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Production of the top-pions at the THERA collider based γp collisions

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Abstract

In the framework of the topcolor-assisted technicolor (TC2) models, we study the production of the top-pions π_t^0, $\pi_t^{\pm}$ via the processes $ep \to \gamma c \to \pi_t^0 c$ and $ep \to \gamma c \to \pi_t^{\pm} b$ mediated by the anomalous top coupling $tc\gamma$. We find that the production cross section of the process $ep \to \gamma c \to \pi_t^0 c$ is very small. With reasonable values of the parameters in TC2 models, the production cross section of the process $ep \to \gamma c \to \pi_t^{\pm} b$ can reach 1.2 pb. The charged top-pions $\pi_t^{\pm}$ might be directly observed via this process at the THERA collider based γp collisions.

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To completely avoid the problems arising from the elementary Higgs field in the standard model (SM), various kinds of dynamical electroweak symmetry breaking (EWSB) models have been proposed, and among which the topcolor scenario is attractive because it provides an additional source of EWSB and solves heavy top quark problem. Topcolor-assisted technicolor (TC2) models [1], flavor-universal TC2 models [2], top see-saw models [3], and top flavor see-saw models [4] are four of such examples. The common feature of such type of models is that the topcolor interactions are assumed to be chiral critically strong at the scale 1 TeV, and it is coupled preferentially to the third generation. EWSB is mainly generated by TC interactions or other strong interactions. The topcolor interactions also make small contributions to EWSB and give rise to the main part of the top quark mass $(1-\epsilon)m_t$ with $0.03 \leqslant \epsilon \leqslant 0.1$. Then, the presence of the physical top-pions in the low-energy spectrum is an inevitable feature of these models. Thus, studying the production of the top-pions at present and future high-energy colliders can help the high-energy experiments to search for top-pions, test topcolor scenario and further to probe EWSB mechanism.

The production and decay of the technipions predicted by the technicolor sector have been extensively studied in the literature [5,6]. Combing resonant and non-resonant contributions, the signals of the technipions are recently studied at the lepton colliders and the

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hadron colliders [7]. The production and decays of the top-pions at the lepton colliders and the hadron colliders are studied in several instances [8–10].

For TC2 models, the underlying interactions, topcolor interactions, are non-universal, and therefore do not possess a GIM mechanism. This is another feature of this kind of models due to the need to single out the top quark for condensation. The non-universal gauge interactions result in the flavor changing neutral current (FCNC) vertices when one writes the interactions in the quark mass eigenbasis. The top-pions have large Yukawa coupling to the third family fermions and can induce the new FC couplings, which generate the large anomalous top couplings tcv ($v = \gamma, Z$, or g) [11]. Thus, the top-pions π_t^0, $\pi_t^\pm$ can be produced via the processes $\gamma c \to t \to \pi_t^0 c$ and $\gamma c \to t \to \pi_t^\pm b$. Our results show that the production rate of the neutral top-pion π_t^0 is very small and π_t^0 cannot be detected at the THERA collider based γp collisions via the process $ep \to \gamma c \to \pi_t^0 c$. For the process $ep \to \gamma c \to \pi_t^\pm b$, we find that several tens and up to thousand events of the charged top-pions $\pi_t^\pm$ can be produced per year by assuming the integrated luminosity $L = 750\ \text{pb}^{-1}$ and the center-of-mass energy $\sqrt{s} = 1000$ GeV for the THERA collider based γp collisions [12]. The charged top-pions $\pi_t^\pm$ may be observed at the THERA collider.

As it is well known, the couplings of the top-pions to the three family fermions are non-universal. The top-pions have large Yukawa couplings to the third generation and can induce large flavor changing couplings. The couplings of the top-pions π_t^0, $\pi_t^\pm$ to quarks can be written as [1,8]:

$$\frac{m_t}{\sqrt{2}F_t}\frac{\sqrt{\nu_w^2 - F_t^2}}{\nu_w}\Big[iK_{UR}^{tt}K_{UL}^{tt*}\overline{t_L}t_R\pi_t^0 + \sqrt{2}K_{UR}^{tt*}K_{DL}^{bb}\overline{t_R}b_L\pi_t^+ + iK_{UR}^{tc}K_{UL}^{tt*}\overline{t_L}c_R\pi_t^0 + \sqrt{2}K_{UR}^{tc*}K_{DL}^{bb}\overline{c_R}b_L\pi_t^+ + \text{h.c.}\Big], \tag{1}$$

where $F_t = 50$ GeV is the top-pion decay constant and $\nu_w = \nu/\sqrt{2} = 174$ GeV. It has been shown that the values of the coupling parameters can be taken as

$$K_{UL}^{tt} = K_{DL}^{bb} = 1, \qquad K_{UR}^{tt} = 1 - \epsilon,$$
$$K_{UR}^{tc} \leqslant \sqrt{2\epsilon - \epsilon^2},$$

with a model-dependent parameter ϵ. In the following calculation, we will take $K_{UR}^{tc} = \sqrt{2\epsilon - \epsilon^2}$ and take ϵ as a free parameter.

The neutral top-pion π_t^0 and the charged top-pions $\pi_t^\pm$ can generate the anomalous top quark couplings tcv ($v = \gamma, Z$, or g) via the tree-level FC couplings $\pi_t^0 tc$ and $\pi_t^\pm bc$, respectively. However, compared the contributions of π_t^0 to the couplings tcv, the contributions of $\pi_t^\pm$ to the couplings tcv are very small and can be safely ignored. The effective form of the anomalous top quark coupling vertex $t - c - \gamma$, which arises from the tree-level FC coupling $\pi_t^0 \bar{t} c$, can be written as [11]:

$$\Lambda_{tc\gamma}^{\mu} = ie\big[\gamma^\mu F_{1\gamma} + p_t^\mu F_{2\gamma} + p_c^\mu F_{3\gamma}\big], \tag{2}$$

where

$$F_{1\gamma} = \frac{2A}{3}\big[B_0 + m_{\pi_t}^2 C_0 - 2C_{24} + m_t^2(C_{11} - C_{12}) - B_0^* - B_1'\big],$$
$$F_{2\gamma} = \frac{4m_t A}{3}[C_{21} + C_{22} - 2C_{23}],$$
$$F_{3\gamma} = \frac{4m_t A}{3}[C_{22} - C_{23} + C_{12}],$$

with

$$A = \frac{1}{16\pi^2}\left[\frac{m_t}{\sqrt{2}F_t}\frac{\sqrt{\nu_w^2 - F_t^2}}{\nu_w}\right]^2 K_{UR}^{tc}K_{UL}^{tt*}.$$

The expressions of two- and three-point scalar integrals B_n and C_{ij} are [13]:

$$B_n = B_n\big(-\sqrt{\hat{s}}, m_t, m_t\big),$$
$$B_n^* = B_n(-p_c, m_{\pi_t}, m_t),$$
$$B_n' = B_n(-p_t, m_{\pi_t}, m_t),$$
$$C_{ij} = C_{ij}\big(p_t, -\sqrt{\hat{s}}, m_{\pi_t}, m_t, m_t\big),$$
$$C_0 = C_0\big(p_t, -\sqrt{\hat{s}}, m_{\pi_t}, m_t, m_t\big).$$

Ref. [11] has shown that the anomalous top quark coupling $tc\gamma$ can give significant contributions to the rare top decay $t \to c\gamma$ and single top production via the process $e^+e^- \to \bar{t}c$. For instance, the value of the branching ratio $Br(t \to c\gamma)$ varies between 7.9×10^{-7} and 4.6×10^{-6} for $m_{\pi_t} = 300$ GeV and the parameter ϵ in the range of 0.01–0.08, which can approach the corresponding experimental threshold. In this Letter, we study the contributions of this anomalous top quark coupling $tc\gamma$ to the production of the top-pions in the THERA collider based γp collisions.

Ref. [1] has estimated the mass of the top-pions in the fermion loop approximation and given 180 GeV $\leqslant m_{\pi_t} \leqslant$ 240 GeV for $m_t = 175$ GeV and $0.03 \leqslant \epsilon \leqslant 0.1$. The limits on the mass of the top-pion may be obtained via studying its effects on various experimental observables. For example, Ref. [14] has shown that the process $b \to s\gamma$, B–$\bar{B}$ mixing and D–$\bar{D}$ mixing demand that the top-pion is likely to be light, with mass of the order of a few hundred GeV. Since the negative top-pion corrections to the $Z \to b\bar{b}$ branching ratio R_b become smaller when the top-pion is heavier, the precise measurement value of R_b gives rise to a certain lower bound on the top-pion mass [15]. It was shown that the top-pion mass should not be lighter than the order of 1 TeV to make TC2 models consist with the LEP/SLD data [16]. We restudied the problem in Ref. [17] and find that the top-pion mass m_{π_t} is allowed to be in the range of a few hundred GeV depending on the models. Thus, the value of the top-pion mass m_{π_t} remains subject to large uncertainty [18]. Furthermore, Ref. [8] has shown that the top-pion mass can be explored up to 300–350 GeV via the process $p\bar{p} \to \pi_t^0 \to \bar{t}c$ and $p\bar{p} \to \pi_t^{\pm} x$ at the Tevatron and LHC. Thus, we will take m_{π_t} as a free parameter and assume it to vary in the range of 200 GeV–450 GeV in this Letter. In this case, the dominant decay modes of the charged top-pions $\pi_t^{\pm}$ are $\bar{t}b$ or $t\bar{b}$.

The production of the top-pions at the THERA collider based γp collisions is mediated by the anomalous top quark coupling $tc\gamma$ via the subprocesses $\gamma c \to t \to \pi_t^0 c$ and $\gamma c \to t \to \pi_t^{\pm} b$ with the relevant Feynman diagrams shown in Fig. 1. Using the effective vertice $\Lambda^{\mu}_{tc\gamma}$ given by Eq. (2), we can obtain the cross section $\hat{\sigma}_1(\hat{s})$ and $\hat{\sigma}_2(\hat{s})$ of the subprocesses $\gamma c \to t \to \pi_t^0 c$ and $\gamma c \to t \to \pi_t^{\pm} b$, respectively:

$$\hat{\sigma}_1(\hat{s}) = \int_0^{\pi} \frac{1}{32\pi} \frac{(\hat{s} - m^2_{\pi_t})}{\hat{s}^2} \overline{\sum} |M_1|^2 \sin\theta \, d\theta, \tag{3}$$

$$\hat{\sigma}_2(\hat{s}) = \int_0^{\pi} \frac{1}{32\pi} \frac{(\hat{s} - m^2_{\pi_t})}{\hat{s}^2} \overline{\sum} |M_2|^2 \sin\theta \, d\theta, \tag{4}$$

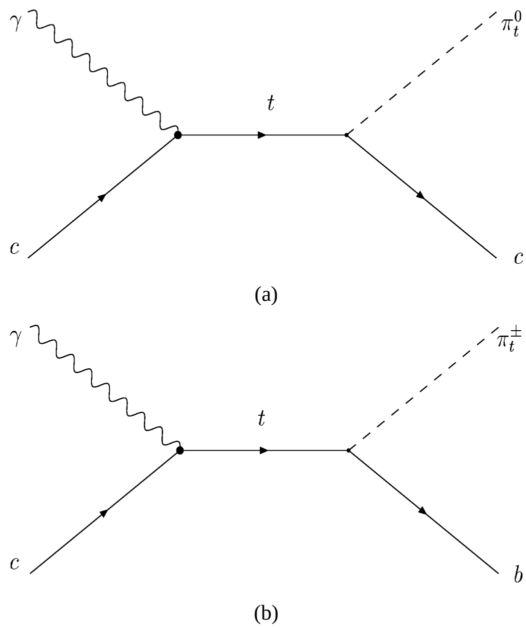

Fig. 1. Feynman diagrams for the top-pion production mediated by the anomalous top quark couplings $tc\gamma$.

with

$$M_1 = -\frac{m_t}{\sqrt{2}F_t} \frac{\sqrt{\nu_w^2 - F_t^2}}{\nu_w} K^{tc}_{UR} K^{tt*}_{UL} \overline{u'_c} \gamma_5 \times \frac{(\gamma \cdot p_t + m_t)}{\hat{s} - m_t^2 + i m_t \Gamma} \Lambda^{\mu}_{tc\gamma} u_c \varepsilon^{\mu},$$

$$M_2 = i \frac{m_t}{F_t} \frac{\sqrt{\nu_w^2 - F_t^2}}{\nu_w} K^{tt*}_{UR} K^{tc}_{DL} \overline{u_b} \gamma_5 \times \frac{(\gamma \cdot p_t + m_t)}{\hat{s} - m_t^2 + i m_t \Gamma} \Lambda^{\mu}_{tc\gamma} u_c \varepsilon^{\mu}.$$

Where $\sqrt{\hat{s}}$ is the center-of-mass energy of the subprocesses $\gamma c \to t \to \pi_t^0 c$ and $\gamma c \to t \to \pi_t^{\pm} b$ in *ep* collisions.

The hard photon beam of the γp collider can be obtained from laser backscattering at *ep* collision in the THERA collider. After calculating the cross section $\hat{\sigma}_i(\hat{s})$ of the subprocess $\gamma c \to t \to \pi_t^0 c$ or $\gamma c \to t \to \pi_t^{\pm} b$, the total production cross sections of the neutral top-pion π_t^0 and charged top-pions $\pi_t^{\pm}$ at the THERA collider can be obtained by folding $\hat{\sigma}_i(\hat{s})$ with the charm quark distribution function $f_{c/p}(x)$ in the proton [19] and the Compton backscattered high-

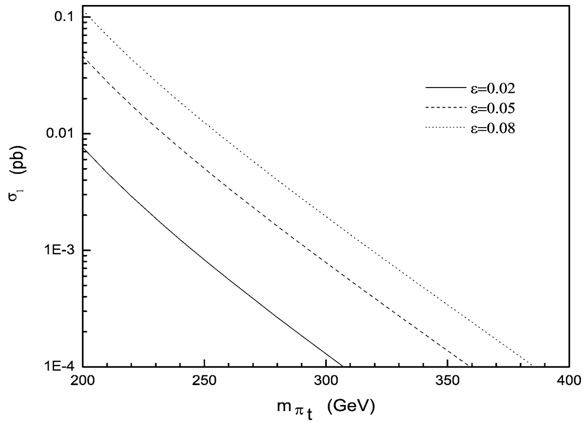

Fig. 2. The production cross section σ_1 of the process $ep \to \gamma c \to \pi_t^0 c$ as a function of m_{π_t} for $\sqrt{s} = 1000$ GeV and three values of the parameter ε.

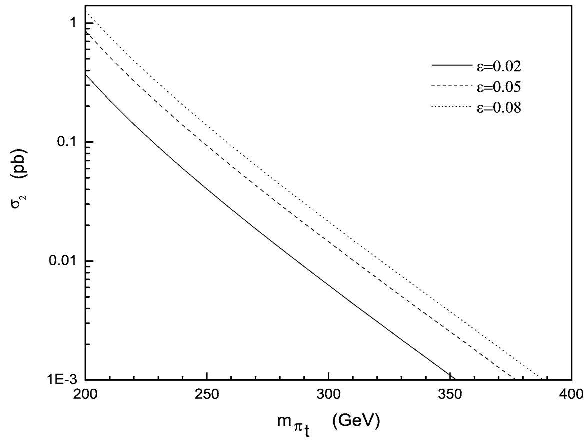

Fig. 3. The production cross section σ_2 of the process $ep \to \gamma c \to \pi_t^{\pm} b$ as a function of m_{π_t} for $\sqrt{s} = 1000$ GeV and three values of the parameter ε.

energy photon spectrum $f_{\gamma/e}(\frac{\tau}{x})$ [20]:

$$\sigma(s) = \int_{\tau_{\min}}^{0.83} d\tau \int_{\tau/0.83}^{1} \frac{dx}{x} f_{\gamma/e}\left(\frac{\tau}{x}\right) f_{c/p}(x)\hat{\sigma}(\hat{s}), \qquad (5)$$

with $\hat{s} = \tau s$, $\tau_{\min} = (m_{\pi_t} + m_q)^2/s$ and

$$f_{\gamma/e}(x) = \frac{1}{1.84}\left[1 - x + \frac{1}{1-x}\left[1 - \frac{4x}{x_0}\left(1 - \frac{x}{x_0(1-x)}\right)\right]\right]$$
$$(x_0 = 4.83).$$

To obtain numerical results, we take the fine structure constant $\alpha_e = \frac{1}{128.8}$, $m_t = 175$ GeV, $m_c = 1.2$ GeV [21] and assume that the total decay width of the top quark is dominated by the decay channel $t \to Wb$, which has been taken $\Gamma(t \to Wb) = 1.56$ GeV. The parton distribution function $f_{c/p}(x)$ of the charm quark runs with the energy scale. In our calculation, we take the CTEQ5 parton distribution function [19] for $f_{c/p}(x)$.

The production cross sections of the neutral top-pion π_t^0 and the charged top-pions $\pi_t^{\pm}$ at the THERA collider are plotted in Fig. 2 and Fig. 3, respectively, as functions of the top-pion mass m_{π_t} for $\sqrt{s} = 1000$ GeV and three values of the parameter ϵ: $\epsilon = 0.02$ (solid line), 0.05 (dash line), 0.08 (dotted line). We can see that the production cross sections decrease with m_{π_t} increasing and the production cross section of $\pi_t^{\pm}$ is larger than that of π_t^0 in all of the parameter space. For $\sqrt{s} = 1000$ GeV, 200 GeV $\leqslant m_{\pi_t} \leqslant$ 400 GeV and $0.02 \leqslant \epsilon \leqslant 0.08$, the production cross section of the processes $ep \to \pi_t^0 c$ and $ep \to \pi_t^{\pm} b$ are in the ranges of 4.1×10^{-6} pb $\sim$ 0.1 pb and 2×10^{-4} pb $\sim$ 1.2 pb, respectively. If we assume the yearly integrated luminosity $L = 750\ \text{pb}^{-1}$ for the THERA collider based γp collision with $\sqrt{s} = 1000$ GeV [12], then the number of the yearly production events of the neutral top-pion π_t^0 is larger than 10 only for $\epsilon \geqslant 0.08$ and $m_{\pi_t} \leqslant 220$ GeV. Thus, it is very difficult to detect π_t^0 via the process $ep \to \pi_t^0 c$ at the THERA based γp collisions. However, it is not this case for the charged top-pions $\pi_t^{\pm}$. There may be several hundreds $\pi_t^{\pm} b$ events to be generated per year in most of the parameter space of the TC2 models.

It is well known that the SM is an effective theory valid only below some high-energy scale Λ, strong EWSB theories might be needed. The strong top dynamical models, such as TC2 models, are the modern dynamical models of EWSB. Such type of models generally predict the existence of the top-pions. Direct observation of these new particles via their large top Yukawa couplings would be confirmation that the EWSB sector realized in nature is not the SM or part of the MSSM. In this Letter, we study the production of the top-pions at the THERA collider based γp collisions in the context of the TC2 models. We find that the top-pions can be produced via the process $ep \to \gamma c \to \pi_t^0 c$ or $ep \to \gamma c \to \pi_t^{\pm} b$

mediated by the anomalous top quark coupling $tc\gamma$, which comes from the tree-level FC scalar couplings $\pi_t^0 tc$ and $\pi_t^\pm bc$. However, the production cross section of the process $ep \to \gamma c \to \pi_t^0 c$ is very small. The neutral top-pion π_t^0 cannot be detected via this process at the THERA collider. For the charged top-pions $\pi_t^\pm$, the production cross section is significantly larger than that of π_t^0. Over a wide range of the parameter space, there are over 100 events of $\pi_t^\pm$ to be generated. Thus, the charged top-pions $\pi_t^\pm$ might be detected via the process $ep \to \gamma c \to \pi_t^\pm b$ at the THERA collider based on γp collisions.

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