Associated production of single top and Higgs at the LHC in the littlest Higgs model with T-parity

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Abstract

In the littlest Higgs model with T-parity (LHT), we study the $t$-channel single top production in association with a Higgs boson at 8 and 14 TeV LHC. We find that the cross section can be enhanced obviously in this model compared to the Standard Model. By performing a simple parton-level simulation through $pp \rightarrow t(\rightarrow \ell^+ \nu_b)h(\rightarrow b\bar{b})j$ at 14 TeV LHC with the luminosity $L = 30 fb^{-1}$, we find that the observability of the signal is remarkable and can be used to probe the LHT effect.

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I. INTRODUCTION

On the 4th of July 2012, the ATLAS and CMS collaborations at the Large Hadron Collider (LHC) have discovered a Higgs-like resonance about 125 GeV [1]. With current data, all properties of the discovered Higgs boson turn out to be in rough agreement with expectations of the Standard Model (SM) [2]. Due to the large experimental uncertainties, there remains a plenty of room for new physics in Higgs sector [3]. In order to ultimately establish its nature, a precise measurement of the Higgs couplings is essential and this task will be performed in the next phase of the LHC and future Higgs factory.

The Yukawa couplings play an important role in probing the new physics since they are sensitive to new flavor dynamics. In view of the large mass, the top quark owns the strongest Yukawa coupling so that it is an appropriate probe for the electroweak symmetry breaking (EWSB) mechanism and new physics [4]. As a direct probe of the top Yukawa coupling, the production of a top pair associated with a Higgs boson ($t\bar{t}h$ production) is a golden channel and has received great attention by the experimenters [5] and theorists [6]. However, the information on the relative sign between the top Yukawa coupling and Higgs coupling to gauge bosons will still be lacking. In this respect, the production of a single top quark associated with a Higgs boson ($tj$ production) can bring a rather unique possibility [7]. The $pp \to t\bar{t}h$ production process can be divided into three different modes characterised by the virtuality of the $W$ boson [8]: (i) $t$-channel, where the $W$ is spacelike; (ii) $s$-channel, where the $W$ is timelike; (iii) $W$-associated, where there is emission of a real $W$ boson. Besides, the anomalous $pp \to t\bar{t}j$ production process can be induced by the top-Higgs flavor changing neutral current (FCNC) interactions [9].

The littlest Higgs model with T-parity (LHT) [10] was proposed as a possible solution to the hierarchy problem and so far remains a popular candidate of new physics. The LHT model predicts new gauge bosons, scalars, mirror fermions and top partner, where the T-even top partner $T_+$ can contribute to the $pp \to t\bar{t}j$ process. Furthermore, some Higgs couplings are modified at the high order and this effect can also influence the process $pp \to t\bar{t}j$. By performing the detailed analysis on the process $pp \to t\bar{t}j$ may provide a good opportunity to probe the LHT signal. At the LHC, the $t$-channel process dominates amongst these production modes. In this work, we focus on $t$-channel process and investigate the observability of $pp \to t\bar{t}j$ with sequent decays $t \to \ell^+\nu b$ and $h \to b\bar{b}$ at 14 TeV LHC.
The paper is organized as follows. In Sec.II we give a brief review of the LHT model related to our work. In Sec.III we calculate the $t$-channel process of $pp \rightarrow thj$ at the LHC and explore the observability by performing a parton-level simulation. Finally, we give a summary in Sec.IV.

II. A BRIEF REVIEW OF THE LHT MODEL

The LHT model was based on a non-linear $\sigma$ model describing an $SU(5)/SO(5)$ symmetry breaking, with the global group $SU(5)$ being spontaneously broken into $SO(5)$ by a $5 \times 5$ symmetric tensor at the scale $f \sim O(\text{TeV})$.

In the top Yukawa Sector, in order to cancel the large radiative correction to Higgs mass parameter induced by top quark, an additional top partner $T_+$ is introduced, which is even under T-parity and transforms as a singlet under $SU(2)_L$. The implementation of T-parity requires a T-odd mirror partner $T_-$. For the top Yukawa interaction, one can write down the following $SU(5)$ and T-parity invariant Lagrangian

$$\mathcal{L}_t = -\frac{\lambda_1 f}{2\sqrt{2}} \epsilon_{ijk} \epsilon_{xy} \left[(\bar{Q}_1)_i \Sigma_{jx} \Sigma_{ky} - (\bar{Q}_2 \Sigma_0)_i \bar{\Sigma}_{jx} \bar{\Sigma}_{ky}\right] u_{R+}$$
$$-\lambda_2 f (\bar{U}_L U_{R1} + \bar{U}_L U_{R2}) + \text{h.c.},$$

where $\epsilon_{ijk}$ and $\epsilon_{xy}$ are antisymmetric tensors, and $i$, $j$ and $k$ run over 1, 2, 3 and $x$ and $y$ over 4, 5. $u_{R+}$ and $U_{Ri}$ ($i = 1, 2$) are $SU(2)$ singlets.

The heavy quark $T_+$ mix with the SM top-quark and leads to a modification of the top quark couplings relatively to the SM. 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. This mixing parameter can also be used by $x_L$ with

$$x_L = \frac{R^2}{1 + R^2}$$

Their masses up to $O(v^2/f^2)$ are given by

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

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

$$m_{T_-} = \frac{f}{v} \sqrt{x_L} \left[1 + \frac{v^2}{f^2} \left(-\frac{1}{3} + \frac{1}{2} x_L (1 - x_L)\right)\right]$$
where $v = v_{SM}(1 + \frac{v_{SM}^2}{f^2})$ and $v_{SM} = 246$ GeV is the SM Higgs VEV. Some typical Higgs couplings involved in our calculations are given by

$$V_{Hbb} = -\frac{m_b}{v} \left( 1 - \frac{v^2}{6 f^2} \right),$$

(6)

$$V_{HW, W\nu} = \frac{2m_W}{v} \left( 1 - \frac{v^2}{6 f^2} \right) g_{\mu\nu},$$

(7)

$$V_{W_\mu \bar{t}b} = \frac{V_{tb}}{\sqrt{2}} g_{\gamma\mu} \left( 1 - \frac{x_L^2 v^2}{f^2} \right) P_L,$$

(8)

$$V_{W_\mu \bar{T}+b} = \frac{V_{tb}}{\sqrt{2}} g_{\gamma\mu} x_L \frac{v}{f} P_L,$$

(9)

$$V_{htt} = -\frac{m_t}{v} \left[ 1 + \frac{v^2}{f^2} (-\frac{2}{3} + x_L - x_L^2) \right],$$

(10)

$$V_{htT_+} = -m_t \left[ \frac{(1 - x_L)}{f} P_R - \frac{\sqrt{x_L}}{v\sqrt{1 - x_L}} P_L \right].$$

(11)

where $P_L = \frac{1 + \gamma_5}{2}$ and $P_R = \frac{1 - \gamma_5}{2}$ are chirality projection operators. The Higgs coupling with down-type quarks have two different cases[11], here we focus on the Case A scenario.

### III. NUMERICAL RESULTS AND DISCUSSIONS

In the LHT model, the lowest-order Feynman diagrams of the process $pp \to thj (j \neq b)$ are shown in Fig. 1. We can see that the T-even heavy quark $T_+$ contributes this process through the Fig. 1(c). In our calculations, the conjugate process $pp \to \bar{t}hj$ has been considered, unless otherwise noted.

![FIG. 1: Feynman diagrams for $pp \to thj$ in the LHT model at the tree level.](image)

We compute the cross sections using the MadGraph5 [12] (and checked against those obtained by CalcHEP [13]), where the CTEQ6L [14] is used as the parton distribution function and the renormalization scale $\mu_R$ and factorization scale $\mu_F$ is set to be $\mu_R = \mu_F = m_t + m_h$. 
The relevant SM input parameters are taken as follows [15]:

\[
m_t = 173.07 \text{ GeV}, \quad m_Z = 91.1876 \text{ GeV}, \quad \alpha(m_Z) = 1/128, \quad \alpha_s(m_Z) = 0.1185.
\]

In Fig. 2 and Fig. 3, we show the relative corrections \(\delta \sigma/\sigma\) of the processes \(pp \to thj\) at the 8 and 14 TeV LHC in the LHT model, respectively. Considering the consistent constraints in Refs. [16], we require the scale \(f\) and the ratio \(R\) to vary in the range \(500 \text{ GeV} \leq f \leq 2000 \text{ GeV}\) and \(0.1 \leq R \leq 3.3\). Combined with the global fit of the current Higgs data and the electroweak precision observables in Ref. [17], the confidence regions (corresponding to 1\(\sigma\), 2\(\sigma\) and 3\(\sigma\) ranges for Case A) are provided in Fig. (2,3).

![Graph showing relative corrections](image)

**Fig. 2:** The relative corrections \((\delta \sigma/\sigma)_{thj}\) at 8 TeV LHC in the LHT model. The red solid lines respectively represent the 1\(\sigma\), 2\(\sigma\) and 3\(\sigma\) confidence regions, the blue dash-dot lines respectively represent the \(m_{T^+} = 1 \text{ TeV}, 2 \text{ TeV}\) and 3 TeV.

From the Fig. 2 and Fig. 3 we can see that the relative corrections \(\delta \sigma/\sigma\) of \(pp \to thj\) at 8 and 14 TeV LHC can be respectively reach 4 and 7 at 3\(\sigma\) level. Furthermore, we can see that the relative corrections \(\delta \sigma/\sigma\) are negative in considerable regions for 8 TeV LHC and non-negligible regions for 14 TeV LHC. The main reasons are as follows:

Due to the small coupling \(hb\), the main contribution to the \(pp \to thj\) comes from Fig. 1(a,c). If we take no account of the heavy quark \(T^+_+\), we can see that the couplings \(hWW\) and \(ht\) have the opposite sign so that the contributions of Fig. 1(a) and Fig. 1(c) cancel each
other. According to the Eq. (10), we can see that the left-handed part \((c_L = m_t \frac{R}{v})\) of the coupling \(ht\bar{T}_+\) has the same sign as the coupling \(hWW\) so that their contributions enhance each other. The same thing happens between the right-handed part \((c_R = -m_t \frac{(1-x_L)}{f})\) of the coupling \(ht\bar{T}_+\) and the coupling \(htt\). As a result, the total contribution induced by the top partner \(T_+\) depends on the surplus after the cancelation between \(c_L\) contribution and \(c_R\) contribution. One can notice that the left-handed coupling \(c_L(\propto R)\) is proportional to the ratio \(R\) and dominates the contribution from the heavy quark \(T_+\). Moreover, the Higgs couplings in the LHT model are modified at \(\mathcal{O}(v^2/f^2)\), which can decrease the \(thj\) cross section. Combining these factors above, we can see that the large relative corrections \(\delta \sigma/\sigma\) come from the region that has small \(f\), small \(m_{T_+}\) and large \(c_L\). By contrast, the small or negative relative corrections \(\delta \sigma/\sigma\) come from the region that has large \(f\), large \(m_{T_+}\), small \(c_L\) or the combination of them. Due to the lower centre-of-mass energy, the relative corrections \(\delta \sigma/\sigma\) at 8 TeV LHC are suppressed by the large \(m_{T_+}\) more strongly so that the negative \(\delta \sigma/\sigma\) regions are larger compared to the case for 14 TeV LHC. Furthermore, for the same ratio \(R\), we can see that the relative corrections \(\delta \sigma/\sigma\) of \(pp \rightarrow thj\) at 8 and 14 TeV LHC both decrease with the scale \(f\) increasing, which means that the LHT effect decouples with the scale \(f\) increasing.
In the following calculations, we will perform a simple parton-level simulation and explore the sensitivity of 14 TeV LHC through the channel $pp \rightarrow t(\rightarrow \ell^+\nu b)h(\rightarrow b\bar{b})j$, the signal is characterised by

$$1\text{forward jet} + 3b + \ell^+ + \not{E}_T$$ (13)

The most relevant backgrounds can be divided into two classes:
(i) reducible backgrounds, $pp \rightarrow t\bar{t}(\rightarrow b\bar{c}s)$ and $pp \rightarrow t\bar{t}(\rightarrow b\bar{c}s)j$;
(ii) irreducible backgrounds, $pp \rightarrow tZ(\rightarrow b\bar{b})j$ and $pp \rightarrow t\bar{b}bj$.

Signal and background events have been generated at the parton level using MadGraph5. To simulate $b$-tagging, we take the single $b$-tagging efficiency as 60% for $b$-jets in the final state. Follow the analysis on $t\bar{t}h$ signature by ATLAS and CMS collaborations\cite{5} at the LHC Run-I, we chose the basic cuts as follows:

$$\Delta R_{ij} > 0.4, \quad i, j = b, j \text{ or } \ell$$

$$p_T^b > 25 \text{ GeV}, \quad |\eta_b| < 2.5$$

$$p_T^\ell > 25 \text{ GeV}, \quad |\eta_\ell| < 2.5$$

$$p_T^j > 25 \text{ GeV}, \quad |\eta_j| < 5.$$ (14)

After basic cuts, the signal is overwhelmed by the backgrounds. In order to reduce the contributions of the backgrounds and enhance the signal contribution, some additional cuts are required and some other kinematic distributions are needed. We display the normalised distributions of $H_T, \eta_j, M_{bb}, \not{E}_T$ in the signal and backgrounds at 14 TeV LHC for $f = 700$ GeV, $R = 1.5$ in Fig.4 where $H_T$ is the total transverse hadronic energy, $\eta_j$ is pseudorapidity of the leading jet, $M_{bb}$ is the invariant mass of the two $b$-jets from the Higgs boson decay and $\not{E}_T$ is the missing transverse energy.

Firstly, we can see that there is a bulge in the $H_T$ distribution of the signal, which arises from the resonance effect of the top partner $T_+$ and this effect also appears in some other distributions. So we require the events to satisfy $H_T > 530$ GeV to isolate the signal and find all the backgrounds are suppressed effectively. After this cut, the backgrounds are still much larger than the signal, especially the two reducible backgrounds $t\bar{t}$ and $t\bar{t}j$. According to the $\eta_j$ distribution, we can see that most events of $t\bar{t}$ and $t\bar{t}j$ have a leading jet in the central region, which differs significantly from the signal, so we apply the cut $|\eta_j| > 2$ to further suppress the $t\bar{t}$ and $t\bar{t}j$ backgrounds. After that, we find that the signal peak of $M_{bb}$
FIG. 4: The normalised distributions of $H_T$, $\eta_j$, $M_{b\bar{b}}$, $E_T$ after the basic cuts in the signal and backgrounds at 14 TeV LHC for $f = 700$ GeV, $R = 1.5$.

TABLE I: Cutflow of the cross sections for the signal and backgrounds at 14 TeV LHC on the benchmark point ($f = 700$ GeV, $R = 1.5$). All the conjugate processes of the signal and backgrounds have been included.

| Cuts                      | $\sigma$(fb) | $\frac{S}{\sqrt{S+B}}$ | $\frac{S}{t\bar{t}}$ |
|---------------------------|--------------|-------------------------|-----------------------|
|                           | Signal       | Backgrounds             |                       |
|                           | $th_j$       | $t\bar{t}$              | $t\bar{t}j$           | $tZj$               | $tb\bar{b}j$          |
| Basic cuts                | 13.43        | 8361.47                 | 7724.55               | 2.33                | 2.04                  | 0.58                  | 0.00083               |
| $H_T > 530$GeV            | 10.98        | 185.54                  | 823.28                | 0.245               | 0.196                 | 1.88                  | 0.01                  |
| $|\eta_j| > 2$             | 9.53         | 9.12                    | 132.48                | 0.118               | 0.107                 | 4.24                  | 0.063                 |
| $|M_{b\bar{b}} - m_h| < 15$GeV | 5.01         | 0.084                   | 10.59                 | 0.0052              | 0.0028                | 6.93                  | 0.32                  |
| $E_T > 100$GeV            | 3.70         | 0.084                   | 1.78                  | 0.0016              | 0.00088              | 8.59                  | 0.66                  |
is more narrow than those of the backgrounds, so we use the cut \( |M_{bb} - m_h| < 15 \text{ GeV} \) to enhance the observability of the signal. Besides, we apply the cut \( E_T > 100 \text{ GeV} \) to further isolate the signal and find that the \( ttj \) background is suppressed effectively. After all cuts above, the background is dominated by \( ttj \) completely due to an extra hard jet with \( tt \). The cut-flow cross sections of the signal and backgrounds for 14 TeV LHC are summarized in Table I.

In order to analyze the observability, we calculate the signal-to-background ratio according to \( S/\sqrt{S+B} \) and the systematic significance \( S/B \) for the luminosity \( \mathcal{L} = 30\text{fb}^{-1} \), where \( S \) represents the number of signal events and \( B \) represents the number of background events. From Table I we can see that \( S/\sqrt{S+B} \) and \( S/B \) are substantially improved by these selected cuts, where the signal-to-background ratio \( S/\sqrt{S+B} \) can reach over 5\( \sigma \) and the systematic significance \( S/B \) can reach 0.66.

**IV. SUMMARY**

In the framework of the LHT model, we investigate the \( t \)-channel process of \( pp \to thj \) at 8 and 14 TeV LHC. With current constraints, we find that the cross section can be enhanced obviously in some parameter space compared to the SM predictions. We further investigate the observability of \( pp \to thj \) with decays \( t \to \ell^+\nu b \) and \( h \to bb \) at 14 TeV LHC with the luminosity \( \mathcal{L} = 30\text{fb}^{-1} \) for \( f = 700 \text{ GeV}, R = 1.5 \). By performing a simple parton-level simulation, we find that the observability of the LHT signal is remarkable.

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