Charged Lepton Flavor Violation at the EIC

Bin Yan
Los Alamos National Laboratory

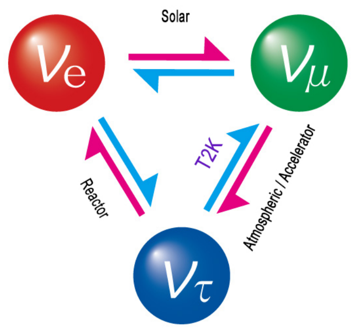
DIS2021
April 12-16, 2021

With V. Cirigliano, K. Fuyuto, C. Lee and E. Mereghetti, JHEP 03 (2021) 256

Charged Lepton Flavor Violation

Lepton Flavor is not conserved:

Neutrino Oscillations

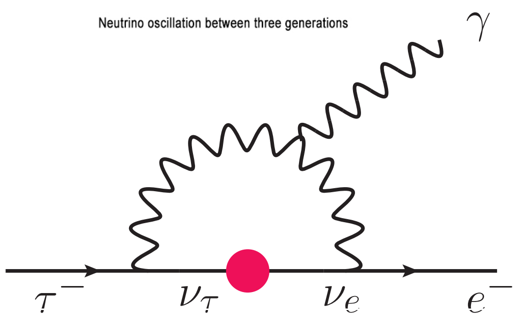


Neutrino oscillation between three generations

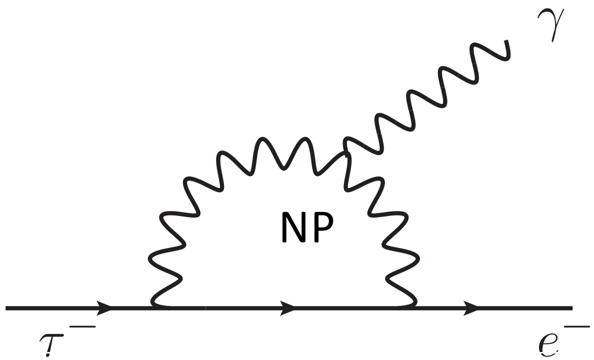
Charged Lepton Flavor Violation (CLFV):

$$BR \sim \left(\frac{m_\nu}{m_W}\right)^2 \sim 10^{-44}$$

S. Petcov, '77; W. Marciano and A. Sanda, '77



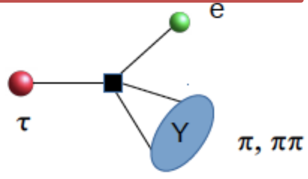
A. CLFV is sensitive to the NP
B. CLFV could be related to the neutrino mass generation mechanism;
   Tree level or Loop level

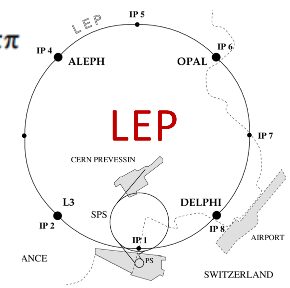


For example: Two loop neutrino mass model
QHC, SLC, E. Ma, Bin Yan, DMZ, PLB779 (2018)430-435

Charged Lepton Flavor Violation

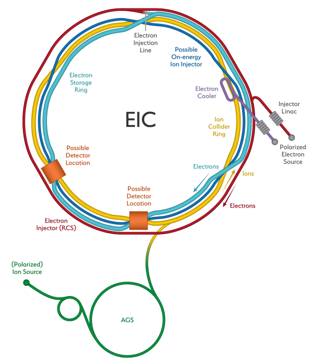
Focus on tau lepton

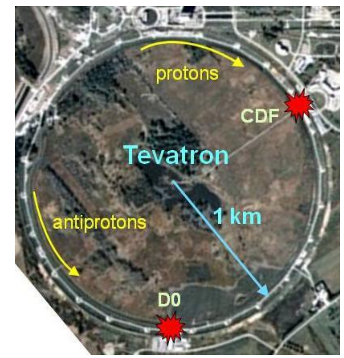




LEP

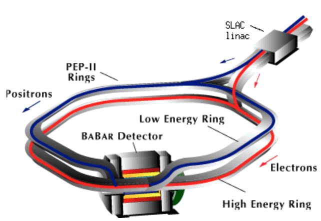
EIC

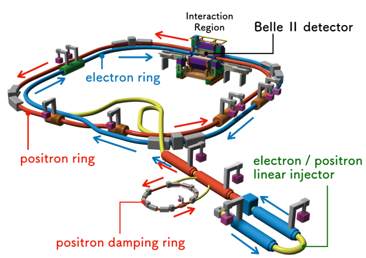


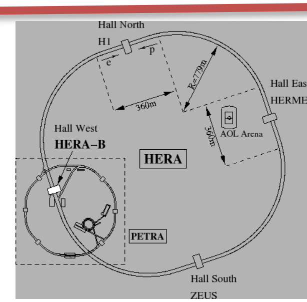


Low energy observables

High energy observables

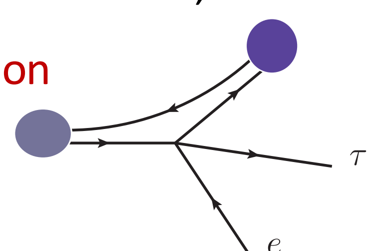




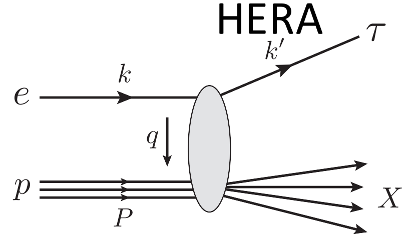


Babar, Bell II

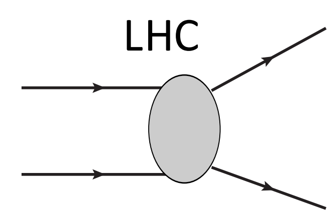
Meson



HERA

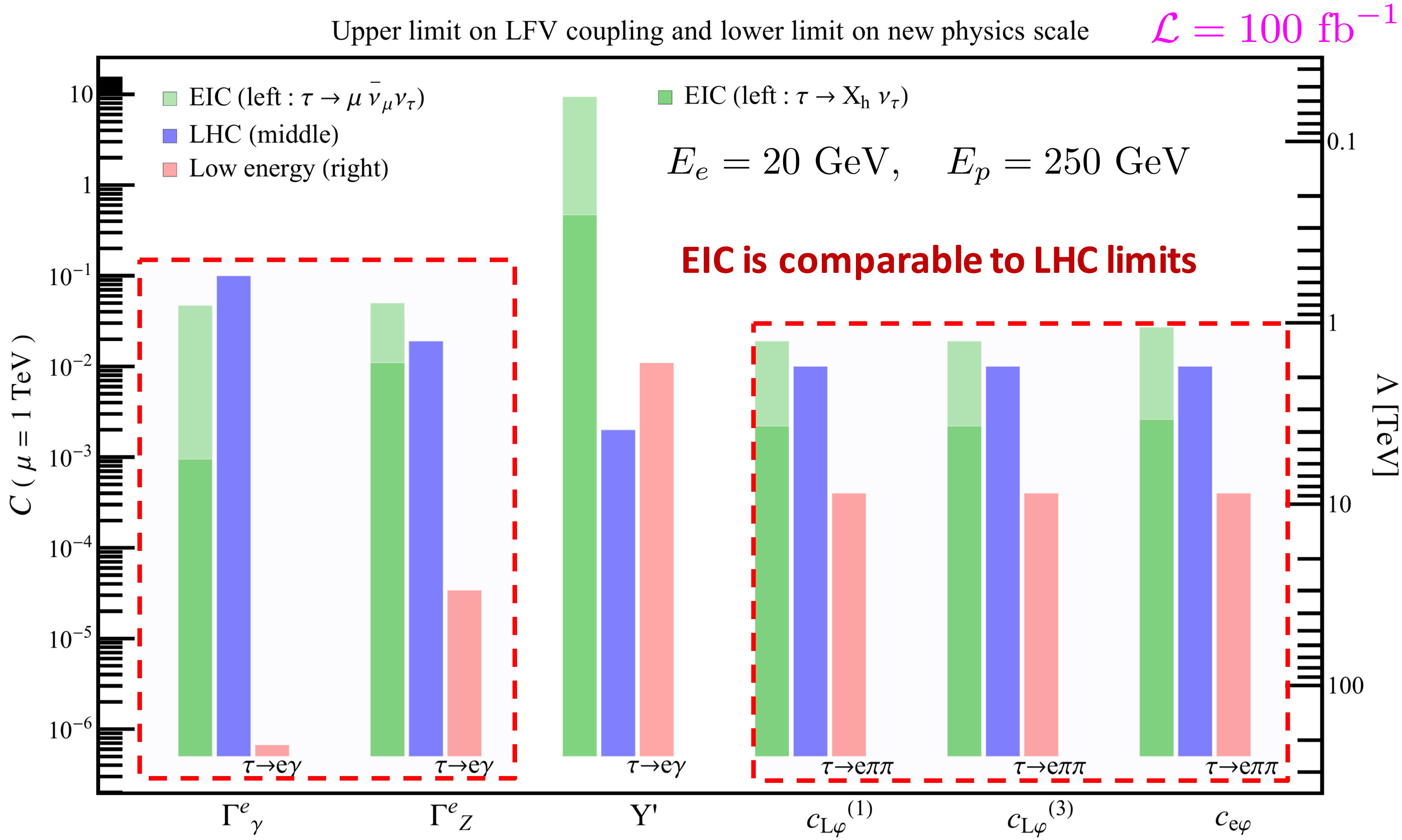


LHC



The first Global Picture

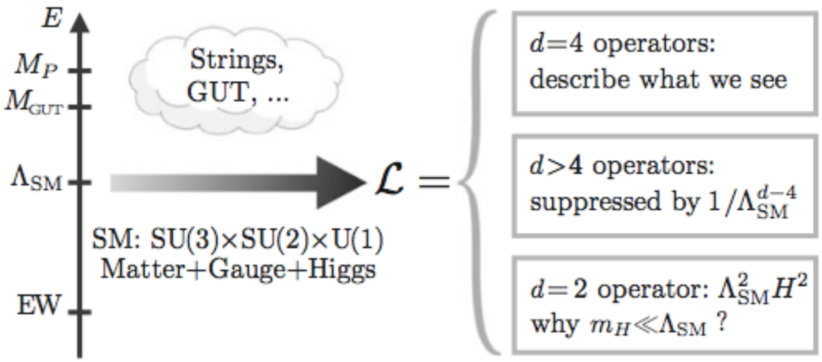
For example: Dipole, Yukawa and Vector/Axial vector current



CLFV and EFT

Linear realized EFT

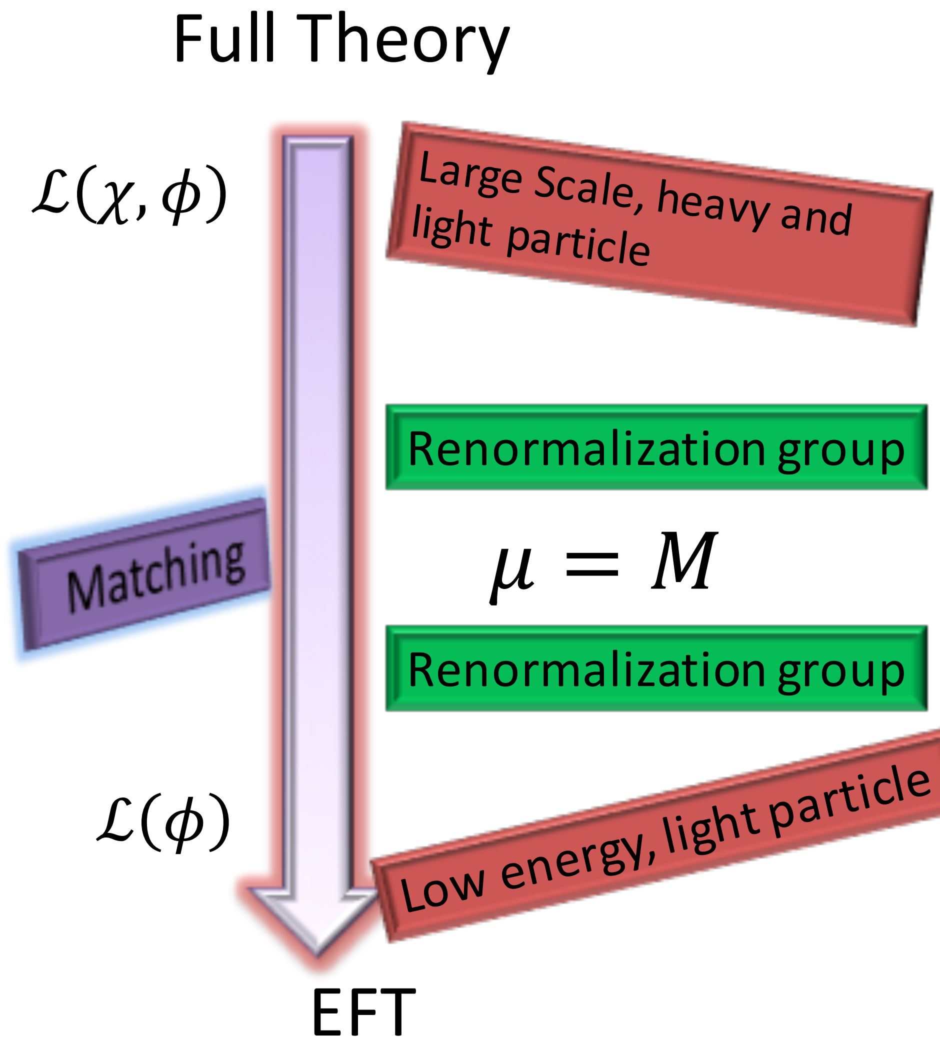
Higgs is a fundamental particle
Weak interacting



Appelquist-Carazzone Decoupling theorem:

W. Buchuller, D. wyler 1986
B. Grzadkowski et al, 2010
L. Lehman, A. Marin, 2015
B. Henning et al, 2015
H-L. Li et al, 2020

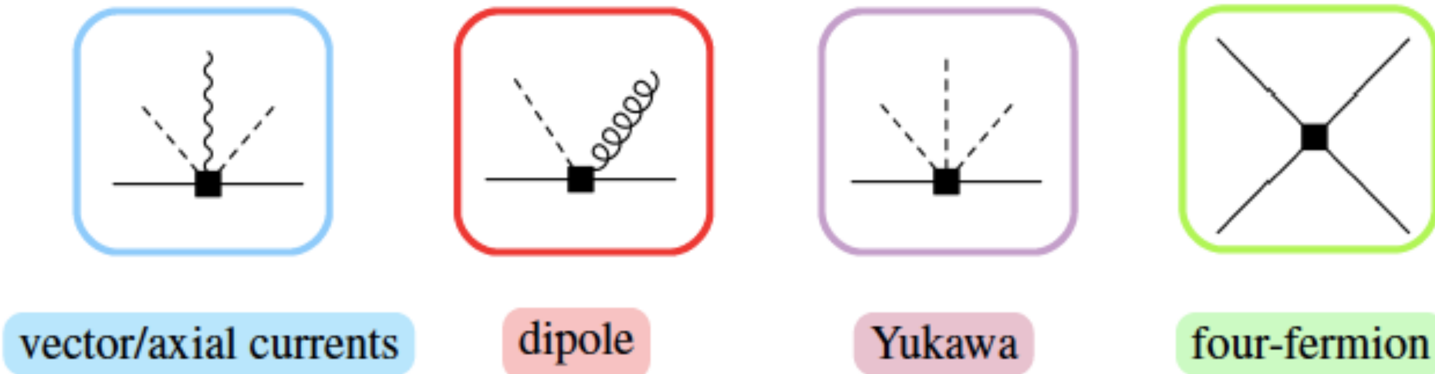
$$\mathcal{L} = C_6 O_6 + C_8 O_8 + \dots$$



Howard Georgi, Annu.Rev.Nucl.Part.Sci.1993.43:209-52

CLFV and EFT

Four types operators:



For example:

$$\mathcal{L} = -\frac{g}{2c_W} Z_\mu \left[\left(c_{L\varphi}^{(1)} + c_{L\varphi}^{(3)} \right)_{\tau e} \bar{\tau}_L \gamma^\mu e_L + c_{e\varphi} \bar{\tau}_R \gamma^\mu e_R \right]$$
$$-\frac{e}{2v} [\Gamma_\gamma^e]_{\tau e} \bar{\tau}_L \sigma^{\mu\nu} e_R F_{\mu\nu} - \frac{g}{2c_W v} [\Gamma_Z^e]_{\tau e} \bar{\tau}_L \sigma^{\mu\nu} e_R Z_{\mu\nu}$$

Four-fermion operatrors:
we assume the generic quark flavor structures

$$[C_{Ld}]_{\tau e} = \begin{pmatrix} [C_{Ld}]_{dd} & [C_{Ld}]_{ds} & [C_{Ld}]_{db} \\ [C_{Ld}]_{sd} & [C_{Ld}]_{ss} & [C_{Ld}]_{sb} \\ [C_{Ld}]_{bd} & [C_{Ld}]_{bs} & [C_{Ld}]_{bb} \end{pmatrix}$$

CLFV and EFT

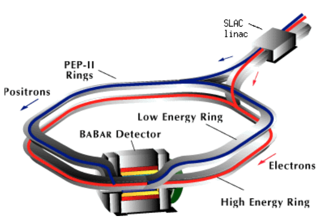
Low energy observables

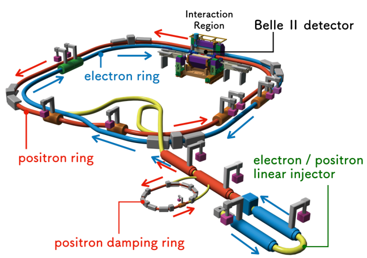
Few GeV

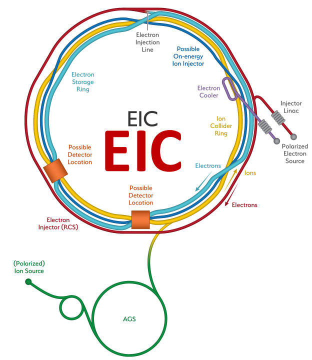
100 GeV

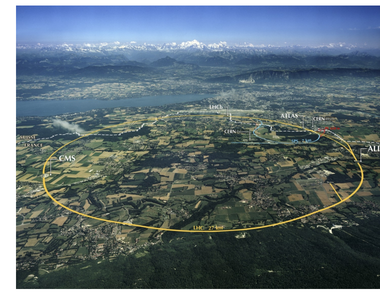
Few TeV

High energy observables







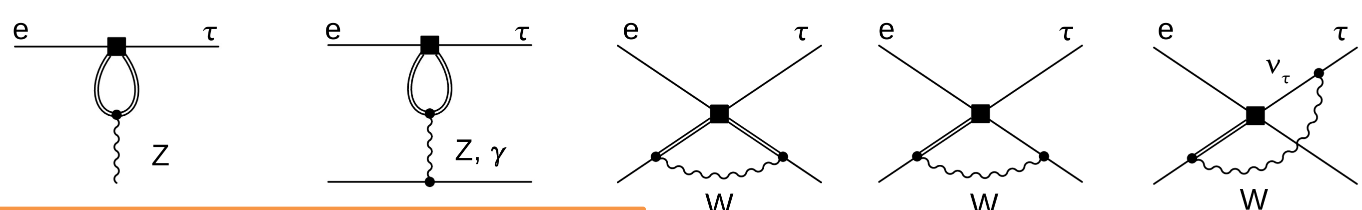


Babar, Bell II

LHC

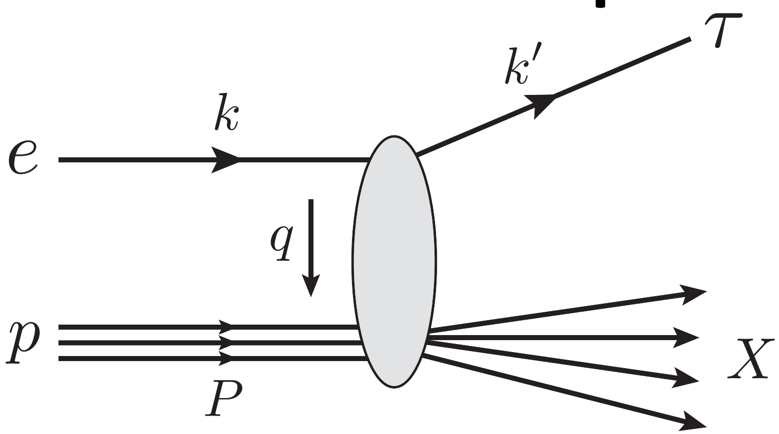
The RG running effects should be included

The operator mixing effects: double lines: top quark



To constrain the top quark component

DIS production @EIC



$$x = \frac{Q^2}{2P.q}, \quad y = \frac{P.q}{P.p_e}$$

The generic cross section:

Unpolarized Cross Section

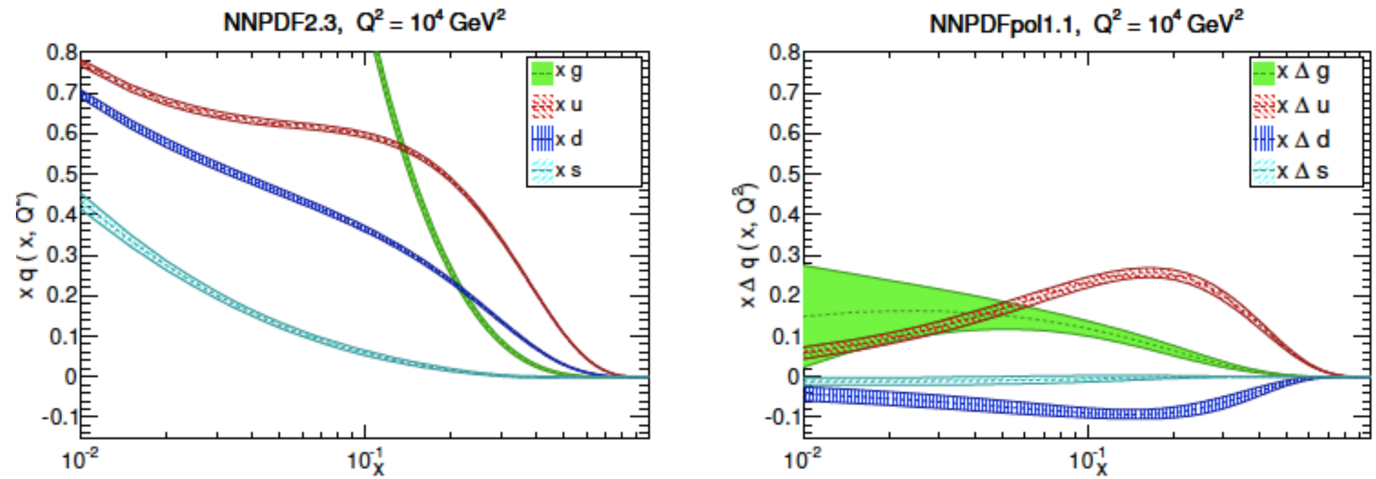
$$\frac{1}{\sigma_0}\frac{d\sigma_{\lambda_e\lambda_T}}{dx\,dy} = \frac{1}{2}\sum_a \left[\frac{1-\lambda_e}{2}\left(\hat{\sigma}^a_{\mathrm{LL}} + \hat{\sigma}^a_{\mathrm{LR}}\right) + \frac{1+\lambda_e}{2}\left(\hat{\sigma}^a_{\mathrm{RL}} + \hat{\sigma}^a_{\mathrm{RR}}\right)\right] f_a(x, Q^2)$$
$$+\frac{1}{2}\sum_a \left[\frac{1-\lambda_e}{2}\left(-\hat{\sigma}^a_{\mathrm{LL}} + \hat{\sigma}^a_{\mathrm{LR}}\right) + \frac{1+\lambda_e}{2}\left(-\hat{\sigma}^a_{\mathrm{RL}} + \hat{\sigma}^a_{\mathrm{RR}}\right)\right] \lambda_T \Delta f_a(x, Q^2)$$

Polarized Cross Section

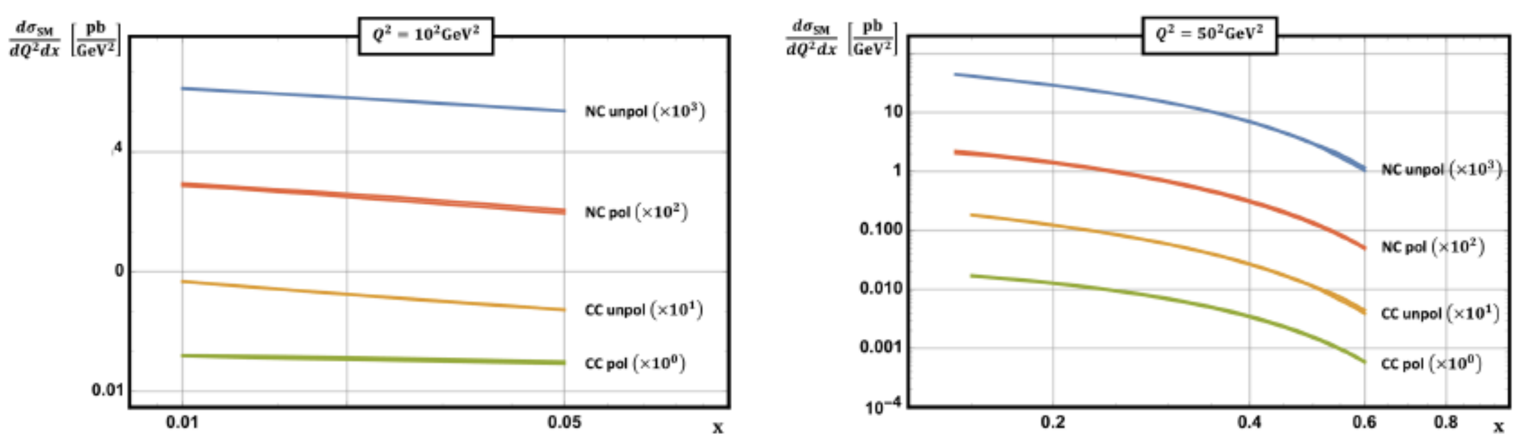
λ_e, λ_T polarization of electron and proton

Polarized and unpolarized cross section

B. Fuks, J. Proudom, J. Rojo and I. Schienbein, JHEP05(2014)045

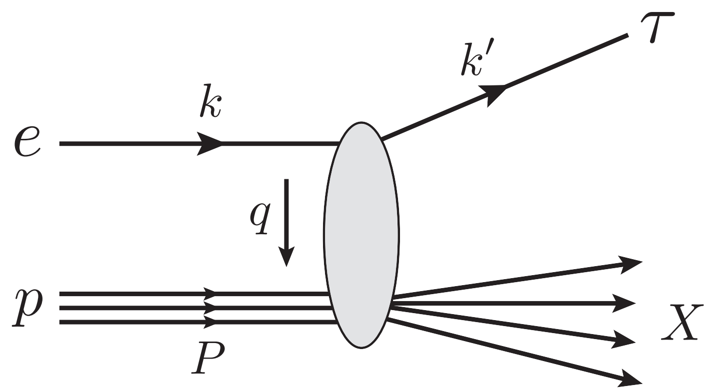


R. Boughezal, F. Petriello, D. Wiegand, arxiv: 2004.00748



Polarized cross section was suppressed by PDF and we will focus on the unpolarized case

Collider analysis @ EIC



Signal: $E_e = 20\ \mathrm{GeV}, \quad E_p = 250\ \mathrm{GeV}$

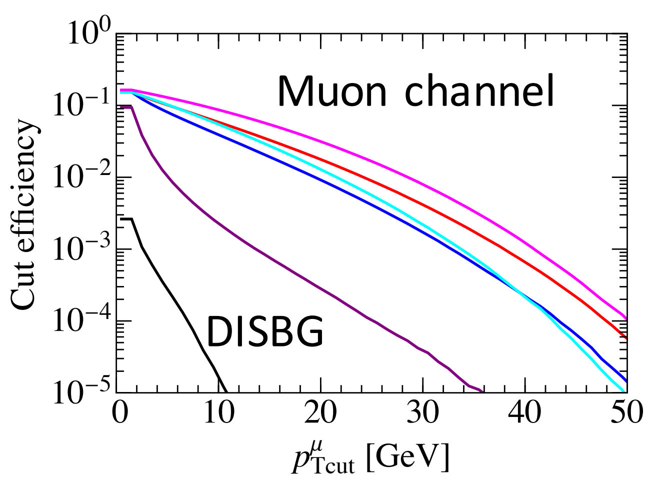
$$(1) e^- p \to \tau^- X \to e^- \bar{\nu}_e \nu_\tau X;$$

$$(2) e^- p \to \tau^- X \to \mu^- \bar{\nu}_\mu \nu_\tau X;$$

$$(3) e^- p \to \tau^- X \to \nu_\tau\, X_h\, X$$

Background: SM DIS production

The electron and hadronic decay channels would be challenge due to the large backgrounds; Background cut efficiency: $\epsilon_{\mathrm{cut}} \sim \mathcal{O}(10^{-4})$



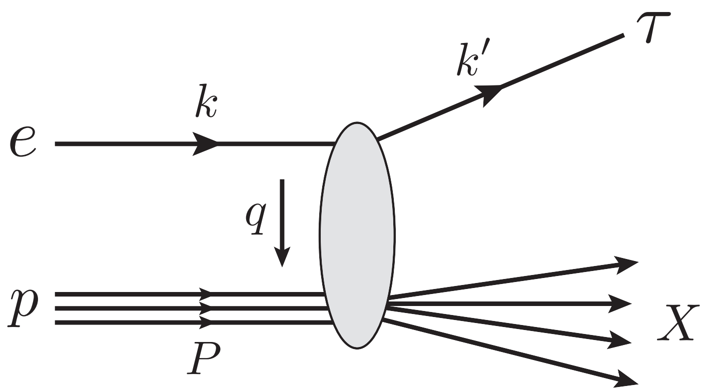
Based on Pythia8+Delphes

$$p_T^\mu > 10\ \mathrm{GeV}, \quad p_T^{j1} > 20\ \mathrm{GeV}$$

$$\not{E}_T > 15\ \mathrm{GeV}, \quad |\eta_{\mu,j1}| < 3.$$

Background free process

The sensitivity of CLFV@ EIC

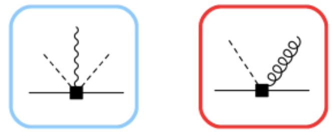


(1) The cut efficiencies are sensitive to the quark flavor in the initial state;
(2) The cut efficiencies are not sensitive to the polarization of tau lepton

τ_L	$(C_{LQ,U})_{uu}$	$(C_{LQ,U})_{cc}$	$(C_{LQ,D})_{dd}$	$(C_{LQ,D})_{ss}$	$(C_{LQ,D})_{bb}$	$c^{(1)}_{L\varphi} + c^{(3)}_{L\varphi}$
$\epsilon_{\rm cut}(\%)$	9.9	2.6	5.8	3.2	0.91	4.9
τ_R	$(C_{eu})_{uu}$	$(C_{eu})_{cc}$	$(C_{ed})_{dd}$	$(C_{ed})_{ss}$	$(C_{ed})_{bb}$	$C_{e\varphi}$
$\epsilon_{\rm cut}(\%)$	9.6	2.5	5.6	3.1	0.85	3.3
	$(C_{GG})_{\tau e}$	$(\Gamma^e_\gamma)_{\tau e}$	$(\Gamma^e_Z)_{\tau e}$	$(C_{GG})_{e\tau}$	$(\Gamma^e_\gamma)_{e\tau}$	$(\Gamma^e_Z)_{e\tau}$
$\epsilon_{\rm cut}(\%)$	6.8	0.15	19	6.4	0.15	18

The sensitivity of CLFV@ LHC

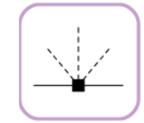
(1) Z and Higgs decays



ATLAS: arxiv:2010.02566

vector/axial currents dipole

$$\mathrm{BR}(Z \to e\tau) < 8.1 \times 10^{-6}$$

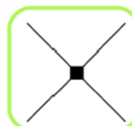


ATLAS: PLB 800 (2020)135069

Yukawa

$$\mathrm{BR}(H \to e\tau) < 4.7 \times 10^{-3}$$

(2) Top quark decays

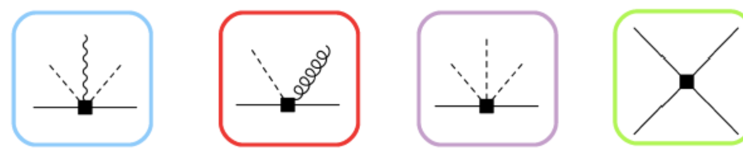


four-fermion

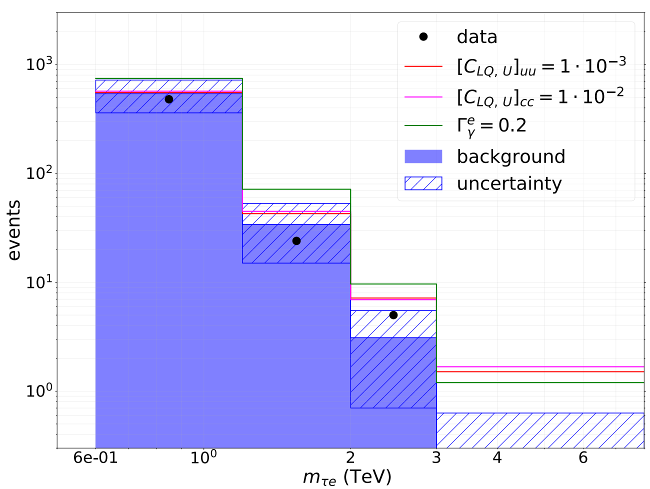
ATLAS-CONF-2018-044

$$\mathrm{BR}(t \to qe\tau) < 2.2 \times 10^{-4}$$

(3) High invariant mass Drell-Yan



vector/axial currents dipole Yukawa four-fermion



POWHEG + Pythia8 + Delphes @NLO

ATLAS: EPJC 76 (2016) 10,541

$$\mathcal{L} = 36\ \mathrm{fb}^{-1} @ 13\ \mathrm{TeV}$$

The sensitivity of CLFV@ low energy

Observable	Upper limit on BR (90% C.L.)
$\tau^- \to e^-\gamma$	$< 3.3 \times 10^{-8}$
$\tau^- \to e^-e^+e^+$	$< 2.7 \times 10^{-8}$
$\tau^- \to e^-\mu^+\mu^-$	$< 2.7 \times 10^{-8}$
$\tau^- \to e^-\pi^0$	$< 8.0 \times 10^{-8}$
$\tau^- \to e^-\eta$	$< 9.2 \times 10^{-8}$
$\tau^- \to e^-\eta'$	$< 1.6 \times 10^{-7}$
$\tau^- \to e^-K_S^0$	$< 2.6 \times 10^{-8}$
$\tau^- \to e^-\pi^+\pi^-$	$< 2.3 \times 10^{-8}$
$\tau^- \to e^-\pi^+K^-$	$< 3.7 \times 10^{-8}$
$\tau^- \to e^-\pi^-K^+$	$< 3.1 \times 10^{-8}$
$B^0 \to e^\pm\tau^\mp$	$< 2.8 \times 10^{-5}$
$B^+ \to \pi^+e^+\tau^-$	$< 7.4 \times 10^{-5}$
$B^+ \to \pi^+e^-\tau^+$	$< 2.0 \times 10^{-5}$
$B^+ \to K^+e^+\tau^-$	$< 4.3 \times 10^{-5}$
$B^+ \to K^+e^-\tau^+$	$< 1.5 \times 10^{-5}$

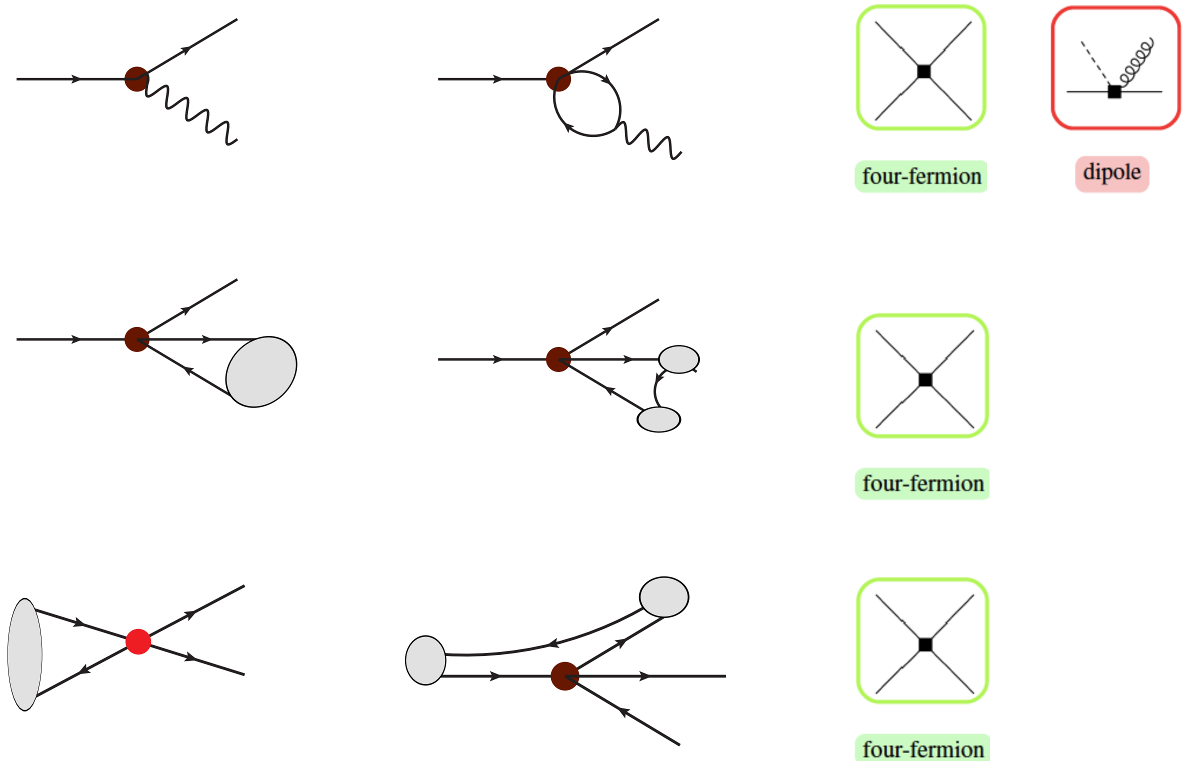
	BR (90% CL)
$\pi \to e\nu$	$(1.230 \pm 0.004) \cdot 10^{-4}$
$K \to e\nu$	$(1.582 \pm 0.007) \cdot 10^{-5}$
$D \to e\nu$	$< 8.8 \cdot 10^{-6}$
$D \to \tau\nu$	$(1.20 \pm 0.27) \cdot 10^{-3}$
$D_s \to e\nu$	$< 8.3 \cdot 10^{-5}$
$D_s \to \tau\nu$	$(5.48 \pm 0.23) \cdot 10^{-2}$
$B \to e\nu$	$< 9.8 \cdot 10^{-7}$
$B \to \mu\nu$	$(6.46 \pm 2.74) \cdot 10^{-7}$
$B \to \tau\nu$	$(1.09 \pm 0.24) \cdot 10^{-4}$

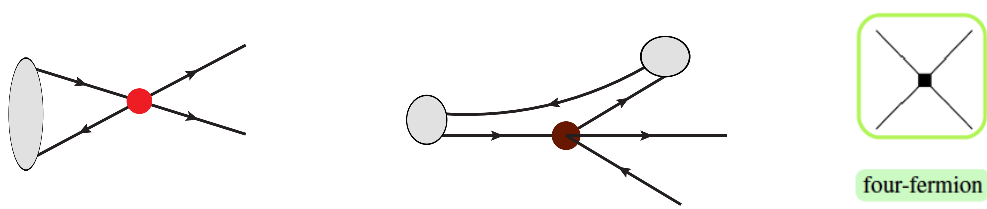
Indirect bounds

	BR (90% CL)
$K^+ \to \pi^+\nu\bar{\nu}$	$< 1.78 \cdot 10^{-10}$
$K_L \to \pi^0\nu\bar{\nu}$	$< 3.0 \cdot 10^{-9}$
$B^+ \to \pi^+\nu\bar{\nu}$	$< 1.4 \cdot 10^{-5}$
$B^+ \to K^+\nu\bar{\nu}$	$< 1.6 \cdot 10^{-5}$

The sensitivity of CLFV@ low energy

Examples:

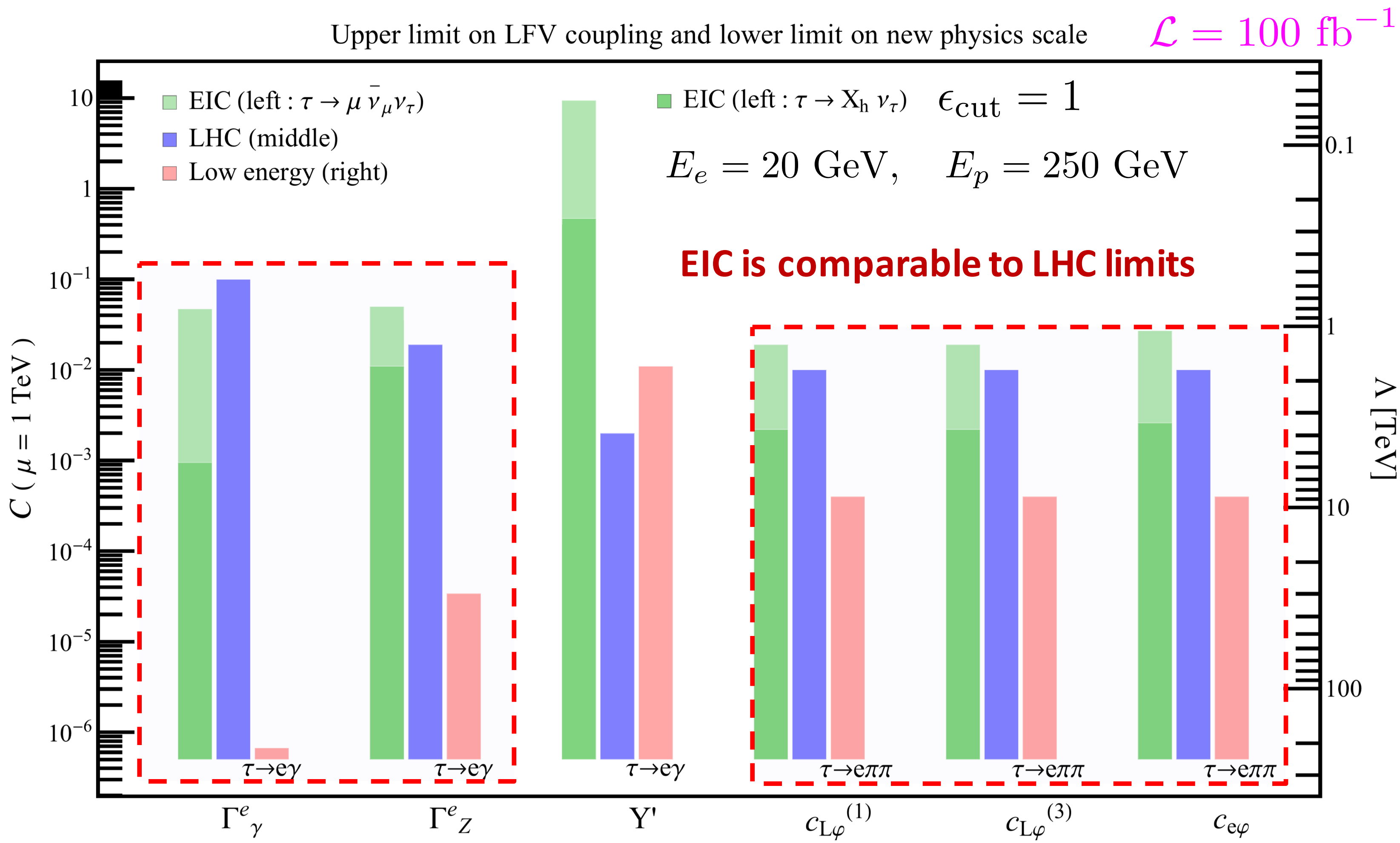




Indirect constraints

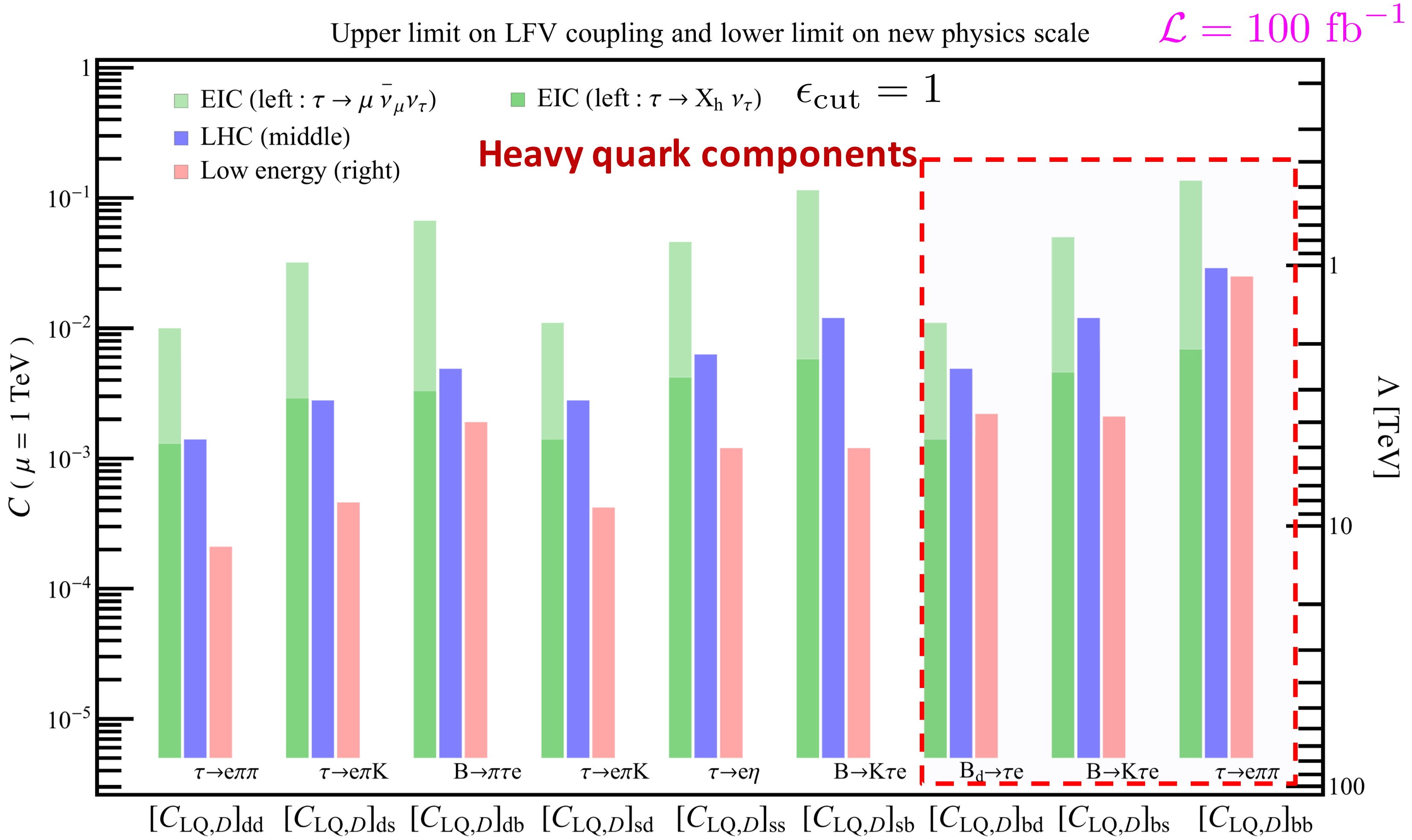
The sensitivity of CLFV

Dipole, Yukawa and Vector/Axial vector current



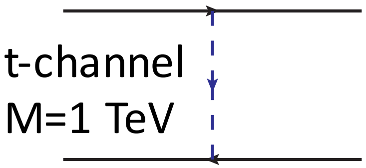
The sensitivity of CLFV

Four-Fermion operators

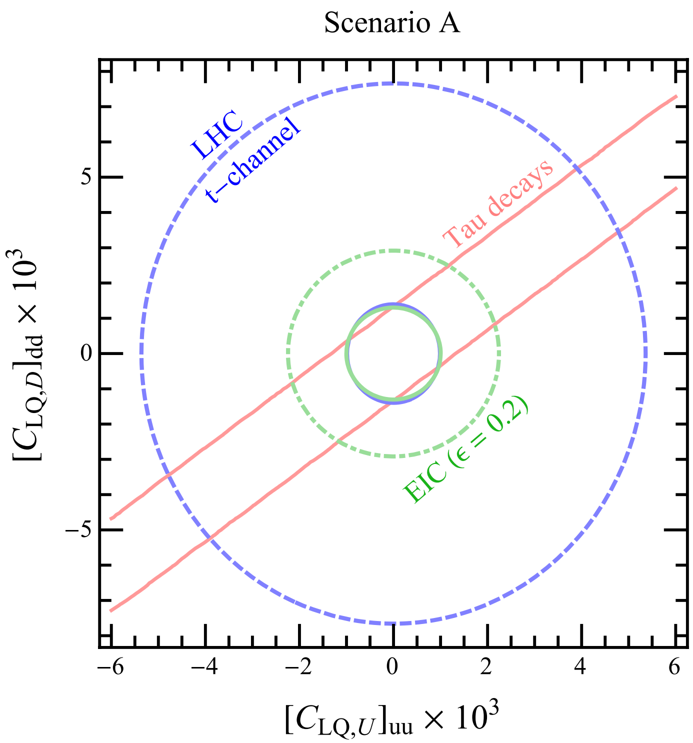


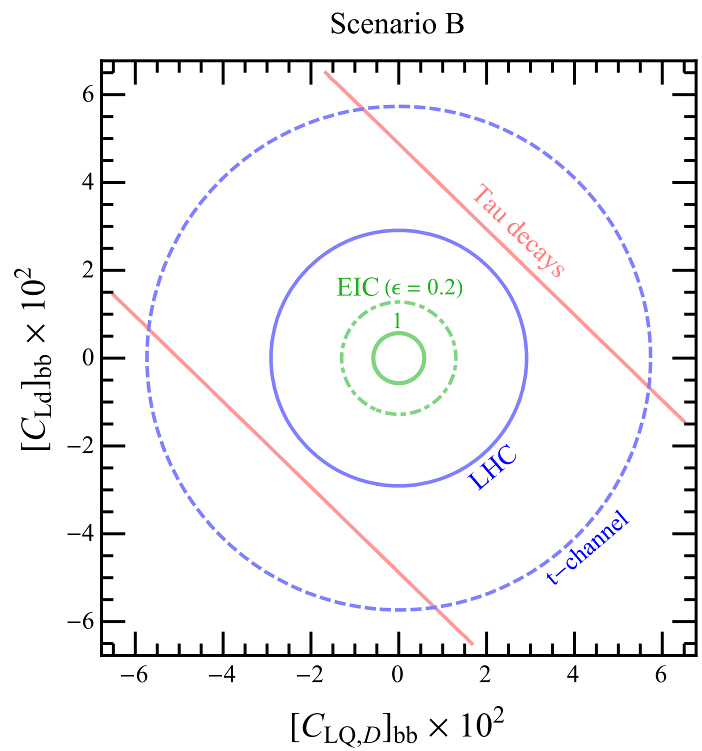
The sensitivity of CLFV@ low energy

Global analysis:



Scenario	Operators
A	$c_{L\varphi}^{(1,3)}$, $[C_{LQ,U}]_{uu}$, $[C_{LQ,D}]_{dd,ss}$, $[C_{Lu}]_{uu}$, $[C_{Ld}]_{dd,ss}$
B	$c_{L\varphi}^{(1,3)}$, $[C_{LQ,D}]_{dd,ss,bb}$, $[C_{Ld}]_{dd,ss,bb}$



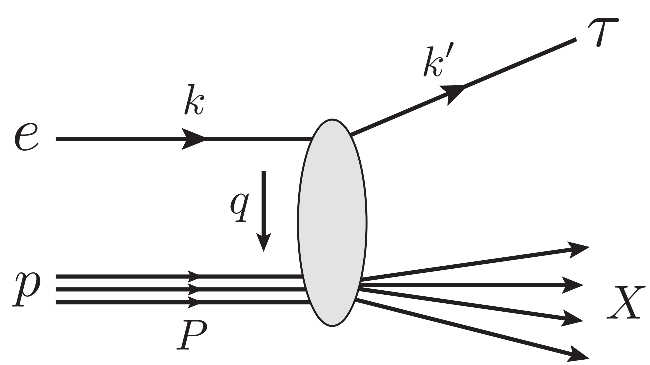


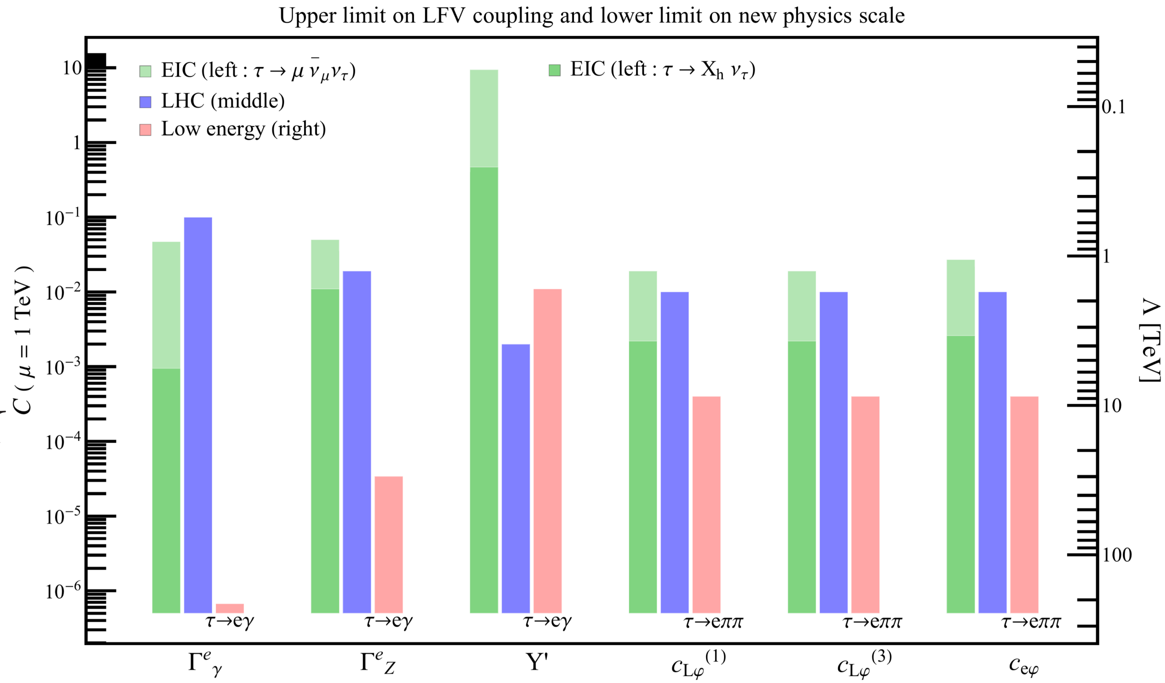
Summary

A. CLFV can unveil/constrain mechanism for neutrino mass generation;

B. EIC is an ideal machine to probe the CLFV effects;

C. EIC is competitive and complementary to LHC and B factories;





Thank you!