Update on top FCNC studies*

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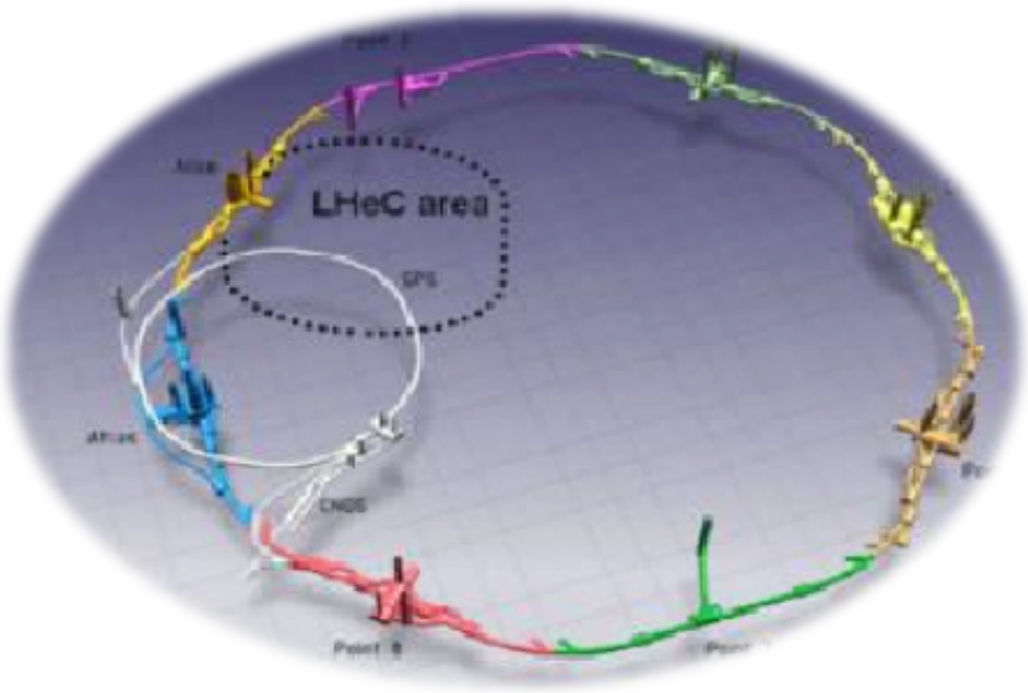
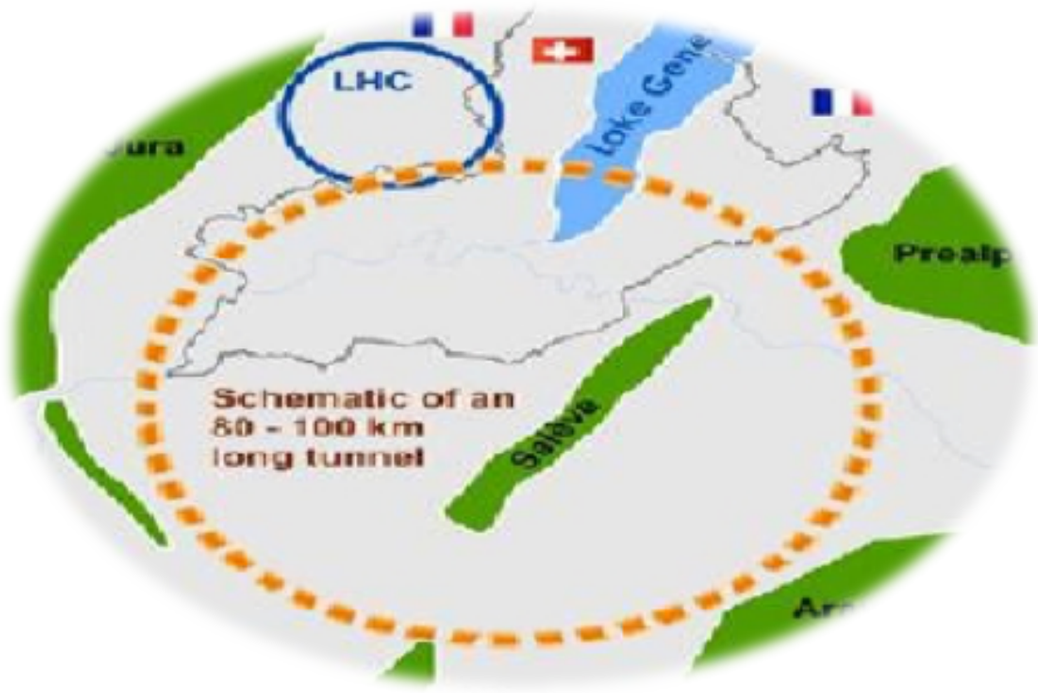
*study is based on arXiv:1701.06932 and arXiv:1705.05419

BSM physics studies at LHeC and FCC-eh, vidyo meeting, 08 September 2017

Future ep colliders





LHeC

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

FCC-eh

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

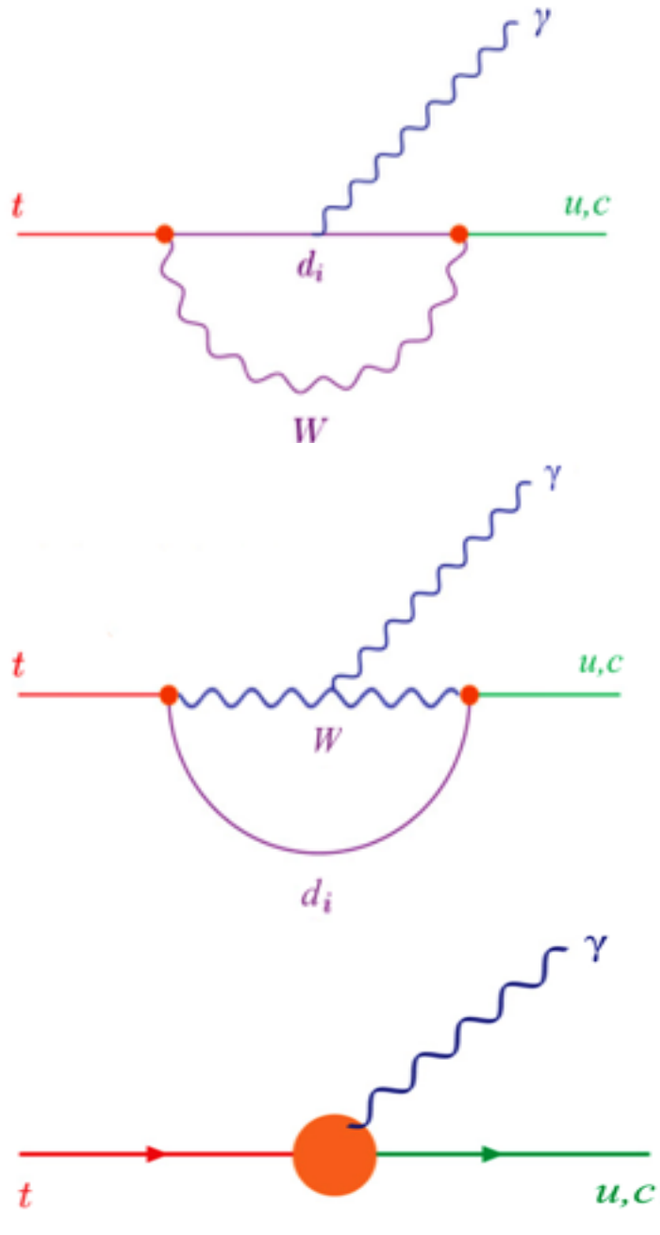
Top quark (t)

$y_t = \sqrt{2}m_t/v = 0.995 \cong 1$

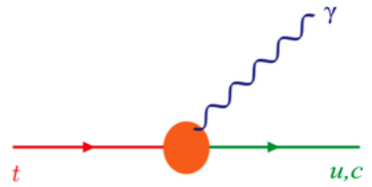
The large mass of the top quark suggest a strong connection with the EW symmetry breaking sector.

The FCNC interactions are absent at tree level in the standard model (SM) and they are suppressed (BR<10^{-10}) at higher orders due to the GIM mechanism. These are far beyond the current sensitivity of the experiments. Any hint of FCNC related to the top is a signal for new physics.

In the model-independent way, this study assumes an effective interaction of $tq\gamma$ ($q=u,c$).



Limits on FCNC branching ratios



Theoretical expectations

Process	SM	QS	2HDM	MSSM	$\not{R}$ SUSY	TC2
$t \to c\gamma$	$\mathcal{O}(10^{-14})$	$\mathcal{O}(10^{-9})$	$\mathcal{O}(10^{-6})$	$\mathcal{O}(10^{-6})$	$\mathcal{O}(10^{-6})$	$\mathcal{O}(10^{-5})$
$t \to u\gamma$	$\mathcal{O}(10^{-16})$	$\mathcal{O}(10^{-9})$	–	$\mathcal{O}(10^{-6})$	$\mathcal{O}(10^{-6})$	$\mathcal{O}(10^{-5})$

Experimental limits

Current upper limits at the 95% confidence level are set on the tuγ and tcγ anomalous couplings and translated into upper limits on the branching fraction of the FCNC top quark decays: BR(t→uγ)<0.013% and BR(t→cγ)<0.17% [CMS 2016].

Previous experimental bounds on FCNC branching ratios: BR(t→qγ)<2.4% from [LEP], BR(t→qγ)<0.75% from [HERA] and BR(t→qγ)<3.2% from [Tevatron].

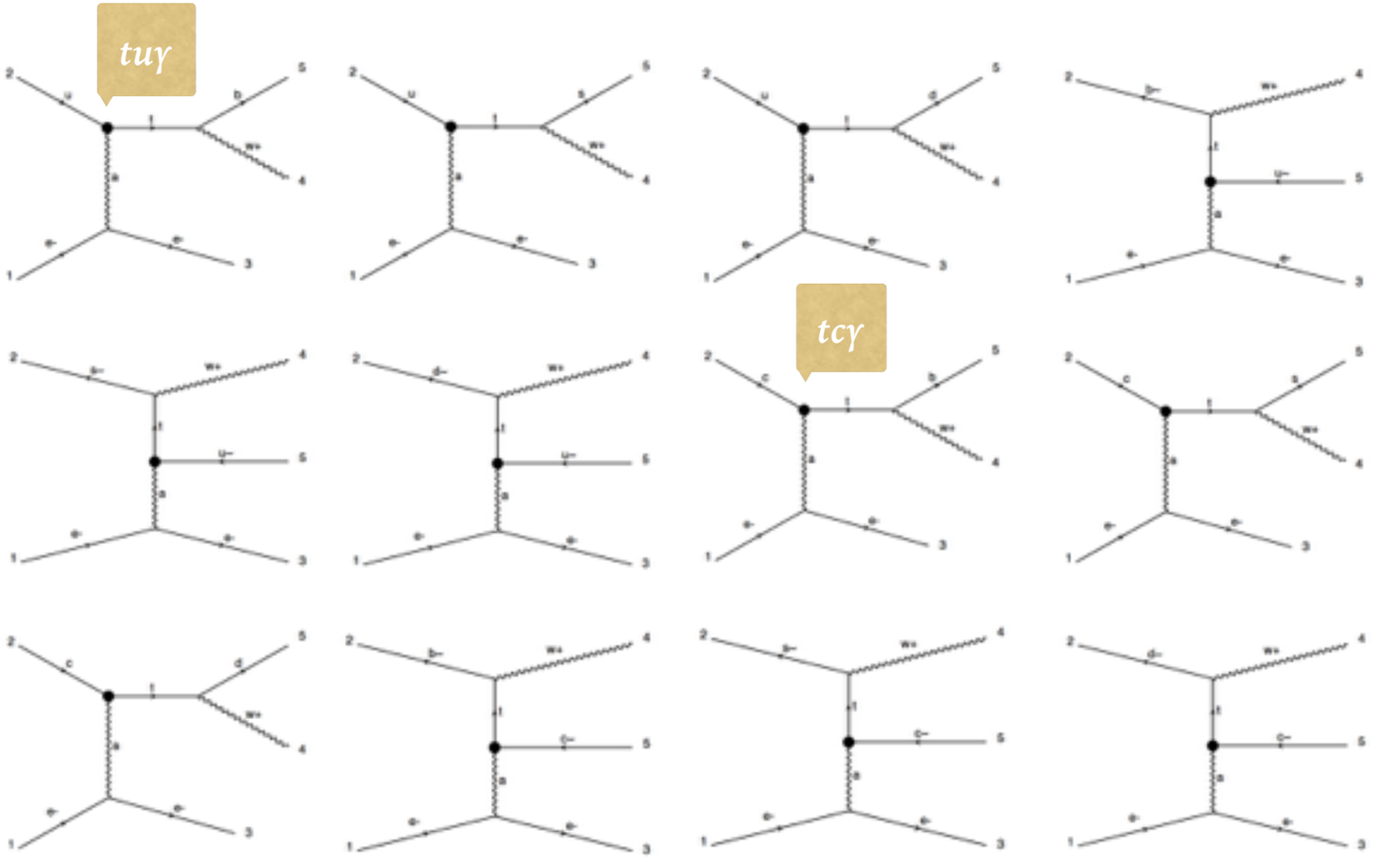
The FCNC effective interactions are described by the Lagrangian

$$L_{eff} = \frac{g_e}{2m_t}\bar{t}\sigma^{\mu\nu}(\lambda_u^L P_L + \lambda_u^R P_R)uA_{\mu\nu} + \frac{g_e}{2m_t}\bar{t}\sigma^{\mu\nu}(\lambda_c^L P_L + \lambda_c^R P_R)cA_{\mu\nu} + h.c.$$

LH coupling | RH coupling | LH coupling | RH coupling

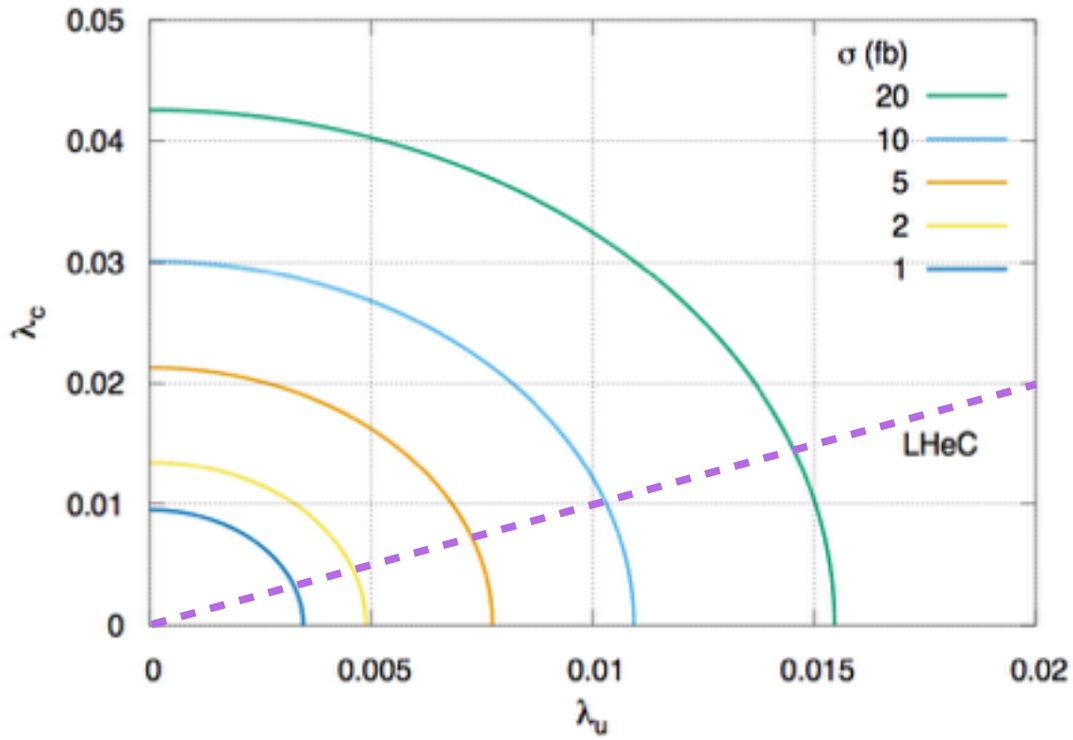
In this study, no specific chirality is assumed, then we take $\lambda^L = \lambda^R = \lambda$. Production process is $e^-p \rightarrow e^-Wq+X$.

There is also similar diagrams for process $e^-p \rightarrow e^-W^-q+X$ with the interchange $q \leftrightarrow q\sim$.

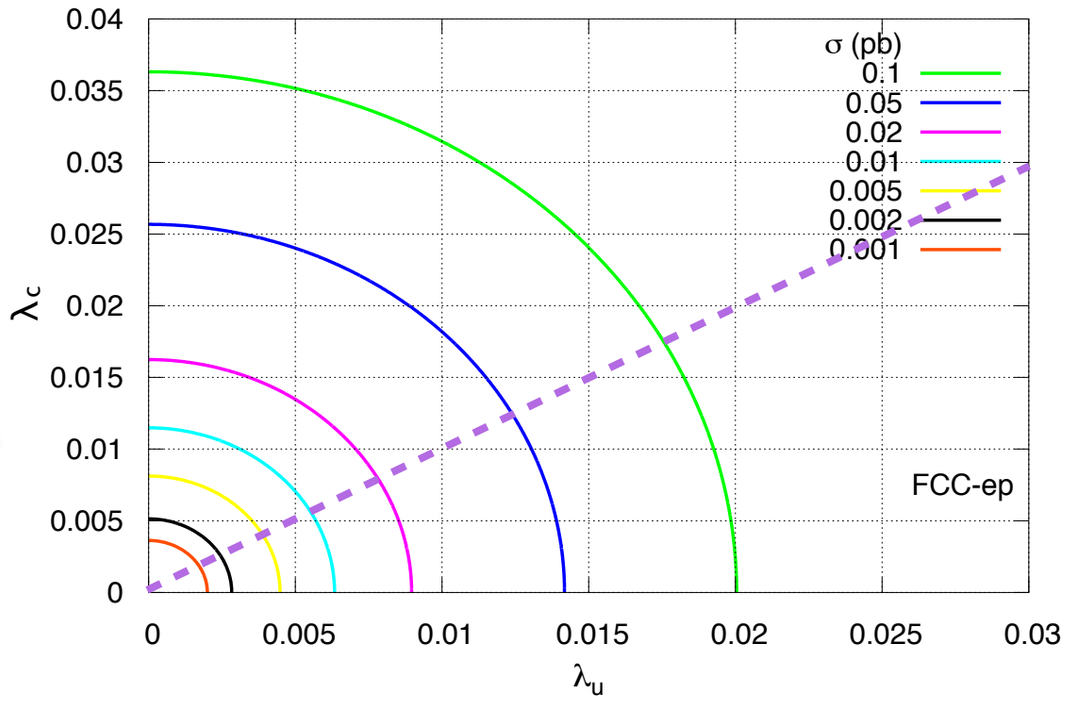


Process: $e^-p \to e^-Wq+X$

Signal cross sections at LHeC collider depending on FCNC tqγ couplings λ_u and λ_c within the interested range.



Signal cross sections at FCC-eh collider depending on FCNC tqγ couplings λ_u and λ_c within the interested range. The dashed line shows equal coupling values and the sensitivity to λ_c are more pronounced at FCC-eh.



Cross section

Process: $e^-p \rightarrow e^-Wq+X$

Cross section for S+B_W at LHeC

λ_u or $\lambda_c \rightarrow$	0.05	0.03	0.02	0.01	0
$\lambda_c = 0$	2.493	2.368	2.329	2.307	2.298
$\lambda_u = 0$	2.324	2.308	2.303	2.299	2.298
$\lambda_u = \lambda_c$	2.519	2.378	2.333	2.307	2.298

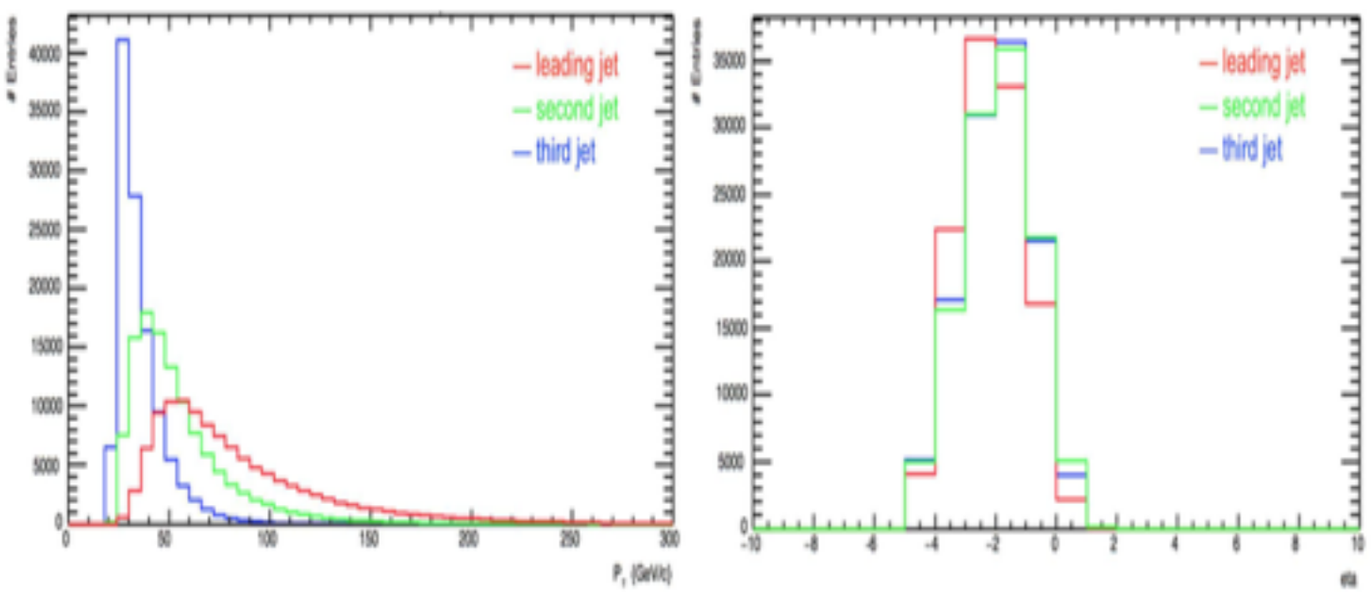
Cross section for S+B_W at FCC-eh

λ_u or λ_c—>	$\lambda=10^{-1}$	$\lambda=10^{-2}$	$\lambda=10^{-3}$
$\lambda(tu\gamma)$	1.072×10^{1}	8.565×10^{0}	8.589×10^{0}
$\lambda(tc\gamma)$	9.243×10^{0}	8.539×10^{0}	8.534×10^{0}
$\lambda(tu\gamma, tc\gamma)$	1.151×10^{1}	8.641×10^{0}	8.613×10^{0}

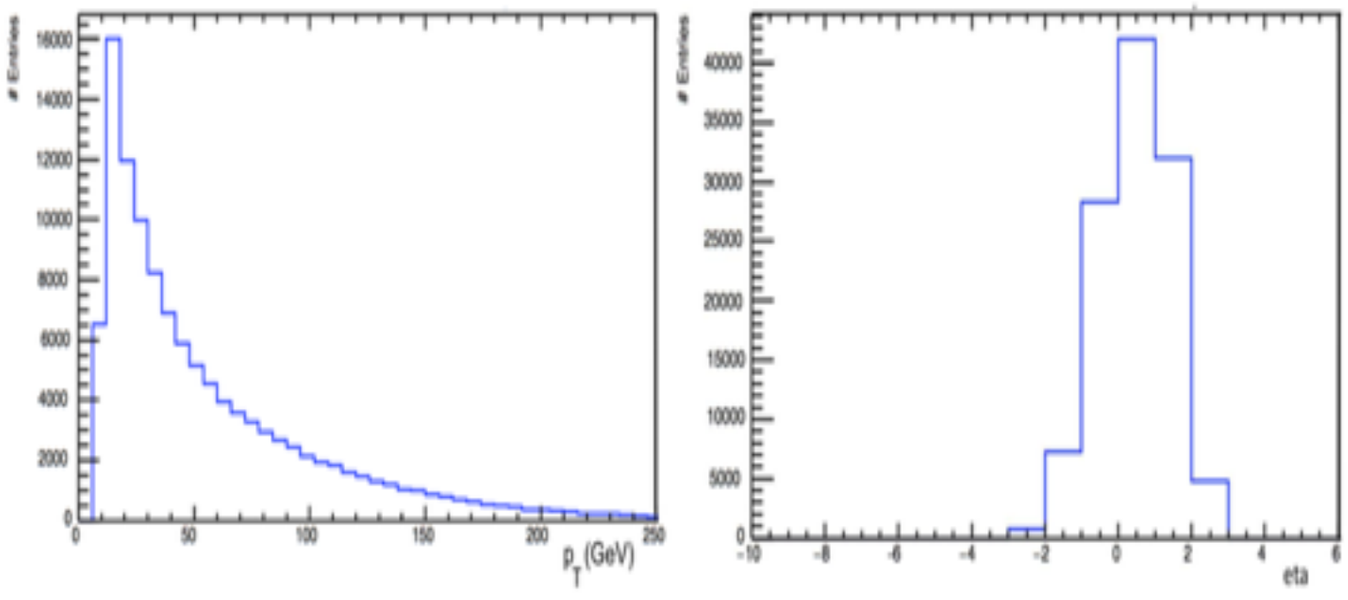
Kinematical distributions

LHeC

Transverse momentum and pseudo-rapidity distributions of three jets from the process $e-p \to e-W \pm q+X$ which includes both the interfering background and signal for $\lambda_u=\lambda_c=0.05$ at the LHeC.

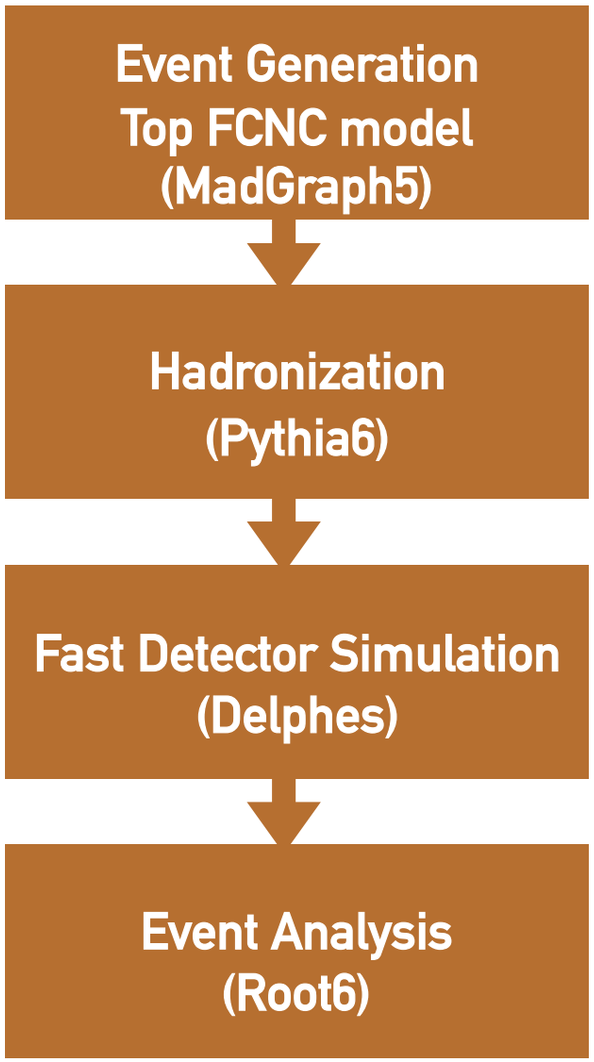


Transverse momentum and pseudo-rapidity distribution of electron for the process $e-p \to e-W \pm q+X$ which includes both the background and signal for $\lambda_u=\lambda_c=0.05$ at the LHeC.



Analysis

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



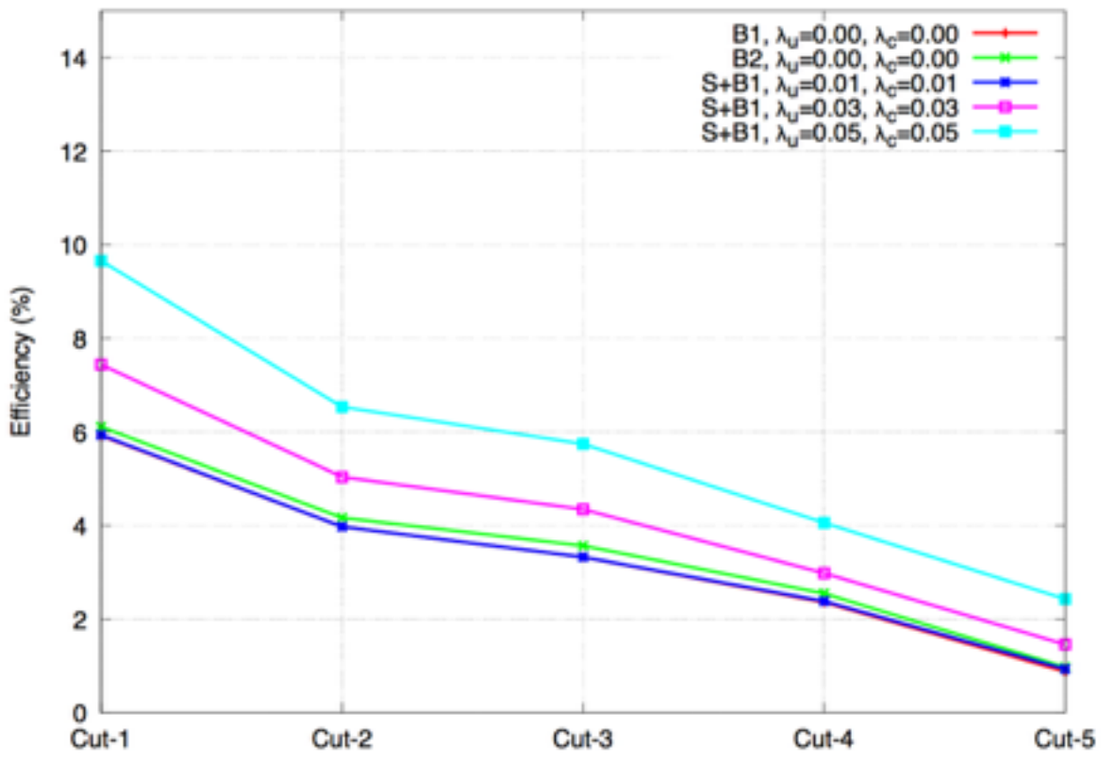
cut flow

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<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

LHeC

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



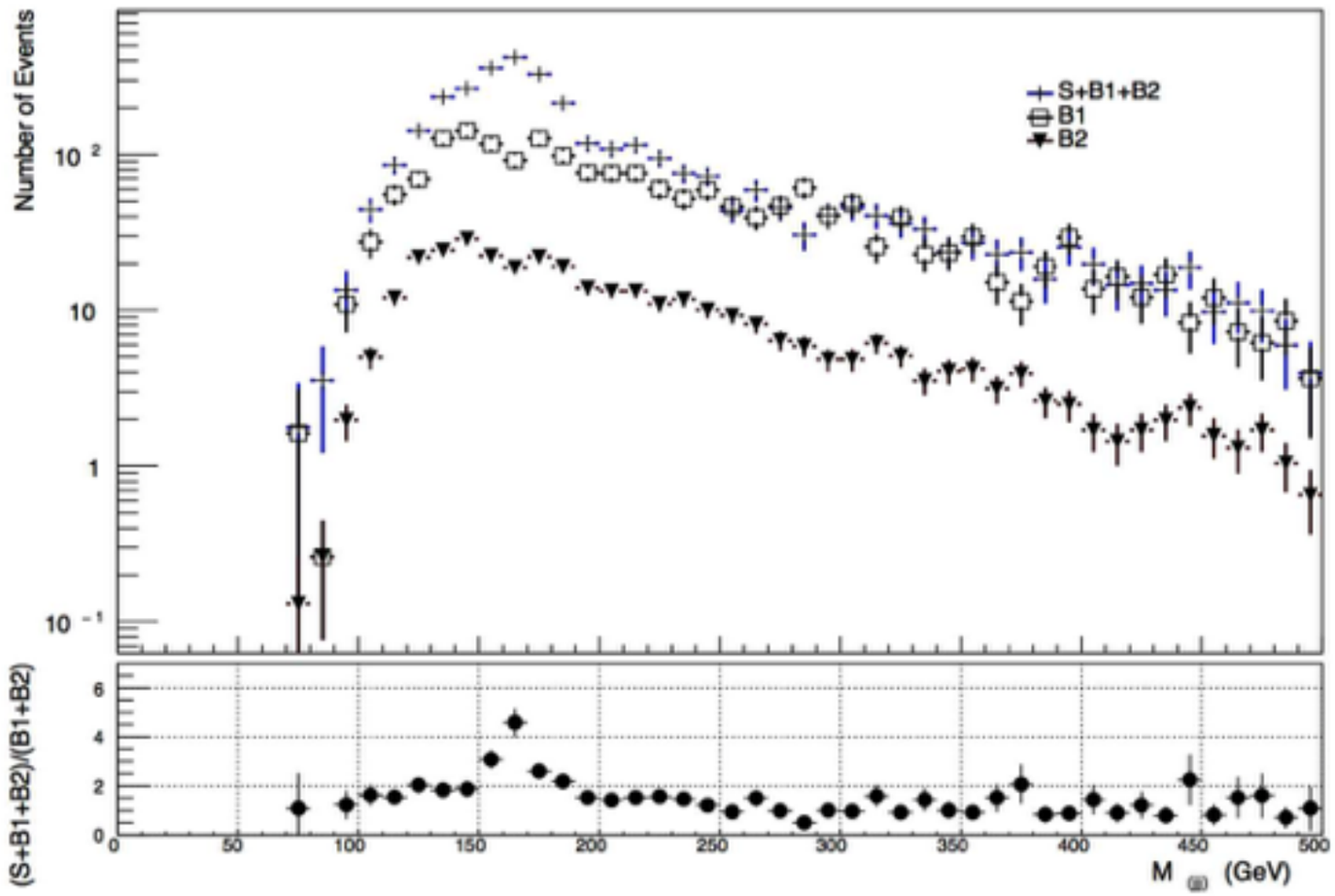
The number of events for background B1 (eWq) and B2 (eZq), and signal with FCNC couplings λ_u and λ_c at LHeC with $L_{int} = 100\ fb^{-1}$.

N	$\lambda_c = 0$	$\lambda_c = 0.01$	$\lambda_c = 0.03$	$\lambda_c = 0.05$
$\lambda_u = 0$	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

LHeC

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 λ=0.05) strength which peaks at the top mass.

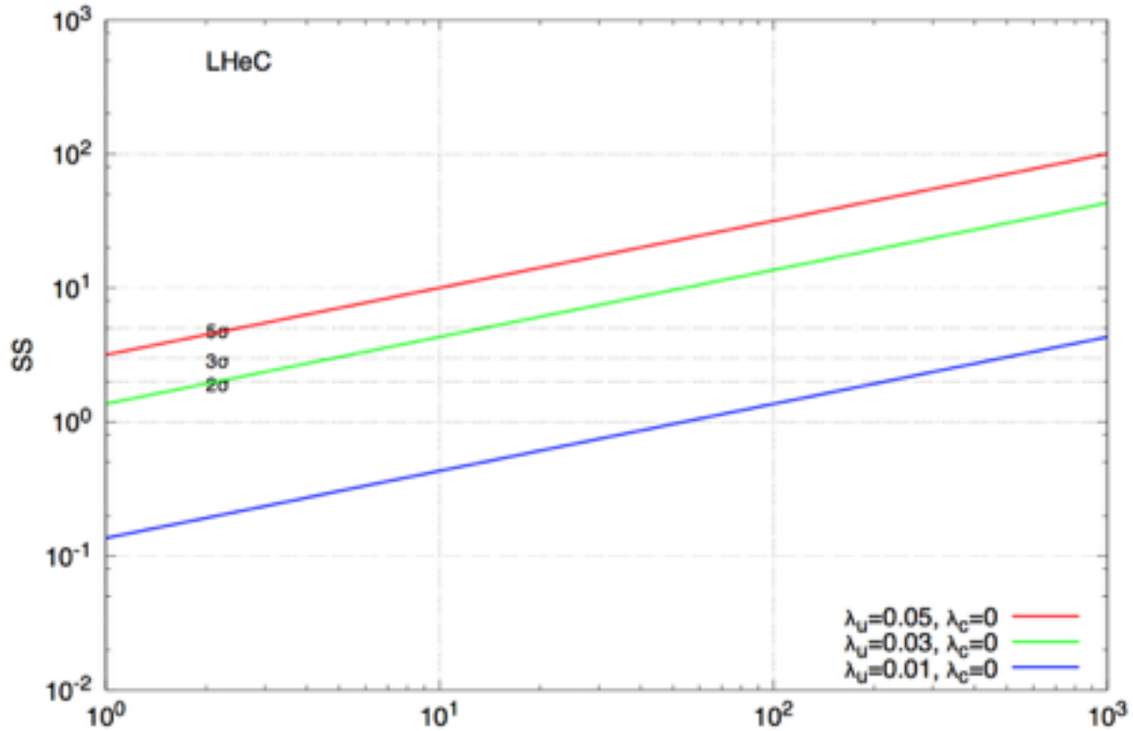


The statistical significance (SS) are calculated at the final stage of the cuts using the signal (S) and total background (B) events.

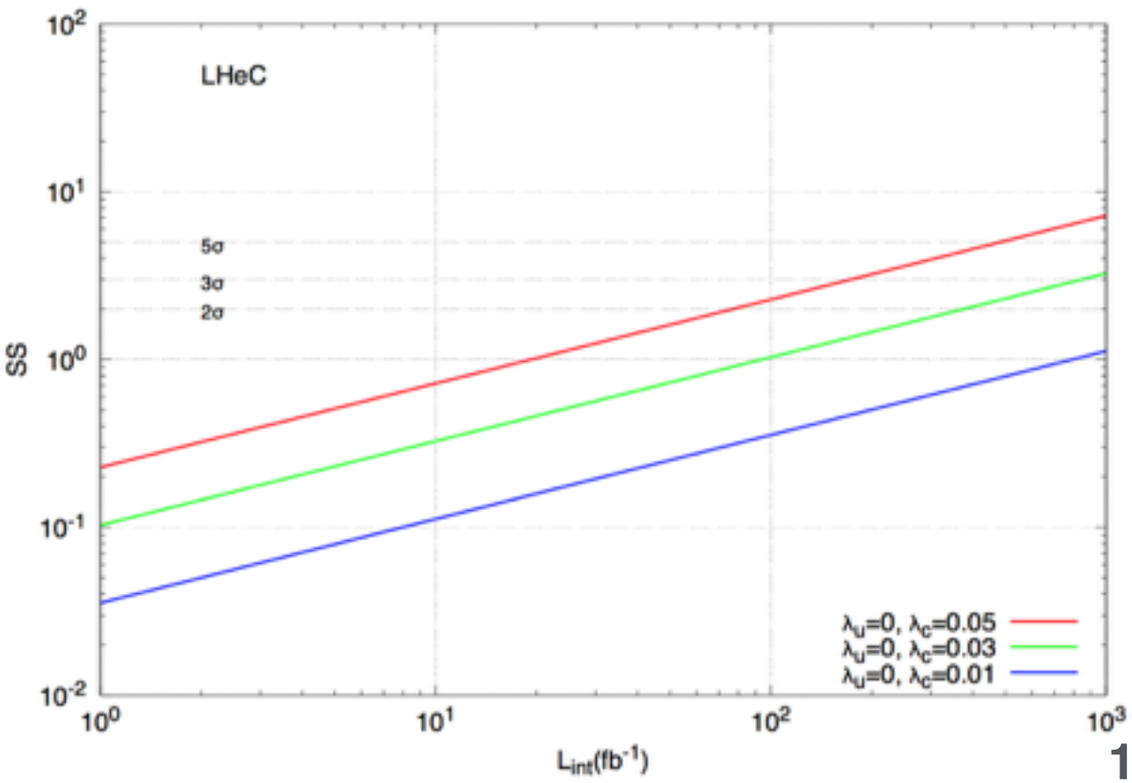
$$SS = \sqrt{2[(S+B)\ln(1+\frac{S}{B}) - S]}$$

Statistical significance

Estimated statistical significance (SS) reach of flavor changing neutral current tuγ coupling (λ_u) 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.

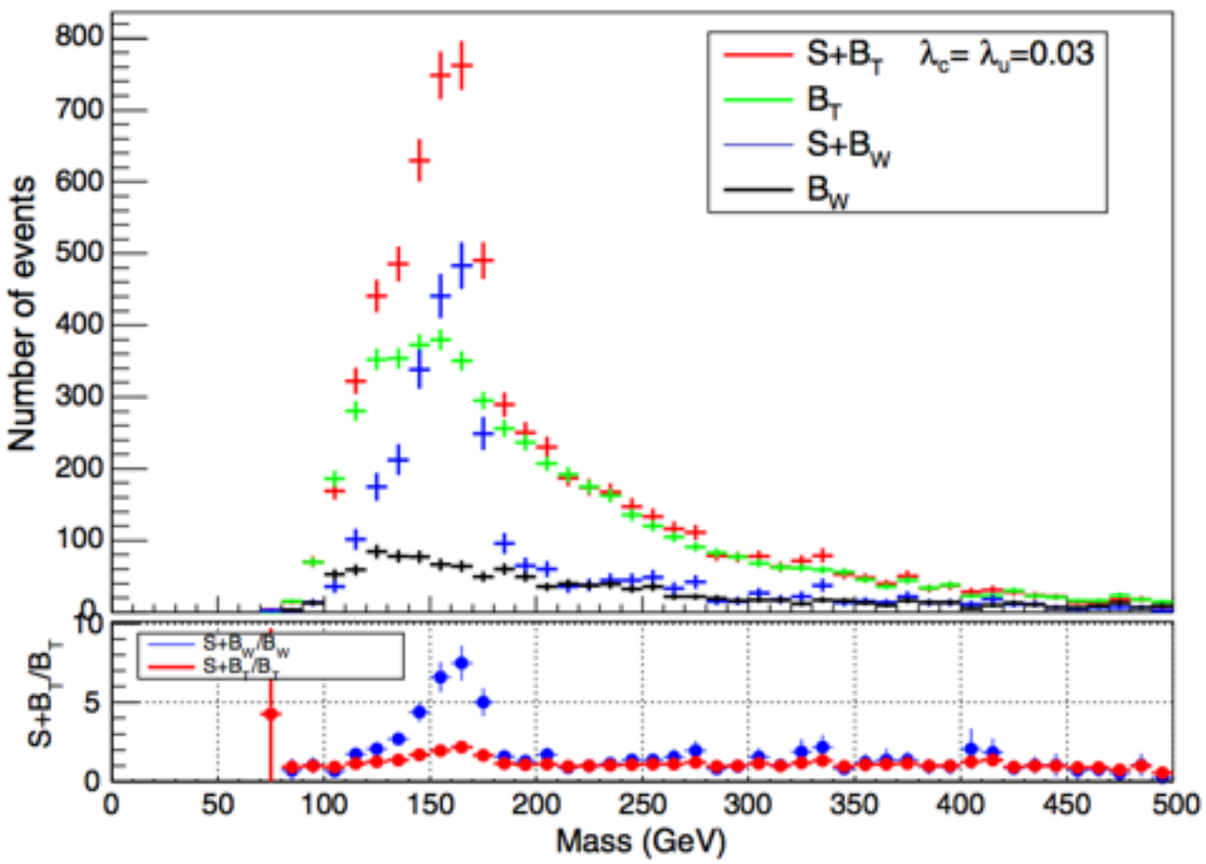


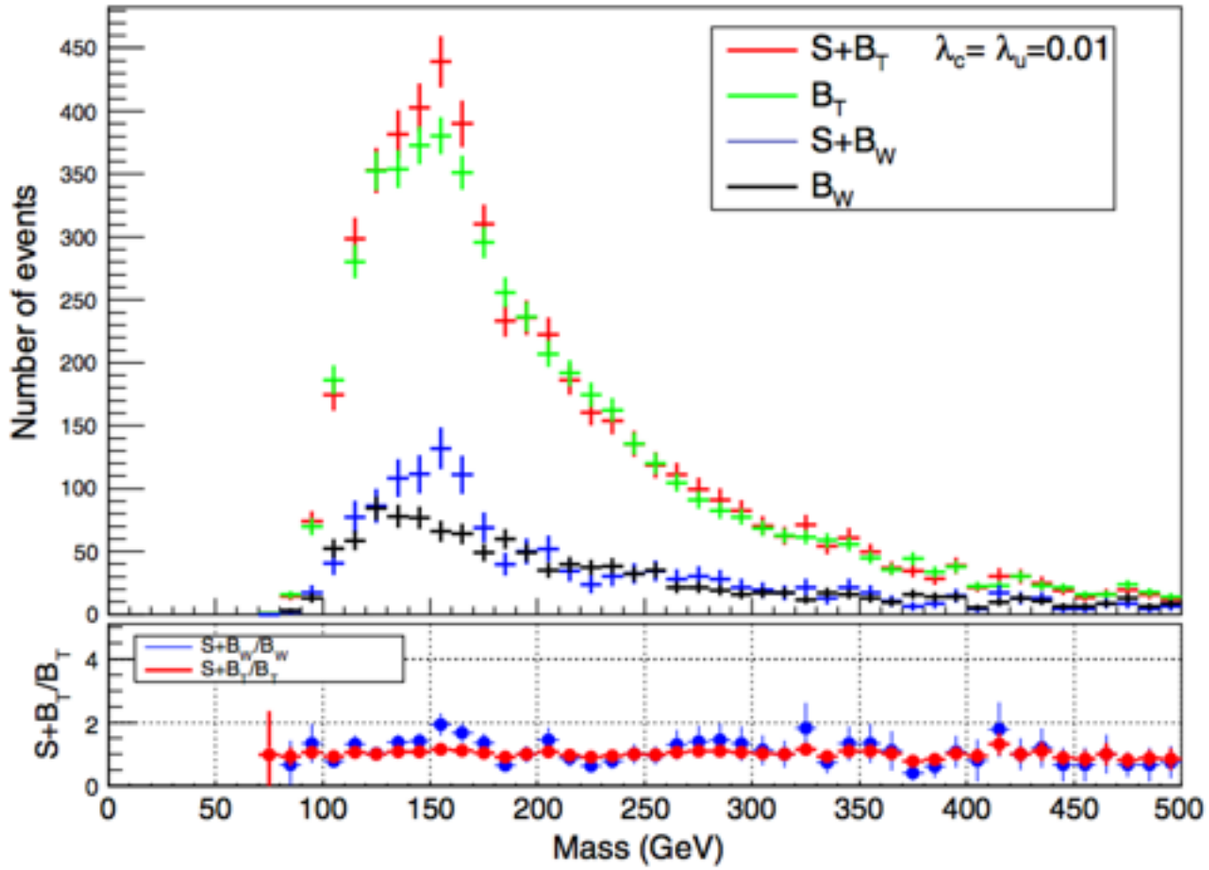
The SS reach for the flavor changing neutral current tcγ coupling (λ_c) depending on the integrated luminosity ranging from 1 fb^{-1} to 1 ab^{-1} at the LHeC.



Invariant mass distributions

FCC-eh





Distributions of reconstructed top quark mass plots for signal and relevant backgrounds with different anomalous FCNC couplings ($\lambda_u=\lambda_c$). The lower part of each plot shows the relative ratio of (S+B) and B.

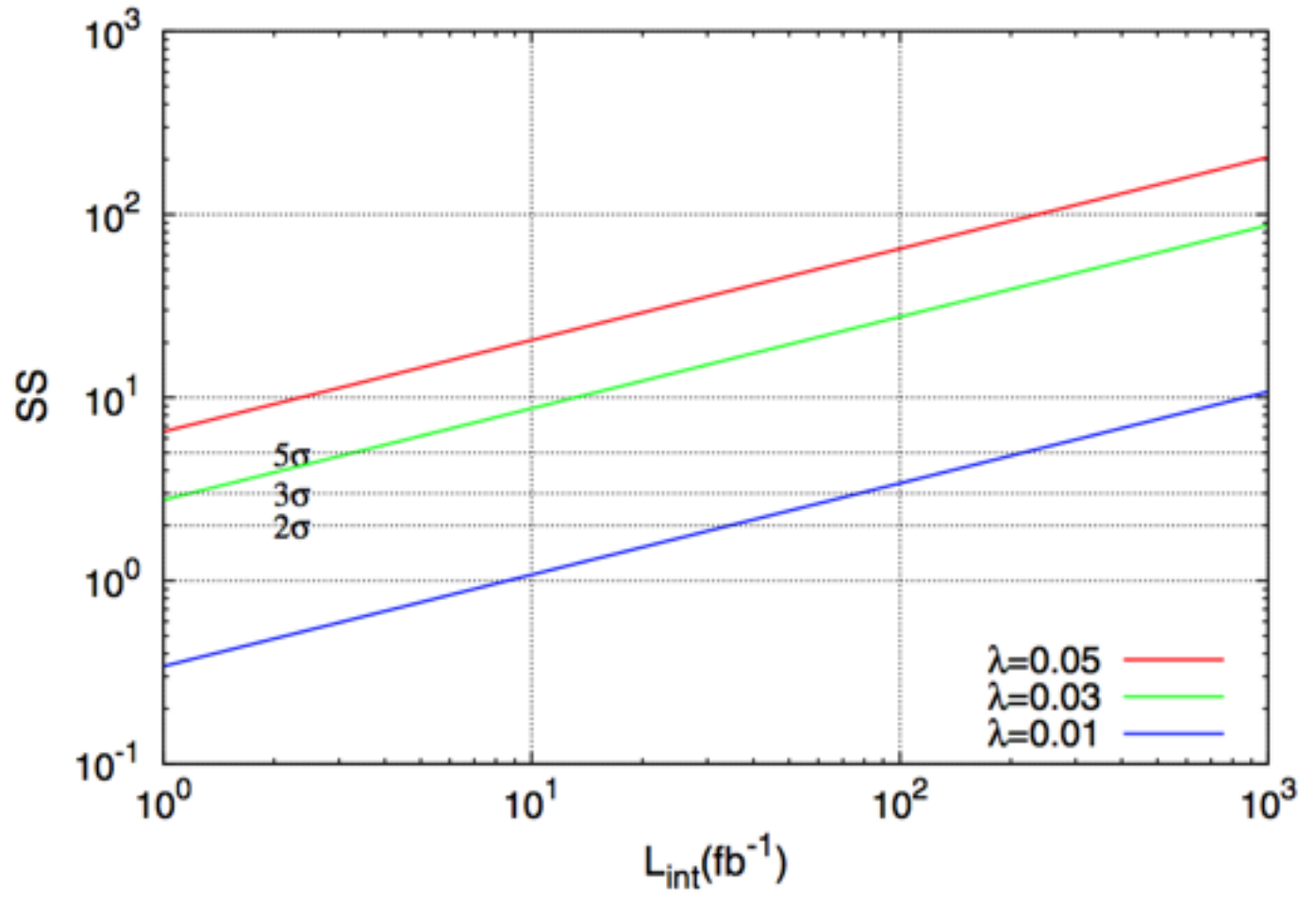
FCC-eh

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_{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.

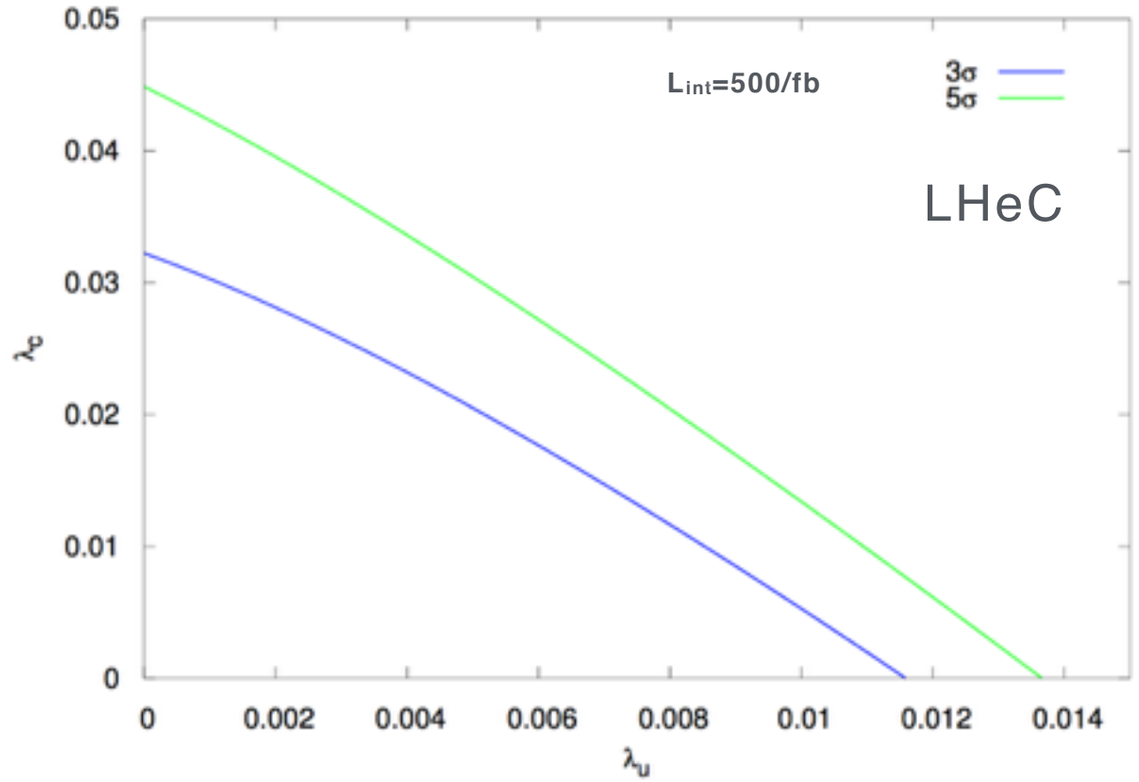


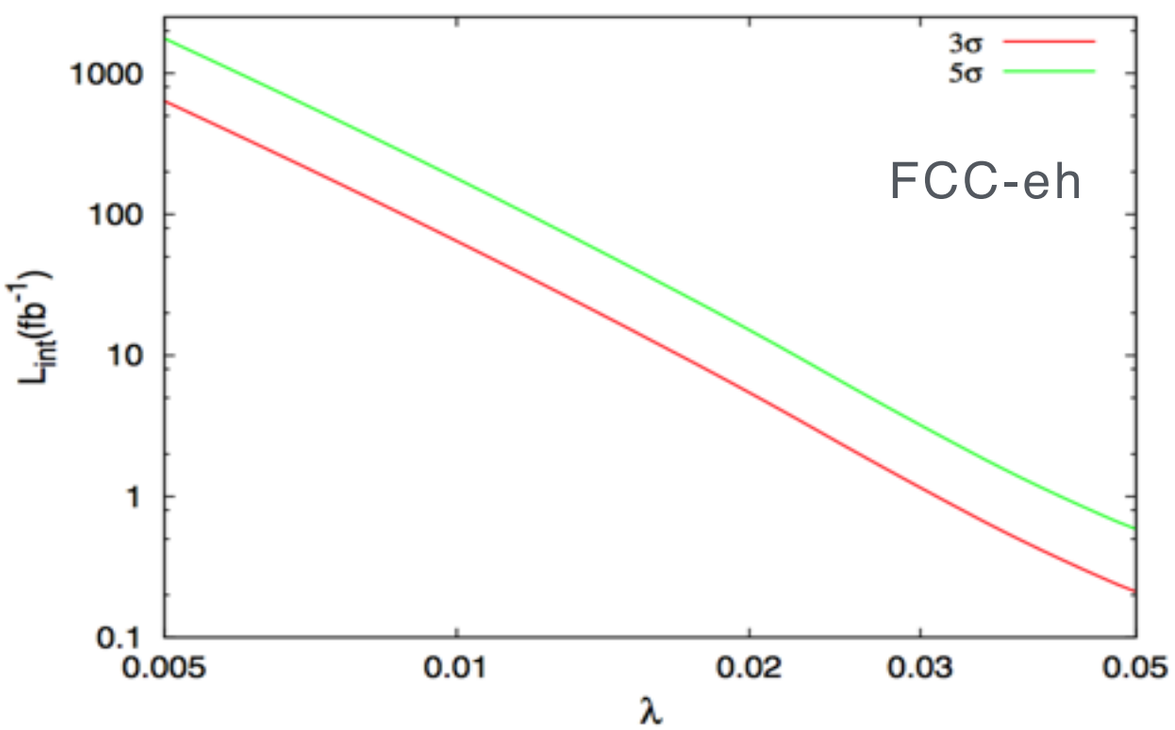
Results on couplings

The contour plot for the couplings λ_u and λ_c at LHeC for an integrated luminosity of 500 fb^{-1}. The 3σ significance results: λ_u= 0.012 and λ_c =0.032. The upper bounds on branching ratios: BR(t→uγ)<1.62×10^{-5} and BR(t→cγ)<1.15×10^{-4} at LHeC.

On the right (bottom) plot, the integrated luminosity versus anomalous FCNC coupling (λ) at 3σ and 5σ significance is shown for FCC-eh. The results can be compared to the HL-LHC expected limits*.

* The expected limits on tqγ couplings at HL-LHC have already reported in Ref.[ATLAS Collaboration, arXiv: 1307.7292], the branching ratios for t→qγ are 8×10^{-5} and 2.5×10^{-5} for L_{int} = 300 fb^{-1} and 3000 fb^{-1}, respectively.





Conclusion

At the LHeC, we have analyzed the process $e^-p \to e^-W^{\pm}q+X$ with the signature including one isolated electron and one b-jet together with two jets in the final state. The signal for this process includes the top quark flavor changing neutral current couplings (tqγ) through photon exchanges in electron-proton collisions. We obtain attainable upper limits on the top quark FCNC couplings from the analysis of signal and background including detector effects through the fast simulation.

The FCC-eh, with an electron energy of 60 GeV and a proton energy of 50 TeV, would provide significant single top quark production event rates via investigated channel. Top quark FCNC couplings ($\lambda>0.01$) can be searched at the level of significance greater than 3σ with an integrated luminosity of larger than 75 fb^{-1} at the projected FCC-he. The b-tagging has an important role in our study.

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), which can be comparable or even better when compared to the bounds from the HL-LHC.

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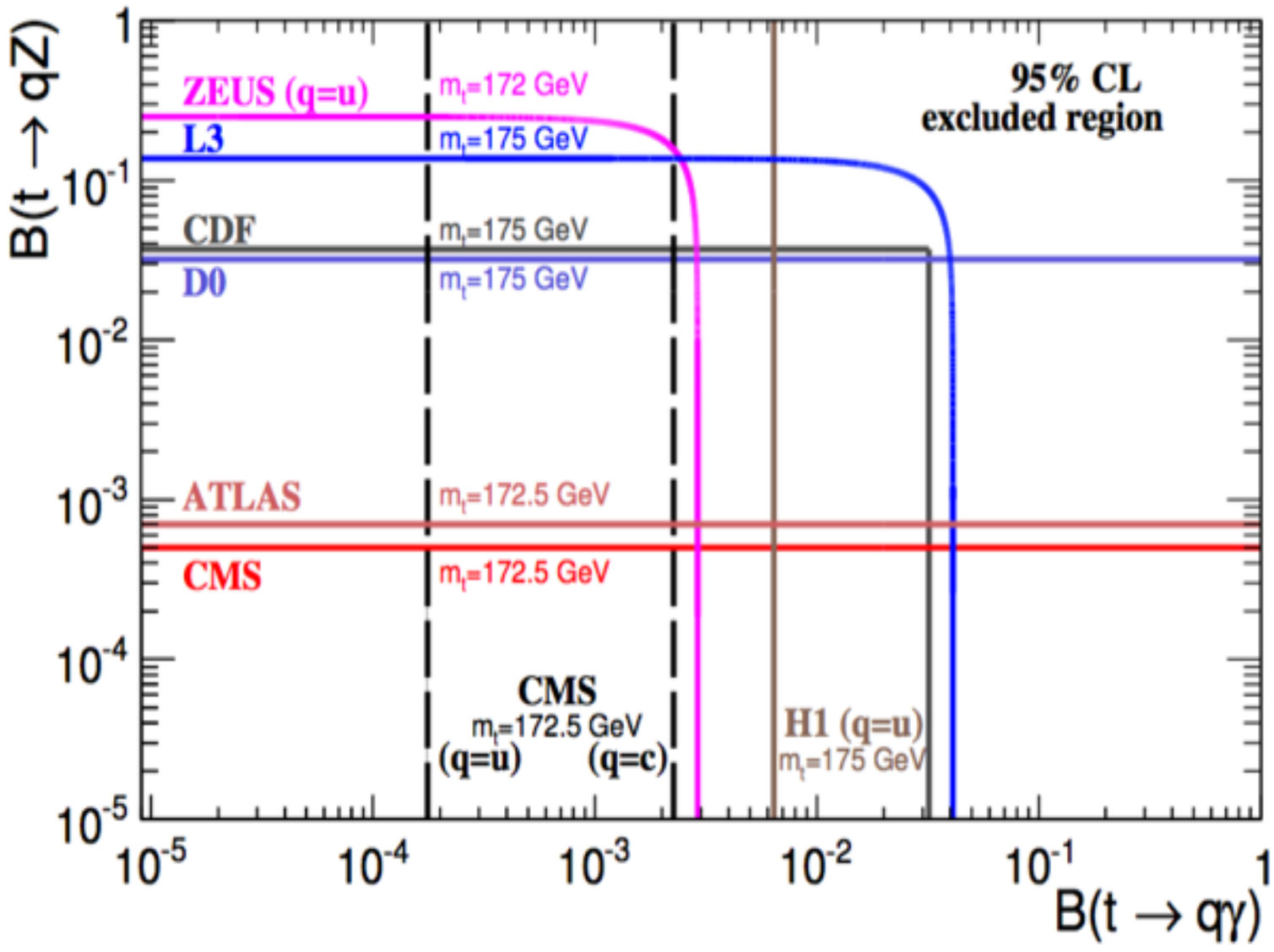
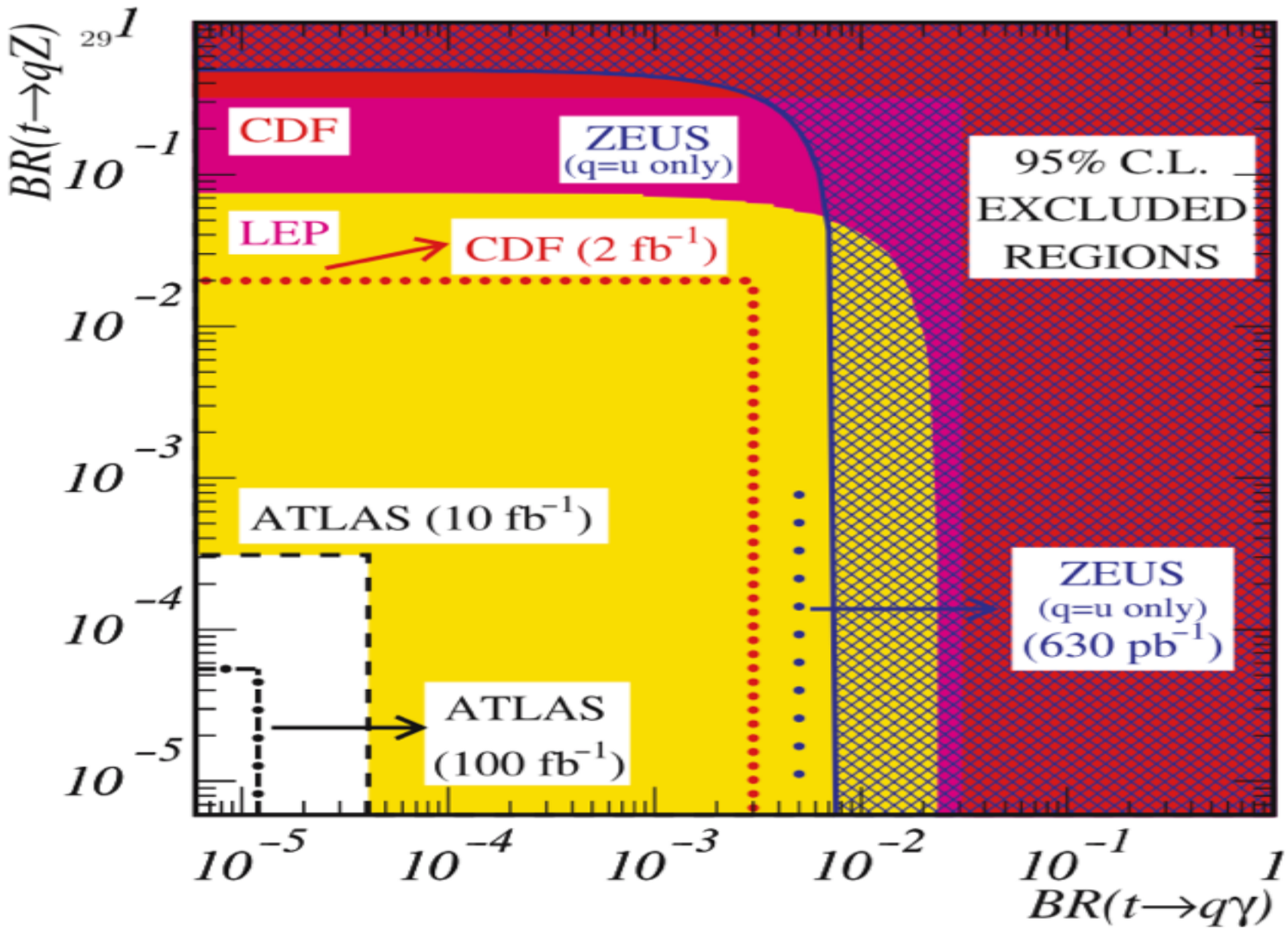
Current experimental limits on tqγ and tqZ



The measured upper limits on B(t→qZ) versus B(t→qγ) from different experiments. The two vertical dashed lines show recent results of the analysis of CMS experiment [CMS Collaboration, JHEP04 (2016) 035].



The 95% CL limits on the BR(t→qγ) vs. BR(t→qZ) plane are shown by ATLAS. The expected sensitivity at the HERA (L=630 pb^{-1}), Tevatron (Run II) and LHC is also represented [ATLAS Collaboration, Eur. Phys. J. C 52, 999–1019 (2007)].

Some issues to mention:

Searches for FCNC top quark couplings have been pursued by various experiments for many years. These include:

- constraints on tqγ and tqZ couplings from LEP data
- limits on tqγ couplings improved from HERA data, comparable sensitivity as tqZ couplings
- given the large number of top pairs at Tevatron, the FCNC decay channels were used to probe tqγ and tqZ couplings, however tqg decay channel suffer from large QCD background
- direct single top production (qg->t, more sensitivity), single top production associated with a jet (less sensitivity) at Tevatron
- after discovery of the SM Higgs boson at the LHC, the ATLAS and CMS experiments have searched for FCNC tqH couplings, and place improved exclusion limits on top FCNC tqV and tqH couplings.

Some issues to mention:

- the LHC has also the physics potential for γγ and γp collisions, this feature (photoproduction) offers some possibility to test the EW properties of SM and probe new BSM scenarios
- presence of extra pp interactions per bunch crossing - pileup issues in high luminosity can effect the signal and background separation
- gluon initiated process qg—>t—>Wb has been analyzed first by ATLAS Collaboration (2016) and set experimental limits on tqg couplings; and a similar analysis through photon initiated processes qγ—>t—>Wb by adding single top (tq, tγ, tqγ) contributions to the signal region has been performed with the fast simulation and using 20.3 fb^{-1} of data they obtained BR(t—>uγ)<0.05% and BR(t—>cγ)<0.14% if all signal channels related to FCNC tqγ are combined by Ref. [R.Goldouzian and B.Clerbaux (2017)].

Comments on lower energy (electron beam) run

- Ee=40 GeV and Ep=7 TeV for LHeC

- Ee=40 GeV and proton beam energy Ep=50 TeV for FCC-eh

Thank you for attention!