Investigating Top-Higgs FCNC Couplings at the FCC-hh

O. M. Ozsimek

Graduate School of Science and Engineering, Hacettepe University, 06800 Ankara, Turkey

V. Ari‡ and O. Cakir‡

Department of Physics, Ankara University, 06100 Ankara, Turkey

(Dated: 10th May 2022)

We have studied the sensitivity to flavor changing neutral current interaction of top and Higgs boson at the future circular collider in the hadron-hadron collision mode (FCC-hh). Our main concerns are the processes of $pp \to th$ (FCNC production) and $pp \to t\bar{t}$ (one top FCNC decay) which contributes to the single lepton, at least three jets and the missing energy transverse in the final state. On the one hand FCC-hh offers very high luminosity and large cross section for these signal processes, on the other hand signal can be distinguished from background which needs application of ingenious methods. Here, we have inspired and followed the searches at the LHC using our analysis path and enhanced attainable limits obtained on the possible top-Higgs FCNC couplings phenomenologically. We obtain new limits which are beyond the current experimental limits obtained from different channels and processes at the LHC. The potential discovery or exclusion limits on branching ratios for $tqH$ FCNC interactions can be set

$$BR_{\text{disc}} = 9.08 \times 10^{-6} \quad \text{or} \quad BR_{\text{exc}} = 2.78 \times 10^{-4}$$

at an integrated luminosity of 30 ab$^{-1}$, respectively. Our results are compatible with the other channels already studied at FCC-hh.

Our work is presented in Arxiv with preprint number: arXiv:2204.13139

I. INTRODUCTION

After the discovery of the top quark at the Tevatron experiments [1, 2], and more recently the Higgs boson at the LHC experiments [3, 4], it has been opened a new era of the searches for new physics beyond the standard model (BSM). Conceptually the Standard Model (SM) suffers from the naturalness/hierarchy problem [5]. The problem originates mainly from the interactions between Higgs and relatively massive particles of SM which contributes the quantum corrections of Higgs mass. As a consequence there is a hierarchy between energy scales which gives known infinities, so there must be a new physics at a higher energy regime to neutralize these infinities and stabilize the electroweak (EW) scale.

In that sense, Higgs boson and top quark are the two heavy particles at SM which implies the most sensitive to TeV scale physics. Besides the contribution from loops with top quark to Higgs mass far more dominant compared to others. Thus fate of BSM physics will be decided by Higgs physics and top physics researches in that regard.

In the quark sector, the flavor changing neutral current (FCNC) interactions [6] are highly suppressed due to presence of CKM matrix. New symmetries such as SUSY (supersymmetry) [7-10] or 2HDMs (two Higgs doublet models) [11-14] at BSM gives opportunities for new interactions. Seemingly there is no reason to keep FCNC preserving structure of SM as we concern recent findings at neutrino searches which allows mixings. Especially, some models which will be mentioned at the following paragraphs have specifically important for our research. But let us give some details before continuing: FCNC interactions of MSSM (minimal supersymmetric standard model) models predict a branching ratio $\leq O(10^{-5})$ [15-17], same branchings are valid for composite Higgs models [18]. Additionally, 2HDMs foresee a braching ratio roughly between $O(10^{-3})$ to $O(10^{-6})$ [15-17]. Finally, RS (Randall-Sundrum) model and quark singlet models are expected to have a branching ratio about $O(10^{-4})$ [15-17].

Many experiments have been performed to find some evidence for FCNC interactions. However, the limits on FCNC couplings and branching ratios have been set by ATLAS and CMS collaborations. Upper limits for branching ratio by the ATLAS collaboration for the $BR(t \to cH)$ and the $BR(t \to uH)$ observed (expected) are $1.1 \times 10^{-3}$ ($7.3 \times 10^{-4}$) and $1.3 \times 10^{-3}$ ($2 \times 10^{-4}$) at the 95% confidence level respectively [19]. In this paper, coupling constants for $tcH$ and $tuH$ limited observed (expected) as 0.064 (0.055) and 0.066 (0.055), respectively [19]. Similar study by the CMS excludes limits as $BR(t \to uH) < 1.9 \times 10^{-4}$ ($3.1 \times 10^{-4}$) and $BR(t \to cH) < 9.4 \times 10^{-4}$ at 95% confidence level respectively for $H \to gg$ channel [20]. Here coupling constants are given as upper limits with 95% CL, observed (expected) for $tcH$ and $tuH$ 0.071 (0.060) and 0.037 (0.047), respectively [20]. Additionally, for $H \to bb$ channel similar research set limits for branchings observed (expected) such that $BR(t \to uH) < 7.9 \times 10^{-4}$ ($1.1 \times 10^{-3}$) and $BR(t \to cH) < 9.4 \times 10^{-4}$ ($1.8 \times 10^{-4}$) by the CMS [21].

At this research limits on couplings also determined as observed (expected) for $tcH$ and $tuH$ 0.081 (0.078) and 0.074 (0.087) respectively at 95% CL [21]. This research is followed by a new study by the ATLAS which...
gives limits as $BR(t \rightarrow uH) < 7.2 \times 10^{-4}$ $(3.6 \times 10^{-3})$ and $BR(t \rightarrow cH) < 9.9 \times 10^{-4}$ $(5.0 \times 10^{-4})$ respectively \[22\]. Then experimental limits are at the edge of $O(10^{-4})$ at best for branchings and the coupling constants are expected to be below roughly 0.05.

Figure 1. The FCNC decay width of top quark according to three scenario presented: For $u+c$ case top quark can decay into both, otherwise decays into only one of them.

Figure 2. FCNC branchings of top quark for three scenarios: $u+c$ indicates top quark can decay both $u$ and $c$. $u$ or $c$ is similar but only one channel preferred. Hence branchings instantly declined to approximately to half. Only $u$ or only $c$ indicates only one of the decay channel is accessible.

Future colliders having higher luminosity and higher center of mass energy are on the agenda. In addition to this, conceptual desing report (CDR) of FCC-hh have been also published \[10\]. Especially with 100 TeV center of mass energy and 30 $ab^{-1}$ luminosity FCC-hh enables for discovering or excluding many BSM scenarios which excites whole physics community. It is obvious that FCC-hh will enhance limits for all type of interactions. Bear in mind top quark and Higgs boson has vital importance for new physics, so they have the leading role also in FCNC interactions. In this study we would like to contribute expectations for possible FCC-hh discovery and or exclusion limits for Higgs-top quark FCNC interactions. While finishing, to close the circle by stressing the importance of FCC we would like to say the expected branchings for FCNC interactions at FCC-hh are about $O(10^{-5})$; we are looking for limits comparable to these expectations. It is obvious that with this capacity FCC-hh can rule out some RS, 2HDMs (especially flavor violating) and quark singlet models. Moreover, taking advantage of its high COM and luminosity, it can also penetrate the MSSM and some other 2HDMs regions where FCNC interactions are predicted. So, we take into account the process $pp \rightarrow th(q)$, $(t \rightarrow W^+ + b, W^+ \rightarrow l^+ + \nu_l, (h \rightarrow b\bar{b})$ interactions (top quark and Higgs produced on-shell) at the FCC-hh and try to exploit the potential discovery and exclusion limits of FCNC interactions.

II. MODEL FRAMEWORK

FCNC interactions studied at numerous scenarios depending on models which have many simple/complex extensions over the SM. Nevertheless, we would like to investigate the problem in the context of EFT, which is quite flexible and suitable for comparing results with experimental results. In that respect EFT provides a model independent research method to exploit the potentials of the new colliders. FCNC interactions including a $tqH$ vertex in generic manner can be described using an effective lagrangian as given as

\[
L_{\text{H}} = \frac{1}{\sqrt{2}} H \bar{q} L_{\eta} P^L \eta_{uR} P^R u + h.c. \\
+ \frac{1}{\sqrt{2}} H \bar{q} L_{\eta} P^L \eta_{cR} P^R c + h.c. 
\]

(1)

where the $\eta_{u/c}^{L/R}$ couplings shows the strenght of interactions among $u$ or $c$ to top quark and Higgs. Superindices $L, R$ denotes chirality which can be taken equal.

We can define more couplings as imaginary numbers but for sake of simplcity we omit those and pick couplings as real numbers. However, it should be noted that we let the number $\frac{1}{\sqrt{2}}$ in Lagrangian to restrict the discovery/exclusion region. It is obvious that it effects both branching ratios and cross sections.

By using that Lagrangian we calculated decay width as

\[
\Gamma(t \rightarrow qh) = \frac{(\eta_{uL}^2 + \eta_{cL}^2)(m_t^2 - m_h^2)^2}{64\pi m_t^4} 
\]

(2)

After we insert all parameters we find depency of decay width depending on FCNC couplings

\[
\Gamma(t \rightarrow qh) \simeq 0.1904(\eta_{uL}^2 + \eta_{cL}^2) \text{ GeV} 
\]

(3)
From the general definition of the branching ratio to FCNC interactions, relation turns into

$$BR(t \rightarrow qh) = \frac{\Gamma(t \rightarrow qh)}{\Gamma(t \rightarrow qh) + \Gamma(t \rightarrow Wq)}$$ (4)

Decay of top quark is special: it decays before hadronisation and leaves a trace with asymmetrical spin behaviour. In the case of decay modes which are dominated by $t \rightarrow Wb$ process, thus leads quadratic increment in branching ratio for small couplings as other contributions will be neglected in denominator.

It is already known that FCNC interactions are suppressed in one loop in SM. In EFT we use dimension six operators as the source of these interactions. To be specific about the model and operators we have introduced, the EFT Lagrangian

$$\mathcal{L}^{\text{eff}} = \sum \frac{C_x}{\Lambda^2} O_x + \ldots$$ (5)

where $C_x$ are being complex constants and $O_x$ are related dimension-six gauge-invariant operators [23, 24].

High powers of $\Lambda$ will suppress other terms and we focus mainly on the contributions comes from the first term. Relevant operators are $(i \neq j)$

$$\frac{i}{2} \left[ \phi^i \tau^f D_\mu \phi - (D_\mu \phi)^i \tau^f \phi \right] (\bar{q}_L, \gamma^\mu \tau^f q_L)$$ (6)

$$\frac{i}{2} \left( \phi^i \tau^f D_\mu \phi \right) (\bar{q}_L, \gamma^\mu q_L)$$ (7)

$$\frac{i}{2} \left( \phi^i \tau^f D_\mu \phi \right) (\bar{u}_R, \gamma^\mu u_R)$$ (8)

where $i, j$ indices show flavor. $\tau^I$ shows Pauli matrices $R, L$ indices shows chiral states as usual. For a complete picture let us show the relationship between both frameworks over coefficients

$$\delta \eta^L_{ct} = -\frac{3}{2} C_{u\phi}^{32*} \frac{v^2}{\Lambda^2} , \quad \delta \eta^R_{ct} = -\frac{3}{2} C_{u\phi}^{23} \frac{v^2}{\Lambda^2}$$ (9)

$$\delta \eta^L_{ut} = -\frac{3}{2} C_{u\phi}^{31*} \frac{v^2}{\Lambda^2} , \quad \delta \eta^R_{ut} = -\frac{3}{2} C_{u\phi}^{13} \frac{v^2}{\Lambda^2}$$ (10)

then we may correlate our result with the previous studies/analyses [23, 24].

III. CROSS SECTIONS OF SIGNAL AND BACKGROUND

After we introduce our framework we would like to present our signal process, decay channel and possible backgrounds before analysis.

We choose both $pp \rightarrow t(\bar{t})h$ and $pp \rightarrow t(\bar{t})hj$ as signal processes (see Fig. 3) in order to give Higgs boson and top quark to be products leading to single lepton, missing transverse momentum and the multijet final state. Here, we expect to enhance signal by taking them both of them and include the processes with $t$ to collect more events.

Since, we would like to optimize cross section to observe maximal number of events while keeping the problem realistic with relevant backgrounds, we impose sufficient conditions at every step of decisions. The signal $2 \rightarrow 2$ type process has high cross section as we know this kind of interactions which gives better statistics. The other process is $2 \rightarrow 3$ type, its cross section is also high.

Our aim is to work with a hadron collider at 100 TeV which produces many jets due to nature of interactions, thus at least one lepton channel would give clear signal footprint. Despite the leptonic channel lowers the cross section, it offers a better analysis.

As we know new physics interactions at BSM introduces a new vertex at effective Lagrangian with a constant absolute value in range $[0,1]$. Hence more new physics vertices give lower cross sections and make analysis harder. Thus we would like to restrict ourselves with less parameters if possible. Furthermore, we would like to avoid interference effects as possible, then we generate events having this property.

We use leptonic decay of $W$ boson to get rid of jet mess while reconstructing top and Higgs, besides Higgs decays to the channel where branching is the highest to get a higher number of events ($h, b$). This leads much more statistics if signal and background can be analysed properly, otherwise advantage of leptonic channel can be lost and there can be still jet mess present. Note that a research for similar channel has been done by CMS Collaboration at the LHC [21], we would like to enlarge scope by letting associated jets, and project it to FCC-hh. In that analysis, analysis region divided so that jet number restricted to three or four and two or three of them tagged as $b$; besides machine learning techniques used. Here, we are using cut-based analysis and to deal with jet mixings we use different analyse path while tagging $b$-jets which is crucial ingredient of the analysis. For now, we would like to stress the importance of the effort and postpone it to several paragraphs later.

We deal with three scenarios while approaching the problem and would like to discuss results in that perspective in order to get situations where at least one of the coupling constant different from zero. While analyzing we will use tree scenario namely $u + c$, only $u$ and only $c$.

The $u$ quark contribution is higher than the $d$ quark to the cross section. This is realised so that up quarks are being valance quarks in proton which have higher distributions. After initial setup, Madgraph5 [25] is used to generate signal and background samples by using parton distribution function (PDF) set NNPDF2.3 [26] at five flavor scheme (topFCNC model was used) [27, 28]. Then by using PYTHIA8 [29], samples generated at partonic level have been hadronised which is followed by fast detector simulation with DELPHES 3 [30] by using FCC-
hh detector card. The samples are produced with default cuts

1. \( p_T^{\text{jets}} > 20 \text{ GeV}, \ |\eta^{\text{jets}}| < 5 \)
2. \( p_T^{\text{leptons}} > 10 \text{ GeV}, \ |\eta^{\text{leptons}}| < 2.5 \)
3. \( \Delta R(i, j) > 0.4, \ i, j \) being jets and leptons.

Finally Root6 [31] is used to analyse resultant sample files. Our signal final state has one lepton, missing transverse energy and at least three jets (where at least two of them required as \( b \) jets) as the characteristic.

Here we would like to mention some other features of signal and background and we will present our analysis strategy at the next section. We observe two features at backgrounds: Top pair plus jet(s) have significantly high cross section while extra particle content mainly includes more jets which increases \( H_T \) but three \( b \) jets are not guaranteed. The others containing Higgs or another boson, still do not guarantee three \( b \) jets and there are extra jets which also increases total hadronic transverse energy \( H_T \) while having low cross sections. The \( B \) (any vector boson) decays to jets, similarity with signal is slightly higher at the backgrounds which have relatively low cross sections. In the case of top pair plus jet(s), their large cross sections would dominate whole region, hence it seems impossible to get rid of them completely.

An important aspect of these interactions are fat jets which are hitting the nearly same region of the detector. Momentum of jets are also crucial while analyzing, many of them comes from decay of two heaviest particles within the SM. There can also be resudually produced jets. Moreover, boosted objects with additional decay process

![Figure 3](image_url) Representative Feynman diagrams of production and decay channels.

![Figure 4](image_url) Comparison of FCNC cross sections: When two FCNC channels are open the cross section is highest for two type of processes as expected. Cross section of \( pp \to thj \) process is also higher nearly one order of magnitude. At hadron colliders there are numerous final jets as a result of nature of interactions, and allowance one jet near interested particles increases cross section considerably, even it is a \( 2 \to 3 \) process compared to the \( 2 \to 2 \) process. Similar to other considerations argued before, there is an optimisation, thus producing more jets is making tagging harder and lowers the relevance of FCNC process.

| Process                  | Cross section(pb) | Final states                                                                 |
|--------------------------|-------------------|------------------------------------------------------------------------------|
| \( pp \to t\bar{t}h \)   |                    | \( \ell^\pm, \nu_{\ell\pm}, b(b), j \)                                       |
| \( pp \to t\bar{t}h_j \) | \( 0.0075 \)       | \( \ell^\pm, \nu_{\ell\pm}, b(b), j \)                                       |
| \( pp \to t\bar{t}h_{\bar{c}} \) | \( 0.203 \)       | \( \ell^\pm, \nu_{\ell\pm}, b(b), j \)                                       |
| \( pp \to t\bar{t}h_{\bar{b}} \) | \( 0.1536 \)      | \( \ell^\pm, \nu_{\ell\pm}, b(b), j \)                                       |
| \( pp \to t\bar{t}B \)   | \( 1.576 \times 10^3 \) | \( \ell^\pm, \nu_{\ell\pm}, 2b(b), j \)                                     |
| \( pp \to t\bar{t}B_j \) | \( 1.656 \times 10^3 \) | \( \ell^\pm, \nu_{\ell\pm}, 2b(b), j \)                                     |
| \( pp \to t\bar{t}h \)   | \( 15.33 \)        | \( \ell^\pm, \nu_{\ell\pm}, 2b(b), j \)                                     |
| \( pp \to t\bar{t}h_{\bar{c}} \) | \( 0.6787 \)       | \( \ell^\pm, \nu_{\ell\pm}, 2b(b), j \)                                     |
| \( pp \to W\bar{h}_{jj} \) | \( 2.75 \)         | \( \ell^\pm, \nu_{\ell\pm}, 2b(b), j \)                                     |
including top quark affects the reconstruction of Higgs, likewise extra top quark which is not decaying leptonically gives alos a pseudo Higgs reconstruction, then such backgrounds including top pair need evolved elaboration.

Additionally, there are jets produced alongside with our mainly interested particles and they are produced residually which should not be $b$ jets necessarily. Thus, some parts of our backgrounds contains at least two or three $b$ jets. Furthermore, mixings and tagging efficiencies plays a major role here, one can not simply analyze signal by only tagging the jets, detector effects such as misidentification of particles, loosing particles or over-counting them require much evolved methods to analyze while tagging $b$ jets there is another optimisation, unique to analysis to eliminate background and still have reasonable number of events. One can put forward several numbers of $b$-tagging as a categorization when the analysis investigated. However, for a cut based analysis at a hadron factory, tagging jets and putting kinematical cuts is not a viable option to analysis (see Fig. 5, 6). We will come to this point at analysis part again due to its importance while reconstructing objects.

To sum up, When all these effects combined with high cross section, result is more realistic physically as we try to get.

Before we advance the analysis we would like to explain briefly why we let Higgs to decay into $b$ jets directly at process shown as $pp \rightarrow Whjj$. It differs from other backgrounds not including top quark which shifts signal reconstruction region drastically. It has low cross section among other backgrounds. Hence, we would like to aid and restore this background a little bit while increasing its similarity with signal.

### IV. ANALYSIS

Bearing in mind we have one lepton, MET and three $b$-jets as final state in the signal events. In addition to this, remembering the interaction occurs at a collider which has 100 TeV COM energy, we need to put basic cuts firsty to work with good objects rather than irrelevant random particles. First of all we would like to start with giving the distributions only generator level cuts present at Fig. 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20. Then we choose basic cuts as shown Table II. We use $\sum p_T$ as the sum of $p_T$ of the objects which are used at reconstruction of top and Higgs.

Defining good objects by using these cuts in a looser manner to keep number of signal events high at first stage to see behaviour of signal and background; then we will use more strict cuts to finalize our analysis while optimise the signal significance. At Table II first two lines show our object selection criteria. MET cut has been included for fulfill event selection criteria as well (then restric- toed to work with detected objects instead at main part of analysis). Then we use the more sensitive regions of detector by applying $\eta$ cuts. $p_T$ cuts included for eliminating irrelevant jets and events basically. Here the $p_T$ cuts somewhat self explanatory: we would like to trim residual jets produced at interaction and mixes the signal according to their decay mechanism. Finally $\Delta R$ cuts are present here for fat jets for possible misleading detection and distorting our analysis. After we see the bare distributions, we continue with strengthen our cuts. To show the evolution of the analysis we would like to divide analysis up to a looser Higgs mass reconstruction criteria with $\chi^2$ method then sharpen our cuts and pass to second part of analysis to give the last shape to analysis.

Notice that the background processes $pp \rightarrow t\bar{t}j$ and $pp \rightarrow t\bar{t}jj$ have highest cross section and has no Higgs as a product. Even though these backgrounds are insep-
arable completely in that sense. We can promote Higgs reconstruction as a discriminator for analysis. We may look for additional criterion to impose for rejecting that $t\bar{t}$ pair and furthermore reduce all backgrounds. This is why we choose Higgs reconstruction as a pin point of analysis.

We apply a $\chi^2$ which reconstructs Higgs bosons invariant mass in a range with ±20 GeV around 125 GeV. To determine the channel properly, we demand at least one of the jets reconstructs Higgs boson must be b-tagged. That b-tagging has vital importance to deduce the channel properly, we demand at least one ant mass in a range with $2\sigma$.

Here we used the relation when we calculate the $\chi^2$ basically

$$\chi^2 = \sum_i \frac{(O_i - E)^2}{\Delta^2}. \quad (11)$$

In this relation we used $O_i$ as observed reconstruction variable for signal and backgrounds at every event. $E$ stands for expected values of these quantities as usual. $\Delta$ shows the error at this event reconstruction. If we adopt this relation to our analysis for the simpler case we may write this relation down as

$$\chi^2 = \frac{(m_{jj} - m_H)^2}{\sigma_H^2}. \quad (12)$$

After we draw a frame for analysis, for a better understanding of cuts we present important kinematical variables with their entries normalized to one and comment on them (here only generator level cuts included).

We present histograms showing the characteristics of jets produced and little comment on them, see Fig. $10, 11, 12, 13, 14, 15$.

That simple approach depends on the best reconstruction of Higgs and relatively the other final state objects with a large event number and in a wide distribution range, fulfilling the true decay channel. This pre-analysis proofs our expectations about the applying cuts in a more sophisticated way and also inseparability of signal and background even with a fundamental level of $\chi^2$ and relevant physical conditions. As you will see from Fig. $22, 23, 24, 25$ the gap between at number of events of signal and background is fairly high. One gets no relevant signal significance for such an analysis. It is reflected at kinematic and derived variables, such that there is no region to separate signal and background by applying cuts to these which is transfered to final histograms.

We would like to give a cut-efficiency table for this pre-analysis to state our analysis path clearly.

In the following paragraphs we present our analysis path and introduce signal significance relation. We will study here for three cases and find search limits separately for $\eta_{u+c}$, $\eta_u$ and $\eta_c$ as promised.

The main part of our analysis is to reconstruct Higgs mass and top quark transverse mass (while considering W bosons transverse mass) from final state objects men-
Entries normalized to one

More over they have a peak around 80 GeV shows that they are mainly coming from disintegration of top quark. Here, boosted structure of jets can be seen.

Figure 10. 1st jet $p_T$: Distributions each having high values.

Figure 11. 1st jet $\eta$ distributions at detector which are mostly central.

Figure 12. 2nd jet $p_T$: Distributions with peak around 60 GeV shows they are elements of Higgs decay.

Figure 13. 2nd jet $\eta$ distribution at detector which are mostly central.

mentioned before in the text. For a complete analysis we must recover both of them, since they are characteristics of our signal process. Nevertheless, a top quark with a leptonic decay can be reconstructed by its $m_T$. There is a missing knowledge due to longitudinal component of neutrino momentum. On the other side we can reconstruct Higgs boson using its invariant mass more precisely. Then we offer a chi square ($\chi^2$) that must restrict Higgs' invariant mass considerably in comparison to tops $m_T$ which can stay looser.

Another important aspect of reconstruction of a top quark and a Higgs is to use b-tagging mentioned as long before. Since we are considering $b \to bb$, henceforth at least one or if possible two jets that reconstructs Higgs must be b-tagged. Separately, when we come to reconstruction of top quark one b-jet is is needed at first glance. However, remembering only source of lepton and MET is top decay for signal case and we can also restrict top quarks transverse mass additionally. Both event selection criteria, $\chi^2$ and $m_T$ limitations cancels this two or three b-tag necessity (W boson's transverse mass is also restricted) and optimise analyse greatly. We just simply impose these cuts at our analysis code. We use

$$m_T^l = \left(\sqrt{(p_T^l+p_T^b)^2 + |p_T^{bT}|^2} + |p_T^l|\right)^2$$

for reconstructing top quarks transverse mass and for transverse mass for W boson

$$m_T^W = \sqrt{2p_T^l E_T^{\text{miss}} - p_T^{lT}p_T^{bT}}.$$ (14)

- Cut 1: $30 < m_T^W < 90$, transverse mass restriction of $W$ for better event reconstruction from final state objects.
- Cut 2: $100 < m_T^l < 200$ transverse mass restriction of top quark for better event reconstruction from final state objects.
We observe a clear decrease in our main backgrounds, but analysis is still incomplete and results must be elaborated to compare with other studies in literature. Main problem is $t\bar{t}+\text{jet(s)}$, must be fully eliminated at some region where signal event has dominance that gives meaningful signal significance value. Besides the other backgrounds still problematic, since elimination is rather difficult due to presence of bosons, besides $pp \rightarrow t\bar{t}j$ process is directly present at SM too. So we need to discriminate them.

To complete analysis we use much more sophisticated variables then use $\Delta R$ cuts considering physics between the objects we are interested in.

- Cut 3: Contransverse mass using the jets that reconstruct Higgs boson as defined as

$$m_{CT} = \sqrt{p_T^1 p_T^2 \cos(1 + \Delta\phi_{b_1,b_2})}$$  
(15)

and we demand $m_{CT} < 400$ GeV. This cut targets mainly $t\bar{t}+\text{jet(s)}$ backgrounds but also effective on the others. By applying this cut we are aiming to put $t\bar{t}+\text{jet(s)}$ backgrounds in pieces and open a way to use $\Delta R$ cuts to trim out these.

- Cut 4: As we know Higgs and additional jet comes from a virtual top quark at signal process we may deal with a hadronic reconstruction of this particle. Although it is virtual particle and its distribution cannot give a sharp peak around its invariant mass, we still get a splayed distribution roughly around 172 GeV. When the subject is reconstruction of signal event from reverse, to narrow the reconstruction circle we apply additional $\chi^2$ as such

$$\chi^2 = \frac{(m_{j_1j_2j_3} - m_{top})^2}{\sigma_{top}^2}$$  
(16)

taking $\sigma = 20$ GeV. By applying this cut we finally extract different $\Delta R$ behaviours of signal and backgrounds, so we can start to trim out regions to maximize signal significance.

- Cut 5: When we consider $pp \rightarrow th(j)$ process,
most favorable momentum configuration is the back to back scatter of top quark and Higgs which resulted with the cut $2.2 < \Delta R(t, h) < 3$. We use the objects which are recognized as top cluster and Higgs cluster after tagging jets accordingly by using previous cuts.

- Cut 6: Same $\Delta R$ correlation holds between “jet from top” and Higgs cluster too. Thus we seek to observe $\Delta R(j_t, h) > 2$.

- Cut 7: After leptonic decay of top quark, lepton and jet is back to back at their rest frame. However, as boosted objects they must be seperated enough as such, $\Delta R(j_t, l) > 1.8$.

- Cut 8: The correlation at the $\Delta R$ variable between top and Higgs cluster partly transfered to final state objects especially the lepton and a ‘jet from Higgs”, so we demand $\Delta R(j_h, l) > 2$.

As one can expect the numbers at $\Delta R$ cuts selected to optimise signal significance. Here we would like to give cut efficiency at Tab. [IV]

Let us comment on cuts and finalize analysis discussion: We started with selecting the proper final objects and region selection then use basic cuts to work with relevant objects before reconstruction of signal process. Selecting one lepton is vital to tag top quark with $m_T^2$, restriction to avoid b-tagging. $\chi^2$ for Higgs and tagging of one of its constituent jet as $b$ is another important step for optimising b-tagging while getting full image of both ingredients of signal process. However, all backgrounds mimic these features, $t\bar{t}+\text{jet(s)}$ backgrounds have one leptonic decayed top and many candidate jets to reconstruct Higgs invariant mass being also transparent to b-tag condition. Their large cross section also enhance many combinations to increase mixings. Other backgrounds which have bosons too also additional options coming from bosons and can be pass these filters. So up to now b-tagging issue and good objects selection is done.
Table II. Region selection and basic cuts for pre-analysis and analysis: Difference occurs at analysis part when an additional MET<100 GeV cut applied.

| Region selection and basic cuts |
|--------------------------------|
| $N(jets) \geq 3$             |
| $N(t^+t^-) = 1$              |
| $p_T > 30$ GeV               |
| $p_T > 25$ GeV               |
| $MET > 30$ GeV               |
| $|\eta^0| < 3$                |
| $\Delta R(t,j)_{All} > 0.4$ |

Table III. Cut efficiencies for signal and background processes for pre-analysis.

| Process  | Region selection (%) | Basic cuts (%) | $\chi^2$ (%) |
|----------|----------------------|----------------|--------------|
| $pp \to t(t)h$ | 64.07               | 15.98          | 4.72         |
| $\eta_u = \eta_c = 0.0075$ |                     |                |              |
| $pp \to t(j)j$ | 56.57               | 15.91          | 3.43         |
| $pp \to tjj$   | 56.79               | 17.06          | 2.70         |
| $pp \to thj$   | 55.34               | 21.33          | 5.75         |
| $pp \to ttB$   | 55.93               | 19.69          | 3.85         |
| $pp \to thj$   | 63.59               | 9.16           | 1.95         |
| $pp \to Whjj$  | 64.59               | 14.80          | 3.12         |

After that point we apply contransverse mass cut and impose $\chi^2$ for hadronically decayed virtual top quark. These cuts sharpens Higgs presence and start to differ signal and background events. Observe that many backgrounds lack of Higgs. Up to this point all backgrounds are in game even though their $\Delta R$ distributions started to become evident. Then we trim out all these differences using the other cuts and count the number of events at a region where signal events are concentrated.

To sum up, we started to apply the cuts where mainly signal oriented, but also backgrounds have common. We keep track of changes and focus on Higgs reconstruction and suppress backgrounds to get a viable results.

V. RESULTS AND CONCLUSIONS

Second part of our analysis allows us to eliminate some of backgrounds at last section. Moreover, the cuts have also suppressed backgrounds which have large number of events comparing to signal at least several order of magnitude at generator level. Now we are ready to evaluate our results by regarding statistical significance ($SS_{disc}$ stands for signal significance with systematics) \[ SS_{disc} = \sqrt{2[(S+B)\ln(1+S/B) - S]} \] (18)

when systematic uncertainties neglected for discovery scenario. On top of that sometimes it is better to exploit the region that a collider can exlude, for this we use the equation

$$SS_{wS_{exc}} = \left[ 2 \left( S - B \ln \left( \frac{B + S + x}{2B} \right) - B^2 \ln \left( \frac{B + S - x}{2B} \right) \right) \right]^{1/2}$$

(19)

where
In Table V, VI, VII, VIII we summarize our results with the discovery and exclusion significance according to $SS_{\text{disc}}$ relations given at Eq. (17), (18) and in Fig. 26, 28 we give fit graphs for signal significance for 3 ab$^{-1}$ and 30 ab$^{-1}$ respectively. Similar results have been shown in Fig. 27 and 29 using $SS_{\text{exc}}$ relations both namely Eq. (19), (20) which are given for 3 ab$^{-1}$ and 30 ab$^{-1}$ respectively.

Table IV. Cut efficiencies for signal and background processes given % ratios. Signal choosen as scenario $\eta_u = \eta_c = 0.0075$.

| Region selection | Signal | $tt_j$ | $ttjj$ | $tth$ | $ttB$ | $th_j$ | Whjj |
|------------------|--------|--------|--------|--------|--------|--------|-------|
| Basic cuts       | 64.07  | 56.57  | 56.79  | 55.34  | 55.92  | 63.59  | 64.59 |
| $X^2/t$          | 12.17  | 11.42  | 11.37  | 13.50  | 12.32  | 7.38   | 9.88  |
| Cut 1            | 0.86   | 0.58   | 0.41   | 0.87   | 0.50   | 0.41   | 0.54  |
| Cut 2            | 0.023  | 0.011  | 0.012  | 0.015  | 0.0081 | 0.069  | 0.025 |
| Cut 3            | 0.0089 | 0.0038 | 0.0065 | 0.0062 | 0.0031 | 0.0038 | 0.0005|
| Cut 4            | 0.0070 | 0.0025 | 0.0031 | 0.0025 | 0.0016 | 0.0022 | 0.0025|
| Cut 5            | 0.0051 | 0.0012 | 0.0010 | 0.00094| 0.00094| 0.0012 | 0.0025|
| Cut 6            | 0.0044 | 0.0012 | 0.00035| 0.00094| 0.00094| 0.00094| -     |
| Cut 7            | 0.0019 | -      | 0.00062| 0.00094| -      | -      | -     |
| Cut 8            | 0.0019 | -      | 0.00031| 0.00094| 0.00094| -      | -     |

As clearly seen from this tables scenario $\eta_{u+c}$ gives better results for $SS_{\text{disc}}$ (and also for $SS_{\text{exc}}$) as expected originated from its larger PDF values. For this scenario, the values mentioned at CDR of FCC-hh [16] reached and this scenario is the prospect future restrictor. Note that, the other scenarios follows $\eta_{u+c}$ case closely, hence the found limits change accordingly. Normally one may give no special importance to the other scenarios unless an additional mechanism blocks the transition from both quarks to top. However, as we are dealing with an effective theory, such a mechanism is quite reasonable (yet needed to be observe), so we would like to cover this cases for any possible FCNC scenario. For $\eta_u$ and $\eta_c$ scenarios, our results for limitations on coupling constants are still better than known LHC limits and will give the first implications of FCNC interactions with hinting an additional quark transition preserving mechanism. The effects of systematics gives no values so much different than the ideal case due to highly reduced background. This is the power of our analysis that role of systematics

$$\Delta B \text{ corresponds to uncertainty of background events; at limiting case } \Delta B = 0 \text{ Eq. (19) reduces to following equation}$$

$$SS_{\text{exc}} = \sqrt{\frac{2 \left( S - B \ln \left( 1 + \frac{S}{B} \right) \right)}{}}$$

$$and \Delta B \text{ corresponds to uncertainty of background events; at limiting case } \Delta B = 0 \text{ Eq. (19) reduces to following equation}$$

$$SS_{\text{exc}} = \sqrt{\frac{2 \left( S - B \ln \left( 1 + \frac{S}{B} \right) \right)}{}}$$

In Table V, VI, VII, VIII we summarize our results with the discovery and exclusion significance according to $SS_{\text{disc}}$ relations given at Eq. (17), (18) and in Fig. 26, 28 we give fit graphs for signal significance for 3 ab$^{-1}$ and 30 ab$^{-1}$ respectively. Similar results have been shown in Fig. 27 and 29 using $SS_{\text{exc}}$ relations both namely Eq. (19), (20) which are given for 3 ab$^{-1}$ and 30 ab$^{-1}$ respectively.
lowered in this sense. Moreover, as we know that the backgrounds have large number of cross-section so, even %5 of uncertainty is disastereous, but tamed for our analysis. The exclusion regions are more or less same for $SS_{\text{disc}}$ and $SS_{\text{excl}}$; hence we can say compatible with each in this sense. To be specific we can push exclusion limits at best to arround 0.00265 which decides the fate of FCNC type interactions. At 3 ab$^{-1}$ luminosity, and as a worst case scenario with %10 systematics included even only $c$ case, coupling constants below the recent limits. For more luminosity results will be enhanced obviously. In literature our results are compatible with other phenomenological results \cite{31} (Bear in mind that our effective Lagrangian is so restrictive in general, thus limits can be improved directly by 4 times when we consider coupling constants).

In this study we have tried to estimate searches using the channel which includes single production of top quark (decay leptonically) with a Higgs boson (decay a bottom pair) via FCNC interaction at FCC-hh. This collider offers large number of events at high energies compared to its predecessor and enhance the potential of new physics searches greatly. Former searches done by both the CMS and the ATLAS collaborations extracts the current limitations of FCNC interactions, \cite{19} \cite{22} nevertheless our research at FCC-hh has potentially decide the limits on coupling constants. Furthermore, first implications of MSSM and 2HDM (FC) can be tested.

This rare process suffers high backgrounds even more in higher energies. To overcome this difficulty one needs to elaborate this type of analysis much more carefully. As explained in detail in analysis section, we regard this features of processes when distinguishing signal from background. We found accessible limits for coupling constants which have been considerably enhanced, furthermore they are even better compared the results given in literature. Besides, we see the value of the coupling constants become very small which hints the interaction is so weak.

Table VI. Upper limits on $\eta_q$ parameter and corresponding branching ratios at 3 ab$^{-1}$ luminosity with %10 systematics.

| Scenario | $SS_{\text{disc}} \geq 2$ |
|----------|--------------------------|
| $\eta_q$ Branching Ratio |
| $\eta_q = \eta_c$ | 0.0068 | $1.21 \times 10^{-6}$ |
| Only $\eta_a$ | 0.0099 | $2.11 \times 10^{-6}$ |
| Only $\eta_c$ | 0.0112 | $3.27 \times 10^{-6}$ |

| Scenario | $SS_{\text{disc}} \geq 3$ |
|----------|--------------------------|
| $\eta_q$ Branching Ratio |
| $\eta_q = \eta_c$ | 0.0088 | $2.02 \times 10^{-6}$ |
| Only $\eta_a$ | 0.0112 | $3.27 \times 10^{-6}$ |
| Only $\eta_c$ | 0.0136 | $4.82 \times 10^{-6}$ |

| Scenario | $SS_{\text{disc}} \geq 5$ |
|----------|--------------------------|
| $\eta_q$ Branching Ratio |
| $\eta_q = \eta_c$ | 0.0126 | $4.14 \times 10^{-6}$ |
| Only $\eta_a$ | 0.0152 | $6.02 \times 10^{-6}$ |
| Only $\eta_c$ | 0.0181 | $8.45 \times 10^{-6}$ |

Table VII. Upper limits on $\eta_q$ parameter and corresponding branching ratios at 30 ab$^{-1}$ luminosity with no systematics.

| Scenario | $SS_{\text{disc}} \geq 2$ |
|----------|--------------------------|
| $\eta_q$ Branching Ratio |
| $\eta_q = \eta_c$ | 0.0027 | $1.90 \times 10^{-6}$ |
| Only $\eta_a$ | 0.0046 | $5.52 \times 10^{-6}$ |
| Only $\eta_c$ | 0.0064 | $1.07 \times 10^{-5}$ |

| Scenario | $SS_{\text{disc}} \geq 3$ |
|----------|--------------------------|
| $\eta_q$ Branching Ratio |
| $\eta_q = \eta_c$ | 0.0039 | $3.99 \times 10^{-6}$ |
| Only $\eta_a$ | 0.0059 | $9.08 \times 10^{-6}$ |
| Only $\eta_c$ | 0.0077 | $1.55 \times 10^{-5}$ |

| Scenario | $SS_{\text{disc}} \geq 5$ |
|----------|--------------------------|
| $\eta_q$ Branching Ratio |
| $\eta_q = \eta_c$ | 0.0059 | $9.08 \times 10^{-6}$ |
| Only $\eta_a$ | 0.0077 | $1.55 \times 10^{-5}$ |
| Only $\eta_c$ | 0.0097 | $2.45 \times 10^{-5}$ |

Table VIII. Upper limits on $\eta_q$ parameter and corresponding branching ratios at 30 ab$^{-1}$ luminosity with %10 systematics.

| Scenario | $SS_{\text{disc}} \geq 2$ |
|----------|--------------------------|
| $\eta_q$ Branching Ratio |
| $\eta_q = \eta_c$ | 0.0036 | $3.38 \times 10^{-6}$ |
| Only $\eta_a$ | 0.0054 | $7.60 \times 10^{-6}$ |
| Only $\eta_c$ | 0.0072 | $1.35 \times 10^{-5}$ |

| Scenario | $SS_{\text{disc}} \geq 3$ |
|----------|--------------------------|
| $\eta_q$ Branching Ratio |
| $\eta_q = \eta_c$ | 0.0050 | $6.32 \times 10^{-6}$ |
| Only $\eta_a$ | 0.0068 | $1.21 \times 10^{-5}$ |
| Only $\eta_c$ | 0.0088 | $2.02 \times 10^{-5}$ |

| Scenario | $SS_{\text{disc}} \geq 5$ |
|----------|--------------------------|
| $\eta_q$ Branching Ratio |
| $\eta_q = \eta_c$ | 0.0074 | $1.43 \times 10^{-5}$ |
| Only $\eta_a$ | 0.0090 | $2.11 \times 10^{-5}$ |
| Only $\eta_c$ | 0.0121 | $3.76 \times 10^{-5}$ |

Figure 26. Signal significance (SS) versus $\eta_q$ coupling parameter for three different scenarios at 3 ab$^{-1}$ luminosity for discovery (disc) case.
In conclusion, it seems that $pp \rightarrow th(j)$ channel plays an important role for future colliders. The significance of observation or discovery for the FCNC interactions at this channel is fairly high if these kind of interactions are really exist in nature. Our results show that potential discovery or exclusion limits on coupling constants for FCNC interactions can be set around 0.0059 (which corresponds to $BR(\eta_{u+c})_{\text{disc}} = 9.08 \times 10^{-6}$) or 0.0027 corresponding to $BR(\eta_{u+c})_{\text{exc}} = 2.78 \times 10^{-6}$, respectively. This will extract nearly full potential of FCC-hh collider for $tqH$ FCNC interactions.

ACKNOWLEDGMENTS

No funding was received for this research.

The authors are grateful to Ulku Ulusoy for a careful reading of the manuscript. We wish to acknowledge the support of the AUHEP group, offering suggestions and encouragement. The numerical calculations reported in this paper were partially performed at TUBI-
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