Abstract

Motivated by the current observation of a 125 GeV Higgs boson, we calculate $t \rightarrow cH$ and $t \rightarrow cg(\gamma)H$ in the unitary gauge in the littlest Higgs model with T-parity (LHT). Due to the large contribution from the new mirror fermions, we find that the branching ratios of $t \rightarrow cH$ and $t \rightarrow cgH$ can be greatly enhanced in the LHT model and maximally reach $O(10^{-5})$ in the allowed parameter space. When the mirror fermion mass $M_3 > 2(1.5)$ TeV and the cut-off scale $f = 500$ GeV, the process of $pp \rightarrow t\bar{t} \rightarrow 3b + c + \ell + E_T^{miss}$ can reach $3\sigma(5\sigma)$ sensitivity at 8(14) TeV LHC with luminosity $L = 20(300)fb^{-1}$.
I. INTRODUCTION

In the light of the discovery of a Standard Model(SM) like Higgs boson and the null results of new physics at the LHC, the electroweak hierarchy problem is highlighted much more than ever before. As the heaviest known elementary particle, top quark has a strong correlation with the hierarchy problem and can be identified as a smoking gun of the TeV-scale physics.

In the SM, the top quark flavor-changing neutral-current(FCNC) processes are highly suppressed by the Glashow-Iliopoulos-Maiani(G.I.M.) mechanism[1]. It indicates that any observation of these processes will be a signal beyond the SM[2–6]. Since weakly constrained FCNC couplings between the second and the third generation up-type quarks are usually predicted in some new physics models, the two-body FCNC decays $t \rightarrow cX (X = g, \gamma, Z, H)$ can be greatly enhanced, such as in the minimal supersymmetric standard model (MSSM) with branching radio $Br(t \rightarrow cH) \sim 10^{-5}$[7], R-parity violating SUSY with branching fraction $Br(t \rightarrow cH) \sim 10^{-6}$[8], the two-Higgs doublet model (2HDM) with branching radio $Br(t \rightarrow cH) \sim 10^{-3}$[9] and so on. The NLO QCD corrections to $t \rightarrow qH (q = u, c)$ in a model-independent method has been studied in the Ref[10].

Besides, three-body FCNC decays of the top quark were also found to be a sensitive probe of the new physics, such as $t \rightarrow cX_1X_2 (X = g, \gamma, Z, H)$[11–13]. Very recently, ATLAS collaboration has measured the top quark decays $t \rightarrow cH$ with $H \rightarrow \gamma\gamma$ and set the upper limit on the $tcH$ coupling as $0.17$[14].

As an extension of the SM, the Littlest Higgs Model(LHT)[15] model can successfully solve the electroweak hierarchy problem by constructing the Higgs as a Pseudogoldstone boson. Meanwhile, the discrete symmetry T-parity in this model also forbids the tree-level contributions from the heavy gauge bosons, thus LHT can safely avoid the constraint from the electroweak precision observables(EPO) that occurs in the littlest Higgs (LH) model[16]. For top quark sector in the LHT, the top quark can interact with new T-odd gauge bosons and T-odd fermions, which may produce large contributions to the top quark FCNC processes[17]. The similar effects have been studied in the rare decays of $K/B$-meson[18], Higgs boson[19] and $Z$ boson[19].

It should be mentioned that the searches for the LHT particles at the LHC can provide the direct evidence of the LHT model or give a strong constraints on the LHT parameter.
space. However, the results usually depend on the assumption of the specific mass spectrum and the branching ratios. For example, the T-odd top partner ($T^-$) pair production has been explored through $pp \rightarrow T^-T^- \rightarrow A_H t A_H \bar{t}$ at 7 TeV LHC [20]. In the analysis, a large mass splitting between the $A_H$ and $T^-$ is required to produce the hard missing energy to suppress the top pair background. But in a general LHT model, the mass of $T^-$ can be close to the mass of $(A_H + t)$ or $A_H$ so that the adopted strategy is not applicable. The similar things can also happen in the searches for other LHT new particles. So in these cases, the searches for the indirect LHT effects via loop corrections will be of great importance because of its weak dependence on the kinematics information. In particular, the processes with low SM backgrounds, such as top quark FCNC decays, will be helpful for testing the LHT model.

In this work, we calculate the top quark FCNC decays with Higgs interactions in unitary gauge in the LHT, that is, $t \rightarrow cH$ and $t \rightarrow cg(\gamma)H$. As a top quark factory, 14 TeV LHC has a power in detecting the branching ratios of $t \rightarrow cH$ up to $Br \sim \mathcal{O}(10^{-6})$ for $\mathcal{L} = 30 fb^{-1}$ and $Br \sim \mathcal{O}(10^{-7})$ for $\mathcal{L} = 300 fb^{-1}$ [21]. So the study of these top FCNC processes can be used to test the LHT at the LHC. The paper is organized as follows. In Sec.II we recapitulate the LHT model related to our work. In Secs.III and Secs.IV we calculate the one-loop contributions of the LHT model to the $t \rightarrow cH$ and $t \rightarrow cg(\gamma)H$ in unitary gauge and present the numerical results. Finally, we give a short summary in Sec.V.

II. A BRIEF REVIEW OF THE LHT MODEL

The LHT model is a non-linear $\sigma$ model based on the coset space $SU(5)/SO(5)$, with the $SU(5)$ global symmetry broken by the vacuum expectation value (VEV) of a $5 \times 5$ symmetric tensor,

$$
\Sigma_0 = \begin{pmatrix}
0_{2 \times 2} & 0_{2 \times 2} \\
0_{2 \times 2} & 1_{2 \times 2} \\
1_{2 \times 2} & 0_{2 \times 2}
\end{pmatrix} \quad (1)
$$

The VEV of $\Sigma_0$ breaks the extended gauge group $[SU(2) \times U(1)]^2$ down to the SM electroweak $SU(2)_L \times U(1)_Y$, which leads to new heavy gauge bosons $W_H^\pm, Z_H, A_H$ with
the masses given to lowest order in $v/f$ by

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

Here $g$ and $g'$ are the SM $SU(2)$ and $U(1)$ gauge couplings, respectively.

When T-parity is implemented in the quark sector of the model, we require the existence of mirror partners with T-odd quantum number for each SM quark. We denote them by $u_H^i, d_H^i$, where $i(i = 1, 2, 3)$ is the generation index. After electroweak symmetry breaking (EWSB), a small mass splitting between $u_H^i$ and $d_H^i$ is induced, and the masses are given by

$$m_{d_H^i} = \sqrt{2}\kappa_i f, \quad m_{u_H^i} = m_{d_H^i}(1 - \frac{v^2}{8f^2})$$ \hfill (3)$$

where $\kappa_i$ are the diagonalized Yukawa couplings of the mirror quarks.

In order to stabilize the Higgs mass, an additional T-even heavy quark $T^+$ is introduced to cancel the large one-loop quadratic divergences caused by the top quark. But the implementation of T-parity requires a T-odd mirror partner $T^-$ with $T^+$. Their masses are given by

$$m_{T^+} = \frac{f}{v} \frac{m_t}{\sqrt{x_L(1 - x_L)}}[1 + \frac{v^2}{f^2}(\frac{1}{3} - x_L(1 - x_L))]$$ \hfill (4)$$

$$m_{T^-} = \frac{f}{v} \frac{m_t}{\sqrt{x_L}}[1 + \frac{v^2}{f^2}(\frac{1}{3} - \frac{1}{2}x_L(1 - x_L))]$$ \hfill (5)$$

where $x_L$ is the mixing parameter between the SM top-quark and its heavy partner $T^+$.

In the LHT model, the mirror quark Yukawa interaction is given by

$$\mathcal{L}_{\text{mirror}} = -\kappa_{ij}f \left(\bar{\Psi}_2^i \xi + \bar{\Psi}_1^i \Sigma_0 \Omega \xi^\dagger \right) \Psi_R^j + h.c.$$ \hfill (6)$$

A new flavor structure can come from the mirror fermions when the mass matrix $\sqrt{2}\kappa_{ij}f$ is diagonalized by two $U(3)$ matrices. One of the important ingredients of the mirror quark sector is the existence of two CKM-like unitary mixing matrices: $V_{Hu}, V_{Hd}$. These mirror mixing matrices parameterize flavor changing interactions between SM quarks and mirror quarks that are mediated by the heavy gauge bosons $W^\pm_H, Z_H, A_H$.

Note that $V_{Hu}$ and $V_{Hd}$ are related through the SM CKM matrix:

$$V_{Hu}^\dagger V_{Hd} = V_{CKM}.$$ \hfill (7)$$

We follow Ref. [22] to parameterize $V_{Hd}$ with three angles $\theta_{12}^d, \theta_{23}^d, \theta_{13}^d$ and three phases $\delta_{12}^d, \delta_{23}^d, \delta_{13}^d$

$$V_{Hd} = \begin{pmatrix}
 c_{12}^d c_{13}^d & s_{12}^d c_{13}^d e^{-i\delta_{12}^d} & s_{13}^d e^{-i\delta_{13}^d} \\
 -s_{12}^d c_{23}^d e^{i\delta_{12}^d} - c_{12}^d s_{23}^d s_{13}^d e^{i(\delta_{13}^d - \delta_{23}^d)} & c_{12}^d s_{23}^d - s_{12}^d s_{23}^d s_{13}^d e^{i(\delta_{13}^d - \delta_{23}^d)} & s_{23}^d c_{13}^d e^{-i\delta_{23}^d} \\
 s_{12}^d s_{23}^d e^{i(\delta_{12}^d + \delta_{23}^d)} - c_{12}^d c_{23}^d s_{13}^d e^{i\delta_{13}^d} & -c_{12}^d s_{23}^d e^{i\delta_{23}^d} - s_{12}^d c_{23}^d s_{13}^d e^{i(\delta_{13}^d - \delta_{12}^d)} & c_{23}^d c_{13}^d
\end{pmatrix}$$ (8)

In our calculation, for the matrices $V_{Hu}, V_{Hd}$, to aid comparisons with Ref. [23], we also follow Ref. [24] to consider the same scenarios as follows

- **Case I**, $V_{Hd} = 1$
- **Case II**, $s_{12}^d = \frac{1}{\sqrt{2}}, s_{23}^d = 5 \times 10^{-5}, s_{13}^d = 4 \times 10^{-2}, \delta_{12}^d = \delta_{23}^d = \delta_{13}^d = 0$
- **Case III**, $s_{12}^d = 0.99, s_{23}^d = 2 \times 10^{-4}, s_{13}^d = 0.6, \delta_{12}^d = \delta_{23}^d = \delta_{13}^d = 0$

### III. BRANCHING RATIO FOR $t \rightarrow cH$ IN THE LHT MODEL

In the LHT model, the relevant Feynman diagrams of the process $t \rightarrow cH$ in unitary gauge are shown in Fig.1. We can see there is no additional mixing between $T^+$ and charm or up quark. This is different from the case in Ref. [25], where a small loop induced coupling between new vector-like quark and charm quark can occur and will be constrained by the low energy physics. We will not consider the higher order couplings between the scalar triplet $\Phi$ and top quark and neglect the high order $O(\nu^2/f^2)$ terms in the masses of new particles. The calculations of the loop diagrams are straightforward. We adopt the definitions of scalar one-loop integral functions in Ref. [26] and compose each loop diagram into some scalar loop functions [27], and list the explicit expressions of these amplitudes in Appendix. We use the package of LOOPTOOLS [28] to perform the numerical loop calculations. In the analytic calculations, we cancel the divergence that is independent on the mirror quark mass by the unitarity of the matrix $V_{Hu}$. We also note that the modified interactions of the up-type mirror fermions with the $Z$ boson in Ref. [29] can cancel the similar divergence in the processes with down-type quarks or leptons as the external particles. However, we checked that such a modification cannot cancel the
divergence in $t \rightarrow cH$ and there is still so-called left-over divergence\textsuperscript{23, 30} as follow,
\[
D = \frac{m_{u_1 H}}{f^2} (V_{Hu})_{12}^* (V_{Hu})_{33} \frac{i}{16\pi^2} \left[ -\frac{1}{80} + \left( \frac{x_L^2}{160} + \frac{3}{64} \right) \frac{v^2}{f^2} \right] \Delta \tag{9}
\]
where $\Delta = \frac{1}{\varepsilon} - \gamma_E + \ln 4\pi$. In Ref.\textsuperscript{30}, this so-called left-over divergence was understood as the sensitivity of the decay amplitudes to the ultraviolet completion of the LHT model.

Follow Ref.\textsuperscript{30}, we remove the divergent term $1/\varepsilon$ in the invariant amplitudes and take the renormalization scale $\mu = \Lambda$ with $\Lambda = 4\pi f$ being the cutoff scale of the LHT model.

FIG. 1: Feynman diagrams of the LHT one-loop correction to $t \rightarrow cH$ in the unitary gauge.

In our numerical calculations, the SM parameters are taken as follows\textsuperscript{31}
\[
G_F = 1.16637 \times 10^{-5} \text{GeV}^{-2}, \quad \sin^2 \theta_W = 0.231, \quad \alpha_e = 1/128, \quad \alpha_s = 0.1076, \\
m_c = 1.27 \text{GeV}, \quad M_Z = 91.1876 \text{GeV}, \quad m_t = 173.5 \text{GeV}, \quad m_h = 125 \text{GeV}. \tag{10}
\]

The relevant LHT parameters in our calculation are the scale $f$, the mixing parameter $x_L$, the mirror quark masses and the parameters in the matrices $V_{Hu}, V_{Hd}$. Considering the constraints in Refs.\textsuperscript{32}, the scale $f$ can be allowed as low as 500 GeV. For the mirror quark masses, it has been shown that the experimental bounds on four-fermi interactions require $m_{H_i} \leq 4.8f^2/\text{TeV}\textsuperscript{33}$, we get $m_{u_1 H} = m_{d_1 H}$ at $O(v/f)$ and further assume
\[
m_{u_1 H} = m_{u_2 H} = m_{d_1 H} = m_{d_2 H} = M_1, m_{u_1 H} = m_{d_3 H} = M_3 \tag{11}
\]

In Fig.2(a), we show the dependance of the branching ratio of $t \rightarrow cH$ on the third generation mirror quark mass $M_3$. We set the scale $f = 500$ GeV, the mixing parameter
FIG. 2: Branching ratios of $t \to cH$ as a function of $M_3$ (a) and $f$ (b) in three cases, respectively.

$x_L = 0.1$ and the first two generation mirror quark masses $M_{12} = 750$ GeV. Due to the large departures from the SM caused by mixing matrices in case III, we can also see that the branching ratio of $t \to cH$ in the case III is much larger than case I and II, which can maximally reach $5.8 \times 10^{-5}$ in case III.

From the Fig.2(a), we can see that the branching ratio of $t \to cH$ increases with $M_3$ increasing, which means that the decay rate is enhanced by the mass splitting between the three generation mirror quarks. According to the analytic expression, we can know the form factors of the loop-induced $tcH$ interaction, $F$, should take the following form

$$F \propto \sum_{i=1}^{3} (V_{Hu}^i)^c_i f(m_{Hi})(V_{Hu})^t_i$$  \hspace{1cm} (12)$$

where $f(m_{Hi})$ is a universal function for three generation mirror quarks, but its value depends on the mass of $i$th-generation mirror quark, $m_{Hi}$. Obviously, for the degeneracy of the three generation mirror quarks, $F$ vanished exactly due to the unitary of $V_{Hu}$, while for the degeneracy of the first two generations as discussed below, the factor behaviors like $(V_{Hu}^i)_c3(f(m_{H3}) - f(m_{H}))(V_{Hu})_{3i}$ with $m_{H}$ being the common mass of the first two generations. The decay rate is enhanced by the mass splitting between the three generation mirror quarks, since we set $M_1 = M_2 = M_{12}$, there is only one mass splitting $M_3 - M_{12}$, which increases with $M_3$ while keeping $M_{12}$ fixed. This agrees with the explanation in Ref.[17].

In Fig.2(b), we show the dependance of the branching ratio of $t \to cH$ on the scale $f$. We set the mixing parameter $x_L = 0.1$, the first two generation mirror quark masses
$M_{12} = 1.5f$ and the third generation mirror quark mass $M_3 = 3f$. We can see that the branching ratio decreases with the scale $f$ increasing, which means that the correction of the LHT model decouples with the scale $f$ increasing. Since the enhancement from mass splitting of mirror fermions can balance the suppression of large scale $f$, we can find that the branching ratio of $t \to cH$ decreases slowly, when the scale $f$ becomes higher. From Fig.2, we can see that the LHT model can enhances the branching ratios of $t \to cH$ as much as $9 \sim 10$ orders of the one in the SM [34]. Similarly, in some other new physics beyond the SM this branching ratio can also be enhanced by several orders of magnitude.

For comparison, we summarize the FCNC decays $t \to cH$ in the LHT model and in other new physics models [8, 35–38] in Table I.

**TABLE I: Branching ratio for top quark decay $t \to cH$ in different models.**

| Model          | SM    | QS    | 2HDM  | FC 2HDM | MSSM  | SUSY  | SUSY-QCD | LHT   |
|----------------|-------|-------|-------|----------|-------|-------|----------|-------|
| $t \to cH$     | $3 \times 10^{-15}$ | $4.1 \times 10^{-5}$ | $1.5 \times 10^{-3}$ | $\sim 10^{-5}$ | $10^{-5}$ | $\sim 10^{-6}$ | $\sim 10^{-5}$ | $\sim 10^{-5}$ |

At the LHC, the dominant background of the search for $t \to cH$ is the final state of $4j/3b\ell\nu\nu$ coming from top quark pair production: $pp \to t\bar{t} \to b\bar{c}\ell\nu b\bar{c} + X$ or $pp \to t\bar{t} \to b\bar{c}\ell\nu b\bar{c} + X$, where a $c$-jet is mis-identified as a $b$-jet. The mis-tagged probability of a $c$-jet as a $b$-jet is approximately 10% reported by the ATLAS and CMS. In order to investigate the observability of $t \to cH$ for case III in the LHT model, we use the monte carlo simulation results in Ref. [39] and plot $3\sigma$ and $5\sigma$ contours of the hadronic cross sections $pp \to t\bar{t} \to b\bar{c}\ell\nu b\bar{c}j$ in Fig 3 for $\sqrt{s} = 8, 14$ TeV. We use the next-to-leading order value of $t\bar{t}$ production rate in the calculation. Since the branching ratio of $t \to cH$ is sensitive to the third generation mirror quark mass, we take $M_3 = 1000 \text{ GeV}, 2000 \text{ GeV}, 3000 \text{ GeV}$ for example, where we set the scale $f = 500 \text{ GeV}$, the mixing parameter $x_L = 0.1$ and the first two generation mirror quark masses $M_{12} = 750 \text{ GeV}$.

On the left panel of Fig 3, we can see that when $M_3 > 2.2 \text{ TeV}$, $t \to cH$ can reach $3\sigma$ sensitivity at 8 TeV LHC with luminosity $\mathcal{L} = 20 fb^{-1}$. But on the middle and right panel of Fig 3, we can find that the 14 TeV LHC has the ability to probe the value of $M_3$ as low as $2.1(1.5) \text{ TeV}$ at $5\sigma$ level when $\mathcal{L} = 30(300) fb^{-1}$. Therefore, we can infer that the precise measurement of $t\bar{t}$ production can give a strong constraint on the parameters space of the LHT model.
FIG. 3: The observability of $t \rightarrow cH$ for case III in the LHT model through the production of $pp \rightarrow t\bar{t} \rightarrow tcH \rightarrow b\nu c\bar{b} + X$ at the LHC with $\sqrt{s} = 8$ TeV and $\sqrt{s} = 14$ TeV. The shadow region is $1\sigma$ combined range of the Higgs boson mass from Ref. [40].

FIG. 4: The observability of $t \rightarrow cH$ as a function of the scale $f$ for three cases in the LHT model through the production of $pp \rightarrow t\bar{t} \rightarrow tcH \rightarrow b\nu c\bar{b} + X$ at the LHC with $\sqrt{s} = 8$ TeV and $\sqrt{s} = 14$ TeV.

In Fig. 4, we show the observability of $t \rightarrow cH$ as a function of the scale $f$ for case III in the LHT model through the production of $pp \rightarrow t\bar{t} \rightarrow tcH \rightarrow b\nu c\bar{b} + X$ at the LHC with $\sqrt{s} = 8$ TeV and $\sqrt{s} = 14$ TeV. We use the monte carlo simulation results and the next-to-leading order value of $t\bar{t}$ production rate as above. The relevant parameters are
taken as follows: $x_L = 0.1$, $M_{12} = 1.5f$, $m_h = 125$ GeV. Based on the same consideration, we take the third generation mirror quark mass $M_3 = 2f, 4f, 6f$ for example. We can see that the favorable observability comes from the region with the low $f$ and the large mass splitting ($M_3 - M_{12}$), which is consistent with the preceding analysis.

IV. BRANCHING RATIO FOR $t \to cg(\gamma)H$ IN THE LHT MODEL

![Feynman diagrams](image)

FIG. 5: Feynman diagrams of the LHT one-loop correction to $t \to cg(\gamma)H$ in the unitary gauge.

In this section, we calculate the branching ratio of $t \to cg(\gamma)H$ in the LHT model. These processes can also be considered as part of the next-to-leading order QCD(QED) corrections to $t \to cH$. The relevant Feynman diagrams of the process $t \to cg(\gamma)H$ in unitary gauge are shown in Fig.5, where the black dot represent the loop-induced $tcH$.
vertex as shown in Fig.1. In the numerical calculations, we take the same parameters and cases as the decay process $t \to cH$ and impose the kinematical cuts on the final massless states to avoid the singularity.

FIG. 6: Branching ratios for $t \to cgH$ as a function of $M_3$ (a) and $f$ (b) in three cases, respectively.

FIG. 7: Branching ratios for $t \to c\gamma H$ as a function of $M_3$ (a) and $f$ (b) in three cases, respectively.

In Fig.6(a), we show the dependance of the branching ratio of $t \to cgH$ decay process on the third generation mirror quark mass $M_3$. We can see that the branching ratio of $t \to cgH$ increases with $M_3$ increasing, the largest branching ratio comes from the case III and the maximum value can reach $1.4 \times 10^{-5}$. In Fig.6(b), we show the dependance
of the branching ratio of $t \to cgH$ decay process on the scale $f$. We can see that the correction of the LHT model decouples with the scale $f$ increasing.

In Fig.7, we show the dependance of the branching ratio of $t \to c\gamma H$ decay process on the third generation mirror quark mass $M_3(a)$ and the scale $f(b)$. We can see that the decay process $t \to c\gamma H$ has the similar behaviors as the decay process $t \to cgH$. The maximum value of the branching ratio can reach $3.5 \times 10^{-7}$.

V. SUMMARY

In this paper, we calculated the top quark FCNC decay $t \to cH$ and $t \to cg(\gamma)H$ in the unitary gauge in the LHT model. We found that the branching ratio for $t \to cH$ and $t \to cg(\gamma)H$ can respectively reach $5.8 \times 10^{-5}$ and $1.4 \times 10^{-5}(3.5 \times 10^{-7})$ in the allowed parameter space. When the mirror fermion mass $M_3 > 2.2$ TeV and the cut-off scale $f = 500$ GeV, $t \to cH$ can reach $3\sigma$ sensitivity at 8 TeV LHC with luminosity $\mathcal{L} = 20 fb^{-1}$. We also noted that the 14 TeV LHC has the potential to observe this channel at $5\sigma$ sensitivity level for $M_3 = 2.1(1.5)$ TeV when $\mathcal{L} = 30(300) fb^{-1}$. Therefore, we can see that $t \to cH$ may be used to test the LHT model at the LHC.

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