Associated production of a neutral top-Higgs with a heavy-quark pair in the $\gamma\gamma$ collisions at ILC*

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Abstract We have studied the associated production processes of a neutral top-Higgs in the topcolor assisted technicolor model with a pair of heavy quarks in $\gamma\gamma$ collisions at the International Linear Collider (ILC). We find that the cross section for $\mathrm{t\bar{t}h_t}$ in $\gamma\gamma$ collisions is at the level of a few fb with the c.m. energy $\sqrt{s}=1000$ GeV, which is consistent with the results of the cross section of $\mathrm{t\bar{t}H}$ in the standard model and the cross section of $\mathrm{t\bar{t}h}$ in the minimal supersymmetric standard model. It should be clear that hundreds of to thousands of $\mathrm{h_t}$ per year can be produced at the ILC. This process of $\gamma\gamma\rightarrow \mathrm{t\bar{t}h_t}$ is really interesting in testing the standard model and searching the signs of technicolor.

Key words topcolor assisted technicolor, top-Higgs, cross section, International Linear Collider

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1 Introduction

The electroweak symmetry breaking (EWSB) mechanism remains an open question in spite of the success of the standard model (SM) compared with the precision measurement data. With the advent of the new collider technique, high energy and high intensity photon beams can be obtained by using Compton laser photons scattering off the colliding electron and positron beams [1]. The collisions of high energy photons produced at the linear collider provide a comprehensive laboratory for testing the SM and probing new physics beyond the SM [2].

As we know, the initial technicolor (TC) [3], as a theory of dynamical EWSB, is one of the important candidates for new physics beyond the SM, especially the topcolor assisted technicolor (TC2) model, proposed by C. T. Hill [4]. This combines technicolor with topcolor, with the former mainly responsible for EWSB and the latter for generating a major part of the top quark mass. Since this model could provide a rational answer to some of the questions, it is of significant interest. This model predicts three top-pions (π_t^0, $\pi_t^{\pm}$) and one top-Higgs ($\mathrm{h_t}$) with large Yukawa couplings to the third generation quarks, so these new particles can be regarded as a typical feature of the model. Many signals of the model have already been studied in the work environment of linear colliders and hadron-hadron colliders [5–7], but much of the attention was focused on the neutral and charged top pions and new gauge bosons. Here we wish to discuss the prospects of neutral top-Higgs.

In the SM, the Higgs boson associated production with a pair of top quarks in the high energy photon collisions has been calculated [8], and Reference [9] presents a study of the process $\gamma\gamma\rightarrow \mathrm{t\bar{t}}\phi$ ($\phi=\mathrm{h^0,H^0,A^0}$) in the minimal supersymmetric standard model (MSSM). In Ref. [10], the authors have calculated the associated production of neutral top-pion with a heavy-quark pair in $\gamma\gamma$ collisions. In this paper, we will study the associated production of a neutral top-Higgs with a heavy-quark pair in $\gamma\gamma$ collisions at the International Linear Collider (ILC).

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2 The cross section of $f\bar{f}h_t$ in the high energy $\gamma\gamma$ collisions

As a rough estimate, we only consider the process $\gamma(p_1)\gamma(p_2) \to f(p_3)\bar{f}(p_4)h_t(p_5)$ $(f = t, b)$ at the tree level. The Feynman diagrams are shown in Fig. 1, in which those diagrams with the interchange of the two incoming photons are not shown.

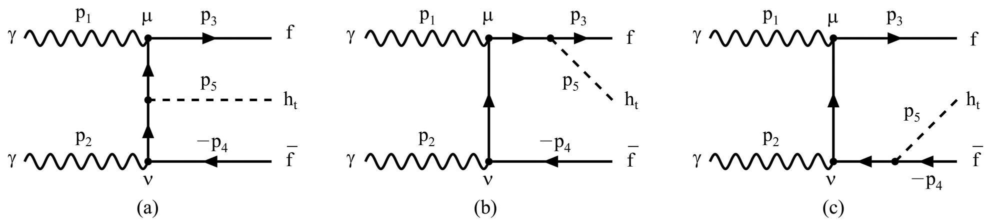

Fig. 1. Feynman diagrams for $f\bar{f}h_t$ associated production in $\gamma\gamma$ collisions. It is not plotted for those diagrams showing the interchange of the two incoming photons.

The amplitudes for this process are given by

$$M_f^{(a)} = \frac{e^2Q_f^2m_f^*}{\sqrt{2}f_{\pi_t}}G(p_3-p_1,m_f)G(p_2-p_4,m_f)\times \bar{u}_f(p_3)\not{\epsilon}(p_1)(\not{p}_3-\not{p}_1+m_f)(\not{p}_2-\not{p}_4+ m_f)\not{\epsilon}(p_2)v_f(p_4), \quad (1)$$

$$M_f^{(b)} = \frac{e^2Q_f^2m_f^*}{\sqrt{2}f_{\pi_t}}G(p_3+p_5,m_f)G(p_2-p_4,m_f)\times \bar{u}_f(p_3)(\not{p}_3+\not{p}_5+m_f)\not{\epsilon}(p_1)(\not{p}_2-\not{p}_4+ m_f)\not{\epsilon}(p_2)v_f(p_4), \quad (2)$$

$$M_f^{(c)} = \frac{e^2Q_f^2m_f^*}{\sqrt{2}f_{\pi_t}}G(p_3-p_1,m_f)G(-p_4-p_5,m_f)\times \bar{u}_f(p_3)\not{\epsilon}(p_1)(\not{p}_3-\not{p}_1+m_f)\not{\epsilon}(p_2)(-\not{p}_4- \not{p}_5+m_f)v_f(p_4). \quad (3)$$

The amplitudes for those diagrams with the interchange of the two incoming photons can be directly obtained by interchanging p_1, p_2 in the above amplitudes. Here the subindex $f = t, b$, m_t^* and m_b^* denote the masses of the top quark and bottom quark generated by the topcolor interaction, $m_t^* = (1-\varepsilon)m_t$ ($\varepsilon \approx$ 0.03–0.1), $m_b^* = k$ 6.6 GeV ($k \approx$0.1–1) [4], and the function G denotes

$$G(p,m) = \frac{1}{p^2-m^2}. \quad (4)$$

With the above amplitudes, we can directly obtain the cross section $\hat{\sigma}(\hat{s})$ for the subprocess $\gamma\gamma \to f\bar{f}h_t$, and the total cross section at the e^+e^- linear collider can be obtained by folding the elementary cross section $\sigma(\hat{s})$ for the subprocess $\gamma\gamma \to f\bar{f}h_t$ with the photon luminosity at the e^+e^- colliders given in Ref. [11], i.e.,

$$\sigma(s) = \int_{x_{\min}}^{x_{\max}} dx_1 \int_{x_{\min}x_{\max}/x_1}^{x_{\max}} dx_2 \times F_{\gamma/e}(x_1)F_{\gamma/e}(x_2)\hat{\sigma}(\hat{s}), \quad (5)$$

where $\sqrt{s}$ and $\sqrt{\hat{s}}$ are the e^+e^- and $\gamma\gamma$ center-of-mass (c.m.) energies, respectively.

For unpolarized initial electron and laser beams, the energy spectrum of the backscattered photon is given by [8, 11]

$$F_{\gamma/e}(x) = \frac{1}{D(\xi)}\left[1-x+\frac{1}{1-x}-\frac{4x}{\xi(1-x)}+ \frac{4x^2}{\xi^2(1-x^2)}\right], \quad (6)$$

with

$$D(\xi) = \left(1-\frac{4}{\xi}-\frac{8}{\xi^2}\right)\ln(1+\xi)+\frac{1}{2}+\frac{8}{\xi}-\frac{1}{2(1+\xi)^2}, \quad (7)$$

where $\xi = 4E_eE_0/m_e^2$, in which m_e and E_e denote, respectively, the incident electron mass and energy, E_0 denotes the initial laser photon energy, and $x_i = E/E_e$ is the fraction which represents the ratio between the scattered photon and the initial electron energy for the backscattered photons moving along the initial electron direction. $F_{\gamma/e}(x)$ vanishes for $x > x_{\max} = E_{\max}/E_e = \xi/(1+\xi)$. In order to avoid the creation of e^+e^- pairs by the interaction of the incident and backscattered photons, we require $E_0x_{\max} \leqslant m_e^2/E_e$, which implies $\xi \leqslant 2+2\sqrt{2} \approx 4.8$ [8, 12]. For the choice $\xi = 4.8$, it can obtain

$$x_{\max} \approx 0.83, \quad D(\xi) \approx 1.8. \quad (8)$$

The minimum value for x is then determined by the production threshold

$$x_{\min}=\frac{\hat{s}_{\min}}{x_{\max}s},\quad \hat{s}_{\min}=(2m_{\rm f}+m_{\rm h_t})^2. \tag{9}$$

3 Numerical results and conclusions

In our numerical evaluation, we take a set of independent input parameters which are known from current experiment. The input parameters are $m_{\rm t}=171.2$ GeV, $m_{\rm b}=4.2$ GeV, $\alpha=1/137.04$ and $\Gamma_{\rm t}=1.377$ GeV [13]. For the c.m. energies of the ILC, we choose $\sqrt{s}=500, 1000$ GeV according to the ILC Reference Design Report [14].

According to the idea of TC2, the masses of the first and second generation quarks are all generated by the extended TC (ETC) interactions. Then, the difference between $\xi_{\rm U}$ and $\xi_{\rm D}$ for, respectively, the coupling coefficients techniquark to up- and down-type quarks reflects the mass difference between the charm and strange quarks [15]. So we have $m'_{\rm t}=(m_{\rm c}/m_{\rm s})m'_{\rm b}$, where $m'_{\rm t}$ and $m'_{\rm b}$ are the top- and bottom-quark masses generated by ETC interactions, respectively. Since $m'_{\rm b}$ is very small, we take approximatively $m^*_{\rm b}\approx m_{\rm b}=4.2$ GeV. The parameter ε and the mass of neutral top-Higgs $\rm h_t$ are all model-dependent. We select them as free parameters, $\varepsilon\sim(0.03, 0.06, 0.1$ and 150 GeV$\leqslant m_{\rm h_t}\leqslant$400 GeV, to estimate the total cross section of $\rm f\bar{f}h_t$ associated production in the high energy photon collisions at the ILC. The final numerical results are summarized in Figs. 2–3.

The cross section $\sigma(\rm e^+e^-\to\gamma\gamma\to t\bar{t}h_t)$ versus the parameter $m_{\rm h_t}$ for various values ε when $\sqrt{s}=1000$ GeV is given in Fig. 2. Because for $\rm t\bar{t}h_t$ production the c.m. energy $\sqrt{s}$=500 GeV is too low to produce it, we only consider the case of $\sqrt{s}$=1000 GeV. From this figure, we can see that: (i) the cross section decreases rapidly as $m_{\rm h_t}$ increases. This is natural since the phase space is depressed strongly by large $m_{\rm h_t}$; (ii) the decrease in the cross section is slight, with ε from 0.03, 0.06 to 0.1; and (iii) the maximum of the cross section reaches the level of a few fb when $m_{\rm h_t}\approx$150 GeV.

Figure 3 gives the results of another associated production $\rm b\bar{b}h_t$ in $\gamma\gamma$ collisions. We find that the cross section of $\rm b\bar{b}h_t$ production is much smaller than that of $\rm t\bar{t}h_t$ production and is only of the order of 10^{-3}–10^{-4} fb. Therefore, it is difficult to detect indirectly $\rm h_t$ via the process $\gamma\gamma\to\rm b\bar{b}h_t$ at the ILC.

We know that the ILC is the important next generation linear collider. According to the ILC Reference Design Report [14], the ILC is determined to

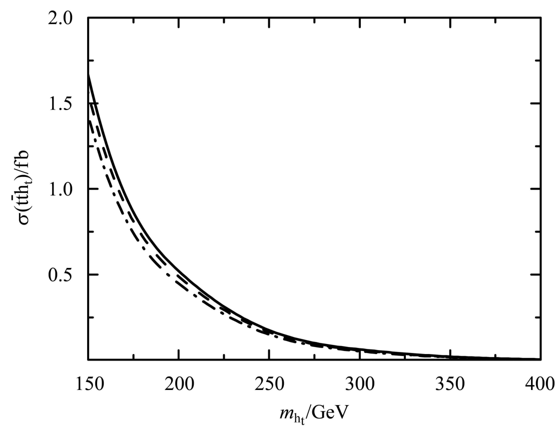

Fig. 2. The total cross section of $\rm e^+e^-\to\gamma\gamma\to t\bar{t}h_t$ versus $m_{\rm h_t}$ with $\sqrt{s}$=1000 GeV for $\varepsilon=0.03$ (solid), 0.06 (dashed) and 0.1 (dot-dashed).

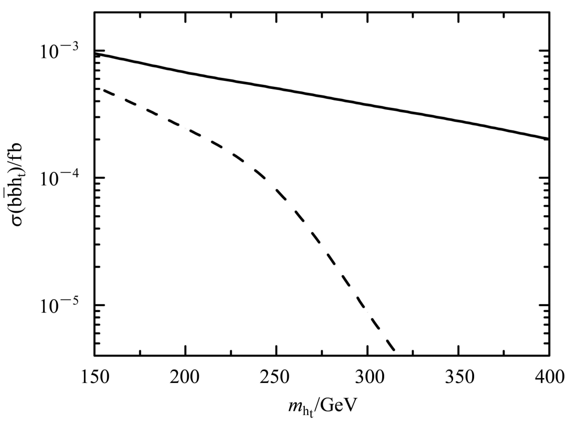

Fig. 3. The curve of $\sigma(\rm e^+e^-\to\gamma\gamma\to b\bar{b}h_t)$ vs. $m_{\rm h_t}$ for $\sqrt{s}$=500 GeV (solid), 1000 GeV (dashed).

run with $\sqrt{s}=500$ GeV (upgradeable to 1000 GeV), and the total luminosity required is $L=500$ fb^{-1} for the first four-year operation and $L=1000$ fb^{-1} during the first phase of operation with $\sqrt{s}=500$ GeV. It means that hundreds of to thousands of $\rm h_t$ per year can be produced in high energy photon collisions at the ILC.

The cross section of the Higgs boson in the SM associated production with a pair of top quarks in the high energy photon collisions is at the level of a few fb [8]. The study of the process $\gamma\gamma\to\rm t\bar{t}\phi$ ($\phi=\rm h^0, H^0, A^0$) in the MSSM shows that the associated $\rm h^0$ production is dominant when $\tan\beta$ is not too large, with the cross section of 1 fb or higher for the favorable parameters [9]. Because $\rm h_t$ is also a scalar particle, its cross section is basically consistent with the results of the cross section of $\rm t\bar{t}H$ in the SM and the cross section of $\rm t\bar{t}h$ in the MSSM at the level of a few fb. Therefore, if the ILC experiment could detect a scalar particle, we need to affirm which model it is from, and it will further require more experimental data and theoretical analysis.

In summary, we have studied the associated production processes of a neutral top-Higgs in the TC2 model with a pair of heavy quarks in $\gamma\gamma$ collisions at the ILC. We find that the cross section for $t\bar{t}h_t$ in $\gamma\gamma$ collisions is at the level of a few fb with the c.m. energy $\sqrt{s}=1000$ GeV, which coincides with the results of the cross section of $t\bar{t}H$ in the SM and the cross section of $t\bar{t}h$ in the MSSM. It should be clearly visible for hundreds to thousands of h_t per year produced by the ILC, so the process of $\gamma\gamma\to t\bar{t}h_t$ is of great interest in testing the standard model and searching the signs of technicolor. Certainly, we need more evidence in order to affirm the existence of h_t.

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