Searching for Lepton Flavor Violation at the EIC

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Los Alamos
NATIONAL LABORATORY

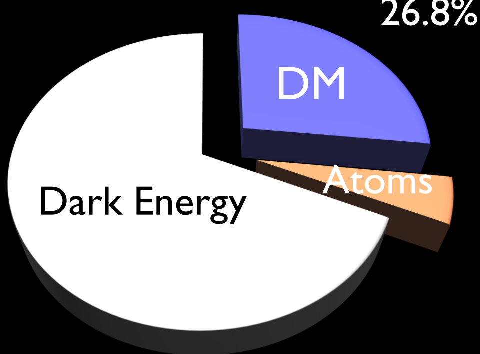
THEORETICAL DIVISION
Since 1943

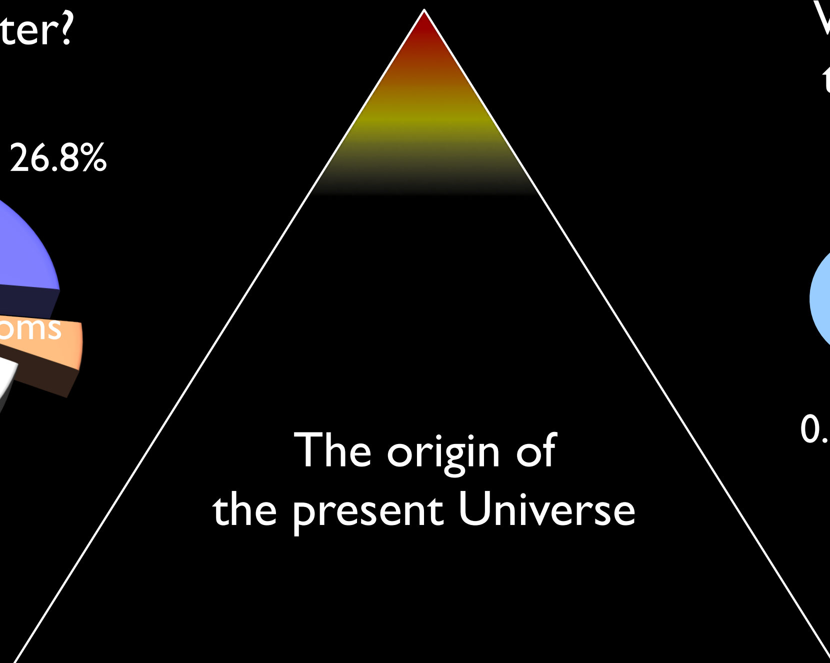
V. Cirigliano, KF, C. Lee, E. Mereghetti, B. Yan, JHEP03(2021)256
S. Banerjee, V. Cirigliano, et al, Snowmass White Papaer, 2203.14919
F. Delzanno, KF, S. Gonzalez-Solis, E. Mereghetti, arXiv 2411.13497

November 21, 2024
At BNL

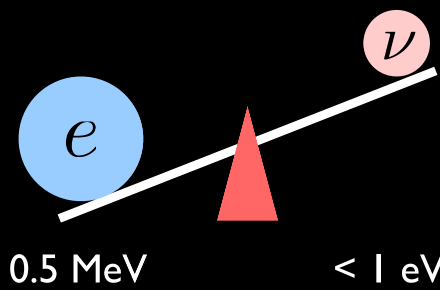
We still don't know much about our Universe.

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

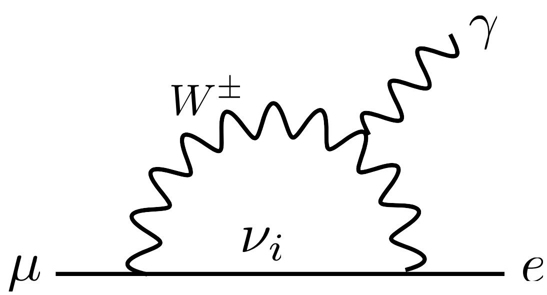
Searches for CLFV are strong tools to probe BSM physics.

*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 ....

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

Dirac or Majorana

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

Extremely small!

Charged Lepton Flavor Violation

Searches for CLFV are strong tools to probe BSM physics.

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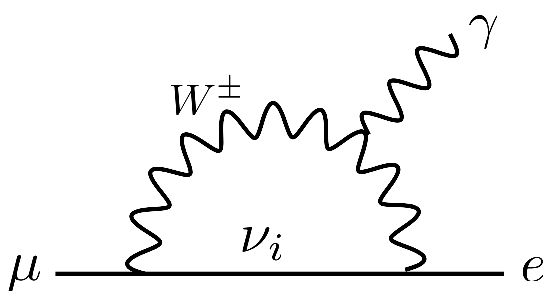
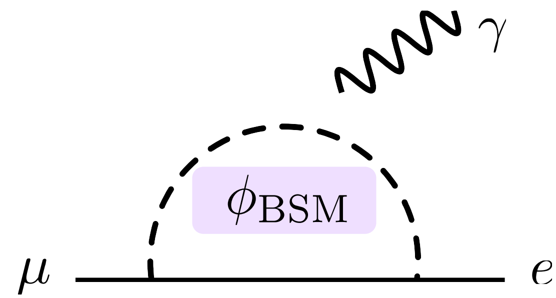


Petcov '77, Marciano-Sanda '77 ....



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

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

*Underlying mechanism of the neutrino mass.

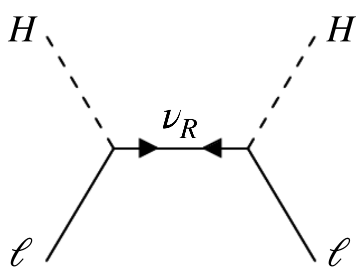
Charged Lepton Flavor Violation

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

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

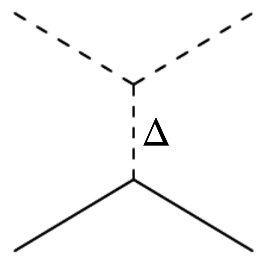
ν mass

Type I



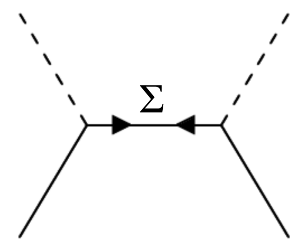
$$m_\nu \sim \frac{Y_\nu^2 v^2}{M_R}$$

Type II



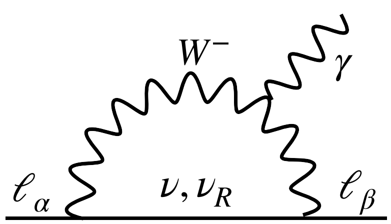
$$m_\nu \sim Y_\Delta v^2 \frac{\mu_\Delta}{M_\Delta^2}$$

Type III

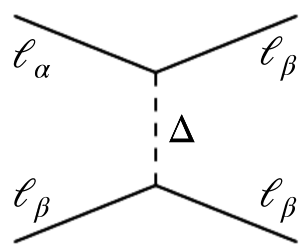


$$m_\nu \sim \frac{Y_\Sigma^2 v^2}{M_\Sigma}$$

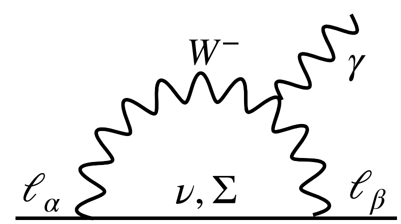
LFV



$$\ell_\alpha \to \ell_\beta \, \gamma$$



$$\ell_\alpha^- \to \ell_\beta^- \ell_\beta^+ \ell_\beta^-$$



$$\ell_\alpha \to \ell_\beta \, \gamma$$

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).

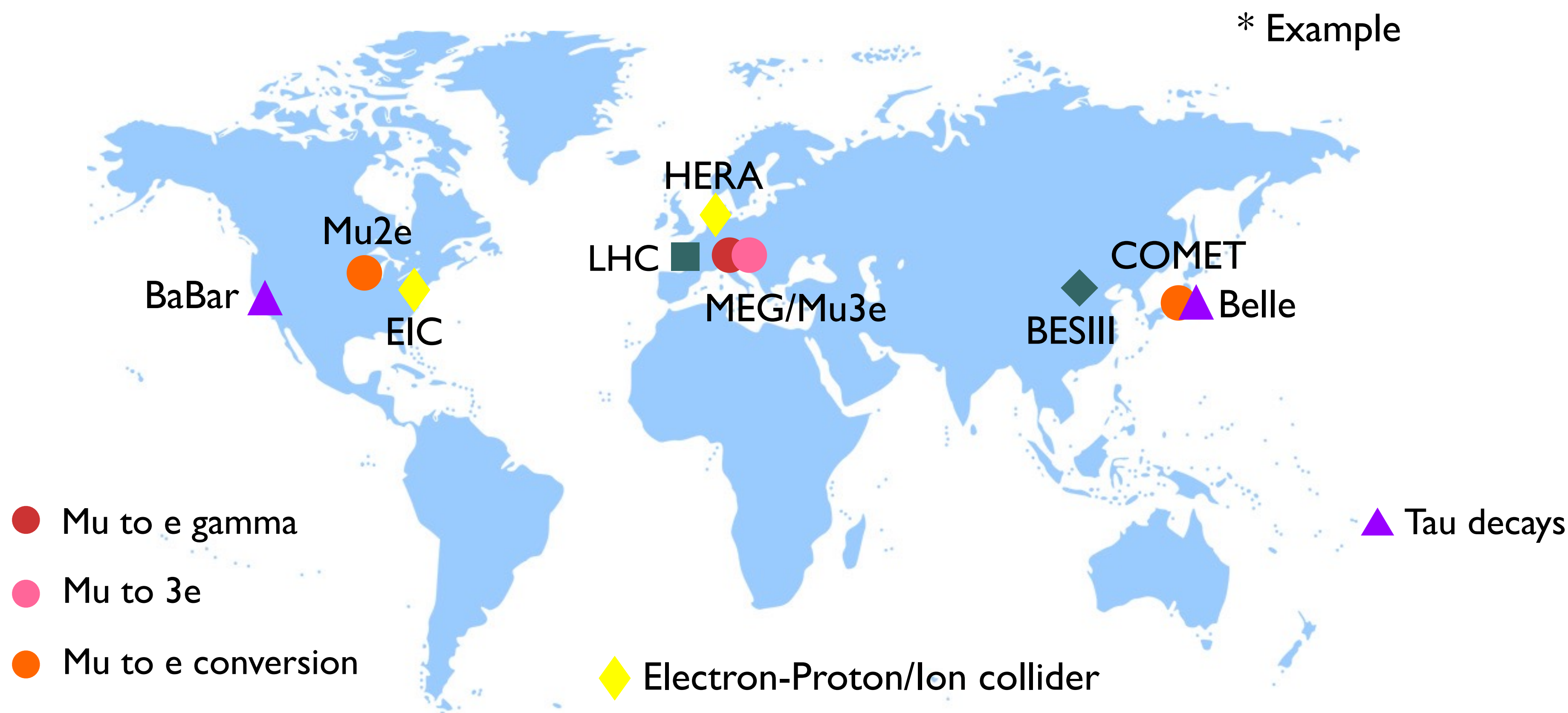
$$\mathrm{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8}$$

BaBar, PRL104 (2010) 021802

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

Belle, PLB719 (2013) 346-353

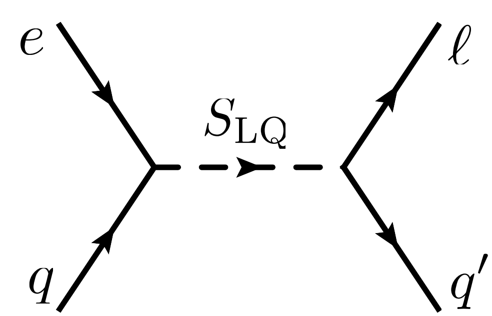
CLFV searches



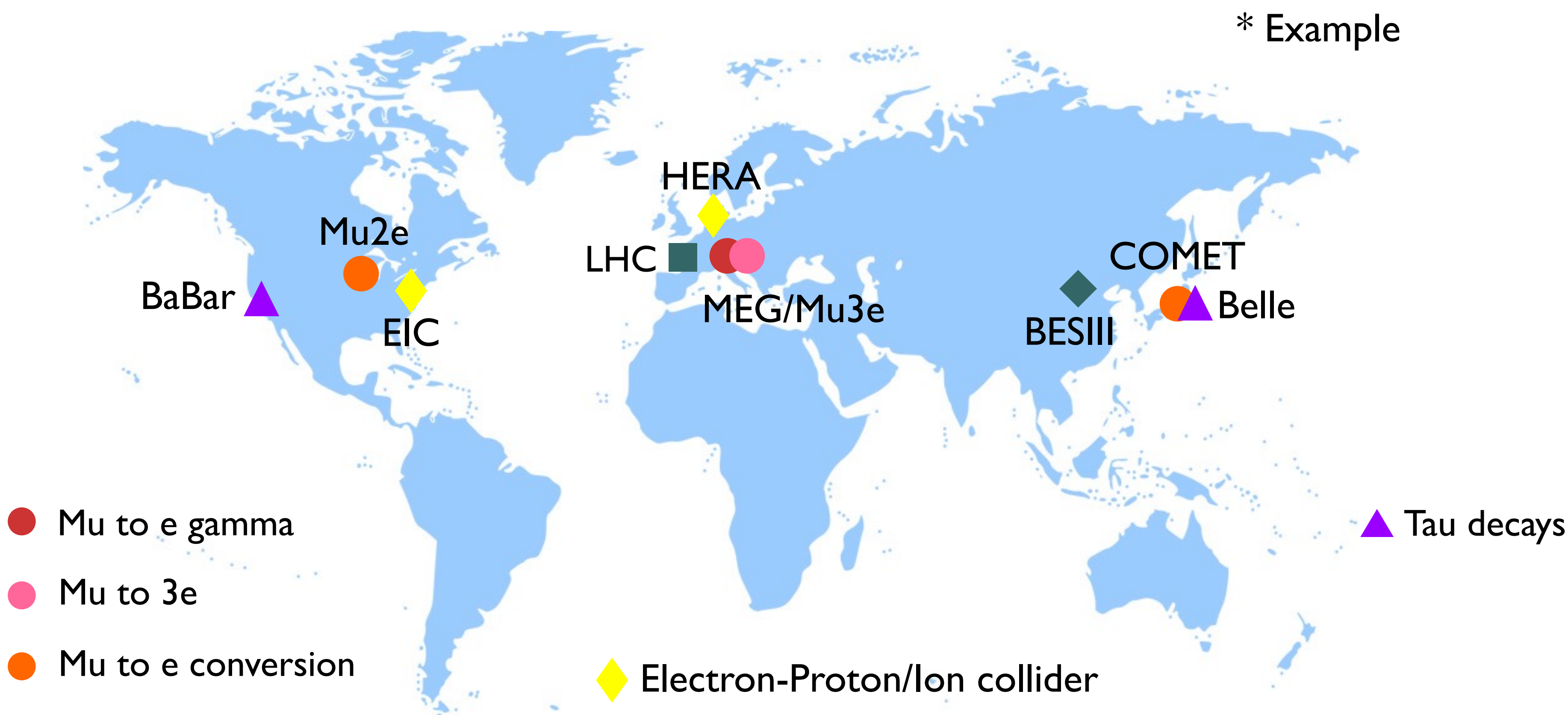
✔ LFV Leptoquark Searches at HERA

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

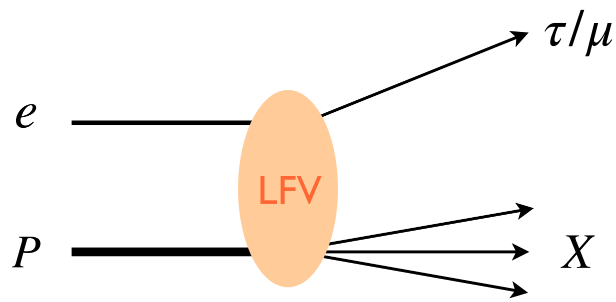
$$\sqrt{S} = 318\ \mathrm{GeV},\quad \mathscr{L} = 10^{31}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$



CLFV searches



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



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

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

*Higher than HERA

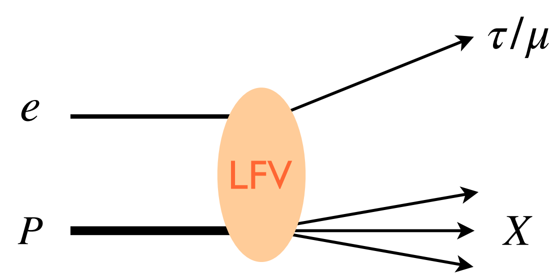
CLFV searches

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

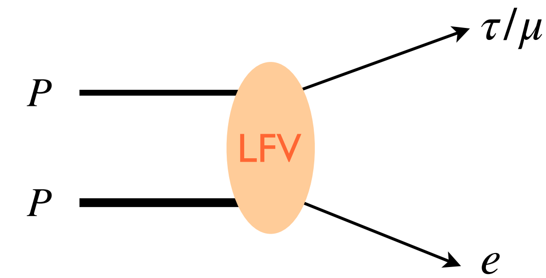
✔ Model-Independent Analysis of CLFV process at low- and high-energy

EIC vs LHC vs Low-Energy CLFV searches

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

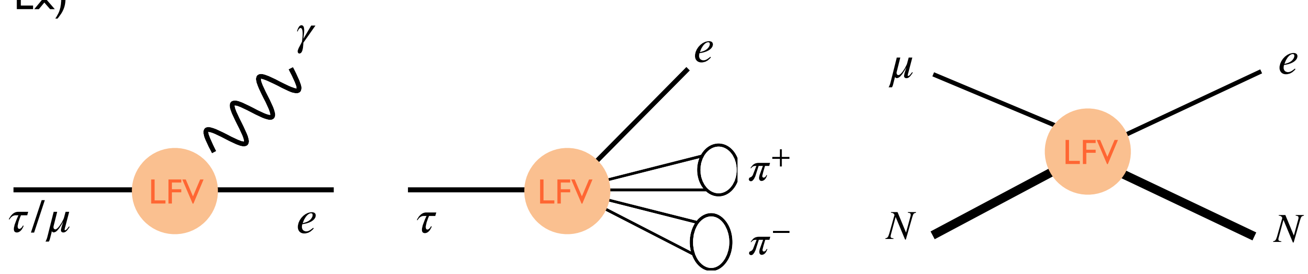


$pp \to e\ \tau/\mu$ @LHC



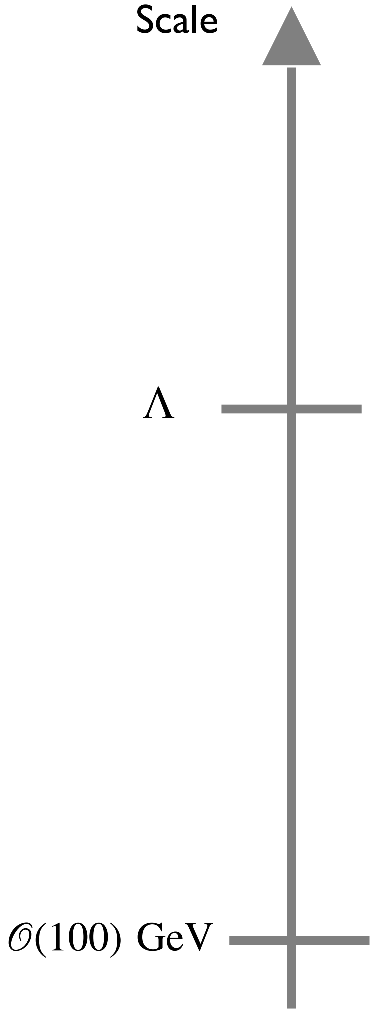
τ, μ, and meson decays

Ex)

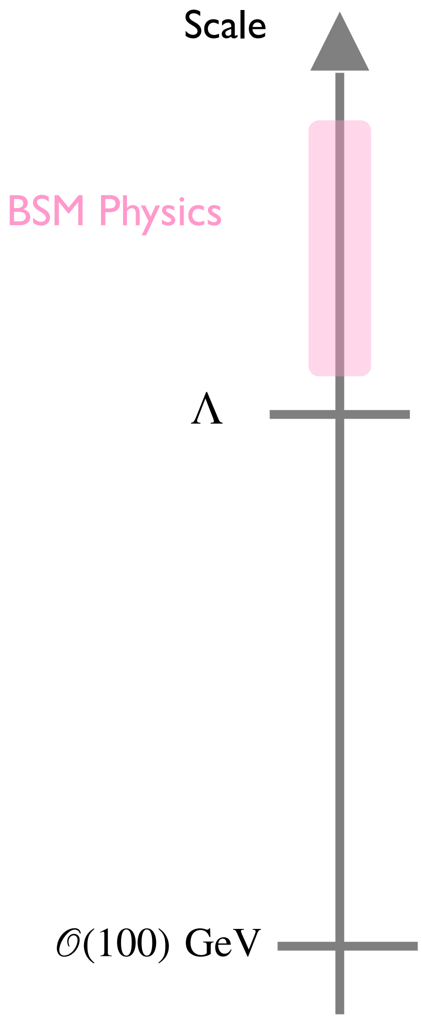


Model-Independent Analysis

SMEFT : Standard Model Effective Field Theory



Model-Independent Analysis



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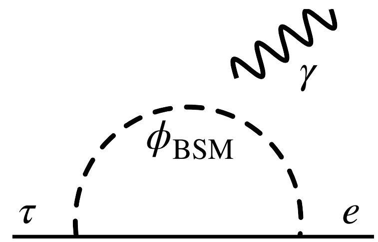
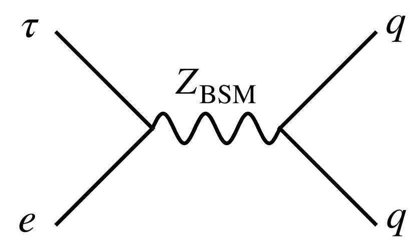
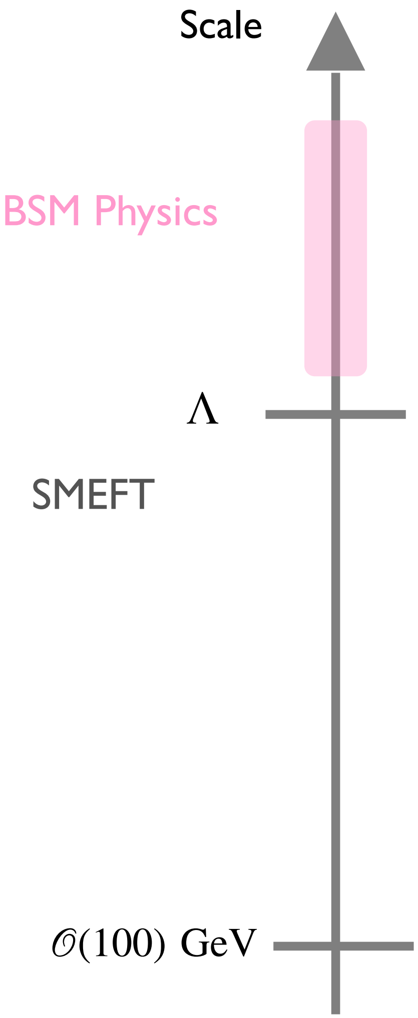




Model-Independent Analysis



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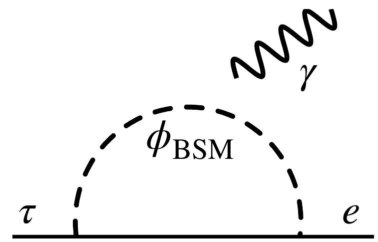
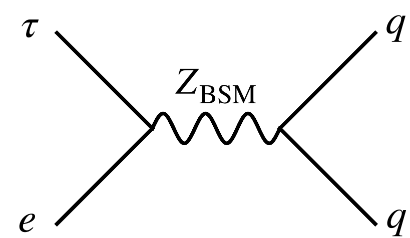
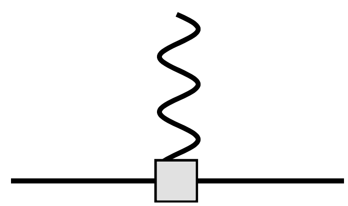




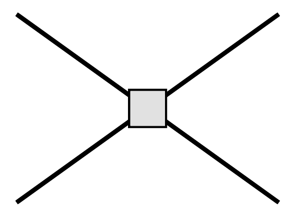
$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_{d=5} \frac{1}{\Lambda^{d-4}} C^d \mathcal{O}^d$$

Higher Dimensional Operators

Dipole



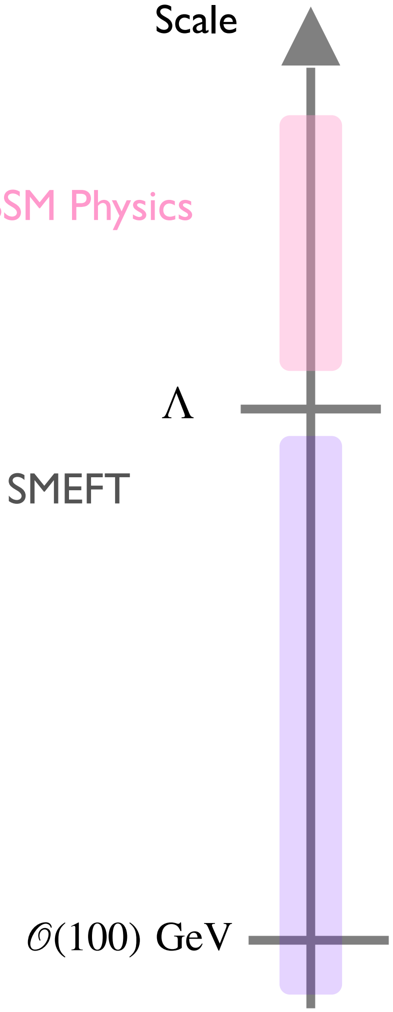
4 Fermion



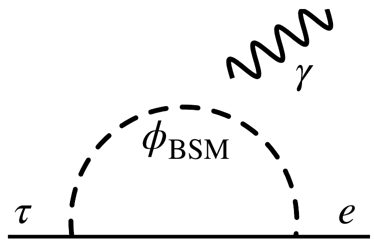
All possible interactions based on gauge and Lorentz invariance

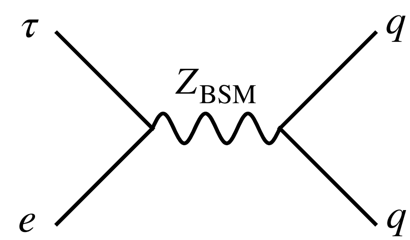
✔ EFT can apply to concrete models

Model-Independent Analysis



SMEFT : Standard Model Effective Field Theory





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

Higher Dimensional Operators

For low-energy observables,

$$\mathrm{e.g.,} \quad \mu \frac{dC}{d\mu} = \frac{g^2}{(4\pi)^2} C$$

Scale Running based on the Renormalization Group Equations

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

CLFV operators

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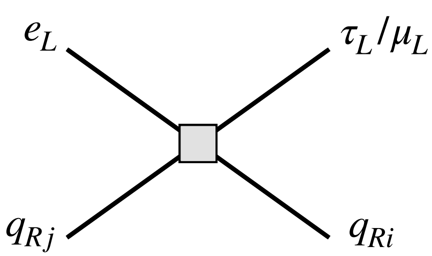
$$\supset -\frac{4G_F}{\sqrt{2}} \sum_{\substack{\ell = \tau, \mu \\ q = u, d}} [C_{Lq}]_{\ell e i j}\, \bar{\ell}_L \gamma^\mu e_L\, \bar{q}_{Ri}\gamma_\mu q_{Rj}$$



*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

Low-Energy Tau and Meson Decay

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$\tau \to e\eta$		9.2×10^{-8}	Belle PLB648(2007)341
$\tau \to e\eta'$		1.6×10^{-7}	Belle PLB648(2007)341

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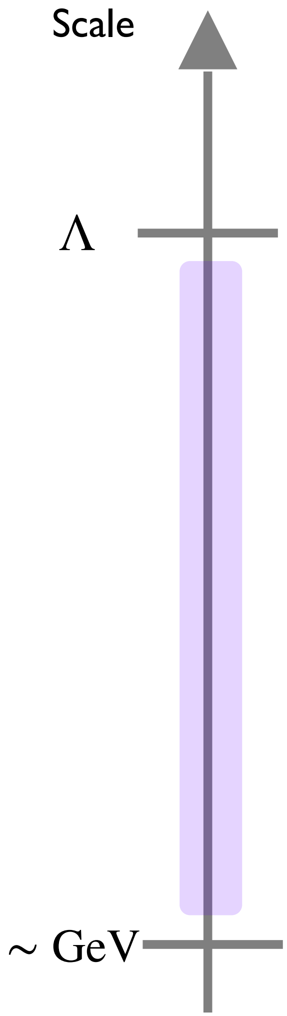
A. Celis, V. Cirigliano, E. Passemar, PRD89(2014)095014

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

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

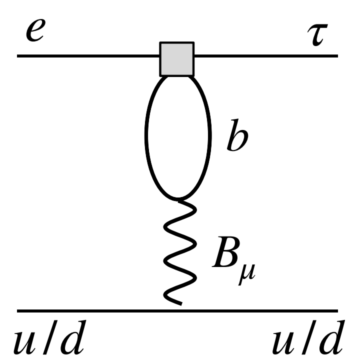
How?

Scale running effects

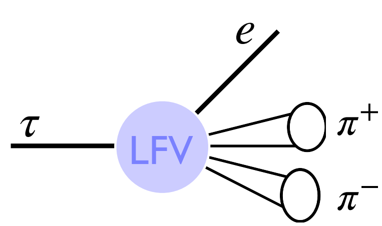


Light-quark operators are induced via the RGEs:

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



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

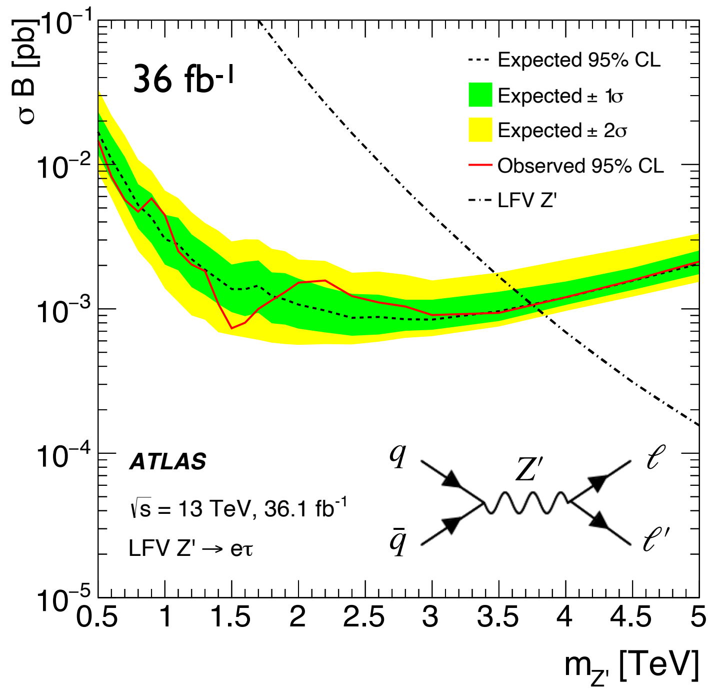


$$[C_{Lu}]_{uu}, [C_{Ld}]_{dd} \sim \frac{g^2}{(4\pi)^2}[C_{Ld}]_{bb}$$

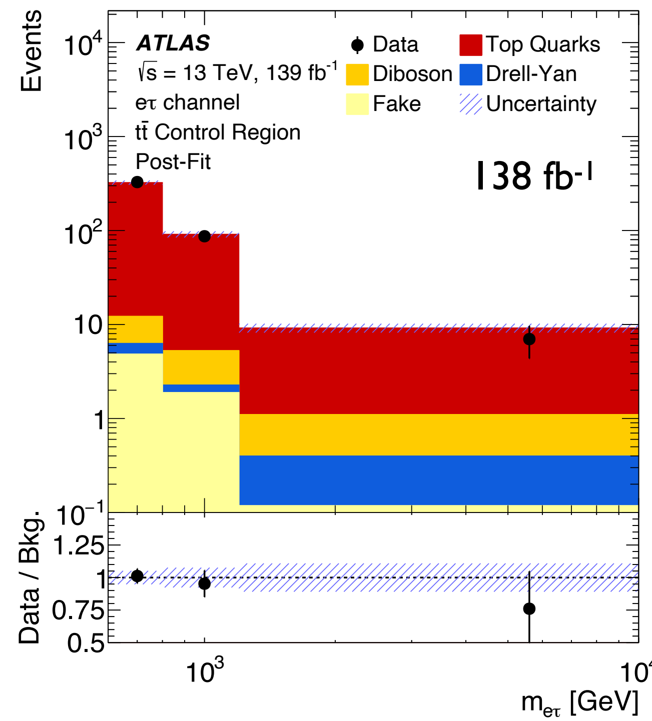
Loop effect $\sim \mathcal{O}(10^{-3})$

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

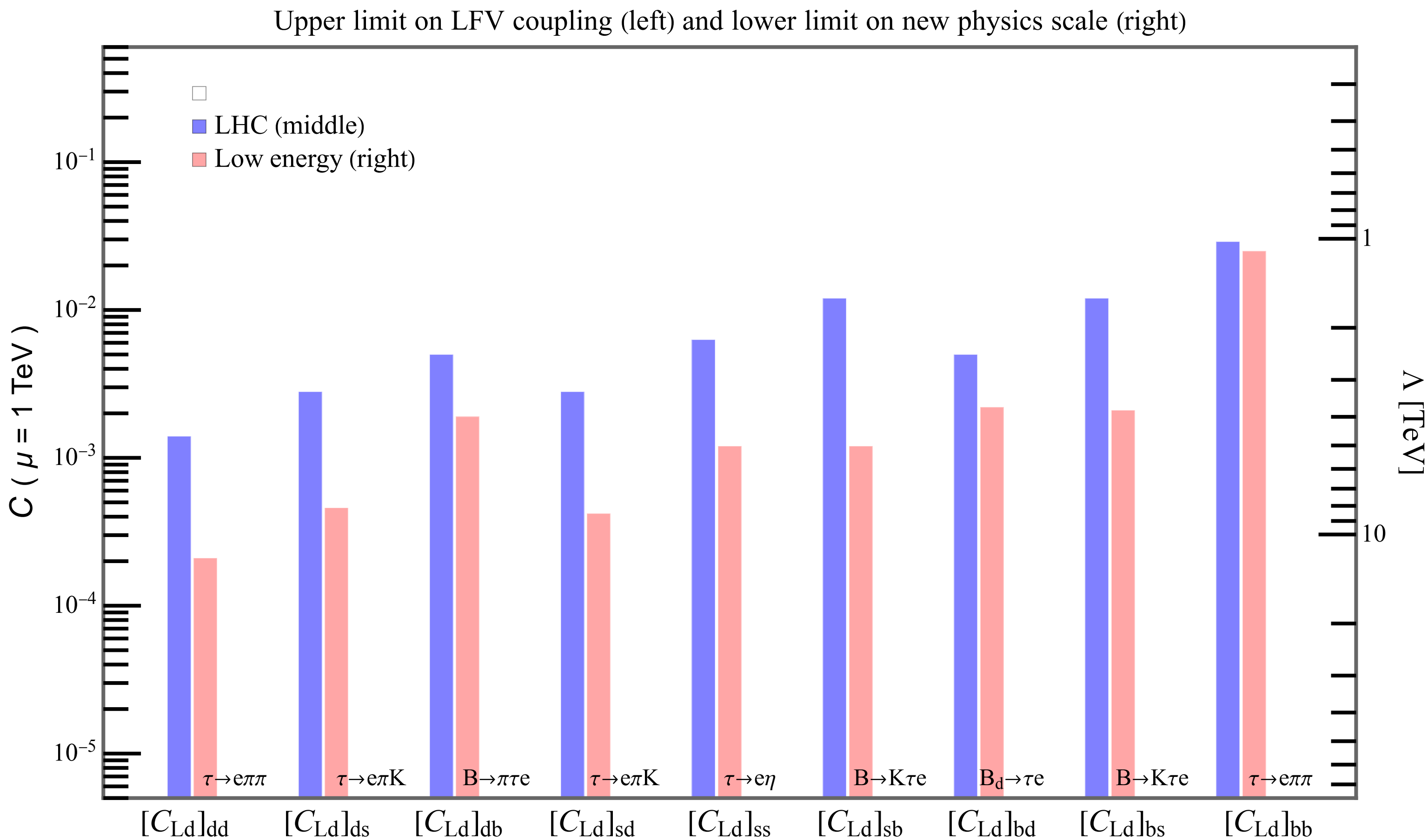
- ATLAS published pp → l l' bounds in high-mass final states using 36 fb^{-1}

  '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



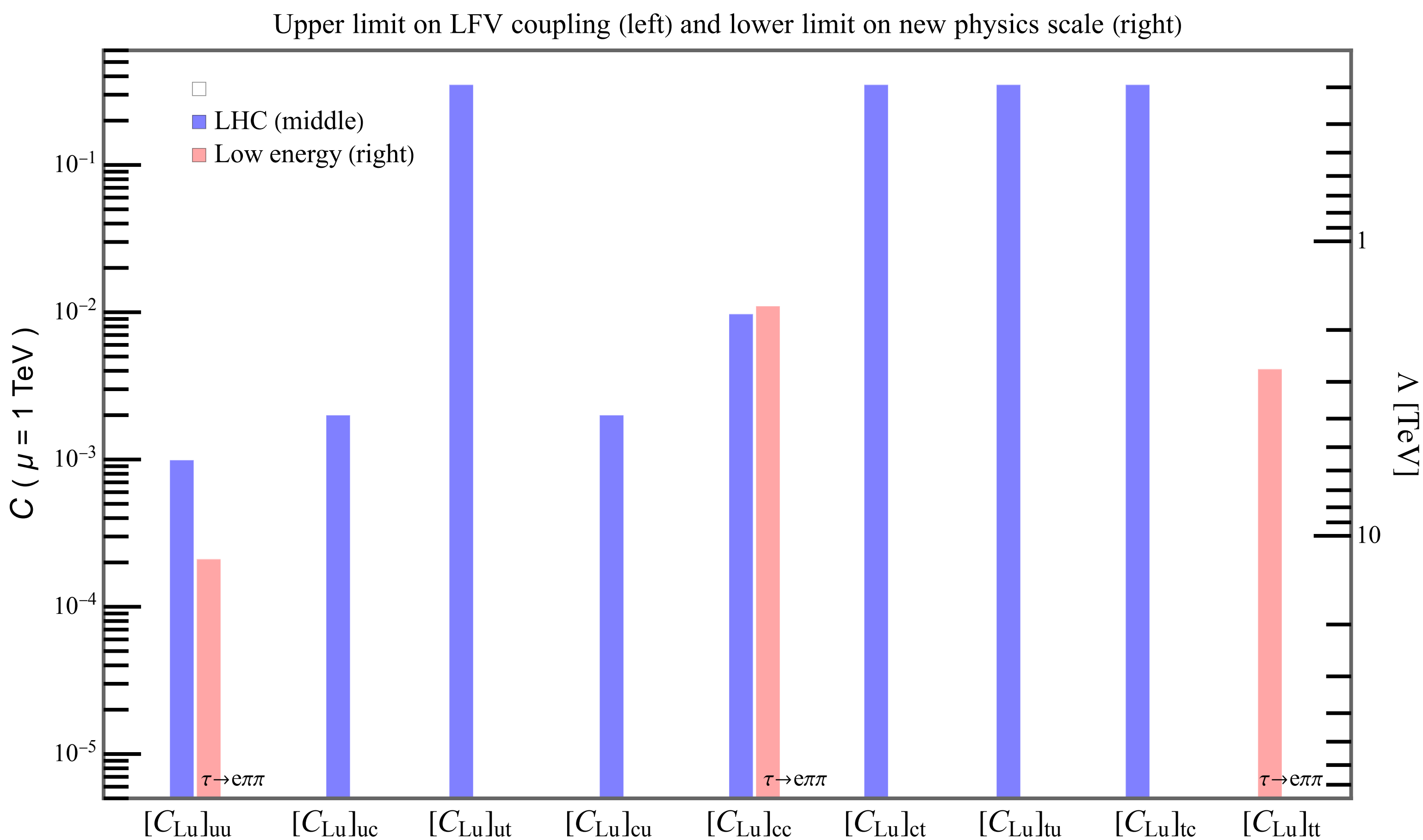
$[C_{Ld}]_{ij}\ \bar{\tau}_L \gamma^\mu e_L\ \bar{d}_{Ri} \gamma_\mu d_{Rj}$

- 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

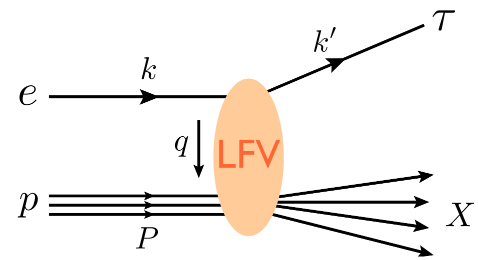
* Single Operator Analysis



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

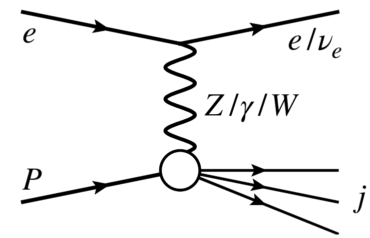
- Less constrained by low energy than d-type operators
- Strong bound on $[C_{Lu}]_{tt}$ from $\tau \to e\pi^+\pi^-$

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 $[C_{Ld}]_{bb}$

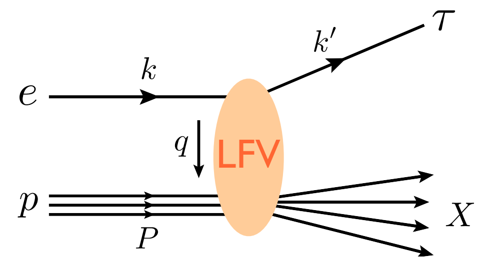


- Major backgrounds 1) Neutral Current $ep \to ej$

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

  * Impose simple cuts to reduce BGs

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 $ep \to \nu_e j$

- Promising ID channel

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

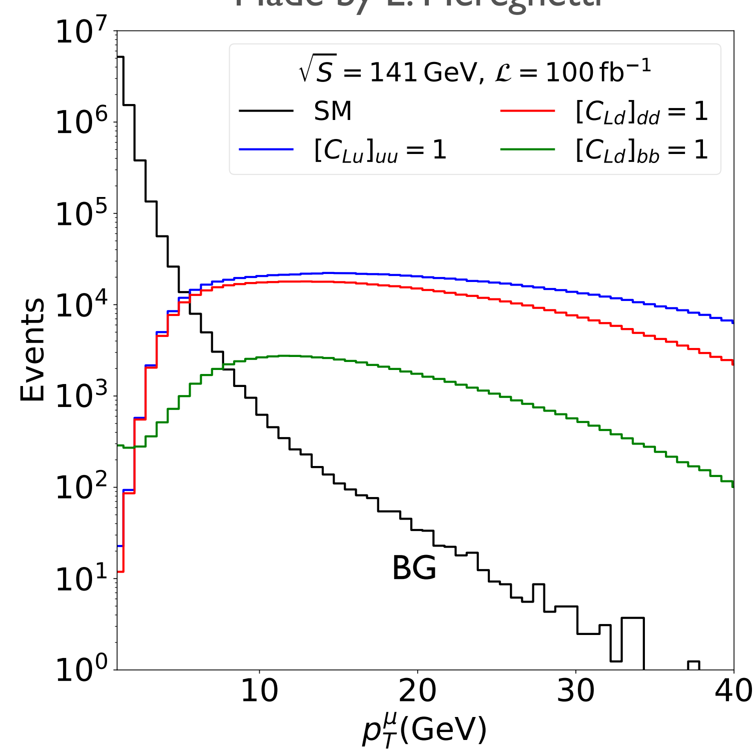
✔ $$\mathrm{BR}(\tau \to \mu\bar{\nu}_\mu\nu_\tau) = 17.39\,\%$$

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

* Eliminate SM backgrounds

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

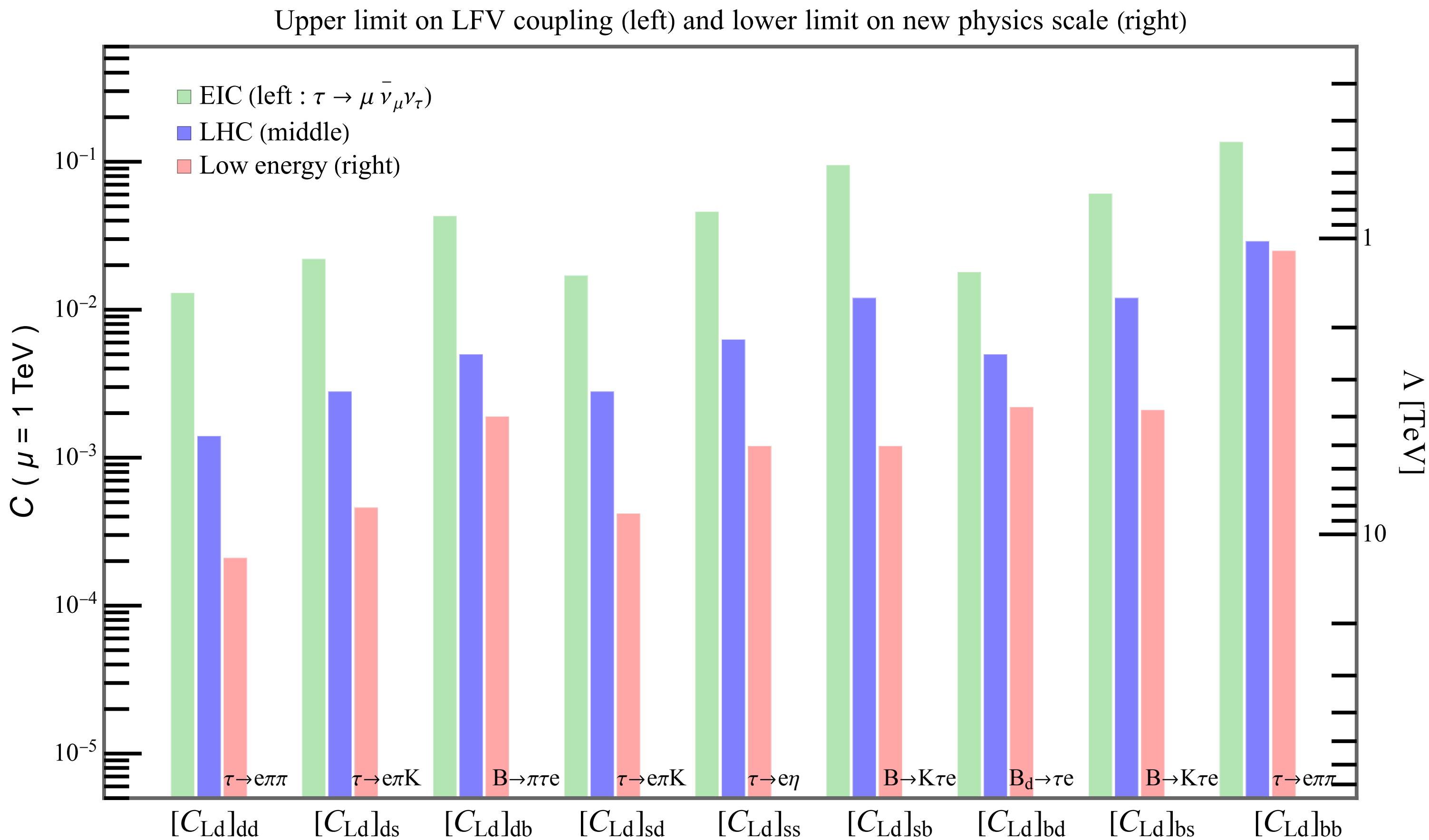
Made by E. Mereghetti



EIC vs Current limits

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

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



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

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

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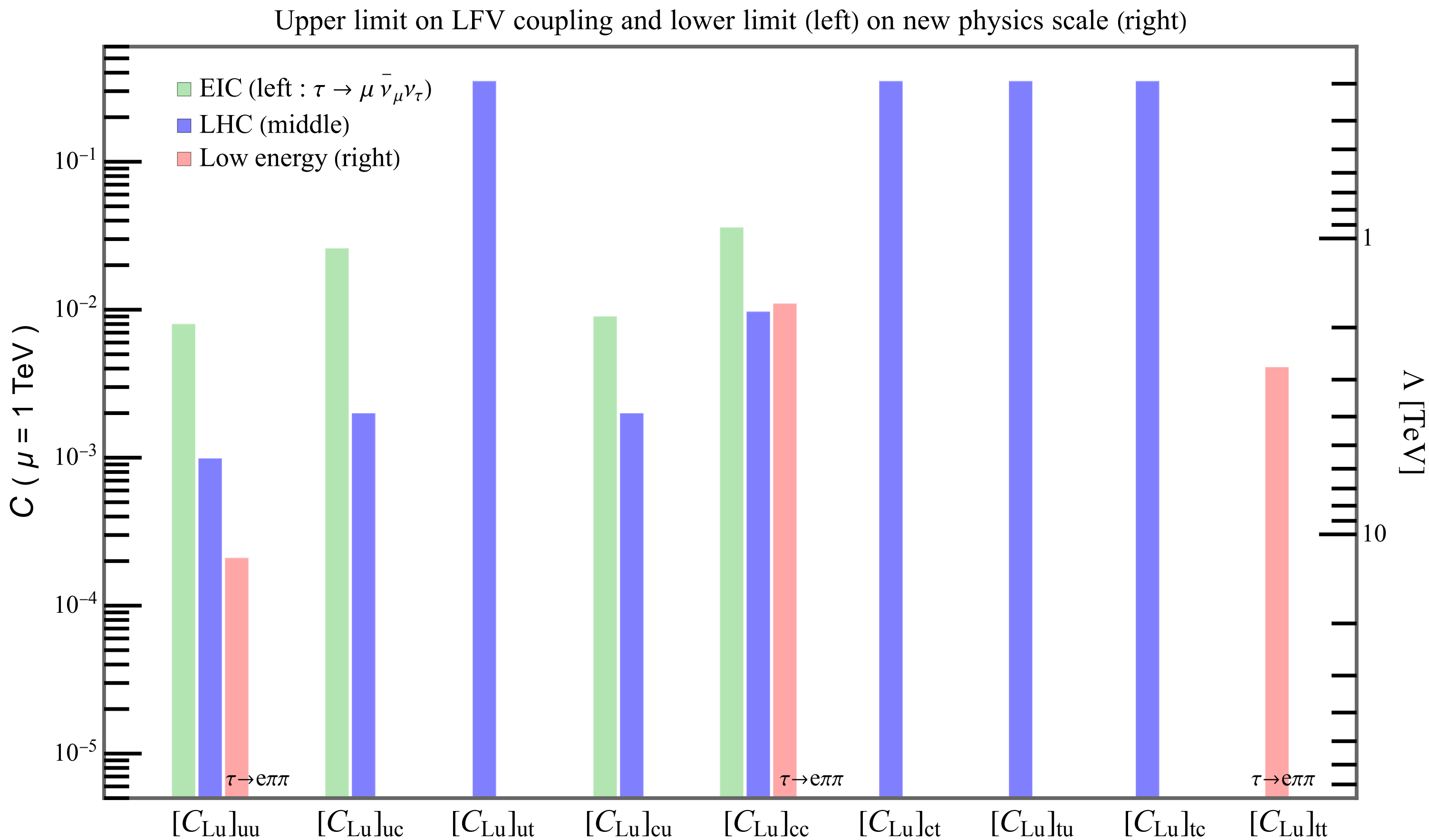

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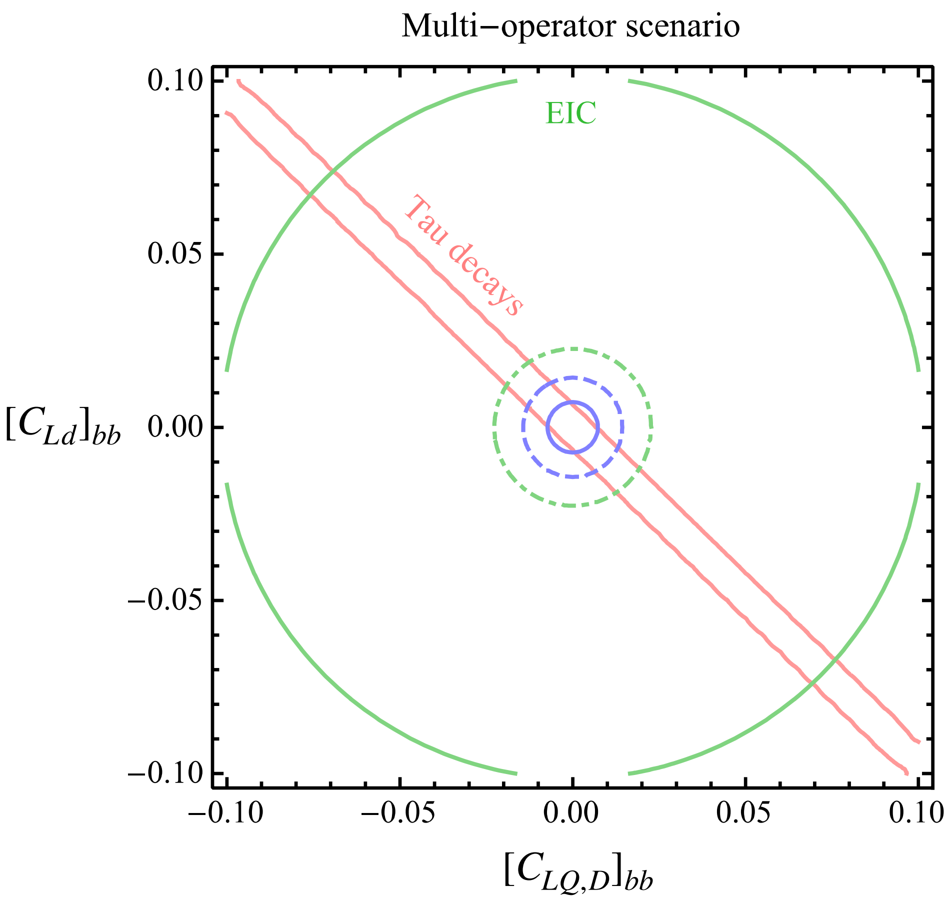
Multi-operator scenario

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



*Case with 8 nonzero CLFV operators

Z couplings + down-type 4F operators

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

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

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

- Collider probes are necessary to close the free direction.

What about $e \to \mu$ case?

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

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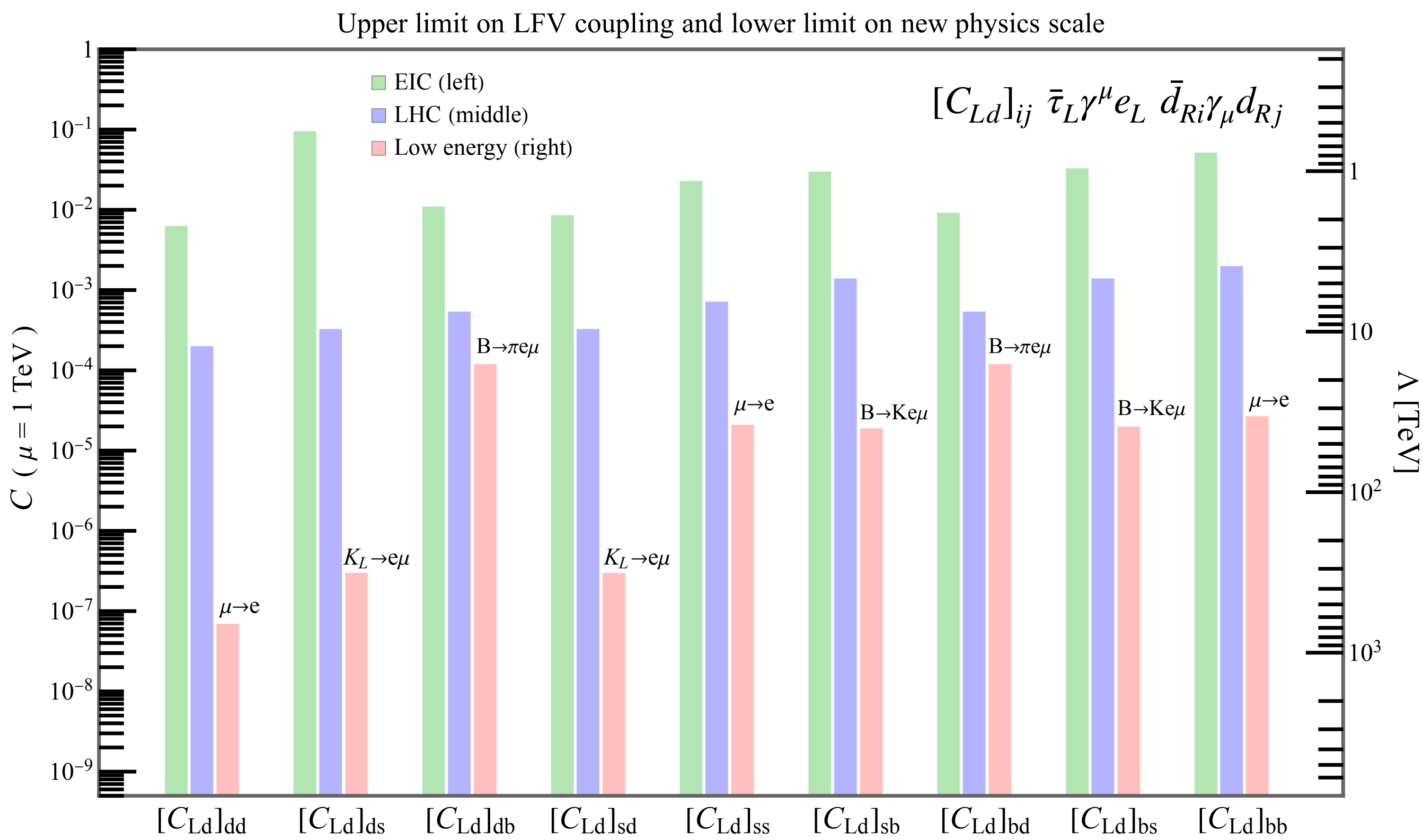

- $\mu \to e$ conversion currently gives strong bound

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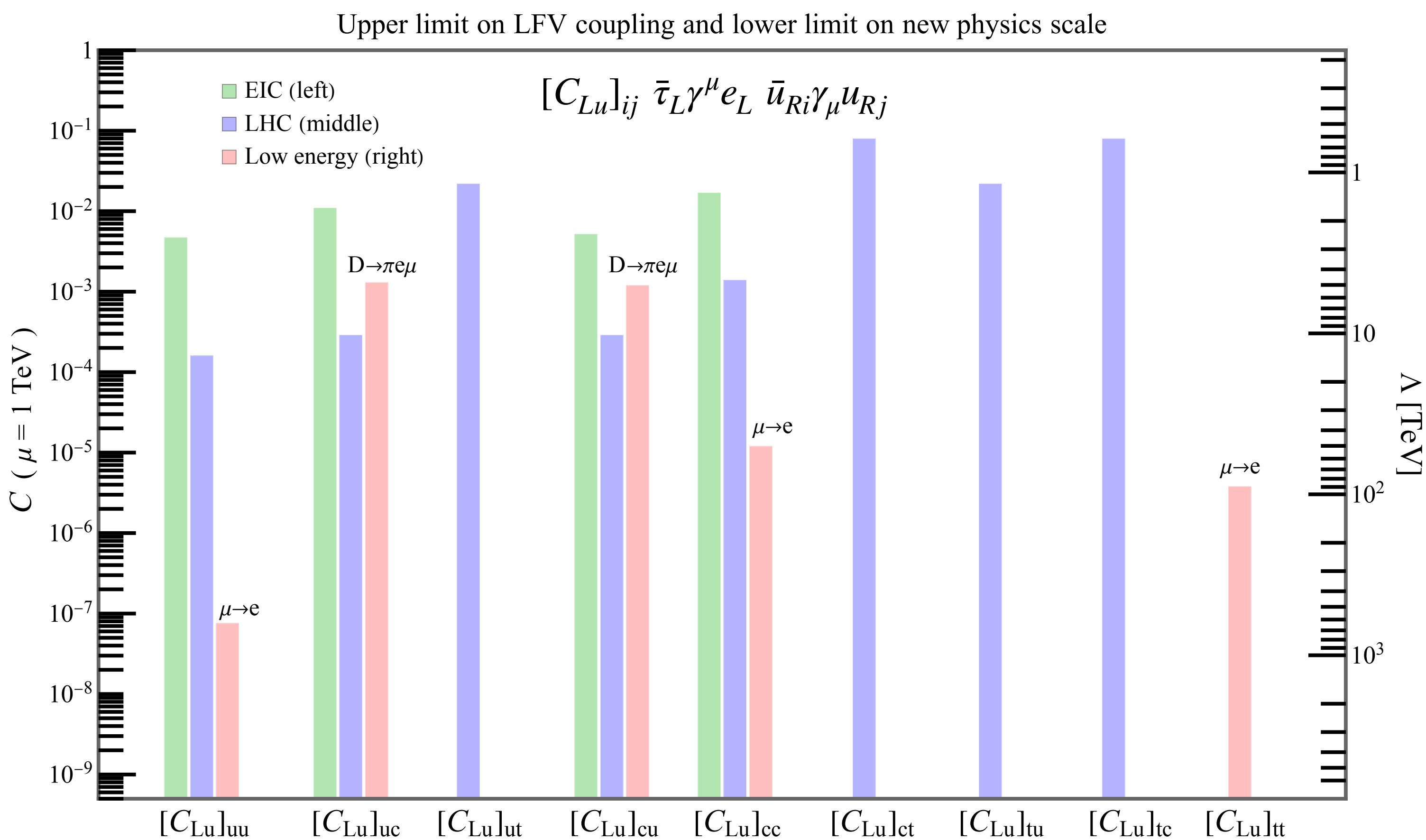
F. Delzanno, KF, S. Gonzalez-Solis, E. Mereghetti, arXiv 2411.13497



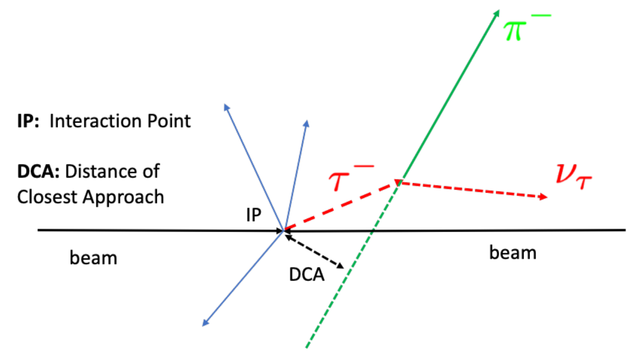
- A factor of 10 weaker bound on $[C_{Lu}]_{cu}$ at the EIC

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



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

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

Benchmark performance:

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

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

Lead by LANL experimental team : J. Kvapil, X. Li, M. Liu, Y. Morales, YD Tsai, Z. Xu

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

Today

- 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

- Z enhancement in $e - A$ collision ?
- Multi-Dimensional Analysis using Machine Learning
- b, c quark and tau lepton tagging

Backup slides

Apple to Apple

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