Top Quark FCNC tqγ and tqZ Couplings 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

Outline

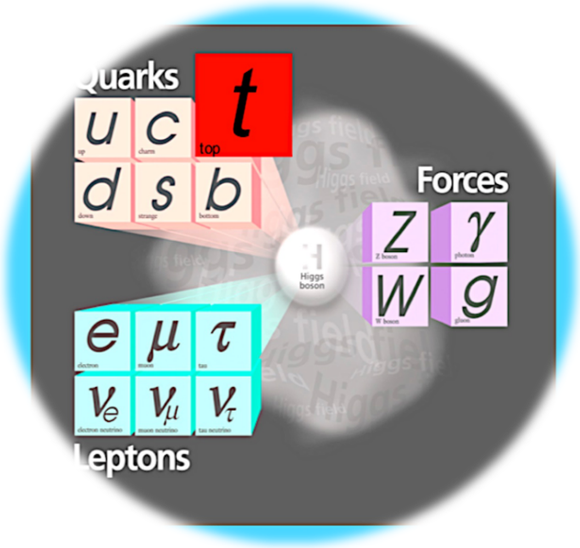
- A short introduction
- Top quark FCNC tqγ and tqZ couplings
- Decay widths and branching ratio
- Production cross sections
- Kinematical distributions
- Statistical analysis
- Limits on couplings and branchings
- Summary and conclusions

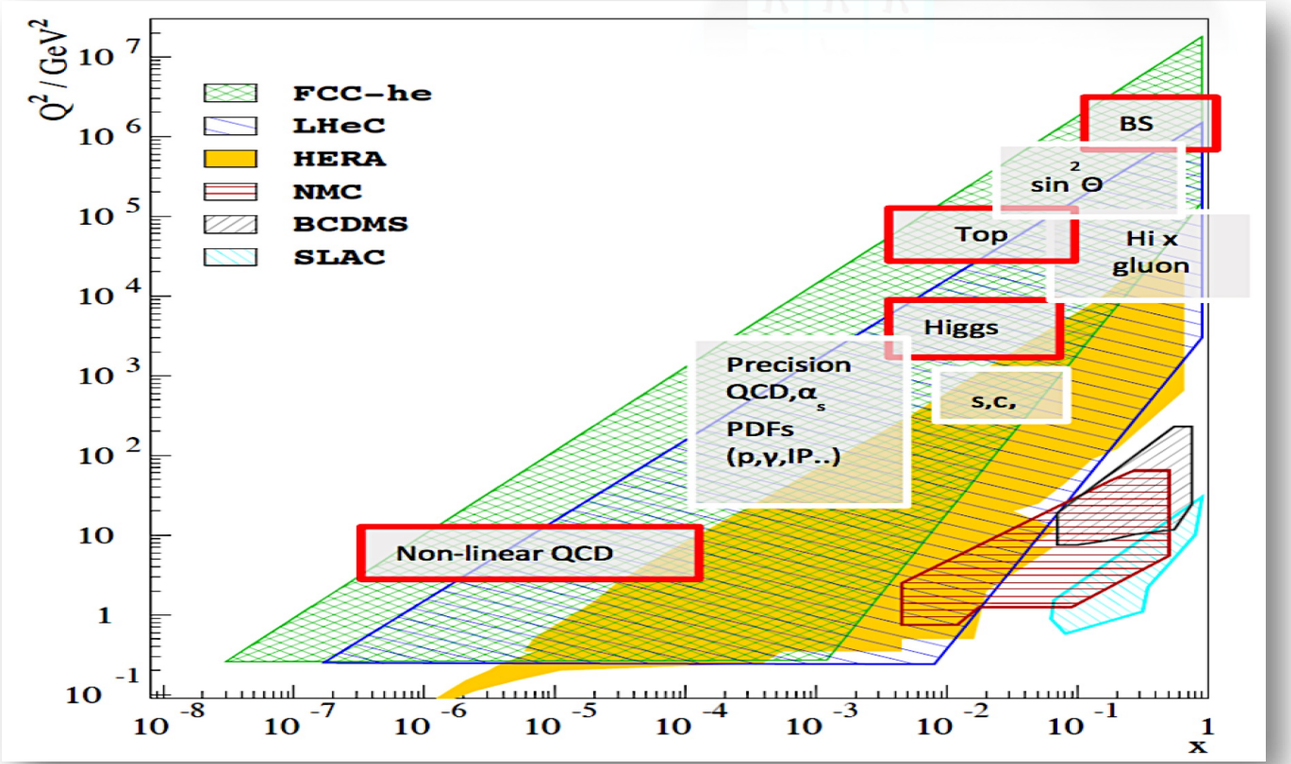
Introduction

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 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.





O. Bruning *et al.*, PoS EPS-HEP2015 (2015) 520

Top Quark FCNC tqγ and tqZ Couplings

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

$$\mathcal{L}_{FCNC} = \sum_{q=u,c} \frac{g_s}{2m_t}\bar{q}\lambda^a\sigma^{\mu\nu}(\zeta^L_{qt}P^L + \zeta^R_{qt}P^R)tG^a_{\mu\nu} - \frac{1}{\sqrt{2}}\bar{q}(\eta^L_{qt}P^L + \eta^R_{qt}P^R)tH -$$
$$-\frac{g_W}{2c_W}\bar{q}\gamma^\mu(X^L_{qt}P_L + X^R_{qt}P_R)tZ_\mu + \frac{g_W}{4c_W m_Z}\bar{q}\sigma^{\mu\nu}(K^L_{qt}P_L + K^R_{qt}P_R)tZ_{\mu\nu} +$$
$$+\frac{e}{2m_t}\bar{q}\sigma^{\mu\nu}(\lambda^L_{qt}P_L + \lambda^R_{qt}P_R)tA_{\mu\nu} + H.c.$$

LH coupling

RH coupling

scaled to top mass

Madgraph5: topFCNC_UFO from FeynRules

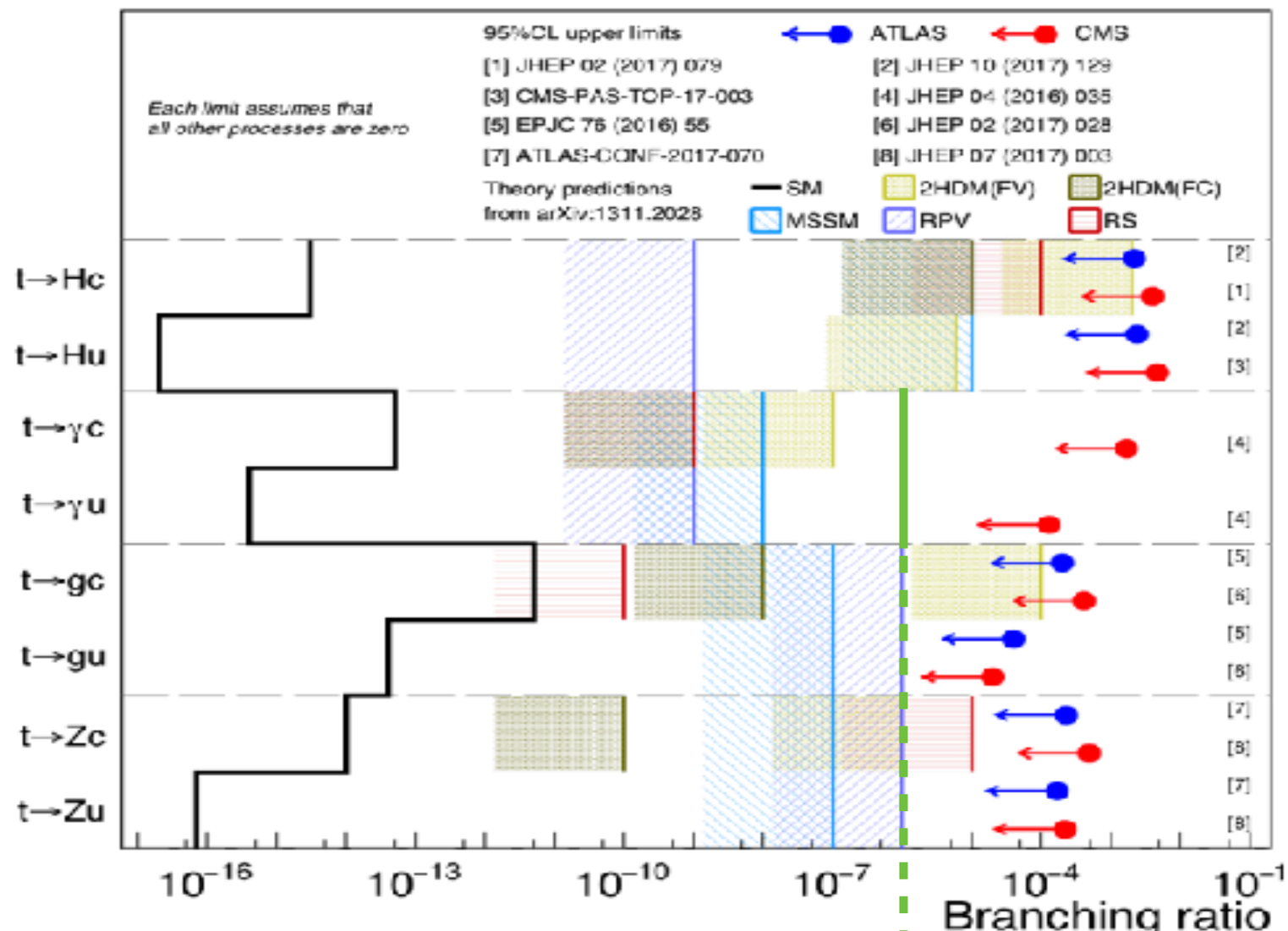
➤ *NPB 812(2009)181*

- We study FCNC tqγ and tqZ vertices at LHeC and FCC-eh

Upper Limits on Branchings

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.

arXiv:1711.01852v2 [hep-ex]



*** HL-LHC estimates at 3 ab^{-1}:**

BR(t→qγ) < 2.5x10^{-5} and BR(t→qZ) < 7.0x10^{-5} for q = u,c.

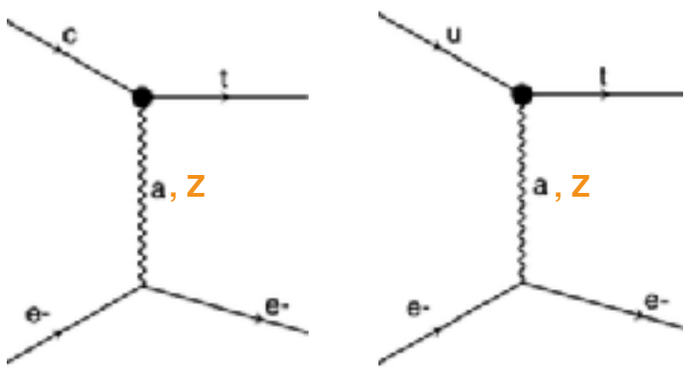
FCC-eh reach at 2 ab^{-1}

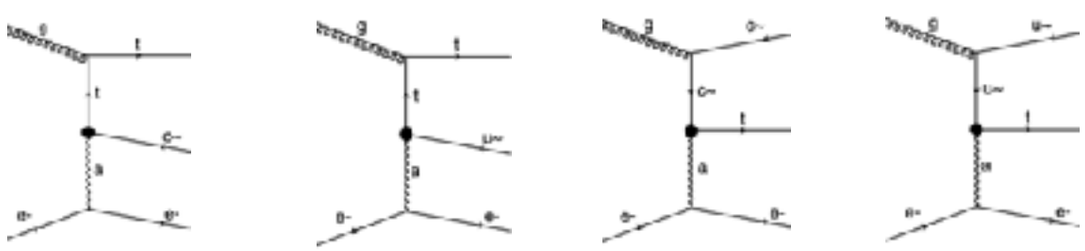
[*] M.L.Mangano et al., arXiv:1607.01831 [hep-ph]

Signal Cross Sections

Production cross sections

LHeC	λ_q=0	λ_q=0.01	λ_q=0.02	λ_q=0.03	λ_q=0.05
κ_q=0	0	9.450×10^{-3}	2.360×10^{-2}	8.050×10^{-2}	2.213×10^{-1}
κ_q=0.01	4.300×10^{-3}	1.360×10^{-2}	3.650×10^{-2}	8.520×10^{-2}	2.268×10^{-1}
κ_q=0.02	1.350×10^{-2}	3.900×10^{-2}	5.050×10^{-2}	9.570×10^{-2}	2.387×10^{-1}
κ_q=0.03	2.860×10^{-2}	4.060×10^{-2}	6.660×10^{-2}	1.123×10^{-1}	2.559×10^{-1}
κ_q=0.05	7.820×10^{-2}	8.850×10^{-2}	1.173×10^{-1}	1.639×10^{-1}	3.082×10^{-1}





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

LHeC	$\lambda_c = 10^{-2}$	$\lambda_c = 10^{-3}$	$\lambda_c = 0$
$\lambda_u = 10^{-2}$	9.468×10^{-3}	8.368×10^{-3}	8.357×10^{-3}
$\lambda_u = 10^{-3}$	1.188×10^{-3}	9.460×10^{-5}	8.365×10^{-5}
$\lambda_u = 0$	1.103×10^{-3}	1.104×10^{-5}	0

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

FCC-he	$\lambda_c = 10^{-2}$	$\lambda_c = 10^{-3}$	$\lambda_c = 0$
$\lambda_u = 10^{-2}$	3.238×10^{-2}	2.490×10^{-2}	2.488×10^{-2}
$\lambda_u = 10^{-3}$	7.834×10^{-3}	3.243×10^{-4}	2.480×10^{-4}
$\lambda_u = 0$	7.576×10^{-3}	7.580×10^{-5}	0

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

FCC-he	$\lambda_c = 10^{-2}$	$\lambda_c = 10^{-3}$	$\lambda_c = 0$
$\lambda_u = 10^{-2}$	8.106×10^{-3}	5.161×10^{-3}	5.150×10^{-3}
$\lambda_u = 10^{-3}$	3.032×10^{-3}	8.132×10^{-5}	5.142×10^{-5}
$\lambda_u = 0$	2.957×10^{-3}	2.973×10^{-5}	0

Signal Cross Sections

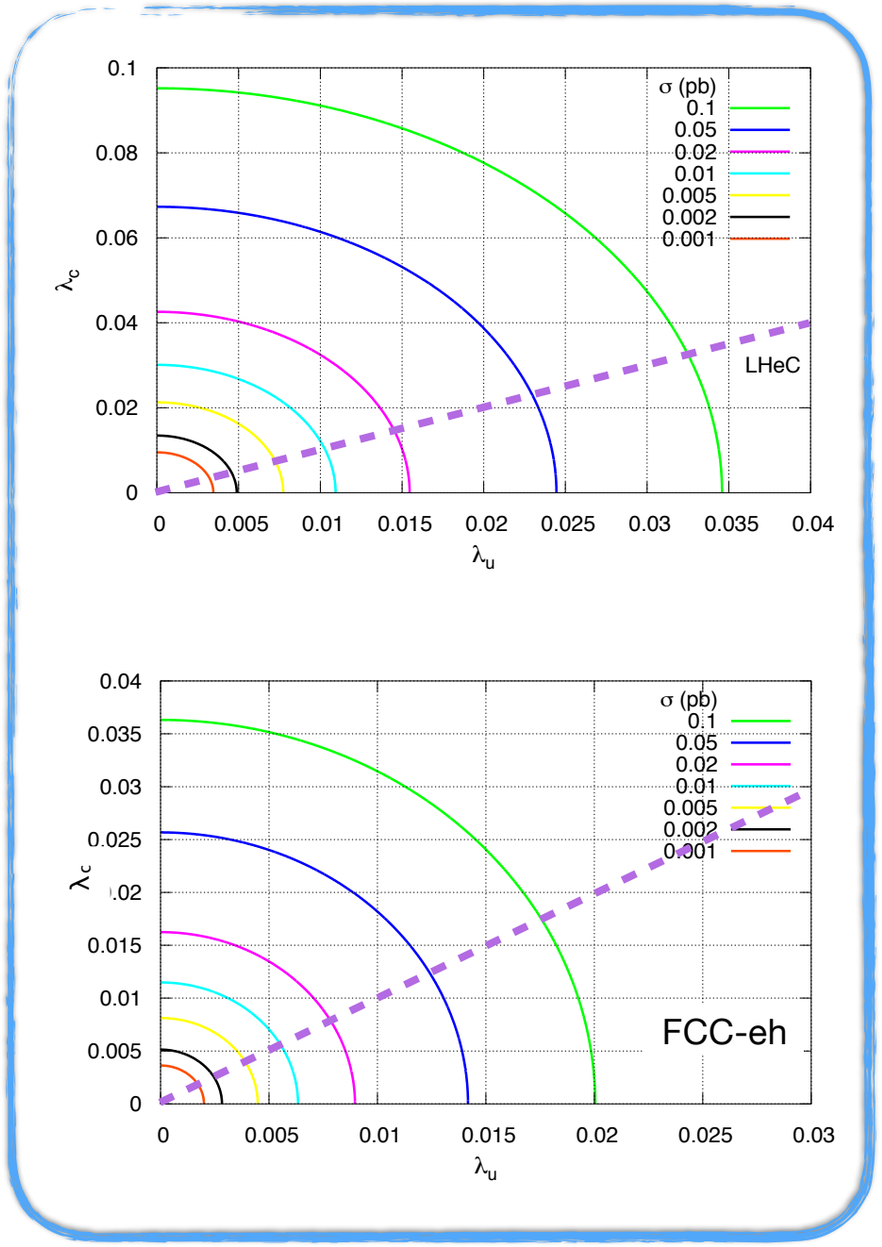
Signal process studied: $e^- p \to e^- W^\pm q + X$

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 λ_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 section depending on two couplings (λ_u, λ_c):
$\sigma(\lambda_u,\lambda_c)=a\lambda_u^2+b\lambda_c^2+c\lambda_u\lambda_c$



Signal Cross Sections

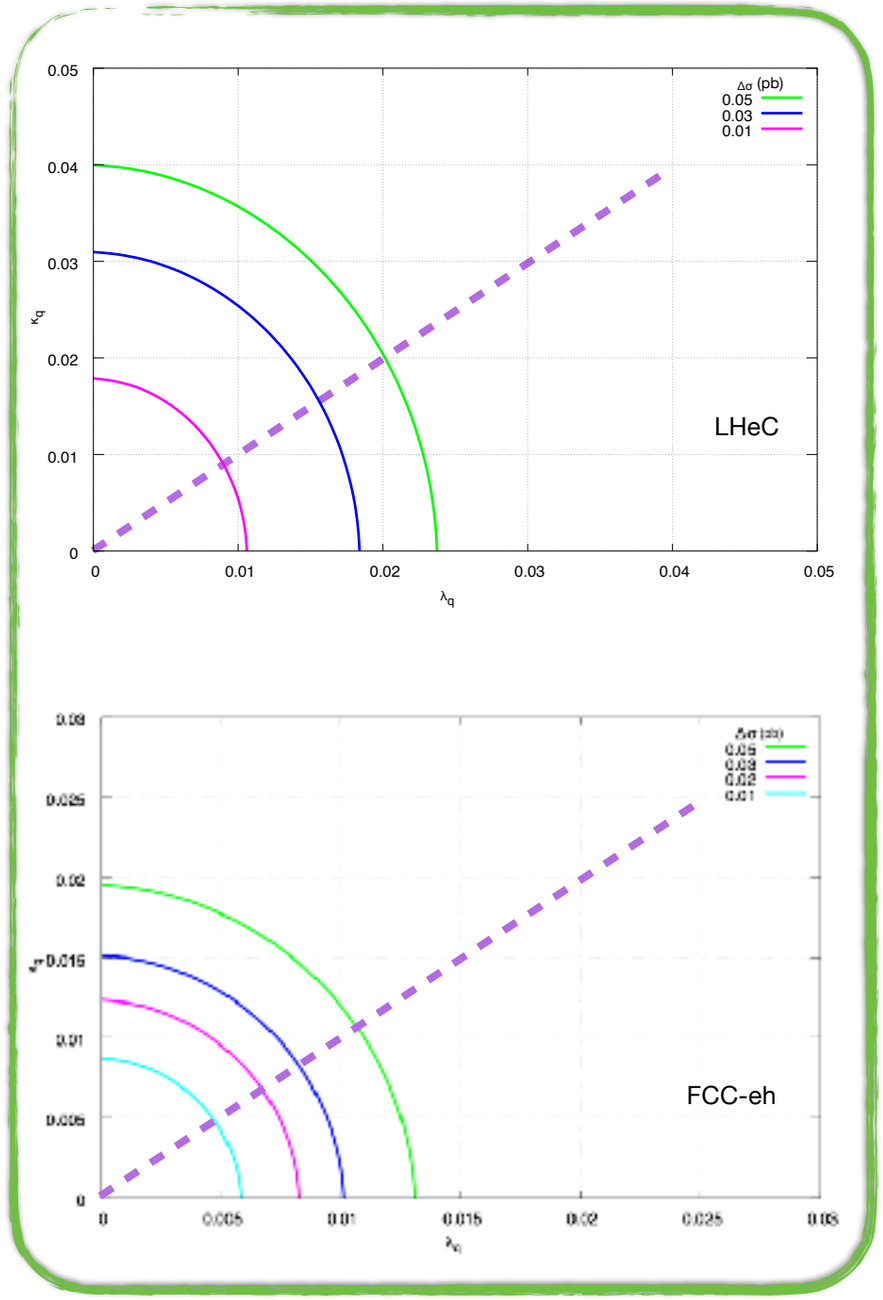
Signal cross section depending on two couplings (λ, κ):
$\sigma(\lambda,\kappa)=a\lambda^2+b\kappa^2+c\lambda\kappa$

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

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 λ_q is more emphasized.

- For coupling κ_q = 0.02, corresponding signal cross section values are 15 fb at **LHeC** and 50 fb at **FCC-eh**.

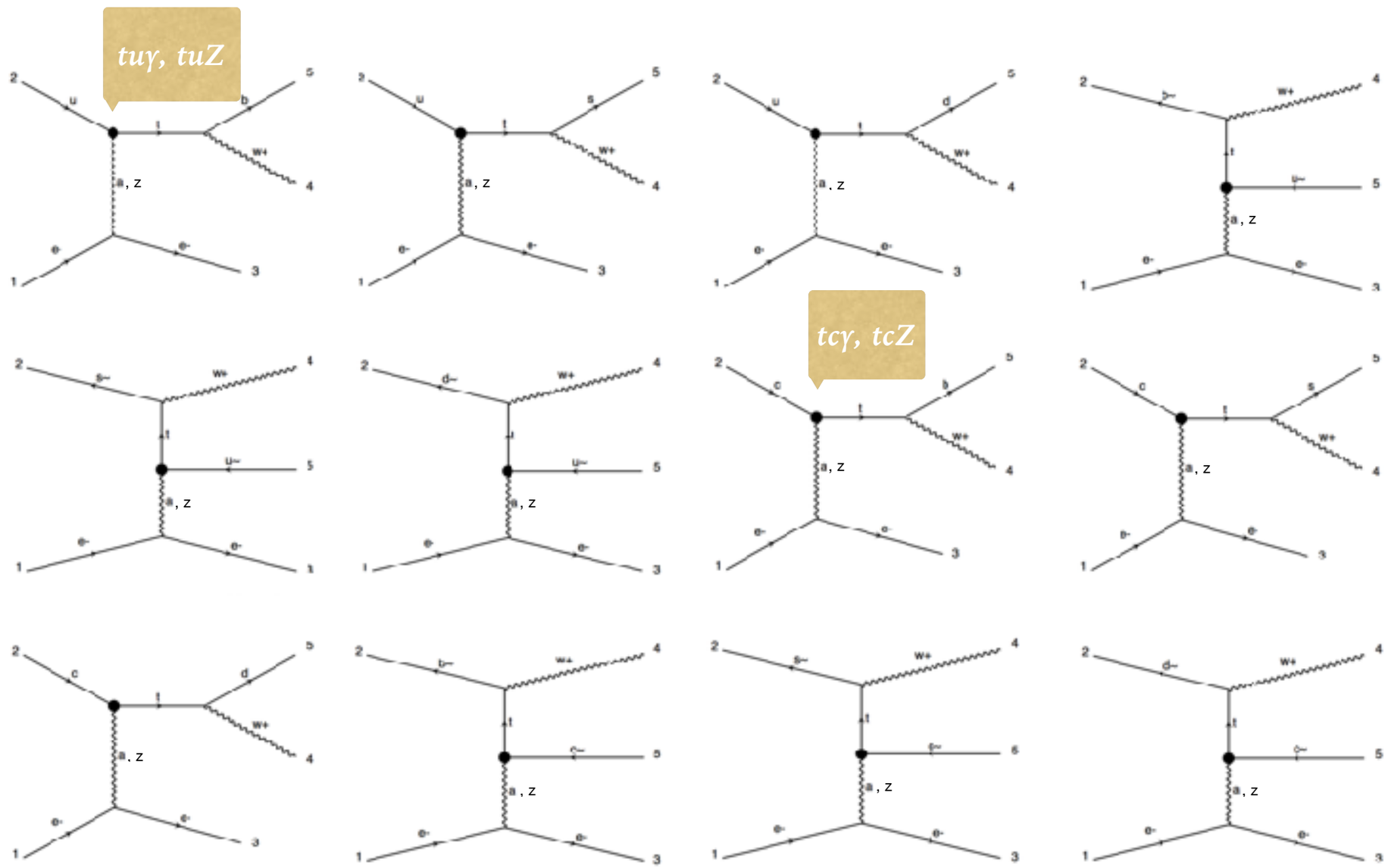


Diagrams for Signal

Analysis is based on the process $e^- p \to e^- W^\pm q + X$.
Only the signal diagrams are shown. Here, no specific chirality is assumed for FCNC tqγ 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 $e^- p \to e^- W^- q+X$ with quarks $q \leftrightarrow q\sim$.

We use **MadGraph 5** for event generation, **Pythia 6** for hadronization and decay, **Delphes 3.3** for detector simulation, **Root 6** for analysis.



Analysis

For the analysis, after pre-selection cuts, we use the analysis cuts for further background suppression.

Event Generation
Top FCNC model
(MadGraph5)

↓

Hadronization
(Pythia6)

↓

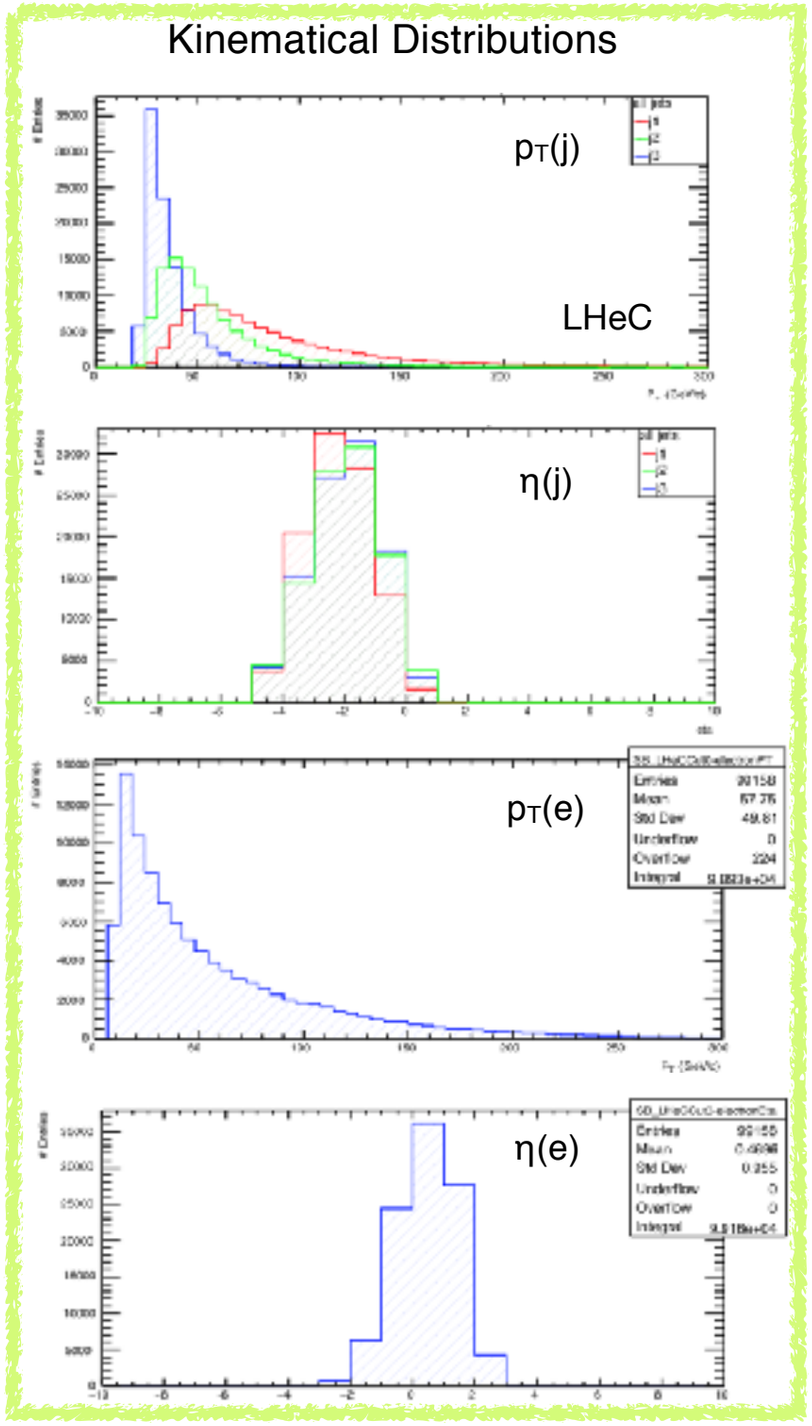
Fast Detector Simulation
(Delphes)

↓

Event Analysis
(Root6)

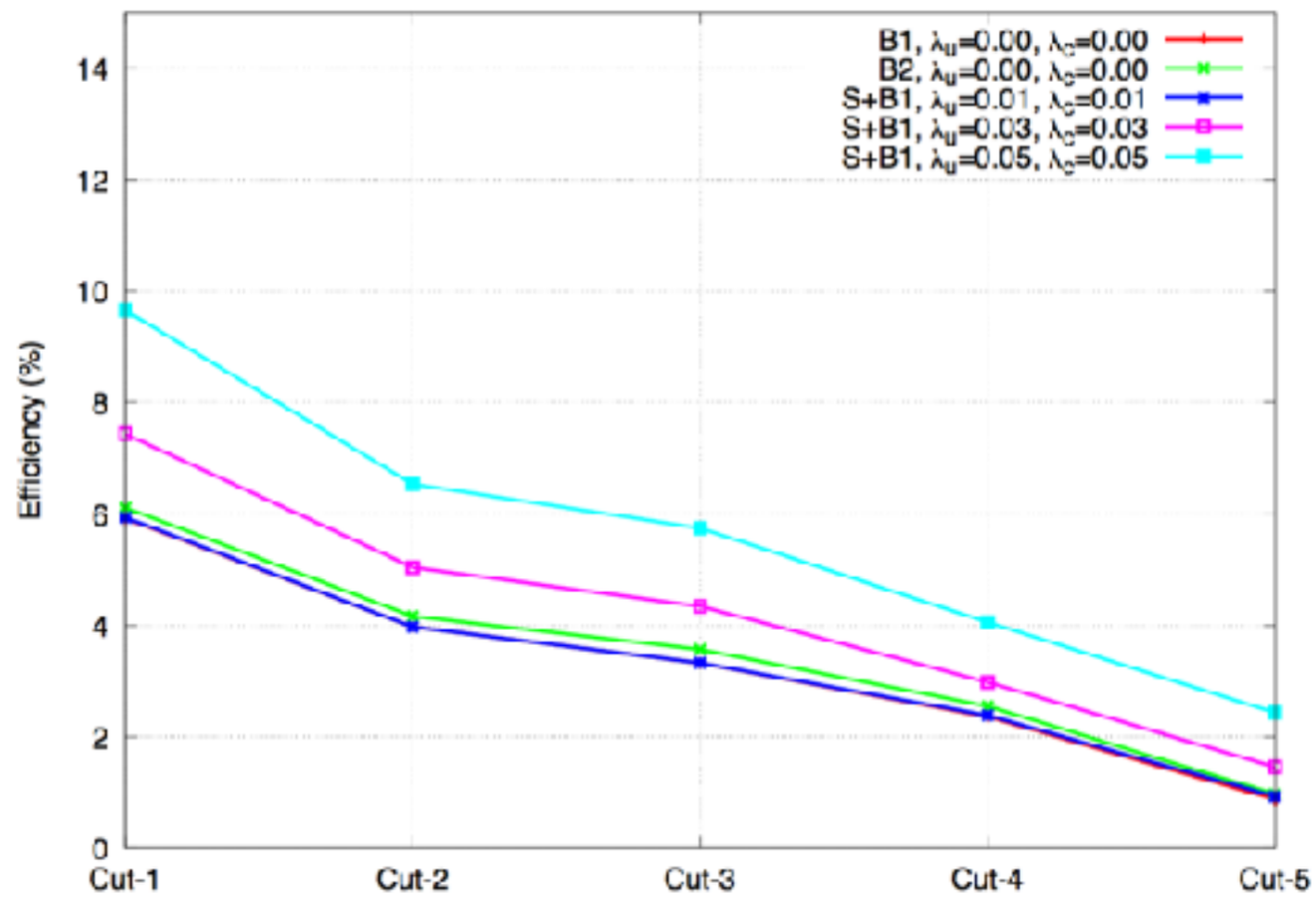
cut flow

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<η<0 ; and electron has -2.5<η<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



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.



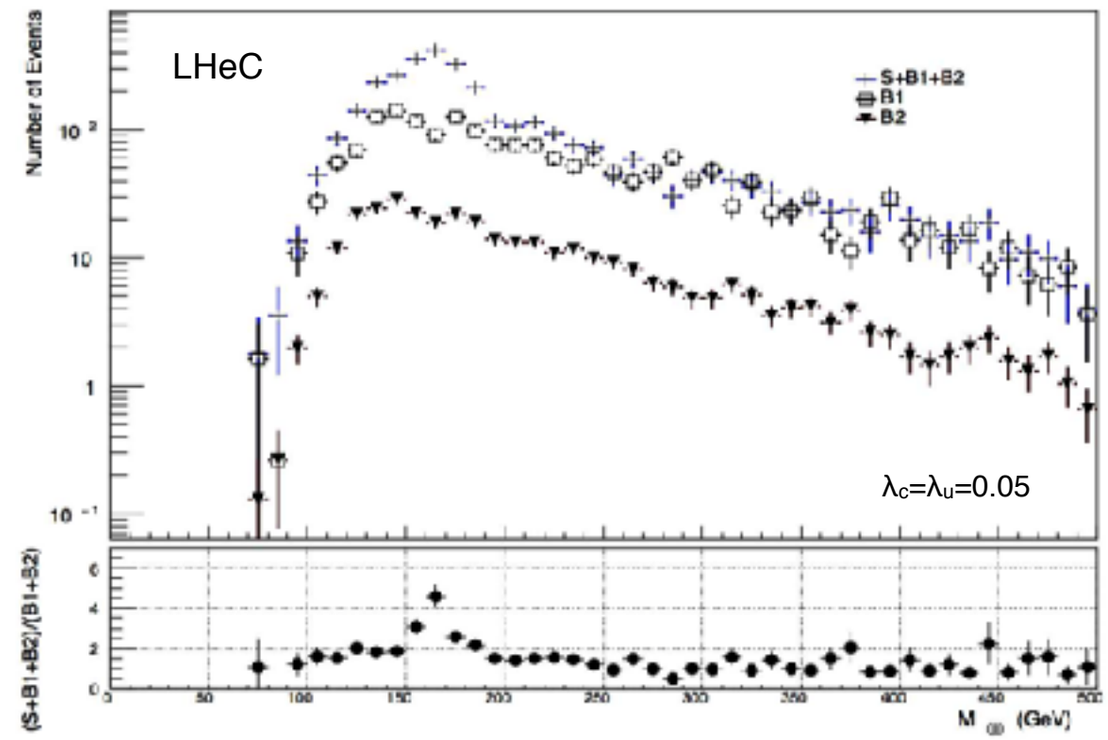
The number of events (N) for background B1 (B2), and signal for different values of λ_u and λ_c at LHeC with L_{int} = 100 fb^{-1}.

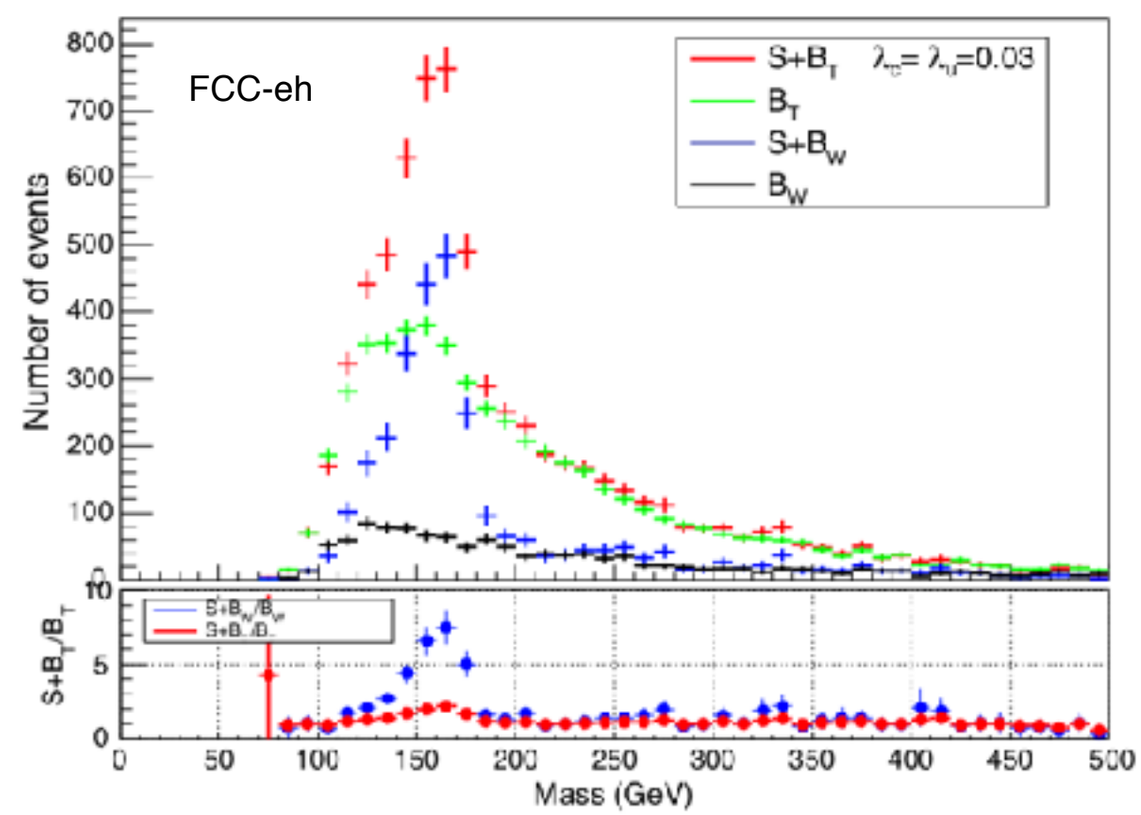
N(100/fb)	$\lambda_c = 0$	$\lambda_c = 0.01$	$\lambda_c = 0.03$	$\lambda_c = 0.05$
$\lambda_u = 0$	584 (149)	592	609	640
$\lambda_u = 0.01$	617	621	692	763
$\lambda_u = 0.03$	943	969	1003	1209
$\lambda_u = 0.05$	1502	1744	1758	1792

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.

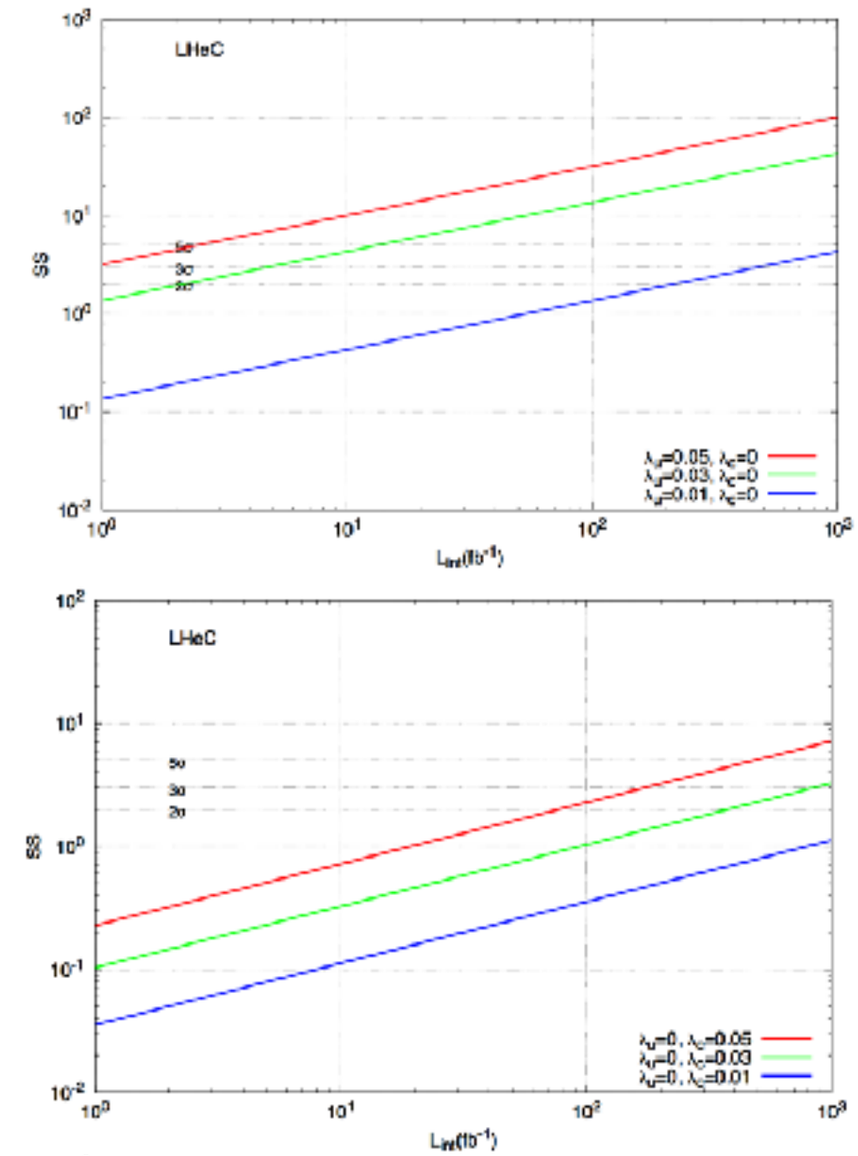




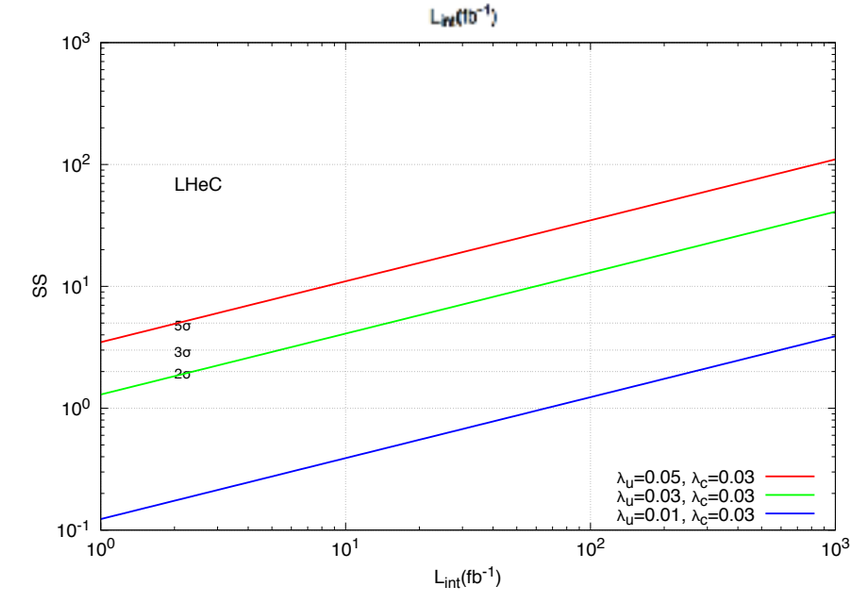
Statistical Significance

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

Estimated statistical significance (SS) reach of flavor changing neutral current **tuγ coupling** (λ_u) and **tcγ coupling** (λ_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 2σ, 3σ and 5σ lines are also shown.

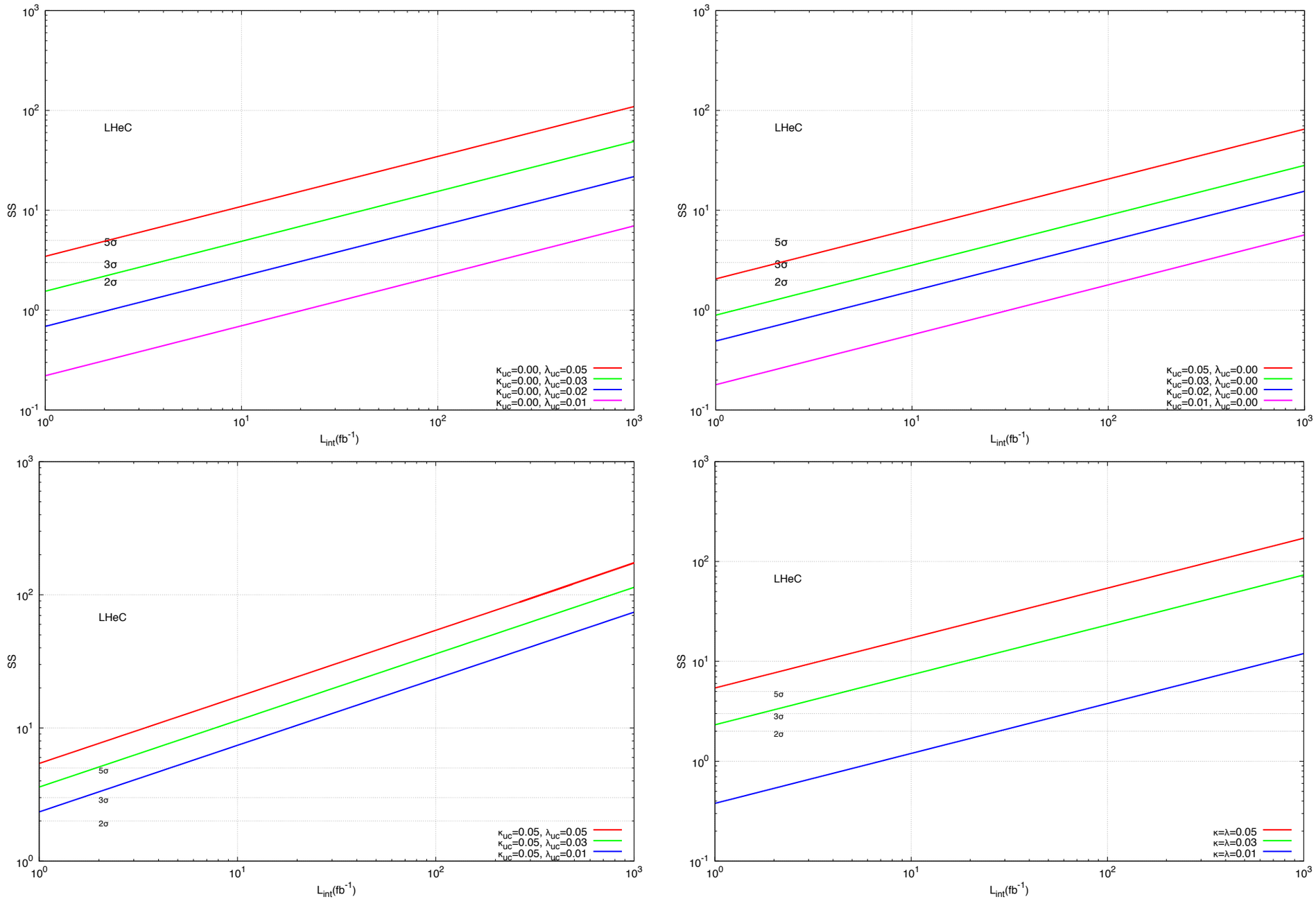


The SS reach for the flavor changing neutral current **tcγ coupling** (λ_c) depending on the integrated luminosity at the LHeC.



Results

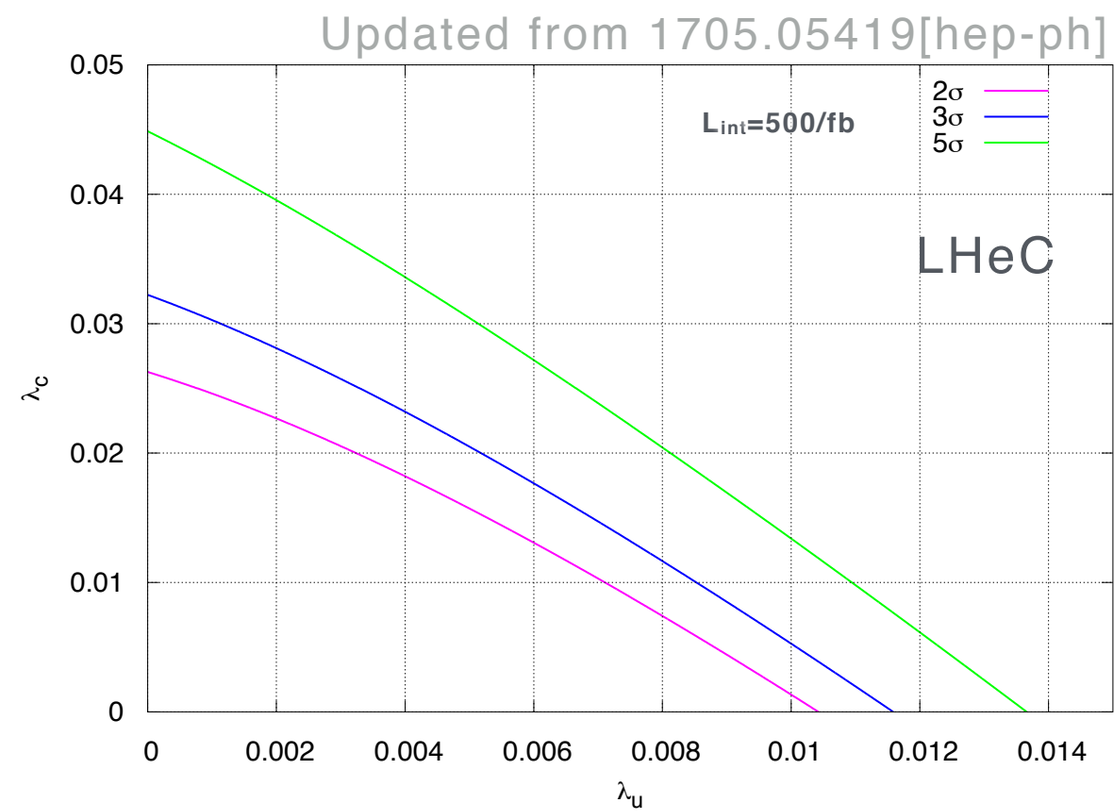
For equal couplings scenario $\kappa_q=\lambda_q=0.01$, the LHeC can probe (with 3σ) these couplings at $L_{int}=70$ fb^{-1}. For a higher luminosity of 500 fb^{-1} (1 ab^{-1}), we have the limit for coupling $\kappa_q=\lambda_q=0.007$ (0.005).

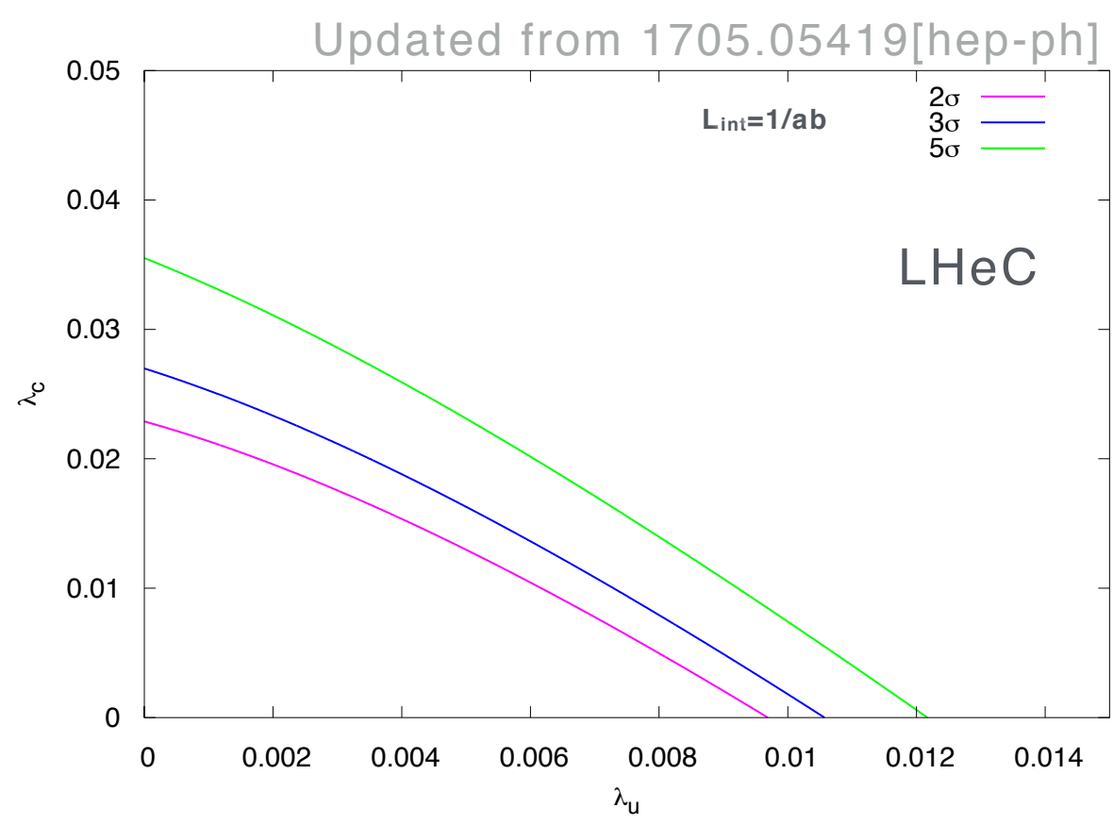


Results on couplings

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

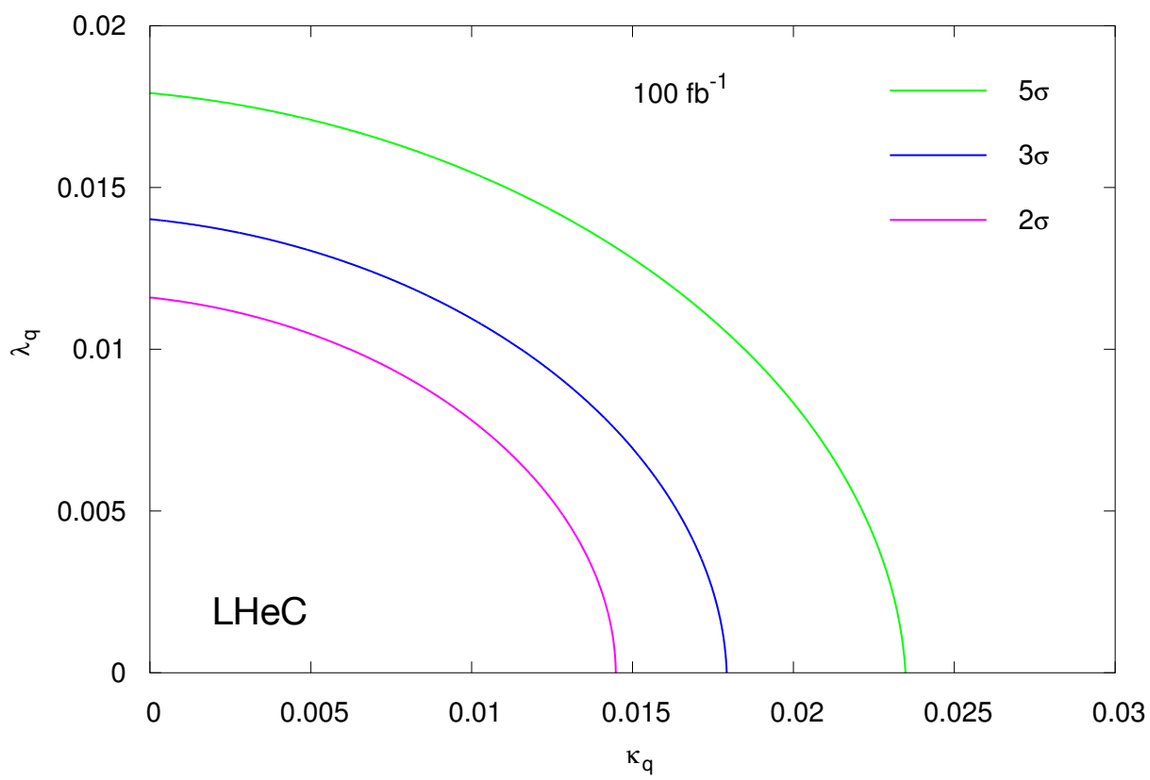
The results can be compared to the HL-LHC expected limits [cf. additional slides].



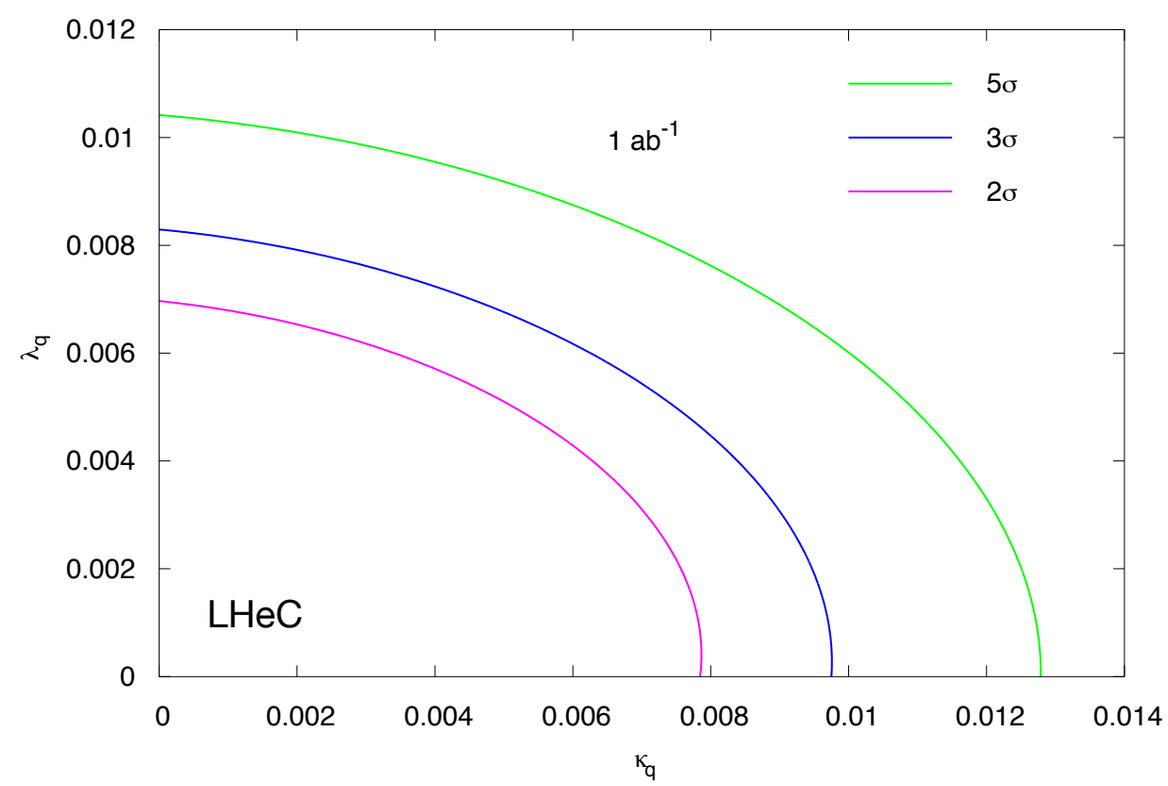


LHeC

Contour plot from the analysis



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



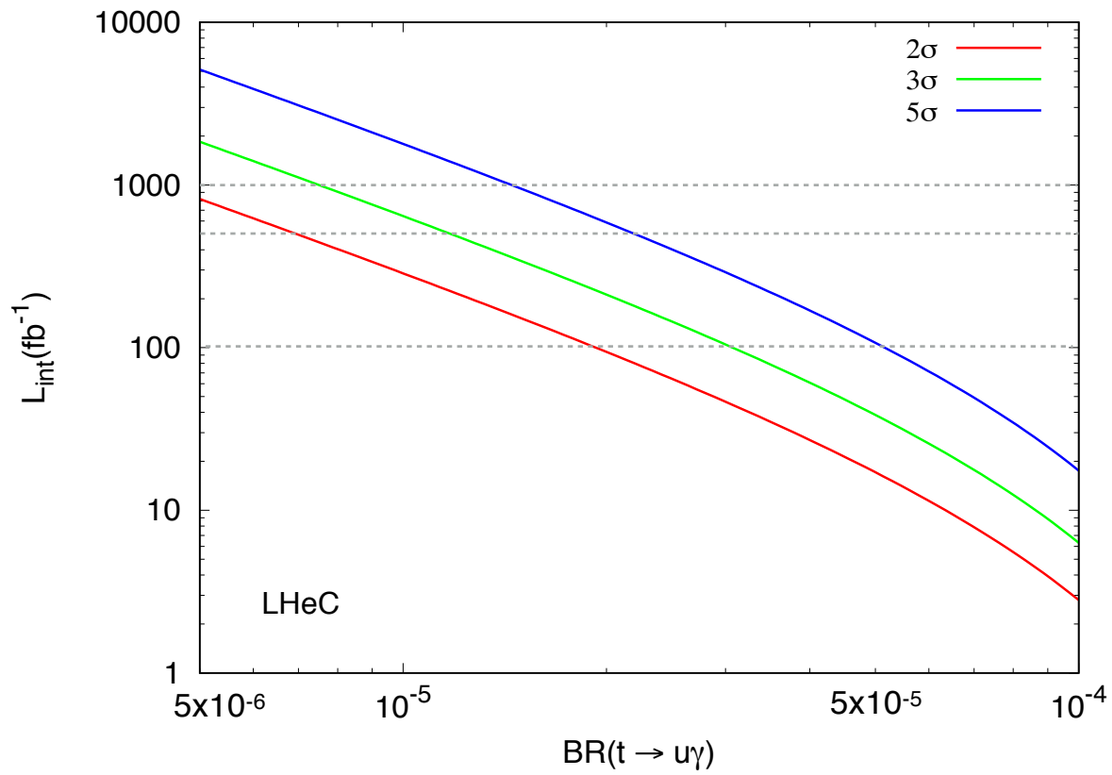
It is found that sensitivity to couplings λ_q (vertex tqγ) is better than κ_q (vertex tqZ) at LHeC.

Luminosity vs Branchings

Limits on Branchings

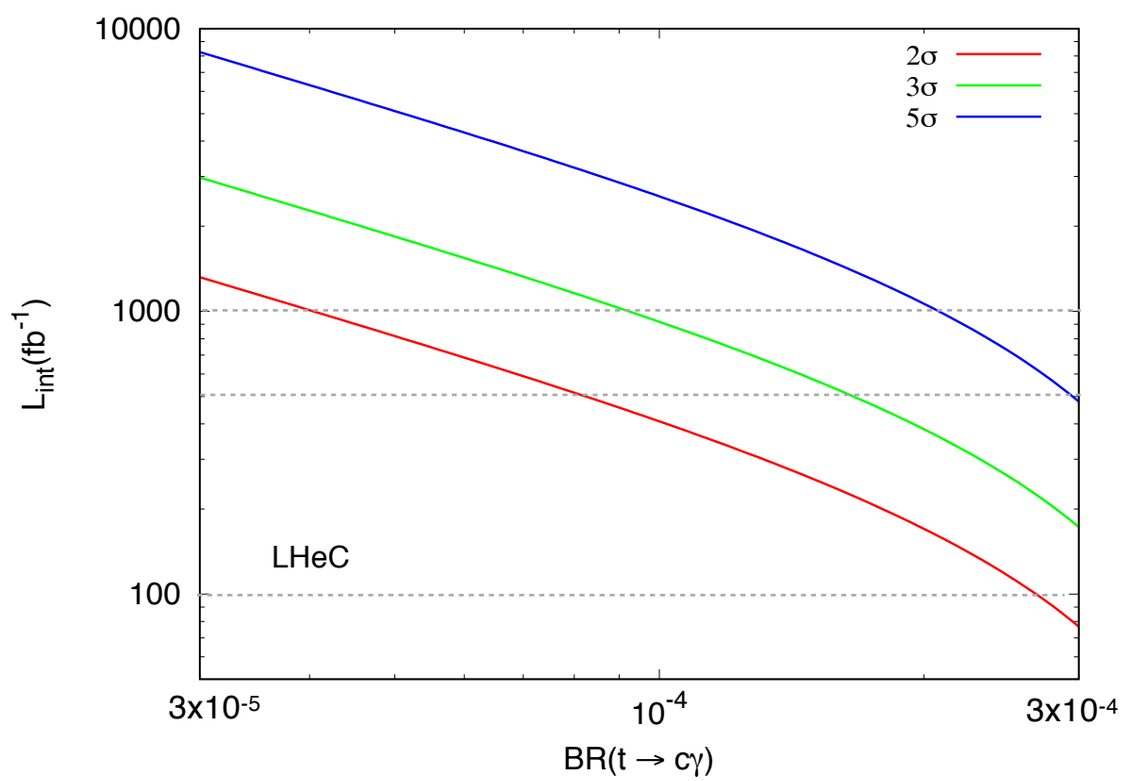
Integrated luminosity versus branching ratio plot for top FCNC (tqγ) at 2σ, 3σ and 5σ significance at LHeC.

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



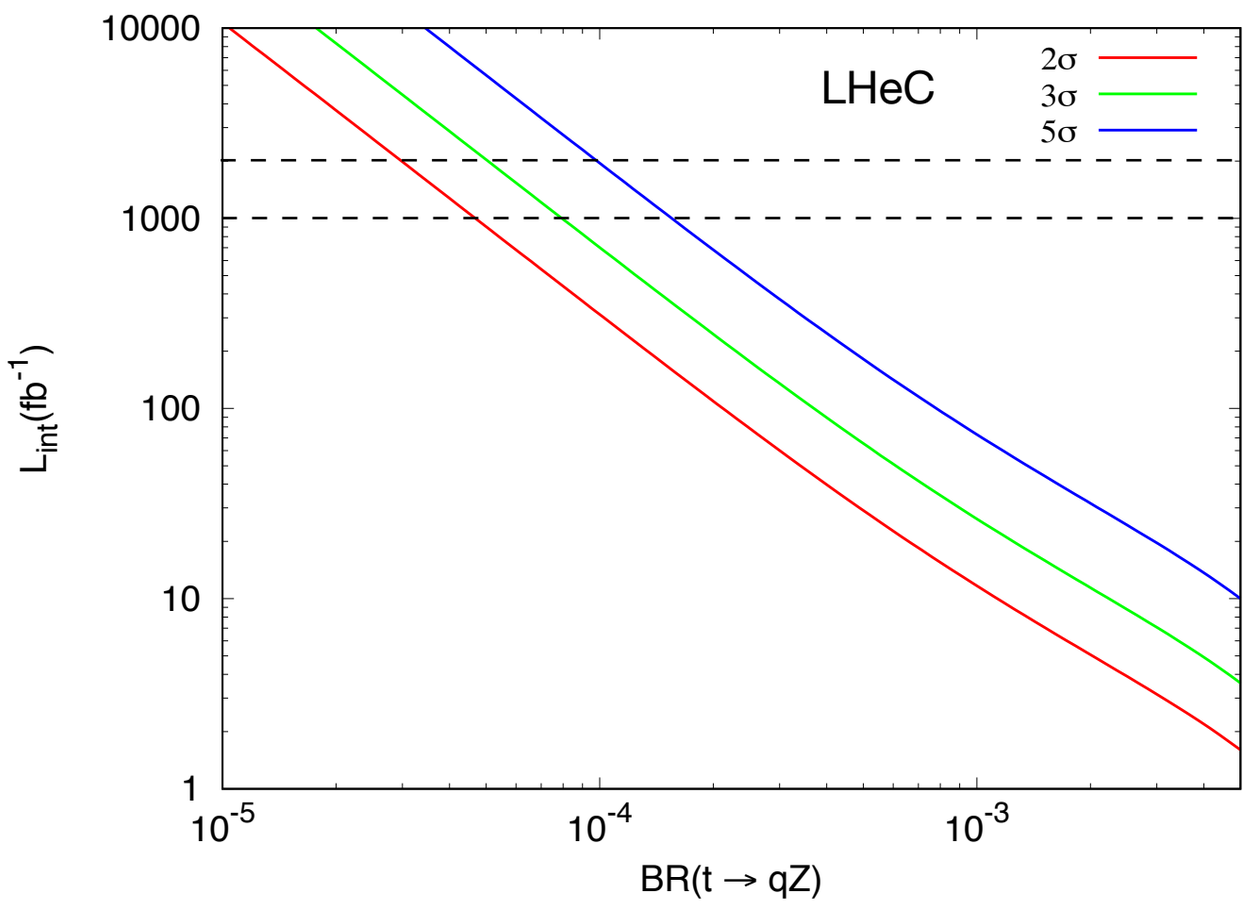
LHeC L_{int}=1 ab^{-1}	2σ	3σ	5σ
BR(t—>uγ)	4.0×10^{-6}	7.5×10^{-6}	1.5×10^{-5}
BR(t—>cγ)	4.0×10^{-5}	9.0×10^{-5}	2.0×10^{-4}

* BR(t—>uγ) ≤ 5.0×10^{-6} and BR(t—>uγ) ≤ 4.5×10^{-5} for 3σ significance at the L_{int}=2 ab^{-1}.



LHeC

For t—>qZ analysis, the integrated luminosity versus branching BR(t—>qZ) for top FCNC at 2σ, 3σ and 5σ significance at the LHeC.



* Upper limits BR(t—>qZ) = 4.0×10^{-5} and BR(t—>qZ) = 3.0×10^{-5} for 2σ significance at the L_{int}=1 ab^{-1} and L_{int}=2 ab^{-1}.

Signal and Background at FCC-eh

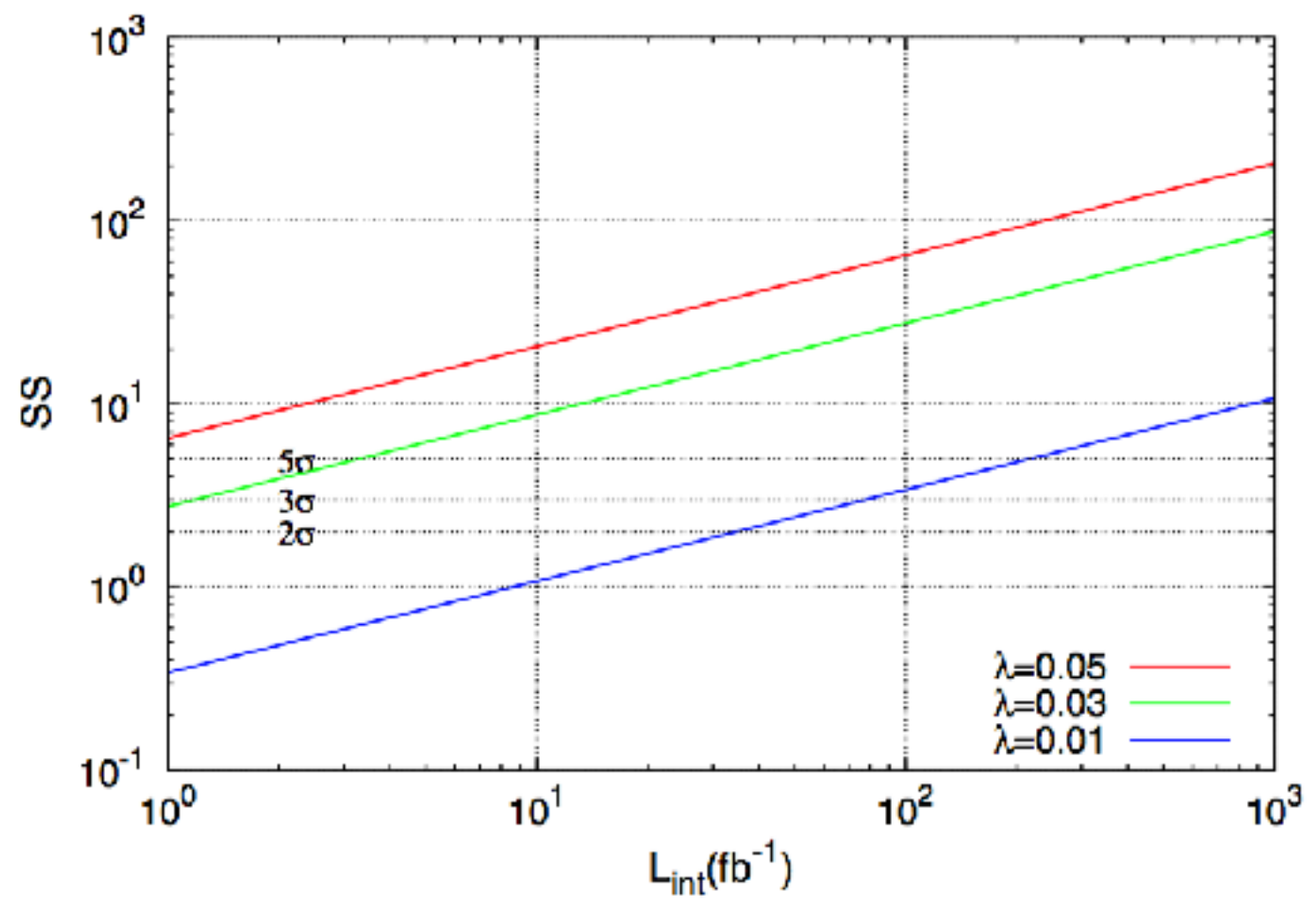
Number of events and statistical significance

FCC-eh

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_{int}=100 fb^{-1} at FCC-eh.

Processes	Cut-0	Cut-1	Cut-2	Cut-3	Cut-4	Cut-5
$S + B_W$ ($\lambda = 0.03$)	206373	11687	8665	7964	2867	1883
$S + B_W$ ($\lambda = 0.01$)	200135	7827	5776	5312	1396	622
S ($\lambda = 0.03$)	6695	4276	3218	2974	1683	1440
S ($\lambda = 0.01$)	457	416	329	322	212	179
B_W	199678	7411	5447	4990	1184	443
B_H	2279	979	802	757	107	47
B_Z	13420	1639	1145	956	246	110
B_{tt}	9752	5594	5339	4974	1079	460
B_{bjj}	48241	17287	9936	9074	2573	1170

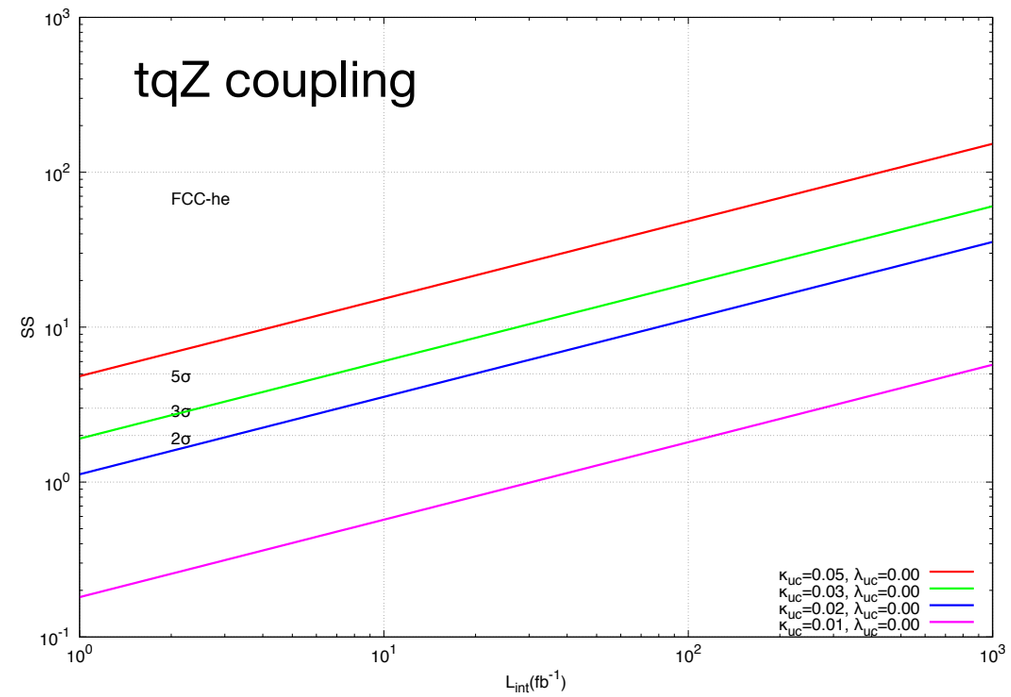
On the right (bottom) plot, the statistical significance (SS) depending on integrated luminosity for different anomalous FCNC couplings (λ) are shown for FCC-eh. The 2σ, 3σ and 5σ lines are also shown.

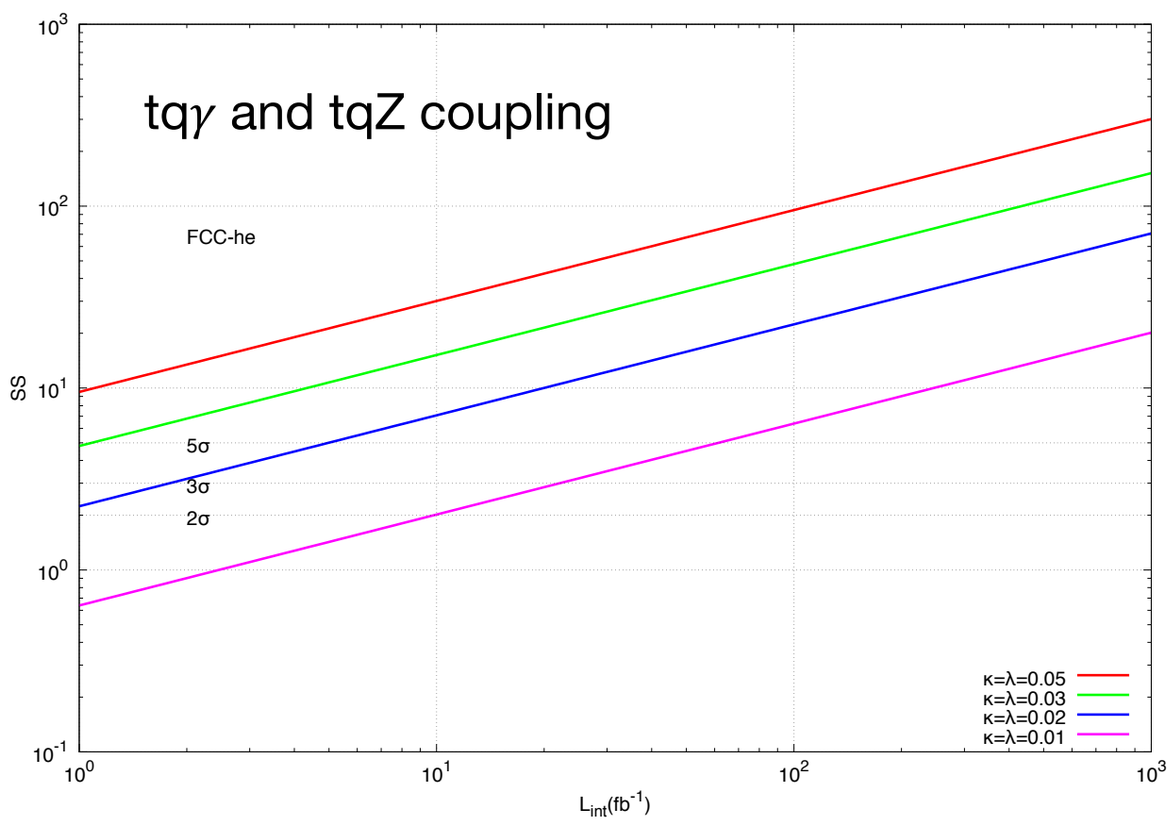


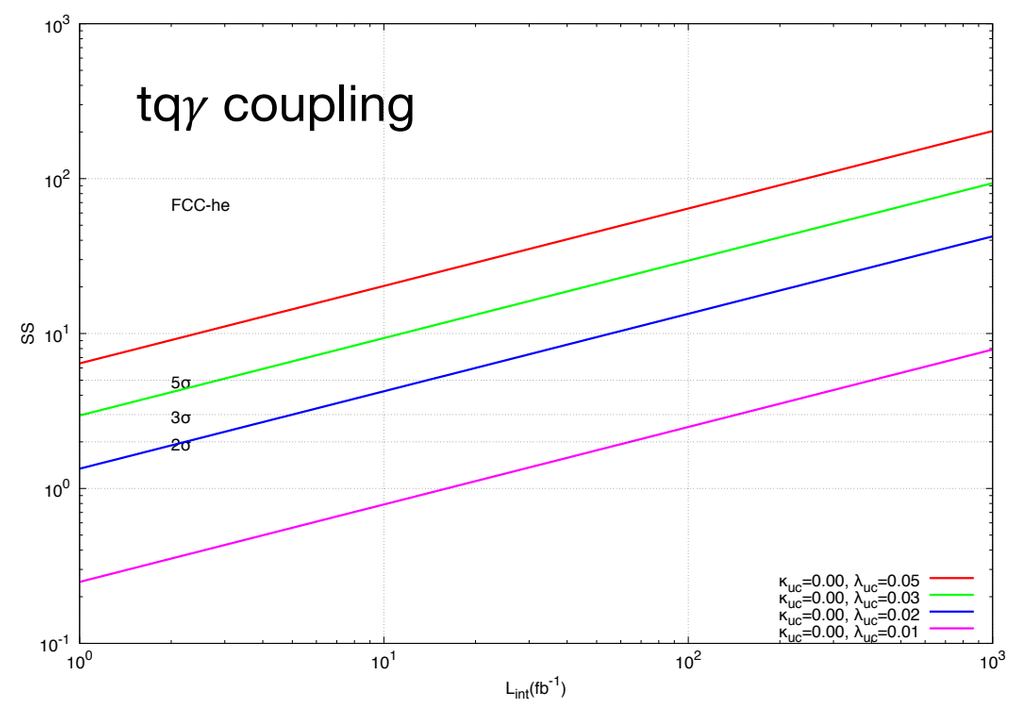
Analysis

FCC-eh

For **one-coupling** (λ or κ) and **two-coupling** (λ and κ) analysis, statistical significance (SS) depending on the integrated luminosity (L_{int}) ranging from 1 fb^{-1} to 1 ab^{-1} at the FCC-eh.





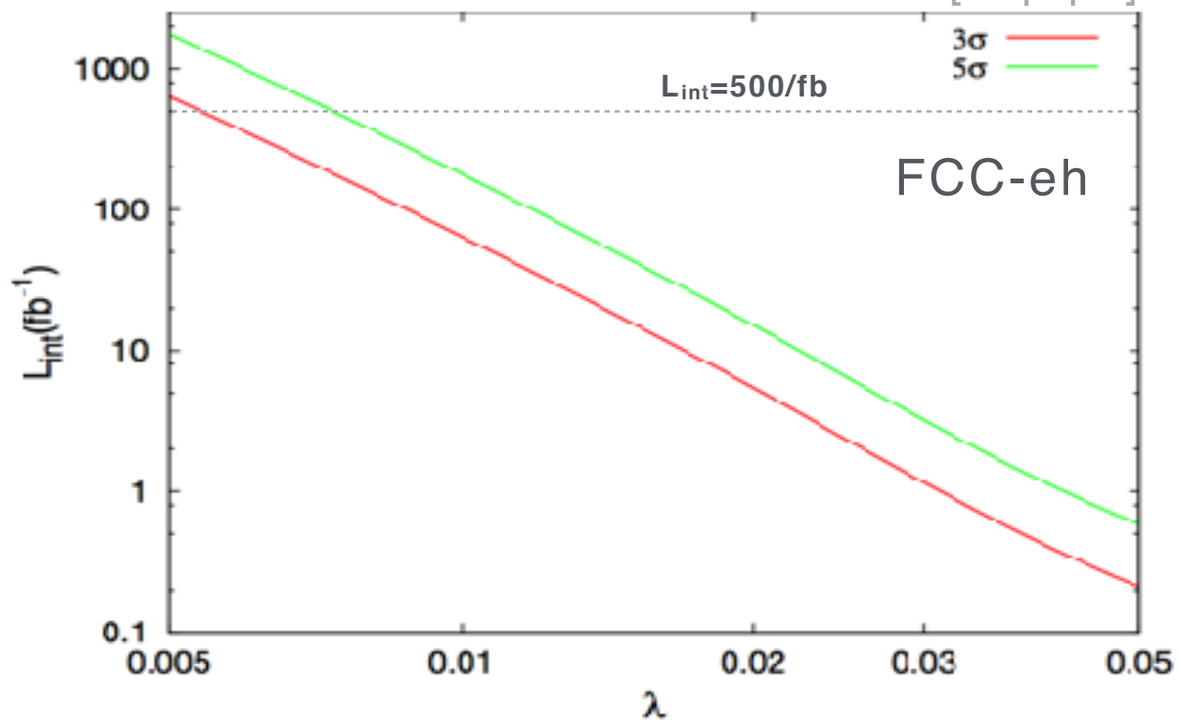


Results on couplings

On the right (bottom) plot, the integrated luminosity versus anomalous FCNC coupling (λ) at 2σ, 3σ and 5σ significance is shown for FCC-eh. We obtain an upper bound λ=0.005 (0.004) at L_{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].

1701.06932[hep-ph]



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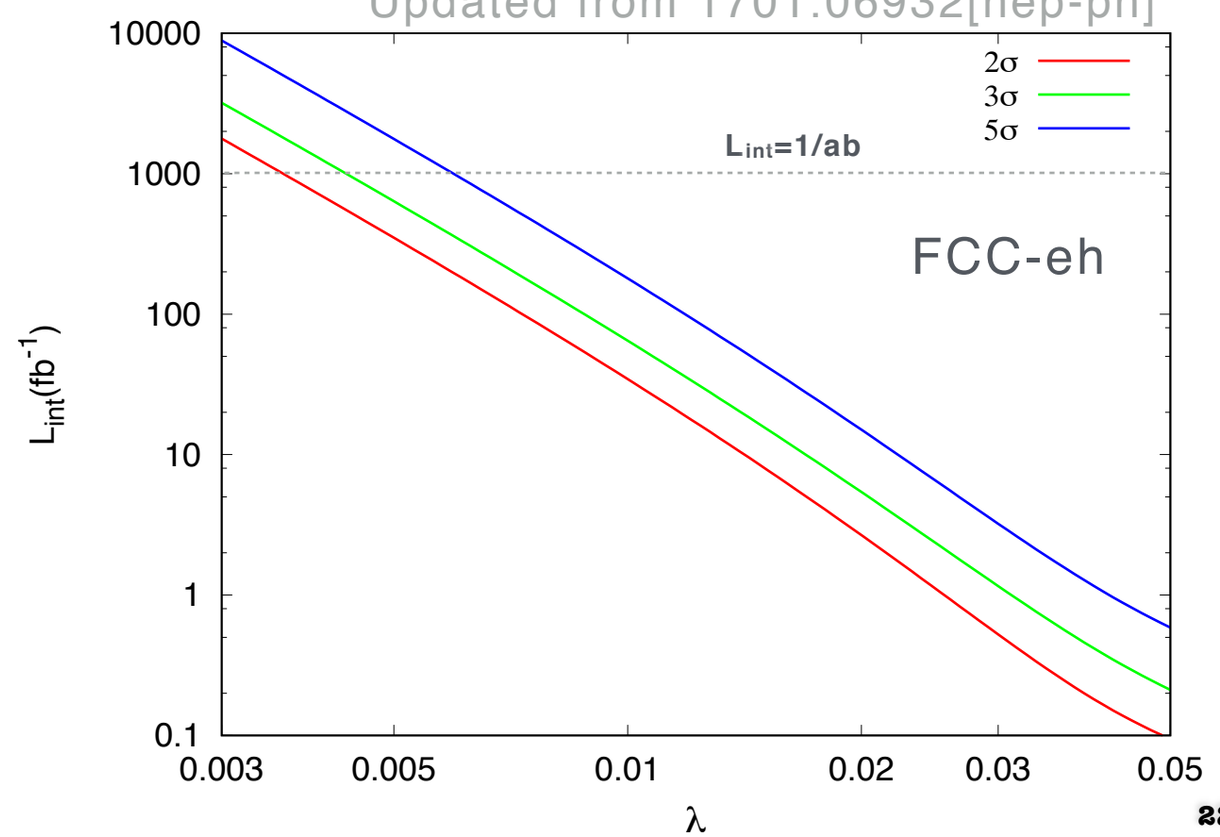
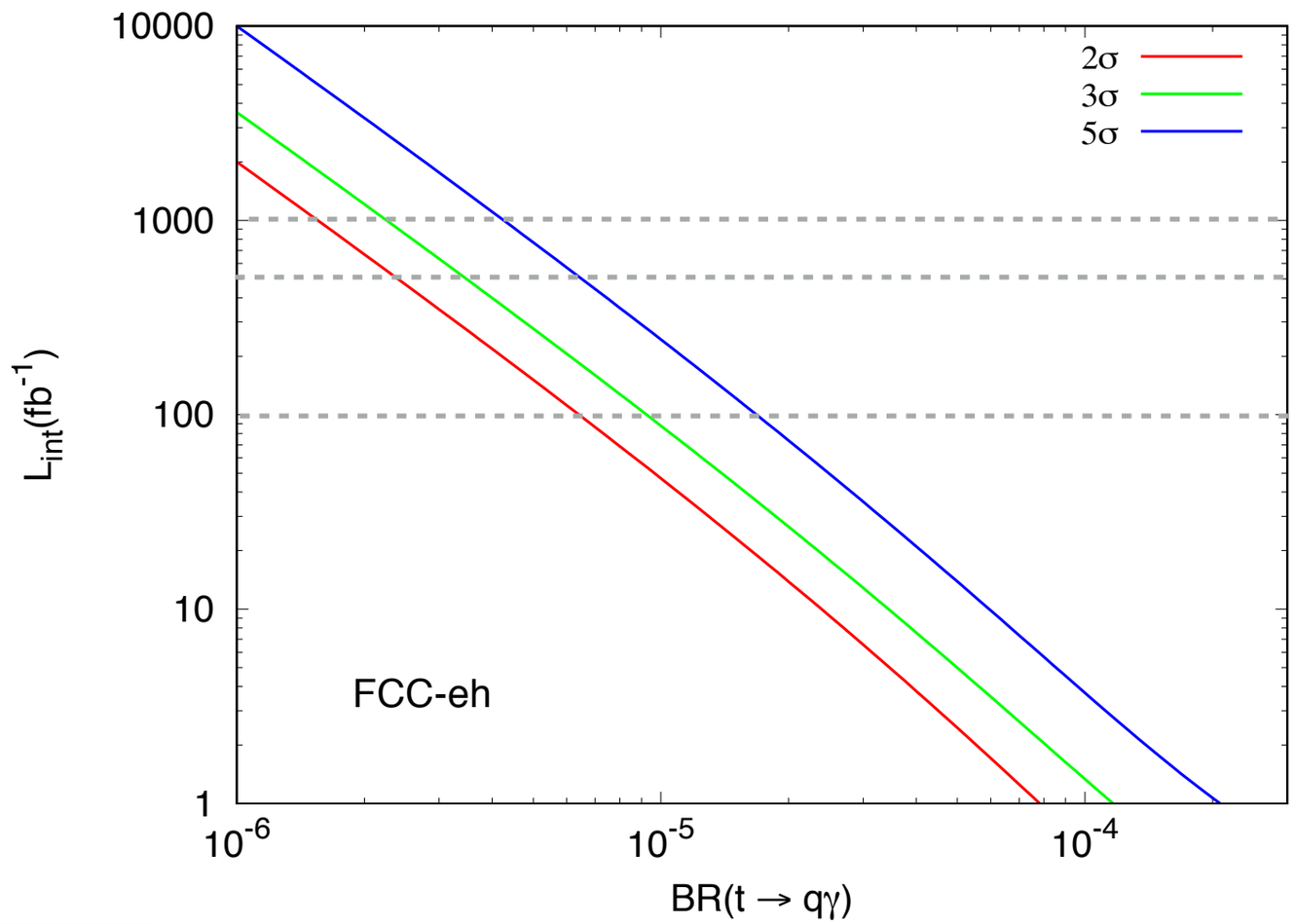


Luminosity vs Branchings

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.

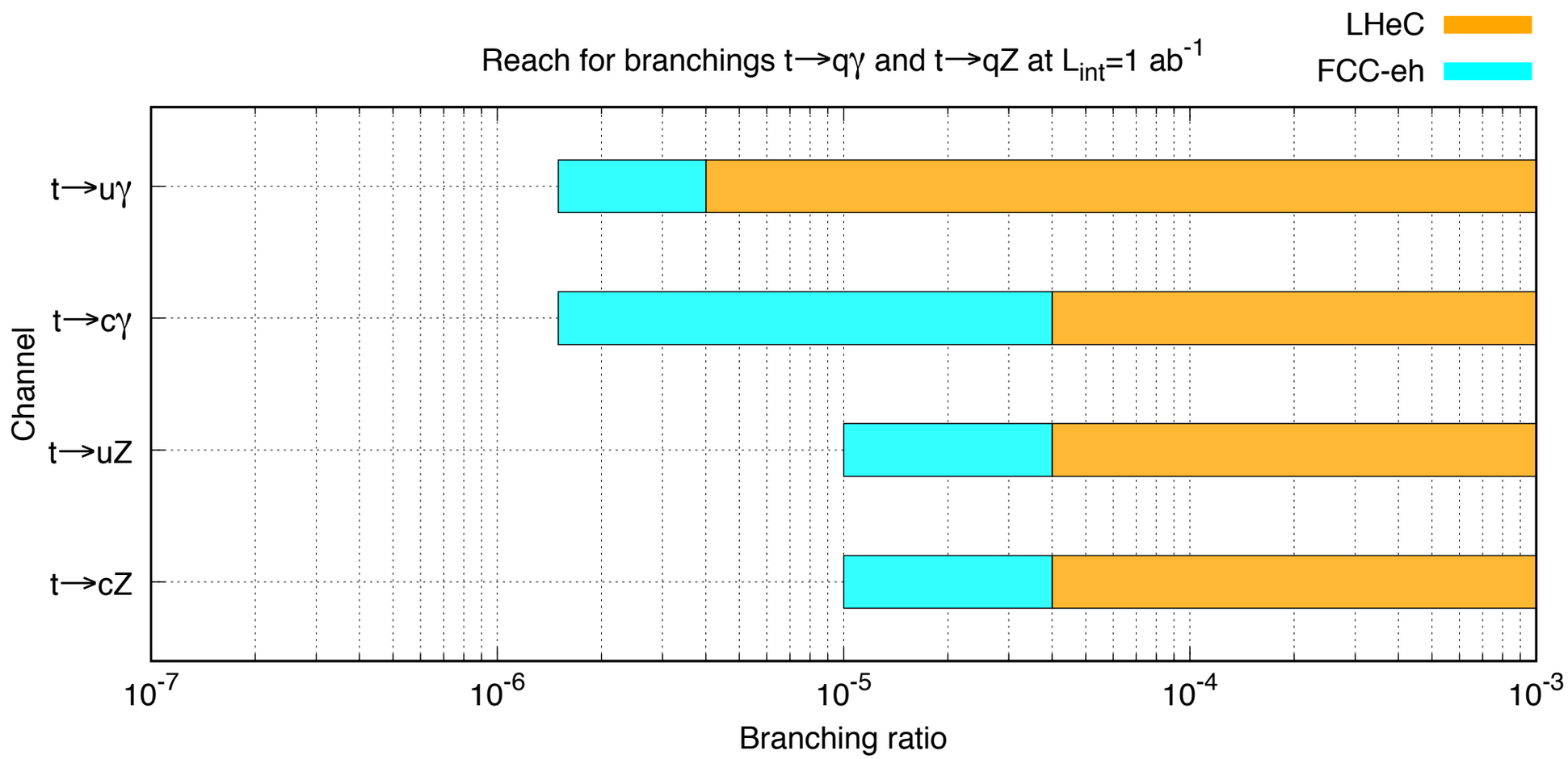


FCC-eh	2σ	3σ	5σ
BR(t—>qγ) at L_{int}=1 ab^{-1}	1.5×10^{-6}	2.2×10^{-6}	4.1×10^{-6}
BR(t—>qγ) L_{int}=2 ab^{-1}	1.0×10^{-6}	1.5×10^{-6}	3.0×10^{-6}

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

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->qγ) from arXiv:1701.06932 and arXiv:1705.05419, and BR(t->qZ) from recent update.

Conclusion

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.

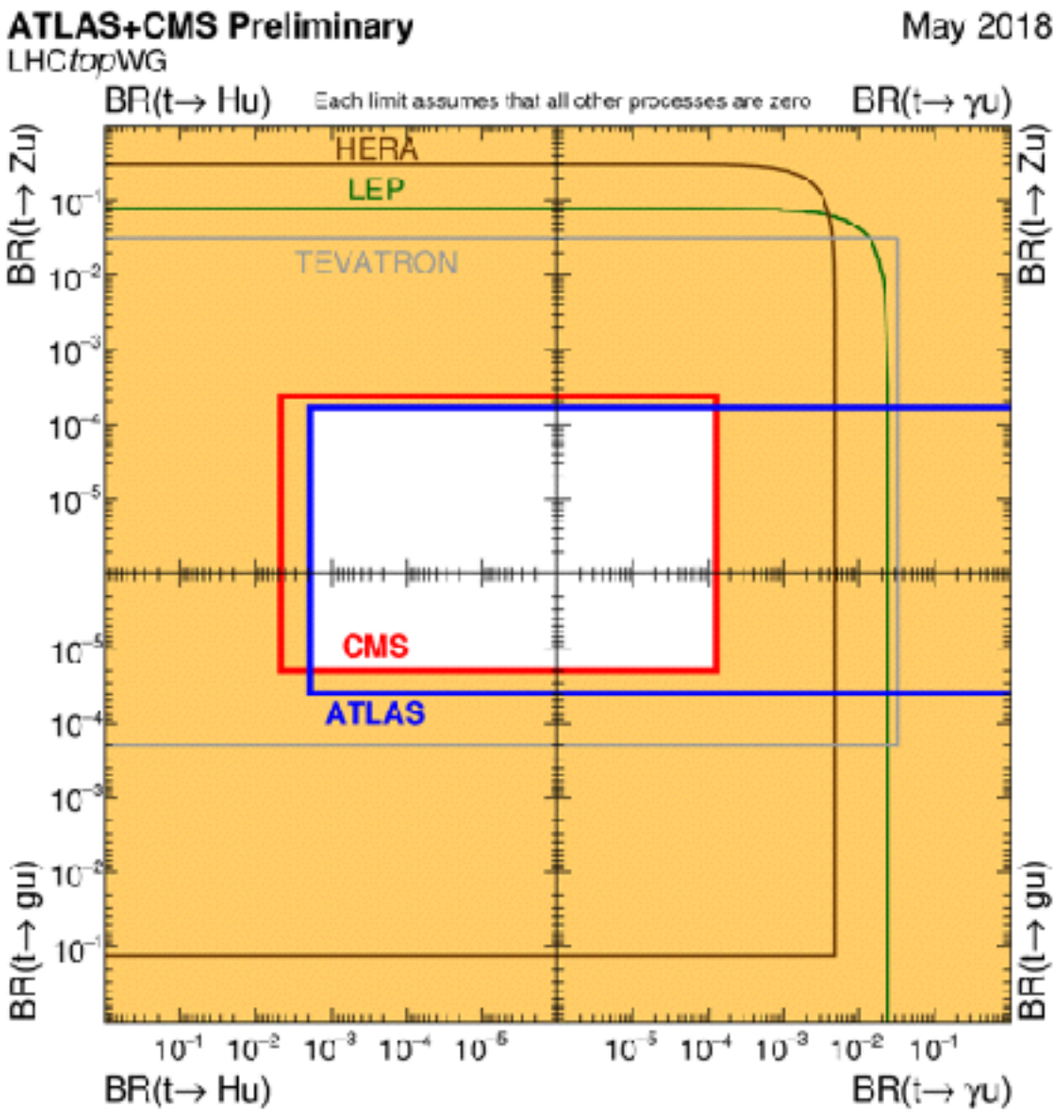
At the LHeC with L_{int}=500 fb^{-1}, we obtain attainable upper limits on the top quark FCNC couplings (λ_u=0.01 and λ_c=0.03) from the analysis of signal and background including detector effects through the fast simulation.

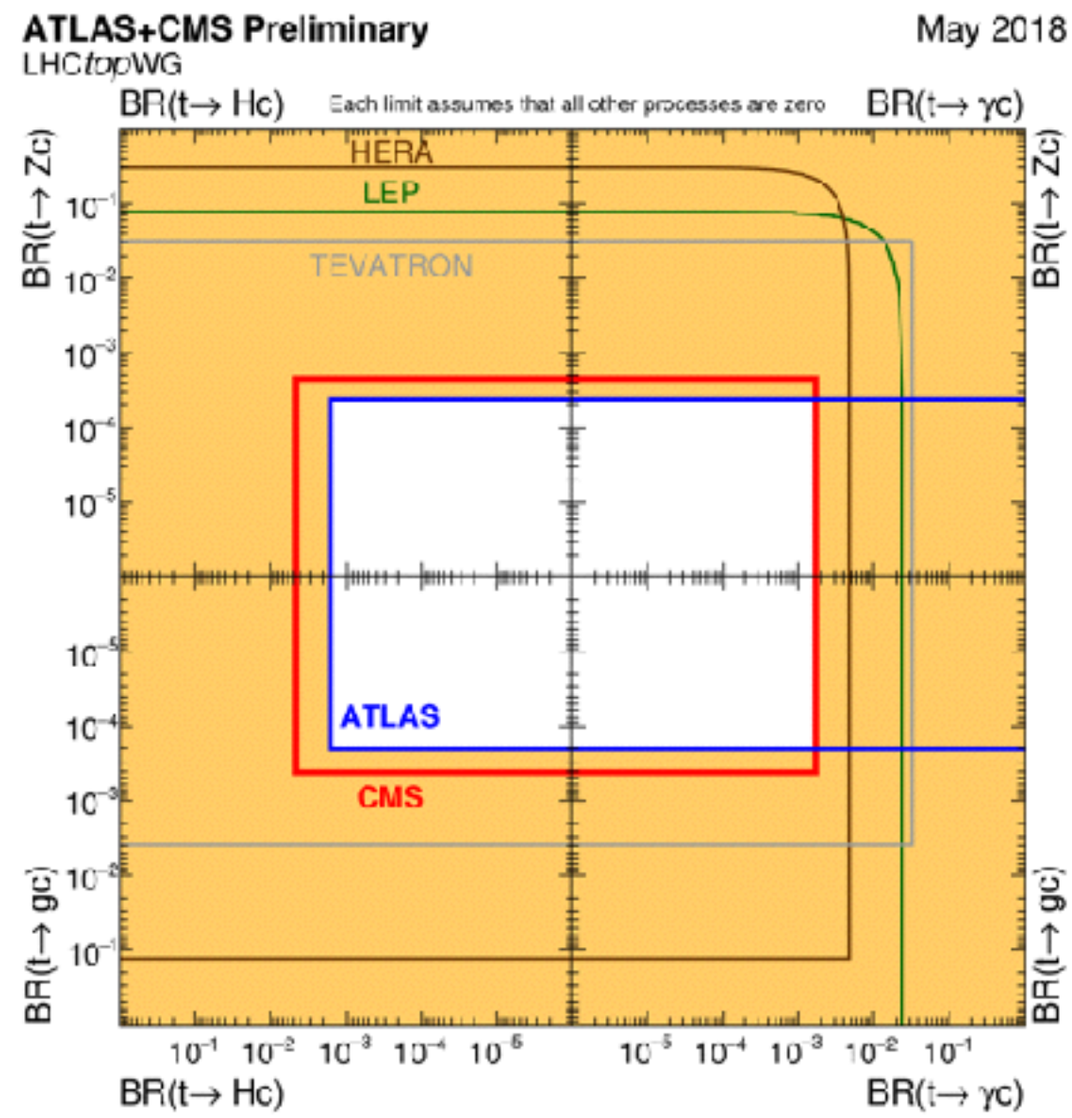
The top quark FCNC couplings (λ_q=0.005) can be searched at the level of significance 3σ with an integrated luminosity of 500 fb^{-1} at FCC-he.

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), 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 (λ_u, λ_c) and (κ_u, κ_c), corresponding to BR ~ 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)





Upper Limits on Branching Ratio for Top Quark FCNC

Branching fraction limits for top quark FCNC decays, com- pared to the SM predictions, as well as to various projections for future experi- ments. 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).

[1-1] ATLAS Collaboration, ATL-PHYS-PUB-2016-019, http://cds.cern.ch/record/2209126.

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[1-3] ATLAS Collaboration, ATL-PHYS-PUB-2013-012, http://cds.cern.ch/record/1604506.

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[1-5] X. Wang, H. Sun, X. Luo, Adv. High Energy Phys. 4693213 (2017), hep- ph/1703.02691.

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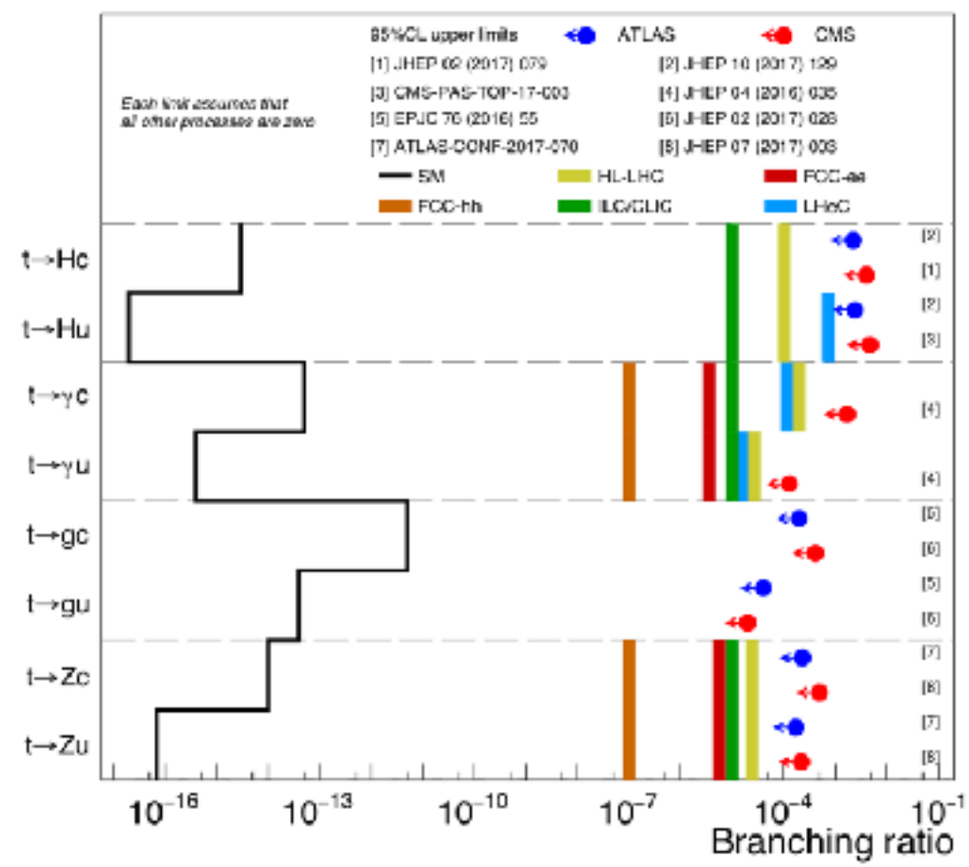

arXiv:1711.01852v2 [hep-ex]