Production of the neutral toppion at the $e\gamma$ colliders

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Abstract

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

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I. Introduction

Although the Glashow-Weinberg-Salam (GWS) theory which bases on the gauge group $SU_L(2) \otimes U_Y(1)$ have made a great success to describe the weak and electromagnetic interactions, the mechanism of the electroweak symmetry breaking (EWSB) is still unknown. So probing the mechanism of the EWSB will not only be one of the main subjects of theoretical research but 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] leads 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, topcolor-assisted technicolor (TC2) model [6] is a more realistic one, which provides an additional source of EWSB and also solves heavy top quark problem. In TC2 theory, the new strong dynamics topcolor is assumed to be chiral 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 $m'_t = \varepsilon m_t (0.03 \leq \varepsilon \leq 0.1)$ [7]. The topcolor 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 toppions $\Pi_0^t, \Pi_{\pm}^t$ are predicted by TC2 model in the few hundred GeV region. The physical particle toppions can be regarded as the typical feature of TC2 model. Thus, the studies of some toppion production processes at present and future high energy colliders can help the experiment to search for toppion and test TC2 theory, furthermore, to probe EWSB mechanism. A comprehensive review on the phenomenological studies in 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 GeV up to several TeV and the luminosity over 100 $fb^{-1}$/year, these are NLC(USA) [9], JLC(Japan) [10], TESLA(Europe) [11].
The search for Higgs particle in SM or some new particles predicted in the models beyond the SM(such as Higgs bosons $A^0, H^0, h^0, H^\pm$ in MSSM and PGB’s in TC model) is one of the most important goals of future high energy $e^+e^-$ colliders. Some Higgs bosons production processes in SM and MSSM in $e^+e^-$ collision have been studied in many literatures[12].

To search for the toppions in TC2 model, the literatures have studied the neutral toppion production processes in high energy $e^+e^-$ collision[13, 14]. Ref.[13] has calculated the production cross sections of the processes $e^+e^- \rightarrow \Pi_0^t\gamma, \Pi_0^tZ$ and the results show that the cross sections are about several fb. Recently, we have studied a flavor-changing neutral toppion production process $e^+e^- \rightarrow t \bar{c} \Pi_0^t$[14]. We find that the resonance effect can enhance the cross section significantly when toppion mass is small. The above studies provide the feasible ways to detect toppion events and test TC2 model. The future $e^+e^-$ colliders can also operate in the $e\gamma$ or $\gamma\gamma$ modes. 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 the same order of magnitude of the parent electron beam and the set of final states at a photon collider is much richer than that at an $e^+e^-$ mode. At the same time, the high energy photons polarizations can relatively easily vary, which is advantageous for experiments. All the virtues of the photon colliders will provide us a good chance to pursuit new physics particles. The production of Higgs bosons in SM and MSSM at $e\gamma$ colliders have been studied in Ref.[15].

In this paper, in the framework of TC2, we will study a neutral toppion production process $e^-\gamma \rightarrow e^-\Pi_0^t$. The results show that the cross section can be up to the level of several tens fb due to strong coupling of $\Pi_0^t$ to $t\bar{t}$ and t-channel effect. The signals of toppion can be easily detected at $e\gamma$ colliders. On the other hand, we find that we can distinguish toppion from other toppion-like particles(such as Higgs bosons in SM and MSSM).

II. The cross section of the process

As it is known, the couplings of toppions to the three family fermions are non-universal and the toppions have large Yukawa couplings to the third generation. The coupling of the neutral toppion $\Pi_0^t$ to a pair of top quarks is proportion to the mass of top quark and the
explicit form can be written as\cite{10}:

\[ i \frac{m_t}{v_w} \tan \beta K_{UR}^{tt} K_{UL}^{tt*} \tau_5 t \Pi_t^0 \]

(1)

where \( \tan \beta = \sqrt{(\frac{\upsilon_t}{v_w})^2 - 1} \) \( v_w = 246 \) GeV is electroweak symmetry-breaking scale, and \( \upsilon_t \approx 60 - 100 \) GeV is the toppion decay constant. \( K_{UL}^{tt} \) 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 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 \( \varepsilon \) as a free parameter changing from 0.03 to 0.1.

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

\[ \Pi_t^0 - \gamma - \gamma \quad iN_c \frac{8 \tan \beta}{9\pi} \frac{m_t^2 (1 - \varepsilon)}{v_w^2} \alpha_e \varepsilon \varepsilon_{\mu \nu \rho \delta} p^\rho p^\delta C_0 \]

(2)

\[ \Pi_t^0 - \gamma - Z \quad iN_c \frac{\alpha_e}{3\pi c_w s_w} \frac{\tan \beta}{v_w} m_t^2 (1 - \varepsilon) \varepsilon \varepsilon_{\mu \nu \rho \delta} (1 - \frac{8}{3} s_w^2) p^\rho p^\delta C_0 \]

(3)

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

With the couplings of \( \Pi_t^0 \gamma \gamma \) and \( \Pi_t^0 Z \gamma \), the neutral toppion can be produced via the process \( e^- \gamma \rightarrow e^- \Pi_t^0 \), the Feynman diagram of the process is shown in Fig.1. The amplitude of the process can be written directly

\[ M = M^\gamma + M^Z \]

(4)

\[ M^\gamma = -iN_c \frac{16 \sqrt{\pi} \tan \beta}{9\pi} m_t^2 \alpha_e^{3/2} C_0 \varepsilon_{\mu \nu \rho \delta} p_2^\rho p_4^\delta \]

(5)

\[ \epsilon_\mu (p_2) \pi_\nu (p_3) \gamma_\nu \upsilon_e (p_1) G(p_2 - p_4, 0) \]
\[ M^Z = iN_c \frac{2 \alpha^{3/2}}{\sqrt{\pi} \alpha_w s_w} \tan \beta (1 - \varepsilon) m_t^2 (1 - \frac{8}{3} s_w^2) C_0 \]

\[ \varepsilon^{\mu \nu \rho \sigma} p_2 \rho \alpha \beta \mu (p_2) \bar{u}_e (p_3) [- \frac{1}{2} L + s_w^2] \gamma_\nu u_e (p_1) \]

\[ G(p_2 - p_1, M_Z) \]

Where, \( L = \frac{1}{2} (1 - \gamma_5) \). \( G(p, m) = \frac{1}{p^2 - m^2} \) denotes the propagator of the particle. We can see that there exists a t-channel resonance effect for 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 \( e^-\gamma \rightarrow e^-\Pi^0 \), the total cross section at the \( e^+e^- \) linear collider can be obtained by folding \( \sigma(\hat{s}) \) with the photon distribution function which is given in Ref[17]

\[ \sigma_{tot} = \int_{M_\Pi^0/s} \frac{dx \hat{s}}{s} f_{\gamma} (x), \]

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

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

In 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, \( \omega_0 \) stands for the laser photon energy, and \( x = \omega/E_e \) stands for the fraction of energy of the incident electron carried by the back-scattered photon. \( f_{\gamma} \) 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 back-scattered photons, we require \( \omega_0 x_{max} \leq m_e^2/E_e \) which implies that \( \xi \leq 2 + 2\sqrt{2} \approx 4.8 \). 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, $s^2_w = 0.23$. The electromagnetic fine structure constant $\alpha_e$ at certain energy scale is calculated from the simple QED one-loop evolution formula with the boundary value $\alpha_e = 1/137.04^{19}$. There are three free parameters in the cross section, i.e., $\varepsilon, M_{\Pi}, s$. To see the influence of these parameters on the cross section, we take the mass of toppion $M_{\Pi}$ to vary in certain range $150$ GeV $\leq M_{\Pi} \leq 450$ GeV, $\varepsilon = 0.03, 0.06, 0.1$, respectively. 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, 1600 GeV, respectively. The final numerical results of the cross section are summarized in Fig.2-4. The Fig.2-4 are the plots of the cross section as the function of $M_{\Pi}$ for $\sqrt{s} = 500$ GeV, 800 GeV, 1600 GeV, respectively. We can see that there is a peak in the plot when $M_{\Pi}$ is about 350 GeV which arises from top quark triangle loop. We can see that the cross section is in the range of a few tens fb. With the luminosity of 100 $fb^{-1}$/year, there are over $10^3$ events of neutral toppion to be produced via the process $e^-\gamma \rightarrow e^-\Pi^0_t$ per year. Such sufficient events can be easily detected experimentally. As have been studied in Refs.\cite{13, 14}, the cross sections of neutral toppion in $e^+e^-$ collision are only at the level of a few fb. The $t$-channel resonance effect can enhance the cross section of the process $e^-\gamma \rightarrow e^-\Pi^0_t$ significantly, this makes process $e^-\gamma \rightarrow e^-\Pi^0_t$ potentially important for the detecting of toppion. Some Higgs bosons production processes in $e\gamma$ collision have been studied in SM and MSSM($e^-\gamma \rightarrow e^-H^0$ in SM and $e^-\gamma \rightarrow e^-H^0(h^0, A^0)$ in MSSM)\cite{15}, the results show that the cross sections are at the level of a few fb, i.e., the cross section of $e^-\gamma \rightarrow e^-\Pi^0_t$ is about one order of magnitude larger than those of some similar processes in SM and MSSM. The reason is that there is a large extra coefficient $\tan\beta$ in the coupling $\Pi^0_t\bar{t}\bar{t}$ compared with the coupling $H\bar{t}\bar{t}$ in SM(MSSM) and $\tan\beta$ can enhance the cross section about one order of magnitude. With such a large cross section of $e^-\gamma \rightarrow e^-\Pi^0_t$, we can easily distinguish neutral toppion in TC2 from Higgs bosons in SM and MSSM. This is another important feature of the process $e^-\gamma \rightarrow e^-\Pi^0_t$.

To determine which channel is the best one to search for neutral toppion, we need to
know its decay branching ratio of each decay modes. The possible decay modes are: $t\bar{t}$ (if $\Pi^0_t > 2m_t), t\bar{c}, t\bar{b}, gg, \gamma\gamma, Z\gamma$. For $\Pi^0_t > 2m_t$, the main decay mode is $\Pi^0_t \rightarrow t\bar{t}$. The decay branching ratio $Br(\Pi^0_t \rightarrow t\bar{c})$ is the largest one when $t\bar{t}$ channel is forbidden. Using the FormCalc[20], we can directly obtain the cross section of the processes: $e^-\gamma \rightarrow e^-t\bar{t}, e^-\gamma \rightarrow e^-t\bar{c}, e^-\gamma \rightarrow e^-b\bar{b}$ in SM, the results are shown in Table 1.

**Table 1**: The cross section of $e^-\gamma \rightarrow e^-t\bar{t}, e^-\gamma \rightarrow e^-t\bar{c}, e^-\gamma \rightarrow e^-b\bar{b}$ in SM.

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

We can see that, in SM, the cross section of $e^-\gamma \rightarrow e^-t\bar{c}$ is very small because there is no tree level flavor-changing neutral current(FCNC) in SM. Therefore, $e^-\gamma \rightarrow e^-\Pi^0_t \rightarrow e^-t\bar{c}$ is the most ideal channel to detect neutral toppion. The decay branching ratio of $\Pi^0_t \rightarrow t\bar{c}$ and the signal per year in the $t\bar{c}$ channel are shown in table 2

**Table 2**: The decay branching ratio of $\Pi^0_t \rightarrow t\bar{c}$ and the signal per year in the $t\bar{c}$ channel.

We take $\varepsilon = 0.06$ and the luminosity $L = 100 fb^{-1}$/year.

| $M_{\Pi^0}(GeV)$ | 160 | 400 |
|-------------------|-----|-----|
| $Br(\Pi^0_t \rightarrow t\bar{c})$ | 0.66 | 0.08 |
| $\sqrt{s}(GeV)$ | 500 | 800 | 1600 |
| Signal/Year in $t\bar{c}$ channel | 600 | 704 | 741 |

We can conclude that there is about a few hundred signals of neutral toppion produced in $t\bar{c}$ channel. With such large numbers of signals and very clean background in SM for this $t\bar{c}$ channel(As it is shown in table 2 that the cross section of $e^-\gamma \rightarrow e^-t\bar{c}$ in SM is only about $10^{-12}$ pb), the neutral toppion can be easily detected via $t\bar{c}$ channel at $e\gamma$ collision.
In conclusion, we have studied a neutral toppion production process $e^-\gamma \rightarrow e^-\Pi_t^0$ in TC2 model. The numerical results show that the cross section is very large (at the level of several tens fb), and over $10^3$ neutral toppion events can be produced in $e\gamma$ collision. With the large $Br(\Pi_t^0 \rightarrow t\bar{c})$ and small cross section of $e^-\gamma \rightarrow e^t\bar{c}$ in SM, $e^-\gamma \rightarrow e^-\Pi_t^0 \rightarrow e^-t\bar{c}$ provide us the best channel to search for neutral toppion. On the other hand, the cross section of $e^-\gamma \rightarrow e^-\Pi_t^0$ is about one order of magnitude larger than those of the production processes of toppion-like particles in SM and MSSM. Therefore, the process $e^-\gamma \rightarrow e^-\Pi_t^0$ provides us a unique way to distinguish TC2 model from other models.
References

[1] S. Weinberg, *Phys. Rev. D* **13**, (1976)974; **19**, (1979)1277.

[2] L. Susskind, *Phys. Rev. D* **20**, (1979)2619; S. Dimopoulos and L. Susskind, *Nucl.Phys. B* **155**, (1979)237; E. Eichten and K. Lane, *Phys. Lett. 90B*, (1980)125.

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

[4] J. Erler and P. Langacker in Review of Particle Physics, *Eur. Phys. J. C* **3**, (1998)90.

[5] K. Hagiwara, D. Haidt and S. Matsumoto, *Eur. Phys. J. C* **2**, (1995)95.

[6] C. T. Hill, *Phys. Lett. B* **345**, (1995)483; K. Lane and E. Eichten, *Phys. Lett. B* **352**, (1995)382; K. Lane, *Phys. Rev. D* **54**, (1996)2204; R. S. Chivukula, B. A. Dobrescu, H. Georgi and C. T. Hill, *Phys. Rev. D* **59**, (1999)075003.

[7] G. Buchalla, G. Burdman, C. T. Hill, D. Kominis, *Phys. Rev. D* **53**, (1996)5185.

[8] G. Cvetic, *Rev.Mod.Phys.* **71**, (1999)513.

[9] The NLC Collaboration, 2001 report on the Next linear collider: A report submitted to snowmass’01, SLAC-R-571.

[10] S. Iwata, The JLC project, Proceedings of the worldwide, Study on Physics and Experiments with Future Linear $e^+e^-$ Colliders, Sitges, Vol.2, 611.

[11] R. Brinkmann et.al., ”TESLA Technical Design Report Part II: The accelerator.” DESY-01-011B.

[12] A. Barroso, J. C. Romao, *Nucl.Phys. B* **267**, (1986)509; A. Dyouadi, J. Kalinowski, P. M. Zerwas, *Z Phys. C* **54**, (1992)255; A. Dyouadi, V. Driesen, W. Hollik, J. Rosiek, *Nucl.Phys. B* **491**, (1997)68; G. Altarelli, B. Mele, F. Pitolli, *Nucl.Phys. B* **287**, (1987)205; A. Dyouadi, H. E. Haber, P. M. Zerwas, *Phys. Lett. B* **375**, (1996)203.

[13] C. X. Yue, Q. J. Xu, G. L. Liu, J. T. Li, *Phys. Rev. D* **63**, (2001)115002.
[14] X.L.Wang, Y.L.Yang, B.Z.Li, J.Y.Zhang, hep-ph/0206182.

[15] O.J.P.Eboli, M.C.Gonzalez-Garcia, S.F.Novaes, Phys. Rev. D49,(1994)91; E.Gabrielli, V.A.Ilyin, and B.Mele, Phys. Rev. D56,(1997)5945; U.Cotti, J.L.Diaz, J.J.Toscano, Nucl.Phys. B404, (1997)308; Y.Liao and W.W.Repko, Phys. Rev. D57,(1998)6998; D.A.Dicus, W.W.Repko, Phys. Rev. D53,(1996)3616.

[16] Hong-Jian He and C. P. Yuan, Phys. Rev. Lett. 83,(1999)28; G. Burdman, Phys. Rev. Lett. 83,(1999)2888.

[17] G. Jikia, Nucl. Nucl Phys. B374,(1992)83; O. J. P. Eboli, et al., Phys. Rev. D47,(1993)1889; K. M. Cheuny, Phys. Rev. D47,(1993)3750.

[18] H.-Y. Zhou, Y.-P. Kuang, C.-X. Yue, H. Wang and G.-R. Lu, Phys. Rev. D57, (1998)4205.

[19] J.F. Donoghue, E. Golowich, and B.R. Holstein, Dynamics of the Standard Model, Cambridge University Press, 1992, P. 34.

[20] T.Hahn, Nucl.Phys.Proc.Suppl.89,(2000)231; Acta Phys.Polon.B30,(1999)3469.
Figure 1: The Feynman diagrams of the process $e^-\gamma \rightarrow e^-\Pi^0_t$.

Figure 2: The cross section of $e^-\gamma \rightarrow e^-\Pi^0_t$ versus toppion mass $M_{\Pi_t}(150-450 \text{ GeV})$ for $\sqrt{s} = 500 \text{ GeV}$ and $\varepsilon = 0.03$(dash line), $\varepsilon = 0.06$ (solid line), $\varepsilon = 0.1$(dot line), respectively
Figure 3: The same plots as Fig.2 for $\sqrt{s} = 800$.

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