Searching for a neutral top-Higgs in association with top-quark pairs at an e^+e^- collider in the TC2 model*

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Abstract: We investigate the associated production of the neutral top-Higgs h_t^0 with a pair of top-quarks in the context of the topcolor-assisted technicolor (TC2) model at the future e^+e^- Linear Colliders (LC) i.e. $e^+e^- \to t\bar{t}h_t^0$. We calculate the production rate and present the distributions of the transverse momenta of top-Higgs and top-quarks. The results show that the total cross section is typically of the order of 1.0–7.5 fb in the energy range between 1000 GeV and 2000 GeV of the LC for the whole top-Higgs mass region of interest. It should be distinctly possible that hundreds or even thousands of h_t^0 signals can be produced per year at the LC given the luminosity $\mathcal{L} = 500\ \mathrm{fb}^{-1}$.

Key words: topcolor-assisted technicolor (TC2) model, top-Higgs, cross section

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1 Introduction

The Higgs mechanism [1] plays a crucial role in the establishment of the Standard Model (SM) [2], where the $SU(2)_L$ Higgs doublet drives electroweak symmetry breaking (EWSB), gives mass to vector bosons $W^\pm$ and Z via the kinematic terms of Higgs fields, and gives mass to fermions via Yukawa coupling of Higgs with fermions. In the SM with a single $SU(2)_L$ doublet, there is only one physical scalar Higgs boson, the CP-even Higgs boson h_{SM}, remaining after EWSB. Due to the remarkable success in explaining the data from particle physics experiments, the SM has been confirmed as the correct model to describe electroweak phenomena at the current experimental energy scale. However, the SM Higgs boson h_{SM} has not yet been directly discovered experimentally to date, except for the fact that the current lower limit on the mass of h_{SM} comes from LEP Higgs searches: $m_{h_{SM}} > 114$ GeV at the 95% confidence level [3]. The discovery of a Higgs boson and the elucidation of the mechanism responsible for EWSB are some of the most important tasks of present and future searches in particle physics.

Over the last two decades, various dynamical EWSB theories have been developed; the topcolor-assisted technicolor (TC2) [4–6] model is a most viable one, and can reasonably give a dynamical elucidation of EWSB and heavy top-quark mass. In additon, the TC2 model can avoid the shortcomings of triviality and unnaturalness arising from the elementary Higgs field in the SM, and accommodate precision tests of electroweak theory. In the TC2 model, EWSB is driven by a different strong interaction sector and the top-quark mass is taken as a “constituent”. The topcolor interaction makes comparatively little contribution to EWSB but provides for the large top-quark mass, $(1-\epsilon)m_t$ $(0.03 \leqslant \epsilon \leqslant 0.1)$ [6], while the technicolor (TC) [7] interaction with an extended technicolor(ETC) interaction is responsible for the bulk of EWSB and the masses of light fermions including a very small portion of the top-quark mass ϵm_t. After dynamical EWSB, corresponding to the technicolor condensate and topcolor condensate there are two groups of scalars denoted as Φ_{TC} and Φ_{topC}, respectively. Either of them can be arranged into a

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$SU(2)$ doublet, and their roles in the TC2 model are quite analogous to the Higgs fields in a two-Higgs doublet model (2HDM) [8]. A linear combination of this effective 2HDM will form the longitudinal degrees of freedom of weak gauge bosons $W^{\pm}$ and Z, while the orthogonal linear combinations represent genuine physical states, top-pions $\pi_t^{0,\pm}$. In the fermion bubble approximation [4], the theory loosely predicts top-pions to lie in the mass range of about 100–300 GeV. Top-pions this light are disfavored by the data for R_b [9], but the contribution of new ETC gauge bosons can help to relax the constraint on the top-pion mass [10]. The two neutral CP-even Higgs modes in this effective 2HDM, labeled h_t^0 and h_{TC}^0, are known as the "top-Higgs" and the "techni-Higgs", respectively. The masses can be estimated in the Nambu-Jona-Lasinio (NJL) model in the large-N_c approximation. For the top-Higgs this is found to be on the order of $m_{h_t} \sim 2m_t$; for the techni-Higgs it is much higher. However, there is no reason to expect the NJL model to be correct; it only serves as a rough indication of where the top-Higgs mass could be; the masses of the top- and techni-Higgs modes may in fact be very small [11].

The presence of physical top-pions $\pi_t^{0,\pm}$, top-Higgs h_t^0, and techni-Higgs h_{TC}^0 in the low-energy spectrum is an essential ingredient of the TC2 model. These typical particle couplings to third-generation quarks and gauge bosons are to a large degree model dependent. Therefore, a study of the production and/or the decay process of these typical particles at present or future high-energy colliders could be used to test the TC2 model. Many signals of the TC2 model have already been studied in the work environment of linear colliders and hadron-hadron colliders [12–14], but much of the attention was focused on the three top-pions $\pi_t^{0,\pm}$. Nevertheless, the study of the top-Higgs production mechanism is also an important aspect in the TC2 phenomenology which could help us to search for top-Higgs at high energy colliders. In this work, we consider the associated production of a neutral top-Higgs with a top-quark pair in the TC2 model, i.e. $e^+e^- \to t\bar{t}h_t^0$, at future e^+e^- linear colliders, namely the International Linear Collider (ILC) with $\sqrt{s}=1$ TeV and the Compact Linear Collider (CLIC) with $\sqrt{s}=3$ TeV.

The remainder of the paper is organized as follows. In Sec. 2 we briefly review the TC2 model and in Sec. 3 we present the calculations for the production process $e^+e^- \to t\bar{t}h_t^0$ at the LC. Section 4 gives the numerical results for the production process, and a summary.

2 The topcolor assisted technicolor model

In the TC2 model two strongly interacting sectors are introduced. The topcolor interaction provides for the large top-quark mass but makes comparatively little contribution to EWSB, while the ETC is responsible for the bulk of EWSB but contributes almost nothing to m_t. Details of the TC2 may be found in Ref. [4]. Here, we briefly review the characteristics of TC2 theory most relevant to the present discussion.

At low energy, we can introduce two $SU(2)$ scalar doublets, Φ_{TC} and Φ_{topC}, corresponding to the technicolor condensates and topcolor condensates, respectively. The kinetic terms of Φ_{TC} and Φ_{topC} are given by

$$\mathcal{L}_{kine} = (D_\mu\Phi_{TC})^\dagger(D^\mu\Phi_{TC}) + (D_\mu\Phi_{topC})^\dagger(D^\mu\Phi_{topC}), \tag{1}$$

where the $SU(2)$ doublets Φ have the form

$$\Phi_{TC} = \begin{pmatrix} (\upsilon_T + H_{TC}^0 + i\Pi_{TC}^0)/\sqrt{2} \\ \Pi_{TC}^- \end{pmatrix}, \tag{2}$$

$$\Phi_{topC} = \begin{pmatrix} (f_\pi + H_t^0 + i\Pi_t^0)/\sqrt{2} \\ \Pi_t^- \end{pmatrix}, \tag{3}$$

where f_π is the vacuum expectation value (vev) of the top-quark pair condensate, υ_T is the vev of the technifermions condensate, and the covariant derivative is

$$D_\mu = \partial_\mu + ig\frac{\tau^i}{2}W_\mu^i + ig_Y\frac{Y}{2}B_\mu. \tag{4}$$

The hypercharge of the doublets is $Y=-1$, g is g_{weak}, and τ^i $(i=1,2,3)$ are the Pauli matrices.

The Pagels-Stokar formula [15] gives the value of the vev f_π in terms of the number of topcolors, the top-quark mass, and the scale at which the condensation occurs:

$$f_\pi^2 \approx \frac{N_c}{16\pi^2}m_t^2\left[\ln\left(\frac{\Lambda^2}{m_t^2}\right)+\kappa\right], \tag{5}$$

where κ is a constant of order 1. For condensation around the EWSB scale of 1 TeV, $f_\pi \simeq 60$ GeV, but it should be understood that this is only a rough guide, and f_π may in fact be somewhat lower or higher, say in the range 40–80 GeV. Allowing f_π to vary over this range does not qualitatively change our conclusions and has only minimal impact on our quantitative results. Therefore, we use the value $f_\pi = 60$ GeV throughout our analysis as a convenient baseline.

We can rotate the two doublets into such that $\langle \Phi_1 \rangle = \frac{\upsilon_{\rm w}}{\sqrt{2}}$ and $\langle \Phi_2 \rangle = 0$,

$$\begin{aligned} \Phi_1 &= (\cos\beta \Phi_{\rm TC} + \sin\beta \Phi_{\rm topC}) \\ &= \begin{pmatrix} (\upsilon_{\rm w} + h^0_{\rm TC} + {\rm i}G^0_{\rm TC})/\sqrt{2} \\ G^-_{\rm TC} \end{pmatrix}, \end{aligned} \tag{6}$$

$$\begin{aligned} \Phi_2 &= (-\sin\beta \Phi_{\rm TC} + \cos\beta \Phi_{\rm topC}) \\ &= \begin{pmatrix} (h^0_{\rm t} + {\rm i}\pi^0_{\rm t})/\sqrt{2} \\ \pi^-_{\rm t} \end{pmatrix}, \end{aligned} \tag{7}$$

where $\tan\beta = f_\pi/\upsilon_{\rm T}$, $\rm G^\pm$ and $\rm G^0$ are the Goldstone bosons whcich form the longitudinal degrees of freedom of $\rm W^\pm$ and Z, the triplet of top-pions $\pi^{0,\pm}_{\rm t}$ becomes physical degrees of freedom which are analogous to the neutral CP-odd and charged Higgs scalars of 2HDM. $\rm h^0_t$ and $\rm h^0_{TC}$ are known as the "top-Higgs" and "techni-Higgs" which are all CP-even.

The top-quark Yukawa term in the Lagrangian, ignoring mixing between the two Higgs modes, is written as

$$\begin{aligned} \mathcal{L}_{\rm Yuk,t} &= -\frac{1}{\sqrt{2}}(Y_{\rm t} f_\pi + \epsilon_{\rm t}\upsilon_{\rm T})\bar{\rm t}{\rm t} \\ &\quad -\frac{1}{\sqrt{2}}(Y_{\rm t} H^0_{\rm t} + \epsilon_{\rm t} H^0_{\rm TC})\bar{\rm t}{\rm t} \\ &\quad -\frac{\rm i}{\upsilon_{\rm w}\sqrt{2}}(Y_{\rm t}\upsilon_{\rm T} + \epsilon_{\rm t} f_\pi)\Pi^0_{\rm t}\bar{\rm t}{\rm t}, \end{aligned} \tag{8}$$

where $Y_{\rm t}$ is the topcolor Yukawa coupling, and $\epsilon_{\rm t}$ is a small ETC contribution. Once f_π is fixed, $\upsilon_{\rm T}$ is uniquely determined by the EWSB requirement that $f^2_\pi + \upsilon^2_{\rm T} = \upsilon^2_{\rm w} \approx (246\ {\rm GeV})^2$. For $f_\pi = 60$ GeV, we must have $\upsilon_{\rm T} = 239$ GeV. The measured top mass then fixes $Y_{\rm t}$ to be of order 2–3 for small $\epsilon_{\rm t}$. The maximal value of $Y_{\rm t}$ is $Y_{\rm t,max} = 4.1$ occurs when $\epsilon_{\rm t} = 0$. In addition, one can immediately see from Eq. (8) that the couplings of both the top-Higgs mode and the top-pion to top-quarks are enhanced by a factor of several ($Y^{\rm TC}_{\rm t}/Y^{\rm SM}_{\rm t} \simeq$3–5 for the top-Higgs and $(Y^{\rm TC}_{\rm t}\upsilon_{\rm T} - \epsilon_{\rm t} f_\pi)/\upsilon_{\rm w} Y^{\rm SM}_{\rm t} \simeq$3–4 for the top-pion) relative to the SM.

The top-quark mass is

$$m_{\rm t} = \frac{Y_{\rm t} f_\pi + \epsilon_{\rm t}\upsilon_{\rm T}}{\sqrt{2}}. \tag{9}$$

As mentioned above, the top-quark mass is a combination of $(1-\epsilon)m_{\rm t}$ generated by the topcolor dynamics and $\epsilon m_{\rm t}$, $\epsilon \ll 1$, generated by the ETC. Therefore $Y_{\rm t}$ and $\epsilon_{\rm t}$ can be written as

$$Y_{\rm t} = \frac{\sqrt{2}(1-\epsilon)m_{\rm t}}{f_\pi}, \quad \epsilon_{\rm t} = \frac{\sqrt{2}\epsilon\ m_{\rm t}}{\upsilon_{\rm T}}. \tag{10}$$

3 $\rm t\bar{t}h^0_t$ production at $\rm e^+e^-$ linear colliders

In the TC2 model, the tree-level Feynman diagrams of the process $\rm e^+e^- \to t\bar{t}h^0_t$ are shown in Fig. 1. There are two kinds of Feynman diagrams to the $\rm e^+e^- \to t\bar{t}h^0_t$ process at the tree-level. The first kind includes diagrams with the Higgsstrahlung off the top-quark line illustrated in Figs. 1(a) and 1(b). The second kind consists of diagrams with a Higgs boson emission off the virtual Z-boson line represented by the diagram in Figs. 1(c) and 1(d). The TC2 tree-level cross section of the process $\rm e^+e^- \to t\bar{t}h^0_t$ becomes practically proportional to $Y^2_{\rm t}$, which makes the reaction so sensitive to the top-Higgs Yukawa coupling.

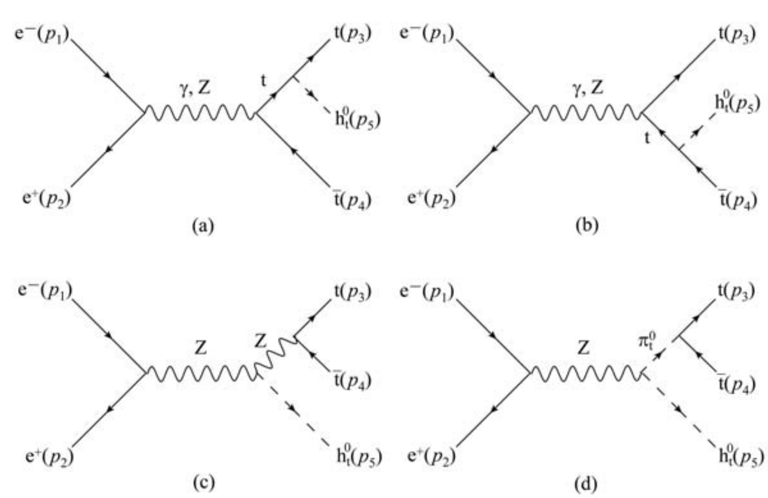

Fig. 1. The tree-level Feynman diagrams for the $\rm e^+e^- \to t\bar{t}h^0_t$ process in TC2 model.

The Feynman rules related to the top-pions and the top-Higgs are shown below [11]:

$$\begin{aligned}
&h_t^0\bar{t}t: -\frac{1}{\sqrt{2}}Y_t, \\
&\pi_t^0\bar{t}t: \frac{i}{\sqrt{2}}\left(Y_t\frac{\upsilon_T}{\upsilon_w}-\epsilon_t\frac{f_\pi}{\upsilon_w}\right)\gamma_5, \\
&Z^\mu Z_\mu h_t^0: \frac{1}{2}f_\pi\frac{g^2}{\cos^2\theta_w}, \\
&Z^\mu h_t^0\pi_t^0: -\frac{i}{2}\frac{\upsilon_T}{\upsilon_w}\frac{g}{\cos\theta_w}(p^\mu_{h_t}-p^\mu_{\pi_t}).
\end{aligned} \tag{11}$$

According to the Feynman diagrams in Fig. 1 and the Feynman rules mentioned above, we can directly write the explicit forms of the production amplitudes for the process $e^-(p_1)e^+(p_2)\to t(p_3)\bar{t}(p_4)h_t^0(p_5)$, which are shown as follows:

$$M = M_a^\gamma + M_a^Z + M_b^\gamma + M_b^Z + M_c^Z + M_d^Z, \tag{12}$$

$$M_a^\gamma = -\frac{\sqrt{2}e^2}{3}Y_t\bar{u}_t(p_3)\frac{(\not{p}_3+\not{p}_5+m_t)}{(p_3+p_5)^2-m_t^2} \times\gamma_\mu v_{\bar{t}}(p_4)\frac{1}{(p_1+p_2)^2}\bar{v}_{e^+}(p_2)\gamma^\mu u_{e^-}(p_1), \tag{13}$$

$$M_a^Z = -\frac{1}{4\sqrt{2}}\frac{g^2}{\cos^2\theta_w}Y_t\bar{u}_t(p_3)\frac{(\not{p}_3+\not{p}_5+m_t)}{(p_3+p_5)^2-m_t^2}\gamma_\mu\left(P_L-\frac{4}{3}\sin^2\theta_w\right)v_{\bar{t}}(p_4) \times\frac{1}{(p_1+p_2)^2-m_Z^2}\bar{v}_{e^+}(p_2)\gamma^\mu(P_L-2\sin^2\theta_w)u_{e^-}(p_1), \tag{14}$$

$$M_b^\gamma = \frac{\sqrt{2}e^2}{3}Y_t\bar{u}_t(p_3)\gamma_\mu\frac{(\not{p}_4+\not{p}_5-m_t)}{(p_4+p_5)^2-m_t^2}v_{\bar{t}}(p_4)\frac{1}{(p_1+p_2)^2}\bar{v}_{e^+}(p_2)\gamma^\mu u_{e^-}(p_1), \tag{15}$$

$$M_b^Z = \frac{1}{4\sqrt{2}}\frac{g^2}{\cos^2\theta_w}Y_t\bar{u}_t(p_3)\gamma_\mu\left(P_L-\frac{4}{3}\sin^2\theta_w\right)\frac{(\not{p}_4+\not{p}_5-m_t)}{(p_4+p_5)^2-m_t^2}v_{\bar{t}}(p_4) \times\frac{1}{(p_1+p_2)^2-m_Z^2}\bar{v}_{e^+}(p_2)\gamma^\mu(P_L-2\sin^2\theta_w)u_{e^-}(p_1), \tag{16}$$

$$M_c^Z = \frac{1}{4}f_\pi\frac{g^4}{\cos^4\theta_w}\bar{u}_t(p_3)\gamma_\mu\left(P_L-\frac{4}{3}\sin^2\theta_w\right)v_{\bar{t}}(p_4)\frac{1}{(p_3+p_4)^2-m_Z^2} \times\frac{1}{(p_1+p_2)^2-m_Z^2}\bar{v}_{e^+}(p_2)\gamma^\mu(P_L-2\sin^2\theta_w)u_{e^-}(p_1), \tag{17}$$

$$M_d^Z = \frac{i}{4\sqrt{2}}\frac{\upsilon_T^2}{\upsilon_w^2}\frac{g^2}{\cos^2\theta_w}Y_t\bar{u}_t(p_3)\gamma_5 v_{\bar{t}}(p_4)\frac{1}{(p_3+p_4)^2-m^2_{\pi_t}}\frac{1}{(p_1+p_2)^2-m_Z^2} \times(p_5-p_3-p_4)_\mu\bar{v}_{e^+}(p_2)\gamma^\mu(P_L-2\sin^2\theta_w)u_{e^-}(p_1), \tag{18}$$

where θ_w is the Weinberg angle, $P_{L,R}=\frac{1}{2}(1\mp\gamma_5)$ are the left and right chirality projectors.

4 Numerical results and discussion

In our numerical evaluation, the independent input parameters involved in the production amplitudes are $m_t = 172.0$ GeV, $m_Z = 91.188$ GeV, $\alpha_s(m_Z) = 0.1184$, and $\sin^2\theta_w = 0.231$ [16]. And there are also four model-dependent parameters in our calculation which are the top-pion decay constant υ_T, the parameter ϵ, and the mass of the top-Higgs $m_{h_t^0}$ and the neutral top-pions $m_{\pi_t^0}$. We take $\upsilon_T = 60$ GeV, $\epsilon = 0.06$, $m_{\pi_t^0} = 300$ GeV for convenience and let $m_{h_t^0}$ to vary in the range of 200–400 GeV [17]. The final numerical results are summarized in Figs. 2–3.

In Fig. 2(a), we plot the dependence of the cross section of $e^+e^-\to t\bar{t}h_t^0$ on the top-Higgs mass $m_{h_t^0}$ for various values of the LC center of mass energy $\sqrt{s} = 1000$ GeV, 1500 GeV, and 2000 GeV, respectively. In addition, to see the effect of $\sqrt{s}$ on the production cross section, in Fig. 2(b) we show the cross section σ as a function of $\sqrt{s}$ with $m_{h_t^0} = 200$ GeV, 300 GeV, and 400 GeV, respectively. From Fig. 2(a) and 2(b), one can see that the dependence of the cross section on $m_{h_t^0}$ is quite obvious, and the cross section decreases as $m_{h_t^0}$ increases, which is because the phase space is depressed by large $m_{h_t^0}$. And the effect of $\sqrt{s}$ on the production cross section is more significant, nearly one order of magnitude change in going from 1000 GeV to 2000 GeV. Furthermore, the total cross section is typically of the order of 1.0–7.5 fb in the energy range between 1000 GeV and 2000 GeV of the LC for the whole top-Higgs mass region of interest.

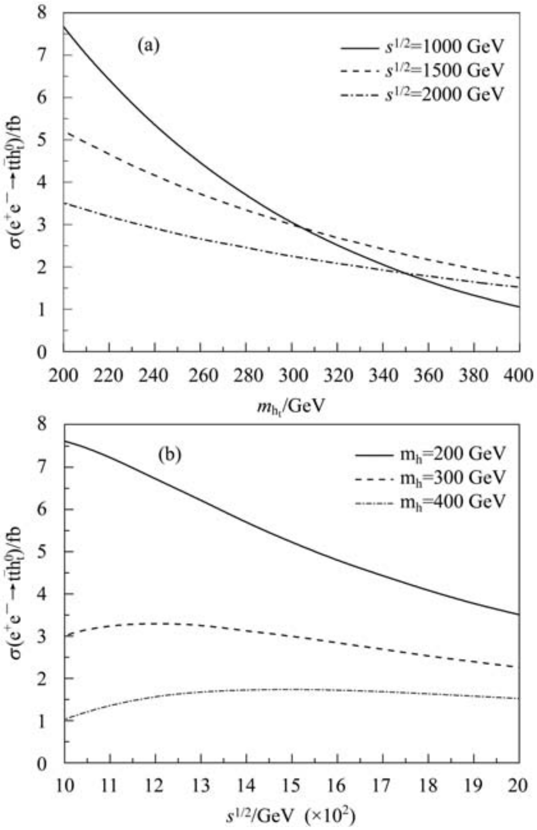

Fig. 2. (a) The cross sections of $e^+e^- \to t\bar{t}h_t^0$ production as a function of the top-Higgs mass $m_{h_t^0}$ for various values of the LC center of mass energy $\sqrt{s}$; (b) The cross sections as a function of $\sqrt{s}$ for various values of $m_{h_t^0}$.

In Fig. 3(a) and 3(b), we show the distributions of the transverse momenta of the final states (p_T^h and p_T^t) for the process $e^+e^- \to t\bar{t}h_t^0$ at the LC. Because of CP conservation, the distributions of the transverse momentum of an anti-top-quark should be the same as that of $d\sigma/dP_T^t$ shown in Fig. 3(b). From Fig. 3(a) and 3(b), we can find that (i) when $m_h = 200$ GeV, the signs of associated production $t\bar{t}h_t^0$ in the regions around $p_T^h \sim 175$ GeV and $p_T^t \sim 225$ GeV are more significant than in other regions, (ii) when $m_h = 400$ GeV, the significant regions of associated production $t\bar{t}h_t^0$ are around $p_T^h \sim 200$ GeV and $p_T^t \sim 175$ GeV. are more significant than in other regions.

Now, we will focus on considering how to detect h_t^0 via the process $e^+e^- \to t\bar{t}h_t^0$ and find the best channel to detect h_t^0. The possible decay modes of h_t^0 are $t\bar{t}$

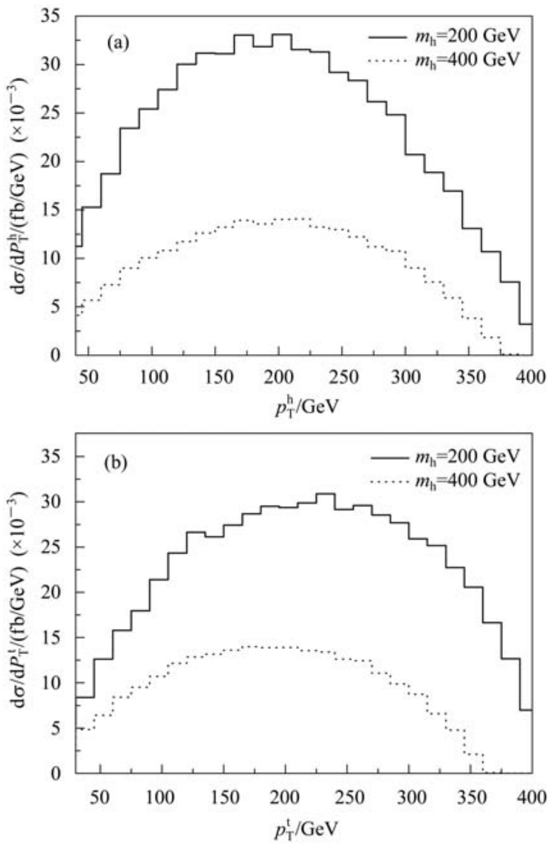

Fig. 3. The distributions of the transverse momenta of top-Higgs, p_T^h (a), and top-quark, p_T^t (b), for the process $e^+e^- \to t\bar{t}h_t^0$ with $m_{h_t^0} = 200$ GeV and 400 GeV, respectively.

(for $m_{h_t^0} > 2m_t$), $t\bar{c}$, $b\bar{b}$, WW, ZZ, and gg [12]. For $m_{h_t^0} > 2m_t$, the main decay mode is $h_t^0 \to t\bar{t}$. As is known, the couplings of h_t^0 to the three families of 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 top-Higgs to top and quark. Below the $t\bar{t}$ threshold the dominant decay mode is the top-charm channel with typical branching ratios of about 70%. In the 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 in the SM. Therefore, when $m_{h_t^0} < 2m_t$, $e^+e^- \to t\bar{t}h_t^0 \to t\bar{t}t\bar{c}$ is the most ideal channel to detect neutral top-Higgs with a clean background in the SM. The cross section of $e^+e^- \to t\bar{t}h_t^0 \to t\bar{t}t\bar{c}$ is about 4.46 fb for $m_{h_t^0} = 260$ GeV and $\sqrt{s} = 1000$ GeV. There are about 1500 signal events can be produced via $t\bar{c}$ channel with annually integral luminosity of 500 fb^{-1} at the LC. Such sufficient signal events could be detected with the clean background.

In summary, the discovery of a Higgs boson and the elucidation of the mechanism responsible for

EWSB are some of the most important tasks of the next generation of high-energy physics collider experiments. The TC2 model is an attractive model which combines the technicolor mechanism with topcolor condensation. The presence of physical top-pions $\pi_t^{0,\pm}$, top-Higgs h_t^0, and techni-Higgs h_{TC}^0 in the low-energy spectrum is an essential ingredient of the TC2 model and these typical particle couplings to third-generation quarks and gauge bosons are to a large degree model dependent. Therefore, a study of the production and/or decay process of these typical particles can be used to test the topcolor idea. In this work, we have studied the associated production processes of the neutral top-Higgs with a pair of top-quarks at the future LC within the TC2 model. The results show that the total cross section is typically of the order of 1.0–7.5 fb in the energy range between 1000 GeV and 2000 GeV of the LC for the whole top-Higgs mass region of interest. Due to the large cross section of $t\bar{t}h_t^0$ production and the top-charm decay mode of h_t^0 for $m_{h_t^0} < 2m_t$, the process $e^+e^- \to t\bar{t}h_t^0 \to t\bar{t}t\bar{c}$ can play an important role in the probe of neutral top-Higgs and the test of the TC2 model with the clean background.

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