

# Single vector-like top partner production in the left-right twin Higgs model at TeV energy $e\gamma$ colliders

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**Abstract:** The left-right twin Higgs model contains a new vector-like heavy top quark, which mixes with the SM-like top quark. In this work, we studied the single vector-like top partner production via process  $e^- \gamma \rightarrow \nu_e \bar{T} b$  at the International Linear Collider. We calculated the production cross section at tree level and displayed the relevant differential distributions. The result shows that there will be 125 events produced each year with  $\sqrt{s}=2$  TeV and the integrated luminosity  $\mathcal{L}_{\text{int}} \approx 500 \text{ fb}^{-1}$ , and the b-quark tagging and the relevant missing energy  $\cancel{E}_T$  cut will be helpful to detect this new effect.

**Key words:** top partner, left-right twin Higgs model, production cross section

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## 1 Introduction

The top quark was first observed at Fermilab Tevatron in 1995 [1] and is by far the heaviest elementary fermion. Due to the large mass, the top quark decays rapidly before forming any hadronic bound state. Furthermore, the top quark has many properties different from other quarks, so it occupies a special position in the Standard Model (SM) and is often speculated to be sensitive to the new physics. For these reasons, probing the properties of the top quark is always one of the forefront topics at the various high energy colliders.

The twin Higgs theories use a discrete symmetry in combination with an approximate global symmetry to stabilize the Higgs mass. This mechanism can be implemented in left-right models with the discrete left-right symmetry [2]. In the left-right twin Higgs(LRTH) model, a vector-like top quark is introduced in order to give the top quark a mass of the order of electroweak scale. There is mixing between the SM-like top quark and the heavy top quark so that the top quark couplings can be modified. At the LHC, a single vector-like top quark can be produced dominantly via s-channel or t-channel W or  $W_H$  exchange, while the production of the vector-like top quark pair can be produced dominantly from gluon exchange. The productions and decays of the vector-like top quark at the LHC have been described in detail in Ref. [3]. If this effect can be detected, it will be the most compelling evidence of the new physics.

Due to the complicated QCD background, the measurement precision of the LHC is limited. By contrast, the background of the International Linear Collider (ILC) is very clean so that it will allow unique opportunities to study the properties and interactions of the SM top quark and vector-like top quark. Besides the  $e^+e^-$  collider mode, the  $\gamma\gamma$  or  $e\gamma$  collider mode can be realized by the backward Compton scattering at the ILC [4]. The search for deviations from the SM couplings in single top quark production has become one of the main points of focus in the on-going and forthcoming collider experiments [5]. In this paper, we study the process  $e^- \gamma \rightarrow \nu_e \bar{T} b$ ; the results will be helpful to test the SM and the LRTH model.

This paper is organized as follows. In Section 2 we give a brief review of the LRTH model. In Section 3 we calculate the production cross section of the process  $e^- \gamma \rightarrow \nu_e \bar{T} b$  and the differential distributions of several observables at the ILC. Finally, we give our conclusions and some comments in Section 4.

## 2 A brief review of the LRTH model

The LRTH model was first proposed in Ref. [6] and some phenomenological analyses have been studied in Ref. [7]. In this section we will briefly review the essential features of the LRTH model related to our work.

In the LRTH model, the global symmetry is  $U(4) \times U(4)$ , with a gauged  $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$  sub-

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group. Two Higgs fields,  $H$  and  $\hat{H}$ , are introduced and each transforms as (4,1) and (1,4) respectively under the global symmetry. They are written as

$$H = \begin{pmatrix} H_L \\ H_R \end{pmatrix}, \quad \hat{H} = \begin{pmatrix} \hat{H}_L \\ \hat{H}_R \end{pmatrix}, \quad (1)$$

where  $H_{L,R}$  and  $\hat{H}_{L,R}$  are two component objects which are charged under the  $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$  as

$$H_L \text{ and } \hat{H}_L: (2,1,1), \quad H_R \text{ and } \hat{H}_R: (1,2,1). \quad (2)$$

$$M_Z^2 = \frac{g_2^2 + g_Y^2}{g_2^2} \frac{2M_W^2 M_{W_H}^2}{M_W^2 + M_{W_H}^2 + \sqrt{(M_{W_H}^2 - M_W^2)^2 + 4 \frac{g_1^4}{(g_2^2 + g_1^2)^2} M_{W_H}^2 M_W^2}}, \quad (4)$$

where  $x = v/(\sqrt{2}f)$  and  $v$  is the electroweak scale,  $g_Y$  is the usual hypercharge coupling in the SM,  $M_{W_H}$  is the mass of the heavy gauge bosons  $W_H^\pm$ , the values of  $f$  and  $\hat{f}$  will be bounded from below by electroweak precision measurements.

In order to give the top quark mass of the order of the electroweak scale, a pair of vector-like quarks  $Q_L$  and  $Q_R$  is introduced. The mass eigenstates, which contain one of the SM-like top quark  $t$  and a heavy top partner  $T$ , are mixtures of the gauge eigenstates. Their masses are given by

$$m_t^2 = \frac{1}{2}(M^2 + y^2 f^2 - N_t), \quad M_T^2 = \frac{1}{2}(M^2 + y^2 f^2 + N_t), \quad (5)$$

where  $N_t = \sqrt{(y^2 f^2 + M^2)^2 - y^4 f^4 \sin^2 2x}$ .

At the leading order, the mixing angles for the left-handed and right-handed fermions are

$$s_L \approx \frac{M}{m_T} \sin x, \quad (6)$$

$$s_R \approx \frac{M}{m_T} (1 + \sin^2 x), \quad (7)$$

where  $M$  is the mass parameter essential to the mixing between the SM-like top quark and the heavy top quark.

### 3 Single vector-like top production via process $e^- \gamma \rightarrow \nu_e \bar{T} b$

At a linear collider the single vector-like top quarks can be produced from the following two processes:

$$T: e^+ \gamma \rightarrow \bar{\nu}_e \bar{T} b, \quad \bar{T}: e^- \gamma \rightarrow \nu_e \bar{T} b, \quad (8)$$

where the photon comes from the original incoming electron and positron, respectively. The relevant Feynman diagrams of the process  $e^- \gamma \rightarrow \nu_e \bar{T} b$  in the LRTH model are shown in Fig. 1.

After Higgses obtain vacuum expectation values (vevs) as  $\langle H \rangle = (0, 0, 0, f)$  and  $\langle \hat{H} \rangle = (0, 0, 0, \hat{f})$ , the global symmetry  $U(4) \times U(4)$  is spontaneously broken down to its subgroup  $U(3) \times U(3)$ . The Higgs vevs also break  $SU(2)_R \times U(1)_{B-L}$  down to the SM  $U(1)_Y$ .

After the SM electroweak symmetry breaking, three Goldstone bosons are eaten by the SM gauge bosons  $W^\pm$  and  $Z$ , their masses can be given by

$$M_W^2 = \frac{1}{2} g_2^2 f^2 \sin^2 x, \quad (3)$$

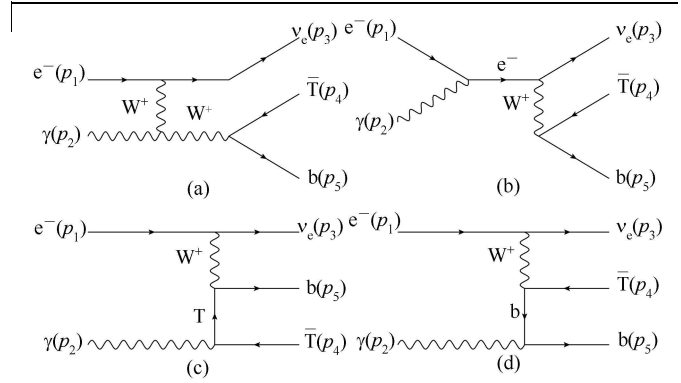


Fig. 1. Feynman diagrams of the process  $e^- \gamma \rightarrow \nu_e \bar{T} b$  in the left-right twin Higgs model.

The invariant production amplitudes of the process  $e^- \gamma \rightarrow \nu_e \bar{T} b$  can be written as:

$$\mathcal{M} = \mathcal{M}_a + \mathcal{M}_b + \mathcal{M}_c + \mathcal{M}_d \quad (9)$$

with

$$\mathcal{M}_a = \varepsilon_\rho(p_2) \bar{u}(p_3) V_{W\nu e}^\mu u(p_1) \bar{u}(p_5) V_{W T b}^\alpha v(p_4) V_{W W \gamma}^{\nu\rho\beta} \times \frac{-ig_{\mu\nu}}{(p_1 - p_3)^2 - m_W^2} \frac{-ig_{\alpha\beta}}{(p_4 + p_5)^2 - m_W^2}, \quad (10)$$

$$\mathcal{M}_b = \varepsilon_\rho(p_2) \bar{u}(p_3) V_{W\nu e}^\mu \frac{i}{(\not{p}_1 + \not{p}_2) - m_e} V_{\gamma e e}^\rho u(p_1) \bar{u}(p_5) \times V_{W T b}^\nu v(p_4) \frac{-ig_{\mu\nu}}{(p_4 + p_5)^2 - m_W^2}, \quad (11)$$

$$\mathcal{M}_c = \varepsilon_\rho(p_2) \bar{u}(p_3) V_{W\nu e}^\mu u(p_1) \bar{u}(p_5) V_{W T b}^\nu \frac{i}{(\not{p}_2 - \not{p}_4) - m_T} \times V_{\gamma T T}^\rho v(p_4) \frac{-ig_{\mu\nu}}{(p_1 - p_3)^2 - m_W^2}, \quad (12)$$

$$\mathcal{M}_d = \varepsilon_\rho(p_2) \bar{u}(p_3) V_{W\nu e}^\mu u(p_1) \bar{u}(p_5) V_{\gamma b b}^\rho \frac{i}{(\not{p}_5 - \not{p}_2) - m_b} \times V_{W T b}^\nu v(p_4) \frac{-ig_{\mu\nu}}{(p_1 - p_3)^2 - m_W^2}, \quad (13)$$

where  $V$  denotes the three-point vertices of the particles, the relevant Feynman rules can be found in Ref. [7].

With the above amplitudes, we can directly obtain the production cross section  $\hat{\sigma}(\hat{s})$  for the subprocess  $e^- \gamma \rightarrow \nu_e \bar{t} b$ . The total cross section at the  $e^+ e^-$  linear collider can be obtained by folding  $\sigma(\hat{s})$  with the photon distribution function that is given in Ref. [8]:

$$\sigma(\text{tot}) = \int_{(m_T + m_b)^2/s}^{x_{\max}} dx \sigma(\hat{s}) f_\gamma(x), \quad (14)$$

where

$$f_\gamma(x) = \frac{1}{D(\xi)} \left[ 1 - x + \frac{1}{1-x} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2} \right], \quad (15)$$

with

$$D(\xi) = \left( 1 - \frac{4}{\xi} - \frac{8}{\xi^2} \right) \ln(1+\xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1+\xi)^2}. \quad (16)$$

where  $\xi = \frac{4E_0\omega_0}{m_e^2}$ ,  $E_0$  and  $\omega_0$  are the incident electron and laser light energies, and  $x = \omega/E_0$ .  $f_\gamma$  vanishes for  $x > x_{\max} = \omega_{\max}/E_0 = \xi/(1+\xi)$ . We require  $\omega_0 x_{\max} \leq m_e^2/E_e$ , which implies that  $\xi \leq 2+2\sqrt{2} \approx 4.8$ . For the choice of  $\xi=4.8$ , we obtain

$$x_{\max} \approx 0.83, \quad D(\xi_{\max}) \approx 1.8. \quad (17)$$

For simplicity, we have ignored the possible polarization for the electron and photon beams, and we also assume that the number of the backscattered photons produced per electron is one.

We take the SM parameters used in our calculations as [9]

$$G_F = 1.16637 \times 10^{-5} \text{ GeV}^{-2}, \quad S_W^2 = 0.231, \quad \alpha_e = 1/128,$$

$$M_Z = 91.2 \text{ GeV}, \quad m_t = 174.3 \text{ GeV}, \quad \Gamma_Z = 2.436 \text{ GeV}. \quad (18)$$

The relevant LRTH parameters in our calculation are the scale  $f$ , the mass parameter  $M$  and the heavy top quark mass  $m_T$ . Recently, the ATLAS Collaboration presented a search that vector-like top quark with mass lower than 656 GeV is excluded at 95% confidence level [10]. Earlier, the CMS Collaboration presented a search that vector-like top quark mass below 557 GeV is excluded at 95% confidence level [11]. Considering these constraints to the relevant LRTH parameters, we take  $M=150$  GeV and make the  $m_T$  and  $f$  satisfy Eq. (5) at all times.

In Fig. 2(a), we discuss the dependence of the production cross section  $\sigma$  on the center-of-mass energy  $\sqrt{s}$  for  $f=800$  GeV. We can see that the cross section  $\sigma$  becomes larger with the  $\sqrt{s}$  increasing.

In Fig. 2(b), we discuss the dependence of the production cross section  $\sigma$  on the scale  $f$  for  $\sqrt{s}=1500$  GeV, 2000 GeV, respectively. We can see the  $\sigma$  decreases as the scale  $f$  increases, which means that the vector-like top

quark production cross section decouples with the scale  $f$  increasing. The maximum of the production cross section can reach 0.17 fb for  $\sqrt{s}=1500$  GeV and 0.25 fb for  $\sqrt{s}=2000$  GeV, respectively. If we take the integrated luminosity  $\mathcal{L}_{\text{int}} \approx 500 \text{ fb}^{-1}$ , there will be 125 events produced each year with  $\sqrt{s}=2$  TeV.

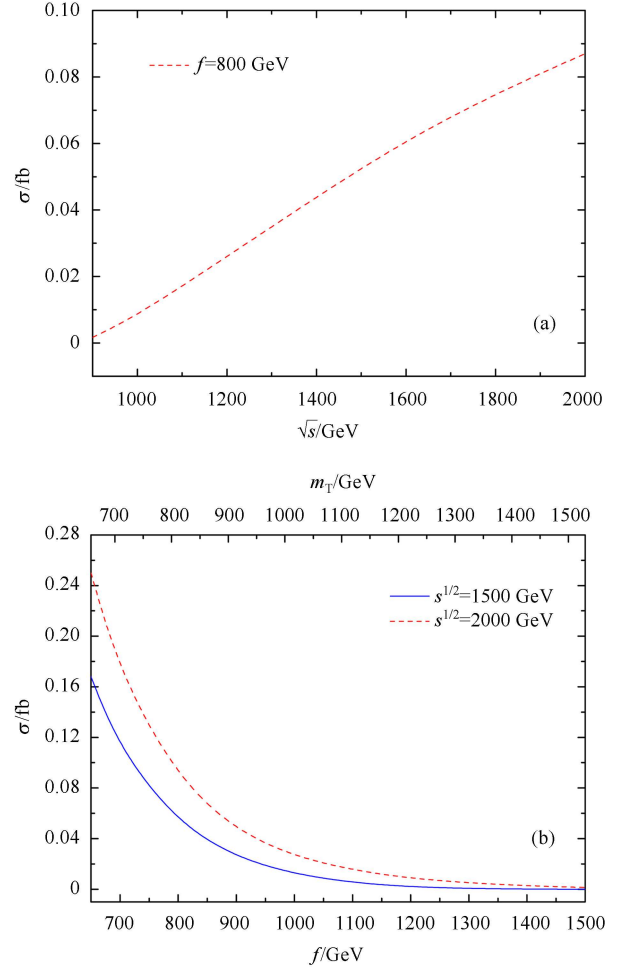


Fig. 2. The production cross section  $\sigma$  as functions of the center-of-mass energy  $\sqrt{s}$  (a) and the scale  $f$  (b).

In Fig. 3, we display the normalized transverse momentum distribution, the normalized distribution for the missing energy and the normalized rapidity of bottom quark of the process  $e^- \gamma \rightarrow \nu_e \bar{t} b$  in the SM and the process  $e^- \gamma \rightarrow \nu_e \bar{t} b$  in the LRTH model.

In Fig. 3(a), we show the normalized transverse momentum distribution behavior of the SM top quark and the heavy top quark. As the neutrino comes from the initial state positron after emitting a W boson, the heavy top quark transverse momentum peaks at  $\sim M_W/2$ , which is very similar to the transverse momentum distribution behavior of the SM top quark.

In Fig. 3(b), we show the normalized distribution for

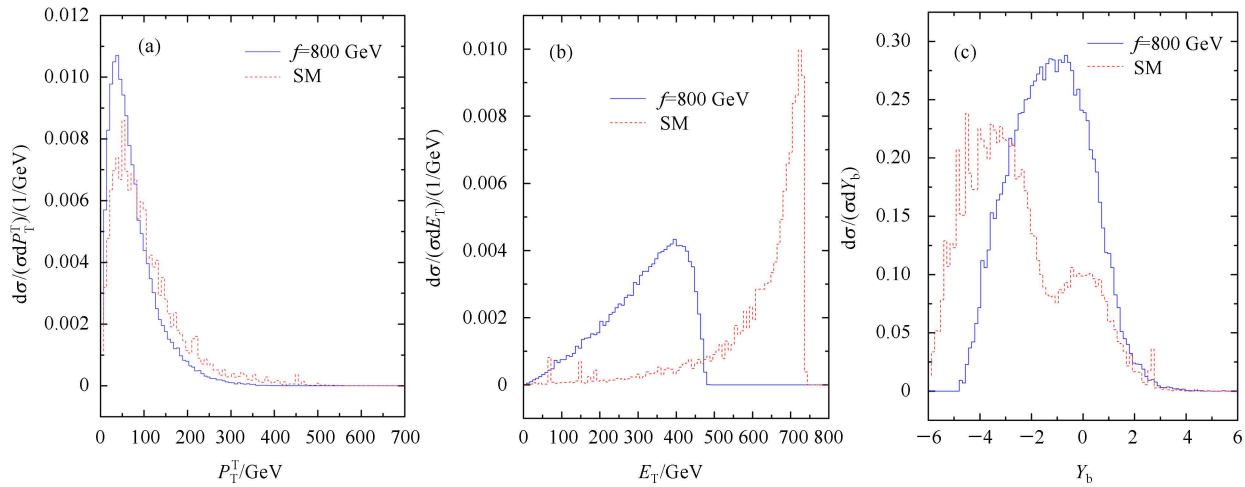


Fig. 3. Normalized differential distributions for the SM top quark and the heavy top quark transverse momentum (a), the missing energy (b) and the rapidity of the bottom quark (c) for  $\sqrt{s}=1500$  GeV.

the missing energy  $E_T$  carried by the final-state neutrino. Compared with the SM top quark, the peak of the normalized distribution moves to the low energy region. With the scale  $f$  increasing, this peak of the normalized distribution moves to the left. If we take a relevant missing energy  $E_T$  cut, such as  $E_T < 500$  GeV for  $f=800$  GeV, the SM background can be suppressed effectively. Considering the subsequent decay of the heavy top quark, the main signal is 4 b jets + one charged lepton (e or  $\mu$ ) + energy  $E_T$ . Because the additional b jet carries off energy, the peak of the missing energy  $E_T$  in the LRTH model is lower than the peak in the SM.

In Fig. 3(c), we show the normalized rapidity distribution of the bottom quark. The WW $\gamma$  diagram (Fig. 1(a)) corresponds to a virtual W boson moving in the positive rapidity region to balance the  $\nu$  emitted from the incoming  $e^-$ . This virtual W boson's decay

products, the b and  $\bar{t}$  quarks, lead to the small kink in the right region. By contrast, the same thing happens in the process  $e^- \gamma \rightarrow \nu_e \bar{t} b$ , but the difference is that the kink is smaller due to the large mass of the heavy top quark.

## 4 Conclusions

In this paper, we studied the single vector-like top production process  $e^- \gamma \rightarrow \nu_e \bar{t} b$  in the LRTH model. The result shows that there will be 125 events produced each year with  $\sqrt{s}=2$  TeV and the integrated luminosity  $\mathcal{L}_{\text{int}} \simeq 500 \text{ fb}^{-1}$  at small value of the scale  $f$  around 650 GeV. Now, by the b-quark tagging efficiency of 70% [12] and the relevant missing energy  $E_T$  cut, these new effects will help to test the LRTH model and probe the new physics at the ILC.

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