The study of a flavor-changing neutral toppion production process $e^+e^- \rightarrow t\bar{c}\Pi_0^T$

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We have studied a flavor-changing toppion production process $e^+e^- \rightarrow \bar{c}t\Pi_0^T$ in the topcolor-assisted technicolor (TC2) model. The studies show that, with high centre of mass energy in TESLA collider, the production cross section of $e^+e^- \rightarrow \bar{c}t\Pi_0^T$ is at the order of magnitude $0.1$ fb in most parameter regions of TC2 model and a few tens events of toppion can be produced each year. The resonance effect can enhance the cross section to a few fb when toppion mass is small. With clean background, the toppion events can possibly be detected at TESLA collider. On the other hand, we find that there exists a narrow peak near $m_t - m_c$ in the toppion-charm invariant mass distribution which could be clearly detected. Therefore, such a toppion production process $e^+e^- \rightarrow t\bar{c}\Pi_0^T$ provides a unique chance to detect toppion events and test the TC2 model.

12.60Nz,14.80.Mz,12.15.Lk,14.65.Ha

I. Introduction

A unified and beautiful description of the weak and electromagnetic interaction is given by the Glashow-Weinberg-Salam (GWS) theory based on the gauge group $SU_L(2) \times U_Y(1)$. Many experimental successes have been credited to this model. However, its symmetry breaking sector is unclear. Probing the electroweak symmetry breaking mechanism will be one of the most important tasks at future high energy colliders.

Dynamical electroweak symmetry breaking, for example technicolor (TC) type theories [1], is an attractive idea that avoids the shortcomings of triviality and unnaturalness arising from the elementary Higgs field of GWS theory. The simplest QCD-like extended technicolor model [2] leads to a too large oblique correction S parameter [3], and is already ruled out by the CERN $e^+e^-$ collider LEP precision electroweak measurement data [4,5]. Various improvements have been proposed to make the predictions consistent with the LEP precision measurement data. A more realistic TC model is topcolor-assisted technicolor (TC2) model [6], which can also solve heavy top quark problem. In TC2 theory, the electroweak symmetry breaking (ESB) is driven mainly by technicolor interactions, the extended technicolor give contributions to all ordinary quark and lepton masses including a very small portion of the top quark mass: $m_t = \varepsilon m_t (0.03 \leq \varepsilon \leq 0.1)$ [7]. The topcolor interactions also make small contributions to the ESB and give rise to the main part of the top mass $(1 - \varepsilon)m_t$.

One of the most general predictions of TC2 model is the existence of three Pseudo-Goldstone Boson in a few hundred GeV region, so called toppions: $\Pi_0^T, \Pi_1^T$. The physical particle toppions can be regarded as the typical feature of TC2 model. Thus, studying the possible signature of toppions and toppion contributions to some processes at the high energy colliders is a good method to test TC2 model. There have been a lot of literatures related to this field [8–10]. Another feature of TC2 model is the existence of flavor-changing coupling of neutral toppion to top and charm quarks. As it is know, there is no flavor-changing neutral current (FCNC) at tree-level in the standard model (SM). The FCNC processes in SM can hardly be detected. Any observation of the flavor-changing coupling deviated from that in the SM would be unambiguously signal of new physics. So, the study of some processes including $\Pi_0^T - t - c$ vertex within the framework of TC2 model would provide some information of the flavor-changing coupling and a feasible method to detect the signals of toppion.

In this paper, we will study a neutral toppion production process $e^+e^- \rightarrow t\bar{c}\Pi_0^T$ which includes the flavor-changing vertex $\Pi_0^T - t - c$. Our results show that, with favorable parameter values, the production cross section of $e^+e^- \rightarrow t\bar{c}\Pi_0^T$ is expected to reach the order of magnitude of 10 fb. The signals of toppion might be detected experimentally at DESY TESLA with high energy and large luminosity.

This paper is organized as follows. In sec II, we shall present the calculations of the production cross section of the process $e^+e^- \rightarrow t\bar{c}\Pi_0^T$. The numerical results of the cross section and the concluding remarks will be presented in sec III.

II The calculations of the production cross section

For TC2 models, the underlying interactions, topcolor interactions are non-universal and therefore does not posses 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. The non-universal gauge interactions result in the new flavor-changing coupling vertices when one writes the interactions in the quark mass eigen-basis. Thus, the toppions predicted by this kind of models have large Yukawa couplings to the third generation and can induce the new flavor-changing couplings. The relevant flavor-changing vertices including the large top-charm transition for the neutral toppion can be writ-

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ten as \[ t \]

\[ m_t \tan \beta \]

\[ v_\omega \]

\[ K_{UL}^{TC}K_{UL}^{TC} + h.c. \]

where \( \tan \beta = \sqrt{\frac{v_\omega^2}{v_t^2} - 1} \), \( v_\omega = 246 \text{ GeV} \) is electroweak symmetry-breaking scale and \( v_t \approx 60 - 100 \text{ GeV} \).\[ 10 \] is the toppion decay constant. \( K_{UL}^{TC} \) 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 \( K_{UR}^{TC} \) are the matrix elements of the right-handed rotation matrix \( K_{UR} \). Their values can be written as:

\[ K_{UL}^{TC} = 1 \]

\[ K_{UL}^{TC} = 1 - \epsilon \]

\[ K_{UL}^{TC} \leq \sqrt{1 - (K_{UL}^{TC})^2} \approx \sqrt{2\epsilon - \epsilon^2} \]

With the flavor-changing coupling \( \Pi_0 - t - c \), the neutral toppion can be produced associated with a single top quark at \( e^+e^- \) colliders, i.e., \( e^+e^- \rightarrow t\bar{\tau}\Pi_0 \). The Feynman diagrams of the process is shown in Fig.1.

\[ \begin{align*}
M = & M_a^2 + M_b^2 + M_c^2 + M_d^2 \\
M_a^2 = & \frac{\sqrt{2}m_t \tan \beta}{2v_\omega}k_{UL}^{TC}k_{UL}^{TC}g(p_3 + p_5, m_e) \\
& G(p_1 + p_2, m_\tau)\frac{g(p_3)(p_4)\gamma^\mu R}{\mp 8g_\tau^2g_\tau^2L\gamma^\mu(p_4 + p_5)} \\
& + m_e[\gamma^\mu L]v_\omega(p_4)\gamma^\mu(p_1)\gamma^\mu u_\omega(p_2) \\
& (-L + 2s_w^2)u_\omega(p_2) \\
M_b^2 = & \frac{\sqrt{2}m_t \tan \beta}{2v_\omega} \frac{k_{UL}^{TC}k_{UL}^{TC}g(p_4 + p_5, m_t)}{G(p_1 + p_2, m_\tau)\gamma^\mu[(2 - 8s_w^2)L(p_4 + p_5)} \\
& - \frac{8}{3}s_w^2m_tR_\omega(p_4)(p_4)\gamma^\mu(-L + 2s_w^2)u_\omega(p_2) \\
M_c^2 = & \frac{8\sqrt{2}m_t \tan \beta}{3} \frac{G_{ED}k_{UL}^{TC}k_{UL}^{TC}}{v_\omega} \\
M_d^2 = & \frac{8\sqrt{2}m_t \tan \beta}{3} G_{ED}k_{UL}^{TC}k_{UL}^{TC}. \\
\end{align*} \]

Here, \( G(p, m) = \frac{1}{p^{2} - m^2} \) is the propagator of the particle, \( L = \frac{1}{2}(1 - \gamma_5) \), \( R = \frac{1}{2}(1 + \gamma_5) \), \( s_w^2 = \sin^2 \theta_w \) (the Weinberg angle). We can see that the time-like momentum may hit the top-pole in the top quark propagator. So we should take into account the effects of the width of top quark in the calculations, i.e., we should take the complex mass term \( m_t^2 - im_t \Gamma_t \) instead of the simple top quark mass term \( m_t^2 \) in the top quark propagator.

The negative \( m_t \Gamma_t \) term is important in the vicinity of the resonance. As it is known, the top quark decays almost to \( W^+b \). So, the total top quark decay width can be replaced approximately by \( \Gamma(t \rightarrow W^+b) \) in our calculation. With above production amplitudes, we can obtain the production cross section directly.

### III. The numerical results and conclusions

In our calculations, we take \( m_t = 174 \text{ GeV} \), \( m_c = 1.5 \text{ GeV} \) \( v_t = 60 \text{ GeV} \). There are two free parameters involved in the production amplitudes, i.e., \( \varepsilon, M_t \). To see the influence of toppion mass and parameter \( \varepsilon \) on the production cross section, we take the mass of toppion \( M_t \) to vary in certain ranges 150 GeV \( M_t \leq 350 \text{ GeV} \) and \( \varepsilon = 0.03, 0.06, 0.1 \) respectively. One of the next generation \( e^+e^- \) colliders is TESLA in Europe.\[ 11 \] In its first stage, TESLA can run at centre of mass energy \( \sqrt{s} = 500 \text{ GeV} \). An upgrade to close to 1 TeV is planned. The predicted maximal luminosity can reach 500 fb\(^{-1} \)/year. In this paper, to study the discovery potential of \( \Pi_0 \) at TESLA, we will take \( \sqrt{s} = 500 \text{ GeV} \), 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 cross section plots as the function of toppion mass and parameter \( \varepsilon \) on the production cross section, we take the mass of toppion \( M_t \) to vary in certain ranges 150 GeV \( M_t \leq 350 \text{ GeV} \) and \( \varepsilon = 0.03, 0.06, 0.1 \) respectively. We can see that the cross section of \( e^+e^- \rightarrow t\bar{\tau}\Pi_0 \) increase with the mass of toppion \( M_t \) decreasing. Specially, when \( M_t < m_t - m_e \), the cross section increase sharply due to the resonance effect in Fig.2(b). The cross section can reach about a few fb for small \( M_t \). With the yearly integrated luminosity of \( L \sim 500 \text{ fb}^{-1} \) expected at TESLA, one could collect a few thousands of \( \Pi_0 \) events each year. With high energy\( (\sqrt{s} = 800, 1600 \text{ GeV}) \), the order of magnitude of the cross section is at 0.1fb in most parameter regions, a few tens of \( \Pi_0 \) events can be produced each year. As it is known, there is no flavor-changing coupling between charm and top quarks in SM. The background of \( e^+e^- \rightarrow t\bar{\tau}\Pi_0 \) should be very clean. So, the events of neutral toppion produced in the process \( e^+e^- \rightarrow t\bar{\tau}\Pi_0 \) should be detected at TESLA, specially,
in case of light $\Pi^0$. Comparing the cross sections for $\sqrt{s}=500,800,1600$ GeV, we can conclude that $\sqrt{s} = 500$ GeV is a favorable centre of mass energy to detect light toppion events. But for heavy toppion, high energy can enhance the cross section. So, high energy is needed to detect the heavy toppion.

Due to the resonance effect for light toppion, there should be a peak near $m_t - m_c$ in the toppion-charm invariant mass distribution. To show the above results, we plot, in Fig.5, the toppion-charm invariant mass distribution with $\sqrt{s}=500$ GeV, $M_{\Pi} =150$ GeV, $\varepsilon = 0.1$. It can be seen that the resonance peak can possibly be observable. So, the study of the invariant mass distribution may provide another good way to detect signal of toppion.

In conclusion, we have studied a flavor-changing process $e^+e^- \rightarrow t\bar{c}\Pi^0$ in TC2 model. We find there are some features about this process. (1) For light toppion ($M_{\Pi} < m_t - m_c$), there exists the resonance effect which can enhance the cross section significantly. So, the process $e^+e^- \rightarrow t\bar{c}\Pi^0$ is favorable for light toppion detecting. High centre of mass is needed for heavy toppion detecting. With $\sqrt{s}=800,1600$ GeV, the cross section of $e^+e^- \rightarrow t\bar{c}\Pi^0$ is at the order of magnitude of 0.1 fb in most parameter regions, a few tens $\Pi^0$ events can be produced via $e^+e^- \rightarrow t\bar{c}\Pi^0$. (2) There is no flavor-changing coupling between charm-top quarks at tree level in SM, the background of this flavor-changing process $e^+e^- \rightarrow t\bar{c}\Pi^0$ might be very clean. So, there is reasonable hope to isolate the events experimentally with a few tens each year. Therefore, the $e^+e^- \rightarrow t\bar{c}\Pi^0$ process provides a feasible test of TC2 model with the detecting of toppion signals.

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FIG. 3. The same plots as Fig.2 for $\sqrt{s}=800$ GeV with $\varepsilon = 0.03$ (dash line), $\varepsilon = 0.06$ (short dash-dot line), $\varepsilon = 0.1$ (solid line) respectively.

FIG. 4. The same plots as Fig.2 for $\sqrt{s}=1600$ GeV with $\varepsilon = 0.03$ (dash line), $\varepsilon = 0.06$ (short dash-dot line), $\varepsilon = 0.1$ (solid line) respectively.

FIG. 5. The toppion-charm invariant mass distribution for $\sqrt{s}=500$ GeV $\varepsilon = 0.1$ and $M_\Pi = 150$ GeV.