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

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1 Introduction

The upgraded $p\bar{p}$ collider Tevatron is now engaged in RUN II, and it will be followed up by the forthcoming Large Hadronic Collider (LHC), with a center of mass (c.m.) energy of 14 TeV. One of the important tasks of these hadron colliders is to detect the signal of 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 electroweak symmetry breaking (EWSB). Therefore, LHC will open a wide window to test the new physics models and, furthermore, to explore EWSB.

Among the various new physics theories, the technicolor (TC) model, introduced by Weinberg and Susskind [1, 2], offers a new possible mechanism of EWSB and solves the problems of the SM neatly. As one of the promising candidates of new physics, TC theory has been in development for many years. In the 1990s, a new dynamical topcolor was introduced to combine with the TC theory; then we arrived at the topcolor-assisted technicolor (TC2) model [3–8]. The TC2 model predicts three CP odd pseudo Goldstone bosons (PGBs) called top-pions ($\Pi_t^\pm, \Pi_t^0$) and a CP even scalar called a top-Higgs particle (h_t^0) in the region of a few hundreds GeV. The existence of these physical particles can be regarded as a typical feature of the TC2 model, and the observation of them is robust evidence for the model. Thus the study of the production processes of these typical particles is a very interesting research work, and a lot of studies of this aspect have been done [9–22]. 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 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 mechanism makes the FC processes in the SM hard to detect, 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 [21–28]. On the other hand, the tree-level FC couplings in the TC2 model can also result in loop-level FC couplings: $tcZ, tc\gamma, tcg$. The contributions of these one-loop FC couplings are also significant, which makes rare top quark decays [24], $t\bar{c}$ production [25, 26], and $tZ(\gamma)$ productions [27] detectable at LHC and ILC. Due to the existence of FC couplings in the TC2 model, top-pions

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and top-Higgs particles 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 backgrounds would be very clean for these FC processes. We have studied the FC production processes, $t\bar{c}\Pi_t^0$, via e^+e^- and $\gamma\gamma$ collisions [21, 22], and we have found that the cross sections are large enough and the backgrounds are very small. So these FC production processes would provide us with a good opportunity to search for the neutral top-pion at the planned ILC. With the running of LHC in 2007, the signal of the TC2 model would be first observed at LHC. As we know, backgrounds at the hadron colliders are much larger than those at linear colliders, which makes the detection of the new particles at the hadron colliders more difficult. But we find that there also exist FC production processes of the top-pions and top-Higgs particles at hadron colliders, i.e., $c\Pi_t^-$ and $c\Pi_t^0(h_t^0)$ productions. In this paper, we study the potential to discover the top-pions and top-Higgs particles via these FC production modes.

We organized the paper as follows. In Sect. 2, we present our calculations and the numerical results of the cross sections. The conclusions are given in Sect. 3.

2 Calculations and numerical results

Since the topcolor interaction treats the third family quarks 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 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 top-pions and top-Higgs particles to quarks can be written as [23, 24]

$$\begin{aligned}\mathcal{L} = \frac{m_t}{v_w}\tan\beta\bigg[&\mathrm{i}K_{UR}^{tt}K_{UL}^{tt*}\overline{t_L}t_R\Pi_t^0 + \sqrt{2}K_{UR}^{tt*}K_{DL}^{bb}\overline{t_R}b_L\Pi_t^+ \\ &+ \mathrm{i}K_{UR}^{tc}K_{UL}^{tt*}\overline{t_L}c_R\Pi_t^0 + \sqrt{2}K_{UR}^{tc*}K_{DL}^{bb}\overline{c_R}b_L\Pi_t^+ \\ &+ \mathrm{i}\frac{m_b^*}{m_t}\overline{b_L}b_R\Pi_t^0 + K_{UR}^{tt}K_{UL}^{tt*}\overline{t_L}t_R h_t^0 \\ &+ K_{UR}^{tc}K_{UL}^{tt*}\overline{t_L}c_R h_t^0 + \text{h.c.}\bigg]\,, \qquad (1)\end{aligned}$$

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, and $K_{U,D}^{ij}$ are the matrix elements of the unitary matrix $K_{U,D}$, from which the Cabibbo–Kobayashi–Maskawa (CKM) matrix can be derived: $V = K_{UL}^{-1}K_{DL}$. Their values can be written as

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

ε is a model dependent parameter that is in the range of $0.03 \le \varepsilon \le 0.1$ [3–8]. The mass m_b^* is the part of the b-quark mass that is induced by the instanton and can be estimated to be [3–8]

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

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

The existence of tree-level FC couplings $\Pi_t^0 t\bar{c}$, $\Pi_t^- b\bar{c}$ and $h_t^0 t\bar{c}$ 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 significant contributions to some processes. These FC couplings can also induce interesting FC production processes of top-pions and top-Higgs at the hadron colliders; i.e., $p\overline{p}(pp) \to c\Pi_t^-$ and $c\Pi_t^0(h_t^0)$. In the following, we focus on the study of these processes.

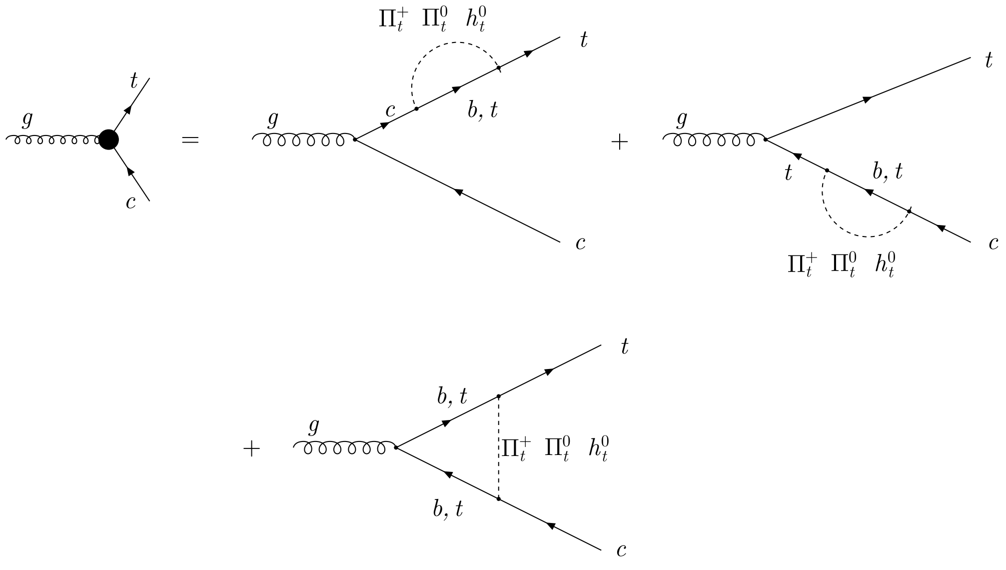

Fig. 1. The Feynman diagrams of the one-loop FC tcg coupling

2.1 $c\Pi_t^-$ production at 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 of physics beyond the SM. The Tevatron can probe the charged (pseudo) scalars' mass up to 300–350 GeV, and LHC can probe the mass range of charged (pseudo) scalars up to $\sim O(1)$ TeV [23]. As is known, 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 collisions. On the other hand, the loop-level FC coupling tcg can also make a contribution to the $c\Pi_t^-$ production. The Feynman diagrams of the $c\Pi_t^-$ production at the hadron colliders are shown in Fig. 2A–C.

The production amplitudes are expressed as follows:

$$M_A = \frac{-\mathrm{i}\sqrt{2}m_t\tan\beta}{\upsilon_w}\sqrt{2\varepsilon-\varepsilon^2}g_{\mathrm{s}}T^a_{ij}G(p_1+p_2,m_b) \times \overline{u}^i_c(p_3)L(\not{p}_1+\not{p}_2+m_b)\not{\epsilon}^a(p_2)u^j_b(p_1)\,, \tag{2}$$

$$M_B = \frac{-\mathrm{i}\sqrt{2}m_t\tan\beta}{\upsilon_w}\sqrt{2\varepsilon-\varepsilon^2}g_{\mathrm{s}}T^a_{ij}G(p_3-p_2,m_c) \times \overline{u}^i_c(p_3)\not{\epsilon}^a(p_2)(\not{p}_3-\not{p}_2+m_c)Lu^j_b(p_1)\,, \tag{3}$$

$$\begin{aligned} M_C = {} & \frac{-\mathrm{i}\sqrt{2}m_t^3 tan^3\beta}{16\pi^2\upsilon_w^3}(1-\varepsilon)^2\sqrt{2\varepsilon-\varepsilon^2}g_{\mathrm{s}}T^a_{ij}G(p_3-p_2,m_t) \\ & \times\big\{\big[2B_1(p_2-p_3,m_b,M_{\Pi_t})+B_1(p_2-p_3,m_t,M_{\Pi_t}) \\ & +B_1(p_2-p_3,m_t,M_{h_t})+B_0(p_2-p_3,m_t,M_{\Pi_t}) \\ & -B_0(p_2-p_3,m_t,M_{h_t})-B_0(-p_3,m_t,M_{\Pi_t}) \\ & +B_0(-p_3,m_t,M_{h_t}) \\ & -m_t^2\big(C_0'+C_0^*\big)-2m_b^2C_0+4C_{24}+2C_{24}'+2C_{24}^*\big] \\ & \times\overline{u}^i_c(p_3)\not{\epsilon}^a(p_2)(\not{p}_3-\not{p}_2)Lu^j_b(p_1) \\ & +\big[2(C_{23}+C_{12})+C_{23}'+C_{12}'+C_{23}^*+C_{12}^*\big] \\ & \times\overline{u}^i_c(p_3)\not{p}_2\not{\epsilon}^a(p_2)\not{p}_3(\not{p}_3-\not{p}_2)Lu^j_b(p_1) \\ & +m_t^2\big(C_0'-C_0^*\big)\overline{u}^i_c(p_3)\not{p}_2\not{\epsilon}^a(p_2)Lu^j_b(p_1) \\ & +m_t^2\big(-C_{12}'+C_{12}^*\big)\overline{u}^i_c(p_3)\not{\epsilon}^a(p_2)\not{p}_3Lu^j_b(p_1)\big\}\,, \end{aligned} \tag{4}$$

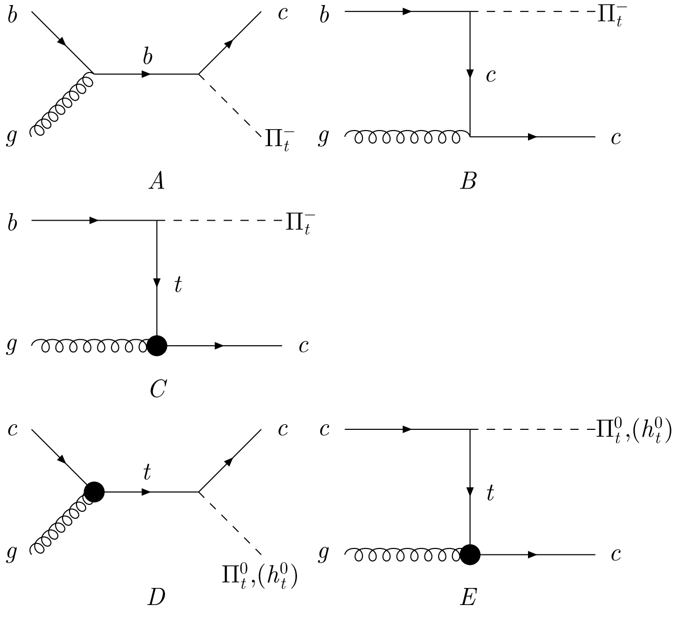

Fig. 2. The Feynman diagrams of $c\Pi_t^-$ and $c\Pi_t^0(h_t^0)$ productions at hadron colliders

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

$$\begin{aligned} C_{ij} &= C_{ij}(p_2,-p_3,m_b,m_b,M_{\Pi_t})\,, \\ C_{ij}' &= C_{ij}(p_2,-p_3,m_t,m_t,M_{\Pi_t})\,, \\ C_{ij}^* &= C_{ij}(p_2,-p_3,m_t,m_t,M_{h_t})\,. \end{aligned}$$

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 the subprocess $bg\to c\Pi_t^-$. The hadronic cross section at hadron colliders can be obtained by folding the cross section of the subprocesses with the parton distribution.

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 [29], $\upsilon_w=246$ GeV and $\upsilon_t=60$ GeV. The strong coupling constant $g_{\mathrm{s}}=2\sqrt{\pi\alpha_{\mathrm{s}}}$ can be obtained from the one-loop evolution formula at the energy of Tevatron and LHC, respectively. There are three free parameters involved in the production amplitudes: the top-pion mass M_{Π_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 ε. In order to see the influence of these parameters on the cross section, we take M_{Π_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 Tevatron and LHC are shown in Figs. 3 and 4, respectively. The cross section should be sensitive to the mass of the final state Π_t^-, and in Figs. 3 and 4 we plot the hadronic cross section as a function of M_{Π_t}. From these figures, we can see that the production cross section decreases sharply with M_{Π_t} increasing, because the large mass of the top-pion can strongly depress the phase space. For $c\Pi_t^-$ production, the top-Higgs particle only makes a virtual contribution to the loop-level coupling tcg, so the cross section is insensitive to the mass of the top-Higgs particle. The dependence of the cross section on ε is obvious, and when ε becomes large the cross section increases. As is known, at the Tevatron, the main contributions come from the light quarks, so the cross section of $c\Pi_t^-$ production is not so large in most of parameter space, and the cross section can reach the level of pb only in a narrow range for a light top-pion. Because there is no clue of the existence of the charged top-pions at the Tevatron, the light charged top-pions are not favorable by the Tevatron experiments. At LHC, the gluon makes the main contribution, and the cross section greatly increases. 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 LHC. So the LHC might provide a good opportunity to probe

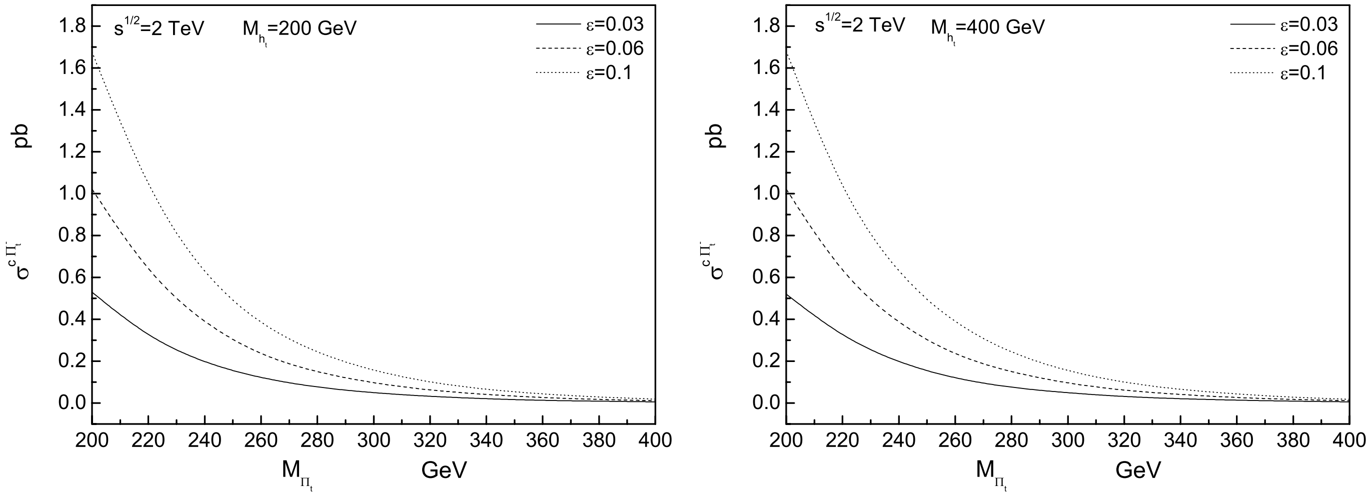

Fig. 3. The hadronic cross section of $c\Pi_t^-$ production as a function of M_{Π_t} at the Tevatron, with $M_{h_t} = 200$, 400 GeV, respectively

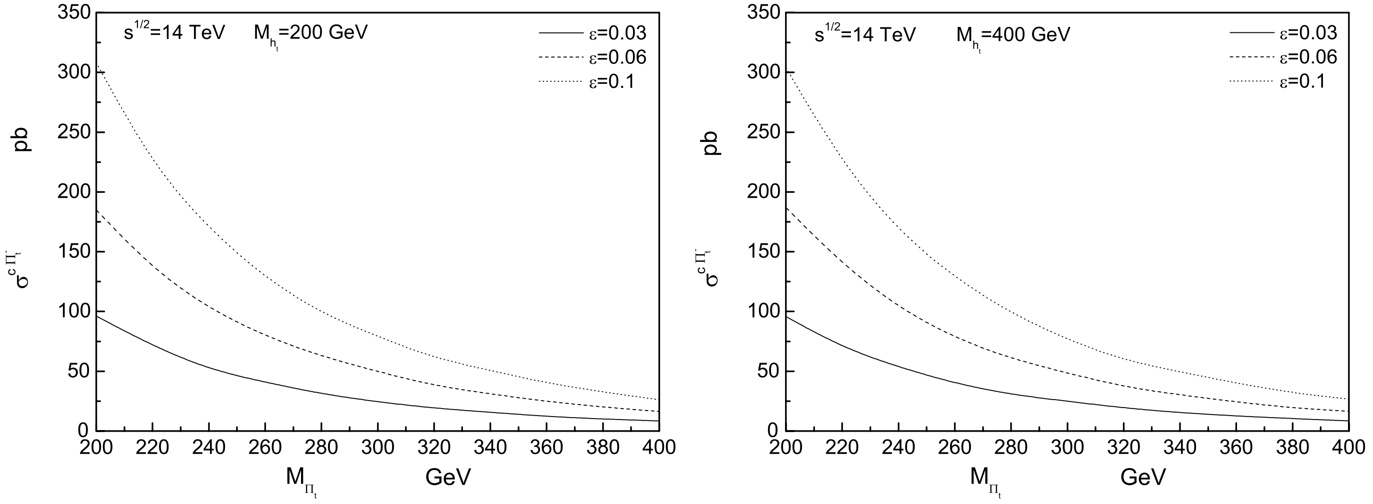

Fig. 4. The hadronic cross section of $c\Pi_t^-$ production as a function of M_{Π_t} at LHC, with $M_{h_t} = 200$, 400 GeV, respectively

charged top-pions. On the other hand, the main contributions come from the tree-level figures of Fig. 2A and B, so such a charged top-pion production mode also provides us with 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 information on the tcg coupling from such a process.

The decay width and the decay branching ratios of the charged top-pions have been studied in [23, 30], and the dominant decay modes of Π_t^- are $b\bar{t}$ and $b\bar{c}$. The signal should include two jets: one is a c-jet, and another jet includes the particles arising from Π_t^- decay. The c-jet can easily be identified, and such an identification is very important; it can help us to confirm that such a production mode is a FC mode and strongly depresses the SM backgrounds. To detect Π_t^- via the decay mode $b\bar{t}$, 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 Π_t^-. The branching ratio of $b\bar{c}$ decay is over 10% [30], so enough signals can be produced via the decay mode $b\bar{c}$ with the yearly luminosity of $100\,\mathrm{fb}^{-1}$ at LHC. Furthermore, the decay mode $b\bar{c}$ involves the FC coupling $\Pi_t^- b\bar{c}$, which is an important feature of the TC2 model. So the $b\bar{c}$ signal is typical, and the SM backgrounds are very clean. Therefore, the discovery of the charged top-pions at LHC would be possible in a wide range of the parameter space of the TC2 model. But a more detailed study of the backgrounds is warranted, in order to establish the experimental sensitivity to the FC $\Pi_t^- b\bar{c}$ coupling. 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 H^- can also decay to $\bar{t}b$ and $b\bar{c}$. But the difference between the charged top-pions and the charged Higgs bosons is that the charged Higgs particle has extra decay modes,

$H^- \to \tau\nu, \bar{c}s$, and such a difference can help us to distinguish the charged top-pions from these charged Higgs bosons.

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

Besides the charged top-pions, there also exist neutral CP odd top-pion and CP even top-Higgs particles in the TC2 model. The loop-level FC tcg coupling can also induce 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. 2D and E.

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

$$\begin{aligned}
M_D^{c\Pi_t^0} = {} & \frac{-m_t^4\tan^3\beta}{16\pi^2 v_w^3}(1-\varepsilon)(2\varepsilon-\varepsilon^2)g_{\mathrm{s}}T_{ij}^a G(p_1+p_2,m_t) \\
& \times\big\{\big[2B_1(-p_1-p_2,m_b,M_{\Pi_t}) \\
& + B_1(-p_1-p_2,m_t,M_{\Pi_t}) + B_1(-p_1-p_2,m_t,M_{h_t}) \\
& + B_0(-p_1-p_2,m_t,M_{\Pi_t}) - B_0(-p_1-p_2,m_t,M_{h_t}) \\
& - B_0(-p_1,m_t,M_{\Pi_t}) + B_0(-p_1,m_t,M_{h_t}) \\
& - m_t^2\big(C_0'+C_0^*\big) - 2m_b^2C_0 + 4C_{24} + 2C_{24}' + 2C_{24}^*\big] \\
& \times \overline{u}_c^i(p_3)\not{\epsilon}^a(p_2)Ru_c^j(p_1) \\
& - \big[2(C_{23}+C_{12}) + C_{23}' + C_{12}' + C_{23}^* + C_{12}^*\big] \\
& \times \overline{u}_c^i(p_3)\not{p}_1\not{\epsilon}^a(p_2)\not{p}_2Ru_c^j(p_1) \\
& - \big(C_0'-C_0^*\big)\overline{u}_c^i(p_3)(\not{p}_1+\not{p}_2)\not{\epsilon}^a(p_2)\not{p}_2Ru_c^j(p_1) \\
& - \big(C_{12}'-C_{12}^*\big)\overline{u}_c^i(p_3)(\not{p}_1+\not{p}_2)\not{p}_1\not{\epsilon}^a(p_2)Ru_c^j(p_1)\big\}\,,
\end{aligned} \tag{5}$$

with the three-point standard functions defined as

$$\begin{aligned}
C_{ij} &= C_{ij}(-p_2,-p_1,m_b,m_b,M_{\Pi_t})\,, \\
C_{ij}' &= C_{ij}(-p_2,-p_1,m_t,m_t,M_{\Pi_t})\,, \\
C_{ij}^* &= C_{ij}(-p_2,-p_1,m_t,m_t,M_{h_t})\,,
\end{aligned}$$

and

$$\begin{aligned}
M_E^{c\Pi_t^0} = {} & \frac{m_t^4\tan\beta^3}{16\pi^2 v_w^3}(1-\varepsilon)(2\varepsilon-\varepsilon^2)g_{\mathrm{s}}T_{ij}^a G(p_3-p_2,m_t) \\
& \times\big\{\big[2B_1(p_2-p_3,m_b,M_{\Pi_t}) \\
& + B_1(p_2-p_3,m_t,M_{\Pi_t}) + B_1(p_2-p_3,m_t,M_{h_t}) \\
& + B_0(p_2-p_3,m_t,M_{\Pi_t}) - B_0(p_2-p_3,m_t,M_{h_t}) \\
& - B_0(-p_3,m_t,M_{\Pi_t}) + B_0(-p_3,m_t,M_{h_t}) \\
& - m_t^2\big(C_0'+C_0^*\big) - 2m_b^2C_0 + 4C_{24} + 2C_{24}' + 2C_{24}^*\big] \\
& \times \overline{u}_c^i(p_3)\not{\epsilon}^a(p_2)Ru_c^j(p_1) \\
& + \big[2(C_{23}+C_{12}) + C_{23}' + C_{12}' + C_{23}^* + C_{12}^*\big] \\
& \times \overline{u}_c^i(p_3)\not{p}_2\not{\epsilon}^a(p_2)\not{p}_3Ru_c^j(p_1) \\
& + \big(C_0'-C_0^*\big)\overline{u}_c^i(p_3)\not{p}_2\not{\epsilon}^a(p_2)(\not{p}_3-\not{p}_2)Ru_c^j(p_1) \\
& + \big(-C_{12}'+C_{12}^*\big)\overline{u}_c^i(p_3)\not{\epsilon}^a(p_2)\not{p}_3(\not{p}_3-\not{p}_2)Ru_c^j(p_1)\big\},
\end{aligned} \tag{6}$$

with the three-point standard functions defined as

$$\begin{aligned}
C_{ij} &= C_{ij}(p_2,-p_3,m_b,m_b,M_{\Pi_t})\,, \\
C_{ij}' &= C_{ij}(p_2,-p_3,m_t,m_t,M_{\Pi_t})\,, \\
C_{ij}^* &= C_{ij}(p_2,-p_3,m_t,m_t,M_{h_t})\,.
\end{aligned}$$

To obtain the numerical results of $c\Pi_t^0$ production, we choose the same parameter values as those in $c\Pi_t^-$ production. The cross section of $c\Pi_t^0$ production at the Tevatron and LHC is shown in Figs. 5 and 6, respectively.

As is shown in Fig. 2D and E, the $c\Pi_t^0$ production only involves the loop-level FC tcg coupling. So the cross section of the $c\Pi_t^0$ production is much smaller than that of the $c\Pi_t^-$ production. We can see from Figs. 5 and 6 that 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 LHC greatly increases. For the light Π_t^0, the cross section is over one hundred fb. Enough $c\Pi_t^0$ signals would be produced at LHC in a wide range of the parameter space. There-

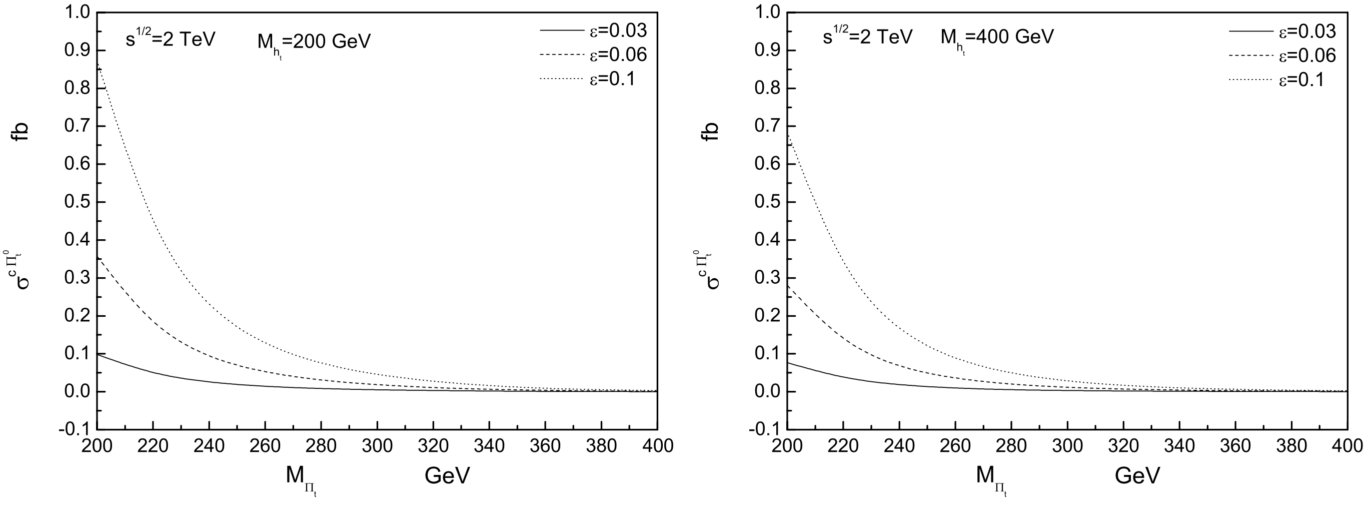

Fig. 5. The hadronic cross section of $c\Pi_t^0$ production as a function of M_{Π_t} at the Tevatron, with $M_{h_t} = 200,\ 400\,\mathrm{GeV}$, respectively

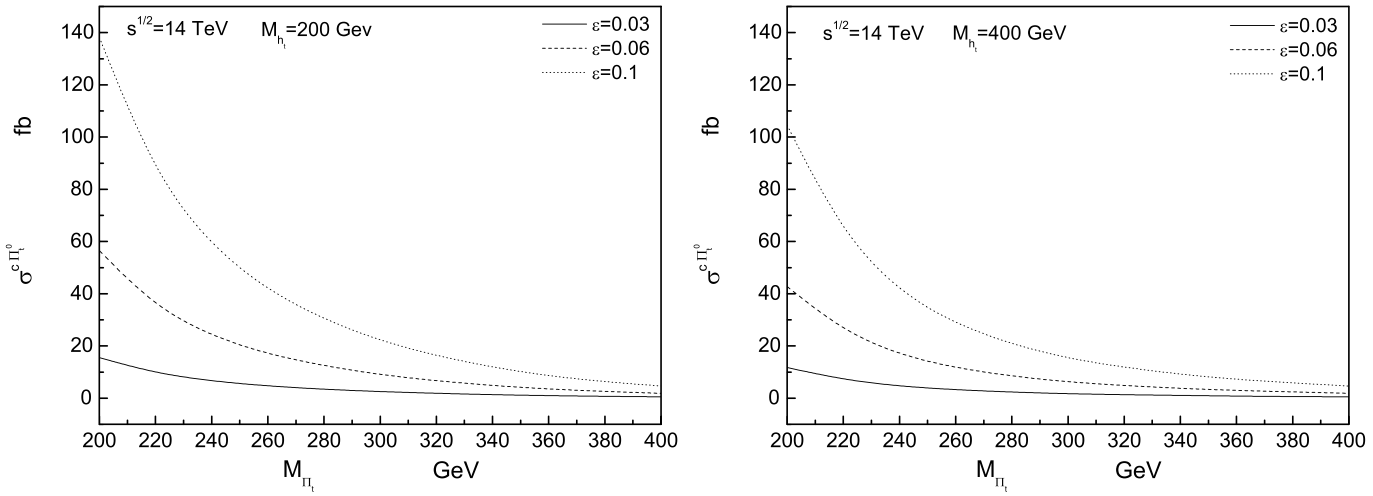

Fig. 6. The hadronic cross section of $c\Pi_t^0$ production as a function of M_{Π_t} at LHC, with $M_{h_t} = 200$, 400 GeV, respectively

fore, the $c\Pi_t^0$ production at LHC will open a good window to search for the neutral top-pion. Furthermore, it should be noted that $c\Pi_t^0$ production only involves the loop-level FC tcg coupling. So $c\Pi_t^0$ production might also provide an opportunity to obtain information on the FC tcg coupling.

The branching ratios of the decay of the neutral top-pion have been calculated in [16]. The main decay modes of Π_t^0 are $t\bar{t}$ and $t\bar{c}$. For heavy Π_t^0 ($M_{\Pi_t} > 2m_t$), the channel $\Pi_t^0 \to t\bar{t}$ is open. In this case, Π_t^0 almost totally decays to $t\bar{t}$ and a large number of $t\bar{t}$ events can be produced. In order to detect Π_t^0 via $t\bar{t}$, one should reconstruct the top quark pair from the final states and measure the invariant mass distribution of $t\bar{t}$, which makes probing of Π_t^0 via $t\bar{t}$ more difficult. So it is hard 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 a clue of the TC2 model. Below the $t\bar{t}$ threshold, the FC decay channel $t\bar{c}$ is dominant. Such a decay mode involves a typical feature of the TC2 model, and the peak of the $t\bar{c}$ invariant mass distribution is narrow. To identify $t\bar{c}$, one needs to reconstruct the top quark from its decay mode W^+b. Furthermore, b- and c-tagging are also needed. The experiments can take b- and c-tagging with a high efficiency [31, 32]. So there should be enough clean $t\bar{c}$ signals to detect Π_t^0, and the FC decay mode $t\bar{c}$ is the most ideal one to detect Π_t^0. On the other hand, it is also necessary to tag another c-jet associated with Π_t^0 production. Such c-tagging may confirm that the process is a FC process and greatly depresses the SM backgrounds.

Now we turn to the study of the h_t^0 production mode ch_t^0. For the production amplitudes, the only difference between the $c\Pi_t^0$ and ch_t^0 productions is that there exists an extra factor i in the $c\Pi_t^0$ production amplitudes, i.e., $M_D^{c\Pi_t^0} = \mathrm{i}M_D^{ch_t^0}$ and $M_E^{c\Pi_t^0} = \mathrm{i}M_E^{ch_t^0}$. So almost identical conclusions apply to the ch_t^0 production mode, where the only difference is that there exist the extra tree-level gauge boson decay modes W^+W^-, ZZ for h_t^0. The decay rates of W^+W^-, ZZ are suppressed by $r^2 (r = m_t/v_t)$, but the branching ratio of $W^+W^- + ZZ$ can still exceed 10% if the decay mode $t\bar{t}$ is forbidden [25]. These gauge boson decay modes might provide a way to distinguish h_t^0 from Π_t^0.

3 Conclusions

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

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