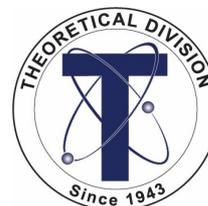# Lepton Flavor Violation Searches at the EIC

Kaori Fuyuto
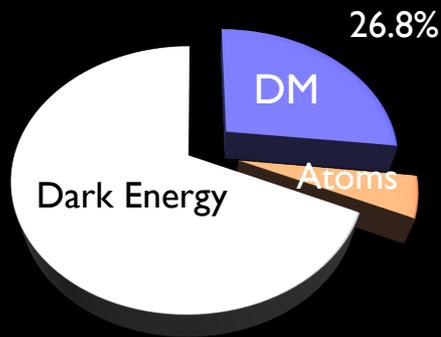
Los Alamos National Laboratory

V. Cirigliano, KF, C. Lee, E. Mereghetti, B. Yan, JHEP03(2021)256
S. Banerjee, V. Cirigliano, et al, Snowmass White Papaer, 2203.14919
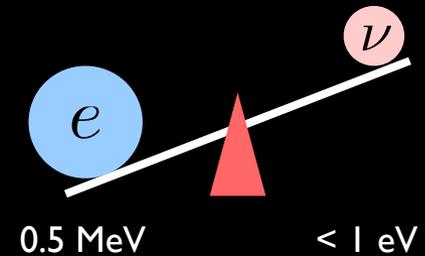F. Delzanno, KF, S. Gonzalez-Solis, E. Mereghetti, arXiv 2411.13497

March 19th, 2025
At Stony Brook U

We still don't know much about our Universe.

What is Dark Matter?

26.8%

DM

Atoms

Dark Energy

What is the origin of tiny neutrino mass ?

ν

e

0.5 MeV   < 1 eV

The origin of
the present Universe

Why is there more matter than antimatter? $\dfrac{n_b - n_{\bar{b}}}{n_\gamma} = 6.1 \times 10^{-10}$

Need Physics Beyond the Standard Model

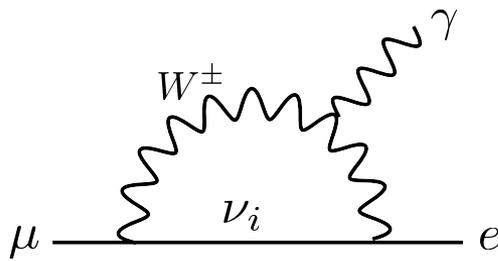# Charged Lepton Flavor Violation

Searches for CLFV are strong tools to probe BSM physics.

*Beyond the minimal extension of the SM

Charged Lepton Flavor Violation

Searches for CLFV are strong tools to probe BSM physics.

Ex) SM + neutrino mass (νSM)

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \boxed{\mathcal{L}_{\nu-\text{mass}}}$$

Dirac or Majorana

Petcov '77, Marciano-Sanda '77 ....
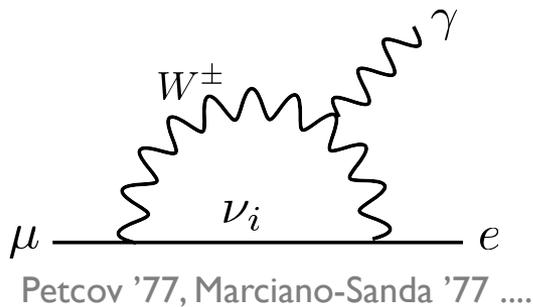
$$\text{Br}(\mu \to e\gamma) = \frac{\alpha_{\text{em}}}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{m^2_W} \right|^2 < 10^{-54} \qquad \text{Extremely small!}$$
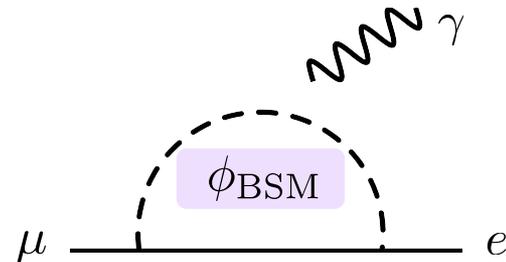
Charged Lepton Flavor Violation

Searches for CLFV are strong tools to probe BSM physics.

Ex) SM + neutrino mass (νSM)

Petcov '77, Marciano-Sanda '77 ....

$$\mathrm{Br}(\mu \to e\gamma) < 10^{-54} \qquad \ll \qquad \mathrm{Br}(\mu \to e\gamma)_{\mathrm{BSM}}$$
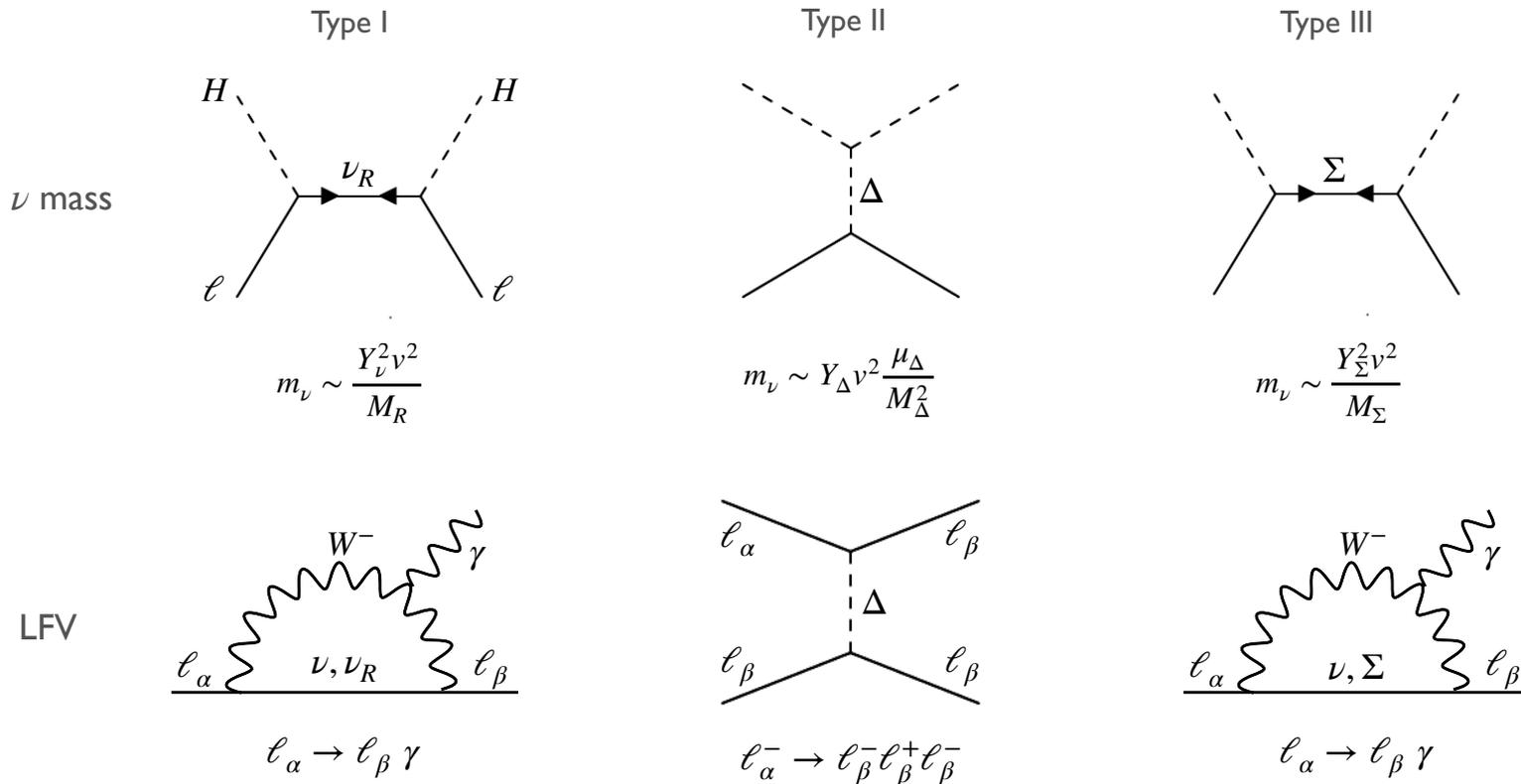
✔ The Observations of CLFV would point to new physics beyond νSM.

*Underlying mechanism of the neutrino mass.

Charged Lepton Flavor Violation

Models that explain neutrino mass usually introduce CLFV at tree or loop level.

e.g., A. Abada, et al, JHEP 12 (2007) 061

	Type I	Type II	Type III
ν mass			

Type I (ν mass)
H, H, ν_R, ℓ, ℓ
$$m_\nu \sim \frac{Y_\nu^2 v^2}{M_R}$$

Type II (ν mass)
Δ
$$m_\nu \sim Y_\Delta v^2 \frac{\mu_\Delta}{M_\Delta^2}$$

Type III (ν mass)
Σ
$$m_\nu \sim \frac{Y_\Sigma^2 v^2}{M_\Sigma}$$

LFV

Type I (LFV)
W^-, γ, ℓ_α, ν, ν_R, ℓ_β
$$\ell_\alpha \to \ell_\beta \gamma$$

Type II (LFV)
ℓ_α, ℓ_β, Δ, ℓ_β, ℓ_β
$$\ell_\alpha^- \to \ell_\beta^- \ell_\beta^+ \ell_\beta^-$$

Type III (LFV)
W^-, γ, ℓ_α, ν, Σ, ℓ_β
$$\ell_\alpha \to \ell_\beta \gamma$$

CLFV searches

* Example

Mu2e

BaBar

LHC

MEG/Mu3e

COMET

BESIII

Belle

● Mu to e gamma

● Mu to 3e

● Mu to e conversion

▲ Tau decays

$$\text{BR}(\mu \to e\gamma) < 3.1 \times 10^{-13}$$

MEG II Collaboration, 2310.12614

$$\text{BR}(\mu^- \text{ Ti} \to e^- \text{ Ti}) < 6.1 \times 10^{-13}$$

P. Wintz, Conf. Proc. C 980420, 534 (1998).

$$\text{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8}$$

BaBar, PRL104 (2010) 021802

$$\text{BR}(\tau \to e\pi^+\pi^-) < 2.3 \times 10^{-8}$$

Belle, PLB719 (2013) 346-353

CLFV searches

* Example

HERA

Mu2e

LHC

COMET

BaBar

MEG/Mu3e

BESIII

Belle

EIC

● Mu to e gamma

● Mu to 3e

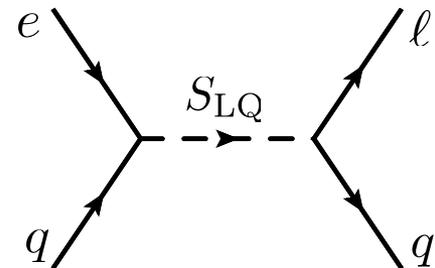● Mu to e conversion

◆ Electron-Proton/Ion collider

▲ Tau decays

✔ LFV Leptoquark Searches at HERA

ZEUS collaboration, Eur. Phys. J. C 44 (2005) 463
H1 collaboration, Eur. Phys. J. C 52 (2007) 833

$\sqrt{S} = 318$ GeV, $\mathscr{L} = 10^{31}$ cm^{-2} s^{-1}

e

ℓ

S_{LQ}

q

q'

CLFV searches

* Example

HERA

Mu2e

LHC

BaBar

EIC

MEG/Mu3e

COMET

BESIII

Belle

- Mu to e gamma
- Mu to 3e
- Mu to e conversion
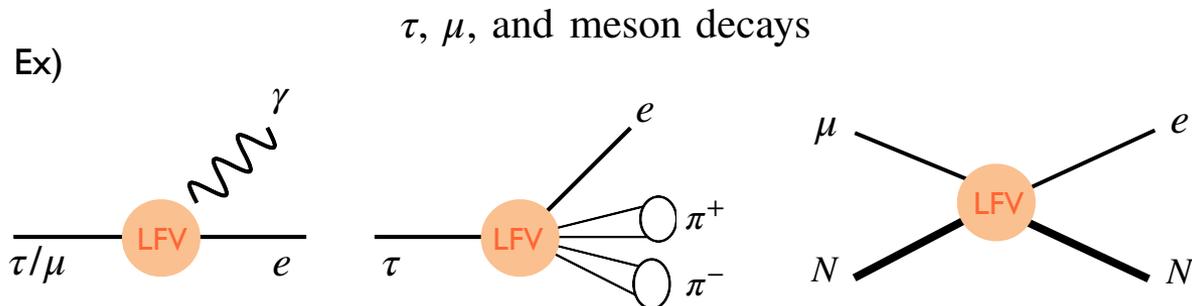- Electron-Proton/Ion collider
- Tau decays

$ep \to \tau/\mu\ X$ @ EIC

$\sqrt{S} = 20 \sim 140$ GeV

$\mathcal{L} = 10^{33-34}$ cm^{-2} s^{-1}
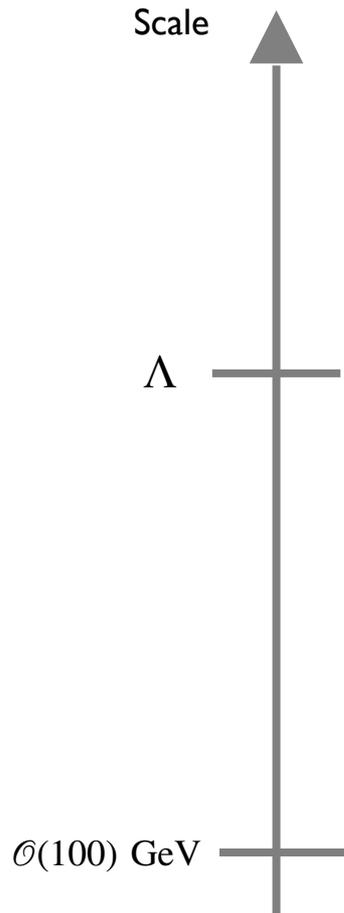
*Higher than HERA

CLFV searches

✔ Model-Independent Analysis of CLFV process at low- and high-energy

EIC vs LHC vs Low-Energy CLFV searches

$ep \rightarrow \tau/\mu \ X$ @ EIC

$pp \rightarrow e \ \tau/\mu$ @LHC
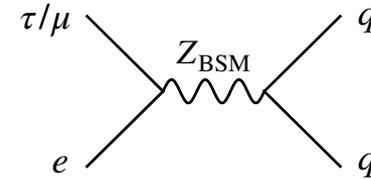
$\tau, \mu,$ and meson decays

Ex)

Model-Independent Analysis

SMEFT : Standard Model Effective Field Theory

Scale

Λ

$\mathscr{O}(100)$ GeV

Model-Independent Analysis

SMEFT : Standard Model Effective Field Theory

Scale

BSM Physics

Λ

$\mathcal{O}(100)$ GeV

τ/μ γ

ϕ_{BSM}
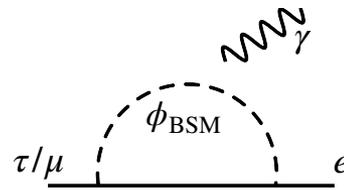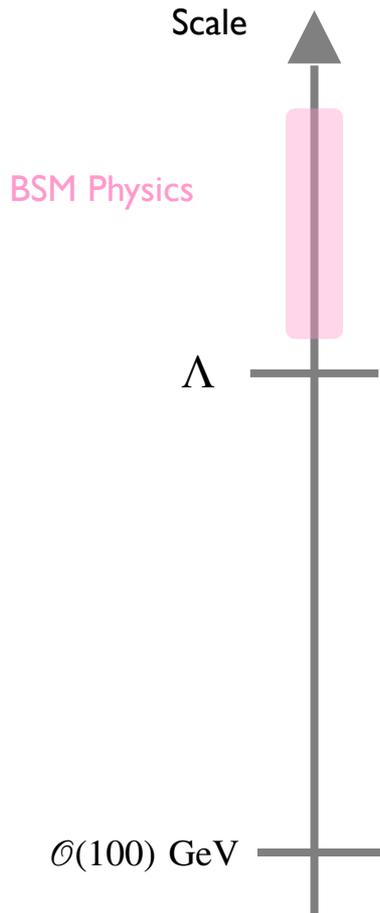
e

τ/μ q
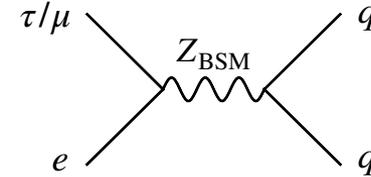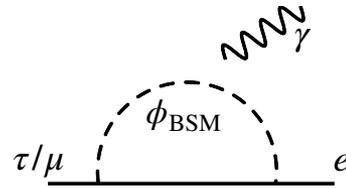
Z_{BSM}

e q

Model-Independent Analysis

SMEFT : Standard Model Effective Field Theory

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{d=5} \frac{1}{\Lambda^{d-4}} C^{(d)} O^{(d)}$$

Higher Dimensional Operators

Dipole   4 Fermion

All possible interactions based on gauge and Lorentz invariance

✔ EFT can apply to concrete models

CLFV operators

4 different types of LFV operators (dim 6)

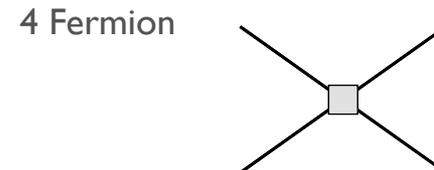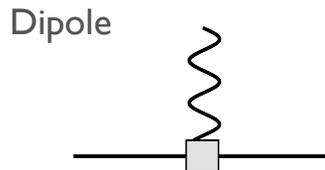$$\mathscr{L}_{\mathrm{LFV}} = \mathscr{L}_{\psi^2 \varphi^2 D} + \mathscr{L}_{\psi^2 X \varphi} + \mathscr{L}_{\psi^2 \varphi^3} + \mathscr{L}_{\psi^4}$$

X : Gauge boson ψ : Fermion φ : Higgs

*$\mathscr{O}(100)$ independent operators

Ex) $\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi \; \bar{e}_{R\alpha} \gamma_\mu e_{R\beta}$ $\bar{\ell}_{L\alpha} \sigma^{\mu\nu} B_{\mu\nu} \varphi e_{R\beta}$ $\varphi^\dagger \varphi \; \bar{\ell}_{L\alpha} \varphi e_{R\beta}$ $\bar{\ell}_L \gamma^\mu \ell_L \; \bar{q}_L \gamma_\mu q_L$

3   2   1   10

x 9 for generic quark flavor

CLFV operators

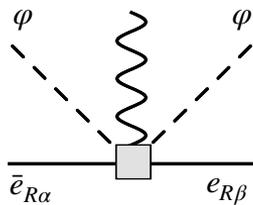4 different types of LFV operators (dim 6)

$$\mathscr{L}_{\text{LFV}} = \mathscr{L}_{\psi^2\varphi^2 D} + \mathscr{L}_{\psi^2 X\varphi} + \mathscr{L}_{\psi^2\varphi^3} + \mathscr{L}_{\psi^4}$$
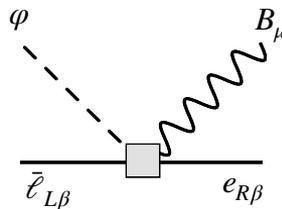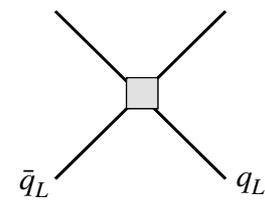
X : Gauge boson $\qquad \psi$: Fermion $\qquad \varphi$: Higgs

$$\supset -\frac{4G_F}{\sqrt{2}} \sum_{\substack{\ell = \tau,\mu \\ q = u,d}} [C_{Lq}]_{\ell eij}\, \bar{\ell}_L\gamma^\mu e_L\, \bar{q}_{Ri}\gamma_\mu q_{Rj}$$

e_L $\qquad$ τ_L/μ_L

q_{Rj} $\qquad$ q_{Ri}

*Assume a generic quark flavor structure

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

*Focus on tau-electron case.

Low-Energy Tau and Meson Decay

Decay mode		Upper limit (90 % C.L.)	
$\tau \to e\pi^+\pi^-$		2.3×10^{-8}	Belle PLB719(2013)346
$\tau \to e\pi^0$		8×10^{-8}	Belle PLB648(2007)341
$\tau \to e\eta$	uu/dd/ss	9.2×10^{-8}	Belle PLB648(2007)341
$\tau \to e\eta'$		1.6×10^{-7}	Belle PLB648(2007)341
$\tau \to eK_S$		2.6×10^{-8}	Belle PLB692(2010)4
$\tau \to e\pi^+K^-$	ds/sd	3.7×10^{-8}	Belle PLB719(2013)346
$\tau \to e\pi^-K^+$		3.1×10^{-8}	Belle PLB719(2013)346
$B^0 \to e^\pm\tau^\mp$		1.6×10^{-5}	Belle PRD104(2021)9
$B^+ \to \pi^+e^+\tau^-$	db/bd	7.4×10^{-5}	BaBar PRD86(2012)012004
$B^+ \to \pi^+e^-\tau^+$		2.0×10^{-5}	BaBar PRD86(2012)012004
$B^+ \to K^+e^+\tau^-$	sb/bs	1.53×10^{-5}	Belle PRL130(2023)26 261802
$B^+ \to K^+e^-\tau^+$		1.5×10^{-5}	Belle PRL130(2023)26 261802

Low-Energy Tau and Meson Decay

Decay mode	Upper limit (90 % C.L.)		
$\tau \to e\pi^+\pi^-$	2.3×10^{-8}	Belle	PLB719(2013)346
$\tau \to e\pi^0$	8×10^{-8}	Belle	PLB648(2007)341
$\tau \to e\eta$	9.2×10^{-8}	Belle	PLB648(2007)341
$\tau \to e\eta'$	1.6×10^{-7}	Belle	PLB648(2007)341

uu/dd/ss

- Certain combinations of CLFV operators can be bounded.

Ex) $\mathrm{BR}(\tau \to e\pi^+\pi^-) \simeq 0.5 \times \left| [C_{Lu}]_{uu} - [C_{Ld}]_{dd} \right|^2$

A. Celis, V. Cirigliano, E. Passemar, PRD89(2014)095014

Low-Energy Tau and Meson Decay

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uu/dd/ss

• Certain combinations of CLFV operators can be bounded.
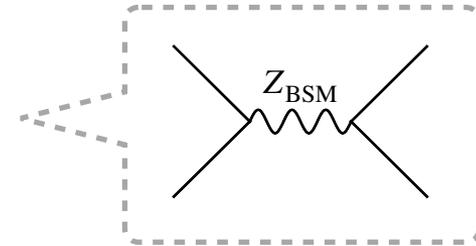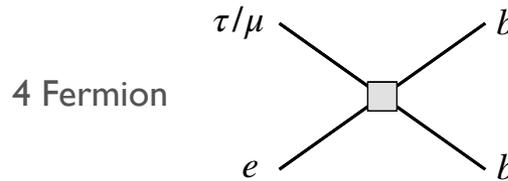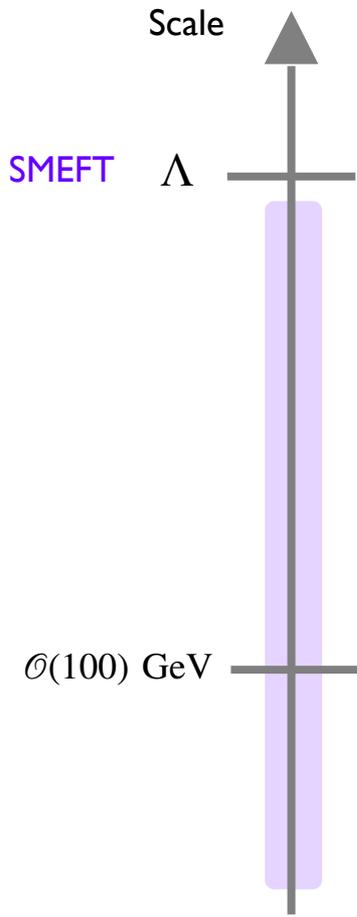
Ex) $\mathrm{BR}(\tau \to e\pi^+\pi^-) \simeq 0.5 \times \left| [C_{Lu}]_{uu} - [C_{Ld}]_{dd} \right|^2$

A. Celis, V. Cirigliano, E. Passemar, PRD89(2014)095014

• Quark-flavor conserving processes are generated by light quarks operators

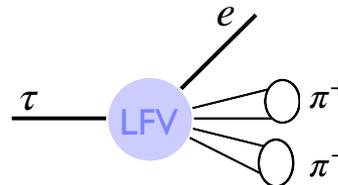$$[C_{Lu}]_{\tau e} = \begin{pmatrix} [C_{Lu}]_{uu} & [C_{Lu}]_{uc} & [C_{Lu}]_{ut} \\ [C_{Lu}]_{cu} & [C_{Lu}]_{cc} & [C_{Lu}]_{ct} \\ [C_{Lu}]_{tu} & [C_{Lu}]_{tc} & [C_{Lu}]_{tt} \end{pmatrix} \qquad [C_{Ld}]_{\tau e} = \begin{pmatrix} [C_{Ld}]_{dd} & [C_{Ld}]_{ds} & [C_{Ld}]_{db} \\ [C_{Ld}]_{sd} & [C_{Ld}]_{ss} & [C_{Ld}]_{sb} \\ [C_{Ld}]_{bd} & [C_{Ld}]_{bs} & [C_{Ld}]_{bb} \end{pmatrix} \quad \text{How?}$$

Model-Independent Analysis

Scale Running Effects based on the Renormalization Group Equations

Ex) $\quad \mu \dfrac{d}{d\mu}[C_{Lu}]_{dd} = \dfrac{4}{3} N_c \dfrac{g_1^2}{(4\pi)^2} y_d^2 \, [C_{Ld}]_{bb}$

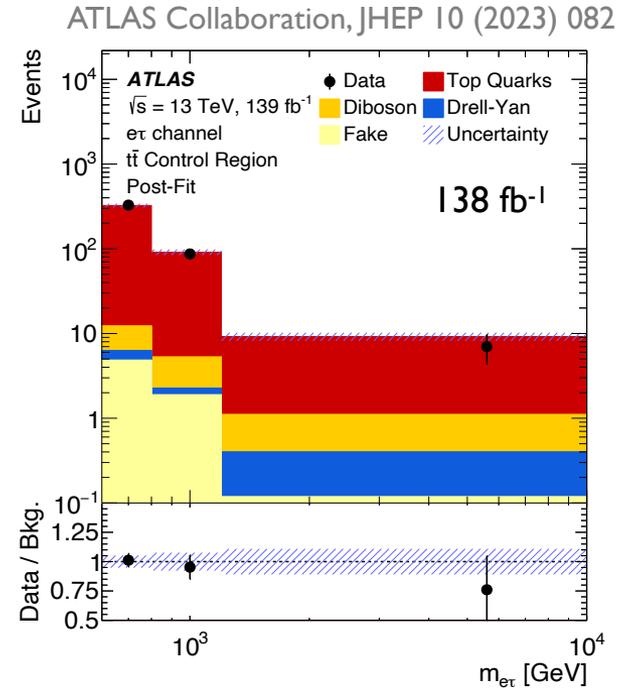For example,

$$[C_{Lu}]_{uu}, [C_{Ld}]_{dd} \sim \dfrac{g^2}{(4\pi)^2}[C_{Ld}]_{bb}$$

Loop effect $\sim \mathcal{O}(10^{-3})$

LHC search

ATLAS Collaboration, PRD98(2018)092008

ATLAS Collaboration, JHEP 10 (2023) 082

- Bound on CLFV top decay by ATLAS with 79.8 fb^{-1}: $\mathrm{BR}(t \to q\ell\ell') < 1.86 \times 10^{-5}$ (95 % CL.)

  ATLAS collaboration, ATLAS-CONF-2018-044

- ATLAS published pp $\to$ ll' bounds in high-mass final states using 36 fb^{-1}

  '22 ATLAS and '23 CMS results with 138 and 139 fb^{-1} ATLAS JHEP 10 (2023) 082
  CMS JHEP 05 (2023) 227

Existing bounds

* Single Operator Analysis

Upper limit on LFV coupling (left) and lower limit on new physics scale (right)

$[C_{Ld}]_{ij}\ \bar{\tau}_L \gamma^\mu e_L\ \bar{d}_{Ri} \gamma_\mu d_{Rj}$

- Operators with d-type quarks sector well constrained by low-energy
- PDF and loop suppression in $[C_{Ld}]_{bb}$

Existing bounds

* Single Operator Analysis

Upper limit on LFV coupling (left) and lower limit on new physics scale (right)

$[C_{Lu}]_{ij} \; \bar{\tau}_L \gamma^\mu e_L \; \bar{u}_{Ri} \gamma_\mu u_{Rj}$

- Less constrained by low energy than d-type operators
- Strong bound on $[C_{Lu}]_{tt}$ from $\tau \to e\pi^+\pi^-$

EIC Analysis

- Cross sections : $\mathcal{O}(1-10)$ pb at $\sqrt{S} = 141$ GeV

  e.g., 19 pb for $[C_{Lu}]_{uu}$ and 0.8 pb for $[C_{Ld}]_{bb}$

- Major backgrounds   1) Neutral Current $ep \to ej$

                             2) Charged Current $ep \to \nu_e j$

EIC Analysis

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- Major backgrounds   1) Neutral Current $ep \rightarrow ej$

                          2) Charged Current $ep \rightarrow \nu_e j$

- Promising ID channel

  $$\mathrm{BR}(\tau \rightarrow e\bar{\nu}_e \nu_\tau) = 17.82\,\%$$

  ✔ $\mathrm{BR}(\tau \rightarrow \mu\bar{\nu}_\mu \nu_\tau) = 17.39\,\%$

  $$\mathrm{BR}(\tau \rightarrow X_h \nu_\tau) = 64.8\,\%$$

  * Eliminate SM backgrounds

  $p_T^\mu > 10$ GeV, $E_T > 15$ GeV, $p_T^{j_1} > 20$ GeV

Cut efficiency

— DISBG   — $[C_{LQ,U}]_{uu}$
— $c_{L\varphi}$ — Γ_τ^e
          — $[C_{LQ,D}]_{bb}$

BG

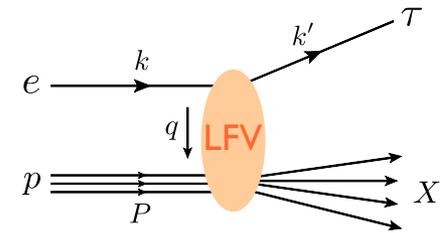p_{Tcut}^μ [GeV]

EIC Analysis

- Cross sections : $\mathcal{O}(1-10)$ pb at $\sqrt{S} = 141$ GeV

  e.g., 19 pb for $[C_{Lu}]_{uu}$ and 0.8 pb for $[C_{Ld}]_{bb}$

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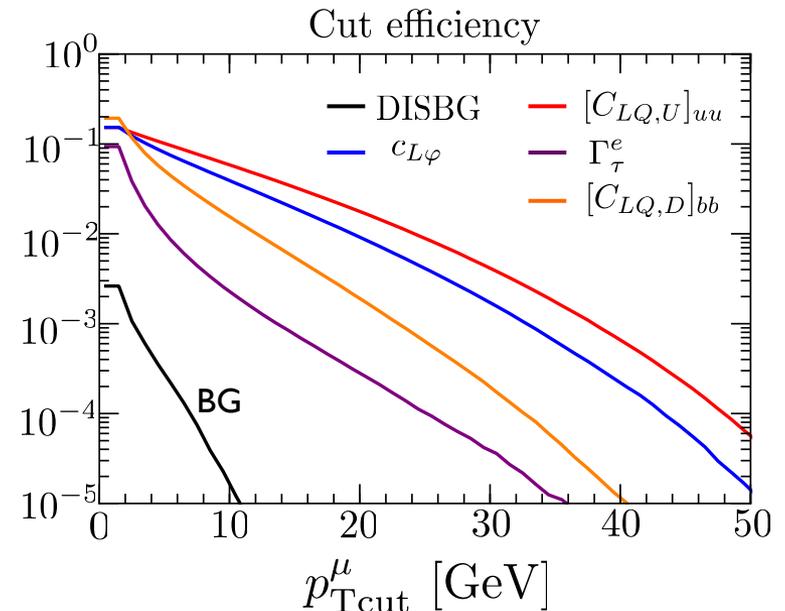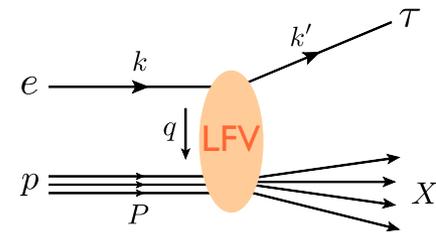 $$\mathrm{BR}(\tau \to e\bar{\nu}_e\nu_\tau) = 17.82\,\%$$

    ✔ $\mathrm{BR}(\tau \to \mu\bar{\nu}_\mu\nu_\tau) = 17.39\,\%$

    $$\mathrm{BR}(\tau \to X_h\nu_\tau) = 64.8\,\%$$

E.g., Cut Efficiencies   6 - 10% for valence quarks

A few % for heavy quarks

Cut efficiency

BG

DISBG $[C_{LQ,U}]_{uu}$
$c_{L\varphi}$ Γ^e_τ
$[C_{LQ,D}]_{bb}$

p^μ_{Tcut} [GeV]

EIC vs Current limits

*Single Operator Analysis

$\sqrt{S} = 141$ GeV, $\mathscr{L} = 100$ fb^{-1} @EIC

Upper limit on LFV coupling (left) and lower limit on new physics scale (right)

$[C_{Ld}]_{ij}\ \bar{\tau}_L\gamma^\mu e_L\ \bar{d}_{Ri}\gamma_\mu d_{Rj}$

- Overall, stronger limits from low-energy and LHC

- Possibility that the EIC can compete is in $[C_{Ld}]_{bb}$ and $[C_{Lu}]_{cc}$

EIC vs Current limits

*Single Operator Analysis

$$\sqrt{S} = 141 \text{ GeV}, \quad \mathscr{L} = 100 \text{ fb}^{-1} \quad @\text{EIC}$$

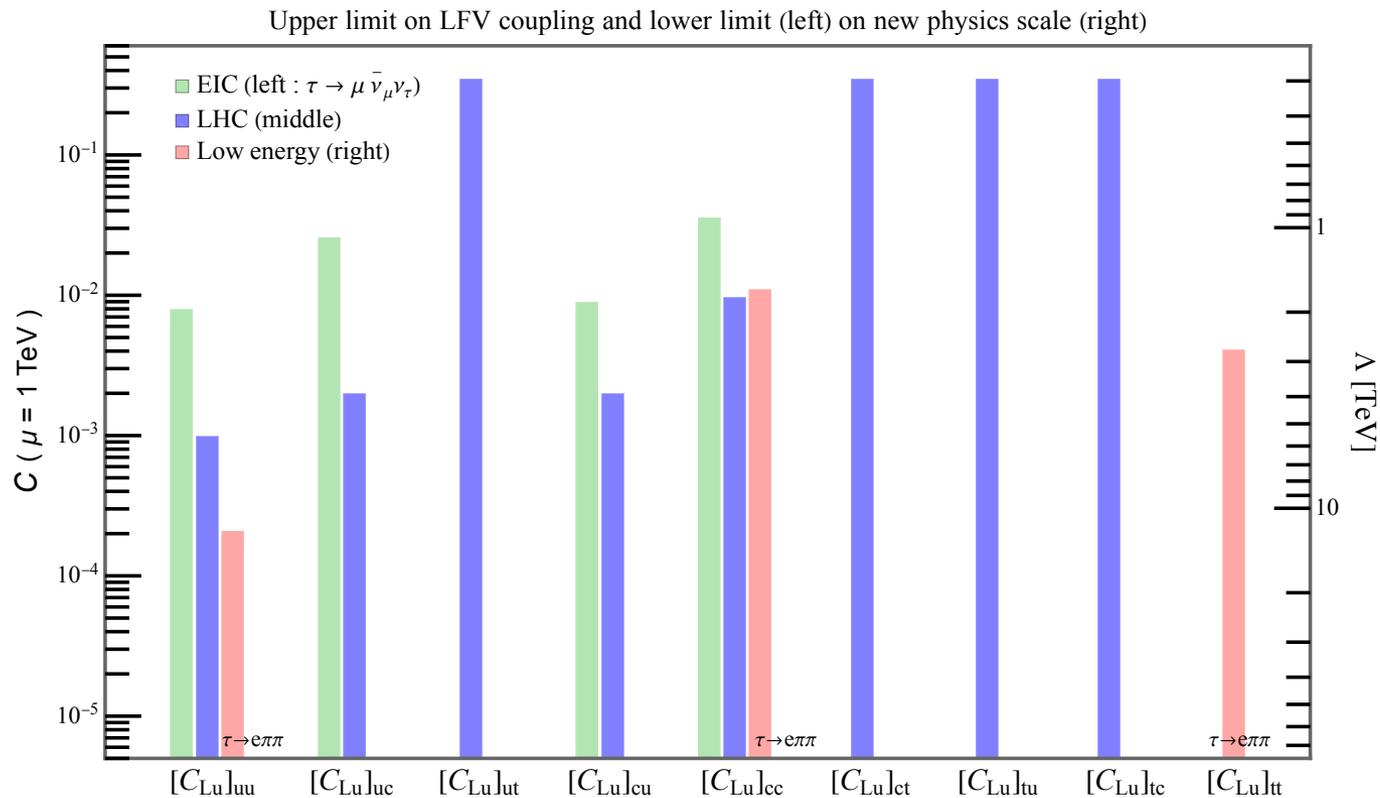Upper limit on LFV coupling and lower limit (left) on new physics scale (right)
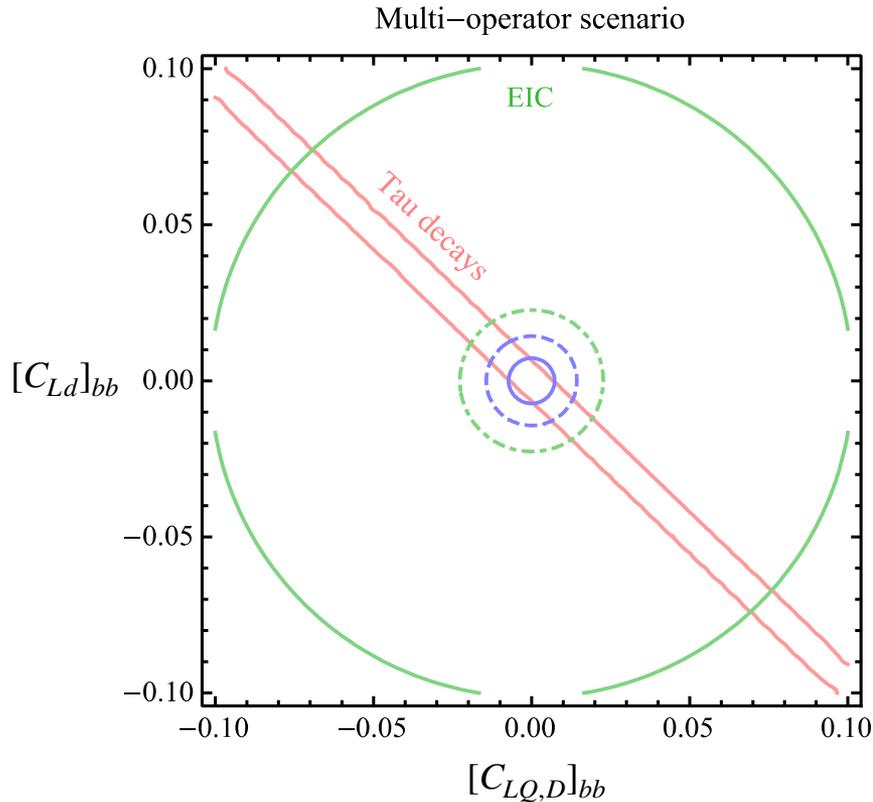
$[C_{Lu}]_{ij} \ \bar{\tau}_L \gamma^\mu e_L \ \bar{u}_{Ri} \gamma_\mu u_{Rj}$

- Overall, stronger limits from low-energy and LHC
- Possibility that the EIC can compete is in $[C_{Ld}]_{bb}$ and $[C_{Lu}]_{cc}$

Multi-operator scenario

Multi−operator scenario

*Case with 8 nonzero CLFV operators

Z couplings + down-type 4F operators

$$\mathscr{L}_{\mathrm{LFV}} \supset -\frac{g_2}{c_W}\left(c_{L\varphi}^{(1)} + c_{L\varphi}^{(3)}\right)\bar{\tau}_L\gamma^\mu Z_\mu e_L$$

$$-\frac{4G_F}{\sqrt{2}}\sum_{a=d,s,b}\left[C_{Ld}\right]_{aa}\bar{\tau}_L\gamma^\mu e_L \bar{d}_{Ra}\gamma_\mu d_{Ra}$$

$$-\frac{4G_F}{\sqrt{2}}\sum_{a=d,s,b}\left[C_{LQ,D}\right]_{aa}\bar{\tau}_L\gamma^\mu e_L \bar{d}_{La}\gamma_\mu d_{La}$$

• Collider probes are necessary to close the free direction.

*Need a numerical approach to deal with multi-coupling scenario

What about $e \to \mu$ case?

F. Delzanno, KF, S. Gonzalez-Solis, E. Mereghetti, arXiv 2411.13497

What about $e \to \mu$ case?

F. Delzanno, KF, S. Gonzalez-Solis, E. Mereghetti, arXiv 2411.13497

Upper limit on LFV coupling and lower limit on new physics scale

$[C_{Ld}]_{ij} \; \bar{\tau}_L \gamma^\mu e_L \; \bar{d}_{Ri} \gamma_\mu d_{Rj}$

- EIC (left)
- LHC (middle)
- Low energy (right)

- $\mu \to e$ conversion currently gives strong bound

What about $e \to \mu$ case?

F. Delzanno, KF, S. Gonzalez-Solis, E. Mereghetti, arXiv 2411.13497

Upper limit on LFV coupling and lower limit on new physics scale

$[C_{Lu}]_{ij} \ \bar{\tau}_L \gamma^\mu e_L \ \bar{u}_{Ri} \gamma_\mu u_{Rj}$

- A factor of 10 weaker bound on $[C_{Lu}]_{cu}$ at the EIC

Study on Experimental Side

Thanks to Ming Liu!

How to tag Tau leptons experimentally?

- Exploit tau-lepton decay topology
  - Displaced track(s) from tau decay
  - Pencil-like isolated track(s)
- Study tau-lepton tagging algorithms using sPHENIX p+p data,
  - Identify displaced tracks with silicon pixel detectors (MVTX)
  - Tag pencil-like "jets" with EMCal and HCal
- EIC/ePIC detector simulations
  - Tau-lepton tagging with algorithms developed from sPHENIX data

IP: Interaction Point

DCA: Distance of Closest Approach

Search for:

- "Tau-> nv_tau + pi+", BR = 11.5%,
  displaced isolated single track
- "Tau -> pi+ 2pi0 + nv_tau" , BR = 9.5%,
  pencil-like jets
- "Tau-> muon/e + nv_mu/e + nv_tau", BR = 17.8%,
  displaced isolated single track

Benchmark performance:

$$\Upsilon \to \tau^+ + \tau^-$$

broad mass of di-hadron and di-lepton of "tau candidates"

Decay mode	Resonance	$\mathcal{B}$ (%)
Leptonic decays		35.2
$\tau^- \to e^- \overline{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$		17.4
Hadronic decays		64.8
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	25.9
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other		3.3

*Study tau tagging algorithms using sPHENIX p+p data and utilize ML to optimize the tagging efficiency.

Summary

★ Searches for Lepton Flavor Violations are Powerful Probes of BSM Physics.

- Systematic Analysis based on SMEFT

    - The RGEs allow to constrain CLFV heavy quark operators

- Operators involving b and c in $e - \tau$ case are promising at the EIC

- Collider searches are essential in multi-operator scenarios

- Strong bound in $e - \mu$ case especially from $\mu \to e$ conversion

Outlook/Discussion

- Multi-Operator Analysis using Machine Learning

- Experimental study of tau lepton tagging

- LNV / Sterile Neutrino Searches at the EIC

Thank you for your attention! 🙋

Backup slides

Apple to Apple