June 9, 2025

Searching for Lepton Flavor Violation

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LANL → KEK

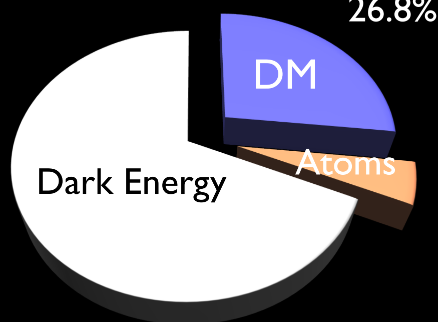
High Energy Accelerator Research Organization

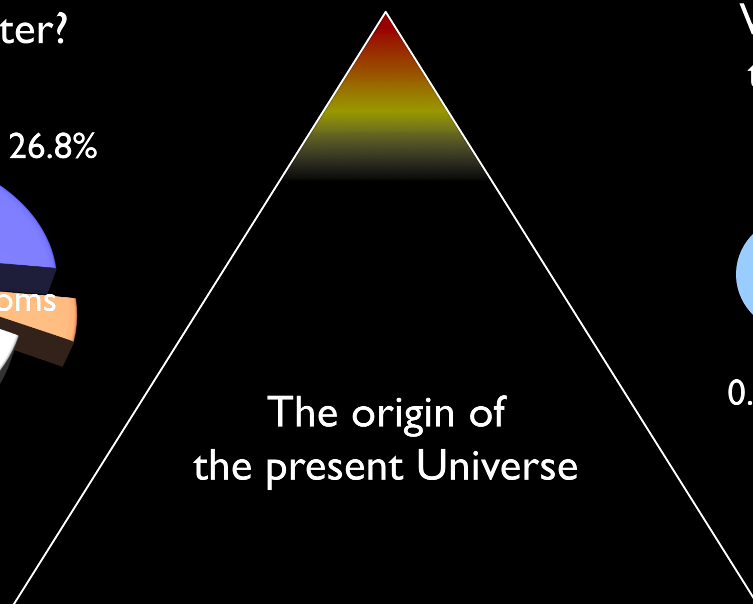
V. Cirigliano, KF, C. Lee, E. Mereghetti, B. Yan, JHEP03(2021)256
S. Banerjee, V. Cirigliano, et al, Snowmass White Papaer, 2203.14919
F. Delzanno, KF, S. Gonzalez-Solis, E. Mereghetti, arXiv 2411.13497

CIPANP 2025
U of Wisconsin Madison

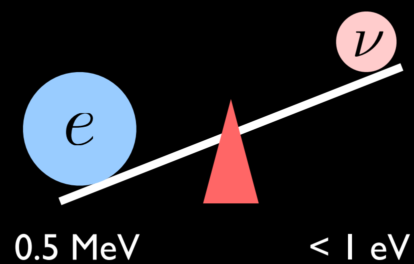
We still don’t know much about our Universe.

What is Dark Matter?





What is the origin of tiny neutrino mass ?



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

Need Physics Beyond the Standard Model

Charged Lepton Flavor Violation

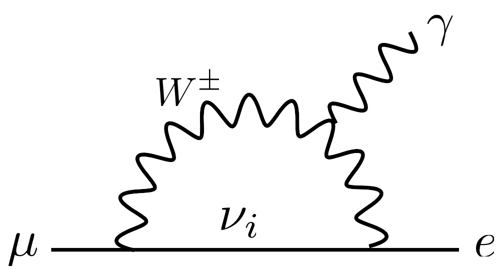
Searches for CLFV are strong tools to probe BSM physics.

*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)



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

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_{\nu-\mathrm{mass}}$$

Dirac or Majorana

$$\mathrm{Br}(\mu \to e\gamma) = \frac{\alpha_{\mathrm{em}}}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{m^2_W}\right|^2 < 10^{-54}$$

Extremely small!

Charged Lepton Flavor Violation

Searches for CLFV are strong tools to probe BSM physics.

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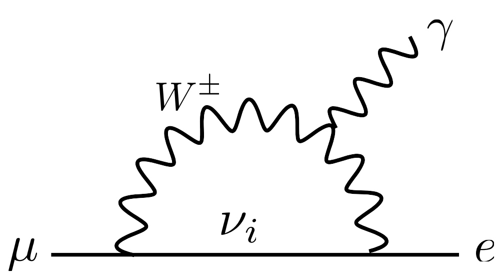

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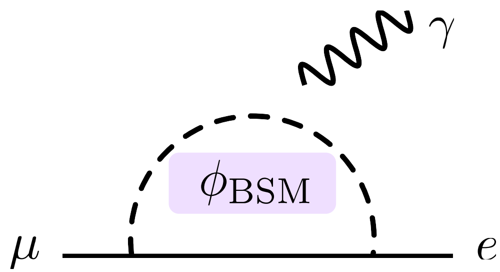
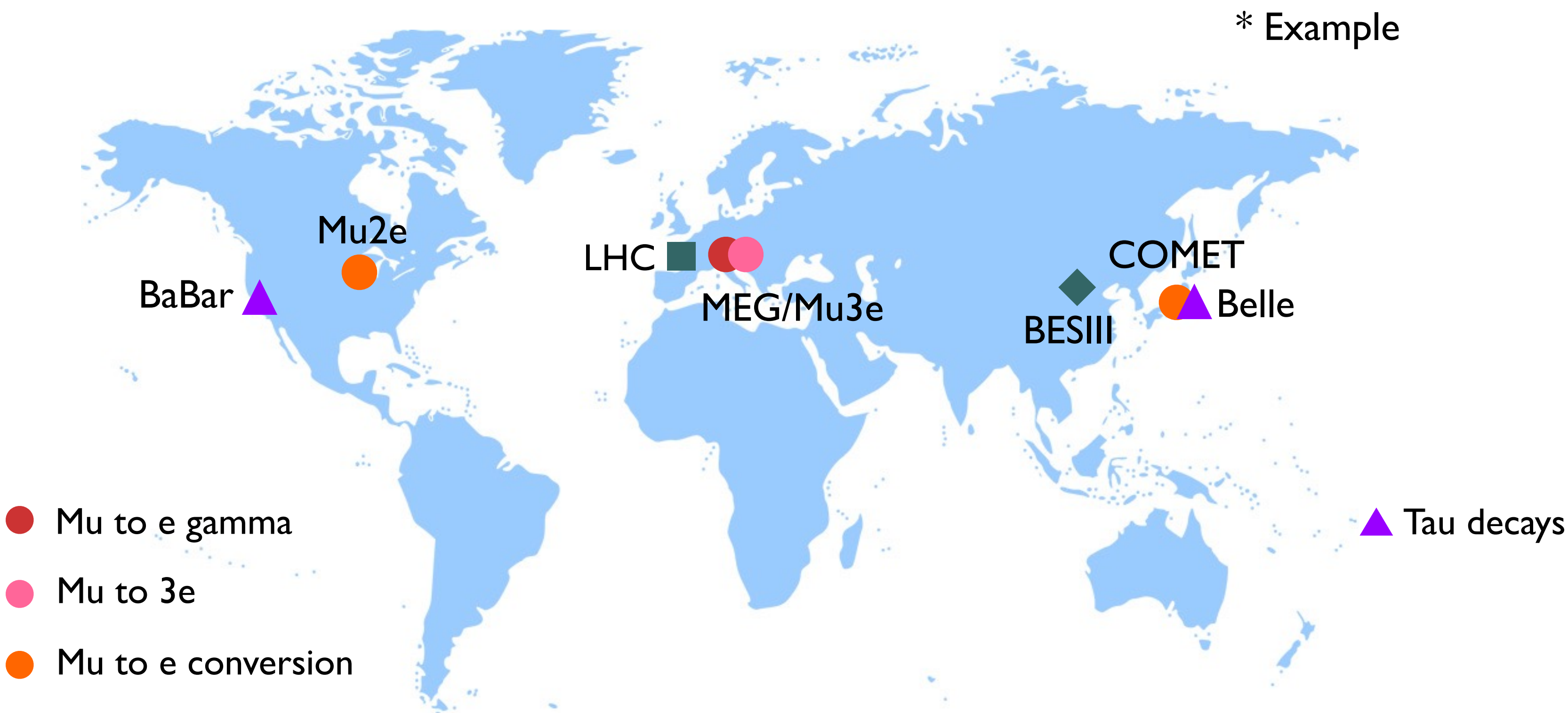


$\mathrm{Br}(\mu \to e\gamma) < 10^{-54}$ $\quad\ll\quad$ $\mathrm{Br}(\mu \to e\gamma)_{\rm BSM}$

✔ The Observations of CLFV would point to new physics beyond νSM.

*Underlying mechanism of the neutrino mass.

CLFV searches



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

MEG II Collaboration, 2310.12614

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

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

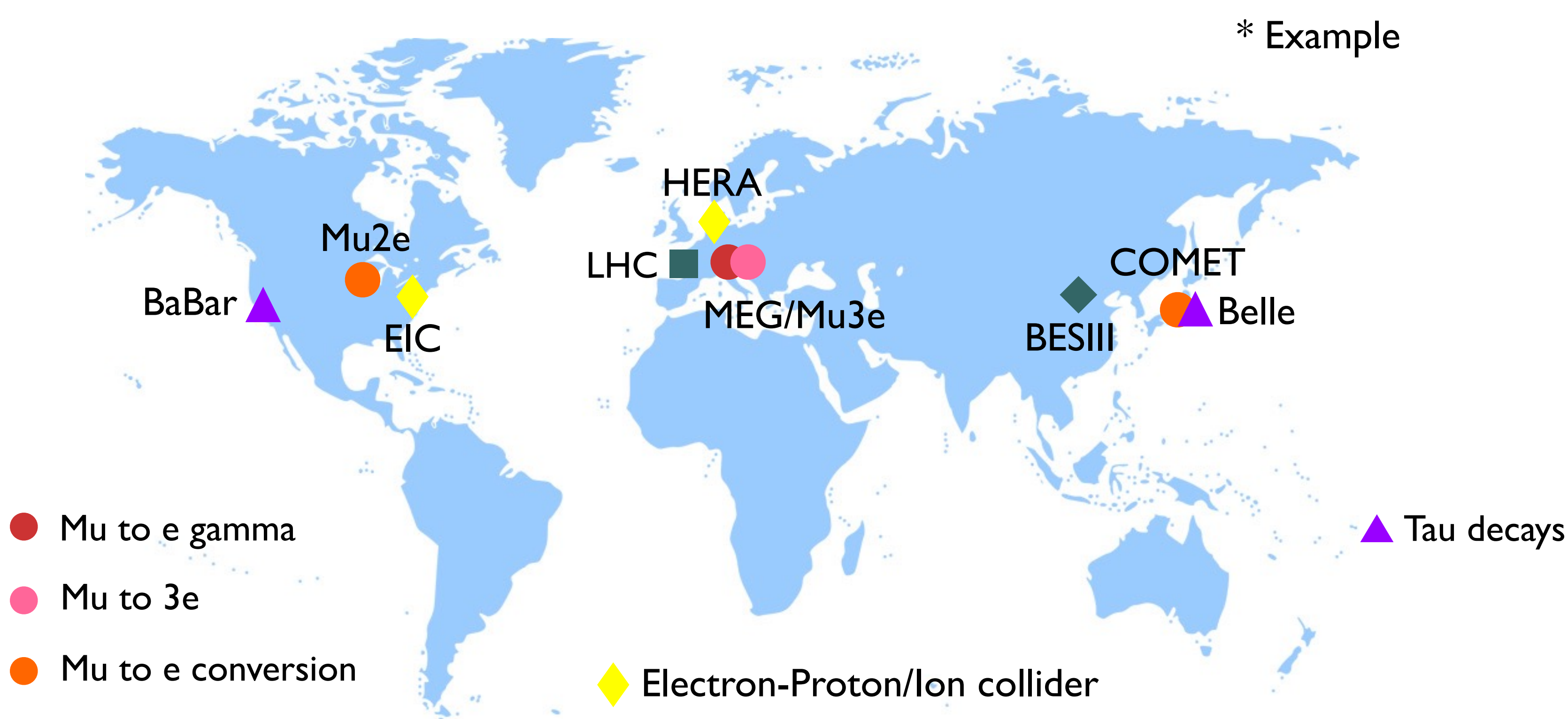
$$\mathrm{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8}$$

BaBar, PRL104 (2010) 021802

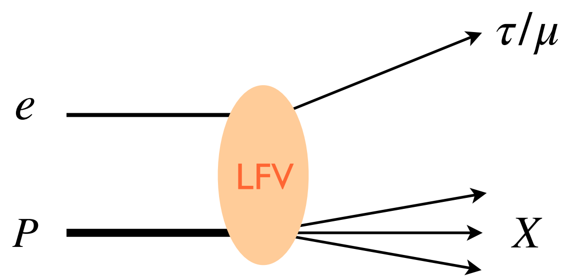
$$\mathrm{BR}(\tau \to e\pi^+\pi^-) < 2.3 \times 10^{-8}$$

Belle, PLB719 (2013) 346-353

CLFV searches



$$ep \to \tau/\mu \ X \ @ \ \text{EIC}$$



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

$$\mathscr{L} = 10^{33-34} \ \text{cm}^{-2} \ \text{s}^{-1}$$

*Higher than HERA

CLFV searches

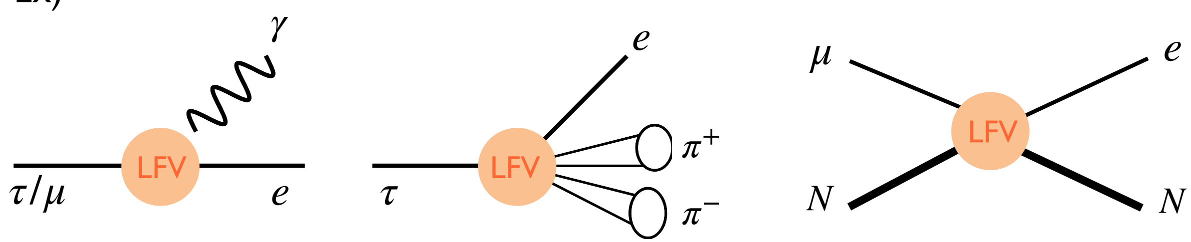
V. Cirigliano, KF, C. Lee, E. Mereghetti, B. Yan, JHEP03(2021)256
F. Delzanno, KF, S. Gonzalez-Solis, E. Mereghetti, arXiv 2411.13497

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

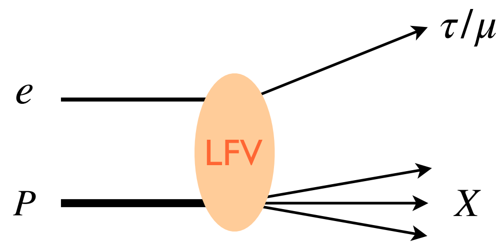
EIC vs LHC vs Low-Energy CLFV searches

τ, μ, and meson decays

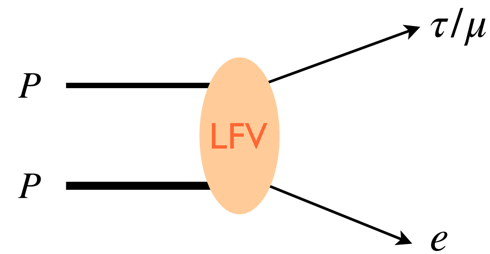
Ex)



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

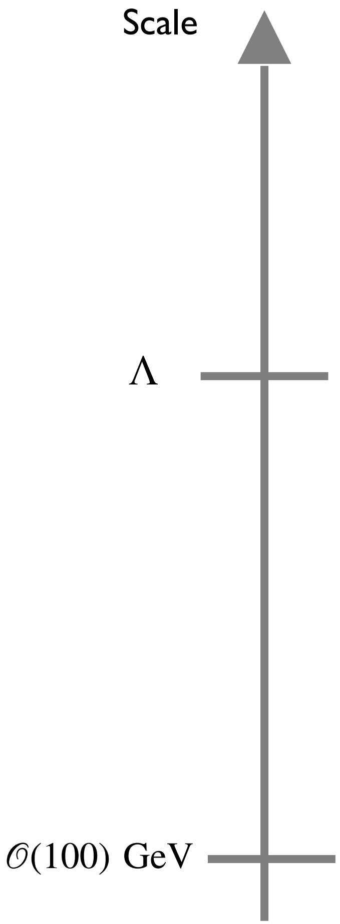


$pp \to e\ \tau/\mu$ @LHC



Model-Independent Analysis

SMEFT : Standard Model Effective Field Theory



Model-Independent Analysis

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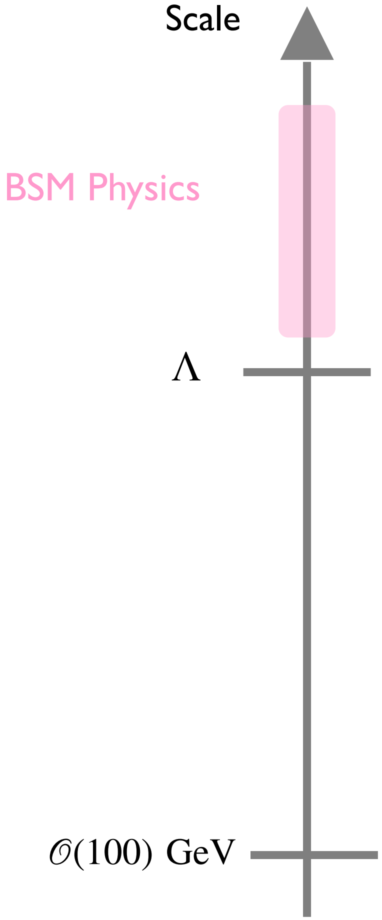

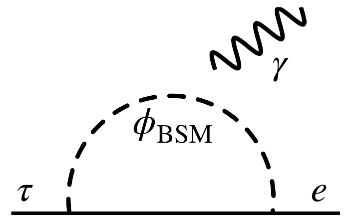

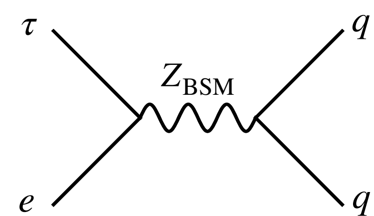

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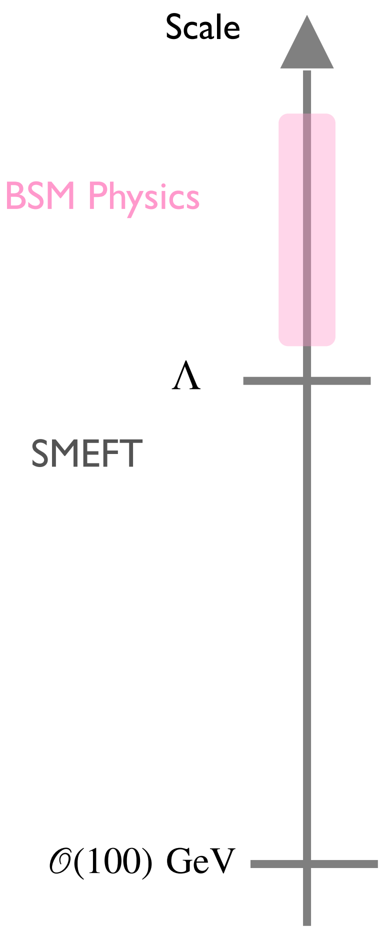

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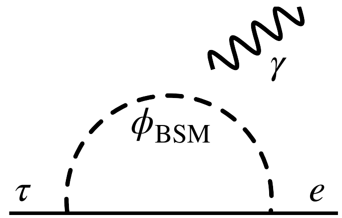
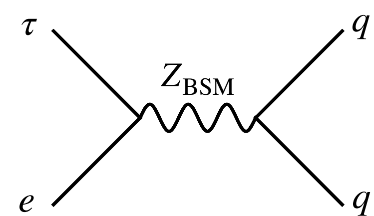
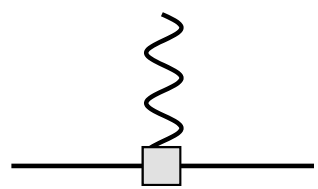




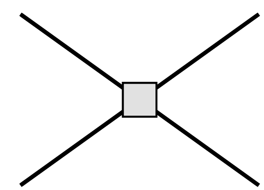
$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{d=5} \frac{1}{\Lambda^{d-4}} C^d \mathcal{O}^d$$

Higher Dimensional Operators

Dipole



4 Fermion



All possible interactions based on gauge and Lorentz invariance

✔ EFT can apply to concrete models

CLFV operators

Total : 16 different types of LFV operators (dim 6)

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

X : Gauge boson ψ : Fermion φ : Higgs

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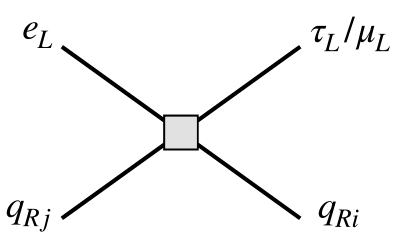
$$\supset -\frac{4G_F}{\sqrt{2}} \sum_{\substack{\ell = \tau,\mu \\ q = u,d}} [C_{Lq}]_{\ell eij}\, \bar{\ell}_L \gamma^\mu e_L\, \bar{q}_{Ri}\gamma_\mu q_{Rj}$$



*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.)	
$\tau \to e\pi^+\pi^-$	uu/dd/ss	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
$\tau \to eK_S$	ds/ds	2.6×10^{-8}	Belle PLB692(2010)4
$\tau \to e\pi^+K^-$		3.7×10^{-8}	Belle PLB719(2013)346
$\tau \to e\pi^-K^+$		3.1×10^{-8}	Belle PLB719(2013)346
$B^0 \to e^\pm\tau^\mp$	db/bd	1.6×10^{-5}	Belle PRD104(2021)9
$B^+ \to \pi^+e^+\tau^-$		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

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- 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

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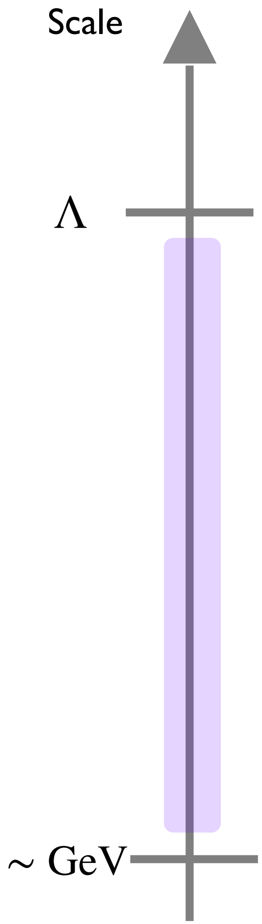
A. Celis, V. Cirigliano, E. Passemar, PRD89(2014)095014

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

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

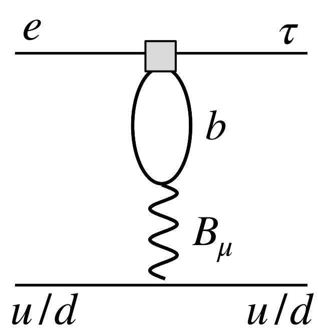
How?

Scale running effects

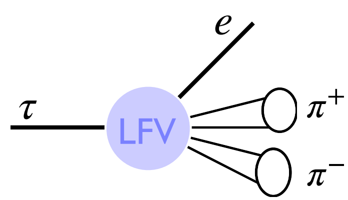


Light-quark operators are induced via the RGEs:

$$\mathscr{L}_{\rm LFV} = -\frac{4G_F}{\sqrt{2}}\,[C_{Ld}]_{\tau ebb}\;\bar{\tau}_L\gamma^\mu e_L\;\bar{b}_R\gamma_\mu b_R$$



Ex) $\mu\frac{d}{d\mu}[C_{Ld}]_{dd} = \frac{4}{3}N_c\frac{g_1^2}{(4\pi)^2}\mathrm{y}_{\rm d}^2\;[C_{Ld}]_{bb}$

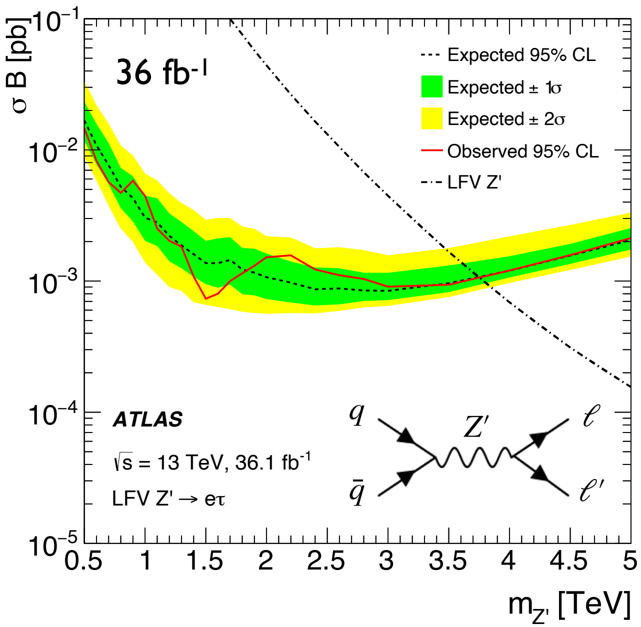


$$[C_{Lu}]_{uu}, [C_{Ld}]_{dd} \sim \frac{g^2}{(4\pi)^2}[C_{Ld}]_{bb}$$

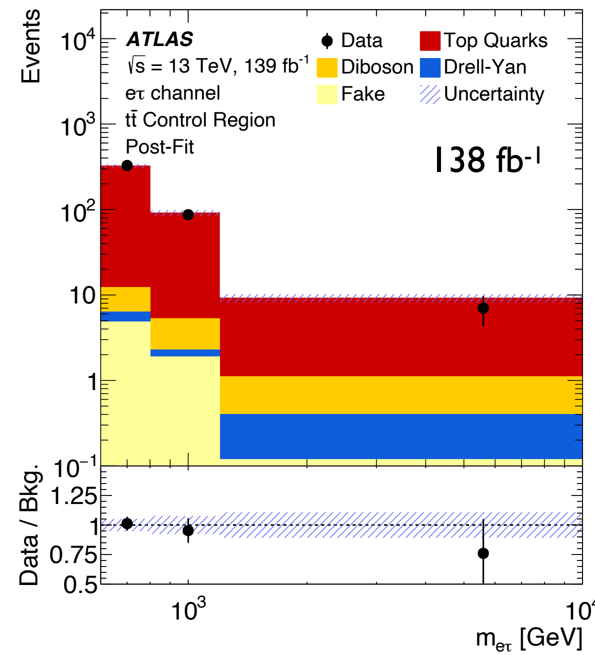
Loop effect $\sim \mathcal{O}(10^{-3})$

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

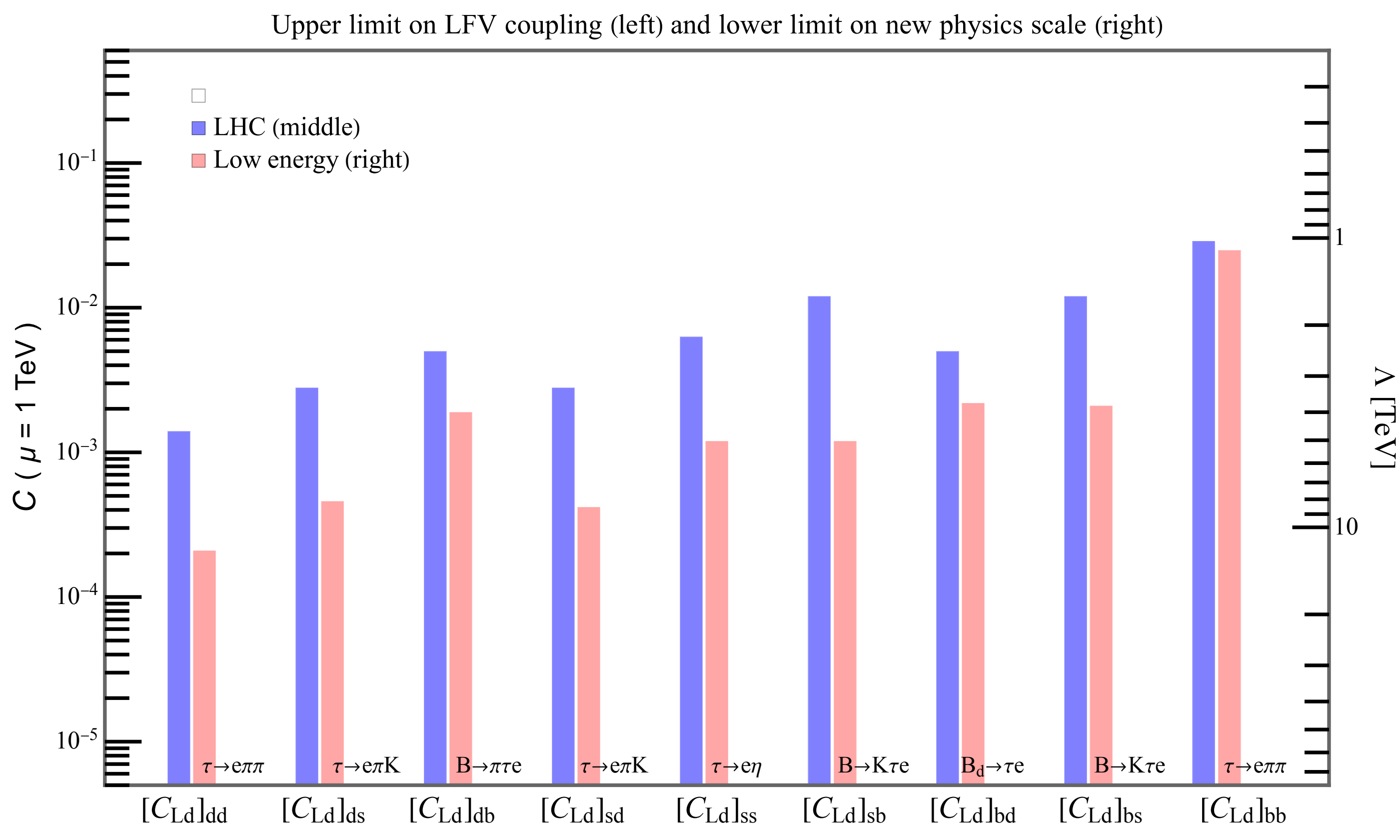
- ATLAS published pp → l l' bounds in high-mass final states using 36 fb^{-1}

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

Existing bounds

V. Cirigliano, KF, C. Lee, E. Mereghetti, B. Yan, JHEP03(2021)256

* Single Operator Analysis



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

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

Existing bounds

V. Cirigliano, KF, C. Lee, E. Mereghetti, B. Yan, JHEP03(2021)256

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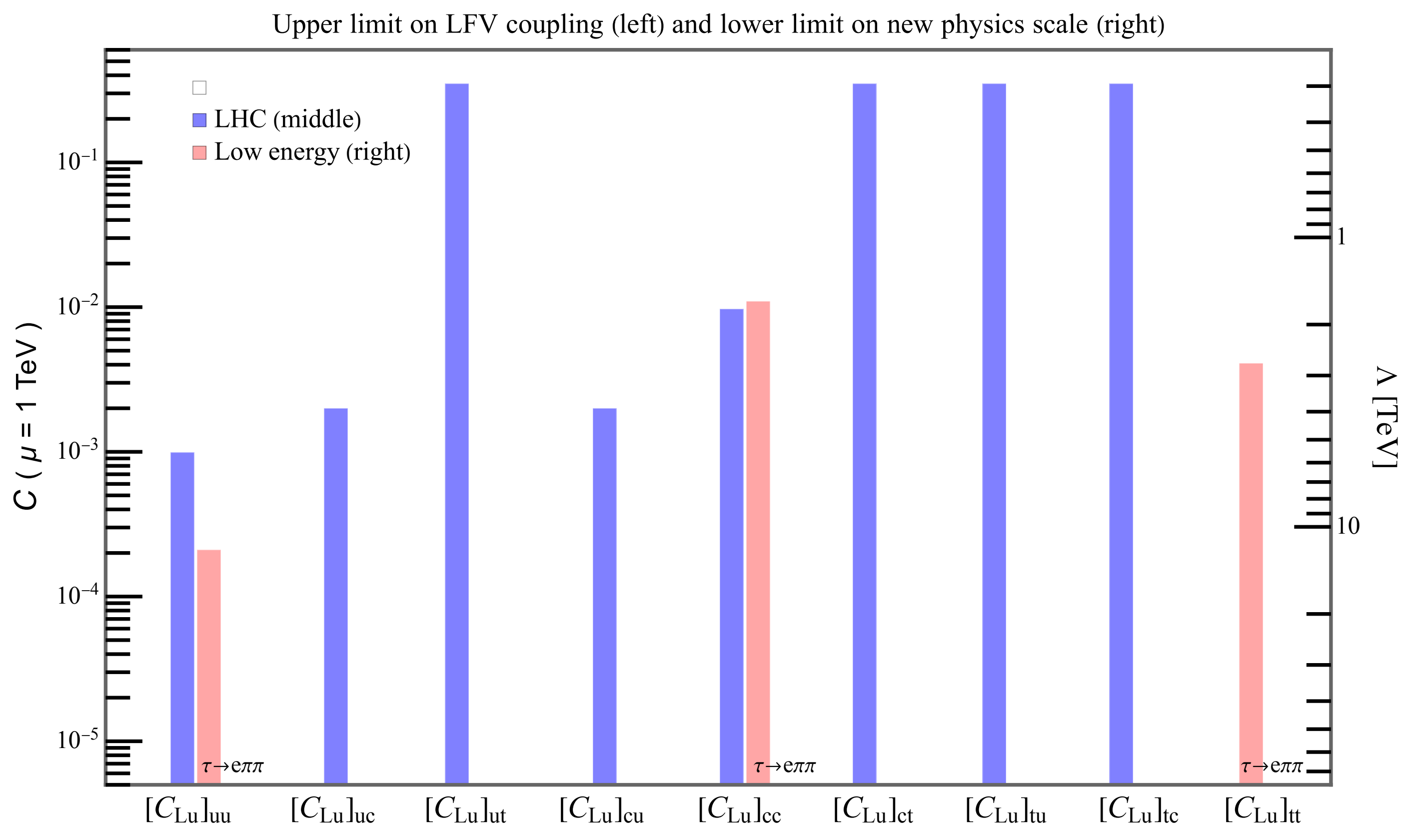
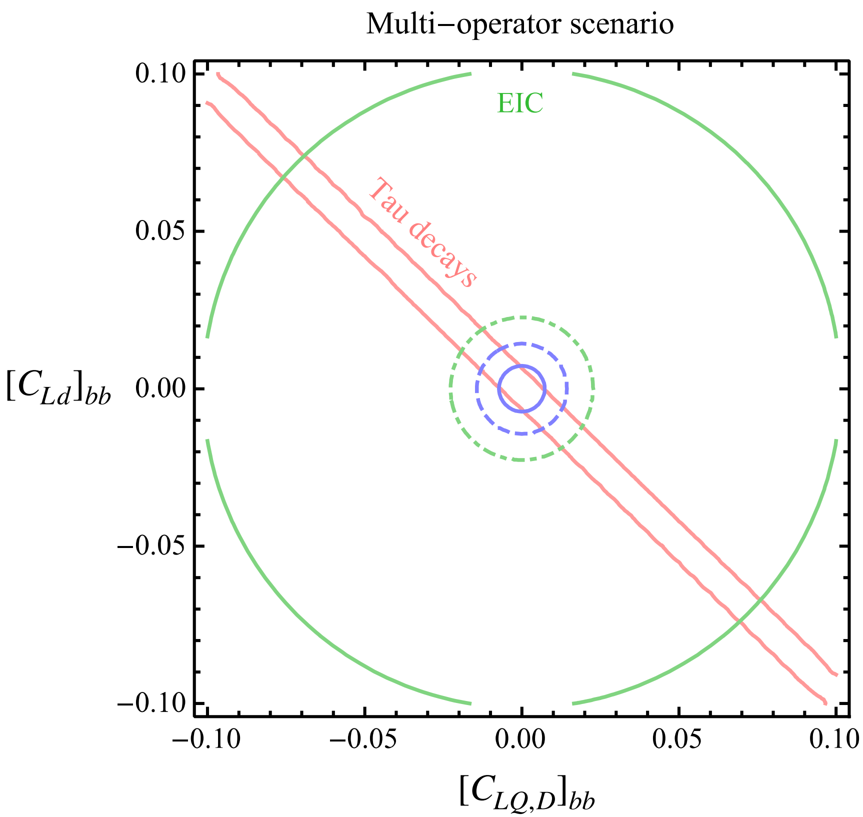


$[C_{Lu}]_{ij}\ \bar{\tau}_L \gamma^\mu e_L\ \bar{u}_{Ri} \gamma_\mu u_{Rj}$

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

Multi-operator scenario

S. Banerjee, V. Cirigliano, et al,
Snowmass White Papaer, 2203.14919



*Case with 8 nonzero CLFV operators

Z couplings + down-type 4F operators

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

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

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

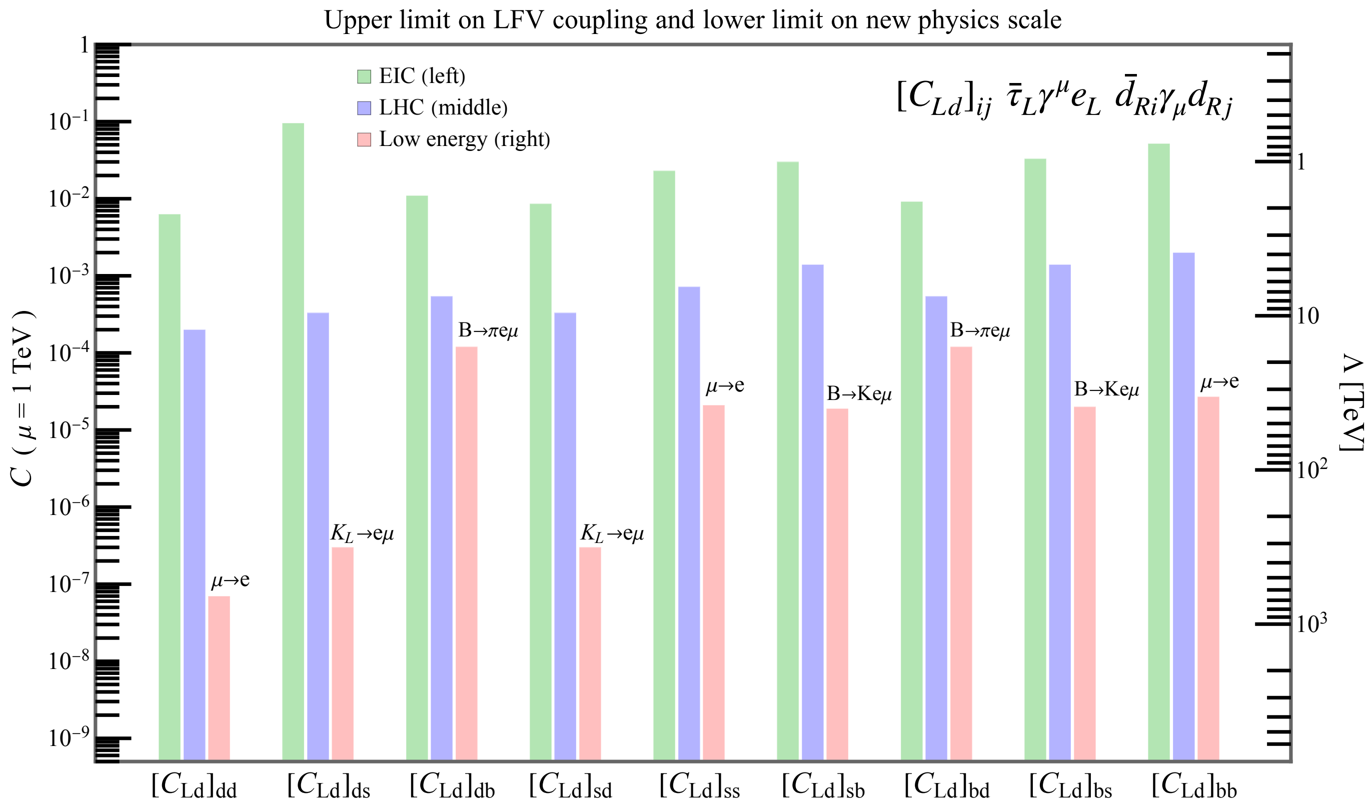
- Collider probes are necessary to close the free direction.

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



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

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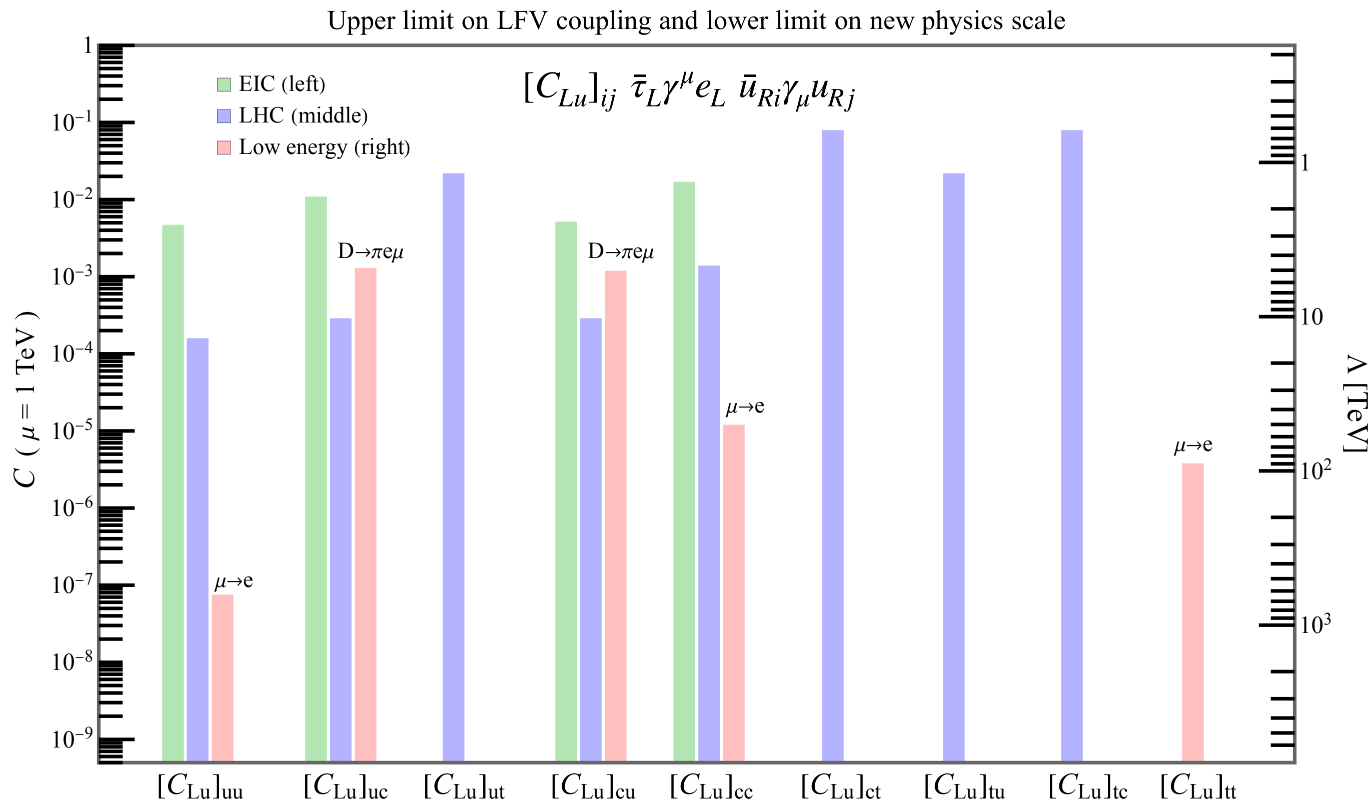
F. Delzanno, KF, S. Gonzalez-Solis, E. Mereghetti, arXiv 2411.13497



- LHC leads the bound on $[C_{Lu}]_{cu}$ and $[C_{Lu}]_{tq/qt}$

Summary

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

Today

- Systematic Analysis based on SMEFT

  - The RGEs allow to constrain CLFV heavy quark operators

- Collider searches are essential in multi-operator scenarios

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

Outlook/Discussion

- Multi-Dimensional Analysis using Machine Learning

- b, c quark and tau lepton tagging