LA-UR-24-28967

Searching for Lepton Flavor Violation

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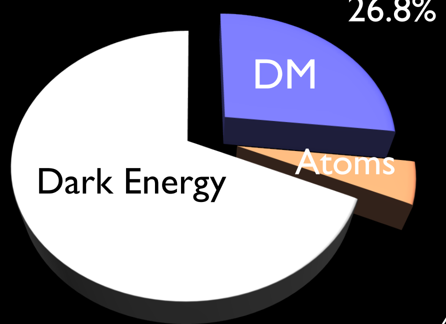
THEORETICAL DIVISION Since 1943

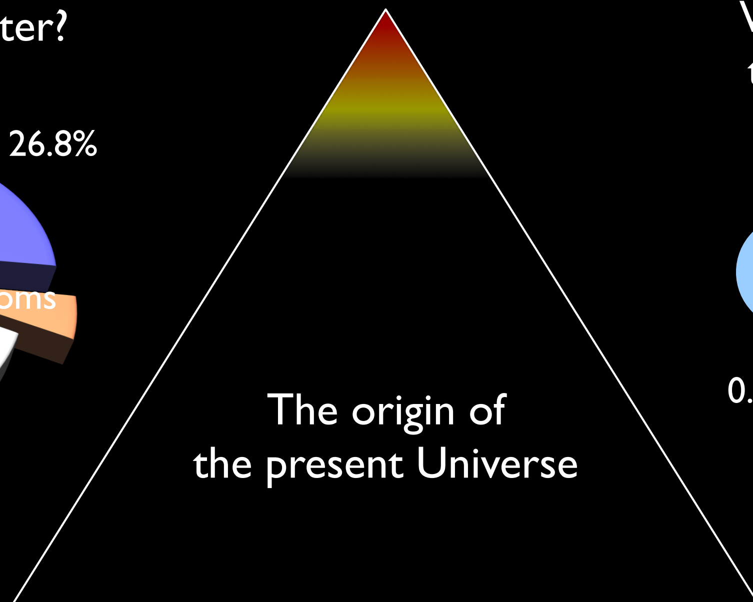
V. Cirigliano, KF, C. Lee, E. Mereghetti, B. Yan, JHEP03(2021)256
S. Banerjee, V. Cirigliano, et al, Snowmass White Papaer, 2203.14919
KF, E. Mereghetti, PRD109(2024)075014
F. Delzanno, KF, S. Gonzalez-Solis, E. Mereghetti, work in progress

August 22, 2024
PPP2024

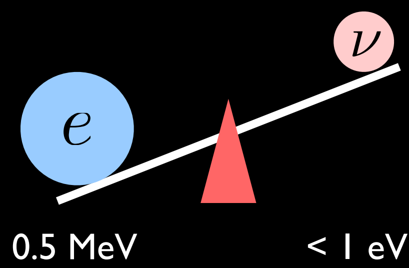
We still don’t know much about our Universe.

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

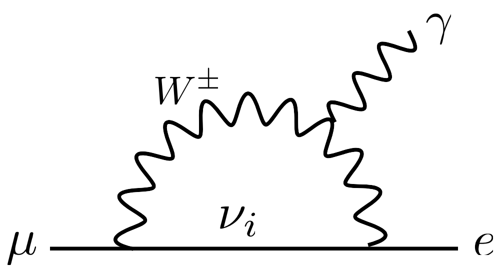
Searches for CLFV are strong tools to probe BSM physics.

*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 ....

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

Dirac or Majorana

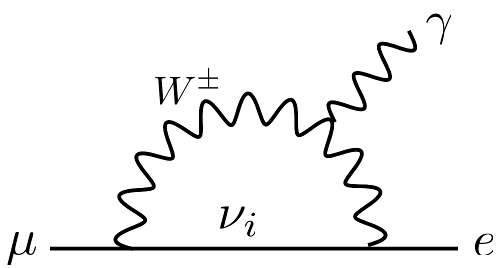
$$\mathrm{Br}\left(\mu \to e\gamma\right) = \frac{3\alpha_{\rm em}}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{m^2_W}\right|^2 < 10^{-54}$$

Extremely small!

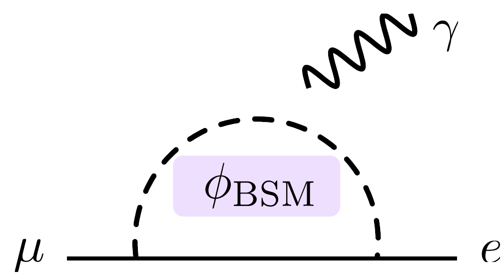
Charged Lepton Flavor Violation

Searches for CLFV are strong tools to probe BSM physics.

Ex) SM + neutrino mass (νSM)



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



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

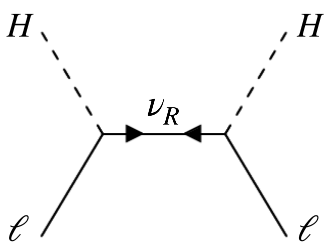
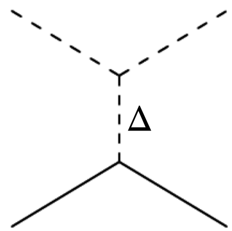
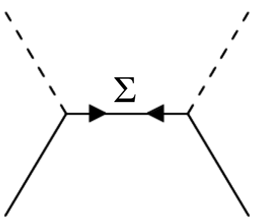
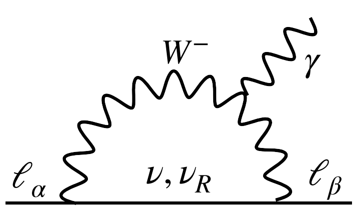
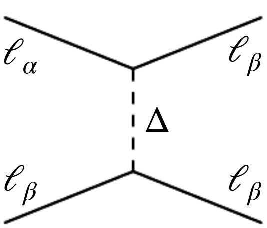
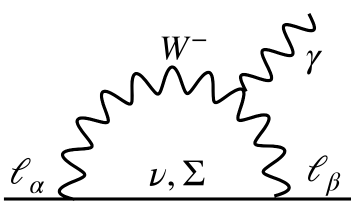
✔ The Observations of CLFV would point to new physics beyond νSM.

*Underlying mechanism of the neutrino mass.

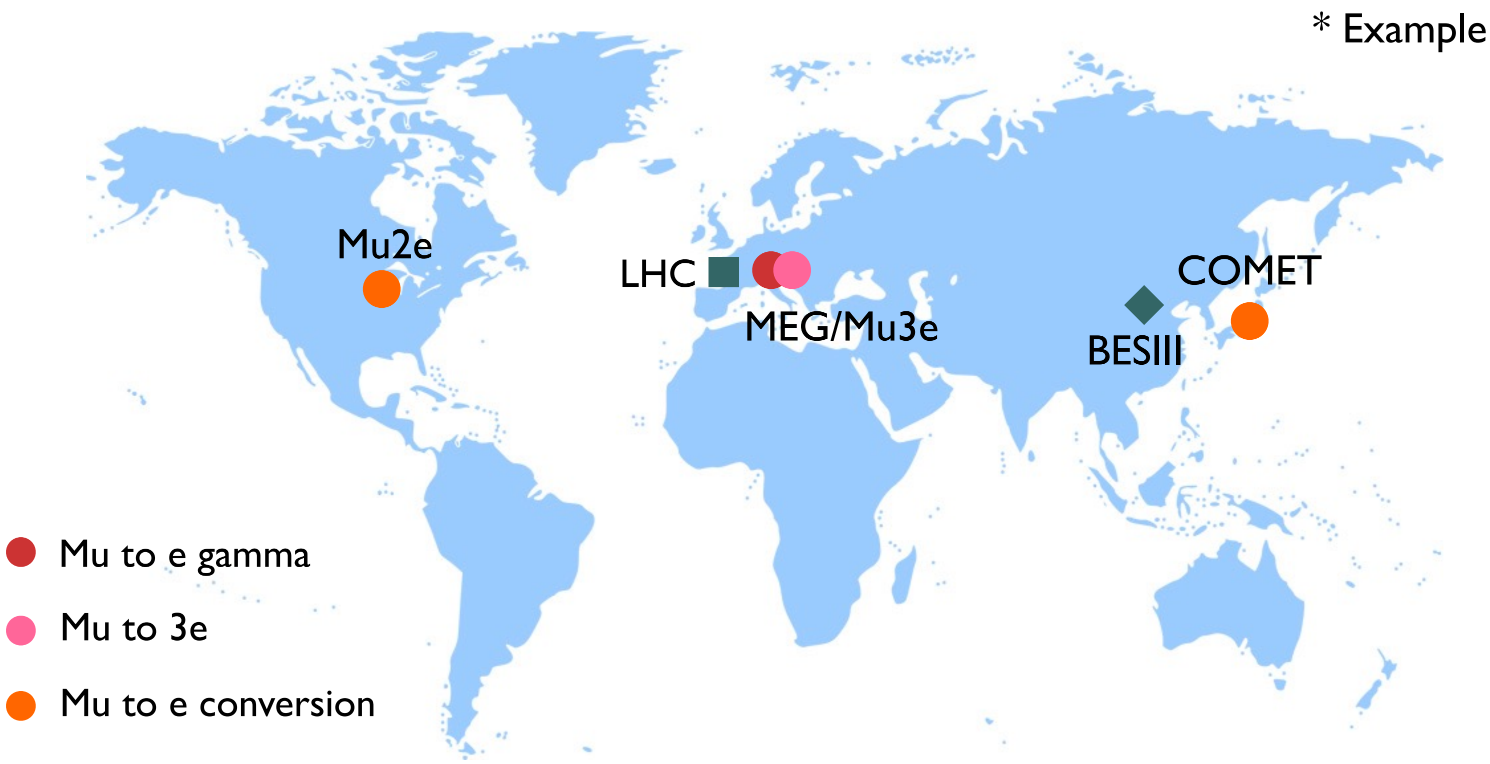
Charged Lepton Flavor Violation

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

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

	Type I	Type II	Type III
ν mass			
	$m_\nu \sim \frac{Y_\nu^2 v^2}{M_R}$	$m_\nu \sim Y_\Delta v^2 \frac{\mu_\Delta}{M_\Delta^2}$	$m_\nu \sim \frac{Y_\Sigma^2 v^2}{M_\Sigma}$
LFV			

CLFV searches



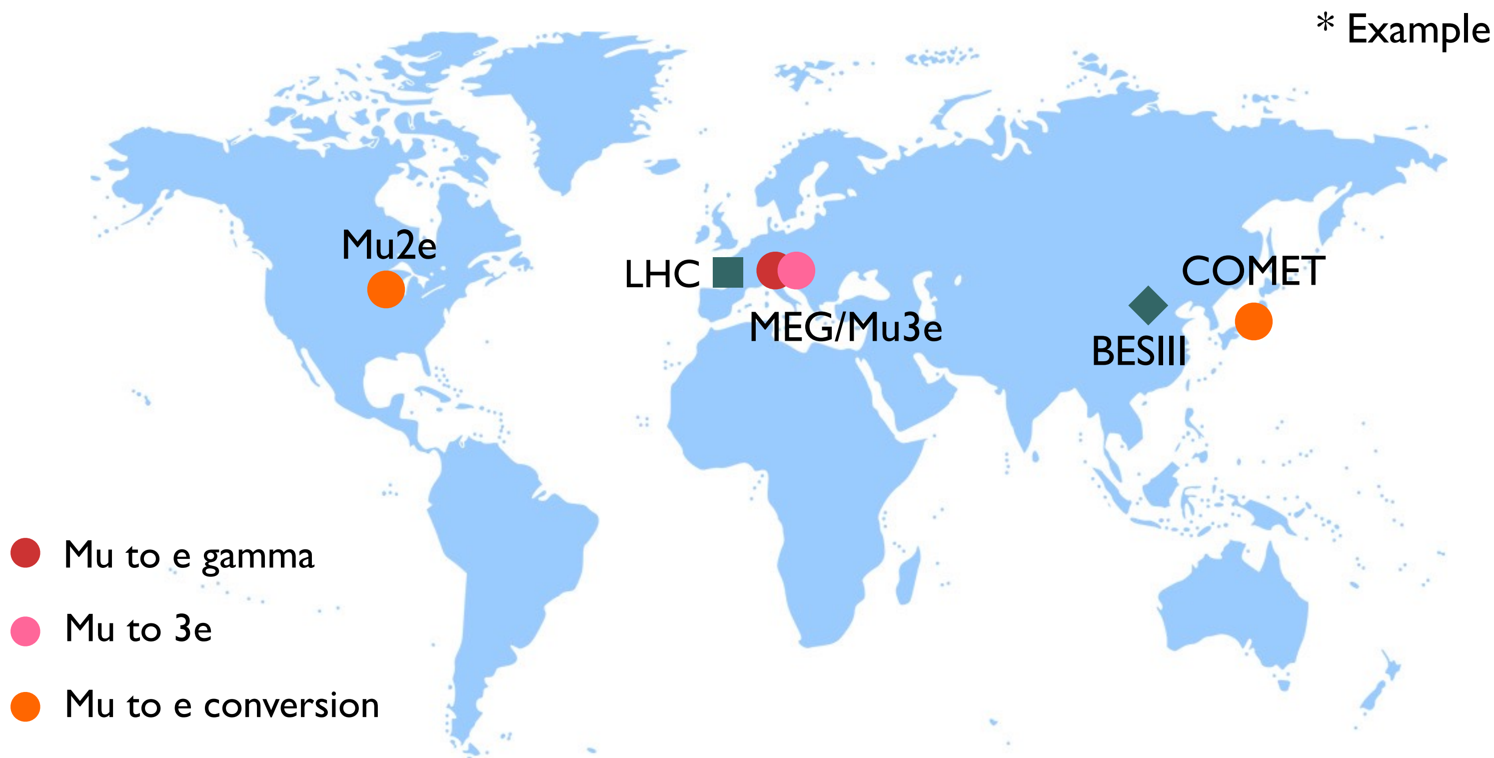
$$\mathrm{BR}(\mu \to e\gamma) < 3.1 \times 10^{-13}$$

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).

CLFV searches



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

Mu2E
at Fermilab, USA

$$\mathrm{BR}(\mu^- \ \mathrm{Al} \to e^- \ \mathrm{Al}) \sim \mathcal{O}(10^{-17})$$

COMET
at J-PARC, JP

CLFV searches

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

BaBar, PRL104 (2010) 021802

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

Belle, PLB719 (2013) 346-353

CLFV searches

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

BaBar, PRL104 (2010) 021802

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

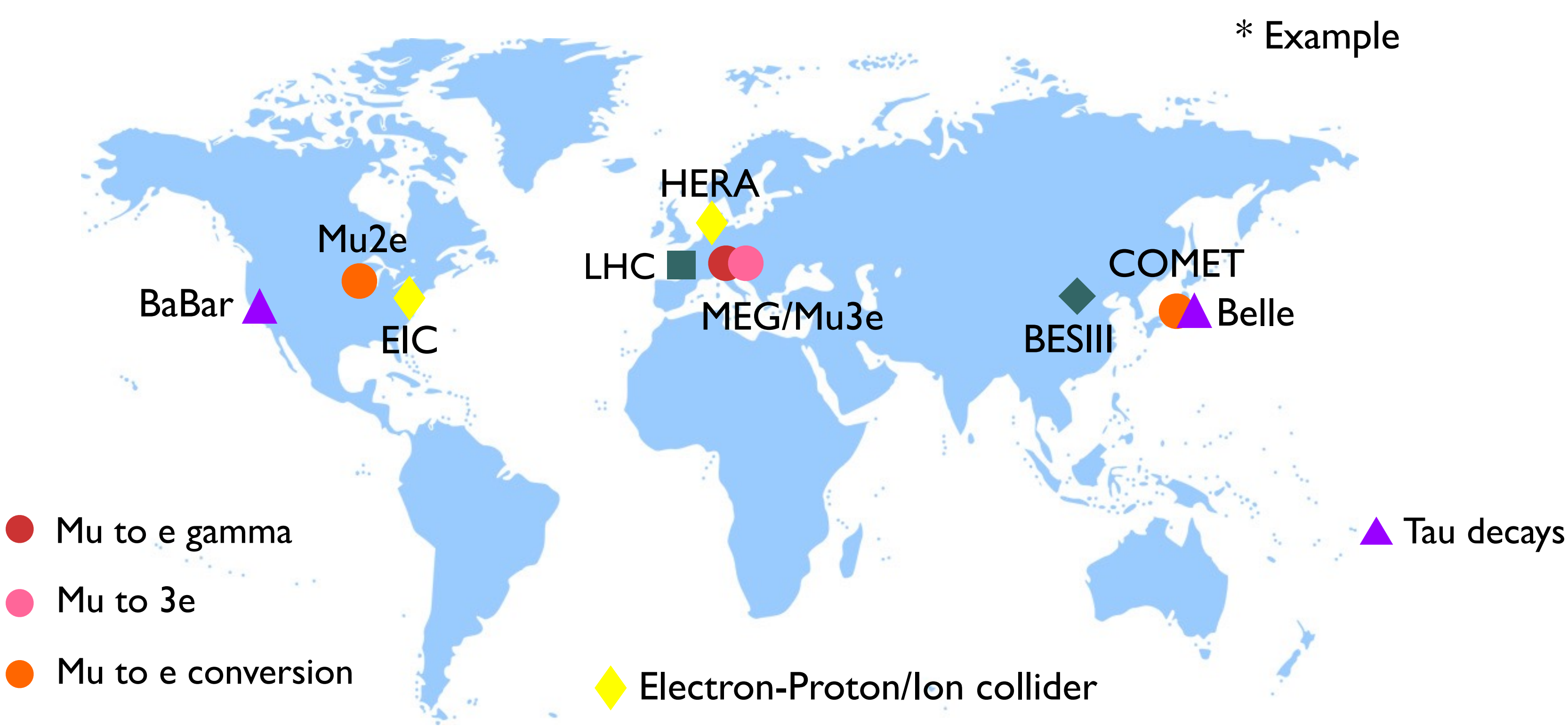
Belle, PLB719 (2013) 346-353

$$\sim 9 \times 10^{-9}$$

$$\sim 5.8 \times 10^{-10}$$

Belle II Collaboration, Snowmass White Paper - Belle II physics reach and plans for the next decade and beyond, 2022.

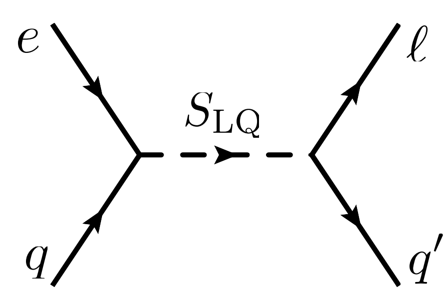
CLFV searches



✔ LFV Leptoquark Searches at HERA

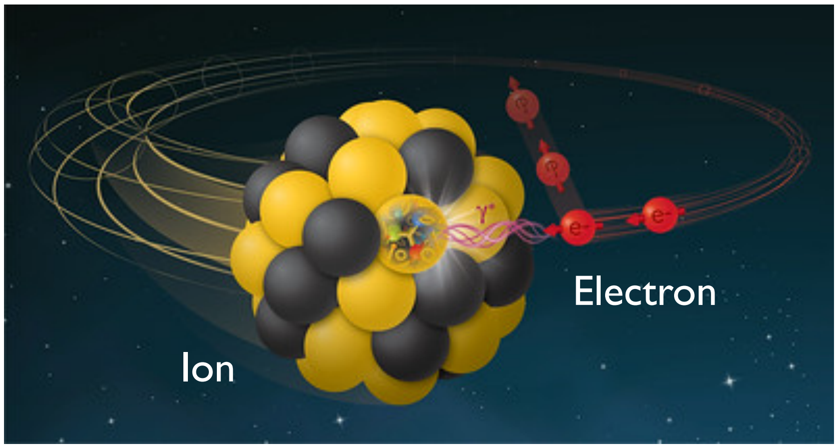
ZEUS collaboration, Eur. Phys. J. C 44 (2005) 463
H1 collaboration, Eur. Phys. J. C 52 (2007) 833

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



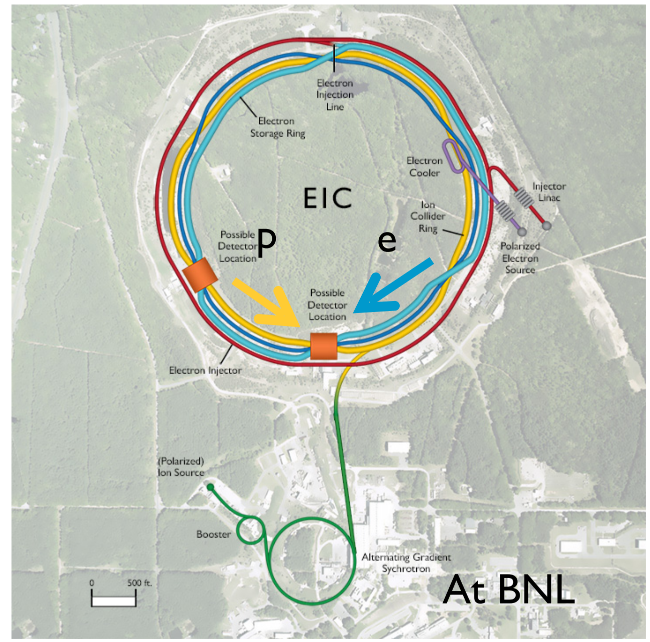
CLFV searches

Another potential search for CLFV at Electron-Ion Collider



Map the structure of the proton and nuclei

https://www.bnl.gov/eic/



EIC Detector Requirements and R&D Handbook
EIC Yellow report, arXiv:2103.05419

$$\sqrt{S} = 20 \sim 140 \text{ GeV} \qquad \mathscr{L} = 10^{33-34} \text{ cm}^{-2} \text{ s}^{-1}$$

*Higher than HERA

Construction is scheduled to begin in 2026, with operations beginning in 2032

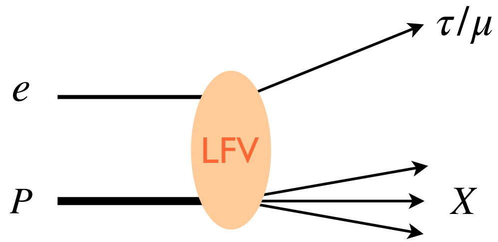
CLFV searches

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

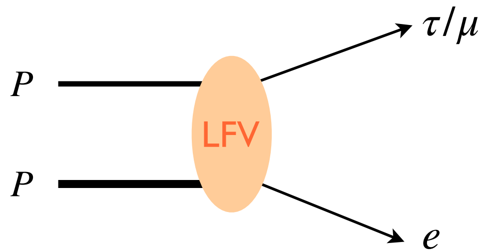
✔ Model-Independent Analysis of CLFV process at low- and high-energy

EIC vs LHC vs Low-Energy CLFV searches

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

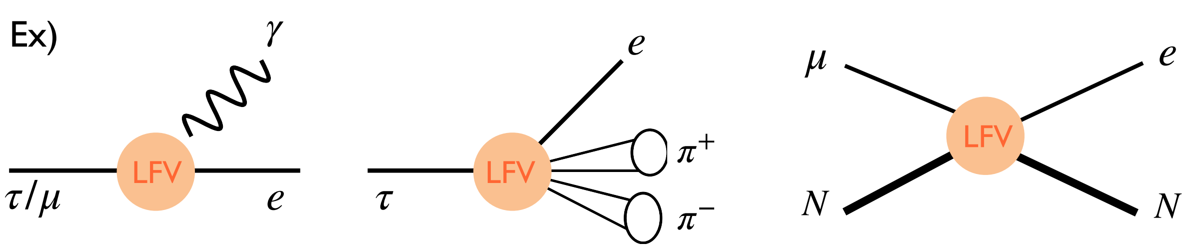


$pp \to e\ \tau/\mu$ @LHC



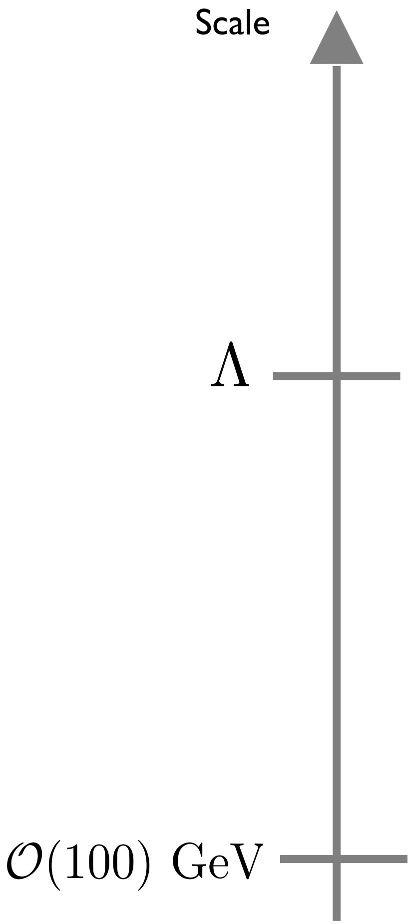
τ, μ, and meson decays

Ex)



Model-Independent Analysis

SMEFT : Standard Model Effective Field Theory



Model-Independent Analysis

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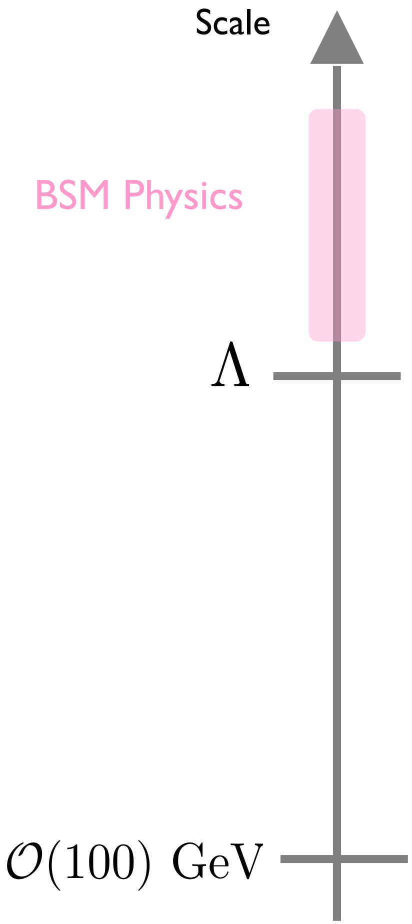
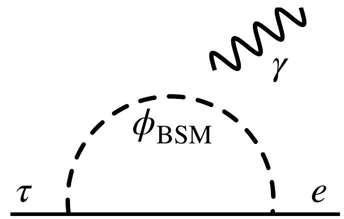
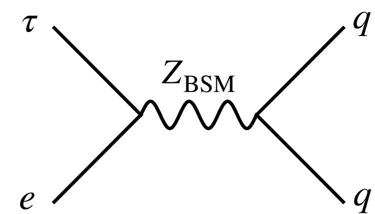
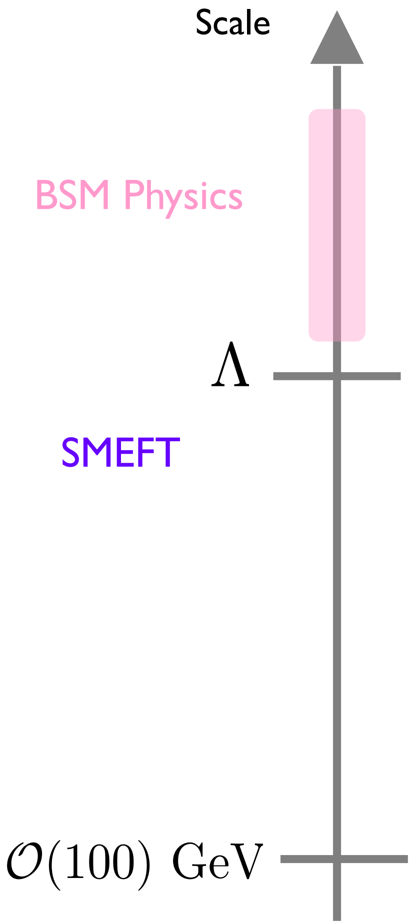






Model-Independent Analysis



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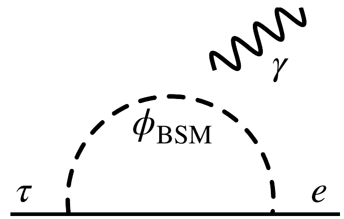
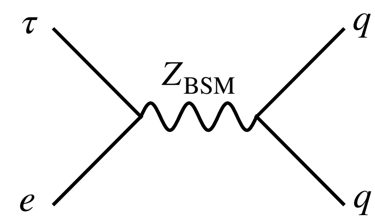
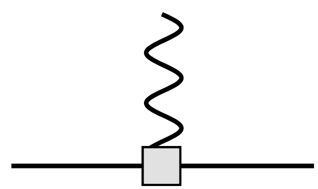




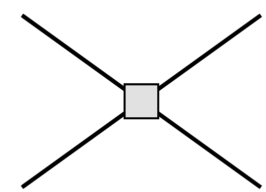
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{d=5} \frac{1}{\Lambda^{d-4}} C^d \mathcal{O}^d$$

Higher Dimensional Operators

Dipole



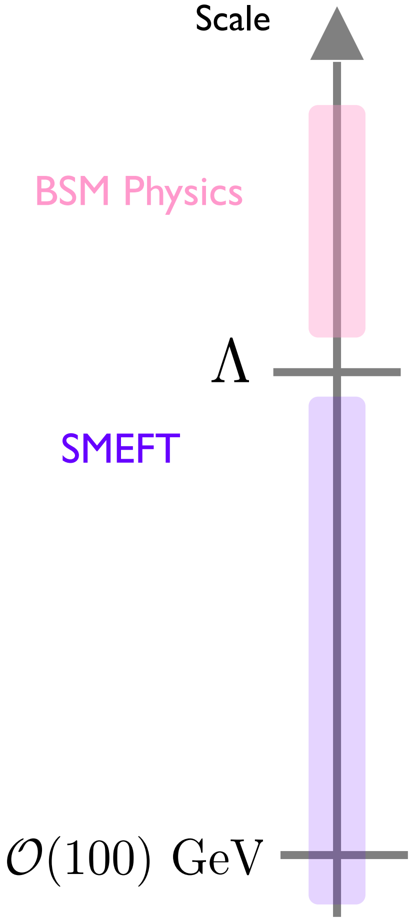
4 Fermion



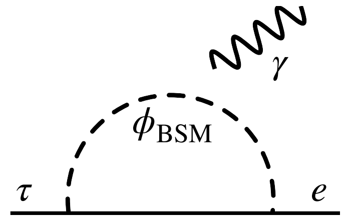
All possible interactions based on gauge and Lorentz invariance

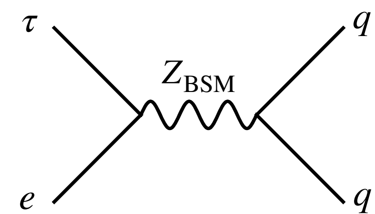
✔ EFT can apply to concrete models

Model-Independent Analysis



SMEFT : Standard Model Effective Field Theory





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

Higher Dimensional Operators

For low-energy decays,

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

Scale Running based on the Renormalization Group Equations

CLFV operators

Total : 16 different type 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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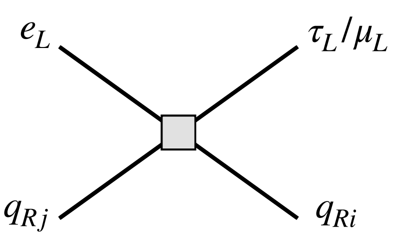
X : Gauge boson ψ : Fermion φ : Higgs

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



*Assume generic quark flavor structure

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

Let's first see 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

Decay mode		Upper limit (90 % C . L.)	
$\tau \to e\pi^+\pi^-$		2.3×10^{-8}	Belle PLB719(2013)346
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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) $$\mathrm{BR}(\tau \to e\pi^+\pi^-) \simeq 0.5 \times \left| [C_{Lu}]_{uu} - [C_{Ld}]_{dd} \right|^2$$

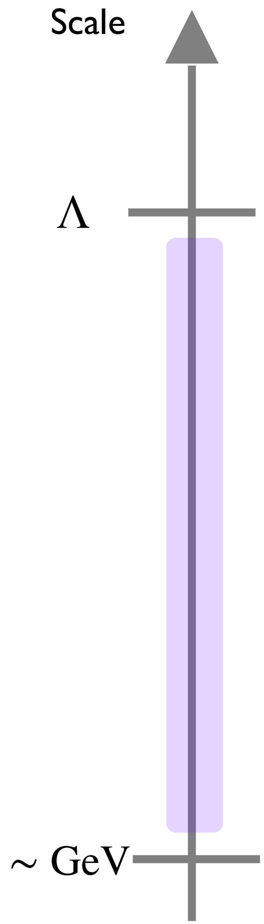
A. Celis, V. Cirigliano, E. Passemar, PRD89(2014)095014

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

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

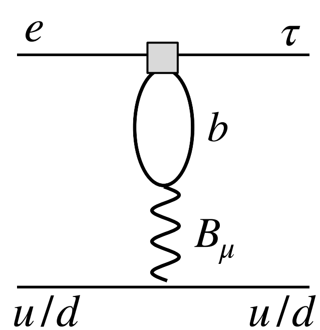
How?

Scale running effects

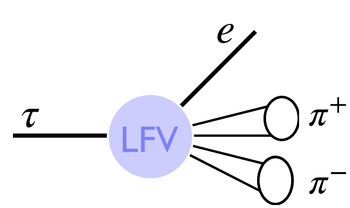


Light-quark operators are induced via the RGEs:

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



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

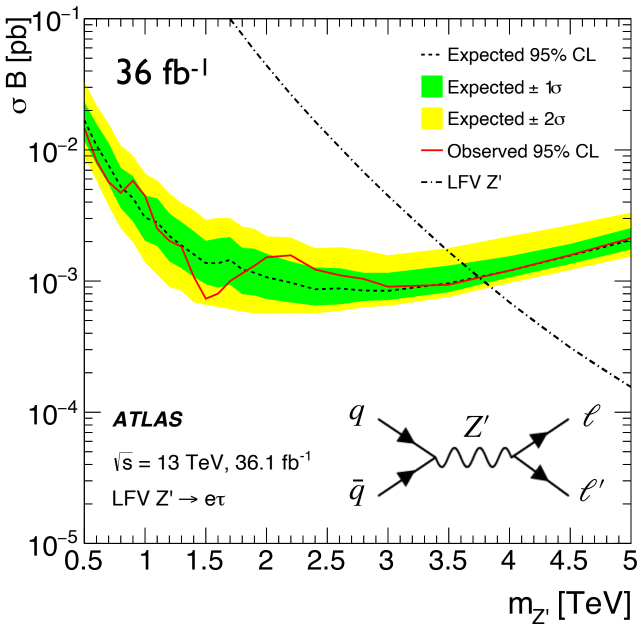


$$[C_{Lu}]_{uu}, [C_{Ld}]_{dd} \sim \frac{g^2}{(4\pi)^2}[C_{Ld}]_{bb}$$

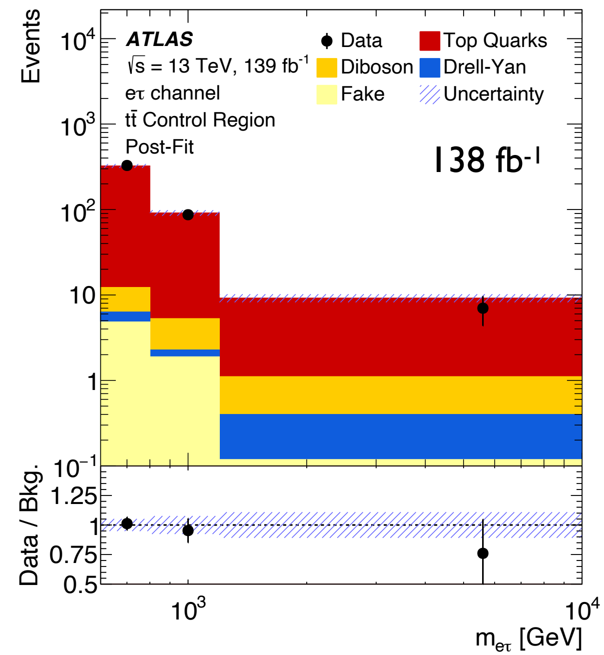
Loop effect $\sim \mathcal{O}(10^{-3})$

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

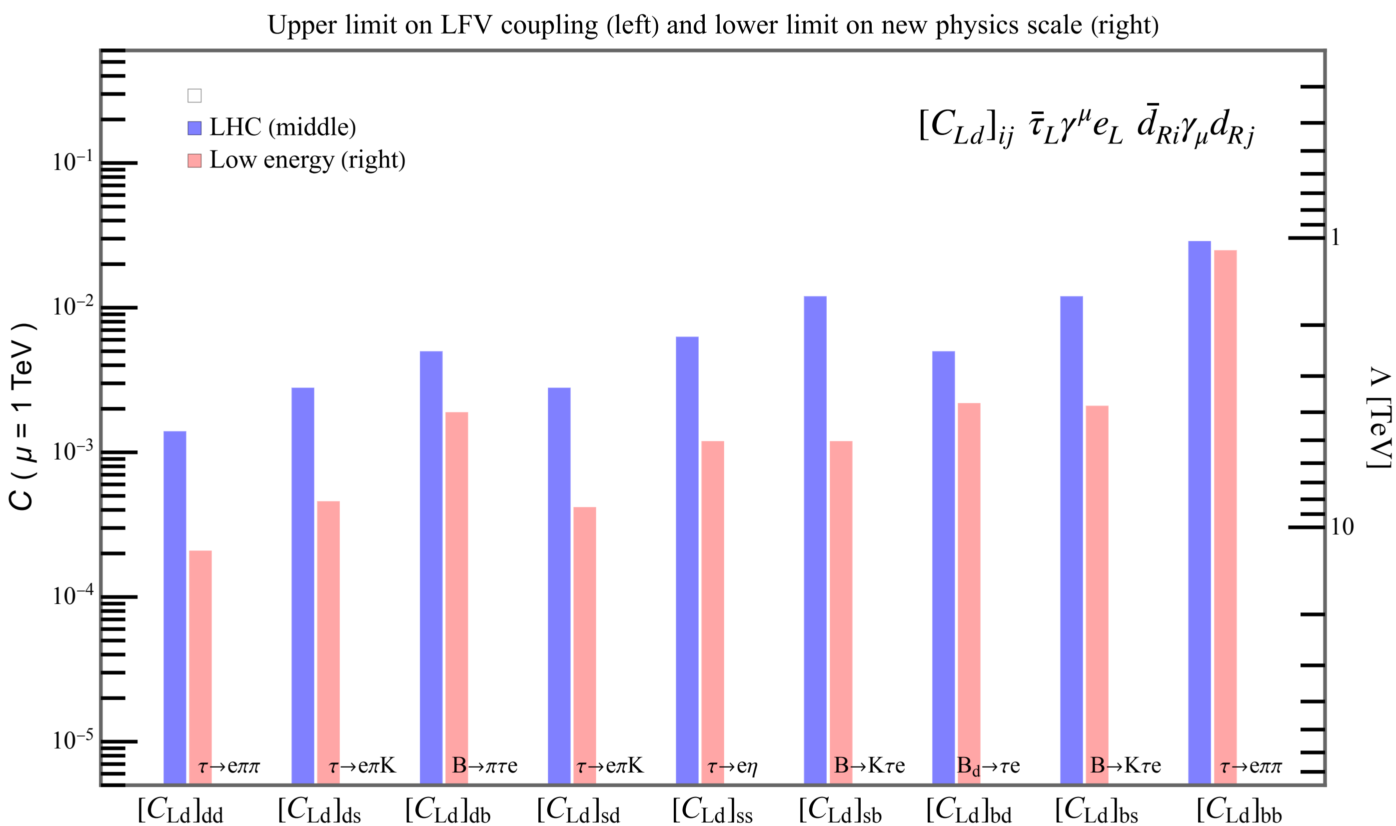
- ATLAS published pp → l l' bounds in high-mass final states using 36 fb^{-1}

  '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

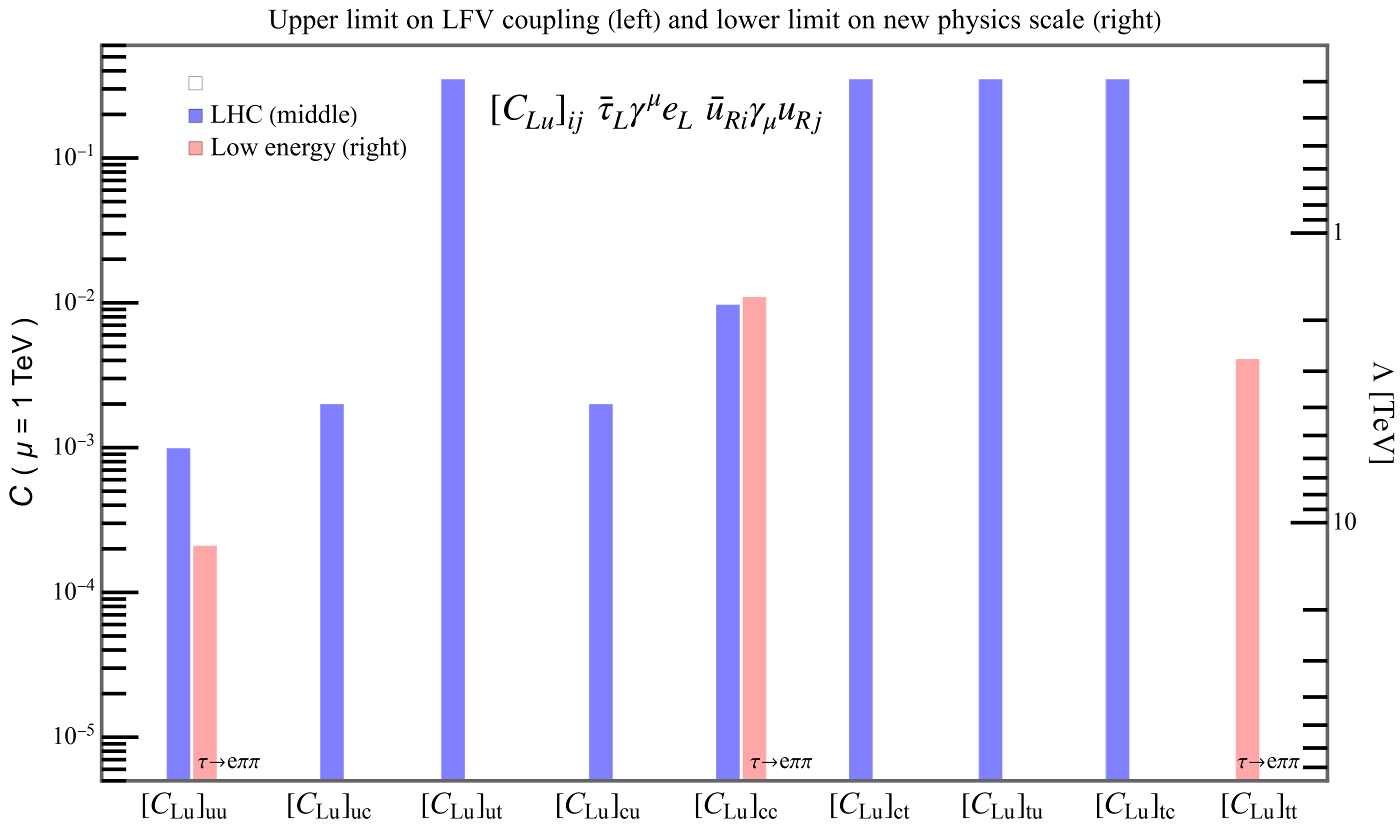


- Operators with d-type quarks sector well constrained by low-energy
- PDF and loop suppression in $[C_{Ld}]_{bb}$

Existing bounds

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

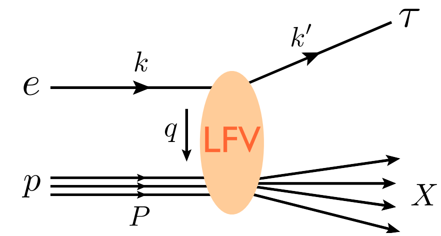
* Single Operator Analysis



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

EIC Analysis

* Impose simple cuts to reduce BGs



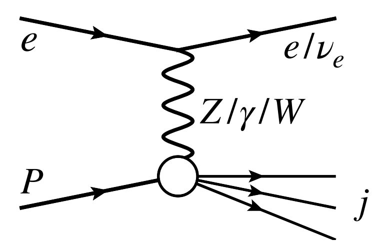
- Cross sections : $\mathcal{O}(1-10)$ pb at $\sqrt{S} = 141$ GeV

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

- Major backgrounds

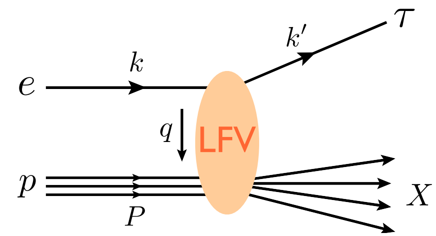
  1) Neutral Current $ep \to ej$

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



EIC Analysis

* Impose simple cuts to reduce BGs



- 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

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

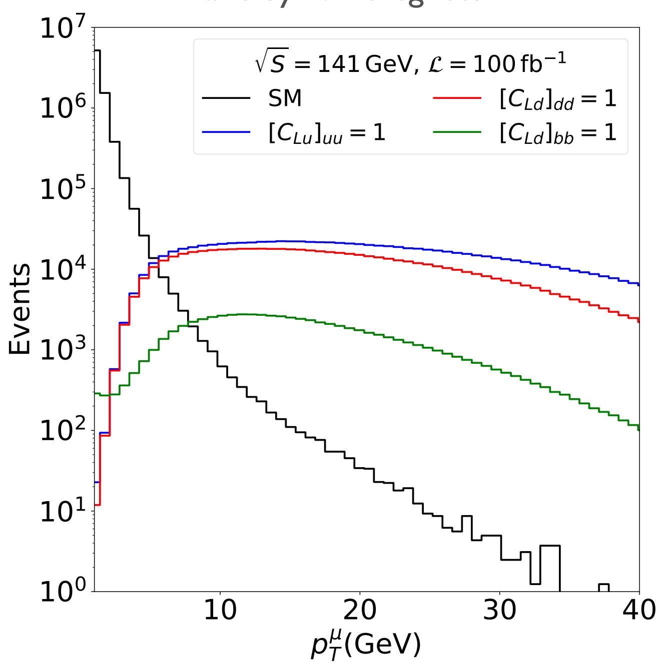
✔ $$\mathrm{BR}(\tau \to \mu\bar{\nu}_\mu\nu_\tau) = 17.39\,\%$$

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

* Eliminate all SM backgrounds

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

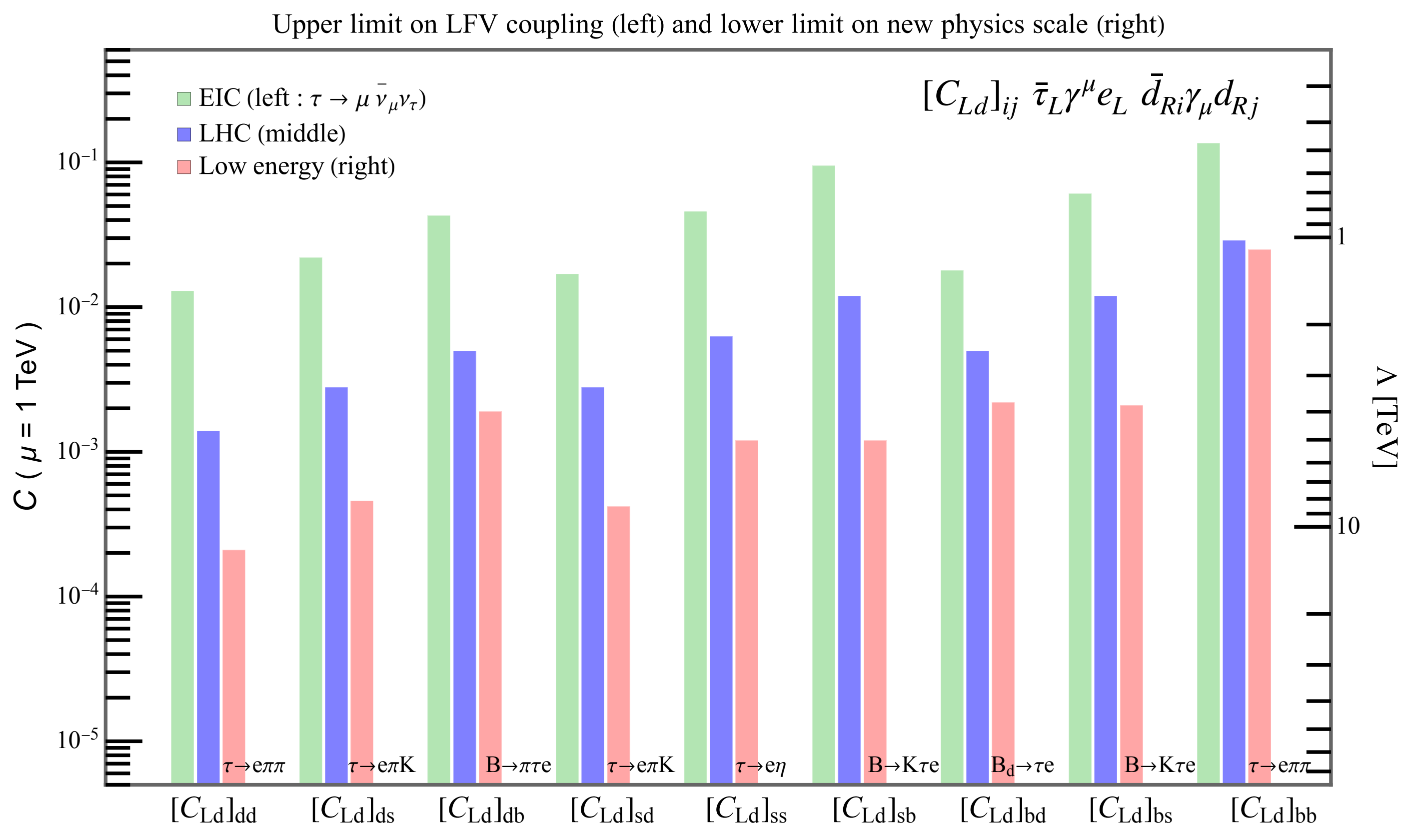
Made by E. Mereghetti



EIC vs Current limits

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

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



- 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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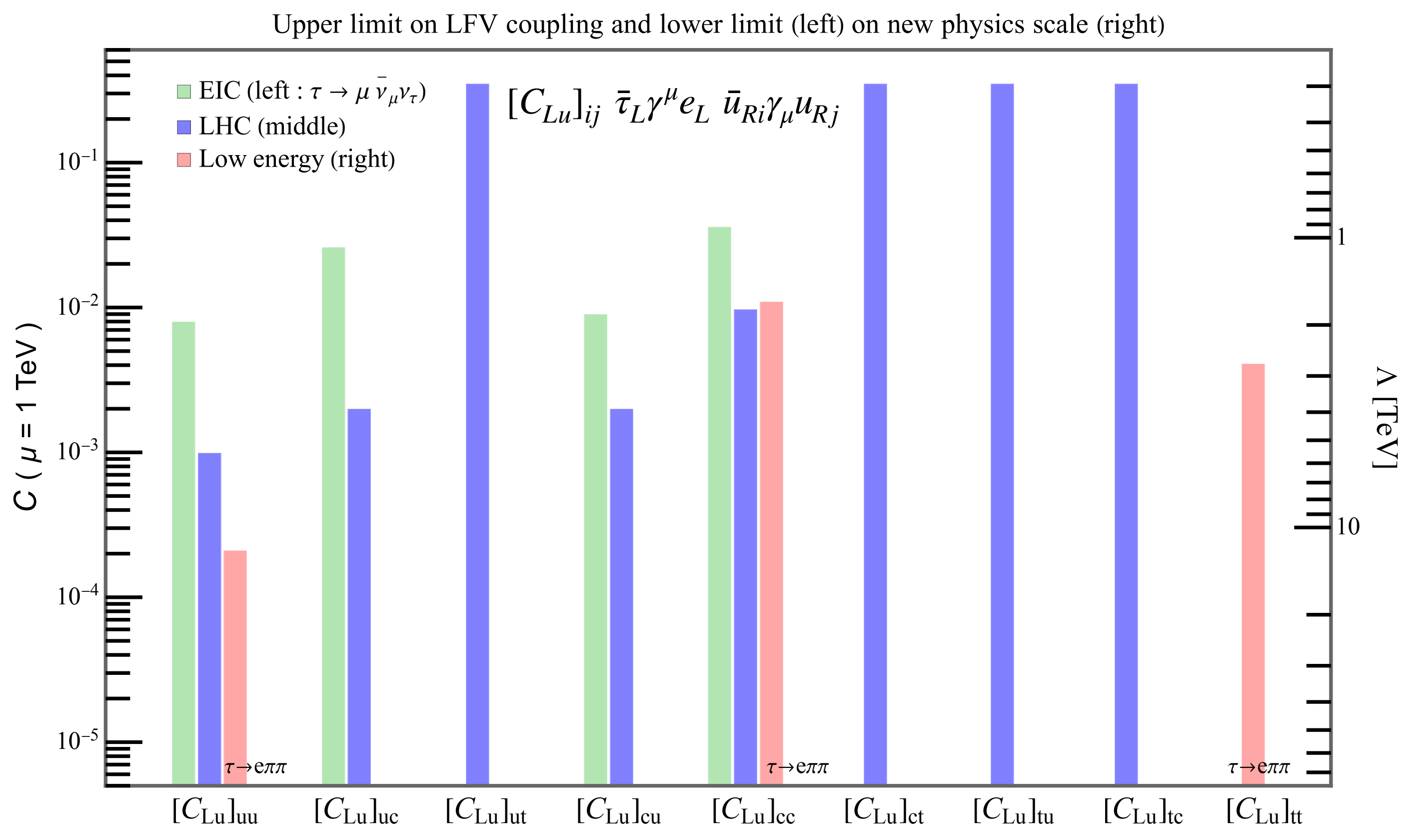
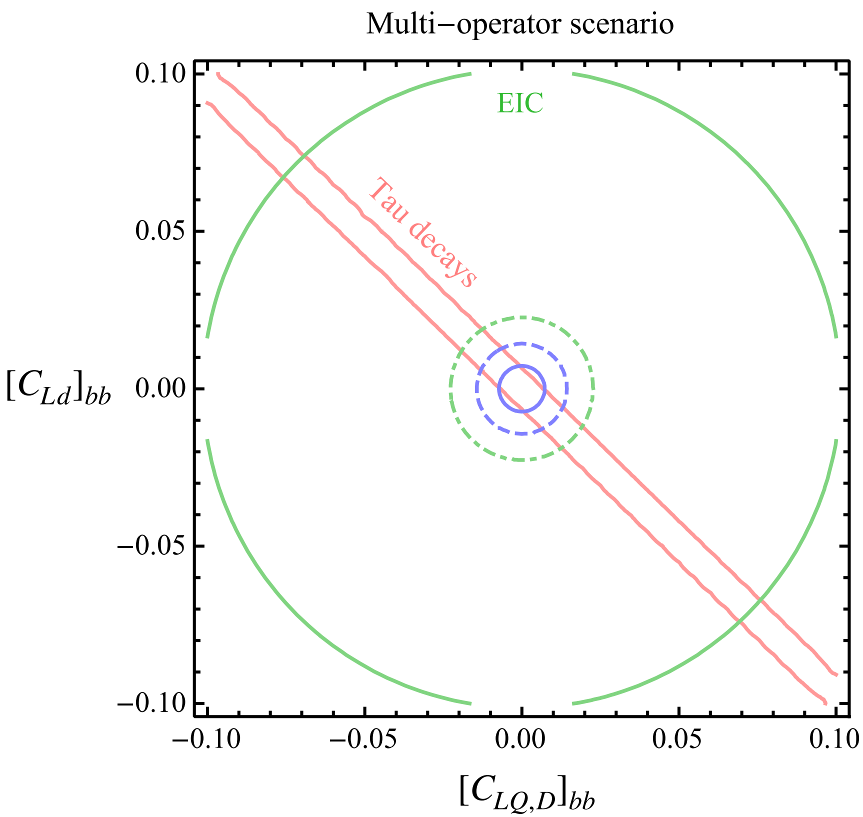


- Overall, stronger limits from low-energy and LHC
- Possibility that the EIC can compete is $[C_{Ld}]_{bb}$ and $[C_{Lu}]_{cc}$

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

$$\mathcal{L}_{\rm LFV} \supset -\frac{g_2}{c_W}\left(c^{(1)}_{L\varphi} + c^{(3)}_{L\varphi}\right)\bar{\tau}_L\gamma^\mu Z_\mu e_L$$
$$-\frac{4G_F}{\sqrt{2}}\sum_{a=d,s,b}[C_{Ld}]_{aa}\,\bar{\tau}_L\gamma^\mu e_L\bar{d}_{Ra}\gamma_\mu d_{Ra}$$
$$-\frac{4G_F}{\sqrt{2}}\sum_{a=d,s,b}[C_{LQ,D}]_{aa}\,\bar{\tau}_L\gamma^\mu e_L\bar{d}_{La}\gamma_\mu d_{La}$$

- Collider probes are necessary to close the free direction.

Discussions on EIC physics

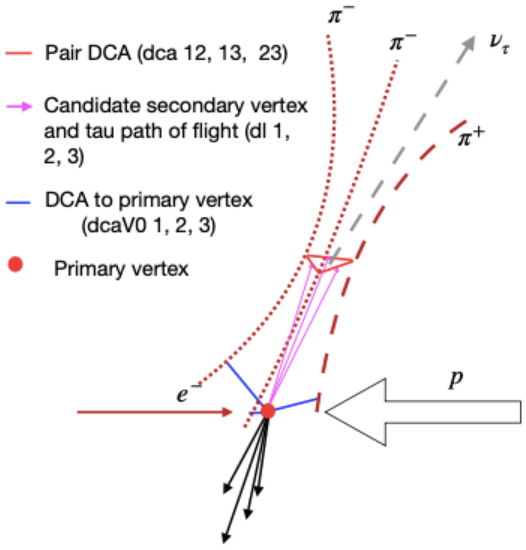
- Improvement with 3-prong decay

$$\tau \rightarrow \pi^-\pi^+\pi^-\nu_\tau$$
$$\tau \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$$

BR = 15.21%

J. L. Zhang et al, 2207.10261

Right : Talk by J. Zhang at EW/BSM Physics at the EIC



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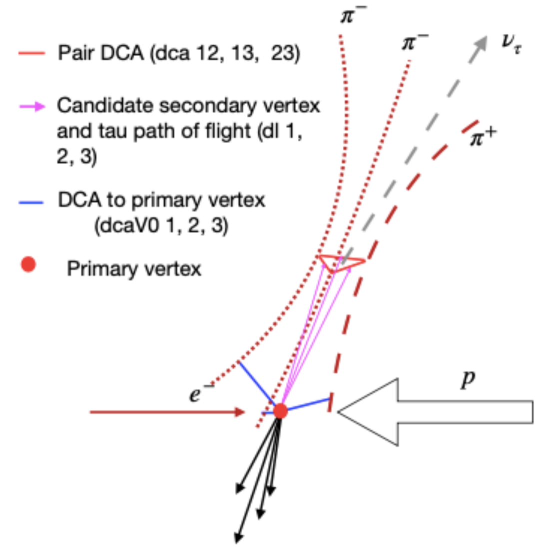
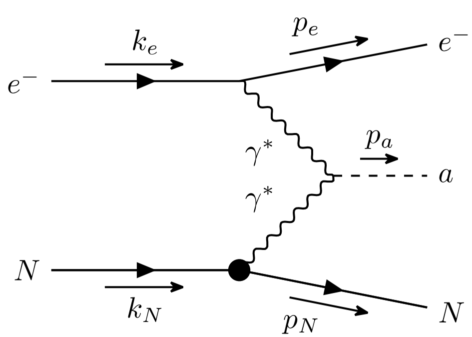
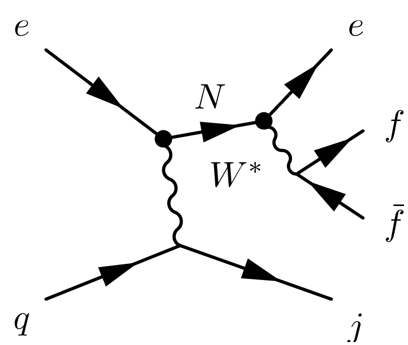


- Other BSM searches at EIC

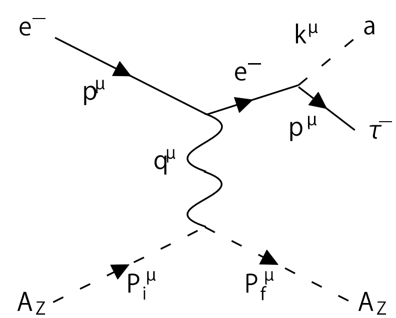
Axion-Like Particle Search
JHEP 02 (2024) 123



Right-Handed Neutrino Search
JHEP 03 (2023) 020



LFV ALP Search
JHEP02(2023)071



Discussions on EIC physics

https://www.int.washington.edu/index.php/programs-and-workshops/24-87w

Electroweak and Beyond the Standard Model Physics at the EIC

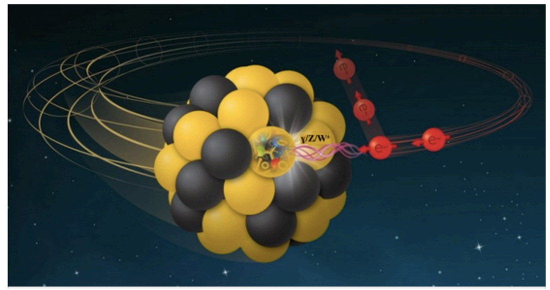
February 12, 2024 - February 16, 2024

ORGANIZERS

Kaori Fuyuto
Los Alamos National Laboratory
kfuyuto@lanl.gov

Ciprian Gal
Thomas Jefferson National Accelerator Facility
ciprian@jlab.org

Sonny Mantry
University of North Georgia
sonny.mantry@ung.edu



SCHEDULE

The application deadline for this event has passed

February 12-16, 2024
Institute for Nuclear Theory
University of Washington

Discussions on EIC physics

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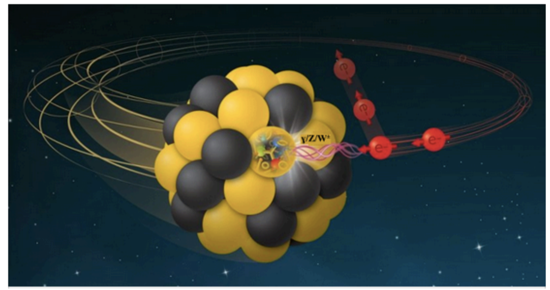

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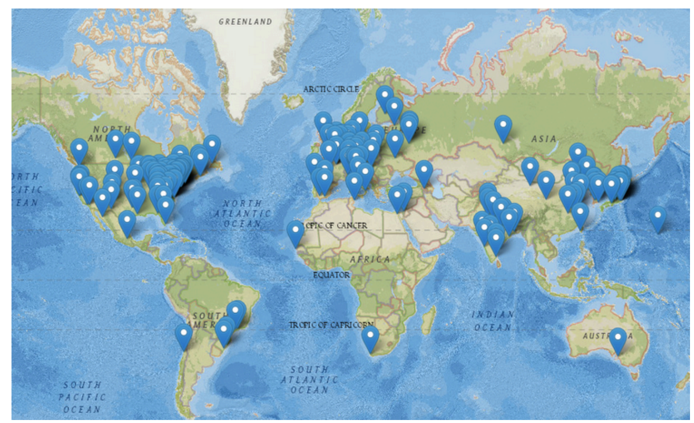
https://www.eicug.org/index.html

EIC User Group consists of more than 1400 physicists from over 290 laboratories and universities from 38 countries, *including Japan*, around the world.

Diversity, Equity and Inclusion (DEI) Committee



EIC UG Climate Survey : Talk by W. Deconinck

https://www.int.washington.edu/sites/default/files/schedule_session_files/Deconinck_W.pdf

What about an electron-muon case?

We can do the same game.

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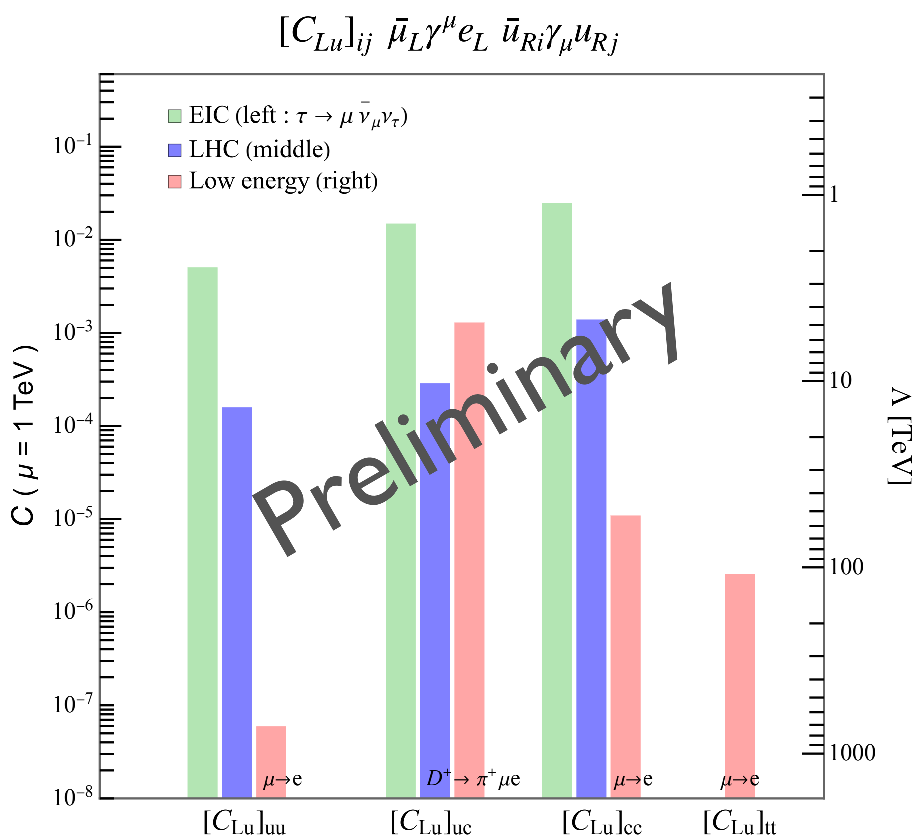


- Strong limit from $\mu \to e$ conversion

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

- Bound on $[C_{Lu}]_{uc}$ LHCb JHEP06(2021)044

  $$\mathrm{BR}(D^+ \to \pi^+ e^+ \mu^-) < 2.1 \times 10^{-7}$$

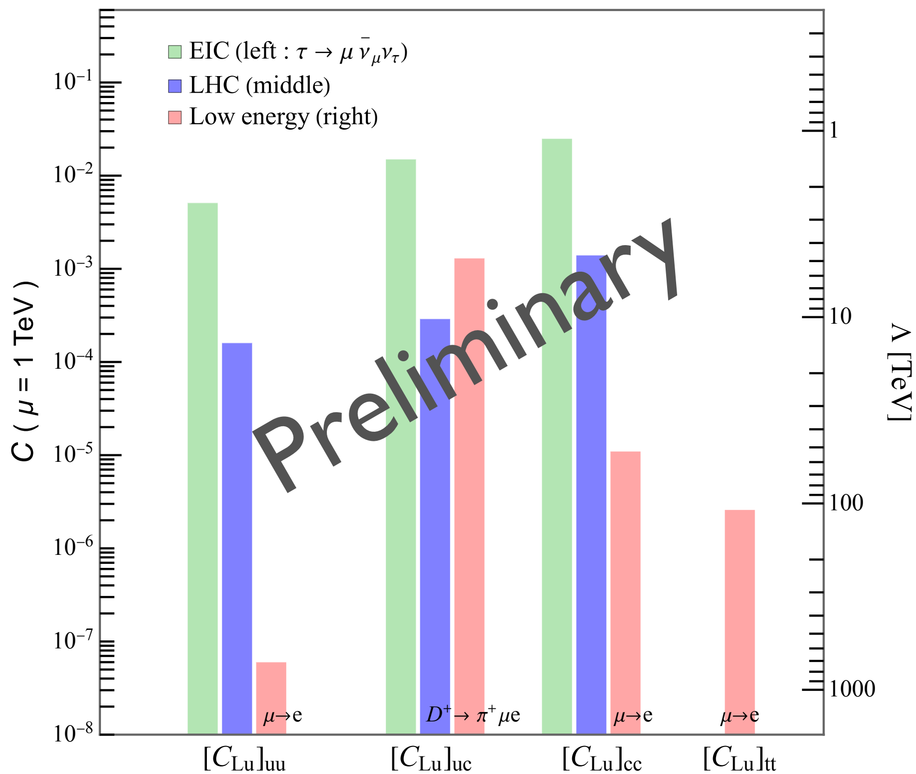
- Free direction in multi-operator case

F. Delzanno, KF, S. Gonzalez-Solis, E. Mereghetti
Work in progress

What about an electron-muon case?

We can do the same game.

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



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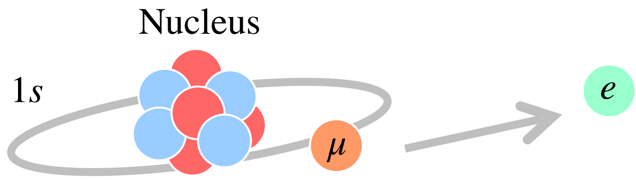
Work in progress

Mu to E conversion

Muon to Electron conversion in Muonic Atom

$$\mu^- + (A,Z) \to e^- + (A,Z)$$

*Mono-energetic electron



$$E_e = m_\mu - B_\mu - E_{\rm rec}$$

$$B_\mu \simeq \frac{(Z\alpha_{\rm em})^2}{2} m_\mu$$

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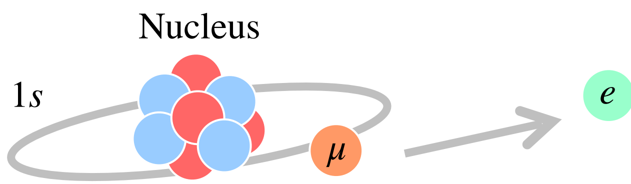
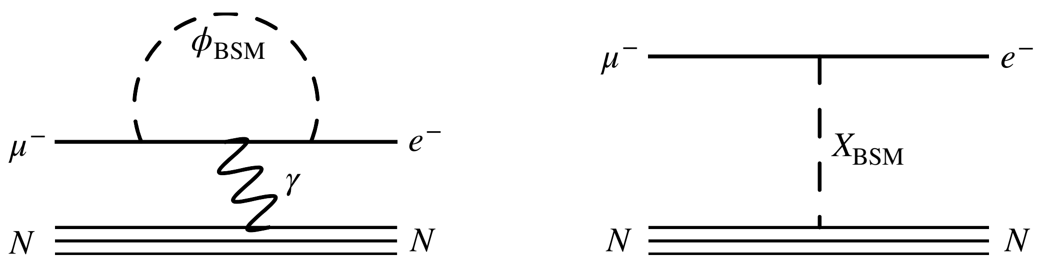


$$E_e = m_\mu - B_\mu - E_{\rm rec}$$

$$B_\mu \simeq \frac{(Z\alpha_{\rm em})^2}{2} m_\mu$$

* Photonic- and Non-photonic Interactions

$*\mu \to e\gamma$



✔ Contributions from various CLFV interactions to the conversion process

Mu to E conversion

$$\mathrm{BR}(\mu \to e) = \frac{\Gamma_{\mathrm{conv}}(\mu^- + (A,Z) \to e^- + (A,Z))}{\Gamma_{\mathrm{capt}}(\mu^- + (A,Z) \to \nu_\mu + (A,Z-1))}$$

* Capture rate : PRC 35, 2212 (1987)

Y. Kuno (for the COMET Collaboration), Prog. Theor. Phys. 2013, 022C01 (2013).

Process	$\Gamma_{\mathrm{capt}} \times 10^{-15}$ [MeV]	Upper Bound
$\mu^- + \mathrm{Ti} \to e^- + \mathrm{Ti}$	1.705	6.1×10^{-13}
$\mu^- + \mathrm{Au} \to e^- + \mathrm{Au}$	8.603	7×10^{-13}

Mu to E conversion

Mu2E

at Fermilab, USA

$$\mathrm{BR}(\mu \to e) = \frac{\Gamma_{\mathrm{conv}}(\mu^- + (A,Z) \to e^- + (A,Z))}{\Gamma_{\mathrm{capt}}(\mu^- + (A,Z) \to \nu_\mu + (A,Z-1))}$$

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COMET

at J-PARC, JP

Y. Kuno (for the COMET Collaboration), Prog. Theor. Phys. 2013, 022C01 (2013).

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$\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}$	0.463	Expected $\mathcal{O}(10^{-17})$

Aluminum Target
@ Mu2E and COMET

* Improvement by 4 orders of magnitude

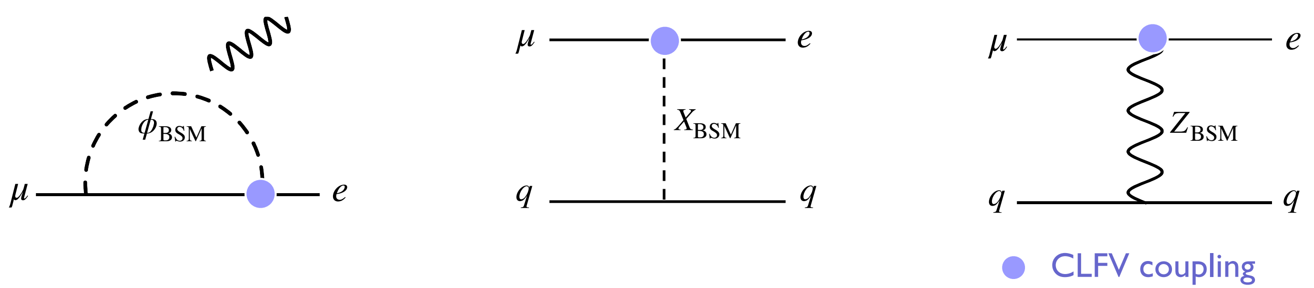
Theoretical Analysis

Model-independent analysis has comprehensively been done.

Weinberg, Feinberg, PRL3(1959)111, Shanker, PRD20(1979)1608,
Czarnecki, et al, AIP Conf. Proc. 435 (1998)
Kitano, et al, PRD66(2002)096002, Cirigliano, et al, PRD80(2009)013002
Cirigliano, et al, PLB771(2017)242, Davidson, et al, EPJC78(2018)109

$$\mathscr{L}_{\rm CLFV} = -\frac{m_\mu}{\Lambda^2} C_{DY}\ \bar{e}\sigma^{\mu\nu} P_Y \mu F_{\mu\nu} - \frac{1}{\Lambda^2} C_{SY}\ \bar{e} P_Y \mu\ \bar{q} q - \frac{1}{\Lambda^2} C_{VY}\ \bar{e}\gamma^\mu P_Y \mu\ \bar{q}\gamma_\mu q$$

Dipole Scalar Vector



Spin-Independent (SI) Process : all nucleons participate in the process.

$$\text{Ex)}\quad \text{BR}(\mu \to e) \propto |C_{DY} Z|^2$$

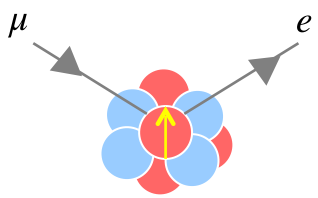
*Rough Idea

Theoretical Analysis

Spin-Dependent (SD) process has no enhancement, so naively *sub-leading* contribution

Ex) $\mathscr{L}_{\mathrm{LFV}} = \frac{1}{\Lambda^2} C_{PY} \bar{e} P_Y \mu \ \bar{q}\gamma_5 q$ $\quad \mathrm{BR}(\mu \to e) \propto |C_{PY} W_{PY}|^2$

Pseudo-scalar



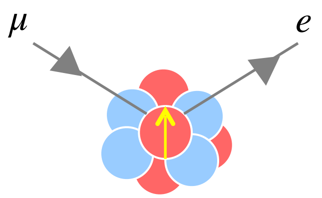
*Nuclear structure calculation is necessary.

Theoretical Analysis

Spin-Dependent (SD) process has no enhancement, so naively *sub-leading* contribution

$$\text{Ex)}\quad \mathscr{L}_{\rm LFV} = \frac{1}{\Lambda^2}\, C_{PY}\bar{e}P_Y\mu\ \bar{q}\gamma_5 q \qquad \mathrm{BR}(\mu\to e)\propto |C_{PY}W_{PY}|^2$$

Pseudo-scalar



*Nuclear structure calculation is necessary.

Recent development

1) Nuclear-Level EFT for SI and SD process

W. Haxton, E. Rule, K. McElvain, M. Ramsey-Musolf, PRC107(2023)035504
Mathematica and Python : https://github.com/Berkeley-Electroweak-Physics/Mu2e

$$\mathscr{L}^N_{\rm LFV} = c_1\ \bar{e}\mu\bar{N}N + c_2\ \bar{e}\mu\bar{N}i\gamma_5 N + \cdots$$

*Nuclear response function by Shell Model

2) Extension to Weak Effective Theory operators

W. Haxton, K. McElvain, T. Menzo, E. Rule, J. Zupan, 2406.13818
MuonBridge : https://github.com/Berkeley-Electroweak-Physics

SI vs SD

Spin-Dependent (SD) process has no enhancement, so naively *sub-leading* contribution

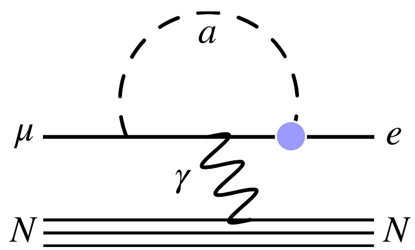
* NOT necessarily

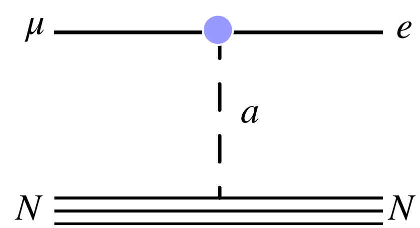
SI vs SD

KF, E. Mereghetti, PRD109(2024)075014

Spin-Dependent (SD) process has no enhancement, so naively *sub-leading* contribution

* NOT necessarily, for example, in LFV ALP Model





● CLFV coupling

$$\mathscr{L}_{\rm LFV} = -\frac{m_\mu}{f_a^2} C_D\, \bar{e}\sigma^{\mu\nu}\mu F_{\mu\nu} \qquad -\frac{1}{f_a^2} C_P\, \bar{e}\mu\bar{q}i\gamma_5 q$$

*SU(2)ChiPT

SI : One-loop

SD : Tree

$$|C_D|^2 \sim \frac{\alpha_{\rm em}^2}{(4\pi)^2} \ll |C_P|^2$$

SI vs SD ?

SI vs SD

Spin-Dependent (SD) process has no enhancement, so naively *sub-leading* contribution

* NOT necessarily, for example, in LFV ALP Model

$$\Gamma(\mu \to e) \propto \frac{m_\mu^5}{f_a^4}\left(|C_D|^2 \, W_D + |C_P|^2 \, W_P \right)$$

W_A : Nuclear Response Function

	Target	Abundance [%]	Spin	W_D	W_P
Mu2e COMET	$^{27}_{13}Al$	100	$5/2^+$	61.67	9.2×10^{-2}

SI vs SD

Spin-Dependent (SD) process has no enhancement, so naively *sub-leading* contribution

* NOT necessarily, for example, in LFV ALP Model

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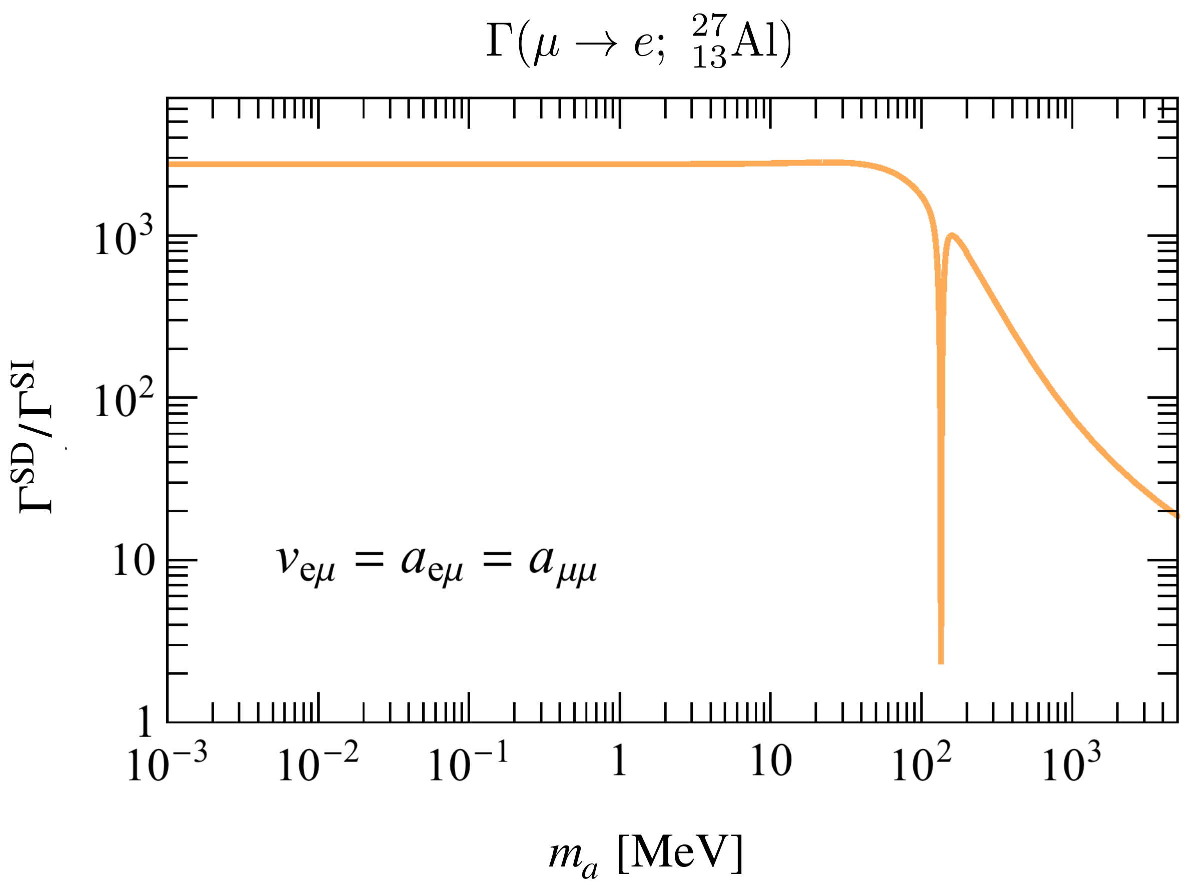
Mu2e COMET	$^{27}_{13}\mathrm{Al}$	100	$5/2^+$	61.67	9.2×10^{-2}
Current	$^{48}_{22}\mathrm{Ti}$	73.72	0^+	116.3	7.1×10^{-3}
	$^{47}\mathrm{Ti}$	7.44	$5/2^-$		
	$^{49}\mathrm{Ti}$	5.41	$7/2^-$		

SI vs SD

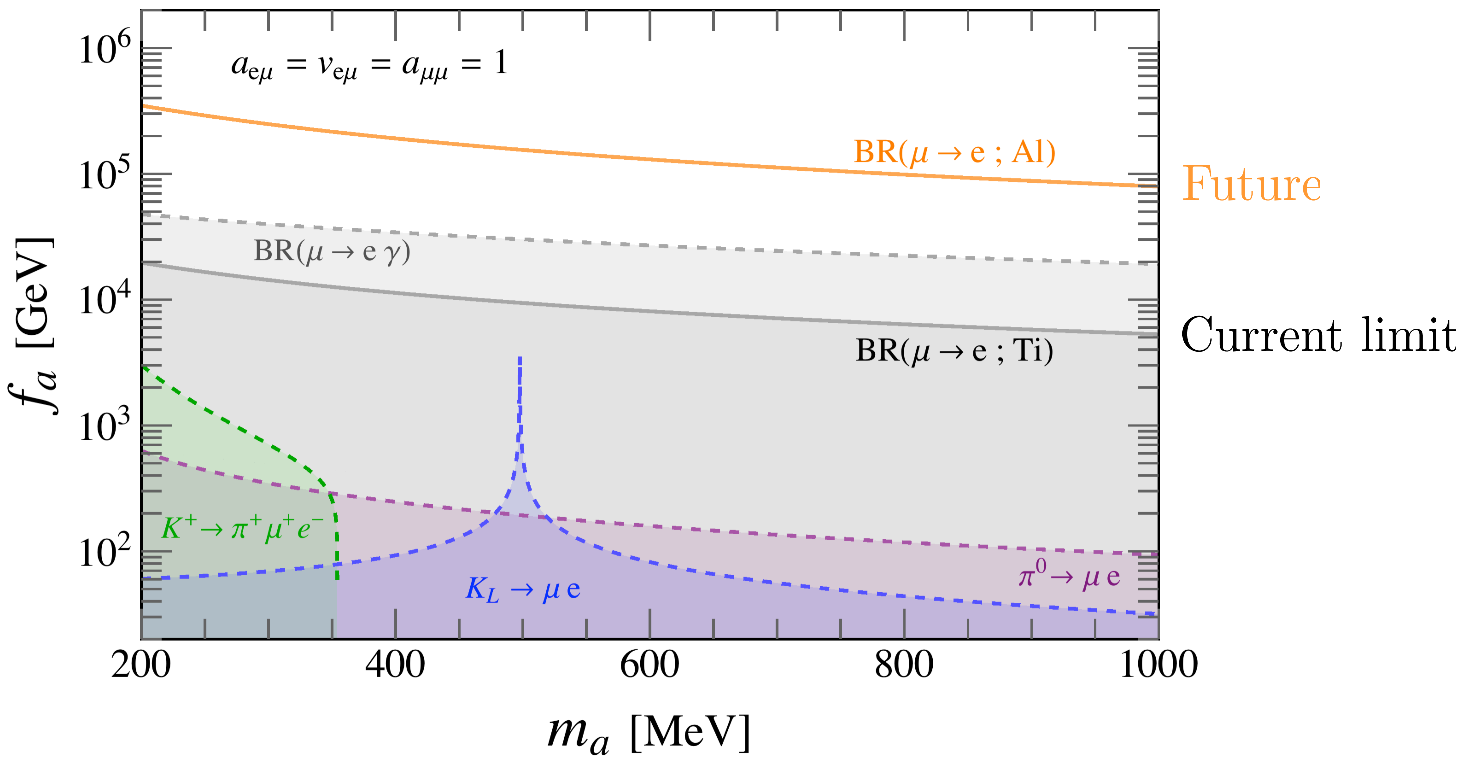
KF, E. Mereghetti, PRD109(2024)075014



The conversion process is dominated by pseudo-scalar interaction.

m_a vs f_a

KF, E. Mereghetti, PRD109(2024)075014



The strongest limit is given by mu to e gamma search.

The future mu2e conversion searches have the great potential to probe LFV ALP scenarios.

Summary

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

Today

- Systematic Analysis based on SMEFT
  - The RGEs allows to constrain CLFV heavy quark operators
  - Complementarity in low- and high-energy searches

**Possibility of another search at EIC*

- Stronger bound in electron-muon case especially from $\mu \to e$ conversion
  - 4-orders of magnitude improvements in BR
  - SD process can dominate the process in LFV ALP model

Outlook/Discussion

- 3-prong decay
- b- and/or c-quark tagging
- Multi-Dimensional Analysis

Any ideas on BSM searches at EIC are welcome!