Top Quark FCNC tqγ and tqZCouplings at LHeC and FCC-eh*

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*study is based on updates and arXiv:1701.06932, arXiv:1705.05419

Electrons for the LHC - LHeC/FCCeh and PERLE Workshop, LAL Orsay, 27-29 June 2018
- A short introduction

- Top quark FCNC tqγ and tqZ couplings

- Decay widths and branching ratio

- Production cross sections

- Kinematical distributions

- Statistical analysis

- Limits on couplings and branchings

- Summary and conclusions
Precise measurements of couplings between the SM gauge bosons and quarks and leptons are sensitive test of new physics (search for deviations), due to its large mass the top quark is expected to be the most sensitive to BSM physics.

The future ep colliders offers excellent prospects for top physics.

The LHeC and FCC-eh are compared to previous DIS experiments. The plot indicates the placement of key physics subjects in the kinematics plane of $x$ and $Q^2$. 

The top quark flavor changing neutral current (FCNC) processes are extremely suppressed within the standard model (SM), however they could be enhanced in a new physics model beyond the SM. Top quark FCNC interactions would be a good test of new physics at present and future colliders. These interactions ($tq\gamma$, $tqZ$, $tqg$ and $tqh$) can be described by the effective Lagrangian

$$\mathcal{L}_{\text{FCNC}} = \sum_{q=u,c} \frac{g_s}{2m_t} \bar{q}\lambda^a \sigma^{\mu\nu} (\zeta_{qt}^L P^L + \zeta_{qt}^R P^R) t G^{a}_{\mu\nu} - \frac{1}{\sqrt{2}} \bar{q} (\eta_{qt}^L P^L + \eta_{qt}^R P^R) t H - \frac{g_W}{2c_W} \bar{q} \gamma^\mu (X_{qt}^L P^L + X_{qt}^R P^R) t Z^\mu + \frac{g_W}{4c_W m_Z} \bar{q} \sigma^{\mu\nu} (K_{qt}^L P^L + K_{qt}^R P^R) t Z^{\mu\nu} + \frac{e}{2m_t} \bar{q} \sigma^{\mu\nu} (\lambda_{qt}^L P^L + \lambda_{qt}^R P^R) t A^{\mu\nu} + H.c.$$
Branching ratio limits for top quark FCNC decays, compared to the SM and new physics models predictions. Experimental results are also shown in the plot.

\[ \text{BR}(t \rightarrow q\gamma) < 2.5 \times 10^{-5} \text{ and BR}(t \rightarrow qZ) < 7.0 \times 10^{-5} \text{ for } q = u, c. \]


FCC-eh reach at 2 ab\(^{-1}\)
Production cross sections

### Cross section (in pb) for e-p→(e-t+e-t~)X

<table>
<thead>
<tr>
<th>LHeC</th>
<th>$\lambda_a=0$</th>
<th>$\lambda_a=0.01$</th>
<th>$\lambda_a=0.02$</th>
<th>$\lambda_a=0.03$</th>
<th>$\lambda_a=0.05$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_q=0$</td>
<td>0</td>
<td>9.450x10^-3</td>
<td>2.360x10^-2</td>
<td>8.050x10^-2</td>
<td>2.213x10^-1</td>
</tr>
<tr>
<td>$\kappa_q=0.01$</td>
<td>4.300x10^-3</td>
<td>1.360x10^-2</td>
<td>3.650x10^-2</td>
<td>8.520x10^-2</td>
<td>2.268x10^-1</td>
</tr>
<tr>
<td>$\kappa_q=0.02$</td>
<td>1.350x10^-2</td>
<td>3.900x10^-2</td>
<td>5.050x10^-2</td>
<td>9.570x10^-2</td>
<td>2.387x10^-1</td>
</tr>
<tr>
<td>$\kappa_q=0.03$</td>
<td>2.860x10^-2</td>
<td>4.060x10^-2</td>
<td>6.660x10^-2</td>
<td>1.123x10^-1</td>
<td>2.559x10^-1</td>
</tr>
<tr>
<td>$\kappa_q=0.05$</td>
<td>7.820x10^-2</td>
<td>8.850x10^-2</td>
<td>1.173x10^-1</td>
<td>1.639x10^-1</td>
<td>3.082x10^-1</td>
</tr>
</tbody>
</table>

### Cross section (in pb) for e-p→(e-tq+e-t~q)X

<table>
<thead>
<tr>
<th>LHeC</th>
<th>$\lambda_c = 10^{-2}$</th>
<th>$\lambda_c = 10^{-3}$</th>
<th>$\lambda_c = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_u = 10^{-2}$</td>
<td>9.468 x 10^{-3}</td>
<td>8.368 x 10^{-3}</td>
<td>8.357 x 10^{-3}</td>
</tr>
<tr>
<td>$\lambda_u = 10^{-3}$</td>
<td>1.188 x 10^{-3}</td>
<td>9.460 x 10^{-5}</td>
<td>8.365 x 10^{-5}</td>
</tr>
<tr>
<td>$\lambda_u = 0$</td>
<td>1.103 x 10^{-3}</td>
<td>1.104 x 10^{-5}</td>
<td>0</td>
</tr>
</tbody>
</table>

### Cross section (in pb) for e-p→(e-tq+e-t~q)X

<table>
<thead>
<tr>
<th>FCC-he</th>
<th>$\lambda_c = 10^{-2}$</th>
<th>$\lambda_c = 10^{-3}$</th>
<th>$\lambda_c = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_u = 10^{-2}$</td>
<td>3.238 x 10^{-2}</td>
<td>2.490 x 10^{-2}</td>
<td>2.488 x 10^{-2}</td>
</tr>
<tr>
<td>$\lambda_u = 10^{-3}$</td>
<td>7.834 x 10^{-3}</td>
<td>3.243 x 10^{-4}</td>
<td>2.480 x 10^{-4}</td>
</tr>
<tr>
<td>$\lambda_u = 0$</td>
<td>7.576 x 10^{-3}</td>
<td>7.580 x 10^{-5}</td>
<td>0</td>
</tr>
</tbody>
</table>

O.Cakir
Signal Cross Sections

Signal process studied: $e^- p \rightarrow e^- W^\pm q + X$

A contour plot for top FCNC couplings within the interested range depending on different value of signal cross sections at LHeC and FCC-eh colliders.

The dashed line corresponds to equal coupling scenarios ($\lambda_u = \lambda_c$), the sensitivity to coupling $\lambda_u$ is more emphasized.

- For a target value of $\lambda_u(\lambda_c)=0.01$, corresponding signal cross section values are 8(1) fb at LHeC and 25(8) fb at FCC-eh.
**Signal Cross Sections**

**Process:** $e^- p \rightarrow e^- W^\pm q + X$

A contour plot for top FCNC couplings within the interested range depending on different value of signal cross sections at LHeC and FCC-eh colliders.

The dashed line corresponds to equal coupling scenarios ($\lambda_q = \kappa_q$), the sensitivity to coupling $\lambda_q$ is more emphasized.

- For coupling $\kappa_q = 0.02$, corresponding signal cross section values are 15 fb at LHeC and 50 fb at FCC-eh.
Analysis is based on the process $e^- p -> e^- W^\pm q + X$. Only the signal diagrams are shown. Here, no specific chirality is assumed for FCNC $tq\gamma$ and $tqZ$ couplings, then we take $\lambda_q^L=\lambda_q^R=\lambda_q$ and $\kappa_q^L=\kappa_q^R=\kappa_q$ to reduce number of parameters.

There are also similar diagrams for process $e^- p -> e^- W^- q+X$ with quarks $q\leftrightarrow q\bar{q}$.

We use MadGraph 5 for event generation, Pythia 6 for hadronization and decay, Delphes 3.3 for detector simulation, Root 6 for analysis.
For the analysis, after pre-selection cuts, we use the analysis cuts for further background suppression.

**cut flow**

<table>
<thead>
<tr>
<th>Cut</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Cut-0</td>
<td>at least one electron and three jets (pre-selection with default MG5 cuts)</td>
</tr>
<tr>
<td>Cut-1</td>
<td>require one of three jets as being b-tag</td>
</tr>
<tr>
<td>Cut-2</td>
<td>b-tagged jet has transverse momentum $p_T&gt;$35 GeV and other jets have $p_T&gt;$25 GeV, and electron has $p_T&gt;$20 GeV</td>
</tr>
<tr>
<td>Cut-3</td>
<td>all jets have pseudo-rapidity $-5.0&lt;\eta&lt;0$ ; and electron has $-2.5&lt;\eta&lt;2.5$</td>
</tr>
<tr>
<td>Cut-4</td>
<td>invariant mass of two jets within $50&lt;m_{jj}&lt;90$ GeV (for W-boson)</td>
</tr>
<tr>
<td>Cut-5</td>
<td>invariant mass of three jets (for top) between $130&lt;m_{bjj}&lt;200$ GeV</td>
</tr>
</tbody>
</table>
Cut efficiency

Efficiency plot for the cuts applied at each step for the analysis of signal (S) + background B1(eWq) and B2(eZq) events. The cut efficiencies are calculated with respect to the pre-selection cuts for each coupling value.

The number of events (N) for background B1 (B2), and signal for different values of $\lambda_u$ and $\lambda_c$ at LHeC with $L_{\text{int}} = 100$ fb$^{-1}$.
Invariant mass distributions

Invariant mass distributions of three jets (one of the jets is required as b-jet) for the signal+background (S+B1+B2), and backgrounds (B1, B2). The ratio plot presents the signal (for equal coupling scenario $\lambda_c=\lambda_u=0.05$ and $\kappa_q=0$) strength which peaks at the top mass.

The statistical significance (SS) are calculated at the final stage of the cuts using the signal (S) and total background ($B_T$) events.
SS=\sqrt{2[(S+B)\ln(1+S/B)-S]}

Estimated statistical significance (SS) reach of flavor changing neutral current \textbf{tuy coupling} (\lambda_u) and \textbf{tcy coupling} (\lambda_c) depending on the integrated luminosity ranging from 1 fb\(^{-1}\) to 1 ab\(^{-1}\) at the LHeC. It includes the contribution from the main backgrounds on the results. The signal significance corresponding to 2\(\sigma\), 3\(\sigma\) and 5\(\sigma\) lines are also shown.

The SS reach for the flavor changing neutral current \textbf{tcy coupling} (\lambda_c) depending on the integrated luminosity at the LHeC.
For equal couplings scenario $\kappa_q = \lambda_q = 0.01$, the LHeC can probe (with 3σ) these couplings at $L_{\text{int}} = 70 \text{ fb}^{-1}$. For a higher luminosity of 500 fb$^{-1}$ ($1 \text{ ab}^{-1}$), we have the limit for coupling $\kappa_q = \lambda_q = 0.007$ (0.005).
Results on couplings

The contour plot for the couplings $\lambda_u$ and $\lambda_c$ at LHeC for an integrated luminosity of 500 fb\(^{-1}\) (1 ab\(^{-1}\)). The 3$\sigma$ significance results: $\lambda_u = 0.012$ (0.0105) and $\lambda_c = 0.032$ (0.027), which can be translated into the upper bounds on branching ratios.

The results can be compared to the HL-LHC expected limits [cf. additional slides].
Contour plot from the analysis

It is found that sensitivity to couplings $\lambda_q$ (vertex $tq\gamma$) is better than $\kappa_q$ (vertex $tqZ$) at LHeC.

Top FCNC evidence, observation and discovery potential of the LHeC at different luminosity projections from the analysis.
Limits on Branchings

Integrated luminosity versus branching ratio plot for top FCNC ($tq\gamma$) at 2σ, 3σ and 5σ significance at LHeC.

* Upper bounds on the branching ratios for 1 ab$^{-1}$ are shown in Table.

<table>
<thead>
<tr>
<th>LHeC $L_{int}$=1 ab$^{-1}$</th>
<th>2σ</th>
<th>3σ</th>
<th>5σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BR(t\rightarrow u\gamma)$</td>
<td>4.0x10$^{-6}$</td>
<td>7.5x10$^{-6}$</td>
<td>1.5x10$^{-5}$</td>
</tr>
<tr>
<td>$BR(t\rightarrow c\gamma)$</td>
<td>4.0x10$^{-5}$</td>
<td>9.0x10$^{-5}$</td>
<td>2.0x10$^{-4}$</td>
</tr>
</tbody>
</table>

* $BR(t\rightarrow u\gamma) \leq 5.0x10^{-6}$ and $BR(t\rightarrow u\gamma) \leq 4.5x10^{-5}$ for 3σ significance at the $L_{int}$=2 ab$^{-1}$. 
For $t\rightarrow qZ$ analysis, the integrated luminosity versus branching $\text{BR}(t\rightarrow qZ)$ for top FCNC at $2\sigma$, $3\sigma$ and $5\sigma$ significance at the LHeC.

* Upper limits $\text{BR}(t\rightarrow qZ) = 4.0\times10^{-5}$ and $\text{BR}(t\rightarrow qZ) = 3.0\times10^{-5}$ for $2\sigma$ significance at the $L_{\text{int}}=1$ ab$^{-1}$ and $L_{\text{int}}=2$ ab$^{-1}$.
Number of events and statistical significance

The number of signal (S) and relevant background events ($B_W, B_H, B_Z, B_{tt}, B_{b jj}$) after each kinematic cuts in the analysis with $L_{\text{int}}=100$ fb$^{-1}$ at FCC-eh.

On the right (bottom) plot, the statistical significance ($S \times S$) depending on integrated luminosity for different anomalous FCNC couplings ($\lambda$) are shown for FCC-eh. The 2$\sigma$, 3$\sigma$ and 5$\sigma$ lines are also shown.
For **one-coupling** ($\lambda$ or $\kappa$) and **two-coupling** ($\lambda$ and $\kappa$) analysis, statistical significance (SS) depending on the integrated luminosity ($L_{\text{int}}$) ranging from 1 fb$^{-1}$ to 1 ab$^{-1}$ at the FCC-eh.
Results on couplings

On the right (bottom) plot, the integrated luminosity versus anomalous FCNC coupling ($\lambda$) at 2σ, 3σ and 5σ significance is shown for FCC-eh. We obtain an upper bound $\lambda=0.005$ (0.004) at $L_{\text{int}}=500/fb$ (1/ab) at 3σ significance level. These can be translated into the bound on branching ratios.

The results can be compared to the HL-LHC expected limits [cf. additional slides].
Limits on BR

The integrated luminosity versus branching (tqγ) for top FCNC at 2σ, 3σ and 5σ significance is shown at FCC-eh.

- Upper bounds on the branching ratio BR(t→qγ) for 1/ab and 2/ab are shown in the following Table.

<table>
<thead>
<tr>
<th></th>
<th>FCC-eh</th>
<th>2σ</th>
<th>3σ</th>
<th>5σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR(t→qγ) at L_int=1 ab⁻¹</td>
<td>1.5x10⁻⁶</td>
<td>2.2x10⁻⁶</td>
<td>4.1x10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>BR(t→qγ) at L_int=2 ab⁻¹</td>
<td>1.0x10⁻⁶</td>
<td>1.5x10⁻⁶</td>
<td>3.0x10⁻⁶</td>
<td></td>
</tr>
</tbody>
</table>

FCC-eh has the potential to discover new physics (significance 5σ) from anomalous FCNC tqγ couplings at an integrated luminosity of 10 ab⁻¹.
Summary of attainable limits for branching ratios of top quark FCNC decay channels at the future ep experiments (LHeC and FCC-eh) for a luminosity projection of 1 ab\(^{-1}\).

*The results for BR(t\(\rightarrow\)q\(\gamma\)) from arXiv:1701.06932 and arXiv:1705.05419, and BR(t\(\rightarrow\)qZ) from recent update.
We have studied tqγ and tqZ effective FCNC interaction vertices through the process e-p→e-Wq+X at future hadron electron colliders, namely LHeC and FCC-eh. We estimate the attainable range of parameters depending on the integrated luminosity, and we present contour plots of couplings according to different significance levels including detector simulation.

At the LHeC with $L_{\text{int}}=500\text{ fb}^{-1}$, we obtain attainable upper limits on the top quark FCNC couplings ($\lambda_u=0.01$ and $\lambda_c=0.03$) from the analysis of signal and background including detector effects through the fast simulation.

The top quark FCNC couplings ($\lambda_q=0.005$) can be searched at the level of significance $3\sigma$ with an integrated luminosity of 500 fb$^{-1}$ at FCC-he.

For comparison with top FCNC tqZ couplings at LHeC with $L_{\text{int}}=500\text{ fb}^{-1}$ (1 ab$^{-1}$), for equal coupling scenario $\kappa_q=\lambda_q$, we obtain upper limits of 0.007 (0.005), respectively.

The future ep colliders LHeC and FCC-ep with the high luminosity of 1 ab$^{-1}$ has the potential in probing the top FCNC couplings ($\lambda_u$, $\lambda_c$) and ($\kappa_u$, $\kappa_c$), corresponding to BR $\sim 10^{-5} - 10^{-6}$, which are better than the bounds from the HL-LHC.
Upper Limits on Branching Ratio for Top Quark FCNC (ATLAS+CMS)

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O. Cakir

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LHeC/FCCeh
Upper Limits on Branching Ratio for Top Quark FCNC

Branching fraction limits for top quark FCNC decays, compared to the SM predictions, as well as to various projections for future experiments. Experimental results are shown from (tgq), (tZq), (tγq), and (tHq). Projections are taken from [1-1, 1-2, 1-3](HL-LHC), [1-4, 1-5](LHeC), [1-6, 1-7](FCC), and [1-8](ILC).


arXiv:1711.01852v2 [hep-ex]