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Littlest Higgs model with *T*-parity and single top production in ep collisions*

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Abstract Based on calculating the contributions of the littlest Higgs model with T-parity (called LHT model) to the anomalous top coupling tqγ (q = u or c), we consider single top production via the t-channel partonic process eq $\rightarrow$ et in ep collisions. Our numerical results show that the production cross section in the LHT model can be significantly enhanced relative to that in the standard model (SM).

Key words LHT model, single top production, production cross section

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1 Introduction

The top quark with a mass of the order of the electroweak scale $m_{\rm t} \sim 172$ GeV[1] is the heaviest particle yet discovered and might be the first place in which new physics effects could appeare. The correction effects on the observables due to the new physics are often more important for the top quark than for the other fermions. In particular, the anomalous top couplings, which affect the top production and decay at high energy colliders, offer a unique place for testing the standard model's (SM) flavor structure[2].

In the SM, the anomalous top quark couplings tqV (q=c or u quark and V = γ, Z or g gauge bosons) which arise from the flavor changing (FC) interactions, vanish at tree level but can be generated at the one-loop level. However, they are very suppressed by the GIM mechanism which cannot be detected in present and near future high energy experiments. It is well known that the anomalous top quark couplings tqV may be large in some new physics models going beyond the SM and single top production is sensitive to these types of couplings. Thus, studying the contributions of the couplings tqV to single production of the top quark is of special interest. It will be helpful to test the SM flavor structure and new physics beyond the SM.

The ep collider, called HERA collider with a center-of-mass (c.m.) energy $\sqrt{s} = 320$ GeV or the THERA collider with a c.m. energy $\sqrt{s} = 1$ TeV[3], is the experimental facility where high energy electron-proton and positron-proton interactions can be studied. Within the SM, a single top quark cannot be produced at an observable level in the HERA and THERA collider experiments[4]. However, the HERA and THERA colliders could possibly provide a good sensitivity on the tqV couplings via single top production[5]. Some studies about this type of single top quark production have appeared in the literature[6, 7], which have shown that the HERA and THERA colliders are powerful tools for searching for the anomalous top quark couplings tqV.

The littlest Higgs model with T-parity (called LHT model)[8] is one of the attractive little Higgs models. To simultaneously implement T-parity, the LHT model introduces new mirror fermions. Under T-parity, particle fields are divided into T-even and T-odd sectors. The T-even sector consists of the SM particles and a heavy top quark T_+, while the T-odd sector contains heavy gauge bosons ($\rm B_H$, $\rm Z_H$, $\rm W_H^{\pm}$), a scalar triplet (Φ), and so-called mirror fermions. The flavor mixing in the mirror fermion sector gives rise to a new source of flavor violation, which might generate significant contributions to some flavor violation

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processes[9—14]. In this paper, we will concentrate on the single top production via the t-channel partonic process eq → et in the HERA and THERA collider experiments.

In the following section we will present in detail our numerical results. Our conclusion and a simple discussion will be given in section 3.

2 Numerical results

At the HERA and THERA colliders a single top quark can be produced via a charged current (CC) process and a neutral current (NC) process. In the SM, the former process can proceed at the tree level with a cross section of less than 1 fb[15], while the latter process can only proceed at the one-loop level, which is GIM suppressed. However, the NC process ep → et + X is sensitive to the anomalous top quark couplings tqV.

The t-channel partonic process eq → et for the NC process ep → et + X can obtain contributions from the anomalous top quark couplings tqγ and tqZ via γ exchange and Z exchange, respectively. However, the contribution from Z exchange is several orders of magnitude smaller than that from γ exchange. Thus, we will neglect the contributions of the coupling tqZ in our numerical estimation.

The effective vertex of the anomalous top coupling tqγ can be generally written as:

$$\mathrm{i}e\sigma^{\mu\nu}q_\nu(K_\mathrm{L}P_\mathrm{L}+K_\mathrm{R}P_\mathrm{R}). \tag{1}$$

Here $\sigma^{\mu\nu}=\dfrac{\mathrm{i}}{2}(\gamma^\mu\gamma^\nu-\gamma^\nu\gamma^\mu)$, q_ν is a 4-momentum of the photon γ, K_L and K_R are the effective coupling coefficients of the tqγ vertex, in which we have extracted out the electron charge factor e as a common factor. $P_\mathrm{L}=\dfrac{1-\gamma_5}{2}$ and $P_\mathrm{R}=\dfrac{1+\gamma_5}{2}$ are the left- and right-handed projection operators, respectively. Then, the differential cross section of the partonic process $e(P_\mathrm{e})+q(P_\mathrm{q})\rightarrow e(P_{\mathrm{e}'})+t(P_\mathrm{t})$ can be written as:

$$\frac{\mathrm{d}\hat{\sigma}(\hat{s})}{\mathrm{d}t}=\frac{(K_\mathrm{L}^2+K_\mathrm{R}^2)e^4}{32\pi\hat{s}^2}\times \left[\frac{-2\hat{s}^2+2\hat{s}m_\mathrm{t}^2-m_\mathrm{t}^4}{t}+2m_\mathrm{t}^2-2\hat{s}-t\right], \tag{2}$$

where $t=q^2=(P_{\mathrm{e}'}-P_\mathrm{e})^2$ and $\sqrt{\hat{s}}$ is the c.m. energy of the t-channel partonic process eq → et. In the above equation, we have neglected the masses of the incoming quarks and the electrons. However, for the Mandelstam variable t, to avoid divergence we will use $m_\mathrm{e}=0.511$ MeV for its upper and lower limits in the phase space integral.

In the LHT model, the anomalous top quark coupling tqγ can be induced by the interactions between the SM quarks and the mirror quarks mediated by T-odd gauge bosons ($\mathrm{B_H}$, $\mathrm{Z_H}$, $\mathrm{W_H^{\pm}}$), as shown in Fig. 1. The heavy scalar triplet Φ has no contributions to the coupling tqγ at the order of ν^2/f^2[10, 11]. In our numerical estimation, we will neglect its contributions. So, in Fig. 1, we have not plotted the Feynman diagrams generated by the heavy scalar triplet Φ. Using the relevant Feynman rules given in Refs. [10,16], we can calculate the values of the effective coupling coefficients K_L and K_R in the context of the LHT model. Since their explicit expressions are lengthy, we will not present them in this paper.

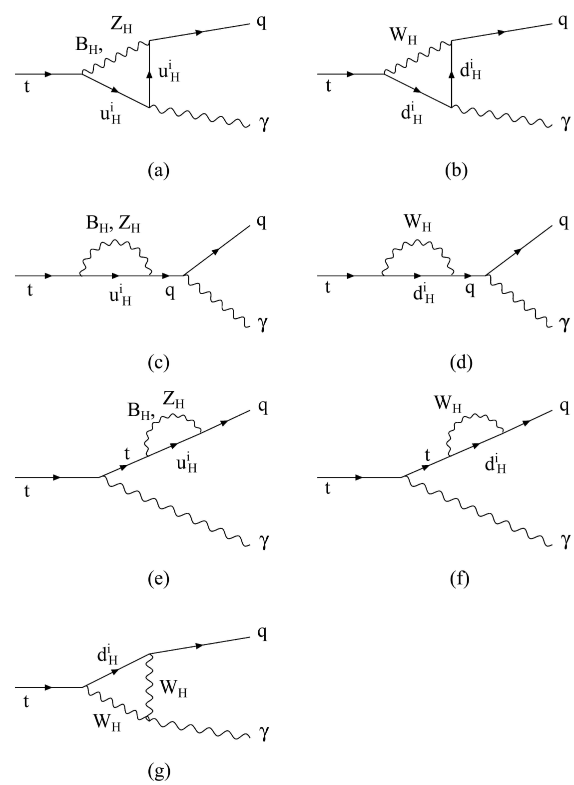

Fig. 1. Feynman diagrams for the tqγ (q=u, or c) vertex in the LHT model.

The effective cross section $\sigma(s)$ of single top production via the partonic process eq → et in an ep collision can be obtained by folding the cross section $\hat{\sigma}(\hat{s})$ with the parton distribution function (PDF):

$$\sigma(s)=\sum_{\mathrm{q=u,c}}\int_{x_\mathrm{min}}^{1}f_\mathrm{q}(x,\mu)\mathrm{d}x\int_{t_\mathrm{min}}^{t_\mathrm{max}}\frac{\mathrm{d}\hat{\sigma}(\hat{s})}{\mathrm{d}t}\mathrm{d}t \tag{3}$$

with $x_\mathrm{min}=\dfrac{m_\mathrm{t}^2+m_\mathrm{e}^2}{s}$ and $\hat{s}=xs$, in which the c.m. energy $\sqrt{s}$ is taken as 320 GeV for the HERA collider and as 1 TeV for the THERA collider. In our numerical calculation, we will use CTEQ6L PDFs[17] for the quark distribution functions and assume that the factorization scale μ is of order $m_{\rm t}$. The upper and lower limits of the Mandelstam variable t are taken as:

$$t_{\max}\approx-\frac{m_{\rm e}m_{\rm t}^2}{\widehat{s}},\quad t_{\min}\approx m_{\rm t}^2-\widehat{s}-\frac{m_{\rm e}^2(m_{\rm e}^2-m_{\rm t}^2)}{\widehat{s}}\ . \quad (4)$$

As can be observed, the cross section $\sigma(s)$ of single top production in an ep collision depends on the model parameters $f, M_{{\rm u}_{\rm H}^i}$, $M_{{\rm d}_{\rm H}^i}$, and $(V_{\rm Hu})_{ij}$. The matrix elements $(V_{\rm Hu})_{ij}$ can be determined via $V_{\rm Hu}=V_{\rm Hd}V_{\rm CKM}^{+}$. The matrix $V_{\rm Hd}$ can be parameterized in terms of three mixing angles and three phases, which can be probed by FCNC processes in K and B meson systems, as discussed in detail in Refs. [10, 12]. It is convenient to consider several representative scenarios for the structure of the matrix $V_{\rm Hd}$. To simplify our calculation, we concentrate our study on the following two scenarios for the structure of the mixing matrix $V_{\rm Hd}$:

Case Ⅰ: $V_{\rm Hd}={\rm I}$, $V_{\rm Hu}=V_{\rm CKM}^{+}$;

Case Ⅱ: $s_{23}^{\rm d}=\frac{1}{\sqrt{2}}$, $s_{12}^{\rm d}=0$, $s_{13}^{\rm d}=0$, $\delta_{12}^{\rm d}=0$, $\delta_{23}^{\rm d}=0$, $\delta_{13}^{\rm d}=0$.

It has been shown that, in both above cases, the constraints on the mass spectrum of the mirror fermions are very relaxed[10, 12]. Furthermore, the masses of the up and down type mirror quarks are equal to each other to leading order of ν/f. Thus, we assume that the masses of the mirror quarks have the relations $M_{{\rm u}_{\rm H}^i}=M_{{\rm d}_{\rm H}^i}=M_1(i=1,2)$ and $M_{{\rm u}_{\rm H}^3}=M_{{\rm d}_{\rm H}^3}=M_2$. In our numerical estimation, we will take the scale parameter f and the mass parameters M_1, M_2 as free parameters.

Our numerical results for Case Ⅰ are summarized in Fig. 2 and Fig. 3. In these two figures, we have taken the values of the CKM matrix elements $(V_{\rm CKM})_{ij}$ given by Ref. [18], in which $V_{\rm CKM}$ is constructed based on PDG parameterization[19]. For the HERA collider with $\sqrt{s}=320$ GeV, the value of $\sigma(s)$ is smaller than 1×10^{-4} fb in most of the parameter space of the LHT model. So, in Fig. 2, we only plot the production cross section $\sigma(s)$ at the THERA collider with $\sqrt{s}=1$ TeV as a function of the scale parameter f for different values of the mass parameters M_1 and M_2. One can see from Fig. 2 that the value of the production cross section $\sigma(s)$ increases as the scale parameter f decreases. The value of $\sigma(s)$ is insensitive to the mirror quark masses. The value of $\sigma(s)$ can reach 2.2×10^{-3} fb for $f=500$ GeV, $M_1=1500$ GeV and $M_2=4000$ GeV, which is too small to be detected at the THERA collider with $\sqrt{s}=1$ TeV. In Fig. 3, we plot the production cross section $\sigma(s)$ as a function of the c.m. energy $\sqrt{s}$ for $M_1=1000$ GeV, $M_2=3000$ GeV, and three values of the scale parameter f. From Fig. 3, we can see that even for $f=500$ GeV and $\sqrt{s}=1.5$ TeV, the value of $\sigma(s)$ is only 3.7×10^{-3} fb.

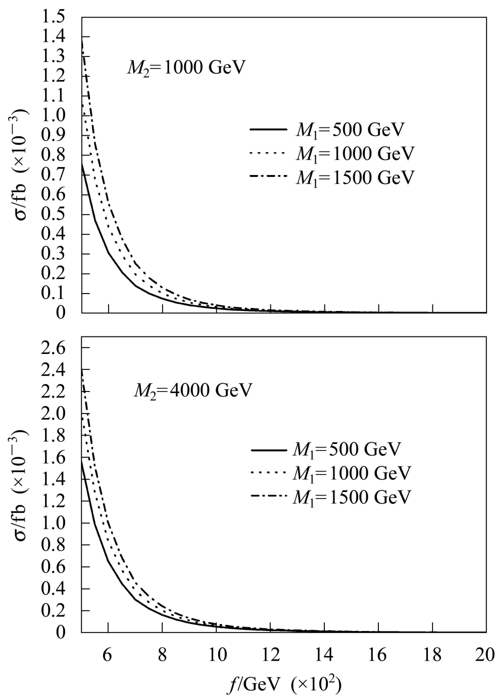

Fig. 2. Case Ⅰ, the cross section $\sigma(s)$ of single top production at the THERA collider with $\sqrt{s}=1$ TeV as a function of f for different values of M_1 and M_2.

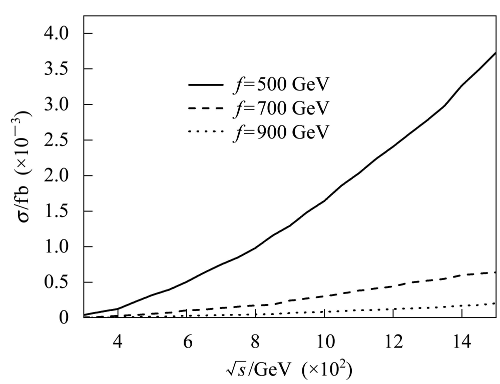

Fig. 3. Case Ⅰ, the cross section $\sigma(s)$ a function of the c.m. energy $\sqrt{s}$ for M_1=1000 GeV, $M_2=3000$ GeV and three values of f.

For Case Ⅰ we have assumed $V_{\rm Hd}={\rm I}$ and $V_{\rm Hu}=V_{\rm CKM}^{+}$, for Case Ⅱ we will assume $V_{\rm Hu}=V_{\rm Hd}V_{\rm CKM}^{+}$ and

$$V_{\rm Hd}=\begin{pmatrix}1&0&0\\0&\frac{1}{\sqrt{2}}&\frac{1}{\sqrt{2}}\\0&-\frac{1}{\sqrt{2}}&\frac{1}{\sqrt{2}}\end{pmatrix}. \quad (5)$$

It is obvious that the value of the factor $\lambda_i = (V_{Hu})^*_{ij}(V_{Hu})_{i3}$ for Case Ⅱ is different from that for Case Ⅰ, which makes the effective production cross section $\sigma(s)$ of the t-channel partonic process eq → et for Case Ⅱ differ from that for Case Ⅰ. In Fig. 4, the dependence of the cross section $\sigma(s)$ on the scale parameter f is presented for Case Ⅱ. One can see from Fig. 4 that the cross section $\sigma(s)$ of single top production for Case Ⅱ is larger than that for Case Ⅰ. For $f = 500$ GeV, $M_2 = 3000$ GeV, and 500 GeV $\leqslant M_1 \leqslant 1500$ GeV, the value of $\sigma(s)$ is in the range of 5.9×10^{-2} fb ∼ 0.14fb. In Fig. 5, we plot $\sigma(s)$ as a function of the c.m. energy $\sqrt{s}$ for $M_1 = 1000$ GeV, $M_2 = 3000$ GeV and three values of the scale parameter f. The value of $\sigma(s)$ can reach 0.18 fb for $f = 500$ GeV and $\sqrt{s} = 1.5$ TeV. If we assume that the THERA collider with $\sqrt{s} = 1$ TeV has a yearly integrated luminosity of $\pounds = 100$ fb^{-1}, then there will be several tens of single top events generated.

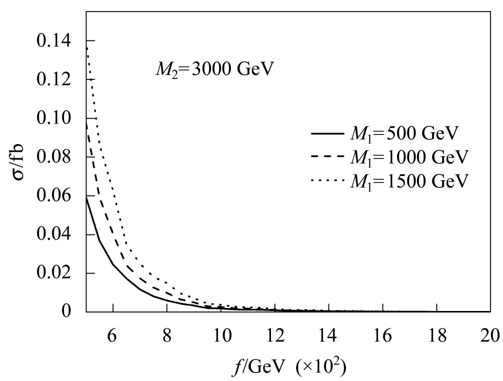

Fig. 4. Case Ⅱ, the cross section $\sigma(s)$ at the THERA collider with $\sqrt{s} = 1$ TeV as a function of f for $M_2 = 3000$ GeV and three values of M_1.

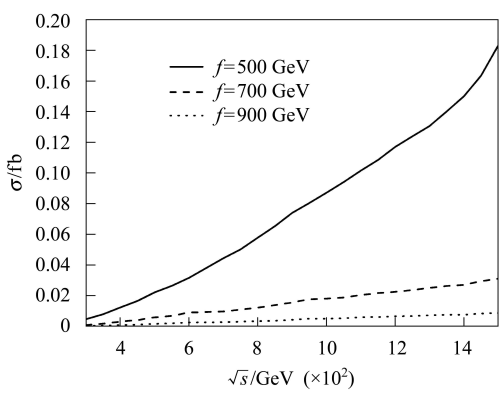

Fig. 5. Same as Fig. 3 but for Case Ⅱ.

3 Conclusion and discussion

The LHT model is one of the attractive little Higgs models that is consistent with electroweak precision tests but also has a much richer flavor structure described by new flavor mixing matrices. This feature makes that the LHT model might generate significant contributions to some flavor violation processes. Based on calculating the contributions of the LHT model to the anomalous top quark coupling tqγ (q=u or c), single top quark production via the t-channel partonic process eq → et in ep collisions is considered in this paper. Our numerical results show that the production cross section is too small to be measured at the HERA collider experiments. However, with reasonable values of the parameters in the LHT model, the production cross section can reach 0.14 fb at the THERA collider with $\sqrt{s} = 1$ TeV. Certainly, whether the effects of the LHT model on single top quark production can be detected in future at the THERA collider, depends on its luminosity.

Single top quark production in ep collisions can also be induced by the anomalous top quark coupling tqg. Using the constraint on the single top production cross section obtained at the HERA collider, Ref. [20] has given upper limits on the coupling constant of the anomalous coupling tqg. The LHT model can generate a large anomalous top quark coupling tqg[13], which can also produce significant contributions to the single top production in ep collisions. However, compared the single top production based on the t-channel partonic process eq → et, it has an additional light jet from a gluon or up type quarks. Thus, single top production in ep collisions induced by the anomalous top quark coupling tqg should be studied further.

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