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Searching for Flavor-Changing Neutral-Current Signals via $e^+e^-(\gamma\gamma) \to t\bar{c}h_t^0$ in Topcolor-Assisted Technicolor Model*

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Abstract *In the context of the top-color-assisted technicolor (TC2) model, the flavor-changing neutral-current (FCNC) interaction induced by the top-higgs (h_t^0) are predicted at tree level. We study the relevant processes of $e^+e^-(\gamma\gamma) \to t\bar{c}h_t^0$ at the International Linear Collider (ILC). It is found that these rare processes production rates can be enhanced significantly in the TC2 model. Especially for the process $\gamma\gamma \to t\bar{c}h_t^0$, the total cross section will reach a few fb in the reasonable parameter space. We also calculate the distributions of transverse momenta, pseudo-rapid and invariant mass of the top-higgs. In view of the main decay modes of top-higgs for $m_{h_t^0} < 2m_t$, we find that there will be several hundreds FCNC events produced at the ILC with annually integral luminosity of 500 fb^{-1}. Due to the clean background, such FCNC signals can possibly be detected at the ILC.*

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Key words: top quark, flavor-changing neutral-current, international linear collider

1 Introduction

It is widely believed that the hadron colliders, such as Tevatron and LHC, can directly probe possible new physics beyond the standard model (SM) up to a few TeV, while the ILC is also required to complement the probe of the new particles with detailed measurement due to the clean environment.[1] A unique feature of the future e^+e^- colliders is that it can be transformed to $e\gamma$ or $\gamma\gamma$ modes by the laser-scattering method. 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 colliders are much richer than that in the e^+e^- mode. Therefore, the ILC will provide us a good chance to pursuit new physics particles.

As the heaviest fermion close to the weak scale,[2] top quark is expected to play a special role in the electroweak symmetry breaking (EWSB) mechanism. So far its properties are measured with a rough precision due to the limited statistics at the Fermilab Tevatron[3] and hence there remains plenty of room for new physics in the top quark sector.[4] Due to the large mass of the top quark, it may be more sensitive to new physics than other fermions and serve as a window to provide fruitful information about new physics beyond the SM. It is well known that the FCNC interaction are forbbiden by the Glashow–Iliopoulos–Maiani (GIM) mechanism at tree level in the SM. Any observable FCNC signals will be the robust harbinger of the new physics. Actually, the top quark FCNC interactions have been extensively studied in various extensions of the SM, such as the supersymmetric model,[5] the little Higgs model.[6] It has been realized that the top quark FCNC interactions modes can be enhanced by several orders of magnitude in some scenarios beyond the SM and might fall in the reach of the future Colliders.[7]

As a possible solution to avoid the shortcomings of the triviality and unnaturalness arising from the elementary Higgs field, the technicolor theory was proposed and so far remains a popular candidate for new physics beyond the standard model (SM). Among the various TC models, the top-color-assisted technicolor (TC2) model is a more realistic one,[8] which can provide an additional source of EWSB and also solve heavy top quark problem. One of the most general predictions of the TC2 model is the existence of three Pseudo–Goldstone Boson, so called top-pions ($\pi_t^{\pm}, \pi_t^0$) and an isospin singlet boson called top-Higgs (h_t^0), which masses are in the range of hundreds of GeV. These new particles couple to the third generation fermions preferentially and can cause the tree-level FCNC couplings with top and charm quarks. As these couplings are proportional to the corresponding quark masses, the FCNC processes induced by $t{-}c{-}(\pi_t^0, h_t^0)$ interaction may be greatly enhanced. So, the study of such processes can provide very important information on the TC2 model.

So far, lots of FCNC signals of this model have already studied in the work environment of linear colliders and hadron-hadron colliders,[9−12] but much of the attention was focused on the loop effects of charged and neutral top-pions and new gauge bosons. Here we wish to discuss the prospects of neutral top-Higgs. We study the tree-

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level production processes $e^+e^-(\gamma\gamma) \to t\bar{c}h_t^0$ at the ILC. Due to the clean environment, these FCNC signals may be discovered at the ILC. Considering the main decay mode of the top-higgs $h_t^0 \to t\bar{c}$ for $m_{h_t^0} < 2m_t$, we also estimate the possible FCNC events and figure out whether they can reach the sensitivity of the ILC.

This paper is organized as follows. In Sec. 2 we briefly review the basics content related to our calculation of the TC2 model and present the calculations for the production process. The numerical results and discussions are shown in Sec. 3. Finally, we give a short conclusion in Sec. 4.

2 Production Cross Section of $e^+e^-(\gamma\gamma) \to t\bar{c}h_t^0$

In the TC2 model, the new strong dynamics top-color is assumed to be chiral critically strong at the scale of 1 TeV, and it is coupled preferentially to the third generation. In this model, the EWSB is driven mainly by TC interactions and extended TC gives the contributions to all ordinary quark and lepton masses, including a very small portion of the top quark masses parameterized by ε: $m_t' = \varepsilon m_t$. The bare value of ε is generated at the extended-technicolor (ETC) scale. From the theoretical and phenomenological point of view, we can take $0.03 \le \varepsilon \le 0.1$[13] in the calculations. The top-color interactions also make small contributions to the EWSB and give rise to the main part of the top quark mass $(1-\varepsilon)m_t$. The top-color interactions are nonuniversal and therefore do not possess the GIM mechanism. The nonuniversal gauge interactions result in new flavor-changing coupling vertexes when one writes the interactions in the quark mass eigenstates. So that this kind of model predicts the top-higgs (h_t^0) with large Yukawa couplings to the third generation and can induce new flavor-changing couplings. The relevant including the top-charm transition for the neutral top-higgs vertices can be written as[8]

$$\mathcal{L} = \frac{m_t \tan\beta}{v_\omega}(1-\varepsilon)K_{\rm UR}^{tc}K_{\rm UL}^{tt^*}\bar{t}_L c_R h_t^0 + \text{h.c.}\,, \qquad (1)$$

where the factor $\tan\beta = \sqrt{(v_\omega/v_t)^2 - 1}$ reflects the effect of the mixing between the top-higgs h_t^0 and the would-be Goldstone bosons,[14] $v_\omega = 174$ GeV is the electroweak symmetry-breaking scale, and $v_t \approx 60$–100 GeV is the top-pion decay constant, which can be estimated from the pagels-strokar formula. $K_{\rm UR}$ and $K_{\rm UL}$ are the rotation matrices that transform the weak eigenstates of right-handed and left-handed up-type quarks to their mass eigenstates, respectively. To yield a realistic form of the Cabibbo–Kobayashi–Maskawa matrix V, it has been shown that their values can be parameterized as[8]

$$K_{\rm UL}^{tt} = 1\,, \quad K_{\rm UR}^{tt} \approx \frac{m_t'}{m_t} = 1 - \varepsilon\,, \qquad (2)$$

$$K_{\rm UR}^{tc} \le \sqrt{1 - (K_{\rm UR}^{tt})^2} \approx \sqrt{2\varepsilon - \varepsilon^2}\,. \qquad (3)$$

With the above flavor-changing coupling $h_t^0 - t - c$, we plot the Feynman diagrams in Fig. 1 for the processes $e^+e^-(\gamma\gamma) \to t\bar{c}h_t^0$.

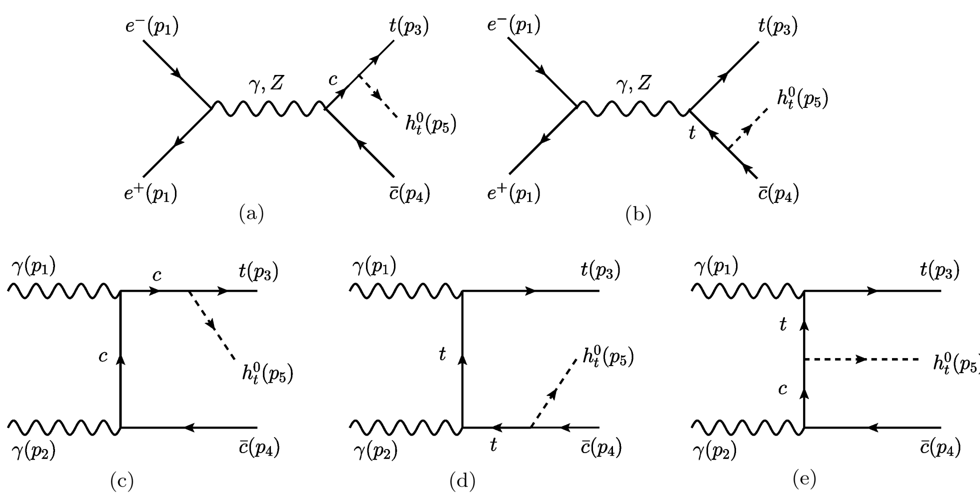

Fig. 1 Feynman diagrams of the processes $e^+e^-(\gamma\gamma) \to t\bar{c}h_t^0$ in the TC2 model. It is not plotted for these diagrams with the interchange of the two incoming photons.

The explicit amplitude expressions for process $e^+e^-(\gamma\gamma) \to t\bar{c}h_t^0$ in Fig. 1 are shown as follows:

$$M_{e^+e^-} = M_a^\gamma + M_b^\gamma + M_a^Z + M_b^Z\,, \quad M_{\gamma\gamma} = M_c + M_d + M_e\,, \qquad (4)$$

$$M_a^\gamma = i\frac{2m_t\tan\beta}{3v_\omega}e^2 K_{\rm UR}^{tc}K_{\rm UL}^{tt^*}G(p_3+p_5, m_c)G(p_1+p_2, 0)\bar{u}_t(p_3)P_R(\not{p}_3 + \not{p}_5 + m_c)\gamma^\mu v_{\bar{c}}(p_4)\bar{v}_{e^+}(p_2)\gamma_u u_{e^-}(p_1)\,, \qquad (5)$$

$$M_b^\gamma = i\frac{2m_t\tan\beta}{3v_\omega}e^2K_{\rm UR}^{tc}K_{\rm UL}^{tt^*}G(p_4+p_5,m_c)G(p_1+p_2,0)\bar{u}_t(p_3)P_R(-\not{p}_4-\not{p}_5+m_c)\gamma^\mu v_{\bar{c}}(p_4)\bar{v}_{e^+}(p_2)\gamma_u u_{e^-}(p_1)\,, \tag{6}$$

$$M_a^Z = -i\frac{m_t\tan\beta}{v_\omega}\frac{g^2}{c_w^2}K_{\rm UR}^{tc}\;K_{\rm UL}^{tt^*}G(p_3+p_5,m_c)G(p_1+p_2,m_Z)\bar{u}_t(p_3)P_R(\not{p}_3+\not{p}_5+m_c)\gamma^\mu \times\Big[\Big(\frac{1}{2}-\frac{2}{3}s_w^2\Big)P_L-\frac{2}{3}s_w^2P_R\Big]v_{\bar{c}}(p_4)\bar{v}_{e^+}(p_2)\gamma_u\Big[\Big(-\frac{1}{2}+s_w^2\Big)P_L+s_w^2P_R\Big]u_{e^-}(p_1)\,, \tag{7}$$

$$M_b^Z = -i\frac{m_t\tan\beta}{v_\omega}\frac{g^2}{c_w^2}K_{\rm UR}^{tc}K_{\rm UL}^{tt^*}G(p_4+p_5,m_t)G(p_1+p_2,m_Z)\bar{u}_t(p_3)\gamma^\mu\Big[\Big(\frac{1}{2}-\frac{2}{3}s_w^2\Big)P_L-\frac{2}{3}s_w^2P_R\Big] \times(-\not{p}_4-\not{p}_5+m_t)P_Rv_{\bar{c}}(p_4)\bar{v}_{e^+}(p_2)\gamma_u\Big[\Big(-\frac{1}{2}+s_w^2\Big)P_L+s_w^2P_R\Big]u_{e^-}(p_1)\,, \tag{8}$$

$$M_c = i\frac{4m_t\tan\beta}{9v_\omega}e^2\;K_{\rm UR}^{tc}K_{\rm UL}^{tt^*}G(p_3+p_5,m_c)G(p_2-p_4,m_c)\bar{u}_t(p_3)P_R(\not{p}_3+\not{p}_5+m_c)\not{\epsilon}(p_1)(\not{p}_2-\not{p}_4+m_c)\not{\epsilon}(p_2)v_{\bar{c}}(p_4)\,, \tag{9}$$

$$M_d = i\frac{4m_t\tan\beta}{9v_\omega}e^2K_{\rm UR}^{tc}K_{\rm UL}^{tt^*}G(p_3-p_1,m_t)G(p_2-p_4,m_c)\bar{u}_t(p_3)\not{\epsilon}(p_1)(\not{p}_3-\not{p}_1+m_t)P_R(\not{p}_2-\not{p}_4+m_c)\not{\epsilon}(p_2)v_{\bar{c}}(p_4)\,, \tag{10}$$

$$M_e = i\frac{4m_t\tan\beta}{9v_\omega}e^2\;K_{\rm UR}^{tc}K_{\rm UL}^{tt^*}G(p_3-p_1,m_t)G(p_4+p_5,m_t)\bar{u}_t(p_3)\not{\epsilon}(p_1)(\not{p}_3-\not{p}_1+m_t)\not{\epsilon}(p_2)(-\not{p}_4-\not{p}_5+m_t)P_Rv_{\bar{c}}(p_4)\,, \tag{11}$$

where, $G(p,m) = 1/(p^2-m^2)$ is the propagator of the particle, $P_{L,R} = (1/2)(1\mp\gamma_5)$ are the left and right chirality projectors, p_1, p_2 are the momenta of the incoming $e^+e^-(\gamma\gamma)$, and p_3, p_4, p_5 are the momenta of the outgoing final states $t, \bar{c}$ and h_t^0, $s_w^2 = \sin_w^\theta$, $c_w^2 = \cos_w^\theta$.

With the above amplitudes M_c, M_d, and M_e, we can directly obtain the production cross section $\hat{\sigma}(\hat{s})$ for the subprocess $\gamma\gamma \to t\bar{c}h_t^0$ and the total cross sections at the e^+e^- linear collider can be obtained by folding $\hat{\sigma}(\hat{s})$ with the photon distribution function $F(x)$ which is given in Ref. [15],

$$\sigma_{\rm tot}(s)=\int_{x_{\min}}^{x_{\max}}dx_1\int_{x_{\min}x_{\max}/x_1}^{x_{\max}}dx_2F(x_1)F(x_2)\hat{\sigma}(\hat{s}), \tag{12}$$

where s is the squared center-of-mass energy of e^+e^- collision. The subprocess occurs effectively at $\hat{s} = x_1x_2s$, and x_i are the fractions of the electron energies carried by the photons. The explicit form of the photon distribution function $F(x)$ is

$$F(x) = \frac{1}{D(\xi)}\Big[1-x+\frac{1}{1-x}-\frac{4x}{\xi(1-x)}+\frac{4x^2}{\xi^2(1-x)^2}\Big], \tag{13}$$

with

$$D(\xi) = \Big(1-\frac{4}{\xi}-\frac{8}{\xi^2}\Big)\ln(1+\xi)+\frac{1}{2}+\frac{8}{\xi}-\frac{1}{2(1+\xi)^2}, \tag{14}$$

where $x_{\max} = \xi/(1+\xi)$, $\xi = 4E_0/\omega_0m_e^2$, E_0 and ω_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 ω_0. So we require $\omega_{\max}\omega_0 \le m_e^2$, which implies $\xi = 2(1+\sqrt{2}) = 4.8$. We can obtain $x_{\max} = 0.83$ and $D(\xi_{\max}) = 1.8$. The minimum value for x is determined by the production threshold

$$x_{\min} = \frac{(m_t+m_c+m_h^0)^2}{x_{\max}s}\,. \tag{15}$$

3 Numerical Results and Discussions

To get the numerical results of the cross sections, we should also fix some parameters in the SM and TC2 model as $m_t = 174.3$ GeV, $m_c = 1.25$ GeV, $s_W^2 = 0.23$, $M_Z = 91.87$ GeV, $\alpha_e = 1/128$, and $v_t = 60$ GeV.[16] There are two free parameters in the TC2 model, which are also involved in the production amplitudes. They are the top-higgs mass $m_{h_t^0}$ and the ε. The parameter ε and the mass of neutral top-Higgs h_t^0 are all model-dependent, we select them as free parameters ε $(0.03\sim 0.1)$ and $m_{h_t^0}$ (150 GeV$\sim$ 400 GeV) to estimate the total cross section of $t\bar{c}h_t^0$ associated production at the ILC. The cross section $e^+e^-(\gamma\gamma) \to t\bar{c}h_t^0$ versus the various values ε and the parameter $m_{h_t^0}$ are summarized in Figs. 2–3. The ILC with the center of mass (c.m.) energy $\sqrt{s} = 300$ GeV–1500 GeV and the yearly luminosity 500 fb^{-1} has been planned,[1] the c.m. energy $\sqrt{s} = 500$ GeV is too low to produce it when choose the bigger $m_{h_t^0}$, so we choose $\sqrt{s} = 1000,\ 1500$ GeV, as examples. Meanwhile, taking account of the detector acceptance and to make the prediction more realistic, we have taken the basic cuts on the transverse momentum and the pseudo-rapidity for the final state particles, we require that the transverse momentum of c-quark is larger than 15 GeV and its pseudo rapidity is less than 2.5. We can see that the time-like momentum may hit the top pole in the top-quark propagator. Thus we 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. We take the width of top quark to be 1.56 GeV,[16] and the charge-conjugate channel $\bar{t}ch_t^0$ production is also included in our calculation.

It can be seen from Fig. 2, we show the dependence on ε for two different top-higgs masses. Obviously, the cross sections of the processes $e^+e^- \to t\bar{c}h_t^0$ and $\gamma\gamma \to t\bar{c}h_t^0$ rise very fast with the ε increasing. The reason is that the coupling $h_t^0 tc$ is proportional to ε. This indicates that the extended technicolor gives sizable contributions to these FCNC processes when choose large ε. Even with stricter constraints on the ε, the large values of the ε can also enhance the cross sections significantly. Meanwhile, in Fig. 3, we can see that the cross section decreases when we choose the bigger $m_{h_t^0}$, it is easy to explain since the phases pace is depressed strongly by large $m_{h_t^0}$. In addition, comparing numerical results of the process $\gamma\gamma \to t\bar{c}h_t^0$ with that of $e^+e^- \to t\bar{c}h_t^0$, we can find that the cross section of $\gamma\gamma \to t\bar{c}h_t^0$ is several orders of magnitude larger than that of $e^+e^- \to t\bar{c}h_t^0$ for the same parameter, which just reach 10^{-1} fb maximally. This is because the process $e^+e^- \to t\bar{c}h_t^0$ suffered a severe s-channel suppression at high center-of-mass energy. Therefore, photon collision mode can provide us a better way to search for neutral top-higgs, and more detailed information about $t\bar{c}h_t^0$ FC couplings in the TC2 model should be obtained via $\gamma\gamma \to t\bar{c}h_t^0$.

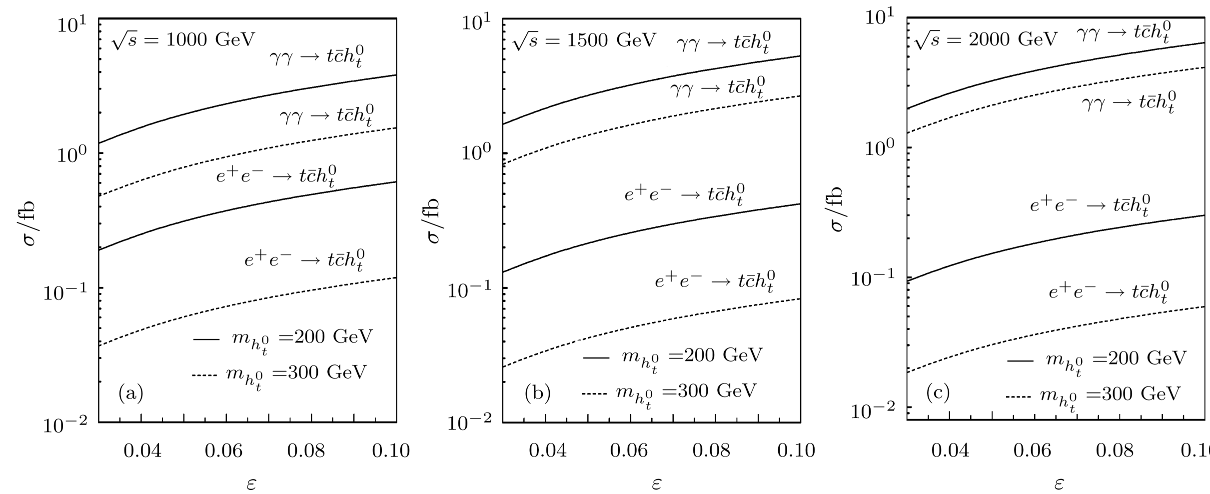

Fig. 2 The cross section of the processes $e^+e^-(\gamma\gamma) \to t\bar{c}h_t^0$ in the TC2 model as a functions of ε.

From Fig. 3, we can see that the cross sections of $\gamma\gamma \to t\bar{c}h_t^0$ will maximally reach to 2 fb at the $\sqrt{s} = 1000$ GeV for $m_{h_t^0} = 300$ GeV. The possible decay modes of h_t^0 are $t\bar{t}$, $t\bar{c}$, $b\bar{b}$, gg, $\gamma\gamma$, $Z\gamma$. The main mode is $h_t^0 \to t\bar{t}$ for $m_{h_t^0} > 2m_t$. If the mass of h_t^0 are less than $2m_t$, then $h_t^0 \to t\bar{c}$ will be the largest one in all possible decay modes.[9] Taking $m_{h_t^0} = 300$ GeV for example, the branching ratio of $h_t \to t\bar{c}$ can be easily evaluated to be 0.63. Then there might be several hundreds events that can be produced with annually integral luminosity of 500 fb^{-1}. Moreover, Since the neutral top-pion with mass less than $2m_t$ decay mainly into $\bar{t}c$ or $t\bar{c}$, the final state should be $\bar{t}tc\bar{c}$ or $ttc\bar{c}$. For the case of $\bar{t}t\bar{c}c$, the large SM background makes it impossible to distinguish the signal form the noise. However, the final state $tt\bar{c}\bar{c}$ is a flavor changing in the SM, and the background of $\gamma\gamma \to t\bar{c}h_t^0 \to tt\bar{c}\bar{c}$ should be very clean. So, it is a better way to probe the neutral top-higgs via $tt\bar{c}\bar{c}$ signals. With large cross section and clean background of signal $tt\bar{c}\bar{c}$, the neutral top-higgs should be detected at future linear colliders. Therefore, the processes $\gamma\gamma \to t\bar{c}h_t$ in which the FCNC effects occur in both productions and decays would provide a unique opportunity to detect FCNC events at the ILC in the TC2 model.

In Figs. 4(a)–4(b), we display the transverse momentum and pseudo-rapid distribution of top-higgs. It can be seen that the energetic top-higgs will be mainly produced at the central region of the detector. As is expected, the $h_t^0 - c$ invariant mass distribution shows a peak near the production threshold of the h_t^0. These characteristic will be helpful to discover top-higgs at the ILC.

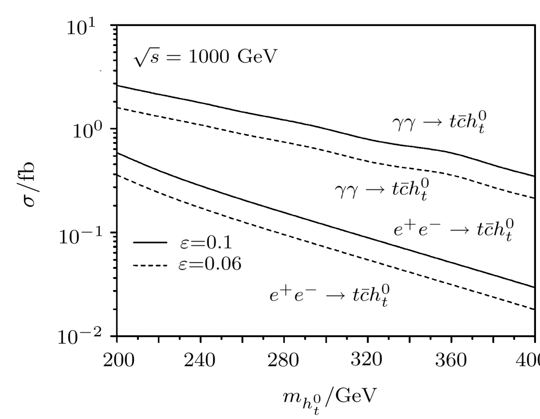

Fig. 3 The cross section of the processes $e^+e^-(\gamma\gamma) \to t\bar{c}h_t^0$ in the TC2 model as a functions of $m_{h_t^0}$.

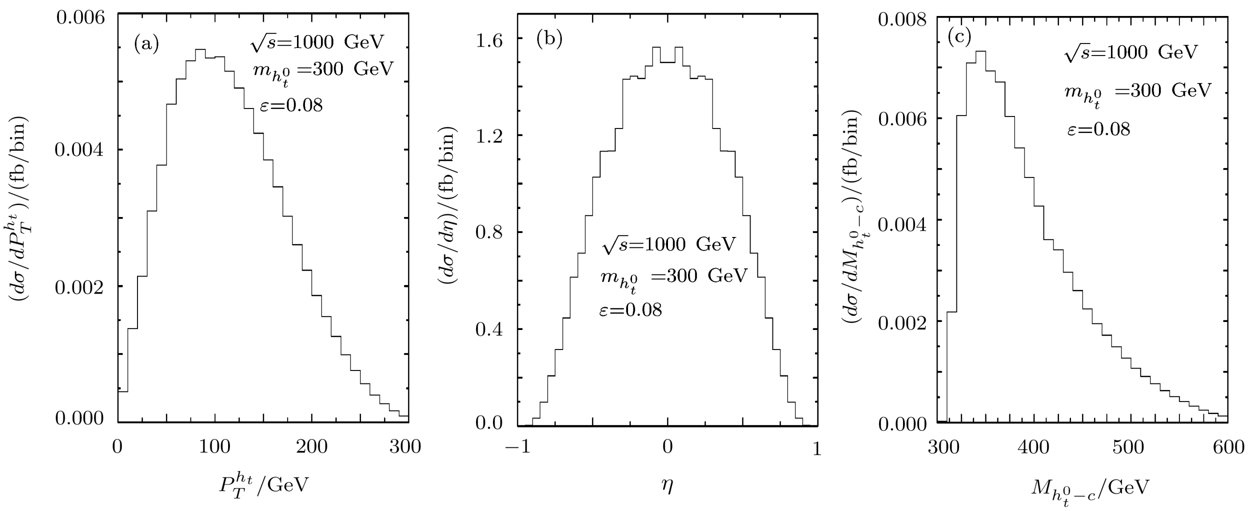

Fig. 4 Transverse momentum (a), pseudo-rapid (b) distribution of top-higgs and top-higgs-charm invariance mass distribution (c).

4 Conclusion

In summary, we evaluate the FCNC neutral top-higgs production process via $e^+e^-(\gamma\gamma) \to t\bar{c}h_t$ at the ILC in the TC2 model. The study shows that cross section of such flavor-changing process can reach the level of a few fb in the reasonable parameter space. Considering main decay mode of h_t for $m_{h_t} < 2m_t$, there will be such copious FCNC events at the ILC. With the large cross section and clean environment, these production processes can be served as the probe to test the TC2 model at the ILC.

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