T-odd top partner pair production in the dilepton final states at the LHC in the littlest Higgs Model with T-parity*

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Abstract: In the littlest Higgs model with T-parity, we discuss the pair production of the T-odd top partner (T_-) that decays almost 100% into the top quark and the lightest T-odd particle (A_H). Considering the current constraints, we investigate the observability of the T-odd top partner pair production through the process $pp \to T_-\bar{T}_- \to t\bar{t}A_H A_H$ in the final states with two leptons at 14 TeV LHC. We analyze the signal significance and found that the lower limits on the T-odd top partner mass are approximately 1.2 TeV, 1.3 TeV, and 1.4 TeV at the 2σ confidence level at 14 TeV LHC with an integrated luminosities of 30 fb^{-1}, 100 fb^{-1}, and 300 fb^{-1}, respectively. This lower limit can be increased to approximately 1.5(1.6) TeV if we used 1000(3000) fb^{-1} of the integrated luminosity.

Keywords: top partner, LHC, littlest Higgs Model with T-parity

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1 Introduction

The discovery of Higgs boson by the ATLAS [1] and CMS [2] collaboration is a major milestone for theoretical and experimental particle physics. Although the standard model (SM) is already highly successful, some unresolved problems still exist. One of them is the naturalness [3]. As the two most important particles, the top quark and the Higgs boson are critical therein [4]. Regarding this problem, various theories beyond the SM have been proposed in the past decades. Among these theories, the littlest Higgs model with T-parity (LHT) [5] is a popular candidate.

The little Higgs models construct the Higgs boson as a pseudo-Nambu–Goldstone particle arising from a global symmetry at the high scale, and the LHT model is an attractive representative of these models. In the LHT model, the T-parity partners cancel the one-loop quadratic divergence contributions to the Higgs mass from the corresponding SM particles. Among these partners, the top partner is highly intriguing, as it is responsible for canceling the largest quadratic divergence of the Higgs mass induced by the top quark loop. Hence, relevant researches have been extensively performed [6].

Recently, many searches for the vector-like top partner through pair or single production have been performed at the LHC [7]. The search for a direct top squark pair production at 13 TeV LHC has been performed by the ATLAS and CMS collaboration in various final states, where the search in the dilepton final states has used 36.1 fb^{-1} of integrated luminosity collected by the ATLAS detector [8], and no evidence was observed for an excess above the expected background from the SM processes. For neutralino masses below 150 GeV, the masses of the lightest top squark below 700 GeV are excluded at the 95% confidence level. The similar search has also been performed by the CMS collaboration with 12.9 fb^{-1} data [9]. In other final states, the exclusion limits of the top squark masses are defined higher. Apart from the direct searches, the indirect searches for the top partners have been extensively investigated [10]. The null results of the top partners, in conjunction with the electroweak precision observables (EWPOs) and the recent Higgs data, have tightly constrained the parameter space of the LHT model [11].

The LHT model also predicts an exotic top partner, i.e., the T-odd under T-parity that needs to be pair-produced. It is noteworthy that this T-odd top partner does not decay to the standard patterns Wb,ht and Zt, but will decay into the lightest odd state and SM particles, to share the same signature with the stop quark pair production in the R-parity conserving supersymmetry. At the LHC, relevant searches have been performed independently in the pair-produced exotic top

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partners, where each decayed to an on-shell top (or anti-top) quark and a long-lived undetected neutral particle [12]. Meanwhile, relevant theoretical studies have also been performed [13]. Particularly, the signals of the T-odd top partner pair production in the fully hadronic channel [14] and semileptonic channel [15] at the LHC have been studied before the discovery of the Higgs boson. In this work, we will focus on the search for the T-odd top partner pair production in the dilepton final states at the LHC.

The paper is organized as follows. In Section 2, we review the top partner in the LHT model. In Section 3, we describe the cross section of the T-odd top partner pair production at the 14 TeV LHC under the current indirect constraints. In Section 4, we investigate the signal and discovery potentiality of the T-odd top partner pair production in the dilepton final states at the LHC. Finally, we present our conclusions in Section 5.

2 Top partner in the LHT model

The LHT model is a nonlinear σ model based on the coset space $SU(5)/SO(5)$. The global group $SU(5)$ is spontaneously broken into $SO(5)$ at scale $f\sim\mathcal{O}(\mathrm{TeV})$ by the vacuum expectation value (VEV) of the Σ field, Σ_0, which is given by

$$\Sigma_0=\begin{pmatrix}\mathbf{0}_{2\times2} & 0 & \mathbf{1}_{2\times2}\\ 0 & 1 & 0\\ \mathbf{1}_{2\times2} & 0 & \mathbf{0}_{2\times2}\end{pmatrix}. \qquad (1)$$

Concurrently, the VEV Σ_0 breaks the gauged subgroup $[SU(2)\times U(1)]^2$ of $SU(5)$ down to the diagonal SM electroweak group $SU(2)_{\mathrm{L}}\times U(1)_{\mathrm{Y}}$. After the symmetry breaking, four new heavy gauge bosons appear, $W_H^{\pm},Z_H,A_H$, whose masses are given at $\mathcal{O}(v^2/f^2)$ by

$$M_{W_H}=M_{Z_H}=gf\left(1-\frac{v^2}{8f^2}\right), \quad M_{A_H}=\frac{g'f}{\sqrt{5}}\left(1-\frac{5v^2}{8f^2}\right) \qquad (2)$$

with g and g' being the SM $SU(2)_L$ and $U(1)_Y$ gauge couplings, respectively. The lightest T-odd particle A_H can serve as a candidate for dark matter (DM). To match the SM prediction for the gauge boson masses, the VEV v needs to be redefined as

$$v=\frac{f}{\sqrt{2}}\arccos\left(1-\frac{v_{\mathrm{SM}}^2}{f^2}\right)\simeq v_{\mathrm{SM}}\left(1+\frac{1}{12}\frac{v_{\mathrm{SM}}^2}{f^2}\right), \qquad (3)$$

where $v_{\mathrm{SM}}=246$ GeV.

For each SM quark, the implementation of the T-parity requires mirror partners with the T-odd quantum number. In the top quark sector, an additional T-even heavy top partner T_+ is introduced to cancel the large one-loop quadratic divergences caused by the top quark to stabilize the Higgs mass. Meanwhile, the implementation of T-parity requires a T-odd mirror partner T_-. The top partner T_+ mixes with the SM top quark and leads to a correction of the top quark couplings with respect to the SM values. The mixing can be parameterized by dimensionless ratio $R=\lambda_1/\lambda_2$, where λ_1 and λ_2 are two dimensionless top quark Yukawa couplings. The Yukawa term generates the masses of the top quark and its partners, which are given at $\mathcal{O}(v^2/f^2)$ by

$$\begin{aligned} m_t &= \frac{\lambda_2 vR}{\sqrt{1+R^2}}\left[1+\frac{v^2}{f^2}\left(-\frac{1}{3}+\frac{1}{2}\frac{R^2}{(1+R^2)^2}\right)\right]\\ m_{T_+} &= \frac{f}{v}\frac{m_t(1+R^2)}{R}\left[1+\frac{v^2}{f^2}\left(\frac{1}{3}-\frac{R^2}{(1+R^2)^2}\right)\right]\\ m_{T_-} &= \frac{f}{v}\frac{m_t\sqrt{1+R^2}}{R}\left[1+\frac{v^2}{f^2}\left(\frac{1}{3}-\frac{1}{2}\frac{R^2}{(1+R^2)^2}\right)\right]. \end{aligned} \qquad (4)$$

Because the T_+ mass is always larger than the T_- mass, the T_+ can decay into $A_H T_-$ in addition to the conventional decay modes (Wb,ht,Zt). The T-odd top partner T_- has a simple decay pattern, which decays almost 100% into the $A_H t$ mode.

3 T-odd top partner pair production at the LHC

In Fig. 1, we show the production cross section of process $pp\to T_-\bar{T}_-$ in the $R\sim f$ plane at the 14 TeV LHC. For clarity, we also show the typical T-odd top partner masses and the 2σ exclusion limits from the indirect measurements in this plane. Here, the indirect constraints on the T-odd top partner mass including the latest Higgs data, EWPOs, and R_b in our previous work [16] have been updated by the package HiggsSignals-2.1.0 [17]and HiggsBounds-5.1.0 [18]. We found that the combined constraints can exclude the scale f up to 930(800)GeV, and m_{T_-} up to 780(700)GeV at the 2σ confidence level for case A(B).

Here, case A and case B denote two possible methods to construct the T-invariant Yukawa interactions of the down-type quarks and charged leptons [19]. In the two cases, the corrections to the Higgs couplings with respect to their SM values are given at order $\mathcal{O}(v_{\mathrm{SM}}^4/f^4)$ by ($d\equiv d,s,b,\ell_i^{\pm}$)

$$\begin{aligned} \frac{g_{h\bar{d}d}}{g_{h\bar{d}d}^{\mathrm{SM}}} &= 1-\frac{1}{4}\frac{v_{\mathrm{SM}}^2}{f^2}+\frac{7}{32}\frac{v_{\mathrm{SM}}^4}{f^4} \qquad \text{Case A}\\ \frac{g_{h\bar{d}d}}{g_{h\bar{d}d}^{\mathrm{SM}}} &= 1-\frac{5}{4}\frac{v_{\mathrm{SM}}^2}{f^2}-\frac{17}{32}\frac{v_{\mathrm{SM}}^4}{f^4} \qquad \text{Case B} \end{aligned} \qquad (5)$$

These two cases do not differ in the collider phenomenology of the LHT model, and only exhibit differences in the discussion of constraints from the Higgs sector and EWPO, as shown in Fig. 1. Therefore, we will focus on case A in the study of the T-odd top partner pair production. Additionally, the heavy photon A_H is the DM candidate, which will be constrained by the relic density. According to our previous work [20], A_H needs to co-annihilate with the T-odd mirror fermions, and the masses of both need to be approximately degenerate to yield the correct DM relic density. It is noteworthy that the measured DM relic density does not affect the phenomenology of this work.

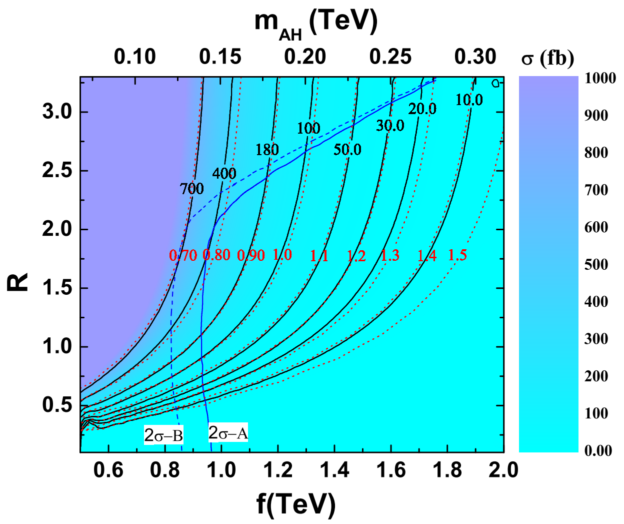

Fig. 1. (color online) The production cross section of $pp\to T_-\bar{T}_-$ in the $R\sim f$ plane at the 14TeV LHC, where the black solid lines correspond to the typical cross sections, the magenta solid(dash) lines correspond to 2σ exclusion limits for Case A(B), the red dot lines correspond to the T-odd top partner masses (in units of TeV).

Recently, the latest research using the LHC-13 TeV data has been performed and showed that the scale f below 950 GeV for case A can be excluded at the 2σ confidence level [21]. We found that the bound on the scale f with the available 13 TeV results only improves little compared to the 8 TeV results. Moreover, the bounds on the top partner masses are not provided explicitly in Ref. [21] owing to the fixed selection of the parameter R. As such, this will be the focus herein. Furthermore, we found that the cross section of the process $pp\to T_-\bar{T}_-$ depends almost entirely on the T-odd top partner mass, and decreases rapidly with the increase in this mass. Considering the 2σ exclusion limits, the cross sections can maximally reach 400(700)fb for case A(B).

4 Signal and discovery potentiality

In Fig. 2, we demonstrate the exemplary Feynman diagrams of the production and the decay of the T-odd vector-like top quark pair at the LHC. We found that the leading production mechanism for the T-odd top partner pair is via QCD interactions.

In the next section, we will discuss our Monte Carlo simulations and explore the sensitivity of the T-odd top partner pair production through the channel,

$$pp\to T_-\bar{T}_-\to t(\to l^+\nu_l b)\bar{t}(\to l^-\bar{\nu}_l\bar{b})A_H A_H\to l^+l^-+2b+\not{E}_{\rm T} \quad (6)$$

implying that the events contain one pair of oppositely charged leptons $l^+l^-(l=e,\mu)$ with high transverse momentum, two high transverse momentum b-jets, and a large missing transverse energy $\not{E}_{\rm T}$.

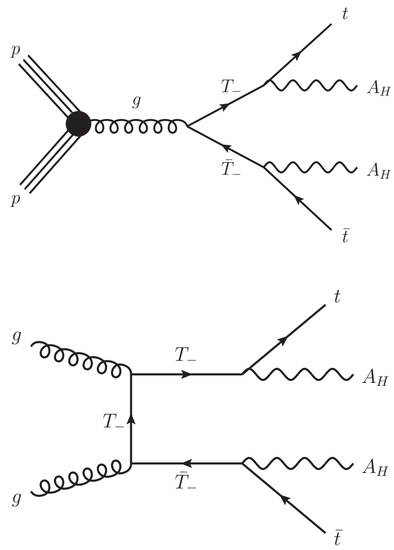

Fig. 2. Exemplary feynman diagrams of the production and decay of the T-odd vector-like top quark pair at the LHC in the LHT model.

For this signal, the dominant background arises from $pp\to t\bar{t}$ in the SM, and the most relevant backgrounds are from tW, $t\bar{t}V(V=W,Z)$, and $VV(WW,WZ,ZZ)$. We generate the signal and background events by MadGraph 5 [22] and use CTEQ6L as the parton distribution functions (PDF). When generating the parton level events, we assume $\mu_R=\mu_F$ to be the default event-by-event value. The cross sections of $t\bar{t}$ and tW production are normalized to their NNLO+NNLL values [23], and the cross sections of $t\bar{t}V$ and VV production are normalized to their NLO values [22].

The basic cuts are chosen as follows:

$$\begin{aligned}\Delta R_{ij} &> 0.4\ , \quad i,j{=}\ell,b \text{ or } j\\ p_{\rm T}^{\ell} &> 10\ \text{GeV}, \quad |\eta_\ell|<2.5\\ p_{\rm T}^{b} &> 20\ \text{GeV}, \quad |\eta_b|<2.5\\ p_{\rm T}^{j} &> 20\ \text{GeV}, \quad |\eta_j|<5.\end{aligned}$$

We input the events into PYTHIA [24] for parton showering and hadronization, and performed a fast detector simulations with Delphes [25]. The b-jet tagging efficiency is used as default value in Delphes, where it is parameterized as a function of the transverse momentum and rapidity of the jets. FastJet [26] is used to cluster the jets by choosing the anti-k_t algorithm [27] with distance parameter ΔR=0.4.

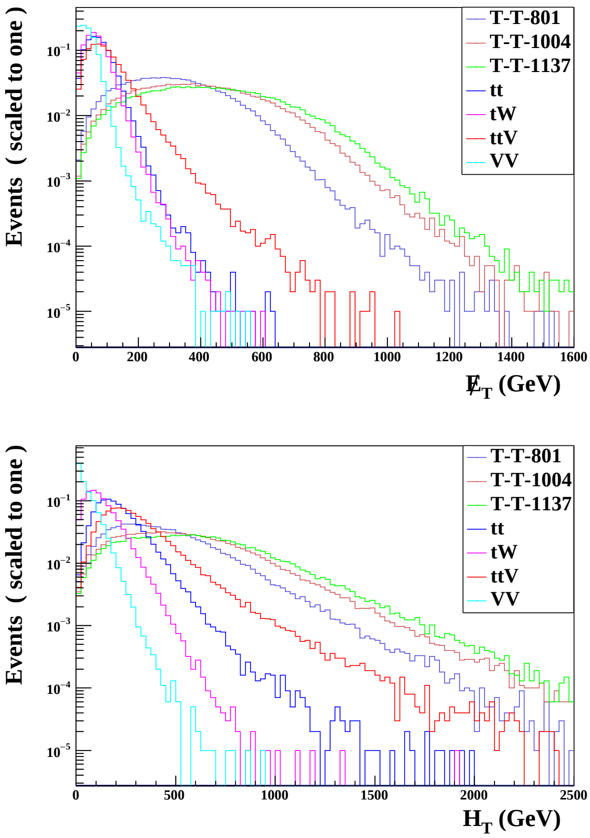

Fig. 3. (color online) Normalized distributions of $\not{E}_{\rm T}$, $H_{\rm T}$ in the signal and backgrounds for the three signal benchmark points at 14 TeV LHC.

The SM parameters are as follows [28]

$$\sin^2\theta_W = 0.231,\ \alpha_e = 1/128,\ \ M_Z = 91.1876\ \text{GeV},$$
$$m_t = 173.5\ \text{GeV},\ m_H = 125\ \text{GeV}.$$

Considering the uncertainty of measurements, we loosen the constraints on the T-odd top partner mass slightly, and use $f=1000$ GeV, $R=2$ (corresponding to $m_{T\_}=801$ GeV), $f=1000$ GeV, $R=1$ (corresponding to $m_{T\_}=1004$ GeV), $f=1000$ GeV, $R=0.8$ (corresponding to $m_{T\_}=1137$ GeV) for three benchmark points. Hence, the heavy photon mass is $m_{A_H}=150$ GeV. To reduce the background and enhance the signal contribution, kinematic distribution cuts are required. Because the dominant background arises from $t\bar{t}$, the cuts should center around the $t\bar{t}$ to suppress the backgrounds. Fig. 3 shows the normalized distributions of the missing transverse energy $\not{E}_{\rm T}$, and the total transverse energy H_T in the signal and backgrounds for the three signal benchmark points at 14 TeV LHC. Firstly, we can choose the large $\not{E}_{\rm T}$ cut to reduce the backgrounds. Subsequently, the H_T distribution can be utilized to remove the $t\bar{t}$ background.

Additionally, for this analysis, the stransverse mass $m_{\rm T2}$ [29] is an effective kinematic variable that has been suggested or used in top-quark mass measurements, and the search for supersymmetric particles at the LHC. This quantity is defined as

$$m_{\rm T2}(\boldsymbol{p}_{\rm T}^{\ell_1},\boldsymbol{p}_{\rm T}^{\ell_2},\boldsymbol{p}_{\rm T}^{\rm miss}) = \min_{\boldsymbol{q}_{\rm T}+\boldsymbol{r}_{\rm T}=\boldsymbol{p}_{\rm T}^{\rm miss}} \left\{\max[m_{\rm T}(\boldsymbol{p}_{\rm T}^{\ell_1},\boldsymbol{q}_{\rm T}),m_{\rm T}(\boldsymbol{p}_{\rm T}^{\ell_2},\boldsymbol{r}_{\rm T})]\right\},$$

where $m_{\rm T}$ indicates the transverse mass, which is defined by

$$m_{\rm T}(\boldsymbol{p}_{\rm T},\boldsymbol{q}_{\rm T}) = \sqrt{2(p_{\rm T}q_{\rm T}-\boldsymbol{p}_{\rm T}\cdot\boldsymbol{q}_{\rm T})}.$$

$\boldsymbol{p}_{\rm T}^{\ell_1}$ and $\boldsymbol{p}_{\rm T}^{\ell_2}$ are the transverse momenta of the two leptons, and $\boldsymbol{q}_{\rm T}$ and $\boldsymbol{r}_{\rm T}$ are vectors that satisfy $\boldsymbol{q}_{\rm T}+\boldsymbol{r}_{\rm T}=\boldsymbol{p}_{\rm T}^{\rm miss}$. The minimization is performed over all the possible decompositions of $\boldsymbol{p}_{\rm T}^{\rm miss}$. We show the normalized distributions of m_{T2} in the signal and backgrounds for the three signal benchmark points at 14 TeV LHC in Fig. 4.

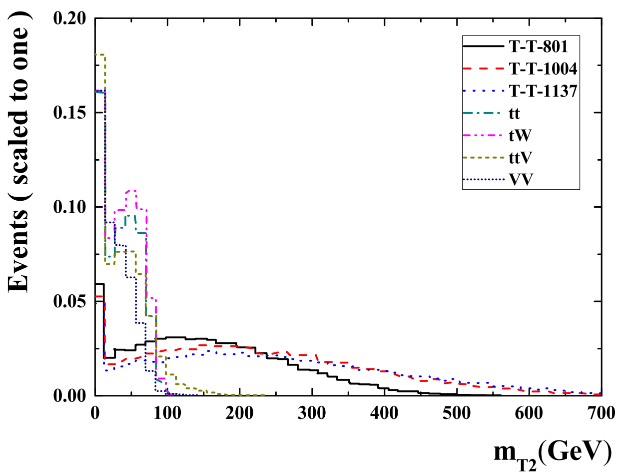

Fig. 4. (color online) Normalized distributions of m_{T2} in the signal and backgrounds for the three signal benchmark points at 14 TeV LHC.

We use CheckMATE-1.2.2 [30] for the analysis and apply charged lepton number $N(l)\geq 2$ to trigger the signal events after the basic cuts. According to the behavioral characteristics of the distributions above, the events are selected to satisfy the following cuts:

Cut-1: $N(l)\geqslant 2$;

Cut-2: $\not{E}_{\rm T}>160$ GeV;

Cut-3: $H_{\rm T}>200$ GeV;

Cut-4: $m_{T2}>120$ GeV.

Table 1. Cut flow of the cross sections for the signal and the backgrounds for the three signal benchmark points m_{T_-} =801,1004,1137 GeV at 14 TeV LHC.

cuts	signal(S)/fb			backgrounds(B)/fb			
	$T_-\bar{T}_-(801)$	$T_-\bar{T}_-(1004)$	$T_-\bar{T}_-(1137)$	$t\bar{t}$	tW	$t\bar{t}V$	VV
basic cuts	11.51	3.20	1.44	43744	3476	33.54	8898
Cut-1	5.23	1.25	0.50	24383	2113	18.79	4025
Cut-2	4.18	1.07	0.44	1766	87.8	5.02	44.2
Cut-3	2.72	0.74	0.31	1081	32.7	3.85	3.47
Cut-4	1.89	0.55	0.24	0.0	0.03	0.24	0.18

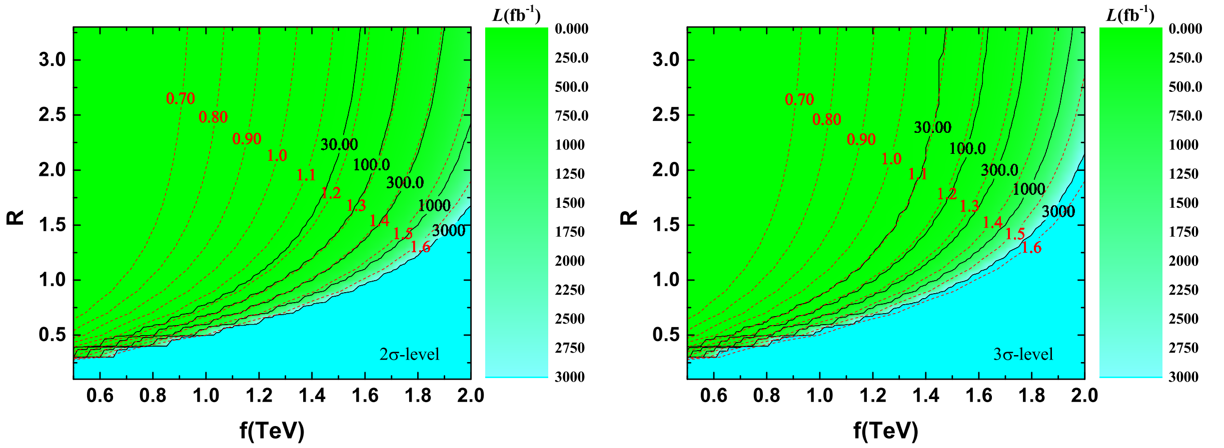

Fig. 5. (color online) Excluded regions at 2σ and 3σ level depending on integrated luminosity in the $R\sim f$ plane at 14TeV LHC, where the red dot lines correspond to the m_{T_-} (in units of TeV).

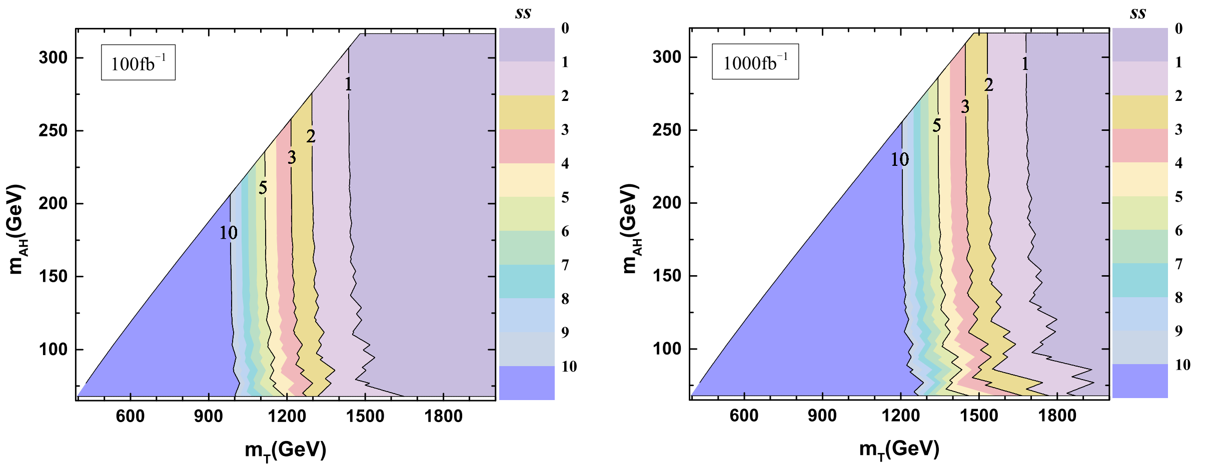

Fig. 6. (color online) Contours of SS with 100fb^{-1} and 1000 fb^{-1} of luminosity in the $m_{\rm T}\sim m_{A_H}$ plane.

For clarity, we summarize the cut-flow cross sections of the signal and backgrounds at 14 TeV LHC in Table 1.

As shown, the total cut efficiency of the signal can reach 16.4%, 18.4%, 17.4% for m_{T_-} = 801,1004,1137 GeV, respectively. To estimate the observability quantitatively, the statistical significance (SS) is calculated after the final cut using the Poisson formula [31]

$$SS=\sqrt{2L\left[(S+B)\ln\left(1+\frac{S}{B}\right)-S\right]}, \qquad (7)$$

where S and B are the signal and background cross sections, and L is the integrated luminosity. We chose the conservative cut efficiency 16.5% of the signal, and the excluded regions at 2σ and 3σ level depending on the integrated luminosity in the $R\sim f$ plane at 14 TeV LHC, as shown in Fig. 5. We found that the T_- mass can be excluded up to approximately 1.2 TeV, 1.3 TeV, and 1.4 TeV at the 2σ level with the integrated luminosities of 30 fb^{-1}, 100 fb^{-1}, and 300 fb^{-1}, respectively. If the integrated luminosity can be increased to L=1000(3000)

fb^{-1}, the lower limit on the T_- mass will be increased to approximately 1.5(1.6)TeV.

To compare our results with those obtained in other modes, we present the contours of SS with luminosities 100 fb^{-1} and 1000 fb^{-1} in the $m_T \sim m_{A_H}$ plane, in Fig. 6. We found that our limit on the T_- mass is mildly stronger than that in the fully hadronic mode [14] and the semileptonic mode [15].

5 Conclusions

We herein discussed the T-odd top partner pair production at the LHC in the LHT model. Under the current constraints, we investigated the observability of the T-odd top partner pair production through process $pp \to T_-\bar{T}_- \to t\bar{t}A_HA_H$ with two leptons in the final states. We presented the excluded regions at the 2σ and 3σ levels depending on the integrated luminosity in the $R \sim f$ plane at 14 TeV LHC, and found that the T-odd top partner mass m_{T_-} could be excluded up to approximately 1.2 TeV, 1.3 TeV, and 1.4 TeV at the 2σ level with the integrated luminosities of 30 fb^{-1}, 100 fb^{-1}, and 300 fb^{-1}, respectively. This lower limit can be enhanced to approximately 1.5(1.6) TeV using an integrated luminosity of 1000(3000) fb^{-1}.

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