Signatures of the neutral top-pion in $e\gamma$ collisions

Chongxing Yue$^{(a,b)}$, Hong Li$^b$, Xuelei Wang $^{(a,b)}$

a: CCAST (World Laboratory) P.O. BOX 8730. B.J. 100080 P.R. China

b: College of Physics and Information Engineering,
Henan Normal University, Xinxiang 453002. P.R. China

Abstract

We calculate the contributions of the neutral top-pion $\pi^0_t$ to the process $e^-\gamma \rightarrow e^-7c$ in the framework of topcolor-assisted technicolor(TC2) models and discuss the possible of detecting $\pi^0_t$ at the high energy linear $e^+e^-$ collider(LC). Our results show that $\pi^0_t$ can give significant contributions to this process. With reasonable values of the parameters in TC2 models, the cross section $\sigma$ can reach 0.19 fb which may be detected at the $e\gamma$ collisions based on the future LC experiments.

---

$^\star$This work is supported by the National Natural Science Foundation of China(19905004), the Excellent Youth Foundation of Henan Scientific Committee(9911), and Foundation of Henan Educational Committee.

$^\dagger$E-mail:cxyue@public.xxptt.ha.cn
The mechanism of electroweak symmetry breaking (EWSB) remains the most prominent mystery in elementary particle physics. Probing EWSB will be one of the most important tasks in the future high energy colliders. Dynamical EWSB, such as technicolor (TC) theory, is an attractive idea that it avoids the shortcomings of triviality and unnaturalness arising from the elementary Higgs field. The simplest QCD-like TC model leads a too large oblique correction to the electroweak parameters $S$ and $U$ and is already ruled out by the CERN $e^+e^-$ collider LEP precision electroweak measurement data. To solve the phenomenological difficulties of TC theories, TC2 models were proposed by combining TC interactions with topcolor interactions for the third generation at the energy scale of about 1 TeV. TC2 theory is an attractive scheme in which there is an explicit dynamical mechanism for breaking electroweak symmetry and generating the fermion masses including the heavy top quark mass. It is one of the important promising candidates for the mechanism of EWSB.

In TC2 theory, EWSB is driven mainly by TC interactions, the extended technicolor (ETC) interactions give contributions to all ordinary quark and lepton masses including a very small portion of the top quark mass, namely $m'_t = \varepsilon m_t$ with a model-dependent parameter $\varepsilon (\varepsilon \ll 1)$. The topcolor interactions also make small contributions to EWSB and give rise to the main part of the top quark mass $m_t - m'_t = (1 - \varepsilon) m_t$ similar to the constituent masses of the light quarks in QCD. This means that the associated top-pions $\pi^0_t, \pi^\pm_t$ are not the longitudinal bosons W and Z, but separately, physically observable objects. Thus top-pions can be seen as the characteristic feature of TC2 theory. Studying the possible signatures of top-pions at future high energy colliders can be used to test TC2 theory and further probe the EWSB mechanism.

The virtual effects of the top-pions on the processes such as $q\bar{q} \rightarrow t\bar{t}$, $qq' \rightarrow tb$, $gg \rightarrow t\bar{t}(hc)$, $e^+e^- \rightarrow tc\gamma(Z)$, $\gamma \gamma \rightarrow t\bar{t}(hc)$, $t \rightarrow cv (v = \gamma, g, or Z)$, and $e\gamma \rightarrow t\bar{b}\nu_e$ have been studied in the literature, where the signatures and observability of these new particles were investigated in hadron colliders, $e^+e^-$ colliders, $\gamma\gamma$ colliders and $e\gamma$ colliders. Ref. has discussed the prospects of the observation of the charged top-pions $\pi^\pm_t$ via the process $e\gamma \rightarrow t\bar{b}\nu_e$ in $e\gamma$ colliders. In this note, we calculate the contributions of
the neutral top-pion $\pi_t^0$ to the flavor changing neutral current (FCNC) process $e^-\gamma \rightarrow e^-\bar{t}c$ and see whether $\pi_t^0$ can be detected via this process at high-energy linear $e^+e^-$ colliders (LC) experiments. We find that this process is important in probing the neutral top-pion. With reasonable values of the parameters in TC2 models, the signal rates can be fairly large, which may be detected at the $e\gamma$ colliders based on the LC experiments.

For TC2 models [4], the underlying interactions, topcolor interactions, are non-universal and therefore do not possess a GIM mechanism. This is an essential feature of this kind of models due to the need to single out the top quark for condensation. This non-universal gauge interactions result in the FC coupling vertices when one writes the interactions in the quark mass eigenbasis. Thus the top-pions predicted by this kind of models have large Yukawa couplings to the third generation and can induce the FC scalar couplings. The couplings of the neutral top-pion $\pi_t^0$ to the ordinary fermions can be written as [4, 5]:

$$\frac{m_t}{\sqrt{2}F_t}\frac{\nu_W^2 - F_t^2}{\nu_W} [k_{UR}^j k_{UL}^{*j} \bar{t}_L t_R \pi_t^0 + \frac{m_b - m_t}{m_t} b_L b_R \pi_t^0 + k_{UR}^{tc} k_{UL}^{*tc} \bar{c}_R c_R \pi_t^0 + h.c.],$$

(1)

where $F_t \approx 50$ GeV is the top-pion decay constant, $\nu_W = \nu/\sqrt{2} \approx 174$ GeV, and $m'_b$ is the ETC generated part of the bottom-quark mass. Similarly to Ref.[6], we take $m'_b = 0.1 \times \varepsilon m_t$. $k_{UL}^{tt}$ is the matrix element of the unitary matrix $k_{UL}$ which the 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 written as:

$$k_{UL}^{tt} = 1, \quad k_{UR}^{tt} = 1 - \varepsilon, \quad k_{UR}^{tc} \leq \sqrt{2\varepsilon - \varepsilon^2}. \quad (2)$$

In the following calculation, we will take $k_{UR}^{tc} = \sqrt{2\varepsilon - \varepsilon^2}$ and take the parameter $\varepsilon$ as a free parameter.

The neutral top-pion $\pi_t^0$, as an isospin-triplet, can couple to a pair of gauge bosons through the top quark triangle loop in an isospin violating way similar to the couplings of QCD pion $\pi^0$ to a pair of gauge bosons. For the top quark triangle loop, the simple ABJ anomaly approach is not sufficient since the top quark mass is only 175GeV. Here, we explicitly calculate the top loop and obtain the following $\pi_t^0 - \gamma - \gamma$ coupling:

$$- \frac{N_C \alpha_e(1 - \varepsilon)m^2}{3\sqrt{2}\pi F_t} C_0 \pi_t^0 \epsilon_{\mu\nu\lambda\rho} \partial^\mu A^\nu(\partial^\lambda A^\rho),$$

(3)
where $N_C$ is the color index with $N_C = 3$, $C_0 = C_0(p_4, -p_4 - p_3, m_t, m_t, m_t)$ is standard three-point scalar integral with $p_3$ and $p_4$ donating the momenta of the two incoming photons.

Ref.[4] has estimated the mass of the top-pion in the fermion loop approximation and given $180 \text{ GeV} \leq m_{\pi_t} \leq 250 \text{ GeV}$ for $m_t = 180 \text{ GeV}$ and $0.03 \leq \varepsilon \leq 0.1$. Since the negative top-pion corrections to the $Z \rightarrow b\bar{b}$ branching ratio $R_b$ become smaller when the top-pion is heavier, the LEP/SLD data of $R_b$ give rise to certain lower bound on the top-pion mass [10]. Ref.[11] has shown that the top-pion mass is allowed to be in the range of a few hundred GeV depending on the values of the parameters in TC2 models. Thus, at numerical estimation, we take the mass of the $\pi^0_t$ to vary in range of $200 \text{ GeV}-400 \text{ GeV}$ in this letter. In this case, the possible decay modes of $\pi^0_t$ are $\bar{t}c$, $b\bar{b}$, $gg$, $\gamma\gamma$, $Z\gamma$ and $tt$ (if kinematically allowed). Then we have

$$
\Gamma = \Gamma(\pi^0_t \rightarrow b\bar{b}) + \Gamma(\pi^0_t \rightarrow \bar{t}c) + \Gamma(\pi^0_t \rightarrow gg) + \Gamma(\pi^0_t \rightarrow \gamma\gamma) + \Gamma(\pi^0_t \rightarrow t\gamma) + \Gamma(\pi^0_t \rightarrow tt) \quad (\text{for } m_{\pi_t} \geq 350 \text{ GeV}).
$$

(4)

In above equation, we have ignored the coupling of $\pi^0_t$ to a pair of gauge bosons $Z$ and taken $S_{\pi^0_tZZ} \approx 0$.

The Feynman diagram for the neutral top-pion $\pi^0_t$ contributions to the process $e^-\gamma \rightarrow e^-\bar{t}c$ is shown in Fig 1. With Eqs. (1)-(4), we can do the explicit calculations of $\pi^0_t$ to the amplitude of the process $e^-\gamma \rightarrow e^-\bar{t}c$.

$$
M = \frac{N_c\alpha_e(1-\varepsilon)^2m_t^2}{6\pi F^2_t} \frac{\nu_W^2 - F^2_t}{\nu_W^2} \frac{k_{tR}C_0(u(p_e)\gamma_5v(p_t))}{p^2_\pi - m^2_\pi + im_\pi \Gamma (p_{e^-} - p_{e^-})^2}
$$

$$
\varepsilon_{\mu\nu\lambda\rho}(\partial^{\mu}\varepsilon^{\nu}_1)(\partial^{\lambda}\varepsilon^{\rho}_2)\varepsilon_\alpha(p_\gamma, \lambda)\bar{u}(p_{e^-})\gamma_\beta u(p_{e^-})
$$

(5)

The hard photon beam of the $e^-\gamma$ colliders can be obtained from laser backscattering at the LC [12]. We define that $\sqrt{\hat{s}}$ and $\sqrt{s}$ are the center-of-mass energies of the $e^-\gamma$ and $e^+e^-$ colliders, respectively. After calculating the cross section $\sigma(\hat{s})$ for the subprocess $e^-\gamma \rightarrow e^-\bar{t}c$, the total cross section $\sqrt{s}$ at the LC experiments can be obtained by folding $\sigma(\hat{s})$ with the backscattered laser photon spectrum $f_\gamma(x)(\hat{s} = x^2s)$

$$
\sigma = \int_{(m_t+m_c)/\sqrt{s}}^{x_{max}} dx \hat{\sigma}(\hat{s}) f_\gamma(x).
$$

(6)
The backscattered laser photon spectrum $f_{\gamma}(x)$ is given in Ref.[12]. Beyond a certain laser energy $e^+e^-$ pairs are produced, which significantly degrades the photon beam. This leads to a maximum $e\gamma$ centre of mass energy of $\sim 0.91 \times \sqrt{s}$.

In our calculation, we restrict the angles of the observed particles relative to the beam, $\theta_{e^-}$ and $\theta_e$ to the range $10^\circ \leq \theta_{e^-}, \theta_e \leq 170^\circ$. We further restrict the particle energy $E_e \geq 10$ GeV. For simplicity, we have ignored the possible polarization for the electron and photon beams. It has been shown [3] that the neutral top-pion $\pi_t^0$ mainly couples to the right-handed top ($t_R$) or charm ($c_R$) and the left-handed rotation element $k_{UL}^{t_R}$ is negligibly small. Thus, we only consider chiral couplings of the $\pi_t^0$ to top-charm. Our results are all based on right-handed couplings. To obtain numerical results, we take $m_t = 175$ GeV, $m_c = 1.2$ GeV and $\alpha_e = \frac{1}{128}$. For estimating the number of the $e^-\bar{t}c$ event, similarly to Ref.[9,14], we consider the $e^+e^-$ centre-of-mass energy $\sqrt{s}$ in the range of 300GeV-1500GeV appropriate to the TESLA/NLC/JLC high energy colliders and assume an integrated luminosity of $L = 500 fb^{-1}$.

In Fig2, we show the cross section $\sigma$ of the process $e^-\gamma \to e^-\bar{t}c$ as a function of the mass of the neutral top-pion $m_{\pi_t}$ for the center-of-mass energy $\sqrt{s} = 500$ GeV and three values of the parameter $\varepsilon$. One can see that neutral top-pion $\pi_t^0$ can give significant contributions to the process $e^-\gamma \to e^-\bar{t}c$. We see from Fig.2 that the cross section $\sigma$ is sensitive to the parameter $\varepsilon$. The $\pi_t^0$ resonance contribution increases as the parameter $\varepsilon$ increasing. This is because the total decay width of $\pi_t^0$ decreases as $\varepsilon$ increasing. The maximum value can reach 0.12fb for $\varepsilon = 0.08$ and $m_{\pi_t} = 270$GeV. Thus, there will be several tens of $e^-\bar{t}c$ events to be generated which may be detected in the future LC experiments.

To see the effect of the center-of-mass $\sqrt{s}$ on the $\sigma$, we plot the $\sqrt{s}$ for $m_{\pi_t} = 250$GeV and three values of the parameter $\varepsilon$ in Fig.3. We can see from Fig.3 that the cross section $\sigma$ is larger than $4 \times 10^{-2} fb$ for $\sqrt{s} \geq 500$GeV. For $m_{\pi_t} = 250$GeV and $0.03 \leq \varepsilon \leq 0.08$, the maximum value can reach 0.19fb. In this case, there are about 90 $\bar{t}c$ events to be generated in the future LC experiments.

TC2 models also predict the existence of the neutral CP-even state, called top-Higgs boson $h_t^0$. The main difference between $\pi_t^0$ and $h_t^0$ is that $h_t^0$ can couple to gauge boson
pairs $WW$ and $ZZ$ at tree-level, which is similar to that of the standard model (SM) Higgs boson $H^0[5]$. However, the coupling coefficients of the couplings $h^0_t WW$ and $h^0_t ZZ$ are suppressed by the factor $\frac{F_{t\nu}}{F_{tW}}$ with respect to that of $H^0$. Thus, the contributions of the top-Higgs boson $h^0_t$ to the process $e^-\gamma \to e^-\bar{t}c$ are similar to that of $\pi^0_t$. In the most of the parameter space of TC2 models, the cross section $\sigma$ contributed by the top-Higgs $h^0_t$ is also in the range of $10^{-1} - 10^{-2} fb$.

The search for FCNC processes is one of the most interesting possibilities to test the SM, with the potential for either discovering or putting stringent bounds on new physics. In the SM, there are no FCNC at tree-level and at one-loop level they are GIM suppressed. In models beyond SM, new particles may appear in the loop and have significant contributions to the FCNC processes. Therefore, the processes can give an ideal place to search the signals of the new particles. In this letter, we calculated the contributions of the neutral top-pion $\pi^0_t$ to the FCNC process $e^-\gamma \to e^-\bar{t}c$ in the framework of TC2 models and discussed the possible of detecting this new particle in the future LC experiments. Our numerical results show that the cross section $\sigma$ given by $\pi^0_t$ is in the range of the $10^{-1} - 10^{-2} fb$. With reasonable values of the parameters, the cross section $\sigma$ can reach to $0.19 fb$. So it is possible to detect the signals of the neutral top-pion $\pi^0_t$ via the process $e^-\gamma \to e^-\bar{t}c$ at the $e\gamma$ colliders based on the LC experiments.
Figure captions

**Fig.1:** Feynman diagram for contributing to the process $e^-\gamma \rightarrow e^-\bar{t}c$ from the neutral top-pion $\pi_t^0$.

**Fig.2:** The cross section $\sigma$ as a function of $m_{\pi_t}$ for the center-of-mass energy $\sqrt{s} = 500$ GeV and $\varepsilon = 0.03$ (solid line), 0.05 (dotted line) and 0.08 (dashed line).

**Fig.3:** The cross section $\sigma$ as a function of $\sqrt{s}$ for the parameter $m_{\pi_t} = 250$GeV and $\varepsilon = 0.03$ (solid line), 0.05 (dotted line) and 0.08 (dashed line).
References

[1] S. Weinberg, *Phys. Rev. D* **13**(1976)974; *D* **19**(1977)1277; L. Susskind, *ibid. D* **20**(1979)2619; S. Dimopoulos and L. Susskind, *Nucl. Phys. B* **155**(1979)237; E. Eichten and K. Lane, *Phys. Lett. B* **90**(1980)125.

[2] M. Peskin and T. Takeuchi, *Phys. Rev. Lett.* **65**(1990)964.

[3] J. Erler and P. Lanagaclar, *Review of Particle Physics, Eur. Phys. J. C* **3** (1998)90; K. Hagiwara, D. Haidt, and S. Matsumoto, *Eur. Phys. J. C* **2**(1998)95.

[4] C. T. Hill, *Phys. Lett. B* **345**(1995)483; K. Lane and F. Eichten, *Phys. Lett. B* **352**(1995)382; K. Lane, *Phys. Lett. B* **433**(1998)96; G. Cvetic, *Rev. Mod. Phys.* **71**(1999)513.

[5] Hong-Jian He and C. P. Yuan, *Phys. Rev. Lett.* **83**(1999)83; G. Burdman, *Phys. Rev. Lett.* **83**(1999)2888.

[6] Chongxing Yue, et al., *Phys. Rev. D* **55**(1997)5541; Gongru Lu, Chongxing Yue and Jinshu Huang, *Phys. Rev. D* **57**(1998)1755.

[7] Chongxing Yue, et al., *Phys. Rev. D* **63**(2001)115002.

[8] Hongyi Zhou, et al., *Phys. Rev. D* **57**(1998)4205; Chongxing Yue, et al., *Phys. Lett. B* **496**(2000)93.

[9] Xuelei Wang, et al., *Phys. Rev. D* **60**(1999)014002.

[10] G. Burdman and D. Kominis, *Phys. Lett. B* **403**(1997)101; W. Loinaz and T. Takuchi, *Phys. Rev. D* **60**(1999)015005.

[11] Chongxing Yue, et al., *Phys. Rev. D* **62**(2000)055005.

[12] G. Jikia, *Nucl. Phys. B* **374**(1992)83; O. J. P. Eholi, et al., *Phys. Rev. D* **47**(1993)1889; K. M. Cheuny, *Phys. Rev. D* **47**(1993)3750.
[13] Paratical Data Group, *Eur. Phys. J. C* **15**(2000)1.

[14] S. Godfrey, P. Kalyniak and N. RomanenKo, hep-ph/0108283; hep-ph/0100191.
Fig. 1

Fig. 2
Fig. 3