Top pair production in the littlest Higgs model with *T*-parity

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Abstract In the framework of the littlest Higgs model with T-parity, we study the top pair production at the next generation colliders like LHC and ILC. We find that the order $O(\alpha_s)$ corrections to the standard model top pair production cross section at LHC can be very small and the magnitude is below 1%. However, the magnitude of corrections to the standard model top pair production rate at ILC may be over 5% for reasonable values of the parameters. Besides this, the corrections to the asymmetry $A_{LR}(t\bar{t})$ may be more sizable. Therefore, the top pair production at ILC may serve as a probe of the littlest Higgs model with T-parity, especially the asymmetry $A_{LR}(t\bar{t})$.

Key words top quark, the littlest Higgs model, LHC, ILC

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1 Introduction

To solve the fine-tuning problem of the Standard Model (SM), the little Higgs theory[1] was proposed as a kind of electroweak symmetry breaking mechanism accomplished by a naturally light Higgs sector. The Higgs boson remains light, being protected by the approximate global symmetry and free from the one-loop quadratic sensitivity to the cutoff scale. The littlest Higgs model[2] provides an economical approach which implements the idea of the little Higgs theory. Most of the constraints from the electroweak precision tests on the little Higgs models[3] come from the tree-level mixing of heavy and light mass eigenstates, which would require raising the mass of the new particles to much higher than TeV scale, thus reintroducing the fine-tuning in the Higgs potential[4]. However, these tree-level contributions can be avoided by introducing a discrete symmetry called T-parity[5, 6]. The littlest Higgs model with T-parity (LHT)[7] alters the top quark Yukawa sector and thus it will have significant effect on some processes involving the top quark and Higgs boson[8].

Even after a decade of experimental research at the Tevatron, the top quark is still a relatively unexplored particle compared with the other quarks and leptons. The situation will change once the LHC operates with the planned luminosity, as it is expected that the large event rates will allow for precise investigations of these quarks. As far as the hadronic top quark pair production is concerned, predictions of the $t\bar{t}$ production rate have been known at the next-to-leading order QCD[9].

ILC will offer an opportunity to make precision measurements of the properties of the electroweak gauge bosons, top quark, Higgs boson and also to constrain new physics (NP)[10]. In the ILC experiments, the top quark pair production cross section is of the order of 1 pb, so that the top quark pair will be produced at large rates in a clean environment. Further, the QCD and electroweak corrections to the process $e^+e^- \to t\bar{t}$ are small and decrease as the centre-of-mass energy increases. Thus, examining the contributions of NP to the process $e^+e^- \to t\bar{t}$ is of much interest for testing NP.

This work is organized as follows. In Sec. 2 we recapitulate the littlest Higgs model with T-parity. In Sec. 3 and 4, we study the $t\bar{t}$ productions at LHC and ILC, as well as the asymmetry $A_{LR}(t\bar{t})$. Finally, we arrive at our conclusion in Sec. 5.

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2 Recapitulating the littlest Higgs model with T-parity

Before presenting our calculations we recapitulate the littlest Higgs model with T-parity[5, 7]. The gauge sector of the LHT can be simply obtained from the original littlest Higgs model without T-parity[2]. T-parity acts as an automorphism which exchanges the $[SU(2)\times U(1)]_1$ and $[SU(2)\times U(1)]_2$ gauge factors. Before electroweak symmetry breaking, the gauge boson mass eigenstates have the simple form

$$W^{\alpha}_{\pm}=\frac{W^{\alpha}_1\pm W^{\alpha}_2}{\sqrt{2}},\quad B_{\pm}=\frac{B_1\pm B_2}{\sqrt{2}}, \tag{1}$$

where W^{α}_j and B_j are $SU(2)_j$ and $U(1)_j$ (j=1, 2) gauge fields. W^{α}_{+} and B_{+} are the SM gauge bosons and are T-even, whereas W^{α}_{-} and B_{-} are additional heavy gauge bosons and are T-odd. After electroweak symmetry breaking, the new mass eigenstates in the neutral heavy sector will be a linear combination of W^{α}_{-} and B_{-} gauge bosons, producing a $B_{\rm H}$ and a $Z_{\rm H}$. The $B_{\rm H}$ is typically the lightest T-odd state and may be a candidate of dark matter. Due to T-parity, the new gauge bosons do not mix with the SM gauge bosons and thus generate no corrections to the precision electroweak observables at tree-level. The top quark sector contains a T-even and T-odd partner, with the T-even one mixing with top quark and canceling the quadratic divergent contribution of the top quark to the Higgs boson mass. The masses of the T-even one (denoted T) and the T-odd one (denoted T_{-}) are given by

$$m_T\approx\frac{m_{\rm t}f}{v}\left(r+\frac{1}{r}\right),\quad m_{T_-}\approx m_T s_{\lambda}, \tag{2}$$

where v is the electroweak breaking scale ($\approx$246 GeV), $r=\lambda_1/\lambda_2$ with λ_1 and λ_2 being the coupling constants in the Lagrangian of the top quark sector, $s_{\lambda}=1/\sqrt{1+r^2}$ and $c_{\lambda}=r/\sqrt{1+r^2}$[7].

In addition, for each SM fermion doublet, there is a new T-odd fermion doublet

$$m_{\rm d_-}\approx\sqrt{2}kf,\quad m_{\rm u_-}\approx\sqrt{2}kf\left(1-\frac{v^2}{8f^2}+\cdots\right), \tag{3}$$

where we have assumed a universal k value for the new T-odd fermions and take $k=0.5$[7]. Although there are still extra T-odd fermions, it is generally assumed that their masses are heavy enough to be decoupled[7].

3 The order $O(\alpha_{\rm s})$ corrections to the top pair production rate at LHC

The upcoming LHC will produce top quarks copiously and allow to scrutinize the top quark nature. At tree-level, the top quark pair production at LHC can proceed through gluon-gluon fusion and $q\bar{q}$ annihilation at parton level. The LHT can mainly give the corrections via the loop diagrams. We calculate the order $O(\alpha_{\rm s})$ corrections of LHT to the SM top quark pair production rate at LHC. At $O(\alpha_{\rm s})$ order, only the three-gluon vertex and gluon self-energy are corrected through the loops of new quarks, and the relevant Feynman diagrams of corrections are shown in Fig. 1(c)—(h).

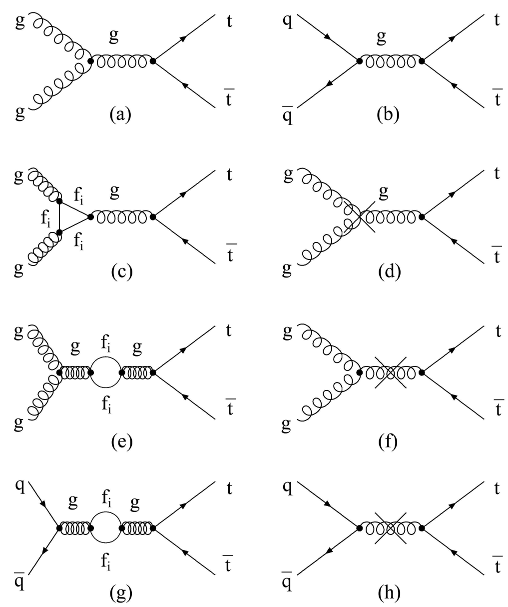

Fig. 1. Feynman diagrams of the order $O(\alpha_{\rm s})$ corrections for the top quark pair production at LHC. Here, $\rm f_i = T, T_-, u_-, d_-$.

In our calculations we use dimensional regularization to control all the ultraviolet divergences in the virtual loop corrections. For the renormalization of the strong coupling constants $g_{\rm s}$ and the gluon wave function, we adopt the $\overline{\rm MS}$ scheme[11] and on-mass-shell scheme, respectively. For the parton distributions we use the CTEQ6L[12] with the renormalization scale $\mu_{\rm R}$ and the factorization scale $\mu_{\rm F}$, chosen to be $\mu_{\rm R}$=$\mu_{\rm F}$=$2m_{\rm t}$. Our calculations will deal with loop diagrams. The calculations of such loop diagrams are straightforward. Each loop diagram is composed of some scalar loop functions[13] which are calculated by using LOOPTOOLS[14].

The SM parameters involved are taken as $m_{\rm t}=$ 172.7 GeV, $m_{\rm Z}$ = 91.187 GeV[15], and the two-loop running coupling constant $\alpha_{\rm s}(Q)$ with $\alpha_{\rm s}(m_{\rm Z})=$ 0.118. The new free parameters involved are the breaking scale f and c_{λ}. In Ref. [16] it is shown that the scale f may be below 1 TeV.

In Fig. 2 we plot the order $O(\alpha_{\rm s})$ corrections of LHT to the SM prediction of the top quark pair production rate at LHC versus the parameter c_{λ} for several values of f. Fig. 2 shows that the corrections depend on the parameters f and c_λ and become more sizable for lower values of f. However, the corrections are very small and the magnitude is below 1%. Therefore, the effects of LHT on the hadronic top quark pair production at LHC can not be detected.

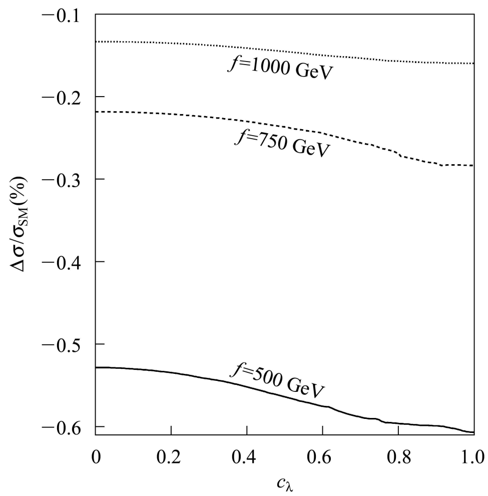

Fig. 2. The order $O(\alpha_s)$ corrections to the SM top quark pair production rate versus the parameter c_λ at LHC.

4 Production of top quark pair at ILC

Now we look at the process $e^-e^+ \to t\bar{t}$ in the littlest Higgs model with T-parity. It is similar to SM and proceeds mainly through the s-channel γ and Z exchange diagrams. Because of the T-parity, other new particles , such as new heavy gauge bosons Z_H and B_H, do not participate in this process[17]. The relevant Feynman diagrams are shown in Fig. 3. The main corrections come from the modified coupling of $Zt\bar{t}$,

$$V^{\mu}_{Zt\bar{t}} = \gamma^{\mu}\frac{e}{S_W C_W}\left[\left(\frac{1}{2}-\frac{2}{3}S_W^2-\frac{c_\lambda^4}{2}\frac{v^2}{f^2}\right)P_L-\frac{2}{3}S_W^2 P_R\right], \quad (4)$$

where the coupling of right-handed part is the same as in the SM, but the coupling of left-handed part is modified. Thus, we define an asymmetry quantity $A_{LR}(t\bar{t})$ by

$$A_{LR}(t\bar{t}) \equiv \frac{\sigma_{t_L}-\sigma_{t_R}}{\sigma_{t_L}+\sigma_{t_R}}, \quad (5)$$

where t_L and t_R denote the left-handed and right-handed polarized top quark, respectively. The contributions to A_{LR} come mainly from the coupling of $Zt\bar{t}$ with different left-handed and right-handed contributions. Therefore, A_{LR} may be more sensitive to the effects of LHT through the modified coupling of $Zt\bar{t}$.

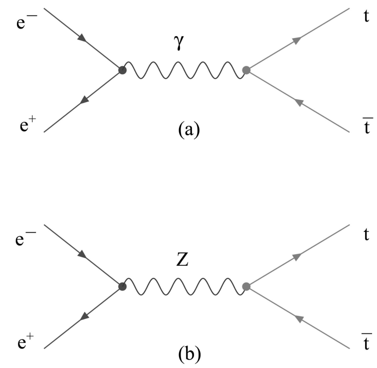

Fig. 3. Feynman diagrams for the top quark pair production at ILC.

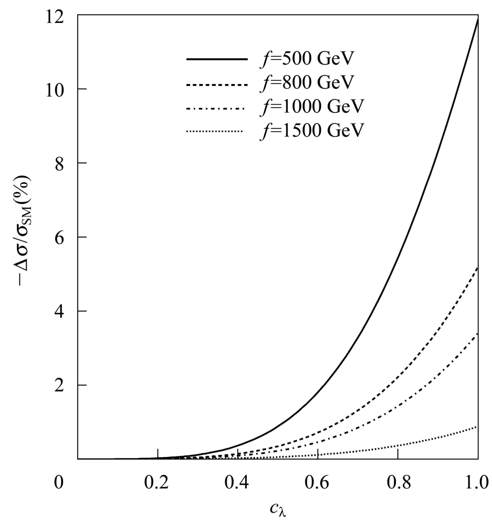

Fig. 4. The corrections to the SM top quark pair production rate versus the parameter c_λ at ILC.

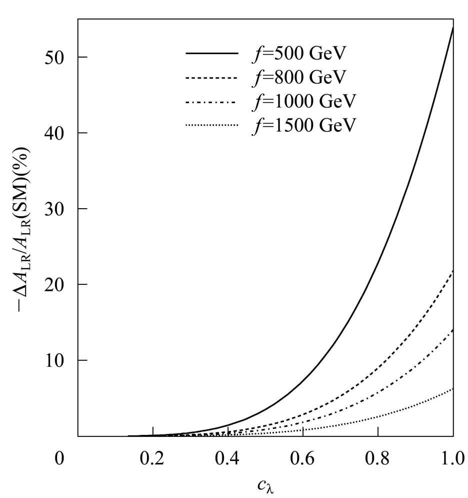

Fig. 5. The corrections to the SM asymmetry $A_{LR}(t\bar{t})$ versus the parameter c_λ.

In Figs. 4—5 we plot the corrections of LHT to the SM predictions of the top quark pair production rate and the asymmetry $A_{\rm LR}(t\bar{t})$ at ILC versus the parameter c_λ for several values of f. Figs. 4—5 show that the corrections depend on the parameters c_λ and f. The contributions of LHT decrease the SM cross section and the asymmetry $A_{\rm LR}$, and become more sizable for the larger values of c_λ and lower values of f. Fig. 4 shows that the magnitude of corrections to the SM cross section may be over 5% with reasonable values of the parameters. From Fig. 5, we can see that the corrections to $A_{\rm LR}$ are more sizable and the magnitude may be over 5% in the larger parameter space. Furthermore, the largest values of the magnitude can reach 54% and 12% for the corrections to the cross section and the asymmetry $A_{\rm LR}$, respectively.

5 Conclusion

In the framework of the littlest Higgs model with T-parity, we studied the top pair production at LHC and ILC. We found that the order $O(\alpha_{\rm s})$ corrections to the SM top pair production cross section at LHC could be very small and the magnitude was below 1%. At ILC, the deviation from the SM top pair production rate may be over 5% with reasonable values of the parameters. Besides, the corrections to the asymmetry $A_{\rm LR}(t\bar{t})$ may be more sizable. Therefore, the top quark pair production at ILC may serve as a probe of the littlest Higgs model with T-parity, especially the asymmetry $A_{\rm LR}(t\bar{t})$.

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