Pair production of charged top-pions in the $\gamma\gamma$ collisions at the ILC

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Abstract

The top-color assisted technicolor (TC2) mode predicts the existence of a pair of charged top-pions $\pi_t^\pm$. In this paper, we study the production of the charged top-pions pair $\pi_t^\pm$ at next generation $\gamma\gamma$ colliders. The results show that the production rates can reach the level of $10^2$ fb with reasonable parameter space. With a large number of events and the clean background, the charged top-pion should be observable at the $\gamma\gamma$ colliders. Therefore, our studies can help us to search for charged top-pion, and furthermore, to test the TC2 model.

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I. INTRODUCTION

It is widely believed that the hadron colliders, such as Tevatron and LHC, can directly probe possible new physics beyond the standard model (SM) up to a few TeV, while the International Linear Collider (ILC) can produce new physics signal events more easily resolved from backgrounds [1]. An $e^+e^-$ ILC can also be designed to operate as a $\gamma\gamma$ collider. This is achieved by using Compton backscattered photons in the scattering of intense laser photons on the initial $e^+e^-$ beams. In this case, the energy and luminosity of the photon beam would be the same order of magnitude of the parent electron beam and the set of final states are much richer than that in the $e^+e^-$ mode. Therefore, the $\gamma\gamma$ collider will provide us a good chance to pursue new physics particles.

As a possible solution to avoid the shortcomings of the triviality and unnaturalness arising from the elementary Higgs field, the technicolor theory was proposed and so far remains a popular candidate for new physics beyond SM [2]. Among the various TC models, the topcolor-assisted technicolor (TC2) model is a more realistic one [3, 4], which is consistent with the current experiment. In the TC2 model, the topcolor interaction makes small contribution to the electroweak symmetry breaking (EWSB), and gives rise to the main part of the top quark mass $(1-\varepsilon)m_t$ with a model dependant parameter $0.03 \leq \varepsilon \leq 0.1$ [4]. One of the most general predictions of the TC2 model is the existence of three Pseudo-Goldstone bosons, so called top-pions ($\pi^\pm_t, \pi^0_t$) and an isospin singlet boson called top-higgs ($h^0_t$), which masses are in the range of hundreds of GeV. Thus, studying the possible signatures of these typical particles in the high energy experiments would provide crucial information for EWSB and fermion flavor physics. Furthermore, the discovery of these new particles can be regarded as direct evidence to test the TC2 model. The TC2 model is expected to give new significant signatures in future high energy colliders and studied in references [5–7], due to the new particles which are predicted by this model.

Because the SM predicts the existence of one neutral Higgs boson, so any observation of charged Higgs particles will mean the signal of a new physics. Therefore, probing of charged top-pions is more important to test the TC2 model. At the high-energy $e^+e^-$ linear colliders, the main signal charged top-pion production processes are $e^+e^-(\gamma\gamma) \rightarrow b\bar{c}\pi^+_t$, $e^+e^-(\gamma\gamma) \rightarrow t\bar{b}\pi^-_t$, and $e^+e^- \rightarrow W^+_tt\pi^-_t$, which have been systematically studied in ref. [8].
So far, the reaction $e^+e^- \rightarrow hh$ have been studied in the SM [9], and the similar processes for the neutral or charged scalar have also been investigated via $e^+e^-$ or $\gamma\gamma$ model in the minimal supersymmetric standard model (MSSM) [10], the two-Higgs doublet model (2HDM) [11], the littlest Higgs (LH) model [12], as well as the left-right twin Higgs (LRTH) model [13, 14]. In the TC2 model the pair production of the charged scalar $e^+e^- \rightarrow \pi^+_t \pi^-_t$ has also been probed in Ref. [15]. Complementing Ref. [15], in this paper we will study the production of the pair charged top-pions via process $\gamma\gamma \rightarrow \pi^+_t \pi^-_t$ at $\gamma\gamma$ colliders within the TC2 model.

The remainder parts of this paper are organized as follows. In Sec II, we shall present the calculations of the production cross section of the process $\gamma\gamma \rightarrow \pi^+_t \pi^-_t$. Numerical results on the cross section and concluding remarks will appear in Sec. III.

II. CALCULATIONS OF PRODUCTION CROSS SECTION

The Feynman diagrams for the process $\gamma\gamma \rightarrow \pi^+_t \pi^-_t$ are given in Fig. 1. And the relevant Feynman rules for the couplings $A^\mu \pi^+_t \pi^-_t$ and $A'^\mu \pi^+_t \pi^-_t$ in the TC2 model can be found in Ref. [16].

With the relevant couplings, the invariant production amplitudes of the process $e^- (p_1)e^+ (p_2) \rightarrow \pi^+_t (p_3)\pi^-_t (p_4)$ can be written as follows:

$$M_a = \frac{i e^2}{(p_3 - p_1)^2 - m^2_\pi} (p_1 - 2p_3)\epsilon^\mu_\mu (p_1) (2p_4 - p_2)\epsilon^\nu_\nu (p_2)$$ (1)

$$M_b = \frac{i e^2}{(p_3 - p_2)^2 - m^2_\pi} (p_2 - 2p_3)\epsilon^\mu_\mu (p_2) (2p_4 - p_1)\epsilon^\nu_\nu (p_1)$$ (2)

$$M_c = 2ie^2g^\mu\nu\epsilon^\mu (p_1)\epsilon^\nu (p_2)$$ (3)

FIG. 1: Feynman diagrams of the processes $e^+e^- \rightarrow W^\pm \pi^\pm$ in the TC2 model.
Here, $\epsilon_\mu(p_1)$ and $\epsilon_\nu(p_2)$ are the polarization vector of the photon, $m_\pi$ denotes the mass of the charged top pions.

With the above amplitudes $M_a$, $M_b$ and $M_c$, we can directly obtain the production cross section $\hat{\sigma}(\hat{s})$ for the subprocess $\gamma \gamma \rightarrow \pi^+_t \pi^-_t$ and the total cross sections at the $e^+e^-$ linear collider can be obtained by folding $\hat{\sigma}(\hat{s})$ with the photon distribution function $F(x)$ which is given in Ref. [17],

$$\sigma_{tot}(s) = \int_{s_{\max}}^{E_0/\sqrt{s}} \frac{d\mathcal{L}_{\gamma\gamma}}{dz} \hat{\sigma}(\gamma \gamma \rightarrow \pi^+_t \pi^-_t, \text{at } \hat{s} = z^2s)$$

(4)

where $E_0 = 2m_\pi$, $s$ is the squared c. m. of $e^+e^-$ collision,

$$\frac{d\mathcal{L}_{\gamma\gamma}}{dz} = 2z \int_{z^2/x_{\max}}^{x_{\max}} \frac{dx}{x} F_{\gamma/e}(x) F_{\gamma/e}(\frac{z^2}{x}),$$

(5)

For the initial unpolarized electrons and laser photon beams, the energy spectrum of the backscattered photon is given by

$$F_{\gamma/e} = \frac{1}{D(\xi)} \left[ 1 - x + \frac{1}{1 - x} - \frac{4x}{\xi(1 - x)} + \frac{4x^2}{\xi^2(1 - x)^2} \right],$$

(6)

with

$$D(\xi) = \left( 1 - \frac{4}{\xi} - \frac{8}{\xi^2} \right) \ln(1 + \xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1 + \xi)^2},$$

(7)

The definitions of parameters $\xi$, $D(\xi)$ and $x_{\max}$ can be found in [17]. In our numerical calculation, we choose $\xi = 4.8$, $D(\xi) = 1.83$ and $x_{\max} = 0.83$.

### III. NUMERICAL RESULTS AND CONCLUSIONS

To get the numerical results of the cross section, we should also fix the parameter in the SM as $\alpha_e = 1/128.8$ [18]. In addition, the top-pions mass $m_\pi$ is also involved in the production amplitudes. The TC2 model loosely predicts top-pions to lie in the mass range of about 100 $-$ 300 GeV. Top-pions this light are disfavored by the data for $R_b$ [19], but the contribution of new ETC gauge bosons can help to relax the constraint on the top-pions mass [20]. In this work, we take $m_\pi$ as a free parameter and expand the mass range to 150 $-$ 350 GeV to estimate the total cross section of $\pi^+_t \pi^-_t$ associated production at the ILC.
FIG. 2: The production cross section of the processes $\gamma \gamma \rightarrow \pi^+_t \pi^-_t$ in the TC2 model as a function of $m_\pi$.

In Fig. 2, we plot the cross section $\sigma$ of the process $\gamma \gamma \rightarrow \pi^+_t \pi^-_t$ as a function of the mass parameter $m_\pi$ with the three values of the center of mass energy. The plot shows that the cross section $\sigma$ decreases with $m_\pi$ increasing, this is because the phase space is depressed strongly by large $m_\pi$. In general, the production rate is at the level of $10^1 \sim 10^2 \text{ fb}$ in a large part of the allowed parameter space. For $\sqrt{s} = 1000 \text{ GeV}$, $\sqrt{s} = 1500 \text{ GeV}$, and for $150 \text{ GeV} \leq M_\pi \leq 350 \text{ GeV}$, the value of $\sigma$ is in the range of $8.3 \sim 180.5 \text{ fb}$ and $27.5 \sim 163.7 \text{ fb}$, respectively. According to the ILC Reference Design Report [1], the ILC is determined to run with $\sqrt{s} = 500 \text{ GeV}$ (upgradeable to 1000 GeV) and the total luminosity required is $\mathcal{L} = 500 \text{ fb}^{-1}$ with the first four-year operation and $\mathcal{L} = 1000 \text{ fb}^{-1}$ during the first phase of operation with $\sqrt{s} = 500 \text{ GeV}$. If we assume the integrated luminosity $\mathcal{L} = 500 \text{ fb}^{-1}$, there will be up to several hundreds of $\pi^+_t \pi^-_t$ events to be generated per year at the ILC experiments.

To see the effect of the c.m. energy on the production cross section, in Fig. 3 we plot the cross section $\sigma$ as the function of $\sqrt{s}$ with $m_\pi = 150, 250$ and $350 \text{ GeV}$, respectively. Due to the contributions to the cross section come mainly from the t-channel and u-channel, thus the large $\sqrt{s}$ can enhance the cross section significantly and the values of the cross section can reach $180 \text{ fb}$ maximally in the reasonable parameter space.

Considering the subsequent main decay of $\pi^+_t \rightarrow t\bar{b}$ [21] and $t \rightarrow W^+b \rightarrow l^+\nu b$,
FIG. 3: The production cross section of the processes $\gamma\gamma \rightarrow \pi^+_t\pi^-_t$ in the TC2 model as a functions of $\sqrt{s}$.

The possible signal for $\pi^+_t\pi^-_t$ production at the ILC is four jets $b\bar{b}b\bar{b}$ + two leptons + missing energy $E_T$. The production rate of the $t\bar{t}b\bar{b}$ final state can be easily estimated $\sigma^s \approx \sigma \times [Br(\pi^+_t \rightarrow t\bar{b}) \times Br(\pi^-_t \rightarrow t\bar{b})]$. Using the value of the branching ratio $B_r(\pi^+_t \rightarrow t\bar{b})$ [21] which is affected by the model-dependent parameter $\varepsilon$, in Fig. 4, we show the numerical results for the production rate of the $t\bar{t}b\bar{b}$. From Fig. 4, one can see that the production rate can reach 50 fb with reasonable values of the free parameters of the TC2 model. The cross section of the irreducible $t\bar{t}b\bar{b}$ background for $\sqrt{s}=800$ GeV has been estimated in reference [13] and found to be 5.5 fb. Thus, it may be possible to extract the signals from the backgrounds in the reasonable parameter space of the TC2 model by considering kinematic distribution of the signal. Certainly, detailed confirmation of the observability of the signals generated by the process $\gamma\gamma \rightarrow \pi^+_t\pi^-_t$ would depend on Monte Carlo simulations of the signals and backgrounds, which is beyond the scope of this paper.

For the light charged top-pions, the branching ratio of $\pi^+_t \rightarrow c\bar{b}$ can be comparative to that of $\pi^+_t \rightarrow t\bar{b}$. In this case, $\pi^+_t \rightarrow c\bar{b}$ is also an important mode which induces the signals $c\bar{b}\bar{c}b$. Although $\pi^+_t \rightarrow c\bar{b}$ is a flavor-changing decay mode, $c\bar{b}\bar{c}b$ production is not the flavor-changing process. Therefore, the SM background can not be ignored. The major irreducible background should come from $e^+e^- \rightarrow ZZ \rightarrow c\bar{c}b\bar{b}$. The mistagging of
FIG. 4: The production rate of the $t\bar{t}b\bar{b}$ final state of the process $\gamma\gamma \rightarrow \pi^+_t \pi^-_t$ as a function of the parameter $m_\pi$ for $\sqrt{s} = 1000$ GeV with $\varepsilon = 0.03$, 0.06 and 0.1, respectively.

b-quark and s-quark will make the $e^+e^- \rightarrow W^+W^-$ become important which significantly enhances the background. So, the efficient b-tagging and mass reconstruction of the charged top-pion are very necessary to reduce the background.

In summary, in the TC2 model we evaluate the signal pair production of charged top-pions via process $\gamma\gamma \rightarrow \pi^+_t \pi^-_t$ at the ILC. It is found that TC2 model can make a significant contribution to this processes. For the process $\gamma\gamma \rightarrow \pi^+_t \pi^-_t$, can reach $10^2$ fb in optimal case. Considering the main decay mode of top-pions, we find that with such cross section, it is possible to detect the signal of the charged top-pions experimentally in the most of the parameter space at the future linear linear colliders operating in $\gamma\gamma$ model at the TeV energy scale. Even if we can not observe the signals in future ILC experiments, at least, we can obtain the bounds on the free parameters of the TC2 model.

IV. ACKNOWLEDGMENTS

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