Probing the top-Higgs FCNC couplings via the $h \rightarrow \gamma\gamma$ channel at the HE-LHC and FCC-hh

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Abstract

We investigate the sensitivity of future searches for the top-Higgs Flavour Changing Neutral Current (FCNC) couplings $tqh$ ($q = u, c$) at the proposed High Energy Large Hadron Collider (HE-LHC) and Future Circular Collider in hadron-hadron mode (FCC-hh). We perform a full simulation for two processes in the $h \rightarrow \gamma\gamma$ decay channel: single top quark FCNC production in association with the Higgs boson (plus a jet) and top quark pair production with FCNC decays $t \rightarrow qh$. All the relevant backgrounds are considered in a cut based analysis to obtain the limits on the Branching Ratios (BRs) of $t \rightarrow uh$ and $t \rightarrow ch$. It is shown that, at the HE-LHC with an integrated luminosity of 15 ab$^{-1}$ and at the FCC-hh with an integrated luminosity of 30 ab$^{-1}$, the BR($t \rightarrow uh$) and BR($t \rightarrow ch$) can be probed down to the order of $10^{-5}$ at the 95% Confidence Level (CL), which is two orders of magnitude better than the current 13 TeV LHC experimental results and one order of magnitude better than the existing projections for the 14 TeV High Luminosity LHC (HL-LHC) with an integrated luminosity of 3 ab$^{-1}$.
I. INTRODUCTION

The discovery of a 125 GeV Higgs boson [1, 2] at the Large Hadron Collider (LHC)\(^1\) was a landmark in the history of particle physics and it has opened up a new area of direct searches for Beyond the Standard Model (BSM) phenomena, since the \(h\) state may well be the portal into a New Physics (NP) world. Possible signals of NP are Flavour Changing Neutral Current (FCNC) interactions between the Higgs boson, the \(t\)-quark and a \(u\)- or \(c\)-quark, i.e., the vertex \(tqh\) \((q = u, c)\). In the SM, the FCNC top quark decays \(t \rightarrow qh\) \((q = u, c)\) are forbidden at the tree level and strongly suppressed at the loop level due to the Glashow-Iliopoulos-Maiani (GIM) mechanism [3]. For instance, the predicted \(\text{BR}(t \rightarrow qh)'s\) with \(q = u, c\) are expected to be of \(\mathcal{O}(10^{-12} - 10^{-17})\) [4–6] at one-loop level and are therefore out of range for current and near future experimental sensitivity. However, in some NP models the BRs for the \(t \rightarrow qh\) decays are predicted to be in the range of \(\mathcal{O}(10^{-6} - 10^{-3})\) [7–18]. Thus, any observation of such FCNC processes would be a clear signal of BSM dynamics.

Recently, the most stringent constraint on the top-Higgs FCNC couplings through direct measurements was reported by the CMS and ATLAS collaborations [19–23], by searching for \(t\bar{t}\) production with one top decaying to \(Wb\) and the other assumed to decay to \(hq\). Corresponding to 36.1 (35.9) fb\(^{-1}\) of data at the center-of-mass (c.m.) energy of 13 TeV for ATLAS (CMS), the 95\% Confidence Level (CL) upper limits are summarised in Tab. I. In addition to the direct collider measurements, indirect constrains on an anomalous \(tqh\) vertex can be obtained from the observed \(D^0 - \bar{D}^0\) mixing and \(Z \rightarrow c\bar{c}\) decays, where the upper limits of \(\text{BR}(t \rightarrow qh) < 5 \times 10^{-3}\) [24] and \(\text{BR}(t \rightarrow qh) < 0.21\%\) [25] are obtained, respectively. From a phenomenological viewpoint, the top-Higgs FCNC interactions have been studied extensively at hadron colliders within many NP scenarios [26–36]. Besides, many phenomenological studies using model-independent methods have also been performed via either anomalous top decay or anomalous top production processes [37–43].

A more promising result was put forward by the ATLAS Collaboration [44, 45], which has predicted the sensitivities \(\text{BR}(t \rightarrow uh) < 2.4 \times 10^{-4}\) and \(\text{BR}(t \rightarrow ch) < 1.5 \times 10^{-4}\) at 95\% CL at the High Luminosity LHC (HL-LHC). One can expect to improve further these limits at higher c.m. energies [46]. The future High Energy LHC (HE-LHC) with 27 TeV c.m.

\(^1\) Henceforth, it will be denoted by the symbol \(h\).
TABLE I: The current experimental upper limits on top-Higgs FCNC decays at 95% CL.

| Detector   | Decay channel | BR($t \rightarrow uh$) | BR($t \rightarrow ch$) |
|------------|---------------|-------------------------|-------------------------|
| ATLAS, 36.1 fb$^{-1}$ [23] | $h \rightarrow b\bar{b}, \tau^+\tau^-$ | $1.2 \times 10^{-3}$ | $1.1 \times 10^{-3}$ |
| CMS, 35.9 fb$^{-1}$ [54]   | $h \rightarrow b\bar{b}$               | $4.7 \times 10^{-3}$ | $4.7 \times 10^{-3}$ |

energy [47] and Future Circular Collider in hadron-hadron mode (FCC-hh) with 100 TeV c.m. energy [48] have great potential to pursue direct evidence of top-Higgs FCNC couplings with integrated luminosities of 15 ab$^{-1}$ and 30 ab$^{-1}$ in their final stages, respectively. While rather distant in the future, there are a lot of studies in literature that have shown how these machines can greatly improve the scope of previous accelerators in pursuing BSM searches [49–52]. So it is rather appropriate to assess their scope in accessing $tqh$ vertices too, the main reason being the common prejudice in the particle physics community that BSM phenomena are likely to manifest themselves in the interactions between the two heaviest states of the SM, indeed $t$ and $h$, which are in fact intimately related to the hierarchy problem of the SM, the main puzzle that Nature has forced upon us.

In our present paper, we perform an updated study of top-Higgs FCNC interactions at the HE-LHC and FCC-hh, by considering both single top quark production in association with the Higgs boson (plus a jet) and top quark pair production followed by a Higgs decay of one (anti)top state. A previous study done in Ref. [53] has investigated the top-Higgs FCNC interactions through $pp \rightarrow t h j$ with the subsequent decays $t \rightarrow b\ell^+\nu$ and $h \rightarrow \gamma\gamma$ at the HL-LHC. Here, we intend to revisit that analysis in the context of the aforementioned higher energy and luminosity hadron machines.

Furthermore, past literature also included the study of single top and Higgs boson associated production via the process $pp \rightarrow t h$, affording one with an improved sensitivity to especially the $tuh$ coupling (and somewhat less so to the $tch$ one) [54]. Specifically, the authors of Ref. [55] investigated the top-Higgs FCNC interactions through the $pp \rightarrow t(\rightarrow b\ell^+\nu) h(\rightarrow \gamma\gamma)$ process at the HL-LHC. However, one realises that the final numbers of events for these signals at the 14 TeV LHC are too small against the overwhelming SM background rate, even considering the high luminosity option of 3 ab$^{-1}$, also because the signals suffer from a small BR (0.23%)
for the $h \rightarrow \gamma\gamma$ channel. Yet, this is possibly the cleanest probe of the SM-like Higgs boson, so it ought to be nonetheless explored. In contrast, at both the HE-LHC and FCC-hh, the same production cross sections for signal (and SM background) can be enhanced significantly due to the higher energies available therein, so that one can find it a more favourable environment than the 13 and 14 TeV LHC to study the top-Higgs FCNC couplings via the $h \rightarrow \gamma\gamma$ decay channel, at the same time benefiting a larger luminosity.

This paper is arranged as follows. In Sec. II, we give a brief introduction to the top-Higgs FCNC couplings and perform a complete calculation of $pp \rightarrow thj$ by considering such interactions at tree level. In Sec. III, we discuss the observability (against the SM background) of such top-Higgs FCNC couplings through the process $pp \rightarrow thj$ with the top producing leptonic decay modes accompanied by $h \rightarrow \gamma\gamma$ at the HE-LHC and FCC-hh. Finally, conclusions and outlook are presented in Sec. IV.

II. TOP-HIGGS FCNC INTERACTIONS AND PRODUCTION PROCESSES

A. Top-Higgs FCNC couplings

Although the anomalous FCNC couplings between the top quark and Higgs boson may arise from different sources, an effective field theory approach can describe the effects of NP beyond the SM in a model-independent way [5]. The most general Lagrangian for the top-Higgs FCNC interactions is written as

$$\mathcal{L} = \kappa_{tuH} \bar{t}Hu + \kappa_{tcH} \bar{t}Hc + h.c.,$$

(1)

where $\kappa_{tuH}$ and $\kappa_{tcH}$ represent the strength of top-Higgs FCNC interactions. In this study we take them as real and symmetric, i.e., $\kappa_{tqH} = \kappa_{tqH}^\dagger = \kappa_{qtH} = \kappa_{qtH}^\dagger$ ($q = u, c$), since we here do not intend to consider CP-violating effects.

The decay width of the dominant top quark decay mode $t \rightarrow Wb$ could be found in Ref. [56]. Neglecting the light quark masses and assuming the dominant top decay width $t \rightarrow Wb$, the Next-to-Leading Order (NLO) BR($t \rightarrow qh$) is given by [57, 58]

$$\text{BR}(t \rightarrow qh) = \frac{\kappa_{tqH}^2}{\sqrt{2}m_t^2G_F} \frac{(1 - x_h^2)^2}{(1 - x_W^2)^2(1 + 2x_W^2)} \lambda_{\text{QCD}} \simeq 0.58\kappa_{tqH}^2,$$

(2)

with the Fermi constant $G_F$ and $x_i = m_i/m_t$ ($i = W, h$). Here the factor $\lambda_{\text{QCD}}$ is the NLO QCD correction to $\text{BR}(t \rightarrow qh)$ and equals about 1.1 [59–61]. In our work, we require $\kappa_{tqH} \leq 0.04$. 

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FIG. 1: Representative Feynman diagrams for: the $gg$ fusion induced top pair production $gg \to t\bar{t}$ and $\bar{t} \to \bar{q}h$ decay (a-b), the $gg$ fusion induced top-Higgs associated production $gg \to th\bar{q}$ (c-d) and the $qg$ fusion induced top-Higgs associated production $qg \to thq$ (e-f). Here $q = u, c$.

to satisfy the direct constraint from the ATLAS result mentioned in the previous section.

**B. Production processes**

At the LHC, the cross section for $pp \to thj$ involving top-Higgs FCNC couplings would be coming from two subprocesses: (i) top pair production followed by one FCNC top decay, $pp \to t\bar{t} \to thj$, shown in Fig. 1(a-b) (henceforth referred to as ‘top FCNC decay’); (ii) single top-Higgs associated production in presence of a jet, $pp \to thj$, as shown in Fig. 1(c-f), which includes a $gg$ (henceforth referred to as ‘$tH$ associated production’) and a $qg$ (henceforth referred to as ‘$qg$ fusion’) induced subchannels, respectively yielding a(n) (anti)quark or gluon in the final state. The contribution of other subprocesses, such as $q\bar{q}$ fusion channels, is smaller than
the above ones due to the suppression from colour factors and Parton Distribution Functions (PDFs) and thus is not shown in the Feynman diagrams, but all the contributions are included in our calculations. Obviously, the conjugated processes can also occur at tree level and are accounted for.

For the simulations of the HE-LHC and FCC-hh dynamics, we first use the FeynRules package [62] to extract the Feynman rules from the effective Lagrangian and to generate the Universal FeynRules Output (UFO) files and calculate the LO cross sections of $pp \rightarrow thj$ by using MadGraph5-aMC@NLO [63] with NNPDF23L01 PDFs [64], considering the renormalisation and factorisation scales to be $\mu_R = \mu_F = \mu_0/2 = (m_t + m_h)/2$. In our numerical calculations, the SM input parameters are taken as [65]:

\begin{equation}
\begin{align*}
m_h &= 125.1 \text{ GeV}, \quad m_t = 172.9 \text{ GeV}, \quad m_W = 80.379 \text{ GeV}, \\
m_Z &= 91.1876 \text{ GeV}, \quad \alpha_s(m_Z) = 0.1185, \quad G_F = 1.166370 \times 10^{-5} \text{ GeV}^{-2}.
\end{align*}
\end{equation}

In Fig. 2, we show the dependence of the cross sections for the three $thj$ subprocesses on the top-Higgs FCNC coupling parameter at the HE-LHC and FCC-hh for two scenarios, as follows: Case I is for $\kappa_{tqh} = \kappa_{tuh}, \kappa_{tch} = 0$ whereas Case II is for $\kappa_{tqh} = \kappa_{tch}, \kappa_{tuh} = 0$. From Fig. 2 one can see that, for a given coupling parameter $\kappa_{tqh}$, the production cross sections can be very significant at the higher c.m. energies of these two future machine. Besides, we also have the following observations.

1. For both Case I and II, the dominant contribution to the $thj$ final state is from (resonant) pair production, $pp \rightarrow t\bar{t} \rightarrow thj$. However, the other two contributions from $tH$ associated production and $qg$ fusion cannot be neglected, especially for Case I. To be specific, in this scenario, when $\sqrt{s} = 27 (100)$ TeV and $\kappa_{tuh} = 0.04$, the cross section of the top FCNC decay process is about 4.44 (44.56) pb while the cross section of the $tH$ associated production process is about 1.94 (13.8) pb with the one for $qg$ fusion being 1.56 (11.6) pb.

2. For the same values of $\kappa_{tuh}$ and $\kappa_{tch}$, the cross sections coming from the $tH$ associated production and $qg$ fusion processes in Case I are much larger than those in Case II: this is because the $u$-quark has a larger PDF than that of the $c$-quark. To be specific, in Case II, when $\sqrt{s} = 27 (100)$ TeV and $\kappa_{tch} = 0.04$, the cross section of the $tH$ associated production process is only about 0.37 (4.03) pb while for $qg$ fusion the rates are 0.22 (2.6).
FIG. 2: The dependence of the cross section $\sigma$ of the three $pp \rightarrow thj$ subprocesses of Fig. 1 on the top-Higgs FCNC couplings $\kappa_{thj}$ at the HE-LHC (top) and FCC-hh (bottom) for Case I (left) and Case II (right) identified in the text. Notice that the charge conjugated processes are also included in the calculation.

Thus, for a given collider energy and luminosity, we can expect the sensitivity to the coupling $\kappa_{thj}$ to be better than that to the $\kappa_{thj}$ one.
III. DISCOVERY POTENTIAL

A. The signal-to-background analysis

In this section, we present the numerical calculations at the HE-LHC and FCC-hh of the processes

$$pp \rightarrow t\bar{t} \rightarrow t(\rightarrow W^+b \rightarrow \ell^+\nu b)h(\rightarrow \gamma\gamma)j, \quad (4)$$

$$pp \rightarrow t(\rightarrow W^+b \rightarrow \ell^+\nu b)h(\rightarrow \gamma\gamma)j, \quad (5)$$

where $\ell = e, \mu$ and $j$ represents (a(n) (anti)quark or gluon) jet, interfaced to the subsequent parton shower by using the MLM matching scheme [66, 67]. The final state of signal process is thus characterised by two photons appearing as a narrow resonance centered around the SM-like Higgs boson mass. The main SM backgrounds that include both a Higgs boson decaying into di-photons in association with other particles and non-resonant production of $\gamma\gamma$ pairs are accounted for here:

- $pp \rightarrow t\bar{t}h$,
- $pp \rightarrow thj$,
- $pp \rightarrow W^\pm jjh$,
- $pp \rightarrow t\bar{t}\gamma\gamma$,
- $pp \rightarrow tj\gamma\gamma$,
- $pp \rightarrow \gamma\gamma W^\pm jj$.

The parton level events for the signal and the SM backgrounds are interfaced to parton shower, fragmentation and hadronisation by using PYTHIA8.20 [68]. Then, we have passed all generated events through Delphes3.4.2 [69] for detector simulation. Finally, event analysis is performed by using MadAnalysis5 [70]. As far as jet reconstruction is concerned, the anti-$k_t$ algorithm [71] with a jet radius of 0.4 is used. For the HE-LHC and FCC-hh analysis, we have used the default HL-LHC and FCC-hh detector card configuration implemented into the aforementioned detector emulator.
The cross sections of the signal and dominant backgrounds at LO are adjusted to NLO QCD through \( K \)-factors, i.e., \( K = 1.4 \) for the \( pp \rightarrow t\bar{t} \rightarrow thj \) process \([72]\), \( K = 1.5 \) for the \( tH \) associated production process \([37, 38]\) and \( K = 1.3 \) for the \( pp \rightarrow t\bar{t}h \) process \([72–74]\). For the sake of simplicity, we have rescaled the other SM background processes by a \( K \)-factor of 1.5. This approximation does not have a significant impact on our derived sensitivities and can be fully addressed in a future analysis.

In order to identify objects, we impose the following basic cuts to select the events \([46, 75]\):

\[
\begin{align*}
\text{HE – LHC} : & \quad p_T^{\ell/j/b} > 25 \text{ GeV}, \quad p_T^\gamma > 20 \text{ GeV}, \quad |\eta| < 2.5, \quad \Delta R_{ij} > 0.4 \quad (i, j = \ell, b, j, \gamma), \\
\text{FCC – hh} : & \quad p_T^{\ell/\gamma} > 25 \text{ GeV}, \quad p_T^{j/b} > 30 \text{ GeV}, \quad |\eta| < 4, \quad \Delta R_{ij} > 0.4 \quad (i, j = \ell, b, j, \gamma),
\end{align*}
\]

where \( \Delta R \) is the angular distance between any two objects.

In order to choose appropriate kinematic cuts, in Fig. 3\(^2\), we plot some differential distributions for signals and SM backgrounds at the HE-LHC at 27 TeV, such as the (ordered) transverse momentum distributions of the two photons, \( p_T^{\gamma_1,2} \), the separation, \( \Delta R_{\gamma\gamma} \), and invariant mass, \( M_{\gamma\gamma} \), distributions of the two photons, the transverse mass distribution for the \( \ell E_T, M_T(\ell) \), and \( b\ell E_T, M_T(b\ell) \), systems. Based on these distributions, we impose a further set of cuts.

- Cut 1: Exactly one isolated lepton and one \( b \)-jet, \( N(\ell) = 1 \) and \( N(b) = 1 \).
- Cut 2: At least two photons with \( p_T^{\gamma_1} > 60 \text{ GeV}, p_T^{\gamma_2} > 30 \text{ GeV} \) and \( 0.4 < \Delta R_{\gamma\gamma} < 3.0 \), since the two photons in the signal and resonant SM backgrounds come from the Higgs boson they have a harder \( p_T \) spectrum than those in the non-resonant SM backgrounds.
- Cut 3: The invariant mass of the di-photon system, \( M_{\gamma\gamma} \), is peaked in both the signals and resonant backgrounds, thus we require \( M_{\gamma\gamma} \) to be in the range \( |M_{\gamma\gamma} - m_h| < 5 \text{ GeV} \).
- Cut 4: The transverse mass \( M_T(\ell) \) and \( M_T(b\ell) \) cuts are \( 50 \text{ GeV} < M_T(\ell) < 100 \text{ GeV} \) and \( 120 \text{ GeV} < M_T(b\ell) < 180 \text{ GeV} \).

For the FCC-hh analysis at 100 TeV, we use the same selection cuts for the signal and SM backgrounds because the distributions are very similar to the case of HE-LHC presented in

\(^2\) Hereafter, in figures and tables, by using ‘thj\_tuh \([pp \rightarrow thj \text{ via } tuh]\)’ and ‘thj\_tch \([pp \rightarrow thj \text{ via } tch]\)’, we will intend the contribution to the signal due to \( tH \) associated production plus \( qg \) fusion when only including the \( tuh \) or \( tch \) coupling on its own, respectively.
Fig. 3. In fact, the difference between the HE-LHC and FCC-hh mainly comes from the different detector configurations. The effects of the suitable cuts on the signal and SM background processes are illustrated in Tab. II and Tab. III at the HE-LHC and FCC-hh, respectively. One can see that, at the end of the cut flow, the largest SM background is the $pp \rightarrow t\bar{t}h$ process, which is 0.017 fb and 0.24 fb at HE-LHC and FCC-hh, respectively. Besides, the $tj\gamma\gamma$ and $\gamma\gamma W^{\pm}jj$ processes can also generate significant contributions for the SM background due to the large production cross sections.
TABLE II: The cut flow of the cross sections (in fb) for the signals and SM backgrounds at the HE-LHC where the anomalous coupling parameters are taken as $\kappa_{tuh} = 0.04$ or $\kappa_{tch} = 0.04$ in the signal, while fixing the other to zero.

| Cuts     | Signal   | Backgrounds |
|----------|----------|-------------|
|          | $t\bar{t} \to thj$ | $thj$ | $W^{\pm} jjh$ | $t\bar{t}\gamma\gamma$ | $t\gamma\gamma$ | $\gamma\gamma W^{\pm} jj$ |
| Basic cuts | 0.23 0.057 0.41 | 0.27 0.035 0.02 | 4.06 5.01 5.98 |
| Cut 1     | 0.21 0.05 0.37 | 0.114 0.025 0.016 | 1.74 3.66 5.33 |
| Cut 2     | 0.13 0.03 0.20 | 0.062 0.015 0.009 | 0.28 0.51 0.74 |
| Cut 3     | 0.11 0.028 0.18 | 0.055 0.013 0.007 | 0.017 0.033 0.04 |
| Cut 4     | 0.055 0.014 0.092 | 0.017 0.0066 0.0014 | 0.0045 0.017 0.0053 |

TABLE III: The cut flow of the cross sections (in fb) for the signals and SM backgrounds at the FCC-hh where the anomalous coupling parameters are taken as $\kappa_{tuh} = 0.04$ or $\kappa_{tch} = 0.04$ in the signal, while fixing the other to zero.

| Cuts     | Signal   | Backgrounds |
|----------|----------|-------------|
|          | $t\bar{t} \to thj$ | $thj$ | $W^{\pm} jjh$ | $t\bar{t}\gamma\gamma$ | $t\gamma\gamma$ | $\gamma\gamma W^{\pm} jj$ |
| Basic cuts | 1.94 0.76 4.78 | 7.93 0.68 0.35 | 77.5 70.6 60.6 |
| Cut 1     | 1.33 0.49 3.33 | 1.75 0.32 0.22 | 17.2 35.3 13.4 |
| Cut 2     | 0.84 0.314 1.87 | 0.89 0.18 0.12 | 3.17 4.9 13.5 |
| Cut 3     | 0.823 0.3 1.85 | 0.87 0.17 0.11 | 0.15 0.27 0.69 |
| Cut 4     | 0.413 0.157 0.98 | 0.24 0.086 0.017 | 0.037 0.14 0.075 |

B. Sensitivities at the HE-LHC and FCC-hh

To estimate the exclusion significance, $Z_{\text{excl}}$, we use the following expression [76–78]:

$$Z_{\text{excl}} = \sqrt{2 \left[ s - b \ln \left( \frac{b + s + x}{2b} \right) - \frac{1}{\delta^2} \ln \left( \frac{b - s + x}{2b} \right) \right] - (b + s - x) \left( 1 + \frac{1}{\delta^2 b} \right)},$$  \hspace{1cm} (7)

with $x = \sqrt{(s + b)^2 - 4\delta^2 sb^2/(1 + \delta^2 b)}$. Here, the values of $s$ and $b$ were obtained by multiplying the total signal and SM background cross sections, respectively, by the integrated lumi-
nosity. Furthermore, $\delta$ is the percentage systematic error on the SM background estimate. In the limit of $\delta \to 0$, this expression can be simplified as

$$Z_{\text{excl}} = \sqrt{2[s - b \ln(1 + s/b)]}.$$ (8)

In this work we choose two cases: no systematics ($\delta = 0$) and a systematic uncertainty of $\delta = 10\%$ for both the HE-LHC and FCC-hh. We define the regions with $Z_{\text{excl}} \leq 1.645$ as those that can be excluded at 95% CL ($p = 0.05$). The limits on the FCNC coupling parameter $\kappa_{tqg}$ can be directly translated in terms of constraints on $\text{BR}(t \to qh)$ by using eq. (2).

![Image](FIG. 4: The exclusion limits at 95% CL on $\text{BR}(t \to uh)$ (left) and $\text{BR}(t \to ch)$ (right) at the HE-LHC with two systematic error cases: $\delta = 0$ and $\delta = 10\%$.)

![Image](FIG. 5: Same as Fig. 4 but for the FCC-hh.)
TABLE IV: The upper limits on $\text{BR}(t \to qh)$ at 95% CL obtained at the HE-LHC and FCC-hh. We consider systematic errors of 0% and 10% on the SM background events only. The 95% CL upper limits obtained at the HL-LHC at 3 ab$^{-1}$ by the ATLAS Collaboration also have been shown for comparisons.

| Branching fraction | HE-LHC, 15 ab$^{-1}$ | FCC-hh, 30 ab$^{-1}$ | HL-LHC [44] |
|--------------------|----------------------|----------------------|-------------|
|                    | $\delta = 0$ | $\delta = 10\%$ | $\delta = 0$ | $\delta = 10\%$ |
| $\text{BR}(t \to uh)$ | $1.96 \times 10^{-5}$ | $5.72 \times 10^{-5}$ | $4.93 \times 10^{-6}$ | $6.62 \times 10^{-5}$ | $2.4 \times 10^{-4}$ |
| $\text{BR}(t \to ch)$ | $2.72 \times 10^{-5}$ | $7.96 \times 10^{-5}$ | $6.04 \times 10^{-6}$ | $8.11 \times 10^{-5}$ | $2.0 \times 10^{-4}$ |

In Figs. 4-5, we plot the exclusion limits at 95% CL in the plane of the integrated luminosity and the $\text{BR}(t \to qh)$’s at the HE-LHC and FCC-hh with the aforementioned two systematic error cases of $\delta = 0$ and $\delta = 10\%$. One can see that our signals are rather robust against the systematic uncertainties on the background determination. The values for 95% CL upper limits are summarised in Tab. IV. With a realistic 10% systematic error, the sensitivities are slightly weaker than those without any systematic error, being of the order of $10^{-5}$ at the 95% CL both at the HE-LHC and FCC-hh. For comparison, the recent 95% upper limits on $\text{BR}(t \to qh)$ obtained at the HL-LHC with an integrated luminosity of 3 ab$^{-1}$ by the ATLAS Collaboration [44] are also presented, which are obtained via the decay mode $t \to qh(\to b\bar{b})$. Besides, the upgraded ATLAS experiment has also estimated top-Higgs FCNC couplings via the decays $t \to ch(\to \gamma\gamma)$ at the HL-LHC and obtained an expected upper limit of $\text{BR}(t \to ch) < 1.5 \times 10^{-4}$ at 95% CL [45]. Altogether, the sensitivity to the BR of the $t \to uh$ and $t \to ch$ channels are two order of magnitude better than the most recent direct limits reported by the ATLAS Collaboration at the 13 TeV LHC and one order of magnitude better than the HL-LHC projections at 14 TeV.

Before closing, let us also review competing limits from other authors. Very recently, the author of Ref. [79] has studied the top-Higgs FCNC couplings in the triple-top signal at the HE-LHC and FCC-hh. The 95% CL upper limits on $\text{BR}(t \to uh)$ (and $\text{BR}(t \to ch)$) were found, respectively, as $7.01 \times 10^{-4}$ ($3.66 \times 10^{-4}$) at the HE-LHC with 15 ab$^{-1}$ and as $2.49 \times 10^{-5}$ ($5.85 \times 10^{-5}$) at the FCC-hh with 10 ab$^{-1}$. Furthermore, in the context of the 2-Higgs Doublet Model (2HDM), the authors of Ref. [80] have recently investigated the prospect for $t \to ch$ decay in top quark pair production via the $h \to WW^* \to \ell^+\ell^- + \not{E}_T$ channel. For
the HE-LHC and FCC-hh, the 95% CL upper limits on BR($t \rightarrow ch$) was found to be at the order of $10^{-4}$ with an integrated luminosity of 3 ab$^{-1}$ and such limits would be increased by an higher integrated luminosity. Finally, at the FCC-hh with an integrated luminosity of 10 ab$^{-1}$, Ref. [81] has investigated the $t \rightarrow ch$ decay and the its BR can be constrained to $O(10^{-5})$ either with or without considering $c$-jet tagging.

IV. SUMMARY

In this work, we have analysed the process $pp \rightarrow thj$ at the HE-LHC and FCC-hh by considering $thq$ FCNC couplings. We have performed a full Monte Carlo simulation for the signals obtained from three different subprocesses via the top leptonic decay mode and $h \rightarrow \gamma\gamma$ against all relevant SM backgrounds. The obtained exclusion limits on the $tqh$ coupling strengths and the ensuing BRs have been summarised and compared in detail to results in literature, namely, the most recent LHC experimental limits and the (projected) HL-LHC ones as well. Our results show that 95% CL limits on the BR($t \rightarrow qh$)'s ($q = u, c$) have been found to be $1.96 (2.72) \times 10^{-5}$ at the HE-LHC with an integrated luminosity of 15 ab$^{-1}$ and $4.93 (6.04) \times 10^{-6}$ at the FCC-hh with an integrated luminosity of 30 ab$^{-1}$, for $q = u$ ($c$), in the case the SM background is known with negligible uncertainty. When a more realistic 10% systematic uncertainty is considered, the sensitivity decreases to $5.72 (7.96) \times 10^{-5}$ at the HE-LHC and $6.62 (8.11) \times 10^{-5}$ at the FCC-hh, again, in correspondence to $q = u$ ($c$). These limits are two orders of magnitude better than the current experimental results obtained from LHC runs at 13 TeV and one order of magnitude better than the existing projections for the HL-LHC at 14 TeV. Therefore, the numerical results presented here for the future HE-LHC and FCC-hh represent good reasons for pursuing further the study of their potential in extracting FCNC effects from NP manifesting themselves in top-Higgs interactions.

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