Probing Anomalous FCNC Top-Higgs Yukawa Couplings at the Large Hadron Electron Collider

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Abstract

In this paper, we study the anomalous flavor changing neutral current Yukawa interactions between the top quark, the Higgs boson, and either an up or charm quark ($tqH, q = u, c$). We probe these couplings in $e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e H \bar{q}$ and the channel $e^- p \rightarrow \nu_e H b$. Both channels are induced by charged current interactions through $e^- p$ collision at the Large Hadron Electron Collider (LHeC). We study the signatures with the Higgs decay modes $H \rightarrow \gamma\gamma, b\bar{b}$ and $\tau^+\tau^-$. Our results show that the flavor changing couplings $\kappa_{tqH}$ can be probed down to a value of 0.0162 in $e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e H \bar{q}$ with $H \rightarrow b\bar{b}$ at a 14 TeV LHeC with a 150 GeV electron beam and 200 fb\(^{-1}\) luminosity. This value of the coupling corresponds to the branching ratio $Br(t \rightarrow qH) = 1.34 \times 10^{-4}$.

Keywords: Top quark, Higgs boson, Anomalous Couplings, LHeC

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1 Introduction

The discovery of the Higgs boson at the Large Hadron Collider (LHC)\cite{1}\cite{2} is a major step towards understanding the electroweak symmetry breaking (EWSB) mechanism and marks a new era in particle physics. In order to ultimately establish the nature of the Higgs, a precise measurement of the Higgs couplings to fermions and gauge bosons as well as the Higgs self-coupling is needed. These precision measurements will be some of the most important tasks for experiments at the LHC and the future colliders. According to the analyses of the ATLAS and CMS collaborations, the couplings of the Higgs boson have been measured with an overall precision of about 15\%, which means that there still remains some room for the existence new physics. Besides the Higgs boson, the measurement of the top quark properties is also important. It is the heaviest known elementary particle which makes it an excellent candidate for new physics searches. To probe new physics through the Higgs boson and top quark, the top-Higgs Yukawa couplings are of special interest since they are sensitive to new flavor dynamics beyond the Standard Model (SM) not too far above the electroweak scale. Furthermore, top quark, as the heaviest SM fermion, it owns the strongest Yukawa coupling. Among the Higgs couplings to quarks, the most promising place to reveal new physics at high energy colliders are processes involving top quarks.

The mass of the top quark is heavier than that of the observed Higgs boson, which makes the top quark flavor changing neutral current (FCNC) processes $t \rightarrow qH (q = u, c)$ kinematically accessible. In the SM, processes that are induced by FCNC in top quark production or decay are extremely suppressed by the Glashow-Iliopoulos-Maiani (G.I.M.) mechanism\cite{3} according to SM computation, with decay rates of the order of $10^{-10}$ or below. However, new physics scenarios, such as the minimal supersymmetric model (MSSM) with/without R-parity Violating\cite{4}\cite{5}\cite{6}\cite{7}\cite{8}\cite{9}\cite{10}\cite{11}, two-Higgs-Doublet Model (2HDM)\cite{12}\cite{13}\cite{14}\cite{15}, Warped Extra Dimensions\cite{16}\cite{17}, Alternative Left-Right symmetric Models (ALRM)\cite{18}, Little Higgs with T parity (LHT)\cite{19}, etc, could enhance the FCNC rates by several orders of magnitude, thus making them detectable using current experimental...
data. Therefore, studying the top-Higgs FCNC interactions is important both from a theoretical as well as an experimental perspective.

Up to now, the searches for $t \rightarrow qH$ have been investigated experimentally at the LHC which gives the strong limits on the top-Higgs FCNC couplings. Among them, the most stringent constraint of $\text{Br}(t \rightarrow cH) < 0.56\%$, $\text{Br}(t \rightarrow uH) < 0.45\%$ at 95% confidence level (C.L.) was reported by the CMS collaboration from a combination of the multilepton channel and the diphoton plus lepton channel\cite{20}. While an upper limit is set on the $t \rightarrow cH$ branching ratio of 0.79% at the 95% confidence level by the ATLAS collaboration\cite{21}\cite{22}. Except for the widely studied $t \rightarrow qH$ decays, the importance of the single top Higgs associated production has been also emphasized in the recent theoretical studies especially at the LHC\cite{23}\cite{24}\cite{25}\cite{26}\cite{27}\cite{28}\cite{29}\cite{30}\cite{31}\cite{32}. In our present paper, we study the anomalous FCNC Yukawa interactions between the top quark, the Higgs boson, and either an up or charm quark ($tqH, q = u, c$) at the Large Hadron Electron Collider (LHeC). The LHeC kinematic range exceeds HERA’s by a factor of about 20, due to the combination of a 7 TeV or higher proton beam from the LHC and a new 60 GeV to 150 GeV electron beam. Its luminosity is projected to be as high as possibly $10^{34}\text{cm}^{-2}\text{s}^{-1}$, with a default design value of $10^{33}\text{cm}^{-2}\text{s}^{-1}$. This is almost a thousand times higher than HERA’s luminosity, which gives the LHeC the potential of a precision measurement Higgs production facility and enables a very large variety of new measurements and searches to be conducted. Typically we choose two channels to study the anomalous FCNC Yukawa interactions at the LHeC. One is the channel $e^-p \rightarrow \nu_e \bar{t} \rightarrow \nu_e H\bar{q}$ with $q = u, c$ and the other is the channel $e^-p \rightarrow \nu_e Hb$. Both channels are charged current (CC) interaction processes induced through $e^-p$ collision at the LHeC.

Our paper is organized as follows: we build the calculation framework in Section 2 including a brief introduction to the anomalous flavor changing $tqH$ couplings and our selected production channels. Section 3 is arranged to present the numerical results as well as the signal and background analysis. Typically, the $H \rightarrow \gamma\gamma, b\bar{b}, \tau^+\tau^-$ decay modes are taken into account. In Section 4 we present bounds on anomalous $tqH$ couplings at the future LHeC. Finally we summarize our conclusions in the last section.
2 Calculation Framework

2.1 Flavor Changing tqH Couplings

Considering the FCNC Yukawa interactions, the SM Lagrangian can be extended simply by allowing the following terms,

\[ \mathcal{L} = \kappa_{tuH} \bar{t}uH + \kappa_{tcH} \bar{t}cH + \text{h.c.,} \]

where the real parameters \( \kappa_{tuH} \) and \( \kappa_{tcH} \) denote the flavor changing couplings of Higgs to up-type quarks. Now we have \( m_t - m_h \) larger than \( m_c, m_u, m_b \). In addition to the usual top decay mode \( t \to W^\pm b \), the top quark can also decay into a charm or up quark associated with a Higgs boson. Therefore, the total decay width of the top-quark \( \Gamma_t \) is

\[ \Gamma_t = \Gamma_{t \to W^- b}^{\text{SM}} + \Gamma_{t \to cH} + \Gamma_{t \to uH}. \]

The decay width of the dominant top quark decay mode \( t \to W^- b \) at the LO and the NLO could be found in ref\[34\]. It is given below

\[ \Gamma_{t \to W^- b}^{\text{SM}} = \Gamma_0(t \to W^- b) \left\{ 1 + \frac{2\alpha_s}{3\pi} \left[ 2\left( 1 - \beta_W^2 \right) \left( 2\beta_W^2 - 1 \right) \left( \beta_W^2 - 2 \right) \right] \ln(1 - \beta_W^2) \right. \\
\left. - \frac{9 - 4\beta_W^2 \ln \beta_W^2 + 2L_i(\beta_W^2) - 2L_i(1 - \beta_W^2) - \frac{6\beta_W^4 - 3\beta_W^2 - 8}{2\beta_W^2(3 - 2\beta_W^2)} - \pi^2 \right] \right. \]

where \( \Gamma_0(t \to W^- b) = \frac{G_F m_t^3}{8\sqrt{2} \pi} |V_{tb}|^2 \beta_W^4 (3 - 2\beta_W^2) \) is the LO decay width and \( \beta_W = (1 - m_W^2/m_t^2) \) is the velocity of the W boson in the top quark rest frame. \( G_F \) is the fermi constant. The \( t \to u(c)H \) partial decay width is given as\[35\]

\[ \Gamma_{t \to u(c)H} = \frac{\kappa_{tu(c)H}^2}{16\pi} m_t \left( \tau_u(c) + 1 \right)^2 - \tau_H^2 \sqrt{1 - (\tau_H - \tau_u(c))^2} \sqrt{1 - (\tau_H + \tau_u(c))^2} \]

where \( \tau_H = \frac{m_H}{m_t}, \tau_u(c) = \frac{m_u(c)}{m_t} \). The leading order branching ration for \( t \to qH \) is then given by

\[ \text{Br}(t \to qH) = \frac{\kappa_{tu(c)H}^2}{\sqrt{2} G_F m_t^2 \left( 1 - m_W^2/m_t^2 \right)^2 \left( 1 + 2m_W^2/m_t^2 \right)} \approx 0.512 \kappa_{tu(c)H}^2. \]

Here the Higgs boson and the top quark masses are chosen to be \( m_H = 125.7 \) GeV and \( m_t = 173.21 \) GeV respectively. Similar to the top quark decay, the new interactions
affect also the width of the Higgs though the additional decay into an off-shell top that
subsequently leads to a single W decay of the Higgs, namely $H \rightarrow u(c)(t^* \rightarrow Wb)$ where
t* denotes off-shell top quark. Therefore we get

$$\Gamma_H = \Gamma_{H}^{SM} + \Gamma_{H \rightarrow u(t^* \rightarrow bW^-)} + \Gamma_{H \rightarrow \bar{u}(t^* \rightarrow bW^+)} + \Gamma_{H \rightarrow \bar{c}(t^* \rightarrow b\bar{W}^-)} + \Gamma_{H \rightarrow c(t^* \rightarrow b\bar{W}^-)}$$

where $\Gamma_{H}^{SM}$ is the normal Higgs decay width in SM. While other terms related to the Higgs
boson three-body decays are numerically estimated following ref[23].

The stringent constraints on the anomalous FCNC couplings are set exploiting the ex-
perimetal data of the CMS and ATLAS Collaborations[20][21][22]. Theoretical, many
other phenomenological studies are performed based on these experimental data. The
analysis of ref[24] emphasizes the importance of anomalous single top plus Higgs pro-
duction at the LHC deriving the 95% C.L. upper limits $\text{Br}(t \rightarrow cH) < 0.15\%$ and
$\text{Br}(t \rightarrow uH) < 0.19\%$. Ref[25] studies the single top and Higgs associated production
$pp \rightarrow tHj$ in the presence of top-Higgs FCNC couplings at the LHC, giving the upper
limits as $\text{Br}(t \rightarrow qH) < 0.12\%$, $\text{Br}(t \rightarrow uH) < 0.26\%$ and $\text{Br}(t \rightarrow cH) < 0.23\%$ with
an integrated luminosity of 3000 fb$^{-1}$ at $\sqrt{s} = 14$TeV. Ref[26] quotes a 95% C.L. limit
Sensitivity in the $t\bar{t} \rightarrow Wb + hq \rightarrow \ell\nu b + \ell\ell (\gamma\gamma)q$ final state of $\text{Br}(t \rightarrow qH) < 5(2) \times 10^{-4}$
with an integrated luminosity of 300(3000) fb$^{-1}$ at $\sqrt{s} = 14$ TeV. As can be seen the
upper limits on the flavour changing top quark decays can be significantly improved as
expected at a High Lumi(HL)-LHC. Ref[27] derives model-independent constraints on the
tcH and tuH couplings that arise from the bounds on hadronic electric dipole moments.
Refs[28] and [29] study the top quark decay into Higgs boson, a light quark and top Higgs
associated production including the next-to-leading order QCD effects. Other related
publications can be found, for example, in refs[30][31][32][33], etc.

2.2 The Processes

Now we turn to study the selected production processes where the effect of the flavor
changing couplings could be significant.
2.2.1 $e^-p \rightarrow \nu_e\bar{t} \rightarrow \nu_eH\bar{q}$ Channel

![Feynman Diagram](image)

Figure 1: Partonic Feynman diagrams for $e^-p \rightarrow \nu_e\bar{t} \rightarrow \nu_eH\bar{q}$ with $q=u,c$. Black blobs represent the anomalous $tqH$ couplings parameterized by Eq.(1).

The first channel we will consider is $e^-p \rightarrow \nu_e\bar{t} \rightarrow \nu_eH\bar{q}$ production. The parton level signal process at the LHeC can be expressed as

$$e^-(p_1) + \bar{b}(p_2) \rightarrow \nu_e + \bar{t} \rightarrow \nu_e(p_3) + H(p_4) + \bar{q}(p_5) \quad (7)$$

with $q = u,c$ and $p_i$ are the four-momentum of initial and final particles, respectively. The Feynman diagram for the partonic process is depicted in Fig[1]. The flavor changing vertex proportional to the flavor changing coupling $\kappa_{tqH}$ occurs via the single top production with its following decay to Higgs plus $u$ or $c$ quark, where this single top quark is induced by the collision of $b$ quark from the proton with the $W^-$ boson emission from the electron beam. We thus expect the cross sections for these processes to be proportional to $c\kappa_{tqH}^2$ where $c$ is some related constants. The parent level signal process $e^-p \rightarrow \nu_eH\bar{q} + X$, the kinematic distributions and integrated cross sections can then be obtained by convoluting the parton level process with the parton distribution function (PDF)[36] of quark in the proton,

$$d\sigma(e^-p \rightarrow \nu_eH\bar{q} + X) = \int dx \ G_{\bar{b}/p}(x, \mu_F) d\hat{\sigma}(e^-\bar{b} \rightarrow \nu_e\bar{t} \rightarrow \nu_eH\bar{q}, \sqrt{\hat{s}}), \quad (8)$$
where $\sqrt{s} = 2\sqrt{s_{\text{c.m.}}}$ is the center-of-mass(c.m.) colliding energy and $x$ is the momentum fraction of anti-$b$ quark from proton.

### 2.2.2 $e^- p \rightarrow \nu_e H b$ Channel

![Feynman diagram](image)

Figure 2: Partonic Feynman diagrams for $e^- p \rightarrow \nu_e H b$. Black blobs represent the anomalous $tqH$ couplings parameterized by Eq. (11).

The second channel we considered is $e^- p \rightarrow \nu_e H b$ production. The parton level signal process at the LHeC can be expressed as

$$e^-(p_1) + q(p_2) \rightarrow \nu_e(p_3) + H(p_4) + b(p_5). \quad (9)$$

The Feynman diagram for the partonic process is depicted in Fig. 2. The FCNC top-Higgs Yukawa couplings are deduced from the initial state $u(c)$-quarks from the proton collision with the anti-top quark from the $W_t b$ coupling. Similarly, the parent level signal process $e^- p \rightarrow \nu_e H b + X$ is present as

$$d\sigma(e^- p \rightarrow \nu_e H b + X) = \int dx \ G_{q/P}(x, \mu_i) d\hat{\sigma}(e^- q \rightarrow \nu_e H b, \sqrt{\hat{s}}) \quad (10)$$

where $q = u, c$ and $\sqrt{\hat{s}}$ is again the c.m. colliding energy at the LHeC.

### 2.2.3 Charged Current and Neutral Current Production at the LHeC

The two channels $e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e H \bar{q}$ and $e^- p \rightarrow \nu_e H b$ that we have presented are charged current (CC) processes where the CC production leads to a top-beauty associated
production through $W^-$ boson emission from the initial electron. In addition to CC production, the flavor changing Yukawa couplings can also be produced through neutral current (NC) productions. In NC it gives rise to pair production of top-antitop quarks from a neutral photon/Z boson emission from the initial electron. A comparison of the cross sections of these CC and NC production channels including the anomalous FCNC top-Higgs Yukawa couplings is presented in Tab. 1. Here the input parameters and the very basic kinematical cuts will be presented in our following discussion.

| channels                     | $\sigma(\kappa_{tuH} = 0.1)$ [fb] |
|------------------------------|-----------------------------------|
| $e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e Hq$ | 41.64                            |
| $e^- p \rightarrow \nu_e Hb$            | 1.987                            |
| $e^- p \rightarrow e^- Ht$              | 0.616                            |
| $e^- p \rightarrow e^- HqW$             | 0.901                            |

Table 1: A comparison of the cross sections of CC and NC production channels including the anomalous FCNC top-Higgs Yukawa couplings with $\kappa_{tuH} = 0.1$.

From Tab. 1 we see that the largest production is CC $e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e Hq$ production. For $\kappa_{tuH} = 0.1$ it is more than 10 times larger than the sum of the other channels. Different from the CC production which leads to a top-beauty final state, the NC production gives rise to pair produced top-antitop quarks. The NC productions are small, but still sizeable at the LHeC especially when the polarized electron beam is considered. Furthermore, in sharp contrast to the LHC, the absence of pile-up and underlying event effects at the LHeC, high rates of single anti-top production is expected to providing a better insight through these production channels. The rapidity distributions of the Higgs boson through different channels are given in Fig. 3. In our paper, we only consider the CC interactions which dominate over all the other production mechanisms. This includes $e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e Hq$ and $e^- p \rightarrow \nu_e Hb$ channels. Looking at Tab. 1 we also find that the cross section of the former channel is larger than that of the latter one by roughly a factor
Figure 3: The rapidity distributions of the Higgs boson through different channels including $e^-p \to \nu_e \bar{t} \to \nu_e Hq$, $e^-p \to \nu_e Hb$, $e^-p \to e^-Ht$ and $e^-p \to e^-HqW$ productions.

of 20. At first sight this seems odd, because the transition $e^-p(\bar{b}) \to \nu_e \bar{t} \to \nu_e Hq$ involves an (anti)bottom-quark PDF, while the transition of $e^-p(q) \to \nu_e Hb$ does not. One is therefore tempted to think that the cross section of $e^-p \to \nu_e \bar{t} \to \nu_e Hq$ is smaller than that of $e^-p \to \nu_e Hb$. However, this naive assertion is incorrect, because for $e^-p \to \nu_e \bar{t} \to \nu_e Hq$ the internal (anti)top is exchanged in the s-channel, while in the case $e^-p \to \nu_e Hb$ the top appears in a t-channel exchange. The PDF suppression is thus over compensated by an on-shell enhancement.

3 Results

3.1 Input Parameters

We take the input parameters as $\alpha_{ew}(m_Z^2)^{-1}|_{\overline{MS}} = 127.9$, $G_F = 1.166370 \times 10^{-5}$ GeV$^{-2}$, $m_Z = 91.1876$ GeV, so we have $m_W = 79.82436$ GeV and $\sin^2 \theta_W = 1 - (m_W/m_Z)^2 = 0.233699$. For the strong coupling constant we take $\alpha_s = 0.1184$. Throughout this paper, we set the quark masses as $m_u = m_d = m_c = m_s = 0$ GeV and $m_b = 4.18$ GeV. The top quark mass is set to $m_t = 173.21$ GeV with its width $\Gamma_t = 1.3604$ GeV when $\kappa_{tH} = 0.1$. 


For the leptons, we keep $m_e = m_\mu = 0$ GeV, and $m_\tau = 1.77682$ GeV. We do not consider the contribution from small CKM matrix $V_{qq'}$ where $q$ and $q'$ are not the same generation. For the mass of the Higgs boson, we take $m_H = 125.7$ GeV with the SM width to be $\Gamma^\text{SM}_H = 4.3$ MeV. The partonic cross sections are convoluted with CTEQ6L1 parton distribution functions (PDF) keeping factorization and renormalization scale $\mu_f = \mu_r = m_t$. For the LHeC colliding energy, we consider the future 14 TeV proton at future LHC and an energetic new electron beam with the energies of 150 GeV. The luminosity is taken to be a running parameter. The FCNC couplings are chosen to be $\kappa_{tuH} = 0.1$ and $\kappa_{tcH} = 0$ for simplicity. This set of parameters will be used as default unless being stated otherwise.

### 3.2 Kinematic Cuts

The event reconstruction is still based on a parameterised, generic LHC-style detector. The general acceptance cuts in the lab frame for the events are:

\[
\begin{align*}
p_T^{\text{jet}} & \geq 25 \text{ GeV},
p_T^b & \geq 25 \text{ GeV},
p_T^\gamma & \geq 25 \text{ GeV},
p_T^\ell & \geq 25 \text{ GeV},
E_T^{\text{miss}} & \geq 25 \text{ GeV},
|\eta^{\text{jet}}| & < 5, |\eta^b| < 2.5, |\eta^\gamma| < 2.5, |\eta^\ell| < 2.5,
\Delta R(jj) & > 0.4, \Delta R(bb) > 0.4, \Delta R(\ell\ell) > 0.4, \Delta R(\gamma\gamma) > 0.4, \Delta R(\gamma\ell) > 0.4
\end{align*}
\]

where $\Delta R = \sqrt{\Delta \Phi^2 + \Delta \eta^2}$ is the separation in the rapidity-azimuth plane, $p_T^{\text{jet,}\ell,\gamma}$ are the transverse momentum of jets (refer as j), leptons and photons while $E_T^{\text{miss}}$ is the missing transverse momentum. We stress here that cuts in Eq.(11) are the very basic ones and might be changed later in our following discussion.
3.3 Decay Modes and Backgrounds

3.3.1 \(e^-p \rightarrow \nu_e \bar{t} \rightarrow \nu_e H \bar{q}\) Channel with H \(\rightarrow \gamma\gamma(b\bar{b}, \tau^+\tau^-)\) Decay Modes

Let's first consider the \(e^-p \rightarrow \nu_e \bar{t} \rightarrow \nu_e H \bar{q}\) Channel with H \(\rightarrow \gamma\gamma\) decay mode. The considered signal production can be written as

\[
e^-p \rightarrow \nu_e \bar{t} \rightarrow \nu_e H \bar{q} \rightarrow \nu_e \gamma\gamma \bar{q} \quad (12)
\]

with \(q = u, c\). Since in our calculation we take the anomalous FCNC couplings to be \(\kappa_{tuH} = 0.1\) and \(\kappa_{tcH} = 0\) for simplicity, only \(q = u\) contributes. Higgs decays to pairs of photons are simulated using MadGraph\[41\] where the implementation of the effective H\(\gamma\gamma\) interaction is adopted \[42\]. For simplicity one can also multiply the production cross sections with the Higgs branching ratio corresponding to the final state. As can be seen, in this case, the studied topology of our signal gives rise to the jet + \(E_T\) + diphoton signature characterized by one jet, a missing transverse momentum (\(E_T\)) from the undetected neutrino and a diphoton signal appearing as a narrow resonance centered around the Higgs boson mass. The irreducible background comes from the SM process \(e^-p \rightarrow \nu_e \gamma\gamma \bar{q}\) which yields the identical final states with the signal. These backgrounds mainly come from the production of W boson with double photon production through WW\(\gamma\gamma\), W\(\gamma\gamma\) couplings or through WW \(\rightarrow\) H \(\rightarrow\) \(\gamma\gamma\) decay associated with jet emission. The others come from jet production associated with emission of photons. In order to obtain the anomalous FCNC \(tqH\) coupling effects, we need to simulate all the signal contributions precisely together with these irreducible backgrounds as well as their interference. The total cross section for these reactions thus can be split into three contributions

\[
\sigma = a_0 + a_1\kappa_{tuH} + a_2\kappa_{tuH}^2 \quad (13)
\]

where \(a_0\) is the SM prediction, the term \(a_1\) linear in \(\kappa_{tuH}\) arises from the interference between SM and the anomalous amplitudes, whereas the quadratic term \(a_2\) is the self-interference of the anomalous amplitudes. Potentially reducible backgrounds come from various other SM processes that yield different final states which are attributed to the
jet + $E_T$ + diphoton signature due to a misidentification of one or more of the final state objects. For example, two light jets production with both jets faking a diphoton pair, one jet one photon associated production with one jet faking a photon or leptons faking photons, etc. The background arising from $e^- p \rightarrow \nu_e \bar{\nu}_e e^- \gamma j$ is smaller than 1 percent of signal after applying all cuts and taking rejection factors into account. We consider all these contributions and take the jet faking a photon rate to be 0.001, the electron faking photon rate to be 0.062 during data analysis. Although the $\gamma\gamma$ decay channel has a small branching ratio, it has the advantage of good resolution on the $\gamma\gamma$ resonance and is also free from the large QCD backgrounds. Typically, we use a narrow invariant mass window $|m_{\gamma\gamma} - m_H| < 5$ GeV to further reduce the non-resonant backgrounds as well as the jet such that the invariant mass of $j\gamma\gamma$ system to be near mass of the top quark, say, $m_{\gamma\gamma}$ belongs to the range $[m_t - 10, m_t + 10]$ GeV.

| Decay   | [pb] | Cross sections for $e^- p \rightarrow \nu_e \bar{\nu}_e \rightarrow \nu_e H\bar{q}$ channel($\kappa_{uH} = 0.1$) | | | |
|---------|------|-------------------------------------------------|-----|-----|-----|
|         |      | Cut I       | Cut II      | Cut III     | Cut IV     |
| $H \rightarrow \gamma\gamma$  | $\sigma_S$ | 9.31 x 10^{-5} | 9.26 x 10^{-5} | 9.21 x 10^{-5} | 9.04 x 10^{-5} |
|         | $\sigma_B$ | 2.75 x 10^{-2} | 1.35 x 10^{-2} | 1.02 x 10^{-3} | 5.29 x 10^{-5} |
|         | S/B | 3.39 x 10^{-3} | 6.86 x 10^{-3} | 9.03 x 10^{-2} | 1.71 |
| $H \rightarrow b\bar{b}$  | $\sigma_S$ | 1.33 x 10^{-2} | 1.33 x 10^{-2} | 1.33 x 10^{-2} | 1.30 x 10^{-2} |
|         | $\sigma_B$ | 2.65 x 10^{-1} | 1.97 x 10^{-1} | 6.12 x 10^{-2} | 3.02 x 10^{-3} |
|         | S/B | 5.02 x 10^{-2} | 6.75 x 10^{-2} | 2.17 x 10^{-1} | 4.30 |
| $H \rightarrow \tau^+\tau^-$  | $\sigma_S$ | 2.24 x 10^{-3} | 2.23 x 10^{-3} | 2.23 x 10^{-3} | 2.23 x 10^{-3} |
|         | $\sigma_B$ | 4.93 x 10^{-2} | 1.87 x 10^{-2} | 6.89 x 10^{-3} | 4.20 x 10^{-4} |
|         | S/B | 4.54 x 10^{-2} | 1.19 x 10^{-1} | 3.24 x 10^{-1} | 5.31 |

Table 2: Signal and total Background cross sections for $e^- p \rightarrow \nu_e \bar{\nu}_e \rightarrow \nu_e H\bar{q}$ channel with different decay modes after the application of Cut I-IV. The rejection factors and b-tagging effects are taken into account in this table.
Figure 4: The signal and total background transverse missing energy ($E_{T}^{\text{miss}}$) distributions, transverse momentum ($p_{T}^{\gamma j}$) distributions and $\Delta R(\gamma \gamma)$ distributions for $e^{-}p \rightarrow \nu_{e}\gamma j$ after considering Cut I-IV. The anomalous coupling is chosen to be $\kappa_{\text{tuH}} = 0.1$. The rejection factors are taken into account.
We define some sets of kinematical cuts as bellow:

- Cut I means the basic cuts present in Eq. (11);
- Cut II means the basic cuts plus $25 < E_T^{miss} < 300\text{GeV}$, $25 < p_T^{jet} < 100\text{GeV}$, $25 < p_T^\gamma < 200\text{GeV}$;
- Cut III means Cut II plus requiring the invariant mass of the diphoton pair to be in the range $[m_H - 5, m_H + 5] \text{GeV}$;
- Cut IV means Cut III plus requiring the invariant mass of the diphoton and light jet system to lie in the range $[m_t - 10, m_t + 10] \text{GeV}$.

In Tab. 2, we display the signal and the main background cross sections for $e^- p \rightarrow \nu_e \gamma \gamma j$ after the application of Cut I-IV. The rejection factors and the b-tagging effects are already taken into account in this table, where $\sigma_S$ means the cross section for signal, $\sigma_B$ for the background. In Fig. 4 we display the signal’s and the total background’s transverse missing energy ($E_T^{miss}$) distributions, transverse momentum ($p_T^{\gamma, jet}$) distributions and $\Delta R(\gamma\gamma)$ distributions for $e^- p \rightarrow \nu_e \gamma \gamma j$ in parton level after considering Cut I-IV. The anomalous coupling is chosen to be $\kappa_{tqH} = 0.1$. The rejection factors are taken into account. We see that the anomalous FCNC $tqH$ couplings can enhance the SM production to a level where it can be detectable at future LHeC. By a simple fit we get the final cross section to be $\sigma_{total} = 5.10 \times 10^{-5} + 5.21 \times 10^{-5} \kappa_{tuH} + 8.63 \times 10^{-3} \kappa_{tuH}^2 \text{[pb]}$.

Now we consider the $e^- p \rightarrow \nu_e \bar{b} \bar{b} \rightarrow \nu_e H \bar{q}$ channel with $H \rightarrow b\bar{b}$ decay mode. In this case, the signal production channel is characterized by a missing energy from the undetected neutrino and a $b\bar{b}$ pair associated with a light jet signal. Still, the $b\bar{b}$ pair signal is appearing as a narrow resonance centered around the Higgs boson mass. The main background processes are $e^- p \rightarrow \nu_e b\bar{b}j, bjj, \bar{b}jj$, etc, with light jets faking $b$ jets. In our analysis, we assume a b-jet tagging efficiency of $\epsilon_b = 60\%$ and a corresponding mistagging rate of $\epsilon_{light} = 1\%$ for light jets (u, d, s quark or gluon) and $\epsilon_c = 10\%$ for a c-jet, consistent with typical values assumed by the LHC experiments [4]. For this decay mode, we take Cut I, III, IV the same while Cut II to be the basic cuts plus
25 < \vec{E}_{\text{T}}^{\text{miss}} < 400\text{GeV}, \hspace{1em} 25 < p_T^{b} < 200\text{GeV}, \hspace{1em} 25 < p_T^{\text{jet}} < 140\text{GeV} \hspace{1em} \text{and} \hspace{1em} \Delta R(bj) < 4.

For the background production, we also need that the special cut for \( \nu_e \bar{b}jj, \nu_e \bar{b}\bar{c}j, \) etc., with the light jets system not belongs to the range \([m_W - 10, m_W + 10]\) GeV. This cut will not affect the signal much but it will reduce the background obviously. Finally we get the signal and total background to be 13 fb and 3.02 fb, respectively, and we get the signal background ratio to be 4.3. The final cross section can be written as 

\[ \sigma_{\text{total}} = 2.87 \times 10^{-3} + 7.68 \times 10^{-3}\kappa_{\text{tuH}} + 1.24\kappa_{\text{tuH}}^2 \text{[pb]} \]

Finally we consider the \( \tau^+\tau^- \) decay mode in this production channel. Our results show that \( e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e H q \) channel with \( H \rightarrow \gamma \gamma \) decay mode can be another good choice. With the four lists of cuts, we take Cut I, III, IV the same while Cut II to be the basic cuts plus \( 25 < \vec{E}_{\text{T}}^{\text{miss}} < 300\text{GeV}, \hspace{1em} 25 < p_T^{b} < 100\text{GeV}, \hspace{1em} 25 < p_T^{\gamma} < 200\text{GeV} \hspace{1em} \text{and} \hspace{1em} \Delta R(\gamma) < 4 \). The total cross section can be parametrised as 

\[ \sigma_{\text{total}} = 3.96 \times 10^{-4} + 1.30 \times 10^{-3}\kappa_{\text{tuH}} + 2.13 \times 10^{-1}\kappa_{\text{tuH}}^2 \text{[pb]} \]

The cross sections of the above decay modes are presented in Tab.2 with different sets of cuts. We see that the \( H \rightarrow \gamma \gamma \) decay mode provides the smallest signal since the branching ratio of \( H \rightarrow \gamma \gamma \) is quite small. By applying the cuts, the background can be reduced to the same level. For the \( H \rightarrow b\bar{b}, \tau^+\tau^- \) decay modes, the signal can be 5 times larger than the backgrounds, thus making the signal over background around 5 for \( \kappa_{\text{tuH}} \) equal 0.1. The distributions of the signals and backgrounds are similar to Fig.4 and we therefore do not display them.

3.3.2 \( e^- p \rightarrow \nu_e H b \) Channel with \( H \rightarrow \gamma \gamma(b\bar{b},\tau^+\tau^-) \) Decay Modes

We apply the similar method to \( e^- p \rightarrow \nu_e H b \) production Channel. However, due to the critical large backgrounds, we use much harder cuts instead: For \( H \rightarrow \gamma \gamma \) decay mode, Cut I still means the very basic cuts present in Eq.(11); Cut II means Cut I plus \( |\eta^{\text{jet}}| < 2.5\text{GeV}, \hspace{1em} p_T^{\gamma} > 100\text{GeV}, \hspace{1em} \Delta R(\gamma j) < 4\text{GeV}; \hspace{1em} \) Cut III means Cut II plus invariance mass of diphoton pair belong to \([m_h - 3, \hspace{1em} m_h + 3]\) GeV; Cut IV means Cut III plus \( p_T^{\gamma} > 150\text{GeV}, \hspace{1em} p_T^{\gamma} > 250\text{GeV}, \hspace{1em} \Delta R(\gamma\gamma) < 1.5\text{GeV}. \hspace{1em} \) For \( H \rightarrow b\bar{b} \) decay mode, we use Cut II to be the basic cuts plus \( |\eta^{\text{jet}}| < 2.5\text{GeV}, \hspace{1em} \Delta R(\gamma j) < 4\text{GeV}, \hspace{1em} \) and Cut IV to be the Cut III plus \( p_T^{b} > 200\text{GeV}. \hspace{1em} \) For \( H \rightarrow \tau^+\tau^- \) decay mode, we use Cut II to be the basic cuts
Table 3: Signal and total Background cross sections for $e^- p \rightarrow \nu_e Hb$ channel with different decay modes after the application of Cut I-IV. The rejection factors and the b-tagging effects are taken into account in this table.

| Decay       | $\sigma_S$ [pb] | $\sigma_B$ [pb] | $S/B$                  |
|-------------|-----------------|-----------------|-----------------------|
| $H \rightarrow \gamma\gamma$ | $2.70 \times 10^{-4}$ | $5.31 \times 10^{-5}$ | $6.15 \times 10^{-3}$ |
| $H \rightarrow b\bar{b}$        | $6.05 \times 10^{-3}$ | $3.14 \times 10^{-3}$ | $7.93 \times 10^{-2}$ |
| $H \rightarrow \tau^+\tau^-$    | $5.42 \times 10^{-4}$ | $2.86 \times 10^{-4}$ | $7.40 \times 10^{-2}$ |

plus $|\eta^{jet}| < 2.5$GeV, $\Delta R(\gamma j) < 4$GeV, Cut IV to be the Cut III plus $p_T^{b} > 200$GeV, $p_T^{\ell} > 125$GeV, $\Delta R(\ell\ell) < 1.5$GeV. When jet fakes b, we replace the cuts for b to jets.

In Tab.3, we display the signal and total background cross sections after the application of Cut I-IV. Here in the table the rejection factors and b-jet tagging efficiency are taken into account.

We see that in order to test the anomalous $tqH$ coupling, the best choice of decay mode through $e^- p \rightarrow \nu_e Hb$ channel is $H \rightarrow b\bar{b}$. Though its cross section is much smaller than that of the one in $e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e H\bar{q}$ channel with associated $b\bar{b}$ decay mode, its signal over background ratio is not small. However, its cross section is small after the critical set of Cut IV which makes the detection a challenge. By a simple fit we get 

$$
\sigma_{total} = 5.41 \times 10^{-9} + 7.43 \times 10^{-9} \kappa_{tuh} + 8.00 \times 10^{-6} \kappa_{tuh}^2 \ [pb] \text{ for } H \rightarrow \gamma\gamma, \\
\sigma_{total} = 1.46 \times 10^{-7} + 1.54 \times 10^{-7} \kappa_{tuh} + 3.43 \times 10^{-4} \kappa_{tuh}^2 \ [pb] \text{ for } H \rightarrow b\bar{b}. \\
\sigma_{total} = 3.68 \times 10^{-7} + 16$$
$1.86 \times 10^{-7} \kappa_{tuH} + 3.42 \times 10^{-4} \kappa_{tuH}^2 [\text{pb}]$ for $H \rightarrow \tau^+ \tau^-$.

### 3.4 Data Analysis and Search Sensitivity

![Figure 5](image_url)

Figure 5: The contour plots in luminosity-$\kappa_{tuH}$ plane for expected 95% C.L. limits at 14 TeV LHeC.

We follow refs [45][46] exactly to obtain the sensitivity limits. Typically, the limits are achieved by assuming the number of observed events equal to the SM background prediction, $N_{\text{obs}} = \sigma_B \times L \times \epsilon$, with $L$ for a given integrated luminosity and $\epsilon$ the detection efficiency. $\sigma_B$ is the cross section of SM background prediction. As can be seen, the SM background events can be less or larger than 10 for different values of the luminosity. We thus estimate the sensitivity limits on the anomalous tqH coupling through both channels by using two different statistical analysis methods depending on the number of observed events $N_{\text{obs}}$. For $N_{\text{obs}} \leq 10$, we employ a Poisson distribution method. In this case, the upper limits of number of events $N_{\text{up}}$ at the 95% C.L. can be calculated from the formula

$$\Sigma_{k=0}^{N_{\text{obs}}} P_{\text{Poisson}}(N_{\text{up}}; k) = 1 - \text{CL}.\quad (14)$$

Values for limits candidate $N_{\text{up}}$ can be found in Ref.[37]. The expected 95% C.L. limits on $\kappa_{tuH}$ can then been calculated by the limits of the observed cross sections. The integrated luminosity $L$ will be taken as a running parameter. For $N_{\text{obs}} > 10$, a chi-square ($\chi^2$)
analysis is performed with the definition

$$\chi^2 = \left( \frac{\sigma_{\text{tot}} - \sigma_B}{\sigma_B \delta} \right)^2$$

(15)

where $\sigma_{\text{tot}}$ is the cross section containing new physics effects and $\delta = \frac{1}{\sqrt{N}}$ is the statistical error with $N = \sigma_B \times L \times \epsilon$. The parameter sensitivity limits on anomalous tqH coupling as a function of the integrated luminosity can then be obtained.

In Fig.5 we plot the contours of expected 95% C.L. limits to $\kappa_{tuH}$ at 14 TeV LHeC with 150 GeV electron beam for $e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e H \bar{q}$ [left panel] and $e^- p \rightarrow \nu_e H b$ [right panel] channels respectively. The solid curve, dotted curve and dashed curve are for $H \rightarrow \gamma\gamma$, $H \rightarrow b\bar{b}$, $H \rightarrow \tau^+\tau^-$ decay modes respectively. From Fig.5 we can see that the probed $\kappa_{tuH}$ limits from $e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e H \bar{q}$ channel is much smaller than that from $e^- p \rightarrow \nu_e H b$ channel. Typically, we get 0.0588, 0.0162, 0.0209 for $\kappa_{tuH}$ by using $H \rightarrow \gamma\gamma$, $H \rightarrow b\bar{b}$, $H \rightarrow \tau^+\tau^-$ decay modes respectively, which corresponds to the branching ratio $\text{Br}(t \rightarrow qH) = 0.177\%$, $\text{Br}(t \rightarrow qH) = 0.0134\%$, $\text{Br}(t \rightarrow qH) = 0.0223\%$ at 14 TeV LHeC with 200 fb$^{-1}$ luminosity for former channel, and 0.177, 0.0701, 0.0776 for the latter, corresponding to the branching ratio $\text{Br}(t \rightarrow qH) = 1.604\%$, $\text{Br}(t \rightarrow qH) = 0.252\%$, $\text{Br}(t \rightarrow qH) = 0.308\%$. Thus, we apply higher luminosity for the latter channel, see, reaching to 1000 fb$^{-1}$. Then the research limits change to 0.118, 0.0468 and 0.0518 for $\kappa_{tuH}$, which corresponds to 0.713%, 0.112%, 0.137% for the branching ratio. We can see that the LHeC sensitivity to the coupling $\kappa_{tuH}$ is much improved by using $e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e H \bar{q}$ channel. And for different decay modes, $H \rightarrow b\bar{b}$ is best one for both channels.

In Tab.4 we give the $\text{Br}(t \rightarrow qH)$ for different decay modes for both channels at 14 TeV LHeC with 10(200) fb$^{-1}$ luminosity respectively. We see that the limits have improved by almost 4 times when the luminosity increases from 10 to 200 fb$^{-1}$. When comparing different decay modes, $H \rightarrow b\bar{b}$ is the best decay modes for both channels. When we come to different channels, $e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e H \bar{q}$ is much better than $e^- p \rightarrow \nu_e H b$ channels by almost 10 times. Finally, we use our best limits in $H \rightarrow b\bar{b}$ decay modes for $e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e H \bar{q}$ channel, and we get 0.0134% for $\text{Br}(t \rightarrow qH)$ as our result at 14 TeV LHeC with 200 fb$^{-1}$ luminosity.
Table 4: Summary for the expected 95% C.L. limits of $\text{Br}(t \rightarrow qH)$ for $e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e Hq$ and $e^- p \rightarrow \nu_e Hb$ channels with $H \rightarrow \gamma\gamma$, $H \rightarrow b\bar{b}$, and $H \rightarrow \tau^+\tau^-$ decay modes at 14 TeV LHeC with 10(200) fb$^{-1}$ luminosity.

4 Summary and Conclusion

In this paper, we have investigated the anomalous flavor changing neutral current (FCNC) Yukawa interactions between the top quark, the Higgs boson, and either an up or charm quark ($tqH$, $q = u, c$). We choose the channel $e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e Hq$ with $q = u, c$ and the channel $e^- p \rightarrow \nu_e Hb$, where both channels are induced by the charged current interaction through $e^- p$ collision at the Large Hadron Electron Collider (LHeC). We consider the $H \rightarrow \gamma\gamma$, $b\bar{b}$ and $\tau^+\tau^-$ decay modes. From the results, we can see that the flavor changing couplings $\kappa_{tuH}$ can be probed to be minimal as 0.0162(0.0136) for the 95% C.L. limits in the $e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e Hq$ channel with $H \rightarrow b\bar{b}$ decay mode, which corresponds to the branching ratios $\text{Br}(t \rightarrow qH) = 1.34(0.947) \times 10^{-4}$ at 14 TeV LHeC with 200(3000) fb$^{-1}$ luminosity. From CMS and ATLAS Collaborations, we get the most stringent constraint of $\text{Br}(t \rightarrow cH) < 0.56\%$, $\text{Br}(t \rightarrow uH) < 0.45\%$ at 95% confidence level (C.L.)[20]. Thus, we can see that our results shows a strong (above 30 times) improvement from experiments. When comparing with the other phenomenological studies, we can see that the LHeC sensitivity our results for $\text{Br}(t \rightarrow qH)$ is smaller than the sensitivity limits of LHC as
Br(t \to qH) < 5(2) \times 10^{-4} \text{ with an integrated luminosity of } 300(3000) \text{ fb}^{-1} \text{ at } \sqrt{s} = 14\text{TeV}[26]. \text{ Furthermore, our results are comparable with those of other studies, such as refs } [24][25]. \text{ For example, ref } [24]\text{ obtains the sensitivity bound of about } 0.1-0.3\% \text{ through different search channels for an integrated luminosity of } 100\text{fb}^{-1} \text{ at the } \sqrt{s} = 13 \text{ TeV LHC data.}

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