Top Quark Physics in FCC-ep

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OUTLINE

➤ Top Quark Weak Interactions
➤ Top Quark Anomalous Interactions
➤ Searches For Top Quark FCNC Interactions
➤ Conclusions
TOP QUARK PHYSICS

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

The single top quark production is about three times less frequent in the LHC collisions, as the production mechanism involves the electroweak interaction, while top pairs can be readily produced by strong interaction processes.

The future ep colliders offers excellent prospects for top physics.
Future ep collider is ideal to study CC interactions of the top quark via single production.
TOP QUARK ANOMALOUS INTERACTIONS

High precision measurements of $V_{tb}$ and search for anomalous $Wtb$ couplings

Sensitive search for FCNC couplings will constrain BSM models

Measurement of top isospin and anomalous $ttZ$ (EDM, MDM)

Measurement of top charge and anomalous $tty$ (EDM, MDM)
TOP QUARK ANOMALOUS INTERACTIONS

The updated plots for FCC-eh (a conservative estimate). The errors are systematically limited (assumed to be similar for LHeC and FCC-eh). A better sensitivity to the hadronic channel.

Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688
Kumar, Ruan, to be publ.
TOP EDM AND MDM

➢ the results can also be applied conservatively to the FCC-ep.

\[
\mathcal{L}_{t\bar{t}\gamma} = e\bar{t} \left( Q_t \gamma^\mu A_\mu + \frac{1}{4m_t^2} \sigma^{\mu\nu} F_{\mu\nu}(\kappa + i\kappa_5) \right) t
\]

electric dipole moment: \( \tilde{\kappa} \)

LHeC:
8% and 16% accuracy
10% 18%
→ systematically limited

27% accuracy (4.59fb\(^{-1}\), 7 TeV)

LHC with 5% accuracy

magnetic dipole moment: \( \kappa \)

TOP EDM AND MDM

Bouzas, Larios, 

<table>
<thead>
<tr>
<th>property</th>
<th>precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM: $\tilde{K} / \tilde{K}_Z$</td>
<td>0.20–0.28/0.6–0.8</td>
</tr>
<tr>
<td>MDM: $K / K_Z$</td>
<td>0.05–0.09/0.9–1.3</td>
</tr>
</tbody>
</table>

LHeC: 10% and 18% accuracy
MEASUREMENT OF $V_{tb}$

- the results can also be applied conservatively to the FCC-ep.


**LHeC, 100 fb$^{-1}$**

$1.000 \pm 0.005$ (expected)

**LHeC**: very high precision measurement

$|V_{tb}|$ = 1.009 $\pm$ 0.031
ANOMALOUS FCNC TOP-HIGGS COUPLINGS

- parametrised assumed resolutions for electrons/photons, muons, jets and unclustered energy using ATLAS values
- b-tag rate of 60%, c-jet fake rate of 10%, light-jet fake rate of 1%
- selections optimized for LHeC and FCC–ep scenarios ($s/\sqrt{(S+B)}$)
- cut-based and MVA-based analyses

**Signal**

- $e^- p \rightarrow \nu_e \bar{t} \rightarrow \nu_e h q \rightarrow \nu_e b \bar{b} q$, $q = u, c$

**Background**

**Irreducible backgrounds:**
- $e^- p \rightarrow \nu_e (h \rightarrow b \bar{b}) j$
- $e^- p \rightarrow \nu_e (z \rightarrow b \bar{b}) j$
- $e^- p \rightarrow \nu_e (g \rightarrow b \bar{b}) j$

**Reducible backgrounds:**
- $e^- p \rightarrow \nu_e j j j$
- $e^- p \rightarrow \nu_e j j b/\bar{b}$
- $e^- p \rightarrow \nu_e \bar{t}$
- $e^- p \rightarrow e^+ j j j$
- $e^- p \rightarrow e^+ j j b/\bar{b}$
- $e^- p \rightarrow e^+ (g \rightarrow b \bar{b}) j$
ANOMALOUS FCNC TOP-HIGGS COUPLINGS

FCC–ep

C. Schwanenberger
@ICHEP2016
UPPER LIMITS ON BRANCHINGS

ATLAS, 4.7(20.3)fb⁻¹@7(8)TeV
CMS, 19.5 fb⁻¹@8TeV
LHC, 3000 fb⁻¹@14TeV

\[ \text{Upper limit of } Br(t \rightarrow hu) \approx 0.074\% \]
\[ Br(t \rightarrow hu) = 0.044\% \]
\[ Br(t \rightarrow hu) = 0.022\% \]

→ improves sensitivity of HL-LHC
The top quark FCNC interactions would be a good test of new physics at present and future colliders. These interactions can be described by the effective Lagrangian

\[
\mathcal{L}_{FCNC} = \sum_{q=u,c} \frac{g_s}{2m_t} \bar{q} \lambda^a \sigma^{\mu\nu} (\zeta_{qt}^L P^L + \zeta_{qt}^R P^R) t G^a_{\mu\nu} - \frac{1}{\sqrt{2}} \bar{q} (\eta_{qt}^L P^L + \eta_{qt}^R P^R) t H - \\
- \frac{g_W}{2c_W} \bar{q} \gamma^\mu (X_{qt}^L P^L + X_{qt}^R P^R) t Z_\mu + \frac{g_W}{4c_W m_Z} \bar{q} \sigma^{\mu\nu} (K_{qt}^L P^L + K_{qt}^R P^R) t Z_{\mu\nu} + \\
+ \frac{e}{2m_t} \bar{q} \sigma^{\mu\nu} (\lambda_{qt}^L P^L + \lambda_{qt}^R P^R) t A_{\mu\nu} + H.c.
\]

» J.A.A-S, NPB812(2009)181
Process $e-p \rightarrow (e^-t + e^+t^-)$. Signal cross sections at FCC-ep collider depending on FCNC $tq\gamma$ couplings $\lambda_u$ and $\lambda_c$ within the range $[-0.1 : 0.1]$.

$FCC$-$ep$: $E_e=60 \text{ GeV}, E_p=50 \text{ TeV}$

PDF: NNPDF2.3

$\sigma (\text{pb})$

$\lambda_u$

$\lambda_c$

- $FCC$-$ep$: cross section $\sigma_u/\sigma_c=3.27$ at $\lambda_q=0.1$
- Sensitivity $\lambda_u/\lambda_c \sim 1.8$

The cross section depends on $\lambda_u$ and $\lambda_c$ with different strength due to proton pdf, one obtain more sensitivity to $\lambda_c$ at FCC-ep than LHeC.

For an estimation with overall acceptance of $A=0.01$ for the final state, contour lines can cover at least 10 signal events at $1 \text{ ab}^{-1}$. 
DIAGRAMS FOR SIGNAL \((e^-p \rightarrow e^-W^+q+X)\)

+ similar diagrams for \(tc\gamma\)

- further diagrams for process \(e^-p \rightarrow e^-W^-q+X\) with the interchange \(q \leftarrow \rightarrow q^-\)
Cross sections (pb) for process $e^- p \rightarrow e^- w w ~ q$ (where $ww=W^+\ or\ W^-\ and\ q\ contains\ all\ quarks\ other\ than\ top\ quark)$ at FCC-ep. The last row presents the results for the case of $\lambda_c=\lambda_u=\lambda$.

<table>
<thead>
<tr>
<th>FCC-ep (60x50000)</th>
<th>$\lambda=10^{-1}$</th>
<th>$\lambda=10^{-2}$</th>
<th>$\lambda=10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>coupling $(tuy)$</td>
<td>$1.072 \times 10^1$</td>
<td>$8.565 \times 10^0$</td>
<td>$8.589 \times 10^0$</td>
</tr>
<tr>
<td>coupling $(tcy)$</td>
<td>$9.243 \times 10^0$</td>
<td>$8.539 \times 10^0$</td>
<td>$8.534 \times 10^0$</td>
</tr>
<tr>
<td>coupling $(tuy, tcy)$</td>
<td>$1.151 \times 10^1$</td>
<td>$8.641 \times 10^0$</td>
<td>$8.613 \times 10^0$</td>
</tr>
</tbody>
</table>
We study signal and background

➤ calculate cross sections with MadGraph5 importing topFCNC_UFO model including CKM matrix elements

➤ set Pythia6

➤ use delphes_card_FCC file and test new delphes_card_FCCep_PK_V2_1 file

➤ analyse events with Root6

➤ evaluate signal significance for FCNC couplings
For the analysis, after pre-selection cuts, we use the analysis cuts for further background suppression

- **Cut-0**: at least one electron and three jets (pre-selection with default MG5 cuts)
- **Cut-1**: require one of three jets as being b-tag
- **Cut-2**: b-tagged jet has transverse momentum $p_T > 35$ GeV and other jets have $p_T > 25$ GeV, and electron has $p_T > 20$ GeV
- **Cut-3**: all jets have pseudo-rapidity $-5.0 < \eta < 0$; and electron has $-2.5 < \eta < 2.5$
- **Cut-4**: invariant mass of two jets within $50 < m_{jj} < 90$ GeV (for W-boson)
- **Cut-5**: invariant mass of three jets (for top) between $130 < m_{bjj} < 200$ GeV
The $p_T$ and eta distributions of three jets events for signal + background.
Electron $p_T$ and eta distributions
Frame of cuts and comparison of signal and background invariant mass distributions

- Signal+Background
- Background

- $M_W = 80.385$ GeV
- $M_{top} = 173.21$ GeV

- $M_{jj}^{(GeV)}$
- $M_{jjj}^{(GeV)}$
FCC-EP : IN Variant Mass Plot

- Top mass reconstruction after each cut applied.
➤ Top mass reconstruction after each cut applied.
Top mass reconstruction from S+B and B events and the ratio plot of (S+B)/B. It is clear from the left and right panel of the figure that there is different sensitivity to FCNC coupling in the vertices $tu\gamma$ and $tc\gamma$. 
FCC-EP: \((S+B)/B\) AND SUM OF RELEVANT BACKGROUNDS

\[
\lambda_c = \lambda_u = 0.03
\]

Cross sections\((\sigma)\):
\[
\begin{align*}
\sigma_W &= 8.611 \text{ pb} \\
\sigma_H &= 0.074 \text{ pb} \\
\sigma_Z &= 0.617 \text{ pb} \\
\sigma_{tt} &= 0.415 \text{ pb}
\end{align*}
\]

- \(S: ep \rightarrow eWj\)
- \(B_W: ep \rightarrow eWj\)
- \(B_Z: ep \rightarrow eZj\)
- \(B_H: ep \rightarrow eHj\)
- \(B_{tt}: ep \rightarrow ett\)

➤ with the relevant backgrounds, the ratio \((S+B)/B\) decreases a factor of \(3/7\) at top mass
FCC-EP : SENSITIVITY TO COUPLINGS

➤ Sensitivity to different couplings depending on integrated luminosity

➤ Sensitivity to equal couplings depending on integrated luminosity

2σ significance:

λ_u=0.01 for L_{int}=40/fb.

λ_c=0.01 for L_{int}=60/fb.

λ_q=0.01 for L_{int}=7/fb.
Statistical significance \( SS = \sqrt{2[(S+B_T)\ln(1+S/B_T)-S]} \) for \( e^-p->e^-+j_{btag}+2j \) with \( tq\gamma \) FCNC interactions. Here, we assume equal coupling scenario \( \lambda_u=\lambda_c=\lambda \).

\[ \lambda=0.1 \quad \lambda=0.05 \quad \lambda=0.03 \quad \lambda=0.01 \quad \lambda=0.007 \]

\( S \) vs \( L_{\text{int}}(\text{fb}^{-1}) \)

- 3\( \sigma \) significance at \( \lambda_q=0.01 \) for \( L_{\text{int}}=40/\text{fb.} \)
- compare with LHeC when \( \lambda_q=0.01 \) for \( L_{\text{int}}=80/\text{fb.} \)

All relevant backgrounds \( (B_T) \) are included.
Using top quark FCNC decay widths and total decay width we can calculate the branchings $\text{BR}(t \rightarrow q\gamma)$ vs coupling $\lambda$. With all the relevant backgrounds, we find $3\sigma$ signal significance results to reach an upper limit $\lambda=0.01$, with an integrated luminosity of 40 fb$^{-1}$ at FCC-ep and 80 fb$^{-1}$ at LHeC. This limit on coupling can also be translated to the branching ratio $\text{BR}(t \rightarrow q\gamma) = 2 \times 10^{-5}$.

**Decay widths:**

\[
\Gamma(t \rightarrow q\gamma) = \frac{\alpha}{8} \lambda_q^2 m_t
\]

\[
\Gamma(t \rightarrow bW) = \frac{\alpha}{16 \sin^2 \theta_W} |V_{tb}|^2 \frac{m_t^3}{m_w^2} \times \left[ 1 - 3 \frac{m_w^4}{m_t^4} + 2 \frac{m_w^6}{m_t^6} \right]
\]

**Branching:**

\[
\text{BR}(t \rightarrow q\gamma) = \frac{\Gamma(t \rightarrow q\gamma)}{\Gamma(t \rightarrow bW) + \Gamma(t \rightarrow u\gamma) + \Gamma(t \rightarrow c\gamma)}
\]
Based on proton-proton collisions at 8 TeV within the CMS detector at the LHC at an integrated luminosity of 19.8 fb\(^{-1}\), the limits (95% CL) on the top quark FCNC couplings

\[
\mathcal{L}_{\text{eff}} = -eQ_t \sum_{q=u,c} \overline{q} \frac{i \sigma^{\mu\nu} q_\nu}{\Lambda} (\kappa_{tq\gamma}^L P_L + \kappa_{tq\gamma}^R P_R) t A_\mu + h.c.,
\]

\[
\text{BR}(t \rightarrow u\gamma) = 1.7 \times 10^{-4}
\]

\[
\text{BR}(t \rightarrow c\gamma) = 2.2 \times 10^{-3}
\]

CMS Collab. JHEP04(2016)035
CONCLUSION

- Future ep collider has a rich physics programme for electroweak interactions of top quarks
- Top anomalous couplings can be measured down to $10^{-2}$ at the FCC-ep
- We study S+B and B for process $e^- p \rightarrow e^- \text{ww} q \text{NP}=1$ (where $\text{ww}=\text{W}^+ \text{or W}^-)$
- For detector simulation we use Delphes card `delphes_card_FCC`, we have some tests for the new `delphes_card_FCCeh_V2_1` card
- For analysis, we use cut based method, top mass reconstruction and W mass reconstruction
- $(S+B)/B$ ratio plot for different couplings ($\lambda_u$, $\lambda_c$)
- Study on different backgrounds ($e\text{Wq}$, $e\text{Zq}$, $e\text{Hq}$, $e\text{tt}$)
- SS vs integrated luminosity plot for different coupling parameters
- Branching vs coupling plot and conversion, comments on the limits.
Future ep colliders

LHeC
7 TeV proton of LHC and 60 GeV electron ($\sqrt{s} \sim 1.3$ TeV)

FCC-eh
50 TeV proton of FCC and 60 GeV electron ($\sqrt{s} \sim 3.5$ TeV)

Both plan to create new electron facility