Production of the neutral top-pion at the $e\gamma$ colliders

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In the framework of the top-color-assisted technicolor (TC2) model, we study a neutral top-pion production process $e^-\gamma\to e^-\Pi_t^0$ in this paper. Our results show that the production cross section of $e^-\gamma\to e^-\Pi_t^0$ can reach the level of several tens of femtobarns, and over 10^3 neutral top-pion events can be produced in the planned e^+e^- linear colliders each year. Therefore, such a top-pion production process provides us a unique chance to detect top-pion events and test the TC2 model. On the other hand, the cross section of $e^-\gamma\to e^-\Pi_t^0$ is about one order of magnitude larger than those of some similar processes in the standard model (SM) and the minimally supersymmetric standard model (MSSM) [i.e., $e^-\gamma\to e^-H$ in the SM and $e^-\gamma\to e^-H^0(A^0,h^0)$ in the MSSM]. So we can easily distinguish the neutral top-pion from other neutral Higgs bosons in the SM and MSSM.

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I. INTRODUCTION

Although the Glashow-Weinberg-Salam (GWS) theory, which is based on the gauge group $SU_L(2)\otimes U_Y(1)$, has achieved great success in describing the weak and electromagnetic interactions, the mechanism of electroweak symmetry breaking (EWSB) is still unknown. So probing the mechanism of EWSB will not only be one of the main subjects of theoretical research but will also be the most important task at future high energy colliders.

Dynamical EWSB, such as technicolor (TC) theory [1], is an attractive idea that avoids the shortcoming of triviality and unnaturalness arising from the elementary Higgs field in the standard model (SM). The simplest QCD-like TC models [2] lead to a large oblique correction to the electroweak parameter S [3] and is already ruled out by the CERN e^+e^- collider LEP precision electroweak measurement data [4,5]. Various improvements have been made to make the predictions consistent with the LEP precision measurement data. Among all these improved TC models, the top-color-assisted technicolor (TC2) model [6] is a more realistic one, which provides an additional source of EWSB and also solves the heavy top quark problem. In TC2 theory, the new strong dynamics top-color is assumed to be chirally critically strong at the scale 1 TeV, and it is coupled preferentially to the third generation. In this model, the EWSB is driven mainly by TC interactions and extended technicolor gives the contributions to all ordinary quark and lepton masses including a very small portion of the top quark masses $m_t'=\varepsilon m_t$ ($0.03\leqslant\varepsilon\leqslant 0.1$) [7]. The top-color interactions also make small contributions to the EWSB and give rise to the main part of the top mass $(1-\varepsilon)m_t$. Three pseudo Goldstone bosons (PGB's) called top-pions $\Pi_t^0,\Pi_t^\pm$ are predicted by the TC2 model in the few hundred GeV region. The physical particle top-pions can be regarded as a typical feature of the TC2 model. Thus, studies of some top-pion production processes at present and future high energy colliders can help in the experimental search for top-pions and test TC2 theory, and furthermore the probe of the EWSB mechanism. A comprehensive review of phenomenological studies in the TC2 model has been given in Ref. [8].

Over the last decade, several laboratories in the world have been working on linear e^+e^- collider projects with an energy from several hundreds of GeV up to several TeV and luminosity over 100 fb^{-1}/yr. These are the Next Linear Collider (NLC) (USA) [9], Japan Linear Collider (JLC) (Japan) [10], and the DESY TeV Energy Superconducting Linear Accelerator (TESLA) (Europe) [11]. The search for Higgs particle in the SM or some new particles predicted in models beyond the SM [such as Higgs bosons $A^0,H^0,h^0,H^\pm$ in minimal supersymmetric standard model (MSSM) and PGB's in the TC model] is one of the most important goals of future high energy e^+e^- colliders. Some Higgs boson production processes in the SM and MSSM in e^+e^- collision have been studied in many publications [12]. To search for top-pions in the TC2 model, the authors have studied the neutral top-pion production processes in high energy e^+e^- collisions [13,14]. Reference [13] calculated the production cross sections of the processes $e^+e^-\to\Pi_t^0\gamma,\Pi_t^0Z$ and the results show that the cross sections are about several femtobarns. Recently, we have studied a flavor-changing neutral top-pion production process $e^+e^-\to t\bar{c}\Pi_t^0$ [14]. We find that the resonance effect can enhance the cross section significantly when the top-pion mass is small. The above studies provide feasible ways to detect top-pion events and test the TC2 model. The future e^+e^- colliders can also operate in the $e\gamma$ or $\gamma\gamma$ mode. High energy photons for $\gamma\gamma,e\gamma$ collisions can be obtained using Compton backscattering of laser light off the high energy electrons. In this case, the energy and luminosity of the photon beam would be of the same order of magnitude as the parent electron beam and the set of final states at a photon collider is much richer than that in an e^+e^- mode. At the same time, the high energy photon polarizations can vary relatively easily, which is advantageous

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for experiments. All the virtues of the photon colliders will provide us with a good chance to pursue new physics particles. The production of Higgs bosons in the SM and MSSM at $e\gamma$ colliders has been studied in Ref. [15].

In this paper, in the framework of TC2, we will study the neutral top-pion production process $e^-\gamma \to e^-\Pi_t^0$. The results show that the cross section can be up to the level of several tens of femtobarns due to strong coupling of Π_t^0 to $t\bar{t}$ and the t-channel effect. The signals of the top-pion can easily be detected at $e\gamma$ colliders. On the other hand, we find that we can distinguish the top-pion from other top-pion-like particles (such as Higgs bosons in the SM and MSSM).

II. THE CROSS SECTION OF THE PROCESS

As is known, the couplings of top-pions to three family fermions are nonuniversal and the top-pions have large Yukawa couplings to the third generation. The coupling of the neutral top-pion Π_t^0 to a pair of top quarks is proportional to the mass of the top quark and the explicit form can be written as [16]

$$i\frac{m_t}{v_w}\tan\beta\, K_{UR}^{tt}K_{UL}^{tt*}\bar{t}\gamma_5 t\Pi_t^0 \tag{1}$$

where $\tan\beta=\sqrt{(v_\omega/v_t)^2-1}$. $v_\omega=246$ GeV is the electroweak symmetry-breaking scale, and $v_t\approx 60$–100 GeV is the top-pion decay constant. K_{UL}^{tt} is the matrix element of the unitary matrix K_{UL} from which the Cabibbo-Kobayashi-Maskawa (CKM) matrix can be derived as $V=K_{UL}^{-1}K_{DL}$ and K_{UR}^{ij} are the matrix elements of the right-handed rotation matrix K_{UR}. Their values can be taken as

$$K_{UL}^{tt*}\approx 1, \quad K_{UR}^{tt}=1-\varepsilon.$$

Here we take the parameter ε as a free parameter changing from 0.03 to 0.1.

With $\Pi_t^0 t\bar{t}$ coupling, the neutral top-pion Π_t^0, as an isospin triplet, can couple to a pair of gauge bosons through the top quark triangle loop in an isospin violating way. Calculating the top quark triangle loop, we can explicitly obtain the couplings of Π_t^0-γ-γ and Π_t^0-γ-Z:

Π_t^0-γ-γ:

$$iN_c\frac{8}{9\pi}\frac{\tan\beta}{v_w}m_t^2(1-\varepsilon)\alpha_e\varepsilon_{\mu\nu\rho\delta}p_2^\rho p_4^\delta C_0, \tag{2}$$

Π_t^0-γ-Z:

$$iN_c\frac{\alpha_e}{3\pi c_w s_w}\frac{\tan\beta}{v_w}m_t^2(1-\varepsilon)\varepsilon_{\mu\nu\rho\delta}\left(1-\frac{8}{3}s_w^2\right)p_2^\rho p_4^\delta C_0 \tag{3}$$

where N_c is the color index with $N_c=3$, $s_w=\sin\theta_w$, $c_w=\cos\theta_w$ (θ_w is the Weinberg angle), and $C_0=C_0(-p_2,p_4,m_t,m_t,m_t)$ is the standard three-point scalar integral with p_2 and p_4 denoting the momenta of the incoming photon and the outcoming top-pion, respectively.

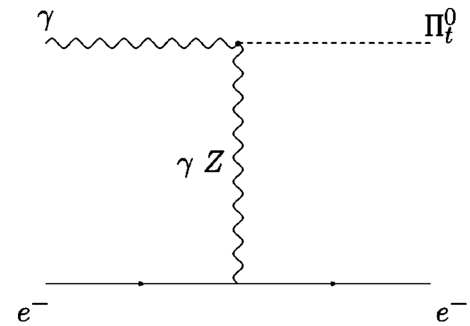

FIG. 1. The Feynman diagrams of the process $e^-\gamma\to e^-\Pi_t^0$.

With the couplings of $\Pi_t^0\gamma\gamma$ and $\Pi_t^0 Z\gamma$, the neutral top-pion can be produced via the process $e^-\gamma\to e^-\Pi_t^0$; the Feynman diagram of the process is shown in Fig. 1. The amplitude of the process can be written directly as

$$M=M^\gamma+M^Z, \tag{4}$$

$$M^\gamma=-iN_c\frac{16\sqrt{\pi}}{9\pi}\frac{\tan\beta}{v_w}m_t^2(1-\varepsilon)\alpha_e^{3/2}C_0\varepsilon^{\mu\nu\rho\delta} \times p_{2\rho}p_{4\delta}\epsilon_\mu(p_2)\bar{u}_e(p_3)\gamma_\nu u_e(p_1)G(p_2-p_4,0), \tag{5}$$

$$M^Z=iN_c\frac{2\alpha_e^{3/2}}{3\sqrt{\pi}c_w^2 s_w^2}\frac{\tan\beta}{v_w}(1-\varepsilon)m_t^2\left(1-\frac{8}{3}s_w^2\right) \times C_0\varepsilon^{\mu\nu\rho\delta}p_{2\rho}p_{4\delta}\epsilon_\mu(p_2)\bar{u}_e(p_3) \times\left[-\frac{1}{2}L+s_w^2\right]\gamma_\nu u_e(p_1)G(p_2-p_4,M_Z), \tag{6}$$

where $L=\frac{1}{2}(1-\gamma_5)$ and $G(p,m)=1/(p^2-m^2)$ denotes the propagator of the particle. We can see that there exists a t-channel resonance effect for the photon; this t-channel resonance effect will enhance the cross section significantly.

The hard photon beam of the $e\gamma$ collider can be obtained from laser backscattering at the e^+e^- linear collider. Let $\hat{s}$ and s be the center-of-mass energies of the $e\gamma$ and e^+e^- systems, respectively. After calculating the cross section $\sigma(\hat{s})$ for the subprocess $e^-\gamma\to e^-\Pi_t^0$, the total cross section at the e^+e^- linear collider can be obtained by folding $\sigma(\hat{s})$ with the photon distribution function that is given in Ref. [17]:

$$\sigma_{tot}=\int_{M_\Pi^2/s}^{x_{max}}dx\,\hat{\sigma}(\hat{s})f_\gamma(x),$$

where

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

with

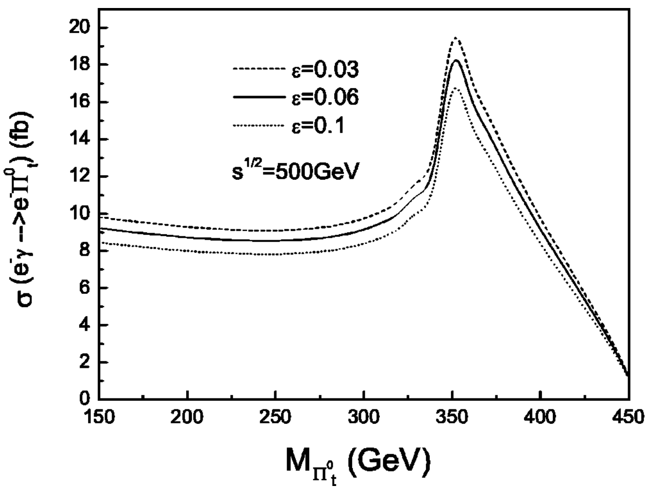

FIG. 2. The cross section of $e^-\gamma \rightarrow e^-\Pi_t^0$ versus top-pion mass M_Π (150–450 GeV) for $\sqrt{s}=500$ GeV and $\varepsilon=0.03$ (dashed line), $\varepsilon=0.06$ (solid line), and $\varepsilon=0.1$ (dotted line), respectively.

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

In the above equation, $\xi=4E_e\omega_0/m_e^2$ in which m_e and E_e stand, respectively, for the incident electron mass and energy, ω_0 stands for the laser photon energy, and $x=\omega/E_e$ stands for the fraction of energy of the incident electron carried by the backscattered photon. f_γ vanishes for $x>x_{max}=\omega_{max}/E_e=\xi/(1+\xi)$. In order to avoid the creation of e^+e^- pairs by the interaction of the incident and backscattered photons, we require $\omega_0 x_{max}\leqslant m_e^2/E_e$, which implies that $\xi\leqslant 2+2\sqrt{2}\approx 4.8$. For the choice of $\xi=4.8$, we obtain

$$x_{max}\approx 0.83, \quad D(\xi)\approx 1.8.$$

For simplicity, we have ignored the possible polarization for the electron and photon beams.

III. THE NUMERICAL RESULTS AND CONCLUSIONS

To obtain numerical results, we take $m_t=174$ GeV, $M_Z=91.187$ GeV, $v_t=60$ GeV, and $s_w^2=0.23$. The electromagnetic fine structure constant α_e at a certain energy scale is calculated from the simple QED one-loop evolution formula with the boundary value $\alpha_e=1/137.04$ [18,19]. There are three free parameters in the cross section, i.e., ε, M_Π, s. To see the influence of these parameters on the cross section, we take the mass of the top-pion M_Π to vary in a certain range 150 GeV$\leqslant M_\Pi \leqslant$450 GeV for $\varepsilon=0.03,0.06,0.1$. Considering the center-of-mass energies $\sqrt{s}$ in planned e^+e^- linear colliders (for example, TESLA), we take $\sqrt{s}=500$ GeV, 800 GeV, and 1600 GeV, respectively. The final numerical results of the cross section are summarized in Figs. 2–4. These figures are plots of the cross section as a function of M_Π for $\sqrt{s}=500$ GeV, 800 GeV, and 1600 GeV, respectively. We can see that there is a peak in the plot when M_Π is about 350 GeV, which arises from the top quark triangle loop. We can see that the cross section is in the range of a few tens of femtobarns. With a luminosity of 100 fb^{-1}/yr, there are over 10^3 events in which the neutral top-pion can be produced via the process $e^-\gamma\rightarrow e^-\Pi_t^0$ per year. This number of events can easily be detected experimentally. As studied in Refs. [13,14], the cross sections of the neutral top-pion in e^+e^- collision are only at the level of a few femtobarns. The t-channel resonance effect can enhance the cross section of the process $e^-\gamma\rightarrow e^-\Pi_t^0$ significantly; this makes the process $e^-\gamma\rightarrow e^-\Pi_t^0$ potentially important for detecting the top-pion. Some Higgs boson production processes in $e\gamma$ collision have been studied in the SM and MSSM [$e^-\gamma\rightarrow e^-H^0$ in the SM and $e^-\gamma\rightarrow e^-H^0(h^0,A^0)$ in the MSSM] [15]; the results show that the cross sections are at the level of a few femtobarns, i.e., the cross section of $e^-\gamma\rightarrow e^-\Pi_t^0$ is about one order of magnitude larger than those of some similar processes in the SM and MSSM. The reason is that there is a large extra coefficient $\tan\beta$ in the coupling $\Pi_t^0 t\bar{t}$ compared with the coupling $Ht\bar{t}$ in the SM (MSSM) and $\tan\beta$ can enhance the cross section by about one order of magnitude. With such a large cross section of $e^-\gamma\rightarrow e^-\Pi_t^0$, we

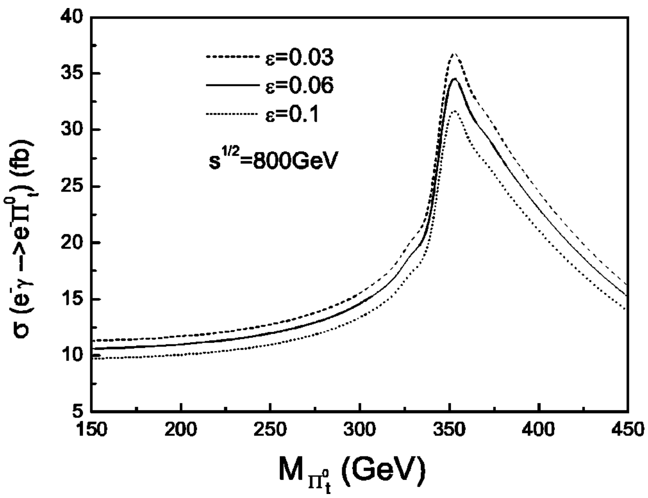

FIG. 3. The same plots as Fig. 2 for $\sqrt{s}=800$ GeV.

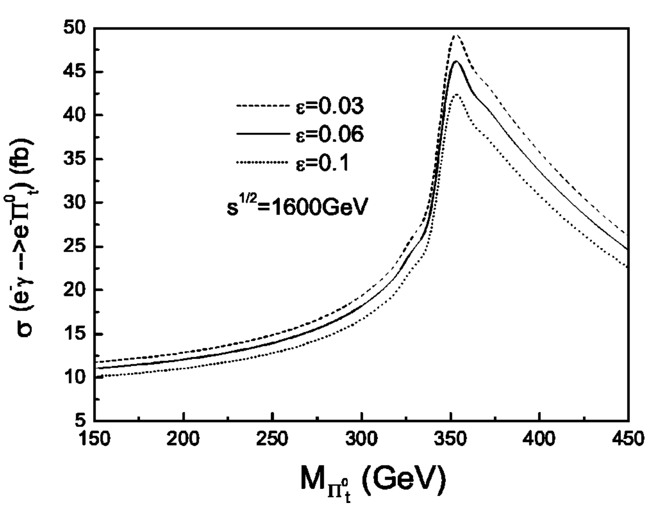

FIG. 4. The same plots as Fig. 2 for $\sqrt{s}=1600$ GeV.

TABLE I. The cross sections of $e^-\gamma\to e^- t\bar{t}$, $e^-\gamma\to e^- t\bar{c}$, $e^-\gamma\to e^- b\bar{b}$ in the SM.

$\sqrt{s}$ (GeV)	$\sigma(e^-\gamma\to e^- t\bar{t})$ (pb)	$\sigma(e^-\gamma\to e^- t\bar{c})$ (pb)	$\sigma(e^-\gamma\to e^- b\bar{b})$ (pb)
500	1.0×10^{-2}	5.5×10^{-12}	10.5
800	2.7×10^{-2}	7.2×10^{-12}	10.9
1600	4.2×10^{-2}	8.6×10^{-12}	11.5

can easily distinguish the neutral top-pion in TC2 from Higgs bosons in the SM and MSSM. This is another important feature of the process $e^-\gamma\to e^-\Pi_t^0$.

To determine which channel is the best one to search for the neutral top-pion, we need to know the decay branching ratio of each decay mode. The possible decay modes are $t\bar{t}$ (if $\Pi_t^0>2m_t$), $t\bar{c}$, $b\bar{b}$, gg, $\gamma\gamma$, and $Z\gamma$. For $\Pi_t^0>2m_t$, the main decay mode is $\Pi_t^0\to t\bar{t}$. The decay branching ratio $\mathrm{Br}(\Pi_t^0\to t\bar{c})$ is the largest one when the $t\bar{t}$ channel is forbidden. Using FORMCALC [20], we can directly obtain the cross section of the processes $e^-\gamma\to e^- t\bar{t}, e^-\gamma\to e^- t\bar{c}, e^-\gamma\to e^- b\bar{b}$ in the SM; the results are shown in Table I.

We can see that, in the SM, the cross section of $e^-\gamma\to e^- t\bar{c}$ is very small because there is no tree level flavor-changing neutral current in the SM. Therefore, $e^-\gamma\to e^-\Pi_t^0\to e^- t\bar{c}$ is the ideal channel to detect the neutral top-pion. The decay branching ratio of $\Pi_t^0\to t\bar{c}$ and the signal per year in the $t\bar{c}$ channel are shown in Table II.

We can conclude that there are a few hundred signals of neutral top-pion production in the $t\bar{c}$ channel. With such large numbers of signals and very clean background in the SM for this $t\bar{c}$ channel (as it is shown in Table II that the cross section of $e^-\gamma\to e^- t\bar{c}$ in the SM is only about 10^{-12} pb), the neutral top-pion can easily be detected via the $t\bar{c}$ channel in $e\gamma$ collision.

TABLE II. The decay branching ratio of $\Pi_t^0\to t\bar{c}$ and the signal per year in the $t\bar{c}$ channel. We take $\varepsilon=0.06$ and the luminosity $L=100\ \mathrm{fb}^{-1}/\mathrm{yr}$.

M_Π (GeV)		160			400	
$\mathrm{Br}(\Pi_t^0\to t\bar{c})$		0.66			0.08	
$\sqrt{s}$ (GeV)	500	800	1600	500	800	1600
Signal/year in tc channel	600	704	741	73	184	269

In conclusion, we have studied the neutral top-pion production process $e^-\gamma\to e^-\Pi_t^0$ in the TC2 model. The numerical results show that the cross section is very large (at the level of several tens of femtobarns), and over 10^3 neutral top-pion events can be produced in $e\gamma$ collision. With the large $\mathrm{Br}(\Pi_t^0\to t\bar{c})$ and small cross section of $e^-\gamma\to e^- t\bar{c}$ in the SM, $e^-\gamma\to e^-\Pi_t^0\to e^- t\bar{c}$ provides us with the best channel to search for the neutral top-pion. On the other hand, the cross section of $e^-\gamma\to e^-\Pi_t^0$ is about one order of magnitude larger than those of the production processes of top-pion-like particles in the SM and MSSM. Therefore, the process $e^-\gamma\to e^-\Pi_t^0$ provides us a unique way to distinguish the TC2 model from other models.

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