The productions of the top-pions and top-Higgs associated with the charm quark at the hadron colliders

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Abstract

In the topcolor-assistant technicolor (TC2) model, the typical physical particles, top-pions and top-Higgs, are predicted and the existence of these particles could be regarded as the robust evidence of the model. These particles are accessible at the Tevatron and LHC, and furthermore the flavor-changing (FC) feature of the TC2 model can provide us a unique chance to probe them. In this paper, we study some interesting FC production processes of top-pions and top-Higgs at the Tevatron and LHC, i.e., $c\Pi_{-}^{T}$ and $c\Pi_{0}^{T}(h_{0}^{T})$ productions. We find that the light charged top-pions are not favorable by the Tevatron experiments and the Tevatron has a little capability to probe neutral top-pion and top-Higgs via these FC production processes. At the LHC, however, the cross section can reach the level of $10 \sim 100$ pb for $c\Pi_{-}^{T}$ production and $10 \sim 100$ fb for $c\Pi_{0}^{T}(h_{0}^{T})$ production. So one can expect that enough signals could be produced at the LHC experiments. Furthermore, the SM background should be clean due to the FC feature of the processes and the FC decay modes $\Pi_{-}^{T} \rightarrow b\bar{c}$, $\Pi_{0}^{T}(h_{0}^{T}) \rightarrow t\bar{c}$ can provide us the typical signal to detect the top-pions and top-Higgs. Therefore, it is hopeful to find the signal of top-pions and top-Higgs with the running of the LHC via these FC processes.

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I. INTRODUCTION

The upgraded $pp$ collider Tevatron is now engaged in RUN II, and followed by the forthcoming Large-Hadronic-Collider (LHC) with the center of mass (c.m.) energy of 14 TeV. One of the important tasks of these hadron colliders is to detect the signal of the physics beyond the standard model (SM). With the running of the LHC, it is possible to find the signal of the new heavy Higgs-like particles in the new physics models related to the electroweak symmetry breaking (EWSB). Therefore, the LHC will open a wide window to test the new physics models, furthermore, explore the EWSB.

Among the various new physics theories, technicolor (TC) model introduced by Weinberg and Susskind [1], offers a new possible mechanism of the EWSB and solves the problems of the SM neatly. As one of the promising candidates of the new physics, TC theory has been developed for many years. In 1990s, a new dynamical topcolor was introduced to combine with the TC theory, then we arrived the topcolor assisted technicolor (TC2) model [2]. The TC2 model predicts three CP odd Pseudo Goldstone bosons (PGBs) called top-pions ($\Pi^\pm_t, \Pi^0_t$) and a CP even scalar called top-Higgs ($h^0_t$) in a few hundred GeV region. The existence of these physical particles can be regarded as the typical feature of the TC2 model and the observation of them is a robust evidence of the model. Thus the study of the production processes of these typical particles is a very interesting research work, and a lot of studies about this aspect have been done [3, 4, 5, 6].

Another feature of the TC2 model is that the topcolor interaction is non-universal, and the Glashow-Lliopoulos-Maiani (GIM) symmetry is violated which results in the significant tree-level flavor-changing (FC) couplings. This is an essential feature of these models due to the need to single out the top quark for condensation. It is known that the existence of the GIM makes the FC processes in the SM to be hardly detected, and hence the FC processes would open an ideal window to probe the TC2 model. Some FC processes in the TC2 model have been studied [6, 7, 8, 9, 10, 11, 12]. On the other hand, the tree-level FC couplings in the TC2 model can also result in the loop-level FC couplings: $tc\gamma, tcZ$. The contributions of these one-loop FC couplings are also significant which makes the rare top quark decays [5], $t\bar{c}$ production [9, 10], and $tZ(\gamma)$ productions [11] become detectable at the future LHC and ILC. Due to the existence of the FC couplings in the TC2 model, the top-pions and top-Higgs can be produced via some FC processes. These FC production processes would play a very important role in probing these new physical particles because the SM background would be very clean for these FC processes. We have studied the FC production processes, $t\bar{c}\Pi^0_t$, via $e^+e^-$ and $\gamma\gamma$ collision [6] and find that the cross sections are large enough and the backgrounds are very small. So these FC production processes will provide us a good chance to search for the neutral top-pion at the planed ILC. With the running of the LHC in 2007, the signal of the TC2 model would be first observed in the LHC. As we know, backgrounds at the hadron colliders are much larger than those at linear colliders which makes the detection of new particles at the hadron colliders become more difficult. But we find that there also exist the FC production processes of the top-pions and top-Higgs at the hadron colliders, i.e., the $c\Pi^\pm_t, c\Pi^0_t(h^0_t)$ productions. In this paper, we study the potential to discover the top-pions and top-Higgs via these FC production modes.

We organize the rest parts of the paper as follow. In section 2, we present our calculations and the numerical results of the cross sections. The conclusions are given in section 3.
II. CALCULATIONS AND NUMERICAL RESULTS

Since the topcolor interaction treats the third family quark differently from the first and the second families, the TC2 model does not possess the GIM mechanism, and the non-universal gauge interaction results in the significant tree-level FC couplings of the top-pions(top-Higgs) to the quark pair when one writes the interactions in the quark mass eigen-basis. The couplings of the top-pions and top-Higgs to the quarks can be written as \[7, 8\]

\[
\mathcal{L} = \frac{m_t}{v_w} \tan \beta [i K_{UR}^{tt} K_{UL}^{\dagger} t_L \overline{t}_R \Pi_0^t + \sqrt{2} K_{UR}^{tb} K_{DL}^{\dagger} b_L \Pi_0^t] + i K_{UR}^{tc} K_{UL}^{\dagger} c_R \Pi_0^t + \sqrt{2} K_{UR}^{bc} K_{DL}^{\dagger} b_L \Pi_0^t + \frac{m_b^*}{m_t} \overline{b}_R \Pi_0^t + K_{UR}^{tt} K_{UL}^{\dagger} t_L \overline{t}_R h_0^t + h.c.].
\]

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

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

\(\varepsilon\) is a model dependent parameter which is in the range of \(0.03 \leq \varepsilon \leq 0.1\)\[2\]. The mass \(m_b^*\) is a part of b-quark mass which is induced by the instanton and can be estimated as

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

where we generally expect \(\kappa \sim 1\) to \(10^{-1}\) as in QCD.

The existence of tree-level FC couplings \(\Pi_0^t \overline{t}_c, \Pi_0^- \overline{b} \overline{c}\) and \(h_0^0 \overline{t} \overline{c}\) can also result in the loop-level FC coupling \(tcg\) as shown in Fig.1. Because there is no corresponding tree-level \(tcg\) coupling to absorb these divergences, the divergences just cancel each other and the total result is finite as it should be. As we have mentioned in the introduction, these tree-level and loop-level FC couplings can make the significant contribution to some processes. These FC couplings can also induce the interesting FC production processes of top-pions and top-Higgs at the hadron colliders. i.e., \(p\overline{p}(pp) \rightarrow c\Pi_1^-, c\Pi_0^0(h_0^0)\). In the following, we focus on studying these processes.

A. The \(c\Pi_1^-\) production at the hadron colliders

We know that there is only one neutral scalar Higgs in the SM, and hence the existence of physical charged (pseudo)scalars can be regarded as an unambiguous signal beyond the SM. The Tevatron can probe the charged (pseudo)scalars mass up to \(300 \sim 350\) GeV, and the LHC can probe the mass-range of charged (pseudo)scalars up to \(\sim O(1)\) TeV\[4\]. As it
is known, the charged top-pions are predicted in the TC2 model. The FC coupling $\Pi_t^- b \bar{c}$ can result in the tree-level production mode $c\Pi_t^-$ via $bg$ collision. On the other hand, the loop-level FC coupling $tcg$ can also make the contribution to the $c\Pi_t^-$ production. The Feynman diagrams of the $c\Pi_t^-$ production at the hadron colliders are shown in Fig.2(A-C).

The production amplitudes are expressed as follow

$$M_A = \frac{-i\sqrt{2}m_t\tan\beta}{v_w}\sqrt{2\varepsilon - \varepsilon^2 g_s T_i^3}G(p_1 + p_2, m_b)\cdot\bar{u}_c(p_3)L(\phi_1 + \phi_2 + m_b)\phi^a(p_2)u_b(p_1),$$

(2)
Where, $G(p, m) = 1/(p^2 - m^2)$ is the propagator of the particle, $L = (1 - \gamma_5)/2$. In the production amplitude $M_C$, the three-point standard functions are defined as

$$M_C = \frac{-i\sqrt{2}m_t^3\tan^3\beta}{16\pi^2\xi^3} (1 - \varepsilon)^2 \sqrt{2\varepsilon - \varepsilon^2} g_s T_{ij}^a G(p_3 - p_2, m_c)$$

\[
\begin{align*}
&\left\{ [2B_1(p_2 - p_3, m_b, M_{tt}) + B_1(p_2 - p_3, m_t, M_{tt})] + B_0(p_2 - p_3, M_{tt}) - B_0(p_2 - p_3, M_{tt}) \right. \\
&- B_0(-p_3, M_{tt}) + B_0(-p_3, M_{tt}) \\
&- m_c^2(C_0^* + C_0^*) - 2m_c^2C_0 + 4C_{24} + 2C_{24}^* - 2C_{24}^* + 2C_{24}^* \cdot \bar{\mathcal{M}}_c(p_3)\phi^a(p_2)(p_3 - p_2)Lu_j(p_1) \\
&\left. + 2(C_{23} + C_{12}) + C_{23}^* + C_{12}^* + C_{23}^* + C_{12}^* \cdot \bar{\mathcal{M}}_c(p_3)\phi_2\phi^a(p_2)\phi_3(p_3 - p_2)Lu_j(p_1) \\
&+ m_c^2(C_0^* - C_0^*) \cdot \bar{\mathcal{M}}_c(p_3)\phi_3\phi^a(p_2)Lu_j(p_1) \\
&+ m_c^2(-C_{12} + C_{12}) \cdot \bar{\mathcal{M}}_c(p_3)\phi^a(p_2)\phi_3 L u_j(p_1) \right. \\
&\left. \right\}
\end{align*}
\]

(4)

FIG. 3: The hadronic cross section of $c\pi^-_1$ production as a function of $M_{tt}$ at the Tevatron, with $M_{tt} = 200, 400$ GeV, respectively.

$$M_B = \frac{-i\sqrt{2}m_t\tan\beta}{\xi^2} \sqrt{2\varepsilon - \varepsilon^2} g_s T_{ij}^a G(p_3 - p_2, m_c)$$

\[
\begin{align*}
&\bar{\mathcal{M}}_c(p_3)\phi^a(p_2)(p_3 - p_2)Lu_j(p_1), \\
&\left\{ [2B_1(p_2 - p_3, m_b, M_{tt}) + B_1(p_2 - p_3, m_t, M_{tt})] + B_0(p_2 - p_3, M_{tt}) - B_0(p_2 - p_3, M_{tt}) \\
&- B_0(-p_3, M_{tt}) + B_0(-p_3, M_{tt}) \\
&- m_c^2(C_0^* + C_0^*) - 2m_c^2C_0 + 4C_{24} + 2C_{24}^* - 2C_{24}^* + 2C_{24}^* \cdot \bar{\mathcal{M}}_c(p_3)\phi^a(p_2)(p_3 - p_2)Lu_j(p_1) \\
&\left. + 2(C_{23} + C_{12}) + C_{23}^* + C_{12}^* + C_{23}^* + C_{12}^* \cdot \bar{\mathcal{M}}_c(p_3)\phi_2\phi^a(p_2)\phi_3(p_3 - p_2)Lu_j(p_1) \\
&+ m_c^2(C_0^* - C_0^*) \cdot \bar{\mathcal{M}}_c(p_3)\phi_3\phi^a(p_2)Lu_j(p_1) \\
&+ m_c^2(-C_{12} + C_{12}) \cdot \bar{\mathcal{M}}_c(p_3)\phi^a(p_2)\phi_3 L u_j(p_1) \right. \\
&\left. \right\}
\end{align*}
\]

Where, $G(p, m) = 1/(p^2 - m^2)$ is the propagator of the particle, $L = (1 - \gamma_5)/2$. In the production amplitude $M_C$, the three-point standard functions are defined as

$$C_{ij} = C_{ij}(p_2, -p_3, m_b, m_b, M_{tt}),$$

$$C_{ij}' = C_{ij}(p_2, -p_3, m_t, m_t, M_{tt}),$$

$$C_{ij}^* = C_{ij}(p_2, -p_3, m_t, m_t, M_{tt}).$$

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

With the above production amplitudes, we can directly obtain the cross section of subprocess $bg \rightarrow c\pi^-_1$. The hadronic cross section at the Hadron colliders can be obtained by folding the cross section of subprocesses with the parton distribution.
FIG. 4: The hadronic cross section of $c\Pi^-_t$ production as a function of $M_{\Pi_t}$ at the LHC, with $M_{h_t} = 200, 400$ GeV, respectively.

To obtain the numerical results of the cross section, we take $m_t = 174$ GeV, $m_b = 4.7$ GeV, $m_c = 1.25$ GeV, $v_w = 246$ GeV, $v_t = 60$ GeV. The strong coupling constant $g_s = 2\sqrt{\pi\alpha_s}$ can be obtained from the one-loop evolution formula at the energy of the Tevatron and the LHC, respectively. There are three free parameters involved in the production amplitudes: the top-pion mass $M_{\Pi_t}$ (We have ignored the mass difference between the neutral top-pion and charged top-pions), the top-Higgs mass $M_{h_t}$, and the parameter $\varepsilon$. In order to see the influence of these parameters on the cross section, we take $M_{\Pi_t}$ to vary in the range $200$ GeV $\leq M_{\Pi_t} \leq 400$ GeV, $\varepsilon = 0.03, 0.06, 0.1$, and $M_{h_t} = 200, 400$ GeV, respectively.

The numerical results of the cross section for the $c\Pi^-_t$ production at the Tevatron and the LHC are shown in Fig.3 and Fig.4, respectively. The cross section should be sensitive to the mass of final state $\Pi^-_t$, and in the Fig.3-4, we plot the hadronic cross section as a function of $M_{\Pi_t}$. From these figures, we can see that the production cross section decrease sharply as $M_{\Pi_t}$ increasing because the large mass of the top-pion can strongly depress the phase space. For the $c\Pi^-_t$ production, the top-Higgs only make a virtual contribution to the loop-level coupling $tcg$, so the cross section is insensitive to the mass of the top-Higgs. The dependence of the cross section on the $\varepsilon$ is obvious, and when $\varepsilon$ becomes large the cross section increases. As it is know, at the Tevatron, the main contribution comes from the light quarks, so the cross section of $c\Pi^-_t$ production is not so large in most parameter space and the cross section can reach the level of pb only in a narrow range for light top-pion. Because there is no clue of existence of the charged top-pions at the Tevatron, the light charged top-pions are not favorable by the Tevatron experiments. At the LHC, the gluon makes the main contribution and the cross section is greatly increased. Via the FC production mode $c\Pi^-_t$, a large number of signals would be produced in a wide range of the parameter space at the LHC. So the LHC might provide a good chance to probe the charged top-pions. On the other hand, the main contribution comes from the tree-level figures of Fig.2(A-B), so such charged top-pion production mode also provide us a unique way to study the FC coupling $\Pi^-_t b\bar{c}$. But the contribution of the FC loop-level coupling $tcg$ is embedded and we can hardly obtain the information of the $tcg$ coupling from such...
The decay width and the decay branching ratios of the charged top-pions have been studied in the references [1, 14], and the dominant decay modes of $\Pi_t^-$ are $b\bar{c}$ and $b\bar{c}$. The signal should include two jets: one is $c$-jet and another jet includes the particles arising from $\Pi_t^-$ decaying. The $c$-jet can be easily identified and such identification is very important which can help us to confirm that such production mode is a FC mode and strongly depress the SM background. To detect $\Pi_t^-$ via the decay mode $bt$, the top quark must be efficiently reconstructed and b-tagging is also needed. On the other hand, the existence of the FC decay mode $b\bar{c}$ provides a unique way to detect $\Pi_t^-$. The decay branching ratio of $b\bar{c}$ is over 10% [14], so there are enough signals can be produced via the decay mode $b\bar{c}$ with the yearly luminosity 100 $fb^{-1}$ at the LHC. Furthermore, the decay mode $b\bar{c}$ involves the FC coupling $\Pi_t^-$ which is an important feature of the TC2 model. So the signal of $b\bar{c}$ is typical and the SM background is very clean. Therefore the discovery of the charged top-pions at the LHC would be possible for a wide range of the parameter space. But the more detailed study of the background is warranted, in order to establish the experimental sensitively to the FC coupling $\Pi_t^-$ $b\bar{c}$. It should be noted that, in contrast to the MSSM (Minimal Supersymmetric SM), the general 2HDM (Two-higgs Doublet Model) also has potentially the same tree-level FC couplings for the charged higgs bosons, thus the similar FC production mode $cH^-$ should exist and the $H^-$ can also decay to $tb$ and $b\bar{c}$. But the difference between the charged top-pions and charged higgs bosons is that charged higgs has the extra decay modes, $H^- \rightarrow \tau\nu, cs$, and such difference can help us to distinguish the charged top-pions from these charged higgs bosons.

B. The $c\Pi_t^0(h_t^0)$ productions at the hadron colliders

Besides the charged top-pions, there exist also the neutral CP odd top-pion and CP even top-Higgs in the TC2 model. The loop-level FC coupling $tcg$ can also induce the FC neutral top-pion and top-Higgs productions $c\Pi_t^0(h_t^0)$ at the hadron colliders. The relevant Feynman diagrams are shown in Fig.2(D-E).

We first study the $c\Pi_t^0$ production. The amplitudes of this production mode are expressed as follow

$$M_{D}^{c\Pi_t^0} = \frac{-m_{t}^{4}\tan^{3}\beta}{16\pi^{2}v_{w}^{3}}(1-\varepsilon)(2\varepsilon-\varepsilon^{2})g_{\pi}T_{ij}^{a}G(p_{1}+p_{2}, m_{t})$$

\begin{align*}
&\{2B_{1}(-p_{1}-p_{2}, m_{b}, M_{\Pi}) + B_{1}(-p_{1}-p_{2}, m_{t}, M_{\Pi}) + B_{1}(-p_{1}-p_{2}, m_{t}, M_{h_{t}}) \\
&+ B_{0}(-p_{1}-p_{2}, m_{t}, M_{\Pi}) - B_{0}(-p_{1}-p_{2}, m_{t}, M_{h_{t}}) \\
&- m_{t}^{2}(C_{0}^{*} + C_{0}^{*}) - 2m_{t}^{2}C_{0} + 4C_{24} + 2C_{24}^{*} + 2C_{24}^{*} \cdot \mathbf{t}_{c}(p_{3})\phi^{a}(p_{2})Ru_{c}^{i}(p_{1}) \\
&- [2(C_{23} + C_{12}) + C_{23}^{*} + C_{12}^{*} + C_{12}^{*} + C_{12}^{*}] \cdot \mathbf{t}_{c}(p_{3})\phi^{a}(p_{2})\phi^{a}(p_{2})Ru_{c}^{i}(p_{1}) \\
&- (C_{0}^{*} - C_{0}^{*}) \cdot \mathbf{t}_{c}(p_{3})\phi^{a}(p_{2})\phi^{a}(p_{2})Ru_{c}^{i}(p_{1}) \\
&- (C_{12} - C_{12}^{*}) \cdot \mathbf{t}_{c}(p_{3})\phi^{a}(p_{2})\phi^{a}(p_{2})Ru_{c}^{i}(p_{1})\},
\end{align*}

(5)

with the three-point standard functions defined as

$$C_{ij} = C_{ij}(-p_{2}, -p_{1}, m_{b}, m_{b}, M_{\Pi}),$$

7
\[ C'_{ij} = C_{ij}(-p_2, -p_1, m_t, m_t, M_{\Pi_t}), \]
\[ C'^*_{ij} = C_{ij}(-p_2, -p_1, m_t, m_t, M_{h_t}), \]

and
\[
M_{E^{\Pi_{0}}} = \frac{m_t^4 \tan \beta^3}{16 \pi^2 m_t^2} (1 - \varepsilon)^2 g_s T^a_{ij} G(p_3 - p_2, m_t) \\
\{[2B_1(p_2 - p_3, m_b, M_{\Pi_t}) + B_1(p_2 - p_3, m_t, M_{\Pi_t}) + B_1(p_2 - p_3, m_t, M_{h_t}) \\
+ B_0(p_2 - p_3, m_t, M_{\Pi_t}) - B_0(p_2 - p_3, m_t, M_{h_t}) \\
- B_0(p_3, m_t, M_{\Pi_t}) + B_0(p_3, m_t, M_{h_t}) \\
- m^2(C'_0 + C'^*_{0}) - 2m^2C'_0 + 4C'_{24} + 2C'^*_{24}] \cdot \bar{\psi}_c(p_3) \psi^a(p_2) Ru_i^i(p_1) \}
\]
\[
\left[ 2(C_{23} + C_{12}) + C'^*_{23} + C'^*_{12} + C_{24} + C'^*_{24}] \cdot \bar{\psi}_c(p_3) \psi^a(p_2) \psi_3 Ru_i^i(p_1) \right] \\
- (C'_0 - C'^*_{0}) \cdot \bar{\psi}_c(p_3) \psi^a(p_2) \psi_3 \psi_2 Ru_i^i(p_1) \\
+ (-C'_{12} + C'^*_{12}) \cdot \bar{\psi}_c(p_3) \psi^a(p_2) \psi_3 \psi_2 Ru_i^i(p_1) \right\}, \quad (6)
\]

with the three-point standard functions defined as
\[ C_{ij} = C_{ij}(p_2, -p_3, m_b, m_b, M_{\Pi_t}), \]
\[ C'_{ij} = C_{ij}(p_2, -p_3, m_t, m_t, M_{\Pi_t}), \]
\[ C'^*_{ij} = C_{ij}(p_2, -p_3, m_t, m_t, M_{h_t}). \]

To obtain the numerical results of the \(c\Pi^0_t\) production, we choose the same parameters values as those in the \(c\Pi^-\) production. The cross section of the \(c\Pi^0_t\) production at the Tevatron and LHC is shown in Fig.5 and Fig.6, respectively.

![Fig. 5: The hadronic cross section of \(c\Pi^0_t\) production as a function of \(M_{\Pi_t}\) at the Tevatron, with \(M_{h_t} = 200, 400\) GeV, respectively.](image)

As it is shown in Fig.2(D-E), the \(c\Pi^0_t\) production only involves the loop-level FC coupling \(tgc\). So the cross section of the \(c\Pi^0_t\) production is much smaller than that of the \(c\Pi^-\) production. We can see from Fig.5 and Fig.6, the cross section at the Tevatron is less than one fb which is too small to detect the neutral top-pion. The cross section at
the LHC can be greatly increased. For the light $\Pi^0$, the cross section is over one hundred fb. There are enough $c\Pi^0$ signals would be produced at the LHC in a wide range of parameter spaces. Therefore, the $c\Pi^0$ production at the LHC will open a good window to search for the neutral top-pion. Furthermore, it should be noted that the $c\Pi^0$ production only involves the loop-level FC coupling $tcg$. So the $c\Pi^0$ production might also provide a chance to obtain the information of the FC coupling $tcg$.

The decay branching ratios of the neutral top-pion have been calculated in the reference[4]. The main decay modes of $\Pi^0$ are $t\bar{t}$, $c\bar{c}$. For heavy $\Pi^0$($M_{\Pi^0} > 2m_t$), the channel $\Pi^0 \to t\bar{t}$ is open. In this case, $\Pi^0$ almost decays to $t\bar{t}$ and a large number of $t\bar{t}$ can be produced. In order to detect $\Pi^0$ via $t\bar{t}$, one should reconstruct the top pair from the final states and measure the invariant mass distribution of $t\bar{t}$ which make the probe for the $\Pi^0$ via $t\bar{t}$ become more difficult. So it is a hard work to detect the heavy neutral top-pion. But the fact that a large number of $t\bar{t}$ events associated with a c-jet are produced might provide the clue of the TC2 model. Below the $t\bar{t}$ threshold, the FC decay channel $t\bar{c}$ is dominant. Such decay mode involves the typical feature of the TC2 mode and the peak of the invariant mass distribution of $t\bar{c}$ is narrow. To identify $t\bar{c}$, one needs reconstruct top quark from its decay mode $W^+b$. Furthermore, the b-tagging and c-tagging are also needed. The experiments can take b-tagging and c-tagging with high efficiency[15]. So there should be enough clean $t\bar{c}$ signals for the discovery of $\Pi^0$, and the FC decay mode $t\bar{c}$ is the most ideal one to detect $\Pi^0$. On the other hand, it is also necessary to tag another c-jet associated with $\Pi^0$ production. Such c-tagging can confirm that the process is a FC process and make the SM background become very clean.

Now we turn to study the $h^0_t$ production mode $ch^0_t$. For the production amplitudes, the only difference between the $c\Pi^0_t$ and $ch^0_t$ productions is that there exists a extra factor $i$ in the $c\Pi^0_t$ production amplitudes, i.e., $M_D^{c\Pi^0} = iM_D^{ch^0}$, $M_E^{c\Pi^0} = iM_E^{ch^0}$. So almost identical conclusions can apply to the $ch^0_t$ production mode, where the only difference is that there exist the extra tree-level gauge boson decay modes: $W^+W^-, ZZ$ for $h^0_t$. The decay rates of $W^+W^-, ZZ$ are suppressed by $r^2(r=m_t/m_W)$, but the branching ratio of $W^+W^- + ZZ$ can still above 10% if the decay mode $t\bar{t}$ is forbidden[9]. These gauge boson decay modes might provide a way to distinguish $h^0_t$ from $\Pi^0$.
III. CONCLUSIONS

In this paper, we study the FC production processes of top-pions and top-Higgs associated with a charm quark. Our study shows that the cross section of $c\Pi^-_t$ production is much larger than those of $c\Pi^0_t(h^0_t)$ productions due to the tree-level contribution of the $b\bar{c}\Pi^-_t$ coupling to the $c\Pi^-_t$ production. At the Tevatron, the cross section is at the order of tens fb for $c\Pi^-_t$ production and below one fb for $c\Pi^0_t(h^0_t)$ production in most cases. The light charged top-pions are not favorable by the Tevatron experiments and the Tevatron has a little capability to probe the neutral top-pion and top-Higgs via these FC production processes. The cross sections of $c\Pi^-_t$ and $c\Pi^0_t(h^0_t)$ productions can be largely enhanced at the LHC. The cross sections at the LHC can reach the level $10 \sim 100$ pb for $c\Pi^-_t$ production and $10 \sim 100$ fb for $c\Pi^0_t(h^0_t)$ productions. With the yearly luminosity $100fb^{-1}$, enough signals could be produced at the LHC. The SM backgrounds, fortunately, should be clean due to the FC feature of these processes. Furthermore, the FC decay modes $\Pi^-_t \rightarrow b\bar{c}$ and $\Pi^0_t(h^0_t) \rightarrow t\bar{c}$ can provide us the typical signal to detect the top-pions and top-Higgs. Therefore, it is hopeful to find the signal of top-pions and top-Higgs with the running of the LHC if they are there indeed.

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