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 ($T_-$) which 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 final states with two leptons at 14 TeV LHC. We analyze the signal significance and find that the lower limit on the T-odd top partner mass are about 1.2 TeV, 1.3 TeV, 1.4 TeV at 2\(\sigma\) confidence level at 14TeV LHC with the integrated luminosity of 30 fb\(^{-1}\), 100fb\(^{-1}\), 300fb\(^{-1}\). This lower limit can be raised to about 1.5(1.6) TeV if we use 1000(3000) fb\(^{-1}\) of integrated luminosity.

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I. INTRODUCTION

The discovery of Higgs boson by the ATLAS[1] and CMS[2] collaborations is a major milestone for theoretical and experimental particle physics. The Standard Model (SM) is already hugely successful, but there are still some unresolved problems, one of them is the naturalness[3]. As the two most important particles, the top quark and the Higgs boson play a key role therein[4]. Around 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 one of the popular candidates.

The little Higgs models construct the Higgs boson as a pseudo-Nambu-Goldstone particle arising from a global symmetry at 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 Higgs mass from the corresponding SM particles. Among these partners, the top partner is very intriguing since it is responsible for canceling the largest quadratic divergence of the Higgs mass induced by the top quark loop. For this reason, the relevant researches have been extensively carried out[6].

Recently, many searches for the vector-like top partner through the pair or single production have been performed at LHC[7]. The search for direct top squark pair production at 13 TeV LHC have been performed by the ATLAS and CMS collaborations in various final states, where the search in dilepton final states has used 36.1 fb\(^{-1}\) of integrated luminosity collected by the ATLAS detector[8] and observes no evidence for an excess above the expected background from SM processes. For neutralino masses below 150 GeV, masses of the lightest top squark below 700 GeV are excluded at 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 top squark masses are pushed higher. Apart from 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 exotic top partner, which is T-odd under T-parity and need to be pair-produced. Note that this T-odd top partner does not decay to the standard patterns \(W_b, h_t\) and \(Z_t\), but will decay into the lightest odd state and SM particles,
which will share the same signature with the stop quark pair production in the R-parity conserving supersymmetry. At the LHC, the relevant search has been performed independently in pair-produced exotic top partners, each decay to an on-shell top (or antitop) quark and a long-lived undetected neutral particle \[12\]. On the other hand, the relevant theoretical studies have also been done \[13\]. Especially, the signals of the T-odd top partner pair production in 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 dilepton final states at the LHC.

The paper is organized as follows. In Sec.II we review the top partner in the LHT model. In Sec.III we give the cross section of the T-odd top partner pair production at the 14TeV LHC under the current indirect constraints. In Sec.IV 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 draw our conclusions in Sec.V.

II. TOP PARTNER IN THE LHT MODEL

The LHT model is a non-linear $\sigma$ model based on the coset space $SU(5)/SO(5)$. The global group $SU(5)$ is spontaneously broken into $SO(5)$ at scale $f \sim \mathcal{O}(\text{TeV})$ by the vacuum expectation value (VEV) of the $\Sigma$ field, $\Sigma_0$, which is given by

$$
\Sigma_0 = \begin{pmatrix}
0_{2 \times 2} & 0 & 1_{2 \times 2} \\
0 & 1 & 0 \\
1_{2 \times 2} & 0 & 0_{2 \times 2}
\end{pmatrix}.
$$

(1)

Concurrently, the VEV $\Sigma_0$ breaks the gauged subgroup $[SU(2) \times U(1)]^2$ of $SU(5)$ down to the diagonal SM electroweak group $SU(2)_L \times U(1)_Y$. After the symmetry breaking, there arise 4 new heavy gauge bosons $W^\pm_H, Z_H, A_H$ whose masses given at $\mathcal{O}(v^2/f^2)$ by

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

(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). In order to match the
SM prediction for the gauge boson masses, the VEV $v$ needs to be redefined as

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

where $v_{SM} = 246$ GeV.

For each SM quark, the implementation of T-parity requires the existence of mirror partners with 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 in order to stabilize the Higgs mass. Meanwhile, the implementation of T-parity requires also 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 $\lambda_1$ and $\lambda_2$ are two dimensionless top quark Yukawa couplings. The Yukawa term generates the masses of the top quark and its partners, which are given at $O(v^2/f^2)$ by

$$m_t = \frac{\lambda_2 v R}{\sqrt{1 + R^2}} \left[ 1 + \frac{v^2}{f^2} \left( -\frac{1}{3} + \frac{1}{2} \frac{R^2}{(1 + R^2)^2} \right) \right]$$

$$m_{T_+} = \frac{f m_t (1 + R^2)}{v} \left[ 1 + \frac{v^2}{f^2} \left( \frac{1}{3} - \frac{R^2}{(1 + R^2)^2} \right) \right]$$

$$m_{T_-} = \frac{f m_t \sqrt{1 + R^2}}{v} \left[ 1 + \frac{v^2}{f^2} \left( \frac{1}{3} - \frac{1}{2} \frac{R^2}{(1 + R^2)^2} \right) \right]$$

Since the $T_+$ mass is always larger than the $T_-$ mass, the $T_+$ can decay into $AHT_-$ 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 $A_Ht$ mode.

### III. T-ODD TOP PARTNER PAIR PRODUCTION AT THE LHC

In Fig. 1, we show the production cross section of process $pp \rightarrow T_-\bar{T}_-$ 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 $2\sigma$ 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 can see that the combined constraints can respectively exclude the scale $f$ up to 930(800) GeV and $m_{T_-}$ up to 780(700) GeV at 2$\sigma$ confidence level for Case A(B).
FIG. 1: The production cross section of $pp \rightarrow T_+ T_-$ in the $R \sim f$ plane at the 14 TeV 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).

Here, the Case A and Case B denote two possible ways 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 $\mathcal{O}(v_{SM}^4/f^4)$ by $(d = d, s, b, \ell^+_i)$

$$\frac{g_{hdd}}{g_{hdd}^{SM}} = 1 - \frac{1}{4} \frac{v_{SM}^2}{f^2} + \frac{7}{32} \frac{v_{SM}^4}{f^4} \quad \text{Case A}$$

$$\frac{g_{hdd}}{g_{hdd}^{SM}} = 1 - \frac{5}{4} \frac{v_{SM}^2}{f^2} - \frac{17}{32} \frac{v_{SM}^4}{f^4} \quad \text{Case B}$$

These two cases do not differ in the collider phenomenology of the LHT model and only arise differences in the discussion of constraints from the Higgs sector and EWPO as shown in Fig[1]. So, we will focus on the Case A in the study of T-odd top partner pair production. Besides, 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 approximatively degenerate to give the correct DM relic density. One should note that the measured DM relic density has no impact on the phenomenology of this work.
Recently, the latest research with the LHC-13 TeV data has been performed and found that the scale $f$ below 950 GeV for Case A can be excluded at 2$\sigma$ confidence level\cite{21}. We can see 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 given explicitly in Ref.\cite{21} due to the fixed selection of the parameter $R$, and this will be the focus of this paper. Furthermore, we can see that the cross section of the process $pp \rightarrow T^-\bar{T}^-$ depends almost entirely on the T-odd top partner mass and decreases rapidly with the increase of this mass. Considering the 2$\sigma$ exclusion limits, the cross sections can maximally reach 400(700)fb for Case A (B).

### IV. SIGNAL AND DISCOVERY POTENTIALITY

In Fig.\ref{fig:2} we show the exemplary feynman diagrams of the production and decay of the T-odd vector-like top quark pair at the LHC. We can see that the leading production mechanism for the T-odd top partner pair is via QCD interactions.

![Exemplary feynman diagrams of the production and decay of the T-odd vector-like top quark pair at the LHC in the LHT model.](image)

**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.

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

$$pp \rightarrow T_-\bar{T}^- \rightarrow t(\rightarrow l^+\nu_b)b(\rightarrow l^-\bar{\nu}_b)A_HA_H \rightarrow l^+l^- + 2b + \not{E_T}$$

which implies 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 large missing transverse energy $\not{E_T}$. 

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For this signal, the dominant background arises from $pp \to t\bar{t}$ in the SM, and the most relevant backgrounds come 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:

$$\Delta R_{ij} > 0.4, \quad i, j = \ell, b \text{ or } j$$
$$p_T^\ell > 10 \text{ GeV}, \quad |\eta_\ell| < 2.5$$
$$p_T^b > 20 \text{ GeV}, \quad |\eta_b| < 2.5$$
$$p_T^j > 20 \text{ GeV}, \quad |\eta_j| < 5.$$  

We fed 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 taken 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 $\Delta R = 0.4$.

![Normalized distributions of $E_T$, $H_T$ in the signal and backgrounds for the three signal benchmark points at 14 TeV LHC.](image)

FIG. 3: Normalized distributions of $E_T$, $H_T$ in the signal and backgrounds for the three signal benchmark points at 14 TeV LHC.

The SM parameters are taken as follows [28]

$$\sin^2 \theta_W = 0.231, \quad \alpha_e = 1/128, \quad M_Z = 91.1876 \text{GeV}, \quad m_t = 173.5 \text{GeV}, \quad m_H = 125 \text{GeV}.$$
Taking into account the uncertainty of measurements, we relax the constraints on the T-odd top partner mass slightly and take $f = 1000$ GeV, $R = 2$ (correspond to $m_{T^+} = 801$ GeV), $f = 1000$ GeV, $R = 1$ (correspond to $m_{T^+} = 1004$ GeV), $f = 1000$ GeV and $R = 0.8$ (correspond to $m_{T^+} = 1137$ GeV) for three benchmark points, and now the heavy photon mass is $m_{A_H} = 150$ GeV. In order to reduce the background and enhance the signal contribution, some cuts of kinematic distributions are needed. Since the dominant background arises from $t\bar{t}$, the cuts should centered around the $t\bar{t}$ to suppress the backgrounds. In Fig. 4 we show the normalized distributions of the missing transverse energy $\not{E}_T$ and 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 $\not{E}_T$ cut to reduce the backgrounds. Then, the $H_T$ distribution can be also utilized to remove the $t\bar{t}$ background obviously.

Besides, for this analysis the ‘stransverse’ mass $m_{T_2}$ [29] is an effective kinematic variable, which has been suggested or used in top-quark mass measurements and search for the supersymmetric particles at the LHC. This quantity is defined as

$$m_{T_2}(p_T^l_1, p_T^l_2, p_T^{miss}) = \min_{q_T + r_T = p_T^{miss}} \left\{ \max[ m_T(p_T^l_1, q_T), m_T(p_T^l_2, r_T) ] \right\},$$

where $m_T$ indicates the transverse mass, which is defined by

$$m_T(p_T, q_T) = \sqrt{2(p_T q_T - p_T \cdot q_T)}.$$
$p_T^f_1$ and $p_T^f_2$ are the transverse momenta of the two leptons, and $q_T$ and $r_T$ are vectors which satisfy $q_T + r_T = p_T^{miss}$. The minimization is performed over all the possible decompositions of $p_T^{miss}$. 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.

We use CheckMATE-1.2.2 [30] for 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 above distributions, events are selected to satisfy the following cuts:

- **Cut-1**: $N(l) \geq 2$;
- **Cut-2**: $H_T > 160$GeV;
- **Cut-3**: $H_T > 200$GeV;
- **Cut-4**: $m_{T2} > 120$GeV.

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

**TABLE I**: Cut flow of the cross sections for the signal and the backgrounds for the three signal benchmark points $m_{T^\pm} = 801, 1004, 1137$ GeV at 14 TeV LHC.

| Cuts        | Signal(S)(fb) | Backgronds(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 |

We can see that the total cut efficiency of the signal can reach 16.4%, 18.4%, 17.4% for $m_{T^\pm} = 801, 1004, 1137$ GeV, respectively. To estimate the observability quantitatively, the Statistical Significance ($SS$) is calculated after final cut by using Poisson formula [31]

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

(7)
FIG. 5: Excluded regions at 2\sigma and 3\sigma level depending on integrated luminosity in the $R \sim f$ plane at 14TeV LHC, where the red dot lines correspond to the $m_{T_\gamma}$ (in units of TeV).

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 2\sigma and 3\sigma level depending on integrated luminosity in the $R \sim f$ plane at 14TeV LHC are shown in Fig.5. We can see that the $T_\gamma$ mass can be excluded up to about 1.2 TeV, 1.3 TeV, 1.4 TeV at 2\sigma level with the integrated luminosity of 30fb$^{-1}$, 100fb$^{-1}$, 300fb$^{-1}$, respectively. If the integrated luminosity can be raised to $L = 1000(3000)$ fb$^{-1}$, the lower limit on the $T_\gamma$ mass will be pushed up to about 1.5(1.6) TeV.

FIG. 6: Contours of $SS$ with 100fb$^{-1}$ and 1000 fb$^{-1}$ of luminosity in the $m_T \sim m_{A_H}$ plane.

In order to compare our results with that obtained in other modes, we also display
the contours of $SS$ with $100\text{fb}^{-1}$ and $1000\text{ fb}^{-1}$ of luminosity in the $m_T \sim m_{A_H}$ plane in Fig.6. We can see that our limit on the $T_-$ mass is mildly stronger than that in the fully hadronic mode[14] and the semileptonic mode[15].

V. CONCLUSIONS

In this paper, we discuss the T-odd top partner pair production at the LHC in the LHT model. Under the current constraints, we investigate the observability of the T-odd top partner pair production through the process $pp \rightarrow T_+\overline{T}_- \rightarrow t\overline{t}A_HA_H$ with two leptons in final states. We display the excluded regions at $2\sigma$ and $3\sigma$ level depending on integrated luminosity in the $R \sim f$ plane at 14 TeV LHC and find that the T-odd top partner mass $m_{T_-}$ can be excluded up to about 1.2 TeV, 1.3 TeV, 1.4 TeV at $2\sigma$ level with the integrated luminosity of $30\text{fb}^{-1}$, $100\text{fb}^{-1}$, $300\text{fb}^{-1}$, respectively. This lower limit can be enhanced to about 1.5(1.6) TeV using 1000(3000) fb$^{-1}$ of integrated luminosity.

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