Searches for the Anomalous FCNC Top-Higgs Couplings with Polarized Electron Beam at the LHeC

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Abstract

In this paper, we study the single top and Higgs associated production \( e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e h \bar{q} (h \rightarrow b \bar{b}) \) in the top-Higgs FCNC couplings at the LHeC with the electron beam energy of \( E_e = 60 \) GeV and \( E_e = 120 \) GeV, combination of a 7 TeV and 50 TeV proton beam. With the possibility of e-beam polarization \( (p_e = 0, \pm 0.6) \), we distinct the Cut-based method and the Multivariate Analysis (MVA) based method, and compare with the current experimental and theoretical limits. It is shown that the branching ratio \( \text{Br} (t \rightarrow uh) \) can be probed to 0.113 (0.093) %, 0.071 (0.057) %, 0.030 (0.022) % and 0.024 (0.019) % with the Cut-based (MVA-based) analysis at \( (E_p, E_e) = (7 \text{ TeV, 60 GeV}), (E_p, E_e) = (7 \text{ TeV, 120 GeV}), (E_p, E_e) = (50 \text{ TeV, 60 GeV}) \) and \( (E_p, E_e) = (50 \text{ TeV, 120 GeV}) \) beam energy and 1\( \sigma \) level. With the possibility of e-beam polarization, the expected limits can be probed down to 0.090 (0.073) %, 0.056 (0.045) %, 0.024 (0.018) % and 0.019 (0.015) %, respectively.

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I. INTRODUCTION

The Large Hadron Electron Collider (LHeC) is the second electron-hadron collider following HERA [1]. With remarkable higher energy and luminosity, the LHeC is a major step towards understanding the Higgs physics and QCD. For the LHeC colliding energy, the 7 TeV proton beam at the LHC as well as the 50 TeV proton beam at the future FCC-he [2] and a new 60 GeV electron beam [1] are envisaged. To probe new physics, the anomalous flavor changing neutral current (FCNC) Yukawa interactions, between the top-Higgs and either an up or charm quark, would provide a clear signal. The SM Lagrangian can be extended by the following terms,

\[
\mathcal{L} = \kappa_{\text{tu}} \bar{t} u h + \kappa_{\text{tc}} \bar{t} c h + \text{h.c.},
\]

where the real parameters \( \kappa_{\text{tu}} \) and \( \kappa_{\text{tc}} \) denote the FCNC couplings of the Higgs to up-type quarks. The total decay width of the top-quark \( \Gamma_t \) is

\[
\Gamma_t = \Gamma_{t \rightarrow W^- b}^{\text{SM}} + \Gamma_{t \rightarrow c h} + \Gamma_{t \rightarrow u h}.
\]

where the decay width \( \Gamma_{t \rightarrow W^- b}^{\text{SM}} \) and \( \Gamma_{t \rightarrow u(c) h} \) can be found in [3] and [4], respectively. Thus, the branching ratio for \( t \rightarrow u(c) h \) can be approximately given by

\[
\text{Br}(t \rightarrow u(c) h) = \frac{\kappa_{tu(c) h}^2}{\sqrt{2} G_F m_t^2 (1 - \tau^2_W)^2 / (1 + 2 \tau^2_W)} \approx 0.512 \kappa_{tu(c) h}^2
\]

where \( G_F \) is the Fermi constant and \( \tau_W = \frac{m_W}{m_t} \). The W boson and top quark masses are chosen to be \( m_W = 79.82 \) GeV and \( m_t = 173.2 \) GeV, respectively.

Up to now, the investigation of \( t \rightarrow q h \) anomalous couplings have been experimented by many groups, which gives the strongest limits on the top-Higgs FCNC couplings. For instance, according to the ATLAS and CMS collaborations, the upper limits of \( \text{Br} (t \rightarrow q h) < 0.79 \% \) [5, 6] and \( \text{Br} (t \rightarrow q h) < 0.45 \% \) [7] have been set at 95 \% confidence level (C.L.). Except for the direct collider measurements, the low energy observable, by bounding the tqH vertex from the observed \( D^0 - \bar{D}^0 \) mixing [8], the upper limit of \( \text{Br} (t \rightarrow q h) < 5 \times 10^{-3} \) may be produced. Furthermore, through \( Z \rightarrow c \bar{c} \) decay and electroweak observables, the upper limit of \( \text{Br} (t \rightarrow q h) < 0.21 \% \) [9] can be obtained.
On the other hand, based on the experimental data, many phenomenological studies are performed from different channels. For instance, [10] found that the branching ratios \( \text{Br}(t \rightarrow qh) \) can be probed to 0.24% at 3\( \sigma \) level at 14 TeV LHC with an integrated luminosity of 3000 fb\(^{-1} \) through the process \( W_t \rightarrow Whq \rightarrow \ell\nu b\gamma\gamma q \). [11] explored the top-Higgs FCNC couplings through \( t\bar{t} \rightarrow Wbqh \rightarrow \ell\nu b\gamma\gamma q \) and found the branching ratios \( \text{Br}(t \rightarrow uh) \) can be probed to 0.23% at 3\( \sigma \) sensitivity at 14 TeV LHC with \( L = 3000 \text{ fb}^{-1} \). And [12] obtained the \( \text{Br}(t \rightarrow qh) \) to be 0.112% based on the process of \( t\bar{t} \rightarrow tqh \rightarrow \ell\nu bbbq \). The process of \( th \rightarrow \ell\nu b\tau^+\tau^- \) has been studied in [13] and they estimated the upper limits of \( \text{Br}(t \rightarrow uh) < 0.15\% \) at 100 fb\(^{-1} \) of 13 TeV data for multilepton searches. The results from different experiments and theoretical channels are summarized in Table I.

**TABLE I:** The results from different experimental and phenomenological channels.

| Channels | Data Set | Limits |
|----------|----------|--------|
| \( tt \rightarrow Wbqh \rightarrow \ell\nu b\gamma\gamma q \) | ATLAS, 4.7 (20.3) fb\(^{-1} \) @ 7 (8) TeV | \( \text{Br}(t \rightarrow qh) < 0.79\% \) [5, 6] |
| \( tt \rightarrow Wbqh \rightarrow \ell\nu b\gamma\gamma q \) | CMS, 19.5 fb\(^{-1} \) @ 8 TeV | \( \text{Br}(t \rightarrow uh) < 0.45\% \) [7] |
| \( D^0 - D^\ast \) mixing data | - | \( \text{Br}(t \rightarrow qh) < 0.5\% \) [8] |
| \( Z \rightarrow c\bar{c} \) and EW observables | - | \( \text{Br}(t \rightarrow qh) < 0.21\% \) [9] |
| \( Wt \rightarrow Whq \rightarrow \ell\nu b\gamma\gamma q \) | LHC, 3000 fb\(^{-1} \) @ 14 TeV, 3\( \sigma \) | \( \text{Br}(t \rightarrow qh) < 0.24\% \) [10] |
| \( tt \rightarrow tqh \rightarrow \ell\nu b\gamma\gamma q \) | LHC, 3000 fb\(^{-1} \) @ 14 TeV | \( \text{Br}(t \rightarrow uh) < 0.23\% \) [11] |
| \( tt \rightarrow tqh \rightarrow \ell\nu bbbq \) | ILC, 3000 fb\(^{-1} \) @ 500 GeV | \( \text{Br}(t \rightarrow qh) < 0.112\% \) [12] |
| \( th \rightarrow \ell\nu b\tau^+\tau^- \) | LHC, 100 fb\(^{-1} \) @ 13 TeV | \( \text{Br}(t \rightarrow uh) < 0.15\% \) [13] |
| \( th \rightarrow \ell\nu b\ell^+\ell^- X \) | LHC, 100 fb\(^{-1} \) @ 13 TeV | \( \text{Br}(t \rightarrow uh) < 0.22\% \) [13] |
| \( th \rightarrow jjbbb \) | LHC, 100 fb\(^{-1} \) @ 13 TeV | \( \text{Br}(t \rightarrow uh) < 0.36\% \) [13] |

In this study, we examined the \( e^- p \rightarrow \nu e\bar{t} \rightarrow \nu e h\bar{q} \) at the LHeC where the Higgs boson decays to \( b\bar{b} \), at a 7 (50) TeV with a 60 (120) GeV electron beam and 1000 fb\(^{-1} \) integrated luminosity. The possibility of e-beam polarization is also considered. The Feynman diagram is plotted in Fig. [1]. The main backgrounds which yield the same or similar final states to
the signal are listed as below:

\[
\begin{align*}
  e^-p &\rightarrow \nu_e (\bar{t} \rightarrow (W^- \rightarrow jj)\bar{b}) \\
  e^-p &\rightarrow e^-jjj \\
  e^-p &\rightarrow \nu_e jjj \\
  e^-p &\rightarrow \nu_e (h \rightarrow bb)j \\
  e^-p &\rightarrow \nu_e (z \rightarrow bb)j,
\end{align*}
\]

where \(j = g, u, \bar{u}, d, \bar{d}, c, \bar{c}, s, \bar{s}, b\) and \(\bar{b}\) if possible. Notice \(e^-p \rightarrow e^-jjj\) is the neutral current multi-jet QCD background, and all the others are belong to charged current (CC) productions. For the single top background \(e^-p \rightarrow \nu_e (\bar{t} \rightarrow (W^- \rightarrow jj)\bar{b})\), the produced top quark will decay to a W boson and a b-jet. The W boson continues to decay to non-b-jet final states, which might mis-tagged as a b-jet. With the same final states, \(e^-p \rightarrow \nu_e (h \rightarrow bb)j\) and \(e^-p \rightarrow \nu_e (z \rightarrow bb)j\) are the irreducible backgrounds corresponding to associated Higgs jet and Z jet which contain three QED couplings. \(e^-p \rightarrow \nu_e jjj\) is the CC multi-jet QCD background. Similar as the single top background, a mis-identification of one or more of the final state light jets to b-jet, makes this process a reducible background.

**FIG. 1:** Feynman diagram for the partonic process \(e^-\bar{b} \rightarrow \nu_e \bar{t} \rightarrow \nu_e h\bar{q} \rightarrow \nu_e b\bar{b}\bar{q}\) at the LHeC through Flavor Changing top-Higgs interactions.

**II. TOOLS AND METHOD**

During the simulation, we first extract the Feynman Rules by using the FeynRules package \[14\] and generate the event with MadGraph@NLO \[15\]. PYTHIA6.4 \[16\] was set to solve the initial and final state parton shower, hadronization, heavy hadron decays, etc. We use CTEQ6L \[17\] as the parton distribution function and set the renormalization and fac-
orization scale to be $\mu_e = \mu_f$. We take the input heavy particle masses as $m_h = 125.7$ GeV, $m_t = 173.2$ GeV, $m_z = 91.1876$ GeV and $m_w = 79.82$ GeV, respectively. We employ the following basic pre-selections cuts to select the events:

$$E_T^{\text{missing}} \geq 15 \text{ GeV},$$

$$p_{T_{k_0}} \geq 15 \text{ GeV}, \quad k_0 = j, b, \ell,$$

$$|\eta^j| < 5, |\eta^b| < 5, |\eta^{\ell}| \leq 3,$$

$$\Delta R(k_1k_2) > 0.4, \quad k_1k_2 = jj, j\ell, jb, bb, b\ell. \quad (5)$$

where $\Delta R = \sqrt{\Delta \Phi^2 + \Delta \eta^2}$ is the separation with $\Delta \eta$ and $\Delta \Phi$ in the rapidity-azimuth plane, $p_{T_{\text{jet}}, b, \ell}$ and $|\eta_{\text{jet}, b, \ell}|$ are the transverse momentum and the pseudo-rapidity of jets, $b$-jets and leptons while $E_T^{\text{missing}}$ is the missing transverse momentum. Then we adopt a Cut-based method and a Multivariate Analysis (MVA) based method for signal and background analysis, respectively.

A. Cut-based method

In order to distinguish between signal-related events and background-related events as much as possible, we set a series of cuts. We list all the Cut-based selections here:

- **cut1**: the basic pre-selection cuts.
- **cut2**: the selection $e^- p \rightarrow E_T^{\text{missing}} + 0 \ell + \geq 3\text{ jets}$, (with at least 2 tagged $b-$jets).
- **cut3**: Missing transverse energy $E_T^{\text{missing}} > 20 \text{ GeV}$.
- **cut4**: the reconstructed top quark mass window $m_t \in [148 \text{ GeV}, 178 \text{ GeV}]$.
- **cut5**: the reconstructed $W$ boson mass window $m_W < 50 \text{ GeV}$ or $m_W > 90 \text{ GeV}$.
- **cut6**: the reconstructed $Z$ boson mass window $m_Z < 55 \text{ GeV}$ or $m_Z > 95 \text{ GeV}$.
- **cut7**: the reconstructed higgs mass window $m_h \in [100 \text{ GeV}, 130 \text{ GeV}]$. 
B. MVA-based method

We implemented the MVA method using the Root Toolkit for Multivariate Analysis (TMVA) [18]. After cut1, cut2 and cut3, we especially select several input variables to discriminate the signal and background events, thus resulting better signal significance. Specifically, we define a set of totally 44 kinematic variables and choose the most effective ones for Boosted Decision Trees (BDT) training, which are: the b-jet number ($N_{b\text{jet}}$), the separation in the $\Phi - \eta$ plane between jets ($\Delta R^{B_1B_2}$, $\Delta R^{B_1J_1}$), the difference in azimuthal angle between jets ($\Delta \Phi^{B_1B_2}$, $\Delta \Phi^{B_1J_1}$), the transverse momentum of the jet ($p_{T}^{J_1}$), the difference in $|\eta|$ between Higgs jet system ($\Delta \eta^{hJ_1}$). It is worth noting that e-beam polarization is considered in both Cut-based method and MVA-based method.

III. RESULTS

In Fig. 2 (60) GeV and Fig. 3 (120) GeV, we show the dependence of the cross section $\sigma$ on the top-Higgs FCNC couplings $\kappa_{tqh}$ at $E_e = 60$ (120) GeV with $p_e = \pm 0.6$ electron beam polarization combination of a 7 (50) GeV proton beam for three different cases. (I) $\kappa_{tqh} = \kappa_{tuh} = 0$, (II) $\kappa_{tqh} = \kappa_{tch}$, $\kappa_{tuh} = 0$ and (III) $\kappa_{tqh} = \kappa_{tuh} = \kappa_{tch}$. Obviously, the cross section of $\kappa_{tqh} = 0.1$ can be 100 times larger than that of $\kappa_{tqm} = 0.01$, and the cross section of 50 TeV can be 9.1 (6.6) times larger than that of 7 TeV with a 60 (120) GeV electron beam. We also find that the cross section between polarized and unpolarized electron beam cases are related as: $\sigma_{e^{-}} = \sigma_{e_{0}^{-}} (1 - p_{e^{-}})$, $\sigma_{e_{+}}^{-} + \sigma_{e_{-}}^{-} = 2\sigma_{e_{0}^{-}}$, independent of being case I, II or III. Here $\sigma_{e_{-}^{-}}$, $\sigma_{e_{+}^{-}}$ and $\sigma_{e_{0}^{-}}$ represent the right, left and without electron beam polarization, respectively.

![Graphs showing cross sections](image)

**FIG. 2:** The cross sections $\sigma_{tqh}$ on the top-Higgs FCNC couplings $\kappa_{tqh}$ at the 7 (50) TeV and 60 GeV LHeC with e-beam polarization $p_e = 0, \pm 0.6$. 

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The cross section of the signal and backgrounds (in units of fb) are summarized in Table II (Cut-based method) and Table III (MVA-based method). From these tables, we calculate the signal significance \( S/\sqrt{S+B} \) as 4.191 (15.341) and 6.652 (19.236) for 7 and 50 TeV by Cut-based method and 4.921 (16.934) and 7.874 (20.785) by MVA-based method after imposing all the relevant event selections (only the first three selections in MVA-based method), respectively. Obviously, compared to the Cut-based method, the MVA-based method can get a better signal significance. As expected, with the \( p_2 = -0.6 \) e-beam polarization, the results are improved as 5.302 (19.404) and 8.414 (24.335) for Cut-based method and 6.224 (21.420) and 9.960 (26.291) for MVA-based method. In addition to effective cuts, enhancing the b-tagging efficiency together with reducing the jet mis-identification rates is one of the other way to improve the signal significance. It is confirmed that the signal significance can be increased from 4.191, 6.652, 15.341 and 19.238 to 8.366, 13.840, 33.750 and 44.154 with \( \epsilon_b = 80 \% \), \( \epsilon_c = 1 \% \), \( \epsilon_{\text{light}} = 0.1 \% \) with the same value of the input parameters and kinematic cuts.

In order to estimate the sensitivity to the anomalous \( tqH \) couplings, we used chi-square (\( \chi^2 \)) function [19] [20]:

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

where \( \sigma_{\text{tot}} \) is the total cross section and \( \delta \) is the statistical error. In Fig. 4 (Cut-based Analysis) and Fig. 5 (MVA-based Analysis) [18], we plot the contours of 1\( \sigma \) limits to \( \kappa_{tqH} \) at 7 (50) GeV LHeC and 60 (120) GeV electron beam with different polarizations. The red, blue and black curves represent the 0.6, -0.6 and without electron beam polarization. From these figures, we can see that the branching ratio \( Br (t \to uh) \) can be probed to 0.113 (0.093)
**TABLE II:** Expected cross sections after all the selections for signal and backgrounds at the LHeC with an integrated luminosity of 1000 fb$^{-1}$, b-tagging efficiency $\epsilon_b = 60\%$, jet mis-identification rates $\epsilon_c = 10\%$, $\epsilon_{light} = 1\%$ by Cut-based method. Especially, we select e-beam polarizations as $p_0 = 0$, $p_1 = 0.6$ and $p_2 = -0.6$.

|               | S  | B  | SS |
|---------------|----|----|----|
| $60\text{ GeV} \oplus 7\text{ TeV} @ \text{LHeC}$ | 0.14 | 0.93 | 4.191 |
|               | 0.05 | 0.37 | 2.651 |
|               | 0.22 | 1.49 | 5.302 |
| $120\text{ GeV} \oplus 7\text{ TeV} @ \text{LHeC}$ | 0.32 | 1.98 | 6.652 |
|               | 0.13 | 0.79 | 4.207 |
|               | 0.51 | 3.16 | 8.414 |
| $60\text{ GeV} \oplus 50\text{ TeV} @ \text{LHeC}$ | 1.29 | 5.80 | 15.341 |
|               | 0.52 | 2.32 | 8.702 |
|               | 2.07 | 9.28 | 19.404 |
| $120\text{ GeV} \oplus 50\text{ TeV} @ \text{LHeC}$ | 2.14 | 10.26 | 19.238 |
|               | 0.86 | 4.10 | 12.167 |
|               | 3.43 | 16.42 | 24.335 |

**TABLE III:** The same as Table II but for MVA-based method. We select e-beam polarizations as $p_0 = 0$, $p_1 = 0.6$ and $p_2 = -0.6$.

|               | S  | B  | SS |
|---------------|----|----|----|
| $60\text{ GeV} \oplus 7\text{ TeV} @ \text{LHeC}$ | 0.125 | 0.520 | 4.921 |
|               | 0.050 | 0.208 | 3.112 |
|               | 0.200 | 0.833 | 6.224 |
| $120\text{ GeV} \oplus 7\text{ TeV} @ \text{LHeC}$ | 0.281 | 0.992 | 7.674 |
|               | 0.112 | 0.397 | 4.980 |
|               | 0.450 | 1.588 | 9.960 |
| $60\text{ GeV} \oplus 50\text{ TeV} @ \text{LHeC}$ | 0.652 | 0.830 | 16.934 |
|               | 0.261 | 0.332 | 10.710 |
|               | 1.043 | 1.328 | 21.420 |
| $120\text{ GeV} \oplus 50\text{ TeV} @ \text{LHeC}$ | 1.082 | 1.629 | 20.785 |
|               | 0.433 | 0.652 | 13.145 |
|               | 1.732 | 2.606 | 26.291 |

%, 0.071 (0.057) %, 0.030 (0.022) % and 0.024 (0.019) % with the Cut-based (MVA-based) Analysis at $(E_p, E_e) = (7\text{ TeV}, 60\text{ GeV})$, $(E_p, E_e) = (7\text{ TeV}, 120\text{ GeV})$, $(E_p, E_e) = (50\text{ TeV}, 60\text{ GeV})$ and $(E_p, E_e) = (50\text{ TeV}, 120\text{ GeV})$ beam energy. As expected, the MVA-based method has a great advantage and also the 50 TeV high energy can get better results than the 7 TeV ones. Furthermore, it is clear that the limits can be probed down to 0.090 (0.073)
%, 0.056 (0.045) %, 0.024 (0.018) % and 0.019 (0.015) % with the e-beam polarization of $p_2 = -0.6$.

Finally, we give a precise integrated luminosity ($L$) corresponding to the critical limits obtained by the experimental results (Table [IV]) and other phenomenological studies (Table [V]). With the e-beam polarization $p_2 = -0.6$, the $L$ needed to get the upper bounds on the $\text{Br}(t \to qh)$ is reduced significantly. A detailed comparison between the LHeC collider(s) and the LHC or linear colliders are given.

IV. CONCLUSION

In this paper, we investigated the anomalous FCNC Yukawa interactions between the top quark, the Higgs boson, and either an up or charm quark with a channel $e^- p \to \nu_e \bar{t} \to \nu_e h \bar{q} (h \to b\bar{b})$ at the LHeC. The signal significance $S/\sqrt{S + B}$ can be obtained as $4.191 (4.921)$, $6.652 (7.874)$, $15.341 (16.934)$ and $19.238 (20.785)$ with the Cut-based (MVA-based) method at $(E_p, E_e) = (7 \text{ TeV}, 60 \text{ GeV})$, $(E_p, E_e) = (7 \text{ TeV}, 120 \text{ GeV})$, $(E_p, E_e) = (50 \text{ TeV}, 60 \text{ GeV})$ and $(E_p, E_e) = (50 \text{ TeV}, 120 \text{ GeV})$. Similarly, our results show that the branching
### TABLE IV: The integrated luminosity ($\mathcal{L}$) needed to get the upper bounds on the $\text{Br}(t \to qh)$ at 95% C.L. obtained from the experiments. Both the Cut (MVA) based results and 1σ (2σ) limits with e-beam polarization are presented.

| Channels and Limits | Method | $\mathcal{L}[^{\text{fb}^{-1}}]_{1\sigma}$ | $\mathcal{L}[^{\text{fb}^{-1}}]_{2\sigma}$ |
|---------------------|--------|------------------------------------------|------------------------------------------|
|                     |        | $p_0$ | $p_1$ | $p_2$ | $p_0$ | $p_1$ | $p_2$ |
| $t\bar{t} \to Wbqh \to \ell\nu b\gamma\gamma q$ | Cut    | 0.93  | 2.32  | 0.58  | 3.60  | 9.00  | 2.25  |
| ATLAS, 4.7 (20.3) fb$^{-1}$ @ 7 (8) TeV |        |       |       |       |       |       |       |
| $\text{Br} (t \to qh) < 0.79 \%$ | MVA    | 0.58  | 1.44  | 0.36  | 2.24  | 5.60  | 1.40  |
| $t\bar{t} \to Wbqh \to \ell\nu b\gamma\gamma q$ | Cut    | 2.86  | 7.15  | 1.79  | 11.10 | 27.76 | 6.94  |
| CMS, 19.5 fb$^{-1}$ @ 8 TeV |        |       |       |       |       |       |       |
| $\text{Br} (t \to uh) < 0.45 \%$ | MVA    | 1.78  | 4.45  | 1.11  | 6.91  | 17.27 | 4.32  |
| $D^0 - D^0$ mixing data | Cut    | 2.32  | 5.79  | 1.11  | 8.99  | 22.48 | 5.62  |
| $\text{Br} (t \to qh) < 0.5 \%$ | MVA    | 1.44  | 3.60  | 0.90  | 5.60  | 13.99 | 3.50  |
| $Z \to c\bar{c}$ and EW observables | Cut    | 13.13 | 32.83 | 8.21  | 51.01 | 127.53| 31.88 |
| $\text{Br} (t \to qh) < 0.21 \%$ | MVA    | 8.17  | 20.43 | 5.11  | 31.74 | 79.35 | 19.84 |

### TABLE V: The same as Table IV but for some other phenomenological studies.

| Channels and Limits | Method | $\mathcal{L}[^{\text{fb}^{-1}}]_{1\sigma}$ | $\mathcal{L}[^{\text{fb}^{-1}}]_{2\sigma}$ |
|---------------------|--------|------------------------------------------|------------------------------------------|
|                     |        | $p_0$ | $p_1$ | $p_2$ | $p_0$ | $p_1$ | $p_2$ |
| $Wt \to Whq \to \ell\nu b\gamma\gamma q$ | Cut    | 10.05 | 25.14 | 6.28  | 39.05 | 97.63 | 24.41 |
| LHC, 3000 fb$^{-1}$ @ 14 TeV |        |       |       |       |       |       |       |
| $3\sigma$, $\text{Br} (t \to qh) < 0.24 \%$ | MVA    | 6.26  | 15.64 | 3.91  | 24.30 | 60.75 | 15.19 |
| $t\bar{t} \to Wbqh \to \ell\nu b\gamma\gamma q$ | Cut    | 10.95 | 27.37 | 6.84  | 42.52 | 106.31| 26.58 |
| LHC, 3000 fb$^{-1}$ @ 14 TeV |        |       |       |       |       |       |       |
| $\text{Br} (t \to uh) < 0.23 \%$ | MVA    | 6.81  | 17.03 | 4.26  | 26.46 | 66.15 | 16.54 |
| $t\bar{t} \to tqh \to \ell\nu bbbq$ | Cut    | 46.20 | 115.50| 28.87 | 179.44| 448.60| 112.15 |
| ILC, 3000 fb$^{-1}$ @ 500 GeV |        |       |       |       |       |       |       |
| $\text{Br} (t \to qh) < 0.112 \%$ | MVA    | 28.75 | 71.86 | 17.97 | 111.65| 279.13| 69.78 |
| $th \to \ell\nu b\tau^+\tau^-$ | Cut    | 25.75 | 64.37 | 16.09 | 100.01| 250.03| 62.51 |
| LHC, 100 fb$^{-1}$ @ 13 TeV |        |       |       |       |       |       |       |
| $\text{Br} (t \to uh) < 0.15 \%$ | MVA    | 16.02 | 40.05 | 10.01 | 62.23 | 155.58| 38.89 |
| $th \to \ell\nu b\ell^+\ell^- X$ | Cut    | 11.97 | 29.92 | 7.48  | 46.48 | 116.20| 29.05 |
| LHC, 100 fb$^{-1}$ @ 13 TeV |        |       |       |       |       |       |       |
| $\text{Br} (t \to uh) < 0.15 \%$ | MVA    | 7.45  | 18.61 | 4.65  | 28.92 | 72.30 | 18.08 |
| $th \to jjbb$ | Cut    | 4.47  | 11.17 | 2.79  | 17.35 | 43.38 | 10.84 |
| LHC, 100 fb$^{-1}@13$TeV |        |       |       |       |       |       |       |
| $\text{Br} (t \to uh) < 0.36 \%$ | MVA    | 2.78  | 6.95  | 1.74  | 10.80 | 26.99 | 6.75  |
ratio $\text{Br} \ (t \rightarrow uh)$ can be probed to 0.113 (0.093) %, 0.071 (0.057) %, 0.030 (0.022) % and 0.024 (0.019) %, and with the e-beam polarization $p_2 = -0.6$, the expected limits can be greatly reduced. Finally, a detailed comparison between our study and the critical limits obtained by the experiments and other phenomenological studies are shown. We thus give an overview of the search potential on the anomalous top-Higgs couplings with polarized electron beam at the LHeC.

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