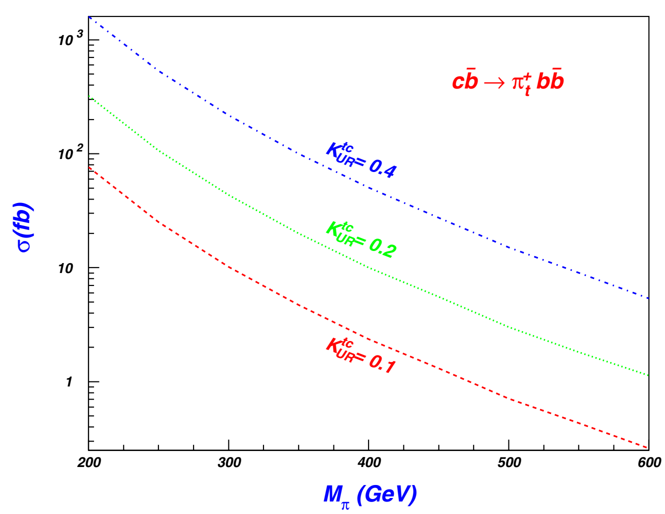

FIG. 2 (color online). Hadronic cross section for the production via $c\bar{b} \to \pi_t^+ b\bar{b}$ at the LHC versus top-pion mass for $K_{UR}^{tc} = 0.1, 0.2, 0.4$, respectively.

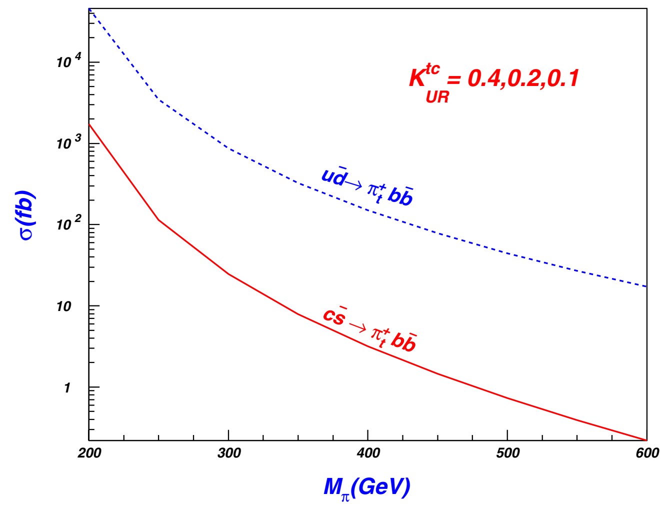

FIG. 3 (color online). Hadronic cross section for the production via $u\bar{d} \to \pi_t^+ b\bar{b}$ and $c\bar{s} \to \pi_t^+ b\bar{b}$ at the LHC versus top-pion mass.

C. Observability of the processes

For the production of $PP \to \pi_t^+ b\bar{b} + X$ at the LHC, the charged top-pions π_t^+ decay to $t\bar{b}$ and $c\bar{b}$ with the branching ratio about 70% and 30% [17], respectively; with the top-pions to $t\bar{b}$, and the top quark to b quark, charge lepton and the missing energy(i.e. the $4b + l + \not{E}$ signal with $\not{E}$, the missing energy);, so, the main SM backgrounds are $pp \to WZh$, WZZ and Whh, where Z/h decays to $b\bar{b}$ and the $W \to l\not{E}$. The background cross sections are very small, about tens of fb. We apply the transverse momenta cuts of the final state and the b-tagging (with 60% b-tagging efficiency) skills. More importantly, the signal will be directly picked out via the invariant mass reconstruction cut of $2b + W$, i.e, top-pion mass reconstruction

$$m_\pi^{\rm rec} = \sqrt{(E_{b_1} + E_{b_2} + E_W)^2 - (\vec{p}_{b_1} + \vec{p}_{b_2} + \vec{p}_W)^2} \quad (5)$$

and imposing the cut $|m_\pi^{\rm rec} - m_\pi| < 10$ GeV. In the SM, $m_Z + m_W \simeq 171$ GeV and $m_h + m_W \simeq 200$ GeV are smaller than the top-pion mass since we prefer a larger top-pion mass though we, in this report, discuss it from 200 GeV to 600 GeV. Since the SM backgrounds are mostly kicked off by this cut, we can draw the conclusion that the production rates arriving at 10 fb may be detected by the LHC.

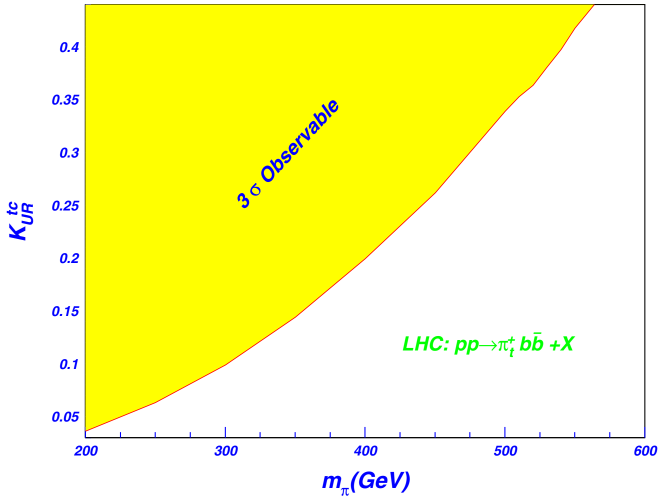

FIG. 4 (color online). The contour of 3σ sensitivity (10 fb) for the cross section of the production via $c\bar{b}\to\pi_t^+ b\bar{b}$ at the LHC in the plane of K_{UR}^{tc} versus top-pion mass.

To show the observability of the production of $c\bar{b}\to\pi_t^+ b\bar{b}+X$, we plot in Fig. 4 the contour of the cross section of the 3σ sensitivity (10 fb) in the plane of K_{UR}^{tc} versus the top-pion mass. We see that, in a large part of the parameter space, the cross section can exceed the 3σ sensitivity.

For the production $u\bar{d}\to\pi_t^+ b\bar{b}$, the cross section is larger than 10 fb in the full space of the the $m_\pi(200\le m_\pi\le 600$ Gev). As for the production $c\bar{s}\to\pi_t^+ b\bar{b}$, as long as the top-pion mass is smaller than 340 GeV, the cross sections will be larger than 10 fb and may be detected at the LHC.

IV. SUMMARY AND CONCLUSION

In conclusion, we examined the charged top-pion productions associated with a bottom pair at the LHC in topcolor-assisted technicolor model. We found that their production rates can exceed the 3σ sensitivity of the LHC in a large part of the parameter space. Therefore, these processes will serve as a good probe for the topcolor-assisted technicolor model.

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