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Probing anomalous top-Higgs couplings at the HL-LHC via $H \rightarrow WW^*$ decay channels

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Probing anomalous top-Higgs couplings at the HL-LHC via $H \rightarrow WW^*$ decay channels^{*}

Yao-Bei Liu(刘要北)^{1;1)} Stefano Moretti^{2;2)}¹ Henan Institute of Science and Technology, Xinxiang 453003, China² School of Physics & Astronomy, University of Southampton, Highfield, Southampton SO17 1BJ, UK

Abstract: We study the prospects of probing the anomalous tHq ($q = u, c$) couplings via SS2L or 3L signatures at the High Luminosity (HL-LHC) run of the 14 TeV CERN collider. We focus on signals of the tH associated production followed by the decay modes $t \rightarrow b\ell^+\nu_\ell$ and $H \rightarrow WW^*$, and $t\bar{t}$ production followed by the decay modes $t \rightarrow b\ell^+\nu_\ell$ and $\bar{t} \rightarrow H(\rightarrow WW^*)\bar{q}$, where $\ell = e, \mu$. Based on two types of $H \rightarrow WW^*$ decay topologies, one assuming the semileptonic decay mode $H \rightarrow WW^* \rightarrow \ell^+\nu jj$ and the other the fully leptonic decay mode $H \rightarrow WW^* \rightarrow \ell^+\nu\ell^-\bar{\nu}$, we perform a full simulation for signals and backgrounds. It is shown that, at the future HL-LHC, the branching ratio $Br(t \rightarrow uh)$ ($Br(t \rightarrow ch)$) can be probed to 1.17 (1.56) $\times 10^{-3}$ for the same-sign di-lepton channel, and to 7.1×10^{-4} (1.39×10^{-3}) for the 3L channel at 3σ sensitivity.

Keywords: anomalous top-higgs couplings, flavor changing neutral currents, LHC

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1 Introduction

Processes mediated by Flavor Changing Neutral Currents (FCNCs) are very rare in the Standard Model (SM) due to the Glashow-Iliopoulos-Maiani (GIM) mechanism [1]. However, because of the extended flavor structures existing in many New Physics (NP) models, the two-body FCNC decays $t \rightarrow qX$ ($q = u/c$ and $X = g/\gamma/Z/H$) can be greatly enhanced: for example, in the Minimal Supersymmetric Standard Model (MSSM) with branching ratio $Br(t \rightarrow cH) \sim 10^{-5}$ [2], in R-parity violating Supersymmetry (SUSY) with branching ratio $Br(t \rightarrow cH) \sim 10^{-6}$ [3], in 2-Higgs-Doublet Models (2HDMs) with branching ratio $Br(t \rightarrow cH) \sim 10^{-5} - 10^{-3}$ [4], in the little Higgs model with T-parity and the warped extra dimensions both with branching ratio $Br(t \rightarrow cH) \sim 10^{-5}$ [5, 6] and so on. Thus any experimental signatures of such FCNC processes will serve as a clear signal for NP Beyond the SM (BSM) [7]. Up to now, top-Higgs FCNC interactions have been studied widely via anomalous top decays or anomalous production processes of single top quark [8–16].

Currently, the ATLAS and CMS collaborations have carried out searches [17–21] for tqH interactions with 7,

8 and 13 TeV data from the LHC. For example, using 13 TeV data, the ATLAS and the CMS experiments have studied the tqH FCNC processes in top quark pair events with $H \rightarrow \gamma\gamma$ for ATLAS and $H \rightarrow b\bar{b}$ for CMS. The resulting observed (expected) limits for $Br(t \rightarrow qH)$ at 95% Confidence Level (CL) have been found to be [19, 20]:

$$Br(t \rightarrow Hu) \leq \begin{cases} 2.4 (1.7) \times 10^{-3} \text{ ATLAS} \\ 4.7 (4.3) \times 10^{-3} \text{ CMS} \end{cases}$$

$$Br(t \rightarrow Hc) \leq \begin{cases} 2.2 (1.6) \times 10^{-3} \text{ ATLAS} \\ 4.7 (4.4) \times 10^{-3} \text{ CMS} \end{cases} \quad (1)$$

Very recently, a search for production of top pairs in which one top quark decays via $t \rightarrow qH$ is reported by the ATLAS Collaboration [21], with the subsequent Higgs boson decay to final states with at least one electron or muon. The upper limits on the branching fractions $Br(t \rightarrow Hc) < 0.16\%$ and $Br(t \rightarrow Hu) < 0.19\%$ at 95% CL are obtained (with expected limits of 0.15% in both cases). Apart from direct collider measurements, the upper limits of $Br(t \rightarrow qH) < 5 \times 10^{-3}$ and $Br(t \rightarrow qH) < 0.21\%$ can be obtained by bounding the tqH vertex from the observed $D^0 - \bar{D}^0$ mixing [22] and

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1) E-mail: liuyaobei@hist.edu.cn

2) E-mail: s.moretti@soton.ac.uk



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$Z \rightarrow c\bar{c}$ [23], respectively.

The upcoming project of the HL-LHC is expected to reach 3 ab^{-1} . Preliminary sensitivity studies for the HL-LHC suggest the upper bound on $Br(t \rightarrow qH)$ to become about 1.5×10^{-4} at 95% CL by the ATLAS Collaboration [24]. Further, many phenomenological studies within model-independent methods have been performed from different channels [25–33]. In this work, we study the prospects of probing the anomalous tHq couplings by considering the processes of tH associated production and $t\bar{t}$ production at the HL-LHC. We analyze two kinds of final states through leptonic top quark decays and $H \rightarrow WW^*$, one with Same Sign 2-Lepton (SS2L) and the other with 3-Lepton (3L) topology, where the Higgs boson decays into a semi-leptonic ($H \rightarrow WW^* \rightarrow \ell^+ \nu jj$) or fully leptonic ($H \rightarrow WW^* \rightarrow \ell^+ \nu \ell^- \bar{\nu}$) mode. The advantage of these channels is that their final states including the SS2L or 3L topologies can be used to significantly suppress QCD backgrounds [34], which have not been fully studied in previous literature.

The organization of this paper is as follows. In Sec. II, we discuss two kinds of final states for the processes of tH associated production with the decay chain $t \rightarrow W^+ b \rightarrow \ell^+ \nu b$ and $H \rightarrow WW^*$ as well as $t\bar{t}$ production with the decay chain $t \rightarrow \ell^+ \nu b$ and $\bar{t} \rightarrow H(\rightarrow WW^*)\bar{q}$. Then we discuss the HL-LHC sensitivity to the anomalous tHq couplings. We summarize in Sec. III.

2 Numerical calculations and discussions

The general Lagrangian for FCNC top interactions with the Higgs boson can be written as

$$\mathcal{L} = \kappa_{tuH} \bar{t} H u + \kappa_{tcH} \bar{t} H c + \text{h.c.}, \quad (2)$$

where the FCNC coupling parameters, κ_{tuH} and κ_{tcH} , are real and symmetric since we do not consider here the CP violating effects.

We perform systematic Monte Carlo (MC) simulations and study the sensitivity to the anomalous tHq couplings through the associated tH and $t\bar{t} \rightarrow tH\bar{q}$ processes at HL-LHC. We first extract the relevant Feyn-

man rules via the FeynRules package [35] and generate the events with MadGraph5-aMC@NLO [36]. The signal and backgrounds samples are simulated at parton level with the NN23LO1 Parton Distribution Function (PDF) set [37] and then passed through PYTHIA6.4 [38] and DELPHES 3 [39] for parton shower and detector simulations, with the MLM matching scheme [40] adopted. Finally, event analysis is performed by using MadAnalysis5 [41].

2.1 Analysis of the SS2L channel

For the final states including the SS2L topology, the signals are generated through the following processes,

$$pp \rightarrow t(\rightarrow W^+ b \rightarrow \ell^+ \nu b) H(\rightarrow WW^* \rightarrow \ell^+ \nu jj), \quad (3)$$

$$pp \rightarrow t(\rightarrow W^+ b \rightarrow \ell^+ \nu b) \bar{t}(\rightarrow Hq \rightarrow WW^* q \rightarrow \ell^+ \nu jjq), \quad (4)$$

where $\ell = e, \mu$. The representative Feynman diagrams are shown in Fig. 1.

For this channel, the typical signal is exactly two same-sign leptons plus at least three jets, with at least one jet identified as b -jet, and missing transverse energy. The main backgrounds are $t\bar{t}V$ ($V = W, Z$), $W^+ W^+ jj$ and $W^+ Z jj$. The $t\bar{t}$ process, which has large cross section, may also contribute to background if a same-sign lepton pair comes from a B -hadron semi-leptonic decay in the b -jet. We do not consider other backgrounds from $t\bar{t}H$, $t\bar{t}t\bar{t}$, tri-boson events and tHj . They are neglected because the cross sections are all negligible after applying the selection cuts.

The cross sections of dominant backgrounds at Leading Order (LO) are adjusted to Next-to-LO (NLO) by means of K -factors, which are 1.04 for $W^+ W^+ jj$ jets [42], 1.24 for $t\bar{t}W$ [43] and 1.39 for $t\bar{t}Z$ [44]. The dominant $t\bar{t}$ background is normalized to the NNLO QCD cross section of 953.6 pb [45]. For the tH production cross section, the K -factor is taken as 1.5 at the 14 TeV LHC [12].

The decay chain $H \rightarrow WW^* \rightarrow \ell \nu jj$ may result in soft leptons and light jets, especially when they are coming from an off-shell W boson. To analyze the signal sensi-

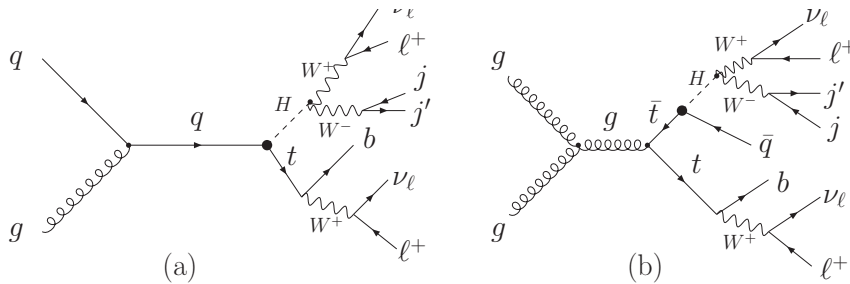


Fig. 1. Representative Feynman diagrams for the associated tH process (left) and the FCNC decay of the top pair production process (right). Here $q = u, c$.

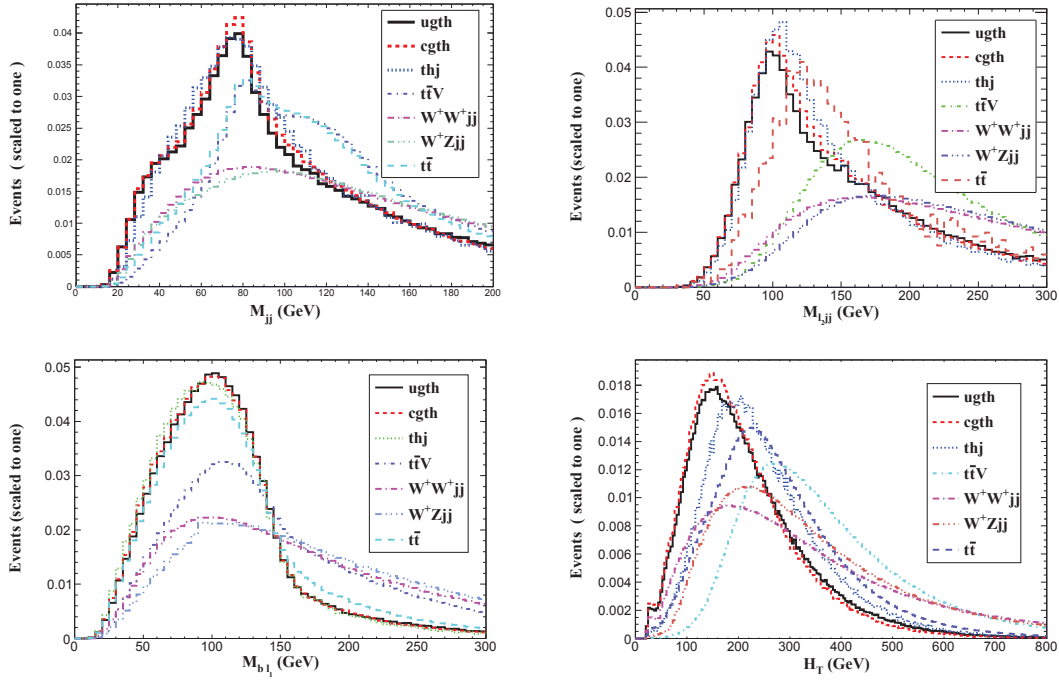


Fig. 2. (color online) Normalized distributions for the signals and the backgrounds.

tivity, we thus employ the following basic cuts to select the events:

Basic cuts: $p_T(\ell) > 10$ GeV, $p_T(j,b) > 15$ GeV, $|\eta_{\ell,j,b}| < 2.5$, where $\ell = e, \mu$.

In order to choose appropriate kinematic cuts, we plot in Fig. 2 examples of kinematic distributions for the signal and backgrounds. Based on these distributions, we impose a further set of cuts.

1) Cut-1: Exactly two same-sign leptons ($N(\ell^+) = 2$) with $p_T(\ell_1) > 20$ GeV and $p_T(\ell_2) > 10$ GeV (ℓ_1 and ℓ_2 denote the higher and lower p_T lepton, respectively) plus exactly one b -tagged jet ($N(b) = 1$). To remove contamination from hadron decay chains including $\ell^+\ell^-$ and Z boson, we choose the invariant mass larger than 12 GeV and $|M_{\ell\ell} - m_Z| > 10$ GeV.

2) Cut-2: At least two jets in the events are required to be successfully reconstructed, i.e., $N(j) \geq 2$. Among those reconstructed jets, there is at least one pair of jets which could come from a W boson either on-shell or off-shell. Thus the invariant mass of the W boson is required to be $M_{jj} < 90$ GeV.

3) Cut-3: The invariant mass of $M_{\ell_2 jj}$ is required to be smaller than 120 GeV.

4) Cut-4: Since the first lepton, ℓ_1 , is assumed to originate from the leptonically decaying top quark, the invariant mass of the b -jet and the leading lepton should be $M_{b\ell_1} < 140$ GeV.

5) Cut-5: The scalar sum of transverse momenta, H_T , is to be smaller than 250 GeV.

The effects of the cuts on the signal and background

processes are illustrated in Table 1 for the SS2L channel, where the anomalous coupling parameters are taken as $\kappa_{tuH} = 0.1$ or $\kappa_{tcH} = 0.1$, while fixing the other to zero. From Table 1 we can see that, after all these cuts, the $t\bar{t}$ backgrounds for the SS2L channel with fake leptons from heavy-flavor jets or charge mis-identifications can be significant.

Obviously, the non-prompt backgrounds may also be significant, where non-prompt leptons are from heavy-flavor decays, mis-identified hadrons, muons from light-meson decays or electrons from un-identified conversions of photons into jets. Recently, the CMS collaboration searched for SS2L signatures [46] and found that the overall non-prompt backgrounds are about 1.5 times the $t\bar{t}W$ background after all cuts. These non-prompt backgrounds are not properly modeled in our MC simulations. Therefore, for simplicity, we add a non-prompt background that is 1.5 times $t\bar{t}W$ [46] after selection cuts to the overall background. Accounting for the theoretical and experimental systematic uncertainties on the background predictions would certainly improve the reliability of the results, yet they can only be neglected in our simulation.

2.2 Analysis of the 3L channel

Next, we consider the final states including 3L via the following processes:

$$pp \rightarrow t(\rightarrow W^+ b \rightarrow \ell^+ \nu b) h(\rightarrow WW^* \rightarrow \ell^+ \nu \ell^- \bar{\nu}), \quad (5)$$

Table 1. The cut flow of the cross sections (in fb) for the signal and SM backgrounds for the SS2L channel. The coupling parameters are taken as $\kappa_{tuH}=0.1$ or $\kappa_{tcH}=0.1$, while fixing the other to zero.

cuts	signal			backgrounds			
	ug	cg	$t\bar{t} \rightarrow tHq$	$t\bar{t}V$	$WWjj$	$WZjj$	$t\bar{t}$
basic cuts	3.12	0.34	3.77	6.73	6.42	20.9	61004
Cut 1	0.48	0.056	0.69	0.85	0.21	0.25	6.52
Cut 2	0.225	0.027	0.34	0.27	0.04	0.046	2.54
Cut 3	0.18	0.022	0.28	0.092	0.016	0.011	1.7
Cut 4	0.15	0.019	0.24	0.058	0.009	0.0063	1.36
Cut 5	0.14	0.017	0.21	0.048	0.007	0.005	1.16

$$pp \rightarrow t(\rightarrow W^+b \rightarrow \ell^+\nu b)\bar{t}(\rightarrow Hq \rightarrow WW^*q \rightarrow \ell^+\nu\ell^-\bar{\nu}q), \quad (6)$$

where $\ell=e, \mu$.

The dominant SM backgrounds are $t\bar{t}V$ ($V=W, Z$), $t\bar{t}H$, WZ + jets and $t\bar{t}$. The multi-jet backgrounds (where jets can fake electrons) are not included since they are negligible in multi-lepton analyses [47].

The pre-selection cuts are taken as follows: there must exist exactly three isolated leptons ($\ell=e, \mu$) and exactly one b -tagged jet with $p_T(\ell_1) > 20$ GeV, $p_T(\ell_{2,3}) > 10$ GeV, $p_T(j, b) > 20$ GeV, $\cancel{E}_T > 100$ GeV and $|\eta_{\ell, j, b}| < 2.5$. These cuts can strongly reduce the $t\bar{t}$ background and its di-boson components.

In Fig. 3, we show the invariant mass distribution of $M_{\ell_2\ell_3}$ and $M_{b\ell_1}$ from the signal and backgrounds at the 14 TeV LHC. To remove contamination from hadron decay chains including $\ell^+\ell^-$ pairs and resonant Z bosons, we choose the invariant mass $M_{\ell_2\ell_3}$ cuts

$$12\text{GeV} < M(\ell_2\ell_3) < 55\text{ GeV}.$$

Similarly, the invariant mass of the b -jet and the leading lepton, $M_{b\ell_1}$, should be smaller than 140 GeV. The effects of the cuts on the signal and background processes are illustrated in Table 2 for the 3L channel. One can see that significant backgrounds also come from the top pair production process with fake leptons or charge misidentifications.

Using the Poisson formula [48],

$$SS = \sqrt{2\mathcal{L}_{\text{int}}[(S+B)\ln(1+S/B)-S]}$$

we estimate the Signal Significance (SS) with fixed coupling parameters κ_{tqH} and a given integrated luminosity

\mathcal{L}_{int} . In Figs. 4 and 5, we plot the contours of $SS=3$ and $SS=5$, respectively, for two channels in the plane of $\mathcal{L}_{\text{int}}-\kappa_{tqH}$. It is clear that, for an integrated luminosity of 3000 fb^{-1} , the FCNC couplings κ_{tuH} (κ_{tcH}) can be probed to 0.045 (0.052) and 0.035 (0.049) at 3σ statistical sensitivity for the SS2L and 3L channels, respectively. After neglecting the masses of light quarks, the branching ratio of $t \rightarrow qH$ is approximately given by [13, 49]

$$\begin{aligned} Br(t \rightarrow qH) &= \frac{\kappa_{tqH}^2}{\sqrt{2}m_i^2 G_F} \frac{(1-x_h^2)^2}{(1-x_W^2)^2(1+2x_W^2)} \lambda_{\text{QCD}} \\ &\simeq 0.58\kappa_{tqH}^2, \end{aligned} \quad (7)$$

in terms of the Fermi constant G_F and with $x_i = m_i/m_t$ ($i=W, h$). In our numerical calculation, the relevant SM input parameters are taken as [50]:

$$m_H=125\text{ GeV}, \quad m_t=173.1\text{ GeV}, \quad m_W=80.379\text{ GeV}, \quad (8)$$

$$\begin{aligned} m_Z &= 91.1876\text{ GeV}, \quad \alpha_s(m_Z) = 0.1185, \\ G_F &= 1.166370 \times 10^{-5}\text{ GeV}^{-2}. \end{aligned} \quad (9)$$

Using Eq. (7), the limits can be translated in terms of constraints on the branching fractions of rare top decays. The 3σ CL upper limits on $Br(t \rightarrow qH)$ are $Br(t \rightarrow uH) = 1.17 \times 10^{-3}$ and $Br(t \rightarrow cH) = 1.56 \times 10^{-3}$ for the SS2L channel, and $Br(t \rightarrow uH) = 7.1 \times 10^{-4}$ and $Br(t \rightarrow cH) = 1.39 \times 10^{-3}$ for the 3L channel. The projected limits from different channels are summarized in Table 3. We can see from the table that our results are comparable with the sensitivity limits at the HL-LHC of $Br(t \rightarrow uH) < 0.036\%$ via the $H \rightarrow \gamma\gamma$ channel [29], $Br(t \rightarrow uH) < 0.05\%$ via the multi-lepton channel and $Br(t \rightarrow uH) < 0.02\%$ via the di-photon channel [51].

Table 2. The cut flow of the cross sections (in fb) for the signal and background processes for the 3L channel.

cuts	signals			backgrounds			
	ug	cg	$t\bar{t} \rightarrow tHq$	$t\bar{t}$	$t\bar{t}V$	$WZjj$	$t\bar{t}h$
basic cuts	1.39	0.17	2.05	21843	1.85	46.2	0.025
after cuts	0.14	0.018	0.106	0.23	0.024	0.021	1.7×10^{-5}

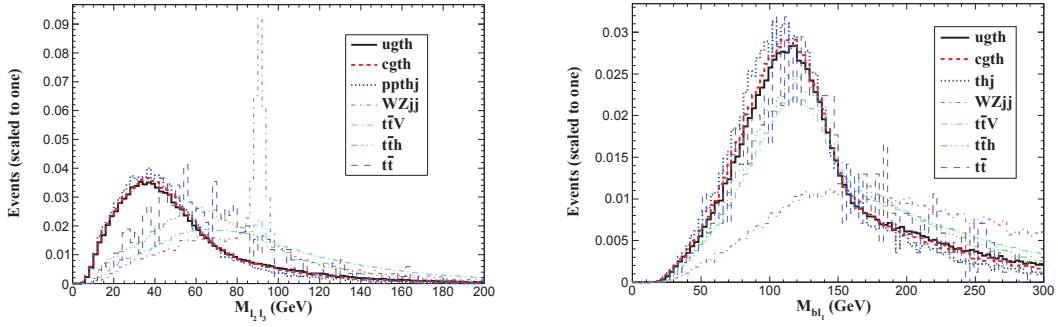
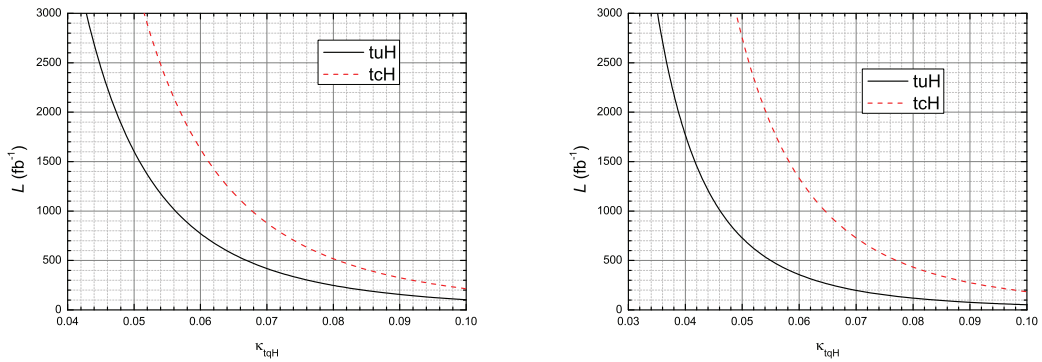

 Fig. 3. (color online) Normalized invariant mass distributions of $M_{\ell_2 \ell_3}$ (left) and $M_{b\ell_1}$ (right).

 Table 3. The projected limits on $Br(t \rightarrow qH)$ from different channels. The last two lines of the table are the results of this work.

channels	data set	limits
$tH \rightarrow \nu b \tau^+ \tau^-$	LHC, 100 fb^{-1} @ 13 TeV, 95% CL	$Br(t \rightarrow uH) < 0.15 \%$ [13]
$tH \rightarrow \nu b \ell^+ \ell^- X$	LHC, 100 fb^{-1} @ 13 TeV, 95% CL	$Br(t \rightarrow uH) < 0.22 \%$ [13]
$t\bar{t} \rightarrow Wb + Hc \rightarrow jjb + \tau\tau c$	LHC, 100 fb^{-1} @ 13 TeV, 95% CL	$Br(t \rightarrow cH) < 0.25 \%$ [14]
$tH \rightarrow jjb\bar{b}$	LHC, 100 fb^{-1} @ 13 TeV, 95% CL	$Br(t \rightarrow uH) < 0.36 \%$ [13]
$Wt \rightarrow WHq \rightarrow \nu b \gamma \gamma q$	LHC, 3000 fb^{-1} @ 14 TeV, 3σ	$Br(t \rightarrow qH) < 0.24 \%$ [28]
$tH \rightarrow \nu b \gamma \gamma q$	LHC, 3000 fb^{-1} @ 14 TeV, 3σ	$Br(t \rightarrow uH) < 0.036 \%$ [29]
$t\bar{t} \rightarrow WbqH \rightarrow \nu b \gamma \gamma q$	LHC, 3000 fb^{-1} @ 14 TeV, 3σ	$Br(t \rightarrow uH) < 0.23 \%$ [30]
$e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e H (\rightarrow b\bar{b}) \bar{q}$	LHeC, 200 fb^{-1} @ 150 GeV \oplus 7 TeV, 95% CL	$Br(t \rightarrow qH) < 0.013 \%$ [31]
$t\bar{t} \rightarrow tqH \rightarrow \nu b \bar{b} \bar{q}$	ILC, 3000 fb^{-1} @ 500 GeV, 95% CL	$Br(t \rightarrow qH) < 0.112 \%$ [32]
$t\bar{t} \rightarrow tqH \rightarrow \nu b \bar{b} \bar{q}$	ILC (unpolarized), 500 fb^{-1} @ 500 GeV, 3σ	$Br(t \rightarrow qH) < 0.119 \%$ [33]
$t\bar{t} \rightarrow tqH \rightarrow \nu b \bar{b} \bar{q}$	ILC (polarized), 500 fb^{-1} @ 500 GeV, 3σ	$Br(t \rightarrow qH) < 0.088 \%$ [33]
$t\bar{t} \rightarrow Wb + Hq \rightarrow \nu b + \gamma \gamma q$	LHC, 3000 fb^{-1} @ 14 TeV, 95% CL	$Br(t \rightarrow qH) < 0.02 \%$ [51]
$t\bar{t} \rightarrow Wb + hq \rightarrow \nu b + \ell \ell q X$	LHC, 3000 fb^{-1} @ 14 TeV, 95% CL	$Br(t \rightarrow qH) < 0.05 \%$ [51]
This work for the SS2L channel	LHC, 3000 fb^{-1} @ 14 TeV, 3σ	$Br(t \rightarrow uH) < 0.117 \%$, $Br(t \rightarrow cH) < 0.156 \%$
This work for the 3L channel	LHC, 3000 fb^{-1} @ 14 TeV, 3σ	$Br(t \rightarrow uH) < 0.071 \%$, $Br(t \rightarrow cH) < 0.139 \%$


 Fig. 4. (color online) The 3σ contour plots for the signal in the $\mathcal{L}_{int} - \kappa_{tqH}$ plane for the SS2L (left) and 3L (right) channels at the 14 TeV LHC.

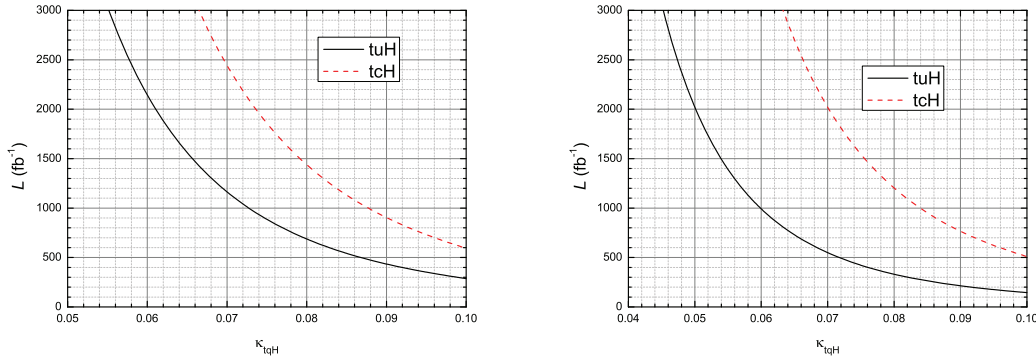


Fig. 5. (color online) The 5σ contour plots for the signal in the $\mathcal{L}_{\text{int}} - \kappa_{tqH}$ plane for the SS2L (left) and 3L (right) channels at the 14 TeV LHC.

3 Conclusions

The discovery of the 125 GeV Higgs boson opens the door to probe NP processes that involve Higgs boson associated production or decay. In this paper, we have investigated the signal of tH associated production via FCNC tqH couplings and $t\bar{t}$ production with $\bar{t} \rightarrow H\bar{q}$ at the 14 TeV LHC. We focused on the final states includ-

ing SS2L and 3L signals from the decay modes $t \rightarrow b\ell^+\nu_\ell$, $H \rightarrow WW^* \rightarrow \ell^+\nu jj$ or $H \rightarrow WW^* \rightarrow \ell^+\nu\ell^-\bar{\nu}$. We have then shown that, at 3σ level, the branching ratios $Br(t \rightarrow uH)$ and $Br(t \rightarrow cH)$ are, respectively, about $Br(t \rightarrow uH) \leq 1.17 \times 10^{-3}$ and $Br(t \rightarrow cH) \leq 1.56 \times 10^{-3}$ for the SS2L channel, and $Br(t \rightarrow uH) \leq 7.1 \times 10^{-4}$ and $Br(t \rightarrow cH) \leq 1.39 \times 10^{-3}$ for the 3L channel at the future HL-LHC.

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