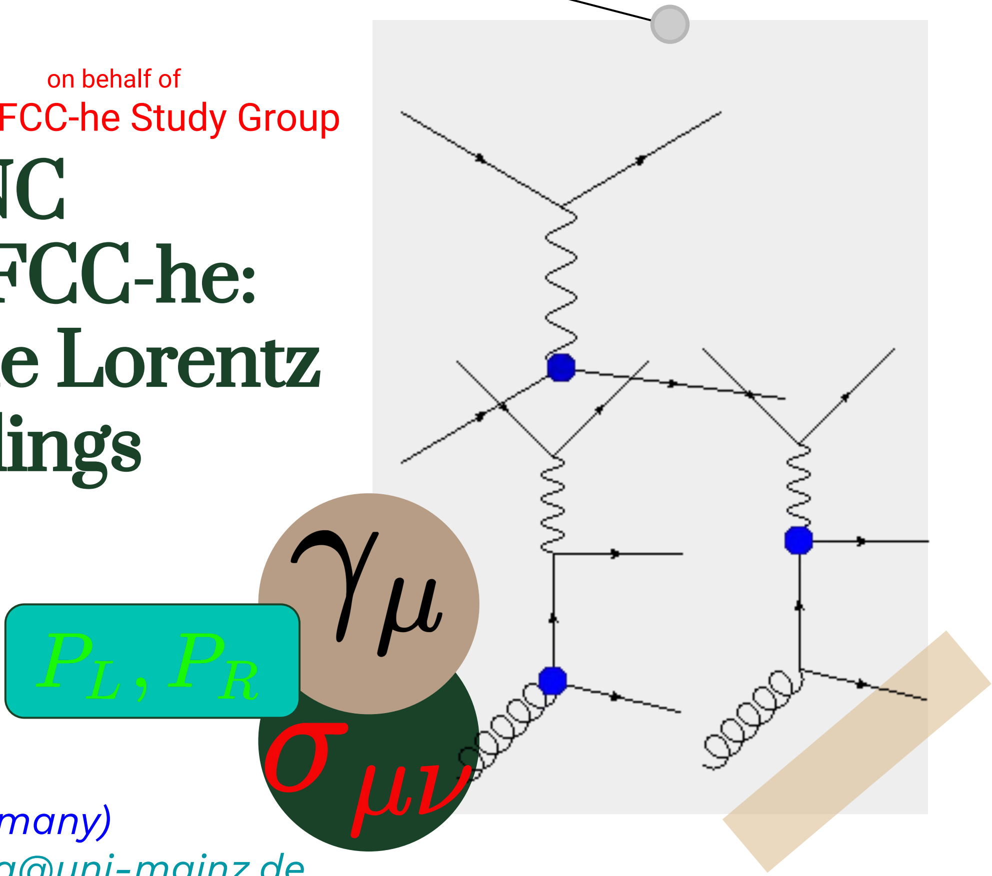
on behalf of
LHeC/FCC-he Study Group

Study of Top Quark FCNC Processes at LHeC and FCC-he: An Attempt to analyse the Lorentz structure of FCNC couplings

30 July, 2021

Based on, Ref: [PRD 100, 015006 (2019), arXiv-2007.02236 S. Behera]



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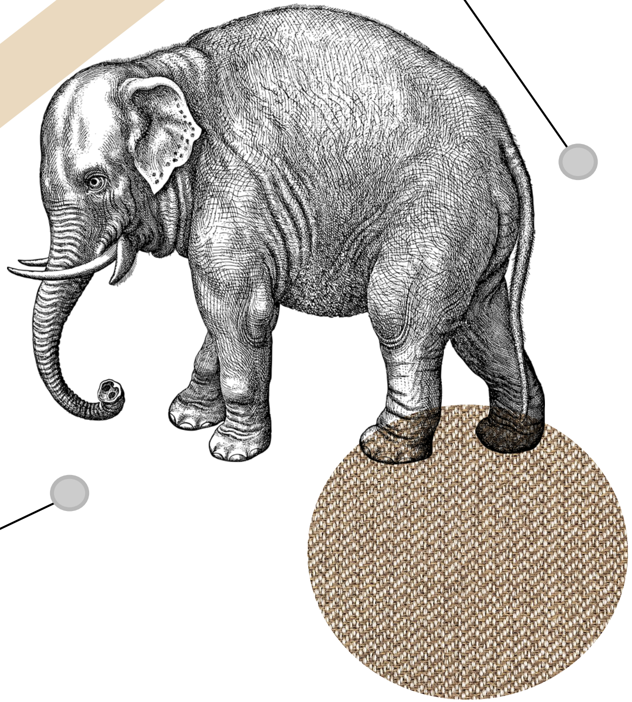
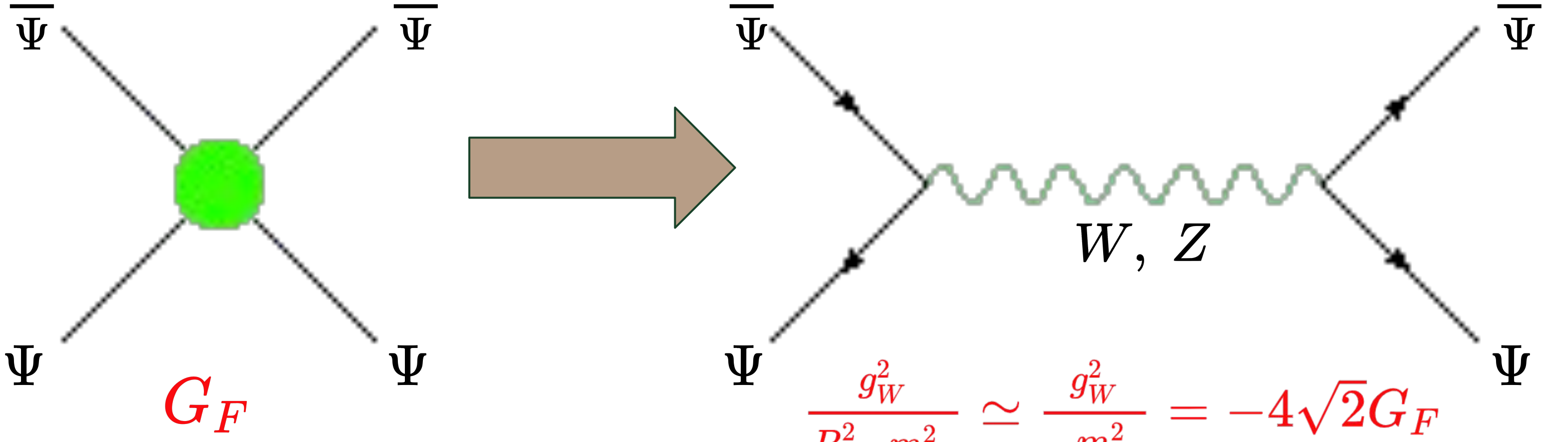
01
Theory I

:EFT Lagrangian, Vector and Tensor couplings



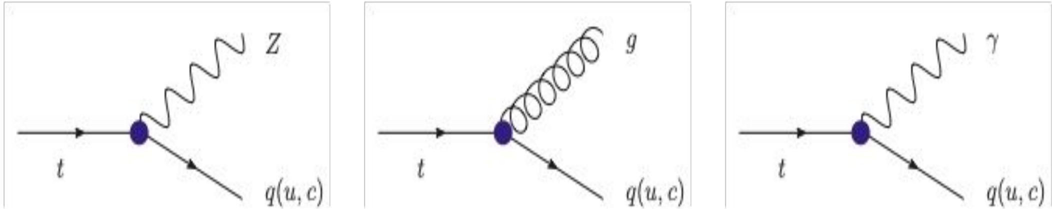
EFT: Why and How?



$$\frac{g_W^2}{P^2 - m_W^2} \simeq \frac{g_W^2}{-m_W^2} = -4\sqrt{2}G_F$$

- If the energy scale of new physics is beyond the reach of recent experiments
- Parameterising lack of information in terms of higher mass dimension operators

Lagrangian for our Study



The complete Effective Lagrangian for top FCNC: [AguilarSaavedra:2008zc]

$$
\begin{aligned}
-\mathcal{L}_{\text{fcnc}} =& g_s \bar{q} \lambda^a \frac{i\sigma^{\mu\nu} q_\nu}{\Lambda} (\kappa^L_{gqt} P_L + \kappa^R_{gqt} P_R) t G^a_\mu \\
&+ e\bar{q} \frac{i\sigma^{\mu\nu} q_\nu}{\Lambda} (\kappa^L_{\gamma qt} P_L + \kappa^R_{\gamma qt} P_R) t A_\mu \\
&+ \frac{g}{2c_W} \bar{q} \gamma^\mu (X^L_{zqt} P_L + X^R_{zqt} P_R) t Z_\mu \\
&+ \frac{g}{2c_W} \bar{q} \frac{i\sigma^{\mu\nu} q_\nu}{\Lambda} (\kappa^L_{zqt} P_L + \kappa^R_{zqt} P_R) t Z_\mu + \text{H.c},
\end{aligned}
$$

Where, $q(\bar{q}) = u(\bar{u}), c(\bar{c})$ and $q_\nu = (P_t - P_q)$ is the momentum transferred.

FCNC Decay width

$$\Gamma_T(t \to qg) = \frac{2\alpha_s}{3}|\kappa_{gqt}^{L,R}|^2 \frac{m_t^3}{\Lambda^2},$$

$$\Gamma_T(t \to q\gamma) = \frac{\alpha}{2}|\kappa_{\gamma qt}^{L,R}|^2 \frac{m_t^3}{\Lambda^2},$$

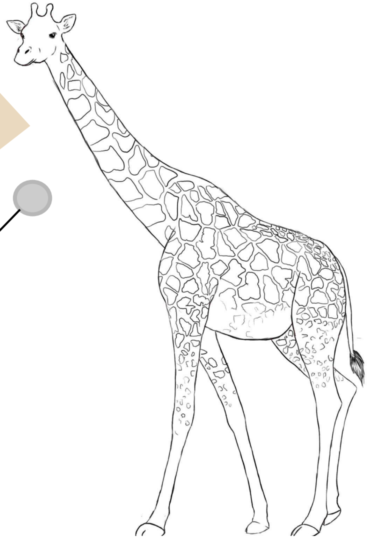
$$\Gamma_V(t \to qZ) = \frac{\alpha}{32 s_W^2 c_W^2}|X_{zqt}^{L,R}|^2 \frac{m_t^3}{M_Z^2}\left[1 - \frac{M_Z^2}{m_t^2}\right]^2\left[1 + 2\frac{M_Z^2}{m_t^2}\right],$$

$$\Gamma_T(t \to qZ) = \frac{\alpha}{16 s_W^2 c_W^2}|\kappa_{zqt}^{L,R}|^2 \frac{m_t^3}{\Lambda^2}\left[1 - \frac{M_Z^2}{m_t^2}\right]^2\left[2 + \frac{M_Z^2}{m_t^2}\right],$$

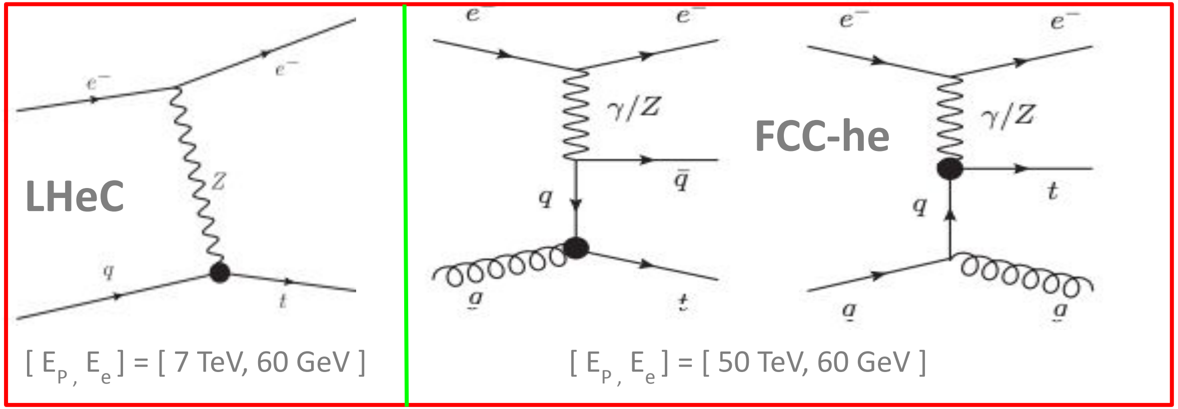
The subscript (T) and (V) represents the decay width involving either a vector or a tensor coupling, respectively.

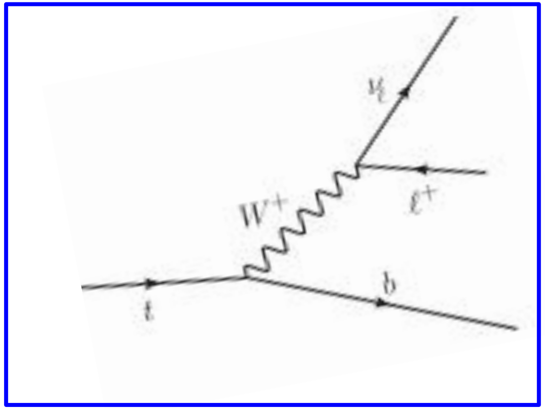
02
Theory II

:Density matrix and Polarization parameters, Asymmetries



Density Matrix Formalism





The top quark on-shell condition in the NWA allows one to write the differential cross section of the complete process as:

$$\frac{1}{\sigma_t}\frac{d\sigma_t}{d\Omega_t} = \frac{1}{4\pi}\sum_{\lambda,\lambda'} \sigma(\lambda,\lambda')\Gamma(\lambda,\lambda')$$

$$\sigma(\lambda,\lambda') = \frac{1}{\sigma_{\text{prod}}}\int \rho(\lambda,\lambda')\, d\Omega_t\,,$$

Density Matrix Formalism

Polarization Vector: $\mathbf{P} = (P_x, P_y, P_z)$

The normalized production density matrix elements can be written as:

$$\sigma(+,+) = \frac{1}{2}(1 + P_z) \qquad \sigma(+,-) = \frac{1}{2}(P_x + iP_y)$$

$$\sigma(-,-) = \frac{1}{2}(1 - P_z) \qquad \sigma(-,+) = \frac{1}{2}(P_x - iP_y)$$

The normalized decay density matrix elements can be written as:

$$\Gamma(+,+) = \frac{1}{2}(1 + cos\theta_l) \qquad \Gamma(+,-) = \frac{1}{2}sin\theta_l\, e^{i\phi_l}$$

$$\Gamma(-,-) = \frac{1}{2}(1 - cos\theta_l) \qquad \Gamma(-,+) = \frac{1}{2}sin\theta_l\, e^{-i\phi_l}$$

Where, θ_l and ϕ_l are the polar and azimuthal angle of the secondary lepton in the **top quark rest frame**.

Polarization Parameters & Spin observables

$$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma}{d\Omega_\ell} = \frac{1}{4\pi}\Big(1 + P_z \cos\theta_\ell + P_x \sin\theta_\ell \cos\phi_\ell + P_y \sin\theta_\ell \sin\phi_\ell\Big)$$

Observables

$$A_x \equiv \frac{1}{\sigma_{\rm tot}}\left[\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\phi_\ell \frac{d\sigma}{d\phi_\ell} - \int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} d\phi_\ell \frac{d\sigma}{d\phi_\ell}\right] = \frac{1}{2}P_x$$

$$A_y \equiv \frac{1}{\sigma_{\rm tot}}\left[\int_{0}^{\pi} d\phi_\ell \frac{d\sigma}{d\phi_\ell} - \int_{\pi}^{2\pi} d\phi_\ell \frac{d\sigma}{d\phi_\ell}\right] = \frac{1}{2}P_y,$$

$$A_z \equiv \frac{1}{\sigma_{\rm tot}}\left[\int_{0}^{1} dc_{\theta_\ell} \frac{d\sigma}{dc_{\theta_\ell}} - \int_{-1}^{0} dc_{\theta_\ell} \frac{d\sigma}{dc_{\theta_\ell}}\right] = \frac{1}{2}P_z$$

Top quark Rest frame

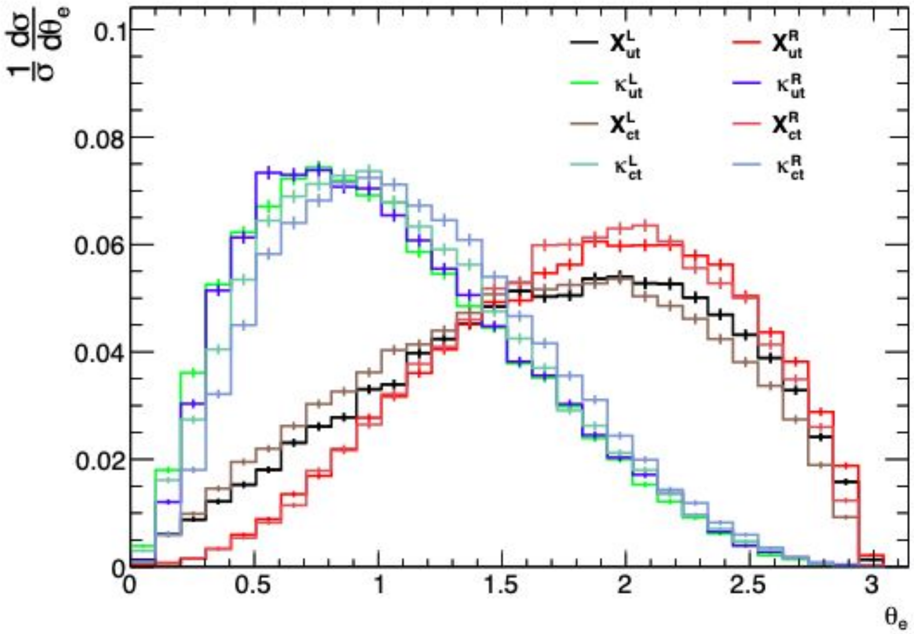
&

Lab frame of the collider

$$A_e^{FB} \equiv \frac{\sigma(\cos\theta_e>0)-\sigma(\cos\theta_e<0)}{\sigma(\cos\theta_e>0)+\sigma(\cos\theta_e<0)}$$

Ref: [PRD 100, 015006 (2019), arXiv-2007.02236 S. Behera]

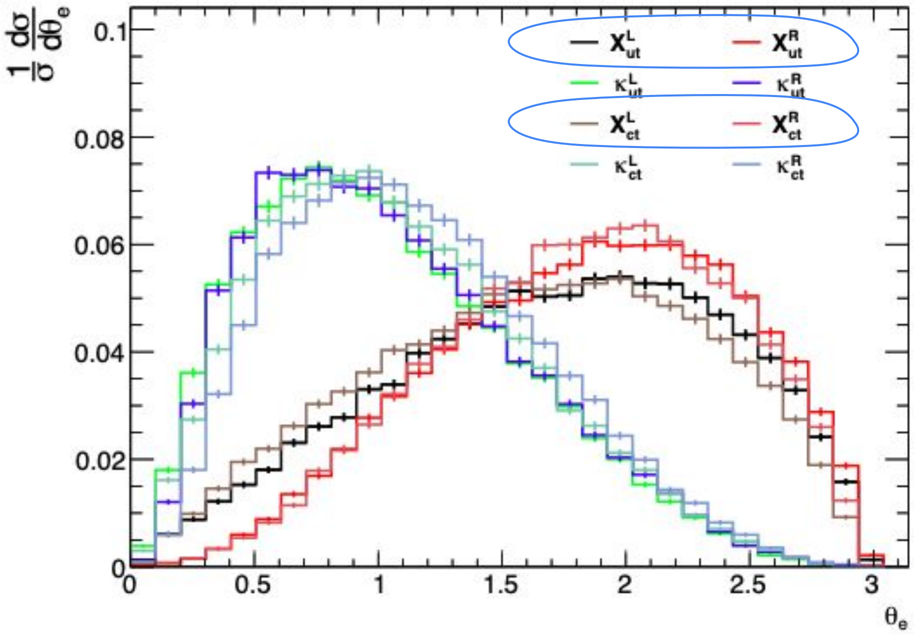
Polarization Parameters & Spin observables



The distributions of polar angle of the scattered electron in the **Lab Frame** of the collider.

➔ The Distributions clearly shows the distinction between the vector and tensor couplings.

Polarization Parameters & Spin observables



The distributions of polar angle of the scattered electron in the **Lab Frame** of the collider.

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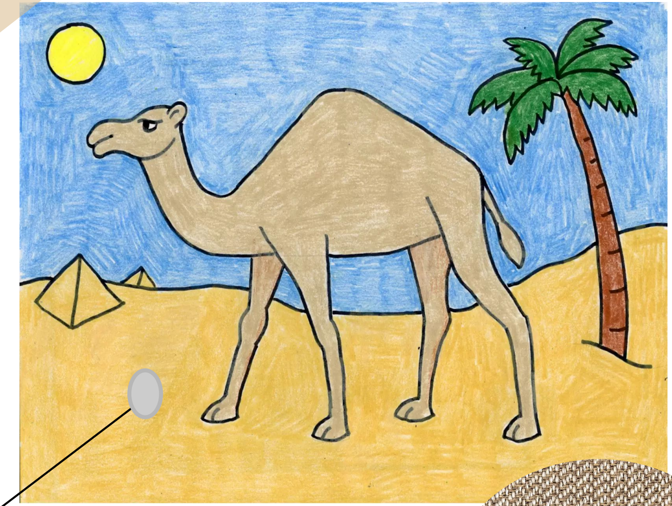
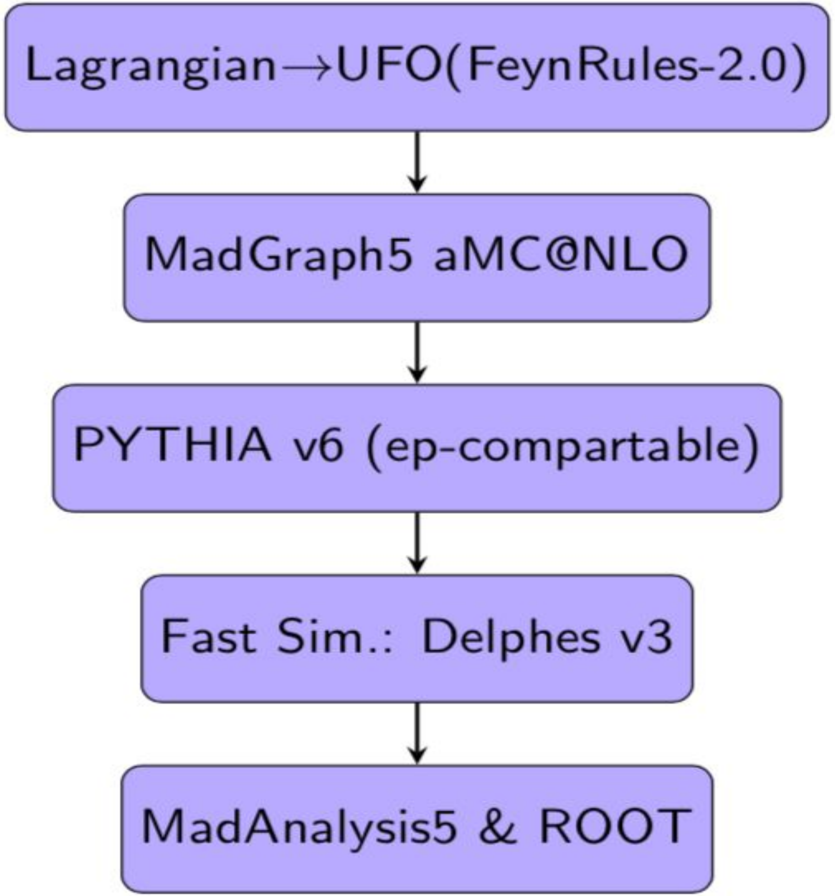
03
Simulation & Analysis

:MadGraph5, Pythia6 and Root for Cut Based approach



Methodology



- MC setup/Observables
  - PDF set: CTEQ6L1, μF=μR=mt,
  - Preselection: P_T > 10 for leptons, jets and E_T^{Miss} > 10 GeV, |η| < 5. For all jets and leptons
  - Leptons and/or Jets are reconstructed with anti-kT algorithm with cone size of R = 0.4
- Selection Cuts [tZq - analysis]
  - $N_{e-} = N_{e-,\ b\text{-}jet} = N_{e-,\ b\text{-}jet,\ l+} = 1$
- Selection Cuts [tgq & $t_{\gamma}q$ - analysis]
  - $N_{e-} = N_{e-,\ b\text{-}jet} = N_{e-,\ b\text{-}jet,\ mu+/mu-} = 1$
  - $N_{Light\text{-}jets} >= 1$
  - Yμ>2.6

CS and Selection Cuts

LHeC

Coupling g_{Ztq}	Cross section σ in fb for $P_e = -80\%$			
	Basic Cuts	$N_{e^-} = 1$	$N_{e^-,b} = 1$	$N_{e^-,b,\ell^+} = 1$
X^L_{ut}	1957.57	1763.82	799.65	745.57
X^R_{ut}	1642.47	1485.97	706.09	629.54
κ^L_{ut}	706.77	636.65	304.56	279.13
κ^R_{ut}	1038.68	933.47	474.90	427.77
X^L_{ct}	136.76	122.54	66.90	62.84
X^R_{ct}	103.82	93.05	51.26	47.65
κ^L_{ct}	26.37	23.65	12.96	12.09
κ^R_{ct}	60.00	53.33	29.70	27.45

Bkg processes	$N_{e^-,b,\ell^+} = 1$
Charged Current int.	0.63
Neutral Current int.	0.00
Photo Production int.	1.64

FCC-he

Coupling	κ^L_{gut}	κ^R_{gut}	$\kappa^L_{\gamma ut}$	$\kappa^R_{\gamma ut}$	κ^L_{gct}	κ^R_{gct}	$\kappa^L_{\gamma ct}$	$\kappa^R_{\gamma ct}$	Bkg
$e^-p \to e^-tj \to e^-bj\ell^+\nu$ (both e^+ and μ^+ included)									
Basic Cuts	1058.0	1113.2	3198.0	3190.0	498.5	546.2	1420.2	1420.0	485.0
$N_{e^-} = N_{\ell^+} = N_b = 1,\ N_j \geqslant 1$	515	550.0	1631.7	1623.2	245.9	271.5	728.1	737.0	8.5
$Y_{\mu^+} > 2.6$	290.1	287.6	530.3	715.8	105.4	82.8	155.9	219.0	0.023
$e^-p \to e^-\bar{t}j \to e^-j\mu^-\nu$									
Basic Cuts	259.4	266.1	831.7	829.1	244.0	248.8	709.4	708.9	485.0
$N_{e^-} = N_{\mu^-} = N_b = 1,\ N_j \geqslant 1$	146.4	150.1	467.7	480.1	130.6	128.8	374.1	376.6	4.8
$Y_{\mu^-} > 2.6$	65.8	53.6	102.5	151.0	58.3	47.2	79.6	118.2	0.009

The CS of signal processes are parameterized as follow:

$$\sigma = |g_{Vtq}|^2 [\sigma(pe^- \to e^- t(j)) \times BR(t \to \ell^+ + b - taggedjet + MET)]$$

Spin Observables

LHeC

Left-polarized e-beam

Coupling	A_x	A_z	A_e^{FB}
X^L	−0.16	−0.43	−0.18
κ^L	−0.17	−0.46	+0.63
X^R	+0.07	+0.32	−0.33
κ^R	+0.04	+0.37	+0.65

Right-polarized e-beam

Coupling	A_x	A_z	A_e^{FB}
X^L	−0.06	−0.43	−0.34
κ^L	−0.01	−0.46	+0.64
X^R	+0.16	+0.32	−0.17
κ^R	+0.16	+0.37	+0.65

Unpolarized e-beam

Coupling	A_x	A_z	A_e^{FB}
X^L	−0.12	−0.43	−0.24
κ^L	−0.12	−0.46	+0.64
X^R	+0.11	+0.32	−0.26
κ^R	+0.08	+0.36	+0.65

FCC-he

Coupling	No pol.			$P_{e^-} = -80\%$			$P_{e^-} = +80\%$		
	A_x	A_z	$A_{e^-}^{FB}$	A_x	A_z	$A_{e^-}^{FB}$	A_x	A_z	$A_{e^-}^{FB}$
κ^L_{gut}	-0.20	–	-0.22	-0.27	–	-0.28	-0.21	–	-0.20
κ^R_{gut}	0.14	0.40	-0.15	0.16	0.42	-0.23	0.11	0.41	-0.16
$\kappa^L_{\gamma ut}$	-0.33	-0.12	–	-0.31	-0.11	–	-0.30	-0.16	–
$\kappa^R_{\gamma ut}$	–	0.46	–	–	0.47	–	–	0.48	–

Top quark

Coupling	No pol.			$P_{e^-} = -80\%$			$P_{e^-} = +80\%$		
	A_x	A_z	$A_{e^-}^{FB}$	A_x	A_z	$A_{e^-}^{FB}$	A_x	A_z	$A_{e^-}^{FB}$
κ^L_{gut}	-0.35	0.26	-0.48	-0.32	0.28	-0.48	-0.34	0.19	-0.46
κ^R_{gut}	–	0.33	-0.39	–	0.41	-0.47	–	0.32	-0.35
$\kappa^L_{\gamma ut}$	-0.44	–	-0.25	-0.43	–	-0.28	-0.45	–	-0.28
$\kappa^R_{\gamma ut}$	-0.11	0.54	-0.44	-0.14	0.56	-0.37	–	0.53	-0.39

Anti-Top quark

Limits on FCNC couplings

LHeC | **FCC-he**

$$L = 2\ ab^{-1}$$

Vector Coupling	Obtainable reach (in part of 10^3) at C.L. = 68%	95%	99%
X^L_{ut}	$\in [-9.8, 9.7]$	$\in [-16.4, 16.4]$	$\in [-20.0, 20.1]$
X^R_{ut}	$\in [-13.7, 13.6]$	$\in [-20.8, 20.9]$	$\in [-24.4, 24.4]$
X^L_{ct}	$\in [-30.8, 31.1]$	$\in [-52.8, 52.7]$	$\in [-65.7, 65.5]$
X^R_{ct}	$\in [-48.0, 47.3]$	$\in [-73.0, 72.7]$	$\in [-85.9, 86.8]$

Tensor Coupling	Obtainable reach (TeV^{-1}) at C.L. = 68%	95%	99%
κ^L_{ut}/Λ	$\in [-0.06, 0.06]$	$\in [-0.10, 0.10]$	$\in [-0.13, 0.13]$
κ^R_{ut}/Λ	$\in [-0.07, 0.07]$	$\in [-0.12, 0.12]$	$\in [-0.16, 0.15]$
κ^L_{ct}/Λ	$\in [-0.23, 0.23$	$\in [-0.40, 0.40]$	$\in [-0.50, 0.50]$
κ^R_{ct}/Λ	$\in [-0.31, 0.31]$	$\in [-0.57, 0.56]$	$\in [-0.71, 0.72]$

Beam polarization	Associated quark	Background events, N_B	Required signal, $N_S(2\sigma)$	Reach of couplings for 95% CL. (TeV^{-1}) κ^L_{gqt}/Λ	κ^R_{gqt}/Λ	$\kappa^L_{\gamma qt}/\Lambda$	$\kappa^R_{\gamma qt}/\Lambda$
Unpolarized	up	46	16	0.029	0.029	0.021	0.019
	charm			0.048	0.054	0.040	0.033
(−80%)	up	34	14	0.028	0.027	0.022	0.017
	charm			0.043	0.037	0.036	0.025
(+80%)	up	28	13	0.030	0.030	0.022	0.019
	charm			0.050	0.056	0.041	0.035

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Limits on FCNC couplings

LHeC

$L = 2\ ab^{-1}$

	BR % ($t \to Zu$)		BR % ($t \to Zc$)
$X^L_{ut} = 0.016$	0.009	$X^L_{ct} = 0.053$	0.095
$X^R_{ut} = 0.021$	0.015	$X^L_{ct} = 0.073$	0.181
$\frac{\kappa^L_{ut}}{\Lambda} = 0.10\ \text{TeV}^{-1}$	0.004	$\frac{\kappa^L_{ct}}{\Lambda} = 0.40\ \text{TeV}^{-1}$	0.068
$\frac{\kappa^R_{ut}}{\Lambda} = 0.12\ \text{TeV}^{-1}$	0.006	$\frac{\kappa^R_{ct}}{\Lambda} = 0.57\ \text{TeV}^{-1}$	0.133

$L = 1\ ab^{-1}$

Coupling	BR % ($t \to Zu$)	Coupling	BR % ($t \to Zc$)
$X^L_{zut} = 0.005$	0.051	$X^L_{zct} = 0.013$	0.444
$X^R_{zut} = 0.005$	0.064	$X^R_{zct} = 0.017$	0.754
$\frac{\kappa^L_{zut}}{\Lambda} = 0.035\ \text{TeV}^{-1}$	0.030	$\frac{\kappa^L_{zct}}{\Lambda} = 0.123\ \text{TeV}^{-1}$	0.377
$\frac{\kappa^R_{zut}}{\Lambda} = 0.041\ \text{TeV}^{-1}$	0.043	$\frac{\kappa^R_{zct}}{\Lambda} = 0.172\ \text{TeV}^{-1}$	0.739

FCC-he

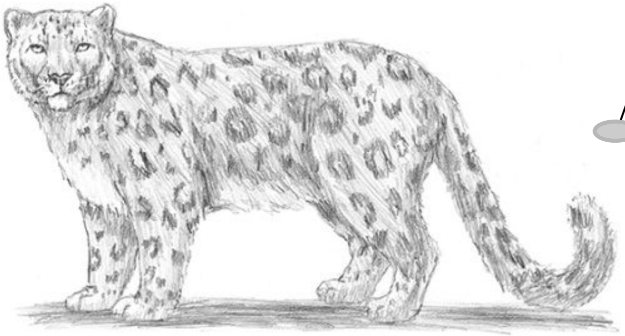
$L = 2\ ab^{-1}$

Coupling	BR $\times 10^5$			
	$t \to ug$	$t \to cg$	$t \to u\gamma$	$t \to c\gamma$
κ^L_{Vqt}/Λ	1.8	4.3	0.74	1.9
κ^R_{Vqt}/Λ	1.7	3.1	0.44	0.95

LHC

BR limits on 95% C.L.	8/13 TeV	3 ab^{-1}, 14 TeV	15 ab^{-1}, 27 TeV
$t \to gu$	$4.0(20) \times 10^{-5}$	3.8×10^{-6}	5.6×10^{-7}
$t \to gc$	..	32.1×10^{-6}	10^{-7}
$t \to Zq$	$1.7(2.4) \times 10^{-4}$	$2.4 - 5.8 \times 10^{-5}$	
$t \to \gamma u$	0.016(0.182)%	8.6×10^{-6}	
$t \to \gamma c$	..	7.4×10^{-5}	
$t \to Hq$	–	10^{-4}	

04 Concluding Remarks



Concluding Remarks

- At the LHC, the top quark FCNC are studied mostly by searching for rare decay of the top quark, whereas at LHeC and FCC-he, we can probe these couplings influencing the production itself.
- Study of the vertex structure is very much favourable at the future ep - collider for EW processes in particular
- Only t-channel, EW processes are possible at the production
- Scattered electron from the primary vertex gives extra handle to probe internal structure
- Top quark polarization can be utilized effectively

Summary

Our studies consolidate further the strong case of LHeC/FCC-he for better understanding of the top quark properties and FCNC couplings.

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Thanks for your attentions!