Single top production associated with a neutral scalar at LHC in topcolor-assisted technicolor

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Abstract The topcolor-assisted technicolor (TC2) model predicts a number of neutral scalars like the top-pion (π_t^0) and the top-Higgs (h_t^0). These scalars have flavor-changing neutral-current (FCNC) top quark couplings, among which the top-charm transition couplings may be sizable. Such FCNC couplings induce single top productions associated with a neutral scalar at the CERN Large Hadron Collider (LHC) through the parton processes $cg \rightarrow t\pi_t^0$ and $cg \rightarrow th_t^0$. In this paper we examine these productions and find their production rates can exceed the 3σ sensitivity of the LHC in a large part of parameter space. Since in the Standard Model and the minimal supersymmetric model such rare productions have unobservably small production rates at the LHC, these rare processes will serve as a good probe for the TC2 model.

Key words top quark, technicolor, LHC

PACS 14.65.Ha, 12.60.Fr, 12.60.Jv

As the heaviest fermion in the Standard Model (SM), the top quark may be a sensitive probe of new physics[1]. So far there remain plenty of room for new physics in top quark sector due to the small statistics of the top quark events at the Fermilab Tevatron collider[2]. Since the upcoming Large Hadron Collider (LHC) at CERN will produce top quarks copiously and allow to scrutinize the top quark nature, the new physics related to the top quark will be either uncovered or stringently constrained.

One of the properties of the top quark in the Standard Model (SM) is its extremely small flavor-changing neutral-current (FCNC)[3] interactions due to the GIM mechanism. Thus, the observation of any FCNC top quark process would be a robust evidence for new physics beyond the SM. Actually, the FCNC top quark interactions can be significantly enhanced in some new physics models, such as the popular minimal supersymmetric model (MSSM)[4—6] and the topcolor-assisted technicolor (TC2) model[7].

The TC2 model predicts a number of neutral scalar bosons like the top-pions and top-Higgs at the weak scale[8]. These scalars have FCNC top couplings at tree-level, among which the top-charm FCNC couplings are most significant. Such anomalous FCNC couplings will induce single top productions associated with a neutral scalar at the LHC through the parton processes $cg \rightarrow t\pi_t^0$ and $cg \rightarrow th_t^0$. In this paper we examine these productions and figure out if their rates can exceed the 3σ sensitivity of the LHC. Since in the SM and the MSSM such rare productions have unobservably small production rates at the LHC, these rare 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[8] 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 the extended technicolor and the topcolor contributions. The diagonalization of this mass matrix will induce FCNC top quark interactions in the Yukawa couplings which involve the composite scalars respectively from topcolor and technicolor condensations.

The top-charm FCNC couplings with the top-pion and top-Higgs can be written as[7]

$$\mathcal{L}_{\mathrm{FCNC}} = \frac{(1-\epsilon)m_{\mathrm{t}}}{\sqrt{2}F_{\mathrm{t}}} \frac{\sqrt{v^2 - F_{\mathrm{t}}^2}}{v} \times$$
$$(\mathrm{i}K_{\mathrm{UL}}^{\mathrm{tt*}}K_{\mathrm{UR}}^{\mathrm{tc}}\bar{t}_{\mathrm{L}}c_{\mathrm{R}}\pi_{\mathrm{t}}^0 + K_{\mathrm{UL}}^{\mathrm{tt*}}K_{\mathrm{UR}}^{\mathrm{tc}}\bar{t}_{\mathrm{L}}c_{\mathrm{R}}h_{\mathrm{t}}^0 + \mathrm{h.c.}),$$

(1)

where the factor $\sqrt{v^2 - F_{\mathrm{t}}^2}/v$ ($v \approx 174$ GeV) reflects the effect of the mixing between the top-pions and the would-be Goldstone bosons[9]. K_{UL} and K_{UR} are the rotation matrices that transform respectively the weak eigenstates of the left-handed and right-handed up-type quarks to their mass eigenstates, which can be parametrized as[7]

$$K_{\mathrm{UL}}^{\mathrm{tt}} \approx 1, \quad K_{\mathrm{UR}}^{\mathrm{tt}} \approx \frac{m_{\mathrm{t}}'}{m_{\mathrm{t}}} = 1 - \epsilon,$$
$$K_{\mathrm{UR}}^{\mathrm{tc}} \leqslant \sqrt{1 - (K_{\mathrm{UR}}^{\mathrm{tt}})^2} = \sqrt{2\epsilon - \epsilon^2},$$

(2)

with m_{t}' denoting the topcolor contribution to the top quark mass. In Eq. (1) we neglected the mixing between up quark and top quark.

As shown in Fig. 1, these FCNC interactions in Eq. (1) induce single top productions associated with a top-pion or a top-Higgs at the LHC through the parton processes $\mathrm{cg} \to \mathrm{t}\pi_{\mathrm{t}}^0$ or $\mathrm{cg} \to \mathrm{th}_{\mathrm{t}}^0$. The amplitude for $\mathrm{cg} \to \mathrm{t}\pi_{\mathrm{t}}^0$ is given by

$$\mathcal{M} = -\frac{1}{\sqrt{2}}g_{\mathrm{s}}\frac{m_{\mathrm{t}}}{F_{\mathrm{t}}}\frac{\sqrt{v^2 - F_{\mathrm{t}}^2}}{v}K_{\mathrm{UR}}^{\mathrm{tt*}}K_{\mathrm{UR}}^{\mathrm{tc}}\bar{u}_{\mathrm{t}} \times$$
$$\left[\frac{1}{\hat{s}}(\not{p}_{\mathrm{c}} + \not{p}_{\mathrm{g}})\gamma^\mu + \frac{1}{\hat{u} - m_{\mathrm{t}}^2}\gamma^\mu(\not{p}_{\mathrm{t}} - \not{p}_{\mathrm{g}} + m_{\mathrm{t}})\right]P_{\mathrm{R}}u_{\mathrm{c}},$$

(3)

where $P_{\mathrm{R}} = (1 + \gamma_5)/2$, and $p_{\mathrm{t,c,g}}$ are the momenta of top quark, charm quark and gluon, respectively.
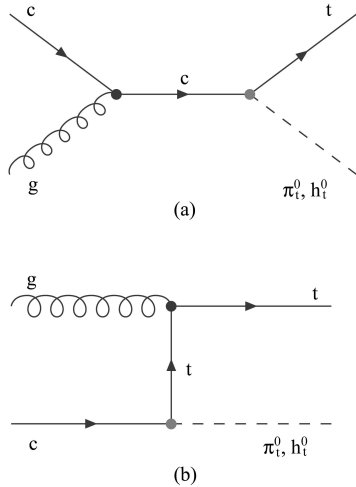
Fig. 1. Feynman diagrams for parton-level process $\mathrm{cg} \to \mathrm{t}\pi_{\mathrm{t}}^0$ and $\mathrm{cg} \to \mathrm{th}_{\mathrm{t}}^0$.

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[10] to generate the parton distributions with the renormalization scale μ_{R} and the factorization

scale μ_{F} chosen to be $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = m_{\mathrm{t}} + M_{\mathrm{S}}$ (M_{S} denotes the top-pion mass or the top-Higgs mass).

The parameters involved in our calculations are the masses of the top-pions and top-Higgs, the parameter $K_{\mathrm{UR}}^{\mathrm{tc}}$, 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. In our numerical calculations, we take $F_{\mathrm{t}} = 50$ GeV, $\epsilon = 0.1$, $K_{\mathrm{UL}}^{\mathrm{tt}} = 1$, $K_{\mathrm{UR}}^{\mathrm{tt}} = 0.9$ and retain $K_{\mathrm{UR}}^{\mathrm{tc}}$ as a free parameter with a value less than $\sqrt{2\epsilon - \epsilon^2} = 0.43$. The top quark mass is taken as $m_{\mathrm{t}} = 170.9$ GeV[2].

For the masses of the neutral top-pion and top-Higgs, current constraints are rather weak. Theoretically the top-pion masses are model-dependent and are usually of a few hundred GeV[8]. The top-Higgs mass, as analysed in Ref. [7], has a lower bound of about $2m_{\mathrm{t}}$, which however is an approximate analysis and the mass below $\mathrm{t}\bar{\mathrm{t}}$ threshold is also possible[11]. Experimentally, the neutral top-pion mass can be constrained if we assume the degeneracy of neutral and charged top-pion masses (the mass splitting between the neutral top-pion and the charged top-pion comes only from the electroweak interactions and thus should be small). The charged top-pion mass is constrained from the absence of $\mathrm{t} \to \pi_{\mathrm{t}}^+\mathrm{b}$, which gives a lower bound of 165 GeV[12], and also from R_{b} data, which yields a lower bound of about 250 GeV[13]. In our numerical results we will show the dependence on the masses of neutral top-pion and top-Higgs.

In the following we present some results for the hadronic production cross section via $\mathrm{cg} \to \mathrm{t}\pi_{\mathrm{t}}^0$. These results are also applicable to the production through $\mathrm{cg} \to \mathrm{th}_{\mathrm{t}}^0$, with the top-pion mass replaced by the top-Higgs mass.
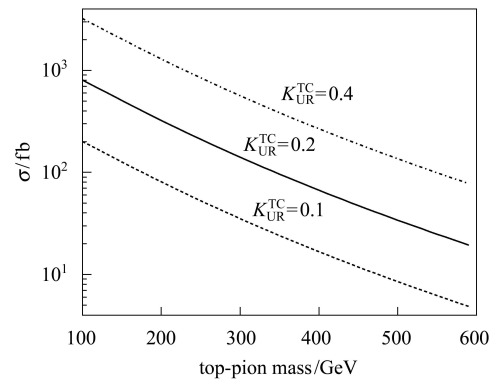
Fig. 2. Hadronic cross section for the production via $\mathrm{cg} \to \mathrm{t}\pi_{\mathrm{t}}^0$ at the LHC versus the top-pion mass.

Figure 2 shows that the hadronic cross section versus the top-pion mass for different values of $K_{\mathrm{UR}}^{\mathrm{tc}}$. We see that the cross section increases with the increasing $K_{\mathrm{UR}}^{\mathrm{tc}}$ since the cross section is simply proportional to $(K_{\mathrm{UR}}^{\mathrm{tc}})^2$ as shown in Eq. (3). As the top-pion mass increases, the cross section decreases. The cross section

is about several hundreds fb in most of the parameter space.

Due to the large QCD backgrounds at the LHC, for the productions of $PP \to t\phi^0 + X$ (ϕ^0 is a neutral scalar and can be top-pion or top-Higgs) we search for the final states from the subsequent decays $t \to Wb \to \ell\nu b$ ($\ell = e, \mu$) and $\phi^0 \to b\bar{b}$. So the main SM background is the production of $t\bar{t}$ and $Wb\bar{b}jj$, where one light jet is mis-identified as a b-jet while the other light jet is not detected if it goes along the pipeline or its transverse momentum is too small.

The observability of the signal at the LHC has been investigated in the effective Lagrangian approach[14]. Assuming a luminosity of 100 fb^{-1}, we know from Table 2, Table 4 and Eq. (4) in Ref. [14] that the 3σ sensitivity for the production of $PP \to t\phi^0 + X$ is about 200 fb. Although this sensitivity is based on the effective Lagrangian approach and may not be perfectly applicable to a specified model, we can take them as a rough criteria to estimate the observability of these channels.

To show the observability of the production of $PP \to t\pi_t^0 + X$, we plot in Fig. 3 the contour of the cross section of the 3σ sensitivity (200 fb) in the plane of K_{UR}^{tc} versus $m_{\pi_t^0}$. We see that in a large part of the parameter space the cross section can exceed the 3σ sensitivity. As we mentioned earlier, the production $PP \to th + X$ is unobservably small in the SM due to the extremely suppressed $ht\bar{c}$ coupling. In the MSSM the $PP \to th + X$ has a rate lower than 10 fb[6] and thus

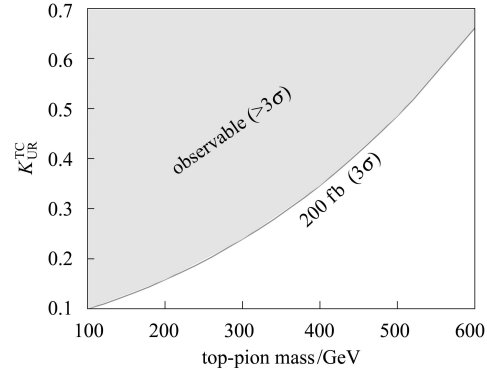also inaccessible at the LHC. So these rare processes will serve as a good probe for the TC2 model.

Fig. 3.   The contour of 3σ sensitivity (200 fb) for the cross section of the production via $cg \to t\pi_t^0$ at the LHC in the plane of K_{UR}^{tc} versus the top-pion mass.

In conclusion, we examined the single top productions associated with a neutral scalor (top-pion or top-Higgs) 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 parameter space. Since in the Standard Model and the minimal supersymmetric model such rare productions have unobservably small production rates at the LHC, these rare processes will serve as a good probe for the topcolor-assisted technicolor model.

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