Top Quark Physics

O. Cakir (AU)*

*on behalf of top physics group of LHeC/FCC-eh

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Outline

- A short introduction
- Top quark CC and NC interactions
- Probing top FCNC tqγ and tqZ couplings at future hadron electron colliders
- Summary and Conclusions
Introduction

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

Top quark anomalous CC/NC Interactions

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

2. Measurement of top charge/isospin and anomalous $tty/ttZ$ (EDM, MDM)

3. Search for anomalous top-Higgs couplings

4. Sensitive search for FCNC couplings will constrain BSM models
Top quark CC Interactions

The CKM matrix element $V_{tb}$ can be measured with a precision of 0.5%.

* results can also be applied conservatively to the FCC-eh

$\Delta |V_{tb}| \cdot 1000$

LHeC: $100 \text{ fb}^{-1}$

$|V_{tb}| = 1.000 \pm 0.005$

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O. Cakir
Top quark CC Interactions

Measuring CKM Vtx (x=d,s) at electron-proton collider

H. Sun

A global CKM fit
\[ |V_{tb}| = 1 - 8.81^{+0.12}_{-0.24} \times 10^{-3} \]
\[ |V_{ts}| = 41.08^{+3.0}_{-5.7} \times 10^{-3} \]
\[ |V_{td}| = 8.575^{+0.076}_{-0.098} \times 10^{-3} \]
Top quark anomalous CC/NC 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.
Top quark Yukawa interactions


**Top Yukawa coupling**

Introduce phase dependent top Yukawa coupling

\[ \mathcal{L} = -i \frac{m_t}{v} \bar{t} [\cos \zeta_t + i \gamma_5 \sin \zeta_t] t h \]

Enhancement of the cross-section as a function of phase

Observe/Exclude non-zero phase to better than $4\sigma$ at LHeC. Achieve <2% error on $k_t$ at the FCC-eh.
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 (tqγ, tqZ, tqg and tqh) can be described by the effective Lagrangian

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

We study FCNC tqγ and tqZ vertices at LHeC and FCC-eh.
The SM predictions at loop level for the branching fractions of FCNC processes as $t \rightarrow \gamma u(c)$ and $t \rightarrow Zu(c)$ are of the order of $10^{-16}(10^{-14})$ and $10^{-17}(10^{-14})$, respectively [*]. Therefore, an observation of the large FCNC induced couplings would indicate the existence of the BSM.

It is notable that even at the future upgrades of the LHC, these bounds would not be improved considerably. For example, the upper bounds on $\text{BR}(t \rightarrow qZ)$ and $\text{BR}(t \rightarrow q\gamma)$ have been predicted to be about $10^{-4}$ for $q = c$ and about $10^{-5}$ for $q = u$ with the integrated luminosity of $3 \text{ ab}^{-1}$ at the HL-LHC [*].

<table>
<thead>
<tr>
<th>Branchings</th>
<th>SM (loop level)</th>
<th>BSM (lowest rate)</th>
<th>ATLAS</th>
<th>CMS**</th>
<th>HL-LHC (3 ab$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \rightarrow u\gamma$</td>
<td>$4 \times 10^{-16}$</td>
<td>$10^{-8}$ (MSSM)</td>
<td>$&lt;1 \times 10^{-4}$</td>
<td>$&lt;1.3 \times 10^{-4}$</td>
<td>$&lt;2.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>$t \rightarrow c\gamma$</td>
<td>$5 \times 10^{-14}$</td>
<td>$10^{-7}$ (2HDM)</td>
<td>$&lt;1 \times 10^{-4}$</td>
<td>$&lt;1.7 \times 10^{-3}$</td>
<td>$&lt;2.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>$t \rightarrow uZ$</td>
<td>$7 \times 10^{-17}$</td>
<td>$1 \times 10^{-6}$ (RPV)</td>
<td>$&lt;2 \times 10^{-4}$</td>
<td>$&lt;1.7 \times 10^{-4}$</td>
<td>$&lt;7.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>$t \rightarrow cZ$</td>
<td>$1 \times 10^{-14}$</td>
<td>$1 \times 10^{-6}$ (2HDM,RPV)</td>
<td>$&lt;2 \times 10^{-4}$</td>
<td>$&lt;2.0 \times 10^{-4}$</td>
<td>$&lt;7.0 \times 10^{-5}$</td>
</tr>
</tbody>
</table>


Signal Cross Sections

Cross section (in pb) for e-p—>(e-t+e-t~)X

<table>
<thead>
<tr>
<th>LHeC</th>
<th>$\lambda_q=0$</th>
<th>$\lambda_q=0.01$</th>
<th>$\lambda_q=0.02$</th>
<th>$\lambda_q=0.03$</th>
<th>$\lambda_q=0.05$</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>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>

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>8.106 x 10^{-3}</td>
<td>5.161 x 10^{-3}</td>
<td>5.150 x 10^{-3}</td>
</tr>
<tr>
<td>$\lambda_u = 10^{-3}$</td>
<td>3.032 x 10^{-3}</td>
<td>8.132 x 10^{-5}</td>
<td>5.142 x 10^{-5}</td>
</tr>
<tr>
<td>$\lambda_u = 0$</td>
<td>2.957 x 10^{-3}</td>
<td>2.973 x 10^{-5}</td>
<td>0</td>
</tr>
</tbody>
</table>
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.
**Process:** $e^- p -> e^- W^\pm q + X$

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 $e^- p \rightarrow e^- W^\pm q + X$. 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 $e^- p \rightarrow e^- W^\pm q + X$ with quarks $q \leftrightarrow \bar{q}$. 

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**

**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 $130 < m_{b\ell j} < 200$ GeV
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 $L_{\text{int}} = 100 \text{ fb}^{-1}$.

<table>
<thead>
<tr>
<th>$\lambda_u$</th>
<th>$\lambda_c = 0$</th>
<th>$\lambda_c = 0.01$</th>
<th>$\lambda_c = 0.03$</th>
<th>$\lambda_c = 0.05$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_u = 0$</td>
<td>584 (149)</td>
<td>592</td>
<td>609</td>
<td>640</td>
</tr>
<tr>
<td>$\lambda_u = 0.01$</td>
<td>617</td>
<td>621</td>
<td>692</td>
<td>763</td>
</tr>
<tr>
<td>$\lambda_u = 0.03$</td>
<td>943</td>
<td>969</td>
<td>1003</td>
<td>1209</td>
</tr>
<tr>
<td>$\lambda_u = 0.05$</td>
<td>1502</td>
<td>1744</td>
<td>1758</td>
<td>1792</td>
</tr>
</tbody>
</table>
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.
Statistical significance

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

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 $3\sigma$) these couplings at $L_{\text{int}}=70$ fb$^{-1}$. For a higher luminosity of 500 fb$^{-1}$ (1 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

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

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

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

- Upper bounds on the branching ratios for $1/ab$ are shown in Table.

<table>
<thead>
<tr>
<th>LHeC $L_{int}=1$ ab$^{-1}$</th>
<th>2\sigma</th>
<th>3\sigma</th>
<th>5\sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR($t\rightarrow u\gamma$)</td>
<td>4.0x$10^{-6}$</td>
<td>7.5x$10^{-6}$</td>
<td>1.5x$10^{-5}$</td>
</tr>
<tr>
<td>BR($t\rightarrow c\gamma$)</td>
<td>4.0x$10^{-5}$</td>
<td>9.0x$10^{-5}$</td>
<td>2.0x$10^{-4}$</td>
</tr>
</tbody>
</table>
Number of events and statistical significance

The number of signal (S) and relevant background events (B\(_W\), B\(_H\), B\(_Z\), B\(_{tt}\), B\(_{bjj}\)) after each kinematic cuts in the analysis with \(L_{\text{int}}=100 \text{ fb}^{-1}\) at FCC-eh.

On the right (bottom) plot, the statistical significance (SS) 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-parameter ($\lambda$ or $\kappa$) and two-parameter ($\lambda$ and $\kappa$) analysis, statistical significance (SS) depending on the integrated luminosity ($L_{\text{int}}$) ranging from $1 \text{ fb}^{-1}$ to $1 \text{ ab}^{-1}$ at the FCC-eh.
Results on couplings

On the right (bottom) plot, the integrated luminosity versus anomalous FCNC coupling ($\lambda$) at 2$\sigma$, 3$\sigma$ and 5$\sigma$ 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 3$\sigma$ 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].
Luminosity vs 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 are shown in the following Table.

<table>
<thead>
<tr>
<th>FCC-eh</th>
<th>2σ</th>
<th>3σ</th>
<th>5σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>L_{int}=1 \text{ ab}^{-1}</td>
<td>1.5x10^{-6}</td>
<td>2.2x10^{-6}</td>
<td>4.1x10^{-6}</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}.
Conclusion

Future ep colliders has a rich physics program for top quark. Single top quark measurements, |V_{tb}| (<1%), top quark couplings to electroweak bosons (Wtb, ttγ, ttZ, ttH), anomalous couplings, FCNC, CP violation in top-Yukawa, …

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_{int}=500 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_{int}=500 fb^{-1} (1 ab^{-1}), for equal coupling scenario \kappa_q=\lambda_q, we obtain upper limits of 0.007 (0.005).

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 can be comparable or even better than the bounds from the HL-LHC.
Comments on lower energy (electron beam) run

- **LHeC** with $E_e=40$ GeV / 60 GeV and $E_p=7$ TeV

<table>
<thead>
<tr>
<th>LHeC</th>
<th>Cross section (pb)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_u$</td>
<td>$E_e=40$ GeV</td>
<td>$E_e=60$ GeV</td>
</tr>
<tr>
<td>0.05</td>
<td>1.699</td>
<td>2.519</td>
</tr>
<tr>
<td>0.03</td>
<td>1.597</td>
<td>2.378</td>
</tr>
<tr>
<td>0.01</td>
<td>1.546</td>
<td>2.307</td>
</tr>
</tbody>
</table>

- **FCC-eh** with $E_e=40$ GeV / 60 GeV and $E_p=50$ TeV

<table>
<thead>
<tr>
<th>FCC-eh</th>
<th>Cross section (pb)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_q$</td>
<td>$E_e=40$ GeV</td>
<td>$E_e=60$ GeV</td>
</tr>
<tr>
<td>0.1</td>
<td>8.449</td>
<td>11.510</td>
</tr>
<tr>
<td>0.03</td>
<td>6.451</td>
<td>8.932</td>
</tr>
<tr>
<td>0.01</td>
<td>6.240</td>
<td>8.641</td>
</tr>
</tbody>
</table>
Current and expected upper limits on tqγ couplings at 95% CL

<table>
<thead>
<tr>
<th></th>
<th>LHC (CMS Obs. Limit at 19.8/fb)*</th>
<th>HL-LHC (Expec. Limit at 500/fb)**</th>
<th>LHeC (500/fb)***</th>
<th>FCC-eh (500/fb)***</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(t\rightarrow u\gamma)$</td>
<td>1.3x10^{-4}</td>
<td>4.5x10^{-5}</td>
<td>1.2x10^{-5}</td>
<td>2.5x10^{-6} $(\lambda_u=\lambda_c)$</td>
</tr>
<tr>
<td>$B(t\rightarrow c\gamma)$</td>
<td>1.7x10^{-3}</td>
<td>3.0x10^{-4}</td>
<td>7.6x10^{-5}</td>
<td>2.5x10^{-6} $(\lambda_u=\lambda_c)$</td>
</tr>
</tbody>
</table>

* Current experimental limit on tqγ, 1511.03951[hep-ex].  
** Expected limits for HL-LHC, CMS DP-2016-064.  
FCNC Branching Ratios at Colliders

E_e=60 GeV  
1000 fb^{-1}  

MVA  
LHeC  
FCC-ep  
LHeC  
cut-based

Plot by C Schwanenberger

- improve limits on BR(t\rightarrow\gamma u), BR(t\rightarrow Hu) considerably

→ test SUSY, little Higgs, technicolor...
Experimental limits on \( t \tau q \gamma \) and \( t \tau q Z \)

The measured upper limits on \( B(t \rightarrow qZ) \) versus \( B(t \rightarrow q\gamma) \) from different experiments. The two vertical dashed lines show recent results (\( L_{\text{int}}=19.8/\text{fb} \)) of the analysis of CMS experiment [CMS Collaboration, JHEP04 (2016) 035].
The expected sensitivities on tqγ and tqZ couplings at ATLAS for HL-LHC (including previous limits on tqγ and tqZ).

The present 95% CL. observed limits on the $BR(t\rightarrow q\gamma)$ vs. $BR(t\rightarrow qZ)$ plane are shown as full lines for the LEP, ZEUS, H1, D0, CDF, ATLAS and CMS collaborations. The expected sensitivity at ATLAS is also represented by the dashed lines. For an integrated luminosity of $L_{int} = 3000$ fb$^{-1}$ the limits range from $1.3\times10^{-5}$ to $2.5\times10^{-5}$ ($4.1\times10^{-5}$ to $7.2\times10^{-5}$) for the $t\rightarrow q\gamma$ ($t\rightarrow qZ$) decay. Limits at $L_{int} = 300$ fb$^{-1}$ are also shown [ATLAS Collaboration, ATL-PHYS-PUB-2013-007].