Associated production of the top-pions and single top
at hadron colliders

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Abstract

In the context of topcolor assisted technicolor (TC2) models, we study the production of the top-pions \( \pi_t^{0,\pm} \) with single top quark via the processes \( pp \to t\pi_t^0 + X \) and \( pp \to t\pi_t^{\pm} + X \), and discuss the possibility of detecting these new particles at Tevatron and LHC. We find that it is very difficult to observe the signals of these particles via these processes at Tevatron, while the neutral and charged top-pions \( \pi_t^0 \) and \( \pi_t^{\pm} \) can be detecting via considering the same sign top pair \( tt\bar{c} \) event and the \( tt\bar{b} \) (or \( t\bar{t}b \)) event at LHC, respectively.

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I. Introduction

The mechanism of electroweak symmetry breaking (EWSB) and origin of the fermion mass remain unknown in elementary particle physics in spite of the success of the standard model (SM) tested by high energy experimental data. Hadron colliders, such as Tevatron and Large Hadron Collider (LHC), are machines extremely well-suited to study these problems. The LHC is expected to directly probe possible new physics beyond the SM up to few $TeV$ and provide some striking evidence of new physics, for instance of a light Higgs boson, in its first months of operation[1].

Tevatron Run II has significant potential to discover a light SM Higgs boson with mass up to about $M_H \leq 130 GeV$[2]. The LHC will have considerably capability to discover and measure almost all the quantum properties of a SM Higgs boson of any mass[1]. However, 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, topcolor, and little Higgs, predict the existence of new scalar or pseudo-scalar particles. These new particles may have cross sections and branching fractions that differ from those of the SM Higgs boson. Thus, studying the production and decays of the new scalars at hadron colliders will be of special interest.

Of particular interest to us is topcolor scenario[3], in which there is an explicit dynamical mechanism for breaking electroweak symmetry and generating the fermion masses including the heavy quark mass. Thus, it is very attractive kind of models beyond the SM. The presence of the physical top-pions $\pi_t^{0,\pm}$ in low energy spectrum is an inevitable feature of the topcolor scenario, regardless of the dynamics responsible for EWSB and other quark mass. One of the most interesting features of $\pi_t^{0,\pm}$ is that they have large Yukawa couplings to the third-generation quarks and can induce the tree-level flavor changing (FC) couplings[4].

In this paper, we will study the associated production of the top-pions $\pi_t^{0,\pm}$ and single top quark via the subprocesses $gc \rightarrow t\pi_t^0$ and $gb \rightarrow t\pi_t^\pm$ and further discuss the possible signatures of these new particles at the Tevatron and LHC experiments. Our numerical results show that the top-pions can be significant produced via these processes at LHC.
and their cross sections are larger than those for the Higgs bosons $H^{0,\pm}$ predicted by the minimal supersymmetric standard model (MSSM). These processes can be used to probe the top-pions and distinguish the Higgs bosons predicted by the MSSM from the top-pions predicted by the topcolor scenario.

To completely avoid the problems arising from the elementary Higgs field in the SM, various kinds of dynamical EWSB models have been proposed, among which the topcolor scenario is attractive because it can explain the large top quark mass and provide a possible EWSB mechanism [3]. The topcolor-assisted technicolor (TC2) models [5] are one kind of the phenomenologically viable models, which has all essential features of the topcolor scenario. So, in the rest of this paper, we will give our results in detail in the context of the TC2 models.

This paper is organized as follows. Section II contains a short summary of the relevant couplings to ordinary particles of the top-pions $\pi^{0,\pm}_t$ in TC2 models. The anomalous top quark coupling $tqv$ has contributions to the process $gq \to t\pi^0_t$. Thus, the anomalous top quark coupling $tqv$ from the FC interactions in TC2 models is also discussed in this section. Sections III and IV are devoted to the computation of production cross sections for the process $p\bar{p} \to t\pi^0_t + X$ and $p\bar{p} \to t\pi^-_t + X$, respectively. Some phenomenological analysis are also included in these sections. Our conclusions are given in Sec. V.

II. The relevant couplings

For TC2 models, the underlying interactions, topcolor interactions, are nonuniversal and therefore do not possess the Glashow-Iliopoulos-Maiani (GIM) mechanism. The nonuniversal gauge interactions result in the new FC coupling vertices when one writes the interactions in the mass eigen basis. Thus, the top-pions $\pi^{0,\pm}_t$ can induce the new FC coupling vertices. The couplings of $\pi^{0,\pm}_t$ to ordinary fermions, which are related to our calculation, can be written as [4,5,6]:

$$\begin{align*}
\frac{m_t}{\sqrt{2}F_t} \frac{\sqrt{2}F_t - F^2_t}{\nu_W} [iK^u_{UR}K^{u*}_{UL}\gamma^5 t\pi^0_t + \sqrt{2}K^{u*}_{UR}b_{DL}\bar{b}_L t_R \pi^-_t + i\frac{m_b - m_b'}{m_t}b\gamma^5 b\pi^0_t] \\
iK^c_{UL}K^{c*}_{UR}L_R \pi^0_t + \sqrt{2}K^{c*}_{UR}b_{DL}\bar{b}_L c_R \pi^-_t + h.c.] + \frac{m_l}{\sqrt{2}\nu_W}l\gamma^5 l\pi^0_t,
\end{align*}$$

(1)

where $\nu_W = \nu/\sqrt{2} = 174 GeV$, $l$ represents the lepton $\tau$ or $\mu$, and $m_b' \approx 0.1 \varepsilon m_t$ is the part
of the bottom-quark mass generated by extended technicolor (ETC) interactions. $K_{UL(R)}$ and $K_{DL(R)}$ are rotation matrices that diagonalize the up-quark and down-quark mass matrix $M_U$ and $M_D$ for which the Cabibbo-Kobayashi-Maskawa (CKM) matrix is defined as $V = K^{UL}_{UL}K_{DL}$. To yield a realistic form of the CKM matrix $V$, it has been shown that their values can be taken as[4]:

$$K^{tt}_{UL} \approx K^{bb}_{DL} \approx 1, \quad K^{tt}_{UR} = 1 - \varepsilon, \quad K^{tc}_{UR} \leq \sqrt{2\varepsilon - \varepsilon^2}. \quad (2)$$

In the following calculation, we will take $K^{tc}_{UR} = \sqrt{2\varepsilon - \varepsilon^2}$ and take $\varepsilon$ as a free parameter, which is assumed to be in the range of $0.01 \sim 0.1[3,5]$.

Figure 1: Feynman diagrams for the contributions of $\pi_t^0$ to the anomalous top quark coupling $tcg$

In the context of the SM, the anomalous top quark couplings $tqv$ (q=up- or c-quark and $v = Z, \gamma$ or $g$ gauge bosons), which are arised from the FC interactions, vanish at the tree-level but can be generated at one-loop level. However, they are strong suppressed by the GIM mechanism, which can not produce observable effects in the present and near future high energy experiments[7]. From Eqs.(1)and(2), we can see that the neutral top-pion $\pi_t^0$ might generate the large top quark coupling $tcg$. The relevant Feynman diagrams are shown in Fig.1. Similar to Ref.[8], we can give the effective form of the anomalous coupling vertex $tcg$:

$$\Lambda^\mu_{tcg} = ig_s\frac{\lambda^a}{2}[\gamma^\mu F_{1g} + p_t^\mu F_{2g} + p_c^\mu F_{3g}], \quad (3)$$

with

$$F_{1g} = \frac{1}{16\pi^2}\left[\frac{m_t}{\sqrt{2F_t}}\frac{\sqrt{\nu_W^2 - F_t^2}}{\nu_W}\right]^2K^{tc}_{UR}K^{tt}_{UL}(B_0 + m_t^2 C_0 - 2C_{24} + m_t^2(C_{11} - C_{12}) - B_0^* - B_1^*), \quad (4)$$
\begin{align}
F_{2g} &= 2m_t \frac{1}{16\pi^2} \left[ \frac{m_t \sqrt{\nu_W^2 - F_t^2}}{\nu_W} \right]^2 K_{UR}^t K_{UL}^{tt*} (C_{21} + C_{22} - C_{23}), \\
F_{3g} &= 2m_t \frac{1}{16\pi^2} \left[ \frac{m_t \sqrt{\nu_W^2 - F_t^2}}{\nu_W} \right]^2 K_{UR}^t K_{UL}^{tt*} (C_{22} - C_{23} + C_{12}),
\end{align}

where \( \lambda^a \) is the Gell-Mann matrix. The expressions of the two and three-point scalar integrals \( B_n \) and \( C_{ij} \) are [9]:

\begin{align}
B_0 &= B_0(p_g, m_t, m_t), \quad B_0^* = B_0(-p_c, m_{\pi_t}, m_t), \\
B_1' &= B_1(-p_t, m_{\pi_t}, m_t), \\
C_{24} &= C_{24}(-p_t, p_g, m_{\pi_t}, m_t), \\
C_{ij} &= C_{ij}(-p_t, -\sqrt{s}, m_{\pi_t}, m_t), \quad i, j = 1, 2, 3.
\end{align}

Certainly, the neutral top-pion \( \pi^0_t \) can also generate the anomalous top quark coupling \( tug \) via the FC coupling \( \pi^0_t tu \). However, it has been argued that the maximum flavor mixing occurs between the third generation and the second generation, and the FC coupling \( \pi^0_t \bar{t}u \) is very small which can be neglected[4]. Hence we will ignore the contributions of the \( tug \) coupling to the process \( p\bar{p} \to t\pi^0_t + X \) in the following discussions.

Similar to the neutral top-pion \( \pi^0_t \), the charged top-pions \( \pi^\pm_t \) can generate the anomalous top quark coupling \( tcg \) via the FC couplings \( \pi^\pm_t bc \). However, compared with those of \( \pi^0_t \), the contributions of \( \pi^\pm_t \) to the \( tcg \) coupling are approximately suppressed by the factor \( m_b/m_t \), which can be safely neglected.

**III. Associated production of the neutral top-pion \( \pi^0_t \) and single top quark**

From above discussions, we can see that, due to the existence of the FC couplings, the neutral top-pion \( \pi^0_t \) can be generated via the subprocess \( gc \to t\pi^0_t \) at hadron colliders, as shown in Fig.2. Fig.2(a) and Fig.2(b) come from the FC coupling \( \pi^0_t \bar{t}c \), while Fig.2(c) and Fig.2(d) come from the anomalous top quark coupling \( tcg \). Although the strength of the coupling \( tcg \) is very smaller than that of the coupling \( gc\bar{c} \) or \( gt\bar{t} \), we can not ignore the contributions of Fig.2(c) to the subprocess \( gc \to t\pi^0_t \) being large \( \pi_t t\bar{t} \) coupling. For Fig.2(d), it is not this case. The \( \pi^0_t c\bar{c} \) coupling is very small and thus the contributions of
Fig. 2: Feynman diagrams for the process $gc \rightarrow t\pi_t^0$

Fig.2(d) to the subprocess $gc \rightarrow t\pi_t^0$ can be neglected. We have confirmed this expectation through explicit calculation.

To obtain numerical results, we need to specify the relevant SM input parameters. These parameters are $m_t = 178 GeV$ and $\alpha_s(m_t) = 0.118[10]$. Through out this paper, we neglect the charm quark mass and use CTEQ6L parton distribution functions with scale $\mu = 2m_t[11]$. The limits on the top-pion mass $m_{\pi_t}$ can be obtained via studying its effects on various observables[3]. It has been shown that $m_{\pi_t}$ is allowed to be in the range of a few hundred GeV depending on the models. As numerical estimation, we will assume that the value of the top-pion mass $m_{\pi_t}$ is in the range of $200 GeV \sim 500 GeV$.

The production cross sections for the process $p\bar{p} \rightarrow t\pi_t^0 + X$ at the Tevatron with $\sqrt{s} = 1.96 TeV$ and the LHC with $\sqrt{s} = 14 TeV$ are plotted as functions of the top-pion mass $m_{\pi_t}$ for three values of the free parameter $\varepsilon$ in Fig.3(a) and Fig.3(b), respectively. From these figures, we can see that the $t\pi_t^0$ production cross section at Tevatron is much smaller than that at LHC in all of the parameter space of the TC2 models. For $0.02 \leq \varepsilon \leq 0.08$ and $200 GeV \leq m_{\pi_t} \leq 500 GeV$, the $t\pi_t^0$ production cross sections at Tevatron and LHC are in the ranges of $2.3 \times 10^{-3} fb \sim 4.1 fb$ and $17 fb \sim 1.82 \times 10^3 fb$, respectively. If we assume the yearly integrated luminosity $\mathcal{L}_{int} = 2 fb^{-1}$ for the Tevatron with $\sqrt{s} = 1.96 TeV$, then the yearly production number of the $t\pi_t^0$ event is smaller than 8 in all of the parameter space. Thus, it is very difficult to detect the possible signals of the neutral top-pion
Figure 3: The cross section $\sigma(s)$ of $t\pi^0_t$ production as function of $m_{\pi_t}$ for three values of the parameter $\varepsilon$ at the Tevatron with $\sqrt{s} = 1.96 \text{TeV}(a)$ and the LHC with $\sqrt{s} = 14 \text{TeV}(b)$.

$\pi^0_t$ via the process $p\bar{p} \rightarrow t\pi^0_t + X$ at the Tevatron experiments. However, there will be $1.7 \times 10^3 \sim 1.8 \times 10^5 \ t\pi^0_t$ events to be generated per year at the LHC with $\sqrt{s} = 14 \text{TeV}$ and $L_{\text{int}} = 100 fb^{-1}$.

The possible decay modes of the neutral top-pion $\pi^0_t$ are $t\bar{t}$, $t\bar{c}(t\bar{c})$, $b\bar{b}$, $gg$, $\gamma\gamma$, $\tau\tau$, and $\mu\mu$. For $m_t < m_{\pi_t} \leq 2m_t$, $\pi^0_t$ mainly decays to $t\bar{c}$ or $t\bar{c}$. It has been shown that the value of the branching ratio $\text{Br}(\pi^0_t \rightarrow t\bar{c} + t\bar{c})$ is larger than 90% for $m_{\pi_t} = 250 \text{GeV}$ and $\varepsilon \geq 0.02[12]$. Thus, for $m_t < m_{\pi_t} \leq 2m_t$, the associated production of $\pi^0_t$ with single top quark can easily transfer to the same sign top pair event $tt\bar{c}$ at LHC. The final state of the same sign top pair is free from huge QCD background $W+\text{jets}$ and also free from $t\bar{t}$ background[13], which can generate characteristic signatures at the LHC experiments. Thus, the same sign top pair can be used to probe new physics beyond the SM[14,15,16,17]. So, we further calculate the production cross section of the same sign top pair final state at LHC. Our numerical results are shown in Fig.4, in which we have assumed $m_t < m_{\pi_t} \leq 2m_t$ and taken $\varepsilon = 0.02$, 0.05 and 0.08. From this figure, we can see that there will be several and up to ten thousands $tt\bar{c}$ events to be generated per year at the LHC with $L_{\text{int}} = 100 fb^{-1}$.

The signal of the same sign top pair event is same sign dileptons, two b-jets, one charm...
Figure 4: The production cross section $\sigma(s)$ of the same sign top pair $tt\bar{c}$ as a function of $m_{\pi_t}$ for three values of the parameter $\varepsilon$ at the LHC with $\sqrt{s} = 14$ TeV.

Quark jet plus missing energy, i.e., $llbbj + \not{E}$. The main background for this signal comes from the process $pp \rightarrow W^{\pm}t\bar{t} \rightarrow lbbj_1j_2 + \not{E}$ with either $j_1$ or $j_2$ missing detection. It has been shown[13,14,15,16] that this background can be significantly suppressed by applying appropriate cuts and so that the $tt\bar{c}$ event should be observed at the LHC experiments, as long as its cross section is larger than several tens $fb$. Thus, in most of the parameter space of TC2 models, the possible signals of the neutral top-pion $\pi^0_t$ with $m_t < m_{\pi_t} \leq 2m_t$ can be detected via the process $p\bar{p} \rightarrow t\pi^0_t + X \rightarrow tt\bar{c} + X$ at the LHC experiments.

Figure 5: Feynman diagrams for the process $qb \rightarrow q't\pi^0_t$. 
In all appearance, the final state which is same as that of \( t\pi_t^0 \) can be reached by single top production followed by \( \pi_t^0 \) bremsstrahlung i.e. the process \( gb \rightarrow q't\pi_t^0 \), as shown in Fig.5. However, due to the unitary constraint, there exists severe cancellation between Fig.5(a) and Fig.5(b) and so that its production cross section is highly suppressed, which is much smaller than that of the subprocess \( cg \rightarrow t\pi_t^0 \)[14,16,18]. Thus, this process can not be taken as an effective process to detect the neutral top-pion \( \pi_t^0 \) at LHC.

For \( m_{\pi_t} > 2m_t \), the neutral top-pion \( \pi_t^0 \) mainly decays to \( t\bar{t} \) and the associated production of \( \pi_t^0 \) with single top quark can also produce the same sign top event \( t\bar{t}t \) at LHC. However, the signal of this kind of event is too difficult to extract because of much large background. Thus, if the neutral top-pion \( \pi_t^0 \) is indeed much heavy, we should consider other processes to detect this type of new particles in the future high energy experiments.

IV. Associated production of the charged top-pions \( \pi_t^\pm \) with single top quark

![Feynman diagrams](image)

Figure 6: The Feynman diagrams for the process \( gb \rightarrow t\pi_t^- \).

For TC2 models, the underlying interactions, topcolor interactions, are assumed to be chiral critically strong at the scale about 1TeV and coupled preferentially to the third generation. Thus, top-pions \( \pi_t^{0,\pm} \) have large Yukawa couplings to the third family quarks. The charged top-pions \( \pi_t^\pm \) should be abundantly produced via the subprocess \( gb \rightarrow t\pi_t^\pm \) at LHC. The relevant Feynman diagrams are shown in Fig.6.

Our numerical results are shown in Fig.7, in which we plot the production cross section \( \sigma(s) \) for the process \( pp \rightarrow t\pi_t^- + X \) at the Tevatron with \( \sqrt{s} = 1.96TeV \)[Fig.7(a)] and the LHC with \( \sqrt{s} = 14TeV \)[Fig.7(b)] as a function of the top-pion mass \( m_{\pi_t} \) for three values of the free parameter \( \varepsilon \). One can see from these figures that the cross section \( \sigma(s) \) is not sensitive to the free parameter \( \varepsilon \) and its value at LHC is much large, which is in the range
Figure 7: The cross section $\sigma(s)$ for $t\pi_t^-$ production as function of $m_{\pi_t}$ for three values of the parameter $\varepsilon$ at the Tevatron with $\sqrt{s} = 1.96TeV$[Fig.7(a)] and the LHC with $\sqrt{s} = 14TeV$[Fig.7(b)].

of $5.24 \times 10^2fb \sim 2.5 \times 10^4fb$ for $0.02 \leq \varepsilon \leq 0.08$ and $200GeV \leq m_{\pi_t} \leq 500GeV$.

The LHC has a good potential for discovery of a charged Higgs boson[19]. Thus, the associated production of the charged Higgs bosons predicted by the MSSM with single top quark has been extensively investigated in Refs.[20,21,22]. They have shown that, considering the complete NLO QCD corrections, the production cross section for the process $p\bar{p} \rightarrow tH^\pm + X$ is smaller than $1pb$ in most of the parameter space of MSSM. Compared with our numerical results, it is smaller than that for the charged top-pions $\pi_t^\pm$. This is because the coupling strength of $H^\pm tb$ is smaller than that of $\pi_t^\pm tb$.

It has been shown that the heavy Higgs bosons $H^\pm$ can be detected via the decay channels $H^\pm \rightarrow \tau\nu_\tau, \ tb$ or $W^\pm h^0$ at LHC[20,21]. For the charged top-pions $\pi_t^\pm$, the dominant decay mode is into $tb$ channel and its branching ratio is larger than 95% in most of the parameter space of TC2 models. It is very difficult to detect the possible signals of $\pi_t^\pm$ via the decay channel $\pi_t^\pm \rightarrow \tau\nu_\tau$. Thus, the possible signals of $\pi_t^\pm$ can only be studied via the process $pp \rightarrow gb \rightarrow t\pi_t^\pm$ in the $tb$ decay channel. According the analysis results of Ref.[20,21], the 3 b-tags is better for detecting the signals of this process than the 4 b-tags. For 3 b-tags, the background of the subprocess $gb \rightarrow t\pi_t^- \rightarrow t\bar{b}$ comes from
the NLO QCD processes:

\[ gg \rightarrow t\bar{t}b \quad gb \rightarrow t\bar{t}b \quad gg \rightarrow t\bar{t}g \]

After the suitable cuts and the reconstruction of the \( \pi_t^- \) mass, the value of the signal/background ratio is large than 5 in most parameter space of TC2 models. Thus, the charged top-pions \( \pi_t^\pm \) should be observed in the near future LHC experiments.

V. Discussions and conclusions

The SM predicts the existence of a neutral Higgs boson, while many popular models beyond the SM predict the existence of the neutral or charged scalar particles. These new particles might produce the observable signatures in the current or future high energy experiments, which is different from that for the SM Higgs boson. Any visible signal from the new scalar particles will be evidence of new physics beyond the SM. Thus, studying the new scalar particle production at LHC is very interesting.

Topcolor scenario is one of the important candidates for the mechanism of EWSB. A key feature of this kind of models is that they predict the existence of the top-pions \( \pi_t^{0,\pm} \) in low-energy spectrum. In this paper, we study the associated production of \( \pi_t^{0,\pm} \) with single top quark at the Tevatron with \( \sqrt{s} = 1.96 TeV \) and the LHC with \( \sqrt{s} = 14 TeV \).

It is well known that the flavor changing neutral current (FCNC) effects can be used to look for the new physics beyond the SM. The neutral top-pion \( \pi_t^0 \) has large FC coupling to top and charm quarks at tree-level. Thus, we first calculate the production cross section of the process \( p\bar{p} \rightarrow t\pi_t^0 + X \) at hadron colliders. We find that the neutral top-pion \( \pi_t^0 \) can be significant generated at the LHC with \( \sqrt{s} = 14 TeV \). Due to \( \pi_t^0 \) mainly decay to \( \bar{t}c \) or \( t\bar{c} \), this process can produce a large number of the same sign top pair \( tt\bar{c} \) events. While the production rates of this kind of events in the SM and the MSSM are far below the observable level. Thus, we can use the process \( p\bar{p} \rightarrow t\pi_t^0 + X \rightarrow tt\bar{c} + X \) to look for the neutral top-pion \( \pi_t^0 \) at LHC.

For a heavy charged scalar, the dominant production process at LHC is its associated production with a top quark via gluon bottom quark fusion. The LHC has good potential for discovering a heavy charged scalar through this process. In the context of the TC2
models, we calculate the production cross sections of the process $p\bar{p} \rightarrow t\pi^\pm + X$ at hadron colliders. Our numerical results show that the production rates are larger than those for the charged Higgs bosons $H^\pm$ from the MSSM. We can detect the possible signals of the charged top-pions $\pi^\pm_t$ at the near future LHC through the process $p\bar{p} \rightarrow t\pi^\pm_t + X$ in their $tb$ decay channel.

All of our numerical results are obtained with the scale chosen $\mu = 2m_t$ for the CTEQ6L parton distribution function integration. Certainly, the numerical results would vary with the chosen value of the factorization scale varying. For example, if we chose the scale $\mu = m_t/2$, then $t\pi^0_t$ production cross section at LHC is in the range of $8.4fb \sim 1.8 \times 10^3fb$ for $0.02 \leq \varepsilon \leq 0.08$ and $200GeV \leq m_{\pi_t} \leq 500GeV$. Comparing with that for the scale chosen $\mu = 2m_t$, its value is decreased by $10\% \sim 50\%$, which is dependent on the value of the top-pion mass $m_{\pi_t}$. However, even in this case, there will be $8.4 \times 10^2 \sim 1.8 \times 10^3 t\pi^0_t$ events to be generated per year at the LHC with $\sqrt{s} = 14TeV$ and $\mathcal{L}_{int} = 100fb^{-1}$, which might be detected in the near future LHC experiments.

TC2 models also predict the neutral CP-even scalar, called the top-Higgs boson $h^0_t$, which is a $t\bar{t}$ bound and analogous to the $\sigma$ particle in low energy QCD. Similar to the neutral top-pion $\pi^0_t$, it also has large coupling to the top- and charm- quark at tree-level and can give rise to the anomalous top quark coupling $tcg$. Thus, it can be abundant produced via the process $p\bar{p} \rightarrow th^0_t + X$ at LHC. Our explicit calculation shows that the signal of the top-Higgs $h^0_t$ can also be detected through this process in the near future LHC experiments.

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