Associated production of neutral toppion with a pair of heavy quarks in $\gamma \gamma$ collisions

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Abstract

We have studied a neutral toppion production process $\gamma \gamma \rightarrow f\Pi_0^t (f = t, b)$ in the topcolor-assisted technicolor (TC2) model. We find that the cross section of $\gamma \gamma \rightarrow t\Pi_0^t$ is much larger than that of $\gamma \gamma \rightarrow b\Pi_0^b$. On the other hand, the cross section can be obviously enhanced with the increasing of c.m.energy. With $\sqrt{s} = 1600$ GeV, the cross section of $t\bar{t}\Pi_0^t$ production can reach the level of a few fb. The results show that $\gamma \gamma \rightarrow t\bar{t}\Pi_0^t \rightarrow t\bar{t}(t\bar{c})$ is the most ideal channel to detect neutral toppion due to the clean SM background. With such sufficient signals and clean background, neutral toppion could be detected at TESLA with high c.m.energy.

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I. Introduction

At present the success of electroweak standard model is well known and doubtness. However, the mechanism of the electroweak symmetry breaking (EWSB) is not yet quite understood. The Higgs particle that is assumed to trigger the EWSB in the EWSM has not been found. In addition, there are prominent problems of triviality and unnaturalness \cite{1,2} in the Higgs section in the EWSB. Generally, it is said that the present theory of EWSB is only valid up to a certain energy scale $\Lambda$, and new physics beyond the EWSB will become dominant above $\Lambda$. Possible new physics are supersymmetry (SUSY) and dynamical EWSB mechanism concerning new strong interactions, etc.

The advantage of dynamical EWSB is that it discards the elementary scale field in the theory, so, it can completely avoid the problems of triviality and unnaturalness. The simplest model realizing this idea is the initial technicolor (TC) model proposed independently by Weinberg and Susskind \cite{2,3}. However, such a simple model predicts a too large oblique correction parameter $S$ and has been refused by LEP data \cite{4,5}. In order to overcome the shortcomings of the simplest model and explain the large mass difference between the top quark and the bottom quark, an important model called topcolor-assisted technicolor (TC2) model is proposed by Hill \cite{6} which is of great value to be studied in the future high energy experiment.

In TC2 theory, the EWSB is driven mainly by technicolor interactions. The extended technicolor gives contributions to all ordinary quark and lepton masses including a very small part of the top quark mass: $m'_t = \varepsilon m_t (0.03 \leq \varepsilon \leq 0.1)$ \cite{6}. The topcolor interaction also makes small contributions to the EWSB and gives rise to the main sector of the top mass $(1 - \varepsilon)m_t$. One of the most general predictions of TC2 model is the existence of three physical partical Pseudo-Goldstone Boson called toppion: $\Pi_t^\pm, \Pi_t^0$, which mass is in the range of hundreds of GeV. The toppions can be regarded as the typical feature of TC2 model. Thus, studying the possible signatures of toppions and toppion contributions to some processes at the high energy colliders is a good method to test TC2 model.

The neutral toppion can be probed directly in the decay processes $\pi_t^0 \rightarrow \gamma\gamma, gg, \gamma z$ through an internal top quark loop, and the decay processes $\pi_t^0 \rightarrow t\bar{c}, b\bar{b}, t\bar{t}$ (if this is
kinetically allowed). These possible decay modes have been calculated in detail [7] and it shows that the dominant decay mode is \( \pi_t^0 \to \bar{t}\bar{c} \) if \( \pi_t^0 \to \bar{t}\bar{t} \) is not allowed. The alternative way to probe toppions is to study some toppion production processes. The future linear colliders (LC) will provide an almost unique place to explore the toppion due to its clean environment and high luminosity. Recently, we have studied the neutral toppion production processes in high energy \( e^+e^- \) and \( e\gamma \) collision [8], the studies provide the feasible ways to detect toppion events and test TC2 model.

In this paper, we shall study an associated production of neutral toppion with a pair of quarks in \( \gamma\gamma \) collisions. i.e., \( \gamma\gamma \to f\bar{f}\Pi_t^0 (f = t, b) \). The advantage of photon colliders for some process has been extensively explained in the literature [9] [10]. Some similar processes have been thoroughly studied in the standard model (SM) (\( \gamma\gamma \to t\bar{t}H \)) [11] and in the minimal supersymmetric extension of the SM (MSSM) (\( \gamma\gamma \to t\bar{t}\phi (\phi = h^0, H^0, A^0) \)) [12].

In the SM, the results show that the cross section of \( \gamma\gamma \to \bar{t}tH \) is at the level of a few fb [11]. In MSSM, it is shown that when \( \tan\beta \) is not too large the associated \( h^0 \) production is dominant, with the cross section of 1.0 fb or higher for phenomenologically favored values of the parameters. The studies in Ref. [13] have shown that \( \gamma\gamma \) collision have the significant advantage to probe charged Higgs boson and a polarized \( \gamma\gamma \) collider can determine the chirality of the Yukawa couplings of fermions with charged Higgs boson via single charged Higgs boson production, and thus discriminate models of new physics.

This paper is organized as follows. In set.II, we will present the calculations of the production cross section of the process \( \gamma\gamma \to f\bar{f}\pi_t^0 (f = t, b) \). The results and conclusion will be shown in set.III.

II The calculation of the production cross section

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 \( \Pi_t^0 \) to a pair of top or bottom quarks is proportion to the mass of quark and the explicit form can be written as [14] [9]

\[
-\frac{\tan\beta}{v_w}[(1-\epsilon)m_t\bar{t}r_5t + m_b\bar{t}r_5b]
\]

(1)
Where $\tan\beta = \sqrt{(\frac{v_t}{v_w})^2 - 1}, v_w = 246$ GeV is the EWSB scale and $v_t \simeq 60 - 100$ GeV [14] is the toppion decay constant. $m_b^* \approx 6.6 k$ is an instanton induced $b$-quark mass, and $k \approx 1$ to 0.1. With above couplings, $\Pi_0^t$ can be produced associated with a pair of top or bottom quarks in $\gamma\gamma$ collisions. The Feynman diagrams for the process $\gamma(p_1)\gamma(p_2) \rightarrow f(p_3)\overline{f}(p_4)\Pi_0^t(p_5)$ ($f = t, b$) are shown in Fig.1 in which the cross diagrams with the interchange of the two incoming photons are not shown.

The amplitudes for the process are given by

\[
M_f^{(a)} = C_f \cdot G(p_3 + p_5, m_f)G(p_2 - p_4, m_f) \nonumber
\]
\[
\mathcal{M}_{f}(p_3)(\phi_3 + \phi_5 - m_f)\psi(p_1)(\phi_2 - \phi_4 - m_f)\psi(p_2)\gamma_5 \nonumber
\]
\[
M_f^{(b)} = C_f \cdot G(p_3 - p_1, m_f)G(p_2 - p_4, m_f) \nonumber
\]
\[
\mathcal{M}_{f}(p_3)\psi(p_1)(\phi_3 - \phi_1 + m_f)(\phi_2 - \phi_4 - m_f)\psi(p_2)\gamma_5 \nonumber
\]
\[
M_f^{(c)} = -C_f \cdot G(p_3 - p_1, m_f)G(p_4 - p_5, m_f) \nonumber
\]
\[
\mathcal{M}_{f}(p_3)\psi(p_1)(\phi_3 - \phi_1 + m_f)\psi(p_2)(\phi_4 + \phi_5 - m_f)\gamma_5 \nonumber
\]

The amplitudes for the diagrams with the interchange of the two incoming photons can be directly obtained by interchanging $p_1, p_2$ in above amplitudes. Here, the subindex $f = t, b$, the coefficient

\[
C_t = \frac{-16\sqrt{2} m_t \tan\beta}{9 v_w} M_Z^2 G_F c_w^2 s_w^2 (1 - \varepsilon) \nonumber
\]

\[
C_b = \frac{-4\sqrt{2} m_b^* \tan\beta}{9 v_w} M_Z^2 G_F c_w^2 s_w^2 \nonumber
\]

and $G(p, m) = \frac{1}{p^2 - m^2}$ is the propagator of the particle, $s_w^2 = \sin^2\theta_w, c_w^2 = \cos^2\theta_w$ ($\theta_w$ is the Weinberg angle)

Fig.1 Feynman diagrams for $t\overline{t}(b\overline{b})\Pi_0^t$ production in $\gamma\gamma$-collisions
With above amplitude, we can directly obtain the cross section \( \hat{\sigma}(\hat{s}) \) for the subprocess \( \gamma\gamma \rightarrow f\bar{f}\Pi^0_t \), the total cross section at the \( e^+e^- \) linear collider can be obtained by folding \( \hat{\sigma}(\hat{s}) \) with the photon distribution function which is given in Ref[10]

\[
\sigma_{\text{tot}}(s) = \int_{x_{\text{min}}}^{x_{\text{max}}} dx_1 \int_{x_{\text{min},x_{\text{max}}/x_1}}^{x_{\text{max}}} dx_2 F(x_1)F(x_2)\hat{\sigma}(\hat{s})
\]

where \( s \) is the c.m. energy squared for \( e^+e^- \) and the subprocess occurs effectively at \( \hat{s} = x_1 x_2 s \), and \( x_i \) are the fraction of the electrons energies carried by the photons. The explicit form of the photon distribution function \( F(x) \) is

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

with

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

\[
x_{\text{max}} = \frac{\xi}{1 + \xi}, \quad \xi = \frac{4E_0\omega_0}{m_e^2}.
\]

where \( E_0 \) and \( \omega_0 \) are the incident electron and laser light energies. To avoid unwanted \( e^+e^- \) pair production from the collision between the incident and back-scattered photons, we should not choose too large \( \omega_0 \). This constrains the maximum value for \( \xi = 2(1 + \sqrt{2}) \).

We obtain

\[
x_{\text{max}} = 0.83, \quad D(\xi) = 1.8
\]

The minimum value for \( x \) is then determined by the production threshold,

\[
x_{\text{min}} = \frac{\hat{s}_{\text{min}}}{x_{\text{max}} s}, \quad \hat{s}_{\text{min}} = (2m_t + M_{\Pi_t})^2
\]

### III The results and conclusions

In our calculations, we take \( m_t = 174 \text{ GeV}, m_b = 4.9 \text{ GeV}, v_t = 60 \text{ GeV}, M_Z = 91.187 \text{ GeV}, s_w^2 = 0.23, G_F = 1.16639 \times 10^{-5} (\text{GeV})^{-2} \). There are three free parameters involved in the production amplitudes, i.e., \( \varepsilon, M_{\Pi}, \sqrt{\hat{s}} \text{(for } tt\Pi_t^0 \text{ production)} \) and \( k, M_{\Pi}, \sqrt{\hat{s}} \text{(for } bb\Pi_t^0 \text{ production)} \). To see the influence of these parameters on the production cross section,
we take the mass of toppion $M_\Pi$ to vary in certain ranges $150 \text{ GeV} \leq M_\Pi \leq 350 \text{ GeV}$, $\varepsilon = 0.03, 0.06, 0.1$ and $k = 0.3, 0.7$ respectively. Considering the center-of-mass energies $\sqrt{s}$ in planned $e^+e^-$ linear colliders (for example: TESLA), we take $\sqrt{s}=500 \text{ GeV}$, $800 \text{ GeV}$, $1600 \text{ GeV}$, respectively (but for $t\bar{t}\Pi^0_t$ production, $\sqrt{s}=500 \text{ GeV}$ is too low to produce $t\bar{t}\Pi^0_t$).

In Fig.2, taking $\sqrt{s}=800 \text{ GeV}$ and $\varepsilon = 0.03, 0.06, 0.1$ respectively, we show the total cross section of $t\bar{t}\Pi^0_t$ production as a function of $M_\Pi$. We can see that the cross section falls sharply as the $M_\Pi$ increasing and the maximum of the cross section reach the level of $0.1 \text{ fb}$. The phase space is depressed strongly by large $M_\Pi$. For $\sqrt{s}=1600 \text{ GeV}$, the results of the cross section is shown in Fig.3. The results shown that the large $\sqrt{s}$ can enhance the cross section significantly and the value of the cross section is at the level of a few $\text{fb}$. This means that large $\sqrt{s}$ is favorable for detecting $\Pi^0_t$.

The another associated production of $\Pi^0_t$ is $\gamma\gamma \rightarrow b\bar{b}\Pi^0_t$. The results are shown in Fig.4-5. We find that the cross section of $b\bar{b}\Pi^0_t$ production is at least two orders of magnitude smaller than that of $t\bar{t}\Pi^0_t$ production. This is because the coupling of $b\bar{b}\Pi^0_t$ is much smaller than the coupling of $t\bar{t}\Pi^0_t$. So, it is difficult to detect $\Pi^0_t$ via the process $\gamma\gamma \rightarrow b\bar{b}\Pi^0_t$. We will not discuss the results of $\gamma\gamma \rightarrow b\bar{b}\Pi^0_t$ in detail.

Now, we will focus on considering how to detect $\Pi^0_t$ via the process $\gamma\gamma \rightarrow t\bar{t}\Pi^0_t$. It can be concluded that the high c.m. energy is needed in order to enhance the production rate and produce enough signals. On the other hand, we should find the best channel to detect $\Pi^0_t$. The possible decay modes of $\Pi^0_t$ are: $t\bar{t} (\text{if } \Pi^0_t > 2m_t), t\bar{c}, b\bar{b}, gg, \gamma\gamma, Z\gamma$. For $\Pi^0_t > 2m_t$, the main decay mode is $\Pi^0_t \rightarrow t\bar{t}$. As it is known, the couplings of toppion to the three families fermions are non-universal and therefore do not posses a GIM mechanism, this non-universal feature results in a large flavor changing coupling of neutral toppion to top and charm. So, the decay branching ratio $Br(\Pi^0_t \rightarrow t\bar{c})$ is the largest one when $t\bar{c}$ channel is forbidden. In SM, the cross section of the processes with $t\bar{c}$ production should be very small because there is no tree level flavor-changing neutral current (FCNC) in SM. Therefore, $\gamma\gamma \rightarrow t\bar{t}\Pi^0_t \rightarrow t\bar{t}(t\bar{c})$ is the most ideal channel to detect neutral toppion with the clean background in SM. Taking $M_\Pi = 160 \text{ GeV}$, we can easy get the branching ratio
of $\Pi^0_t \to t\bar{c}$ as 66%. The cross section of $e^+e^- \to \gamma\gamma \to t\bar{t}\Pi^0_t \to t\bar{t}(t\bar{c})$ is about 4.2 fb for $\sqrt{s} = 1600$ GeV and $\varepsilon = 0.06$. There are about 2000 signals can be produced via $t\bar{c}$ channel with annually integral luminosity of $500fb^{-1}$ at the TESLA. Such sufficient signals can be easily detected with the clean background.

In summary, we have studied a associated production of neutral toppion with a pair of heavy quarks in $\gamma\gamma$ collisions in TC2 model. We find that the production rate for $t\bar{t}\Pi^0_t$ in $\gamma\gamma$ collisions is at the level of serval fb with high c.m. energy(for example: $\sqrt{s} = 1600$ GeV). With such production rate and clean SM background, $\Pi^0_t$ should be detectd experimentally at the TESLA. But due to heavy $t\bar{t}$ pair, it is difficult to find $\Pi^0_t$ for $\sqrt{s} = 800$ GeV, except for light $\Pi^0_t$. 


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Fig. 2. The total cross sections of $t\bar{t}\Pi^0$ production versus the toppion mass $M_{\Pi}$ for the center-mass-energy $\sqrt{s} = 800$ GeV and $\epsilon = 0.03, 0.06, 0.1$.

Fig. 3. The same plots as Fig. 2 but for $\sqrt{s} = 1600$ GeV.
Fig. 4. The total cross sections of $b\bar{b}\Pi^0_t$ production versus the toppion mass $M_{\Pi}$ for $k = 0.3$ and $\sqrt{s} = 500, 800, 1600 \text{GeV}$.

Fig. 5. The same plots as Fig. 4 but for $k = 0.7$. 