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Search for Flavour Changing Neutral Current Couplings of Higgs-up Sector Quarks at Future Circular Collider (FCC-eh)

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***Abstract*—**In the search for new physics beyond the Standard Model, Flavour Changing Neutral Current (FCNC) is a good research field in terms of the observability at future colliders. Increased Higgs production with higher energy and luminosity in colliders is essential for verification or falsification of our knowledge of physics and predictions, and the search for new physics. Prospective electron-proton collider constituent of the Future Circular Collider project is FCC-eh. It offers great sensitivity due to its high luminosity and low interference. In this work, thq FCNC interaction vertex with off-shell top quark decay at electron-proton colliders is studied. By using MadGraph5_aMC@NLO multi-purpose event generator, observability of tuh and tch couplings are obtained with equal coupling scenario. Upper limit on branching ratio of tree level top quark FCNC decay is determined as 0.012% at FCC-eh with $1\,ab^{-1}$ luminosity.

***Keywords*—**FCC, FCNC, Higgs Boson, Top Quark

I. Introduction

FLAVOUR changing neutral current (FCNC) is a type of current that saves the electric charge and changes the flavour from initial fermion to final fermion. In Standard Model (SM), the model that is the most compatible with the observations yet, FCNC doesn't exist at tree level. It can occur at loop level we present with triangle, box and penguin diagrams but branching ratio of these decays are too low as a result of GIM mechanism [1]. Branching ratios of $t \to hq$ FCNC decays are order of $10^{-15} - 10^{-17}$ [2]. Beyond the SM with some new physics scenarios, such as 2HDM, MSSM, R parity violating SUSY, these rates increase to order of $10^{-3} - 10^{-6}$. In this study, FCNC couplings between top quark, Higgs boson and either up or charm quark are examined with effective Lagrangian extensions that allow the couplings. Observability of these couplings at FCC-eh [3] is determined with scenario in which these couplings are equal. Same calculation is also done for Large Hadron Electron Collider (LHeC) [4] and the results are compared with those came from ATLAS [5] and CMS [6] experiments. Experiments brought an upper limit on branching ratio of $t \to hc$ and $t \to hu$ at the 95% confidence level (CL). These limits are $Br(t \to hc)$ of 0.46% and $Br(t \to hu)$ of 0.45% from ATLAS, and $Br(t \to hc)$ of 0.40% and $Br(t \to hu)$ of 0.55% from CMS experiment.

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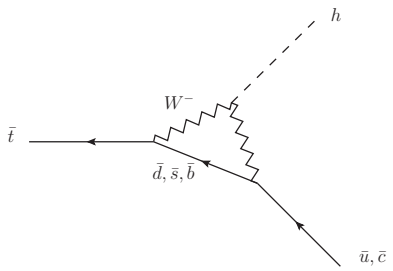


Fig. 1 Triangle FCNC diagram of $\bar{t} \to h\bar{q}$ decay

II. Calculation Framework

Throughout the study, FCNC couplings of Higgs and up sector quarks are taken into account with off-shell top quark decay to Higgs and either up or charm quark at electron-proton collisions. The main signal process is taken as $e^- p \to \nu_e h\bar{q}$ ($\bar{q} = \bar{u}, \bar{c}$) and $h \to b\bar{b}$ decay considered. Most contribution to signal cross section comes from the subprocesses that have $\bar{b}$ at the initial state. Other signal diagrams have $\bar{s}$ and $\bar{d}$ instead of $\bar{b}$. Relevant Feynman diagrams are shown in Fig. 2.

The effective Lagrangian of the flavour changing neutral current (FCNC) effective interactions between top quark and Higgs boson can be written as below.

$$L = \kappa_{tuh}\,\bar{t}uh + \kappa_{tch}\,\bar{t}ch + h.c. \quad (1)$$

κ_{tuh} and κ_{tch} are coupling parameters of couplings between Higgs and up sector quarks. We can have the Lagrangian we need for calculation by adding these Lagrangian terms to SM Lagrangian.

For event generation and amplitude calculation, MadGraph5_aMC@NLO [7] (version 2.4.3) multi-purpose event generator is used. The appropriate model with the Lagrangian is TFCNC_UFO implemented by FeynRules [8], [9]. Wolfenstein parameters and CKM matrix elements

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depending on Wolfenstein parameters [10], [11], are defined into the Model. In this way, quark mixing between third family quarks and other quarks is provided. Energy parameters of the future electron-proton colliders are taken as 60 GeV electron - 50 TeV proton for FCC-eh and 60 GeV electron - 7 TeV proton for LHeC.

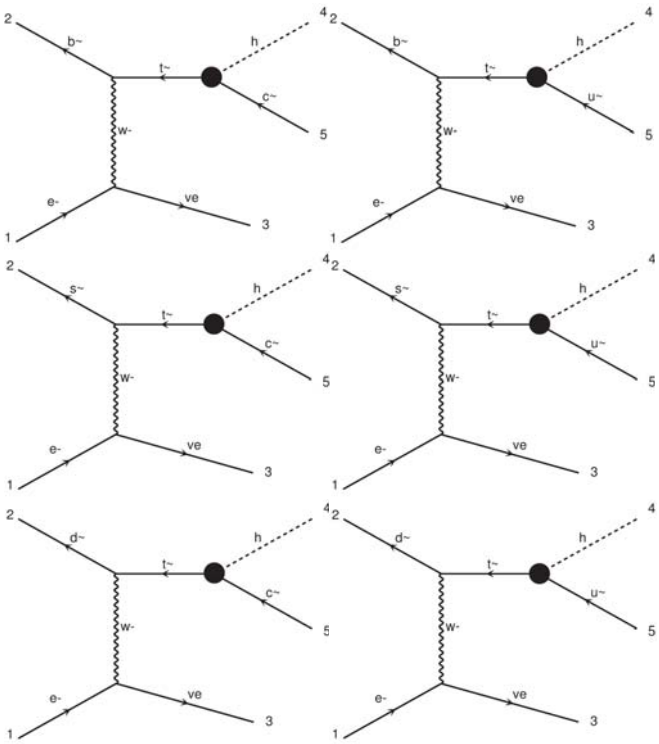


Fig. 2 Feynman diagrams for $e^-p \to \nu_e h\bar{q}$ ($\bar{q} = \bar{u}, \bar{c}$) process that include tqh vertices

III. Cross Sections

The cross section of the signal is calculated with $e^-p \to \nu_e h\bar{q}$ ($\bar{q} = \bar{u}, \bar{c}$) process at FCC-eh $E_e = 60$ GeV, $E_p = 50000$ GeV ($\sqrt{s} = 3464.1$ GeV) and LHeC $E_e = 60$ GeV, $E_p = 7000$ GeV ($\sqrt{s} = 1296.15$ GeV). The cross sections for the process are given by in Table I and Table II for different FCNC coupling values. Background cross sections of the signal processes are at the same order with the total cross sections. At some parameter combinations with 10^{-3} value and below, negative differences appeared and commented as statistical fluctuation appear with this much low parameter.

At the final state of the signal, there is one quark jet with the Higgs boson. Since we considered the Higgs boson decays to pair of beauty quarks, there will be three quark jets at the final state. Background processes are defined with $e^-p \to \nu_e hq$, $e^-p \to \nu_e Zq$, $e^-p \to \nu_e W^-q$ and $e^-p \to \nu_e \bar{t}$ processes when $q = u, d, c, s, b, \bar{u}, \bar{d}, \bar{c}, \bar{s}, \bar{b}$. Cross sections of background processes, and their product with branching ratios and b-tagging efficiencies (ϵ_b^2) are given in Table III.

The contour plots of the parameters κ_{tuh} and κ_{tch} for different signal cross section values at FCC-eh and LHeC are shown in Fig. 4. The FCC-eh has higher center of mass (CM) energy than LHeC, it provides larger cross section therefore the sensitivity to the FCNC couplings becomes larger. In order to estimate the bounds on the couplings, we assume a detector acceptance of 1% and take ten year Luminosity of $100\,fb^{-1}$. For one signal event in year, we obtain these bounds given about $\kappa_{tuh} = [-0.034, 0.034]$ and $\kappa_{tch} = [-0.034, 0.034]$ for FCC-eh, $\kappa_{tuh} = [-0.095, 0.095]$ and $\kappa_{tch} = [-0.097, 0.097]$ for LHeC.

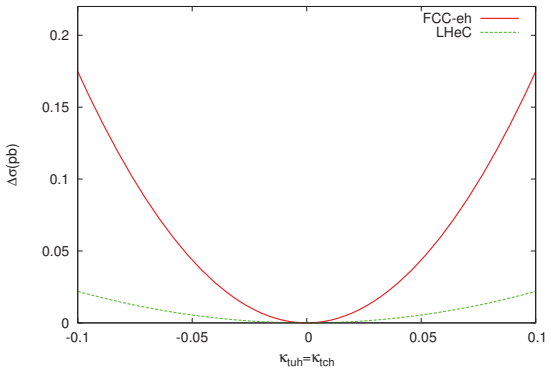


Fig. 3 $\Delta\sigma$ signal dependence to $\kappa_{tuh} = \kappa_{tch}$ parameters at 60 GeV - 50 TeV FCC-eh and 60 GeV - 7 TeV LHeC

We assume equal coupling scenario ($\kappa_{tuh} = \kappa_{tch}$), the signal cross section depending on FCNC parameters are given in Fig. 3. When the coupling changes 10%, the cross section for FCC-eh changes about 18% and the cross section for LHeC changes about 2%.

IV. Analysis

A. Statistical Significance

In order to see the meaningfulness of the signal events, statistical significance (SS) is calculated with the formula given in (2). Here S is event number of the signal and B is event number of total background. Event numbers are calculated with $N = \sigma \times BR \times L_{int} \times \epsilon_b^2$ formula, product of relevant cross section, branching ratio we considered, integrated luminosity and b-tagging efficiencies.

$$SS = \sqrt{2[(S+B)ln(1+\frac{S}{B}) - S]} \tag{2}$$

From Fig. 5 we can read a parameter and a luminosity that give the statistics we demand. For 2σ, $100\,fb^{-1}$ and $1000\,fb^{-1}$ integrated luminosity corresponds to $\kappa_{tuh} = \kappa_{tch} = 0.027$ and $\kappa_{tuh} = \kappa_{tch} = 0.015$ at FCC-eh, $\kappa_{tuh} = \kappa_{tch} = 0.054$ and $\kappa_{tuh} = \kappa_{tch} = 0.030$ at LHeC respectively.

In Fig. 6, we can see the electron polarization effects on statistical significance. $e^-(-0.8)$ refers to 80% left polarization, $e^-(0)$ refers to no polarization and $e^-(+0.8)$ refers to 80% right polarization. With left polarization, SS values increased by a factor of 1.36 and 1.27 at FCC-eh and LHeC respectively. These improvements are same with the result of increasing the integrated luminosity by a factor of 1.84 and 1.61 respectively.

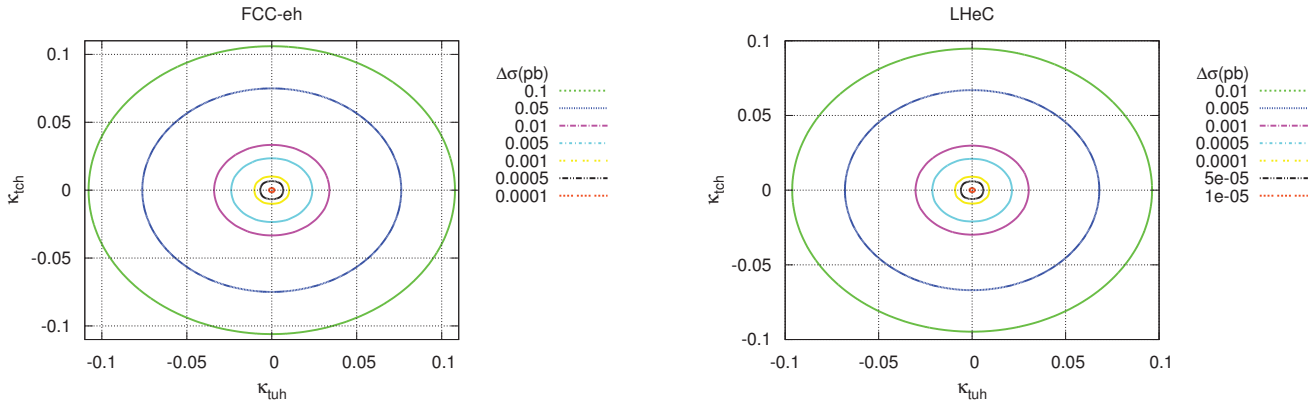


Fig. 4 Contour plots for κ_{tuh} and κ_{tch} parameters according to the $\Delta\sigma$ signal cross section at 60 GeV - 50 TeV FCC-eh and 60 GeV - 7 TeV LHeC

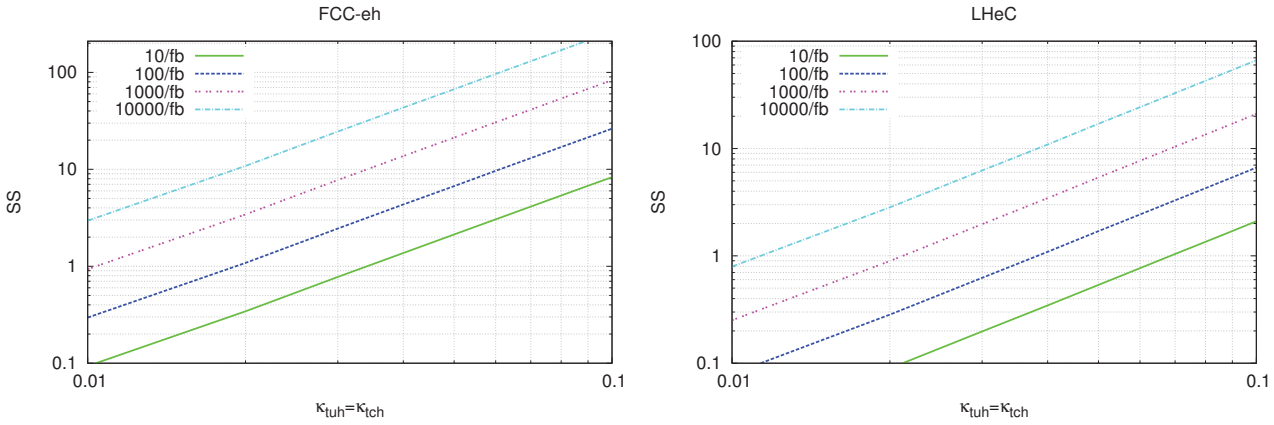


Fig. 5 SS-κ plot for different integrated luminosity values at 60 GeV - 50 TeV FCC-eh and 60 GeV - 7 TeV LHeC

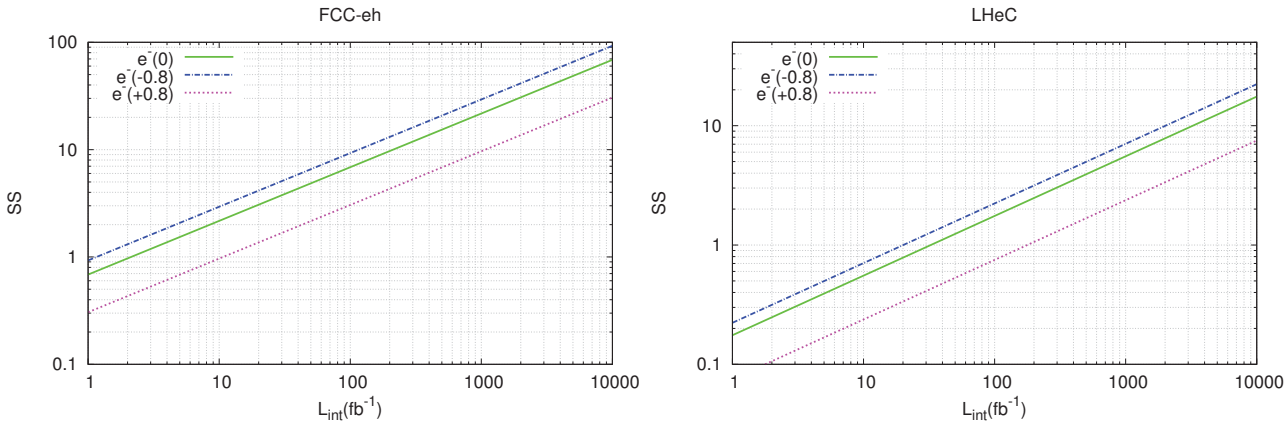


Fig. 6 SS - L_{int} plot for different electron polarizations with $\kappa_{tuh} = \kappa_{tch} = 0.05$ parameter value at the FCC-eh and the LHeC

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TABLE I
CROSS SECTIONS (pb) OF THE SIGNAL PROCESS AT 60 GEV - 50 TEV FCC-EH

FCC-eh	$\kappa_{tch} = 10^{-1}$	$\kappa_{tch} = 10^{-2}$	$\kappa_{tch} = 10^{-3}$	$\kappa_{tch} = 10^{-4}$
$\kappa_{tuh} = 10^{-1}$	2.692×10^{-1}	1.798×10^{-1}	1.802×10^{-1}	1.794×10^{-1}
$\kappa_{tuh} = 10^{-2}$	1.826×10^{-1}	9.507×10^{-2}	9.383×10^{-2}	9.390×10^{-2}
$\kappa_{tuh} = 10^{-3}$	1.829×10^{-1}	9.347×10^{-2}	9.294×10^{-2}	9.295×10^{-2}
$\kappa_{tuh} = 10^{-4}$	1.824×10^{-1}	9.411×10^{-2}	9.311×10^{-2}	9.281×10^{-2}

The background cross section is $\sigma_b = 9.279 \times 10^{-2} pb$.

TABLE II
CROSS SECTIONS (pb) OF THE SIGNAL PROCESS AT 60 GEV - 7 TEV LHEC

LHeC	$\kappa_{tch} = 10^{-1}$	$\kappa_{tch} = 10^{-2}$	$\kappa_{tch} = 10^{-3}$	$\kappa_{tch} = 10^{-4}$
$\kappa_{tuh} = 10^{-1}$	3.300×10^{-2}	2.199×10^{-2}	2.198×10^{-2}	2.188×10^{-2}
$\kappa_{tuh} = 10^{-2}$	2.237×10^{-2}	1.133×10^{-2}	1.125×10^{-2}	1.123×10^{-2}
$\kappa_{tuh} = 10^{-3}$	2.226×10^{-2}	1.117×10^{-2}	1.104×10^{-2}	1.111×10^{-2}
$\kappa_{tuh} = 10^{-4}$	2.224×10^{-2}	1.122×10^{-2}	1.109×10^{-2}	1.108×10^{-2}

The background cross section is $\sigma_b = 1.104 \times 10^{-2} pb$.

TABLE III
CROSS SECTIONS (pb) OF THE BACKGROUND PROCESSES AND THEIR PRODUCTS

Process	LHeC		FCC-eh	
	σ_1	$\sigma_1 \times BR \times \epsilon_b^2$	σ_2	$\sigma_2 \times BR \times \epsilon_b^2$
$e^- p \to \nu_e hq$	9.03×10^{-2}	1.89×10^{-2}	3.18×10^{-1}	6.64×10^{-2}
$e^- p \to \nu_e Zq$	4.92×10^{-1}	2.66×10^{-2}	2.03×10^{0}	1.10×10^{-1}
$e^- p \to \nu_e W^- q$	2.87×10^{0}	5.78×10^{-4}	1.91×10^{1}	3.84×10^{-3}
$e^- p \to \nu_e \bar{t}$	2.06×10^{0}	4.15×10^{-4}	1.65×10^{1}	3.32×10^{-3}

Here $\epsilon_b = 0.60$, BR$(h \to b\bar{b}) = 0.58$, BR$(Z \to b\bar{b}) = 0.15$, BR$(W^- \to b\bar{c}) = 5.59 \times 10^{-4}$, BR$(\bar{t} \to W^- \bar{b}) = 1$.

B. Branching Ratio

Top quark total decay width is widened with decay widths of $t \to ch$ and $t \to uh$ since the SM model Lagrangian is extended. Calculation of the branching ratio of these decays with convenience of equal coupling scenario will lead us to an equation which provides the translation from coupling parameters to branching ratio. Partial decay widths $\Gamma^{SM}_{t \to W^- b}$, $\Gamma_{t \to ch}$, $\Gamma_{t \to uh}$ can be found in previous studies on $t \to qh$ decays [12]-[15].

$$Br(t \to u(c)h) = \frac{\Gamma_{t \to u(c)h}}{\Gamma^{SM}_{t \to W^- b} + \Gamma_{t \to ch} + \Gamma_{t \to uh}} \tag{3}$$

$$Br(t \to u(c)h) = \frac{\kappa^2_{tu(c)h}}{\sqrt{2} G_F m_t^2} \frac{(1 - m_h^2/m_t^2)^2}{(1 - m_W^2/m_t^2)^2 (1 + 2m_W^2/m_t^2)} \tag{4}$$

$$Br(t \to u(c)h) \approx 0.519 \kappa^2_{tu(c)h} \tag{5}$$

Now, we can calculate the limits on $Br(t \to u(c)h)$ from future electron-proton colliders with parameters that give fair statistics. For 95% CL, upper limits on the branching ratio are given in Table IV.

The limits on the $Br(t \to hc)$ and $Br(t \to uh)$ came from ATLAS and CMS as mentioned in introduction.

ATLAS constrained these decays with $\sqrt{s} = 8$ TeV CM energy, $L_{int} = 20.3\ fb^{-1}$ integrated luminosity and $h \to bb, \tau\tau, \gamma\gamma, WW$ decay channels [3], and put the upper limits of 0.46% on $Br(t \to hc)$ and 0.45% on $Br(t \to hu)$.

CMS also constrained these decays with $\sqrt{s} = 8$ TeV CM energy, $L_{int} = 19.7\ fb^{-1}$ integrated luminosity and $h \to bb, \tau\tau, \gamma\gamma, WW, ZZ$ decay channels [4], and put the upper limits of 0.40% on $Br(t \to hc)$ and 0.55% on $Br(t \to hu)$.

The comparison of these experimental limits with our $10\ fb^{-1}$ results in Table IV shows that LHeC has approximate limit with less integrated luminosity, less CM energy ($\sqrt{s} \approx 1.3$ TeV) with electron-proton collisions, and less decay channel ($h \to bb$). FCC-eh ($\sqrt{s} \approx 3.5$ TeV) has more than 3 times better limit in comparison with the ATLAS and CMS experiments.

TABLE IV
$Br(t \to u(c)h)$ LIMITS WITH DIFFERENT INTEGRATED LUMINOSITIES

L_{int}	LHeC	FCC-eh
	$Br(t \to u(c)H)$	$Br(t \to u(c)H)$
$10\ fb^{-1}$	0.490%	0.130%
$100\ fb^{-1}$	0.153%	0.038%
$1000\ fb^{-1}$	0.047%	0.012%

V. CONCLUSION

FCNC couplings between up sector quarks and Higgs boson were examined with top quark $t \to hq$ decay through the signal process $e^- p \to \nu_e h \bar{q}$ ($\bar{q} = \bar{u}, \bar{c}$) and $h \to b\bar{b}$ decay at FCC-eh. Same study is also performed for LHeC in order to have more profound results. Limits on $Br(t \to u(c)h)$ are determined as 0.047% and 0.012% at LHeC and FCC-eh respectively, with $1\ ab^{-1}$ luminosity.

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Results show that FCC-eh is more sensitive to the tqh FCNC couplings than the LHeC. Electron polarization possibility is one precious feature of the electron-proton colliders. With 80% left polarization, the statistical significance values increased by a factor which cause almost same result with doubling the luminosity. Another precious feature is lower interference in comparison with the proton-proton collisions, and its advantage can be seen when the results are compared with the LHC experiments, ATLAS and CMS. All these results show that LHeC and FCC-eh electron-proton collider projects have a complementary potential in the search of Higgs-up sector quarks FCNC couplings.

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