Neutral top-pion $\pi_t^0$ and $t\gamma(z)$ production at the HERA and THERA colliders

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Abstract

In the context of top-color assisted technicolor ($TC2$) models, we calculate the contributions of the neutral top-pion $\pi_t^0$ to $t\gamma$ and $tz$ production via the processes $ep \to \gamma c \to t\gamma$ and $ep \to \gamma c \to tz$ at the HERA and THERA colliders. Our results show that the cross sections $\sigma_{t\gamma}(s)$ and $\sigma_{tz}(s)$ are very small at the HERA collider with $\sqrt{s} = 320 GeV$. However, in most of the parameter space, $\sigma_{t\gamma}(s)$ or $\sigma_{tz}(s)$ is in the range of about $0.1 pb \sim 1 pb$ at the THERA collider with $\sqrt{s} = 1000 GeV$.
Single top quark production is very sensitive to the anomalous top quark couplings \( tqv \), in which \( q \) represents the up quark or charm quark and \( v \) represents the gauge bosons \( z, \gamma \), or \( g \)[1]. This type of couplings can be generated in supersymmetry, top-color scenario, and other specific models beyond the standard model (SM). Thus, studying the contributions of the \( tqv \) couplings to single top production is of interest. This fact has led to many studies involving single top production via the \( tqv \) couplings in lepton colliders[2,3] and hadron colliders[4,5].

The HERA collider and the HERA collider[6] with the center-of-mass energy \( \sqrt{s} = 320 GeV \) and \( 1000 GeV \), respectively, are the experimental facilities where high energy electron-proton and positron-proton interactions can be studied. It is well known that, in the SM, single top quark can not be produced at an observable rate in these high energy colliders. However, it has been shown that the HERA collider and the HERA collider can provide a very good sensitivity on the \( tqv \) couplings via single top production[7]. This type of single top production may be detected in these colliders[5,8]. The HERA and HERA colliders are powerful tools for searching for the anomalous top quark couplings \( tqv \).

The presence of the top-pions \( \pi_{t}^{0,\pm} \) in low-energy spectrum is an inevitable feature of top-color scenario[9]. These new particles have large Yukawa couplings to the third family quarks and can induce the tree-level flavor changing (FC) couplings, which have significant contributions to the anomalous top quark couplings \( tqv \)[10]. In Ref.[5] we study the contributions of the \( tqv \) couplings generated by \( \pi_{t}^{0} \) exchange to single top production via the t-channel process \( eq \rightarrow et \) at the HERA and HERA colliders. We have shown that it can generate significant effects on the process \( ec \rightarrow et \), which may be observable in the HERA collider. The aim of this Letter is to consider the contributions of the \( tcv \) couplings given by \( \pi_{t}^{0} \) exchange to the processes \( ep \rightarrow \gamma c \rightarrow t\gamma \) and \( ep \rightarrow \gamma c \rightarrow tz \) in the context of topcolor-assisted technicolor (TC2) models[11], and see whether the effects of the neutral top-pion \( \pi_{t}^{0} \) on \( t\gamma \) and \( tz \) production can be detected in the HERA collider or the HERA collider.

For TC2 models[9,11], the underlying interactions, topcolor interactions, are assumed
to be chiral critically strong at the scale about 1 TeV and coupled preferentially to the third generation, and therefore do not posses GIM mechanism. The non-universal gauge interactions result in the tree-level FC coupling vertices when one writes the interactions in the mass eigen-basis, which can induce the anomalous top quark couplings $tuv$ and $tcv$. However, the $tuv$ couplings can be neglected because the FC scalar coupling $\pi^0_t tu$ is very small [12]. The effective forms of the $tc\gamma$ and $tcz$ coupling vertices $\Lambda_{tc\gamma}, \Lambda_{tcz}$ have been given in Eq.[4] and Eq.[5] of Ref.[10].

Figure 1: Feynman diagrams for $t\gamma(z)$ production contributed by the anomalous top coupling vertices $\Lambda_{tc\gamma}(\Lambda_{tcz})$.

From the above discussion, we can see that the neutral top-pion $\pi^0_t$ can generate contributions to the subprocesses $\gamma c \rightarrow t\gamma$ and $\gamma c \rightarrow tz$ via the anomalous top quark couplings $tc\gamma$ and $tcz$ generated by the $\pi^0_t t\bar{c}$ coupling. The relevant Feynman diagrams are shown in Fig.1.

For the subprocesses $c(p_c) + \gamma(p_{\gamma}) \rightarrow t(p_t) + \gamma(p'_{\gamma})$ and $c(p_c) + \gamma(p_{\gamma}) \rightarrow t(p'_{t}) + z(p_z)$, we define the kinematical invariants $\hat{s} = (p_t + p'_{\gamma})^2 = (p'_{t} + p_z)^2, t = (p_{\gamma} - p_t)^2$, and
The parton distribution function $f_{t'}(p_{t} - p'_{t})^2$. The renormalized amplitudes for these processes can be written as:

$$M^{t\gamma} = M_{s}^{t\gamma} + M_{t}^{t\gamma} = u_{t}A_{t\gamma}^{\mu}i\varepsilon_{\mu} \frac{i[\gamma \cdot (p_{t} + p'_{t}) + m_{c}]}{s - m_{c}^{2} + i\mu} i\varepsilon^{\nu}(\frac{2}{3}i\varepsilon_{\mu})u_{c}$$

$$+ \bar{u}_{t}(\frac{2}{3}i\varepsilon_{\mu})i\varepsilon_{\mu} \frac{i[\gamma \cdot (p_{t} + p'_{t}) + m_{c}]}{s - m_{t}^{2} + im_{t}\Gamma_{t}} i\varepsilon^{\nu}(\frac{2}{3}i\varepsilon_{\mu})u_{c}$$

$$+ \bar{u}_{t}\Lambda_{t\gamma,\mu}^{\mu} i\varepsilon_{\mu} \frac{i[\gamma \cdot (p_{t} - p_{t}) + m_{c}]}{t - m_{c}^{2} + i\mu} i\varepsilon^{\nu}(\frac{2}{3}i\varepsilon_{\mu})u_{c}$$

$$+ \bar{u}_{t}(\frac{2}{3}i\varepsilon_{\mu})i\varepsilon_{\mu} \frac{i[\gamma \cdot (p_{t} - p_{t}) + m_{c}]}{t - m_{c}^{2} + im_{t}\Gamma_{t}} i\varepsilon^{\nu}(\frac{2}{3}i\varepsilon_{\mu})u_{c},$$

(1)

$$M^{tz} = M_{s}^{tz} + M_{t}^{tz} = u_{t}A_{t\mu}^{\mu}i\varepsilon_{\mu} \frac{i[\gamma \cdot (p'_{t} + p_{z}) + m_{c}]}{s - m_{z}^{2} + i\mu} i\varepsilon^{\nu}(\frac{2}{3}i\varepsilon_{\mu})u_{c}$$

$$+ \bar{u}_{t}\Lambda_{tz,\mu}^{\mu} i\varepsilon_{\mu} \frac{i[\gamma \cdot (p_{z} - p'_{t}) + m_{c}]}{s - m_{t}^{2} + im_{t}\Gamma_{t}} i\varepsilon^{\nu}(\frac{2}{3}i\varepsilon_{\mu})u_{c}$$

$$+ \bar{u}_{t}\Lambda_{tz,\mu}^{\mu} i\varepsilon_{\mu} \frac{i[\gamma \cdot (p_{z} - p'_{t}) + m_{c}]}{t - m_{c}^{2} + i\mu} i\varepsilon^{\nu}(\frac{2}{3}i\varepsilon_{\mu})u_{c}$$

$$+ \bar{u}_{t}(\frac{2}{3}i\varepsilon_{\mu})i\varepsilon_{\mu} \frac{i[\gamma \cdot (p_{z} - p'_{t}) + m_{c}]}{t - m_{c}^{2} + im_{t}\Gamma_{t}} i\varepsilon^{\nu}(\frac{2}{3}i\varepsilon_{\mu})u_{c},$$

(2)

with

$$\Lambda_{zzt}^{\mu} = \Lambda_{ztz}^{\mu} = \frac{e}{s_{W}c_{W}}[(\frac{1}{2} - \frac{2}{3}s_{W})\gamma^{\mu}(1 - \gamma_{5})\frac{1 - 2}{2} - \frac{2}{3}s_{W}\gamma^{\mu}(1 + \gamma_{5})\frac{1 + 2}{2}].$$

Where $\mu$ is a real parameter, which is introduced to make the integral convergent. $\Gamma_{t}$ is the total decay width of the top quark.

After calculating the cross section $\sigma_{i}(\tilde{s})$ of the subprocesses $\gamma c \rightarrow t\gamma$ or $\gamma c \rightarrow tz$, the total cross section $\sigma_{i}(s)$ of $t\gamma$ production or $tz$ production can be obtained by folding $\sigma_{i}(\tilde{s})$ with the charm quark distribution $f_{c/p}(x)$ in proton and the backscattered high energy photon spectrum $f_{\gamma/e}(\frac{1}{x})$:

$$\sigma_{i}(s) = \int_{\tau_{min}}^{0.83} d\tau \int_{\tau/0.83}^{1} \frac{dx}{x} f_{\gamma/e}(\frac{\tau}{x}) f_{c/p}(x) \sigma_{i}(\tilde{s})$$

with $\tilde{s} = \tau s$, $\tau_{min} = \frac{m_{t}^{2} + m_{s}^{2}}{s}$ and $f_{\gamma/e}(x)$ can be written as [13]:

$$f_{\gamma/e}(x) = \frac{1}{1.84}[1 - x + \frac{1}{1 - x}(1 - \frac{4x}{x_{0}(1 - x)}))] \quad (x_{0} = 4.83).$$

The parton distribution function $f_{c/p}(x)$ of the charm quark runs with the energy scale. In our calculation, we will take the CTEQ5 parton distribution function for $f_{c/p}(x)[14]$. 

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Figure 2: The cross section $\sigma_{t\gamma}(s)$ as a function of the top-pion mass $m_{\pi_t}$ for three values of the parameter $\varepsilon$ at the HERA collider.

Figure 3: Same as Fig.2 but for the cross section $\sigma_{t\bar{z}}(s)$

To obtain numerical results, we take the fine structure constant $\alpha_e = \frac{1}{128.8}$, $m_t = 175 GeV$, $m_c = 1.2 GeV$, $m_z = 91.2 GeV$, and assume that the total decay width $\Gamma_t$ of the top quark is dominated by the decay channel $t \rightarrow w\bar{b}$, which has been taken
\( \Gamma(t \rightarrow wb) = 1.56 \text{GeV} \) [15]. The limits on the mass \( m_{\pi_t} \) of the top-pion \( \pi_t^0 \) may be obtained via studying it’s effects on observables [9]. It has been shown that \( m_{\pi_t} \) is allowed to be in the range of a few hundred \( \text{GeV} \) depending on the models. For \( TC^2 \) models, top-color interactions make small contributions to electroweak symmetry breaking and give rise to the main part of the top quark mass, \((1-\varepsilon)m_t\), with the parameter \( \varepsilon \ll 1 \). As numerical estimation, we will take \( m_{\pi_t} \) and \( \varepsilon \) as free parameters.

![Figure 4: The cross section \( \sigma_{t\gamma}(s) \) as a function of \( m_{\pi_t} \) for three values of the parameter \( \varepsilon \) at the THERA collider.](image)

Figure 4: The cross section \( \sigma_{t\gamma}(s) \) as a function of \( m_{\pi_t} \) for three values of the parameter \( \varepsilon \) at the THERA collider.

Our numerical results are summarized in Fig.2-Fig.5. From these figures, we can see that the cross sections \( \sigma_{t\gamma}(s) \) and \( \sigma_{tz}(s) \) of \( t\gamma \) and \( tz \) production at the \( HERA \) and \( THERA \) colliders increase as the parameter \( \varepsilon \) increases and \( m_{\pi_t} \) decreases. In all of the parameter space, we have that the cross section \( \sigma_{t\gamma}(s) \) of the process \( ep \rightarrow \gamma c \rightarrow t\gamma \) is larger than the cross section \( \sigma_{tz}(s) \) of the process \( ep \rightarrow \gamma c \rightarrow tz \). For \( \varepsilon \leq 0.08 \) and \( m_{\pi_t} \geq 200\text{GeV} \), \( \sigma_{t\gamma}(s) \) and \( \sigma_{tz}(s) \) at the \( HERA \) collider are smaller than 0.14pb and 0.066pb, respectively. However, at the \( THERA \) collider with \( \sqrt{s} = 1000\text{GeV} \), \( \sigma_{t\gamma}(s) \) and \( \sigma_{tz}(s) \) are in the ranges of 0.14pb \( \sim \) 1.37pb and 0.13pb \( \sim \) 1.35pb, respectively, for \( 0.02 \leq \varepsilon \leq 0.08 \) and \( 200\text{GeV} \leq m_{\pi_t} \leq 400\text{GeV} \).
If we assume that the HERA collider with $\sqrt{s} = 320$GeV has a yearly integrated luminosity of $\mathcal{L} = 160pb^{-1}$ and the THERA collider with $\sqrt{s} = 1000$GeV has a yearly integrated luminosity of $\mathcal{L} = 470pb^{-1}[6]$, then the yearly production events of $t\gamma$ and $tz$ can be easily estimated. In most of the parameter space of TC2 models, there may be only about 10 or less of $t\gamma$ events or $tz$ events generated a year in the HERA collider, which is very difficult to detect. However, there may be hundreds of $t\gamma$ events or $tz$ events to be generated a year in the THERA collider. For example, for $m_{\pi^0_t} = 300$GeV and $\varepsilon = 0.05$, the THERA collider can generate 252 $t\gamma$ events and 240 $tz$ events. Thus, the effects of the neutral top-pion $\pi^0_t$ on $t\gamma$ production and $tz$ production may be detected at the THERA collider.

![Graph](image)

Figure 5: Same as Fig.4 but for the cross section $\sigma_{tz}(s)$.

In conclusion, TC2 models predict the existence of the neutral top-pion $\pi^0_t$, which can induce the anomalous top quark couplings $tc\gamma$ and $tcz$ and further contribute to single top quark production. In this letter, we calculated the contributions of $\pi^0_t$ to $t\gamma$ production and $tz$ production via the processes $ep \rightarrow \gamma c \rightarrow t\gamma$ and $ep \rightarrow \gamma c \rightarrow tz$ at the HERA and THERA colliders. We find that the cross sections of $t\gamma$ and $tz$ production are very small.
at the HERA collider. The effects of the neutral top-pion $\pi_t^0$ on $t\gamma$ and $tz$ production can not be observed at the HERA collider. However, $\pi_t^0$ exchange can generate several hundred $t\gamma$ or $tz$ events at the THERA collider.

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