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Title: Searching for Muon to Electron Conversion

Author(s): Fuyuto, Kaori

Intended for: I'll give a seminar talk at Washington University in St. Louis on Thursday, March 28th.

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Los Alamos
NATIONAL LABORATORY

LA-UR-24-21027

Searching for Muon to Electron Conversion

Kaori Fuyuto

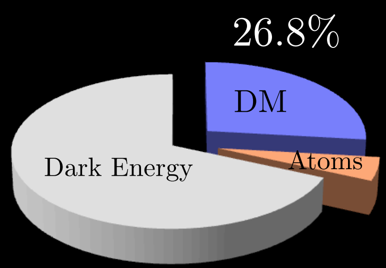
Los Alamos National Laboratory

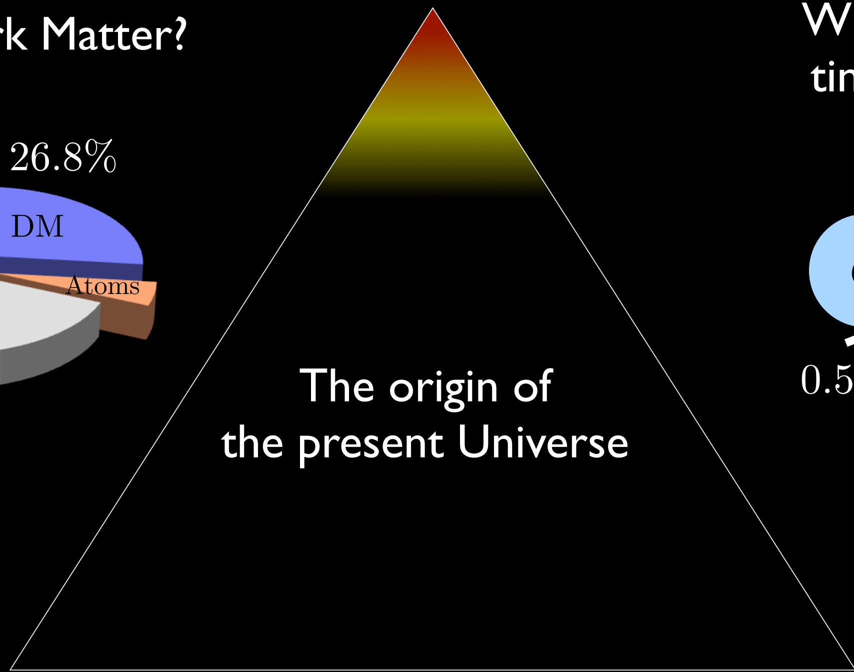
KF, E. Mereghetti
2307.13076 accepted by PRD

March 28, 2024
Washington U in St. Louis

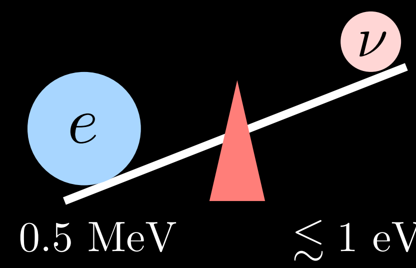
We still don't know much about our Universe.

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

Fundamental Symmetry Tests

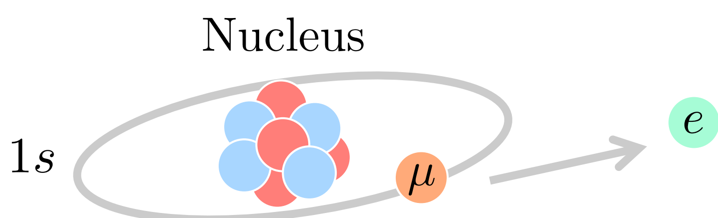
Searches for violations of fundamental symmetries / conservation laws

Fundamental Symmetry Tests

Searches for violations of fundamental symmetries / conservation laws

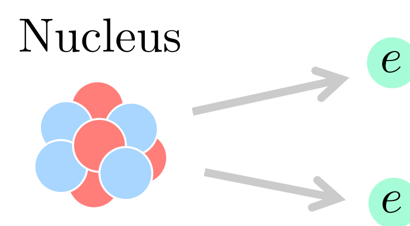
Ex) Lepton Flavor and Number Violation

e.g., Muon to electron conversion



$$\Delta L_\mu = -1,\ \Delta L_e = +1$$

Neutrinoless Double Beta Decay



$$\Delta L = 2$$

No CLFV and LNV process in the SM

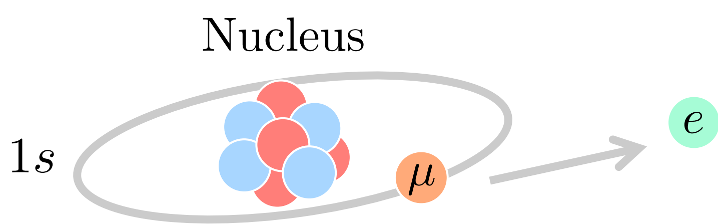
Observations of these processes would immediately imply BSM physics.

Fundamental Symmetry Tests

Searches for violations of fundamental symmetries / conservation laws

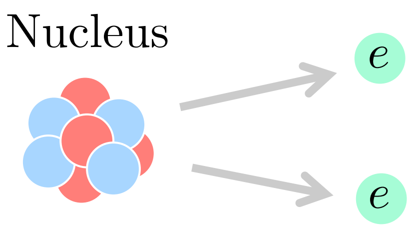
Ex) Lepton Flavor and Number Violation

e.g., Muon to electron conversion



$\Delta L_\mu = -1, \; \Delta L_e = +1$

Neutrinoless Double Beta Decay



$\Delta L = 2$

No CLFV and LNV process in the SM

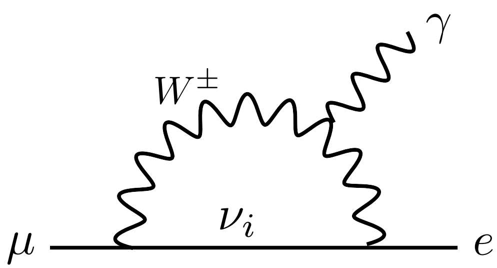
Today : CLFV searches

Charged Lepton Flavor Violation

CLFV searches

Searches for CLFV are strong tools to probe BSM physics.

Ex) SM + neutrino mass (νSM)



Petcov ’77, Marciano-Sanda ’77 ....

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

Dirac or Majorana

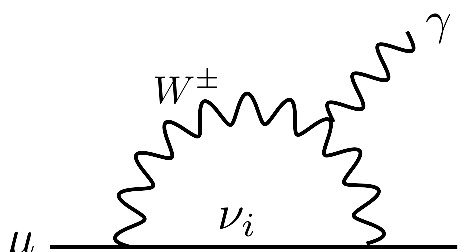
$$\mathrm{Br}\left(\mu \to e\gamma\right) = \frac{3\alpha_{\rm em}}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{m_W^2}\right|^2 < \boxed{10^{-54}}$$

Extremely small!

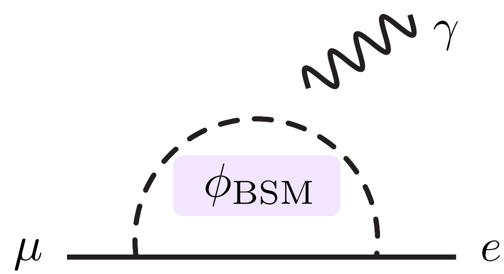
CLFV searches

Searches for CLFV are strong tools to probe BSM physics.

Ex) SM + neutrino mass (νSM)



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

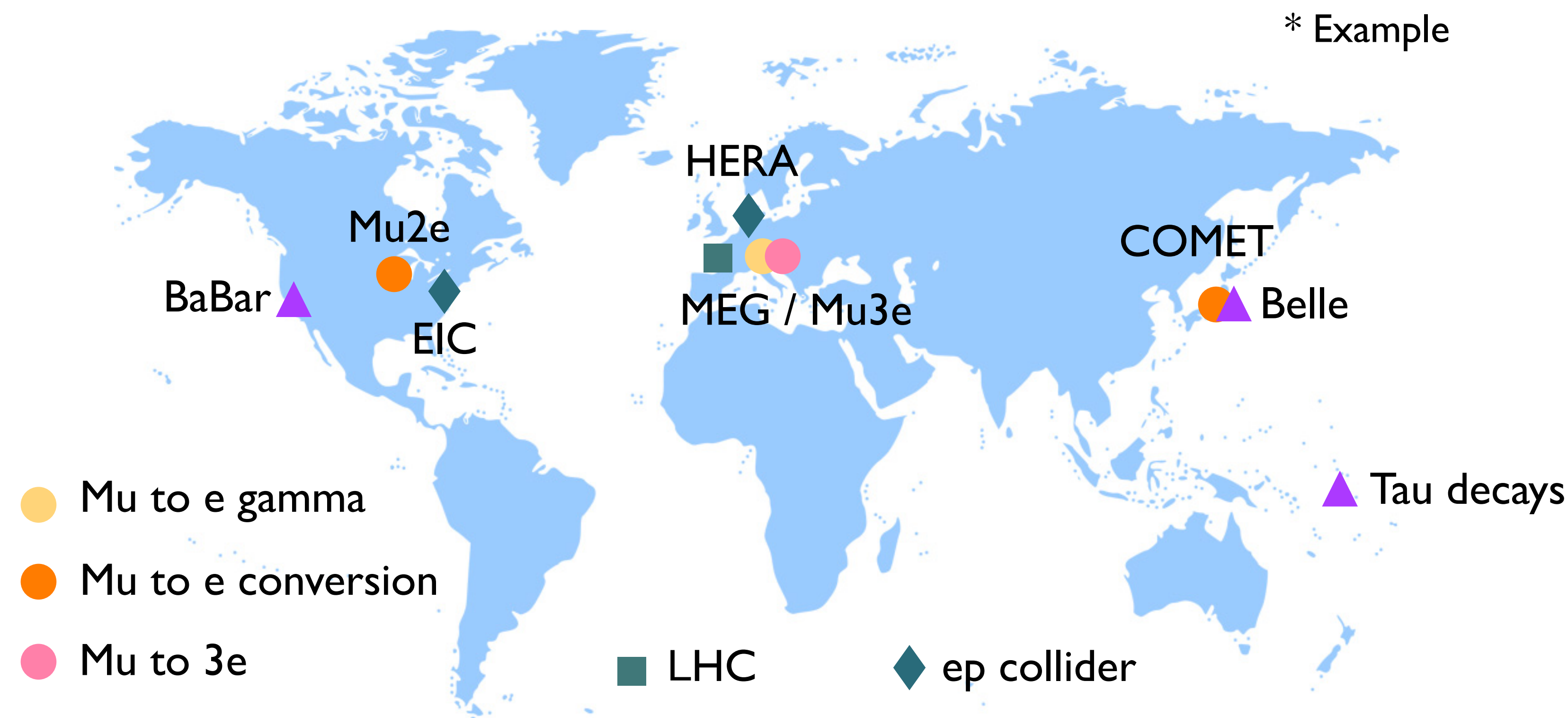


$$\mathrm{Br}(\mu \to e\gamma) < 10^{-54} \quad \ll \quad \mathrm{Br}(\mu \to e\gamma)_{\mathrm{BSM}}$$

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

*Underlying mechanism of the neutrino mass.

CLFV searches



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

MEG II Collaboration, 2310.12614

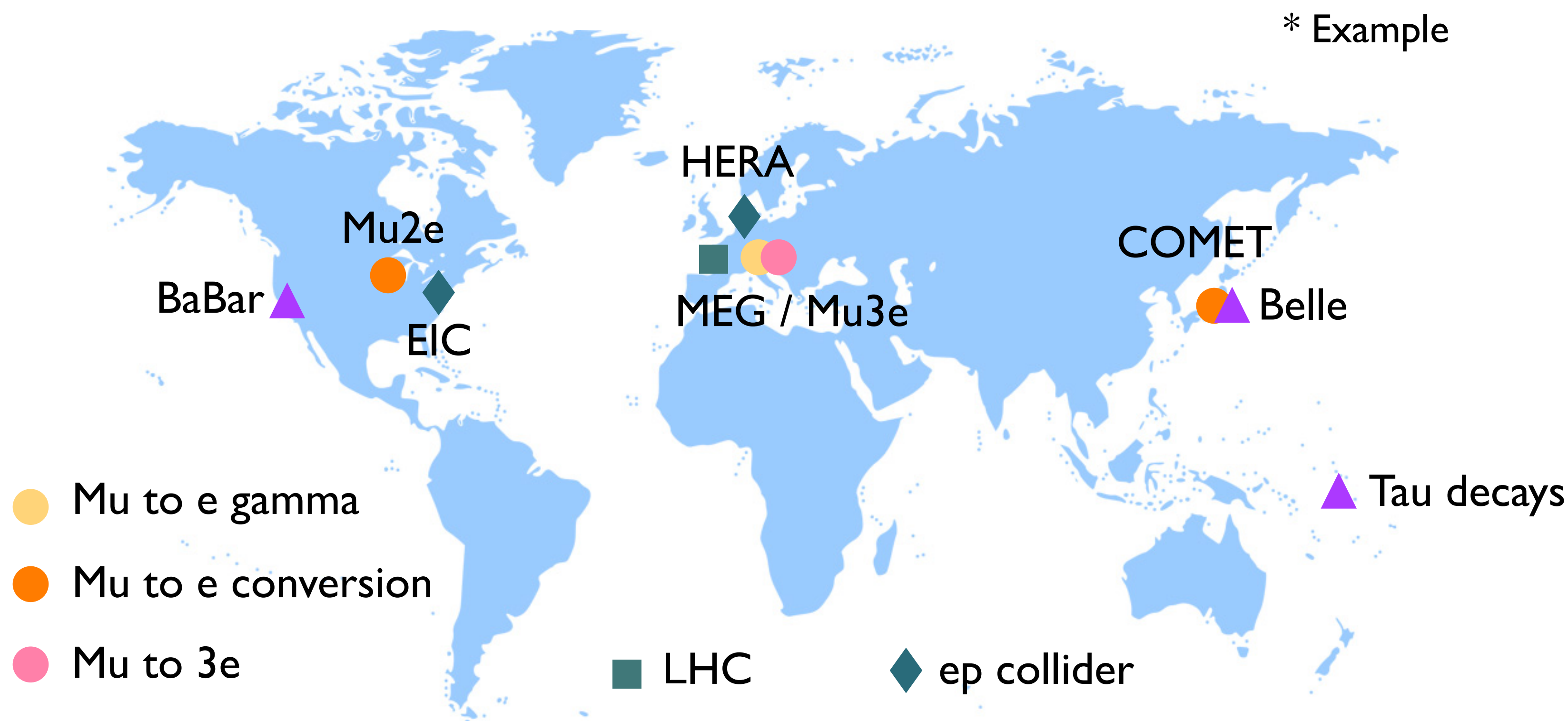
$$\mathrm{BR}(\mu^- \ \mathrm{Ti} \to e^- \ \mathrm{Ti}) < 6.1 \times 10^{-13}$$

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

$$\Lambda_{\mathrm{NP}} \gtrsim 80 \ \mathrm{TeV}$$

*From one-loop contribution

CLFV searches



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

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

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

BaBar, PRL104 (2010) 021802

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

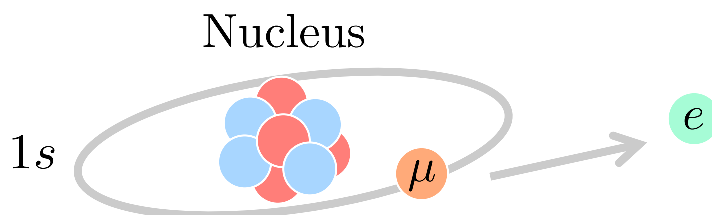
Belle, PLB719 (2013) 346-353

Mu to E conversion

Muon to Electron conversion in Muonic Atom

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

*Mono-energetic electron



$$E_e \simeq m_\mu - B_\mu$$

$$B_\mu \simeq \frac{\alpha_{\mathrm{em}}^2 Z^2}{2} m_\mu$$

Mu to E conversion

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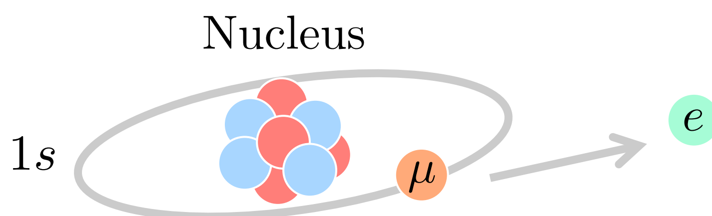
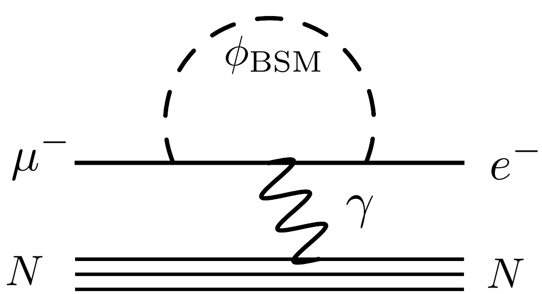


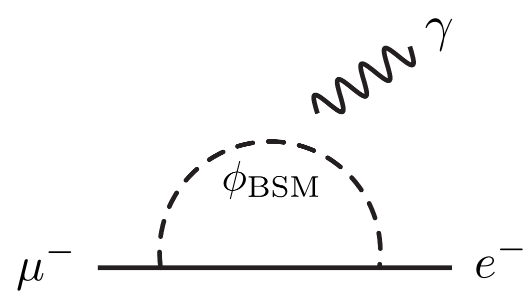
$$E_e \simeq m_\mu - B_\mu$$

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

Ex) Photonic interaction



Mu to e conversion

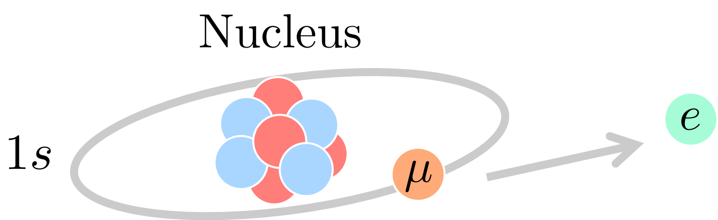


Mu to e gamma

Mu to E conversion

Muon to Electron conversion in Muonic Atom

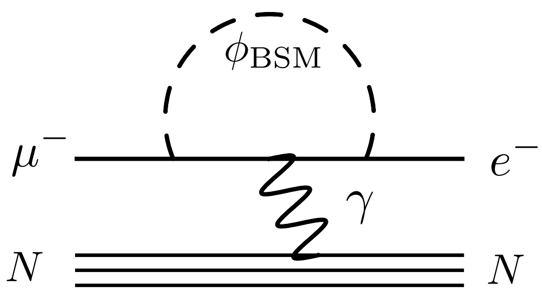
$$\mu^- + (A, Z) \to e^- + (A, Z)$$

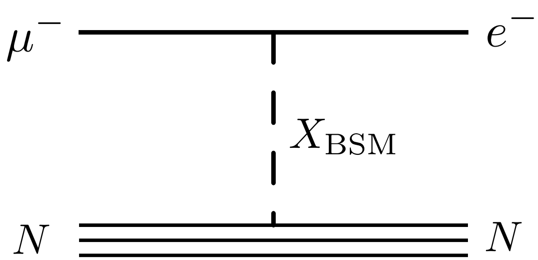


$$E_e \simeq m_\mu - B_\mu$$

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

Ex) Photonic- and Non-photonic interaction

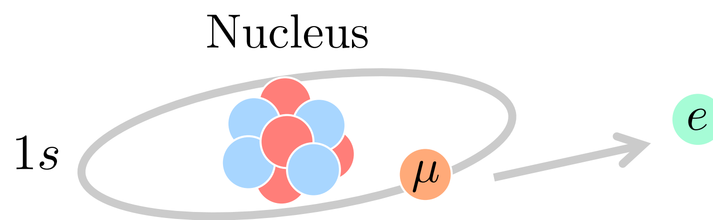




✔ Contributions from various CLFV interactions to the conversion process

Mu to E conversion

Muon to Electron conversion in Muonic Atom



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

* Capture rate : PRC 35, 2212 (1987)

Process	Γ_{capt} $[10^{-15}$ 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}
$\mu^- + \mathrm{Pb} \to e^- + \mathrm{Pb}$	8.853	4.6×10^{-11}

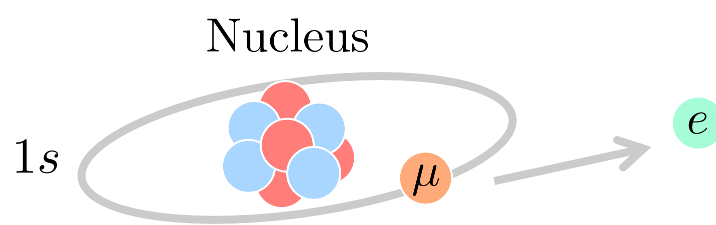
Y. Kuno (for the COMET Collaboration), Prog. Theor. Phys. 2013, 022C01 (2013).

Mu to E conversion

Muon to Electron conversion in Muonic Atom

Mu2E

at Fermilab, USA



COMET

at J-PARC, JP

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

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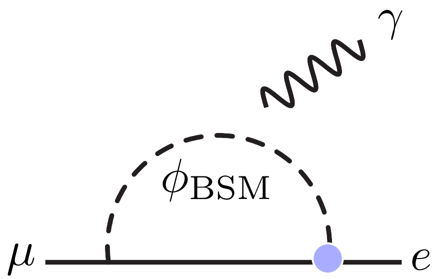
	$\mu^- + \mathrm{Au} \to e^- + \mathrm{Au}$	8.603	7×10^{-13}
Mu2E COMET	$\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}$	0.463	Expected $\mathcal{O}(10^{-17})$

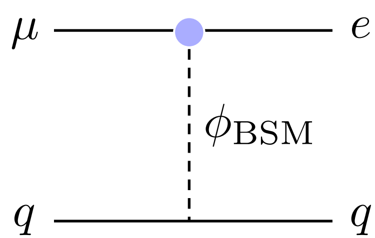
* Improvement by 4 orders of magnitude

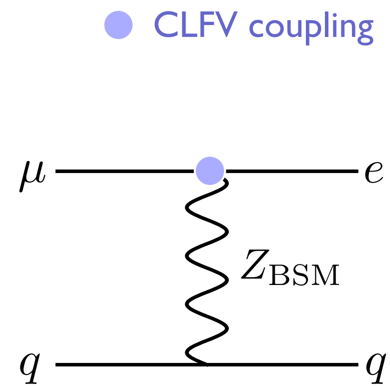
Theoretical Approach

Theoretical Analysis

- CLFV interactions are generated in various BSM models:







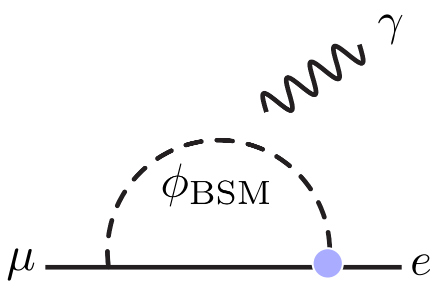
$$\text{Ex)} \quad \mathcal{L}_{\rm CLFV} = -\frac{m_\mu}{\Lambda^2} C_D \bar{e}\sigma^{\mu\nu} P_R \mu F_{\mu\nu} - \frac{1}{\Lambda^2} C_S \bar{e} P_R \mu \bar{q} q - \frac{1}{\Lambda^2} C_V \bar{e}\gamma^\mu \mu \bar{q}\gamma_\mu q$$

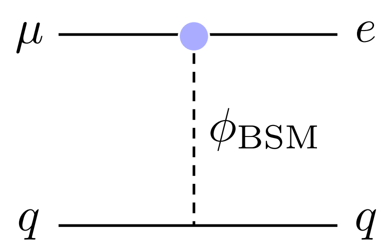
Photon Dipole Scalar Vector

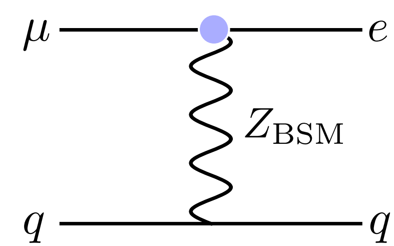
*Spin-Independent Process : All nucleons participate in the process

Theoretical Analysis

- CLFV interactions are generated in various BSM models: ● CLFV coupling







$$\text{Ex)}\quad \mathcal{L}_{\rm CLFV} = -\frac{m_\mu}{\Lambda^2} C_D \bar{e}\sigma^{\mu\nu} P_R \mu F_{\mu\nu} - \frac{1}{\Lambda^2} C_S \bar{e} P_R \mu \bar{q} q - \frac{1}{\Lambda^2} C_V \bar{e}\gamma^\mu \mu \bar{q}\gamma_\mu q$$

Photon Dipole — Scalar — Vector

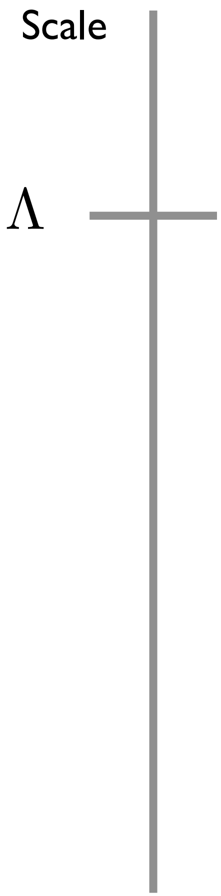
- Model-independent analysis has been comprehensively done (mainly SI interactions).

  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

- Need to match BSM CLFV processes with those at lower scale like nucleon (or nuclear).

Theoretical Analysis

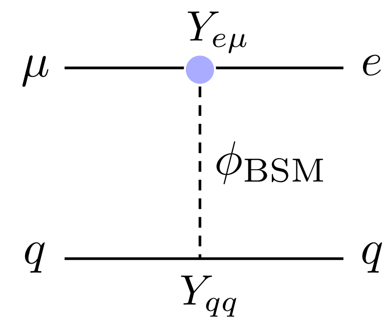
Kitano, et al, PRD66(2002)09600
Cirigliano, et al, PRD80(2009)013002



CLFV interactions in BSM physics

$$\mathcal{L}_{\rm CLFV} = -\frac{1}{\Lambda^2}\sum_{q=u,d} C^q_{S\alpha} G_F m_\mu m_q \bar{e} P_\alpha \mu \bar{q} q$$

$$\text{e.g.,}\quad \frac{C_S}{\Lambda^2} \sim \frac{1}{m_\phi^2} Y_{qq} Y_{e\mu}$$



Theoretical Analysis

Kitano, et al, PRD66(2002)09600
Cirigliano, et al, PRD80(2009)013002

Scale

Λ

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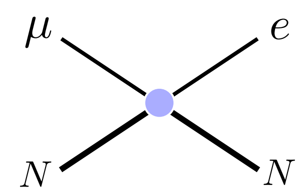
GeV

Nucleon scale (e.g., Lattice QCD/Chiral PT)



$$\mathcal{O}_{\mathrm{scalar}} \sim \frac{m_\mu}{\Lambda^2} G_F \sigma_{\pi N} C^q_{S\alpha} \bar{e} P_\alpha \mu \bar{N} N$$

with $N = \begin{pmatrix} p \\ n \end{pmatrix}$ $\quad \sigma_{\pi N}\ [\mathrm{MeV}] = \frac{1}{2}\langle N|(m_u + m_d)(\bar{u}u + \bar{d}d)|N\rangle$

$$= 59.1(3.5)\ \mathrm{MeV}$$

M. Hoferichter, et al, PRL115(2015)092301

Theoretical Analysis

Kitano, et al, PRD66(2002)09600
Cirigliano, et al, PRD80(2009)013002

Scale

Λ — CLFV interactions in BSM physics

$$\mathcal{L}_{\text{CLFV}} = -\frac{1}{\Lambda^2}\sum_{q=u,d} C^q_{S\alpha} G_F m_\mu m_q \bar{e} P_\alpha \mu \bar{q} q$$

GeV — Nucleon scale (e.g., Lattice QCD/Chiral PT)

MeV — Atomic/Nuclear scale

$$\langle A,Z|\bar{p}p|A,Z\rangle = Z\rho^{(p)}$$: Nucleon Density

$$\langle A,Z|\bar{n}n|A,Z\rangle = (A-Z)\rho^{(n)}$$

$$\Gamma_{\text{SI}}(\mu \to e) = \frac{m_\mu^5}{\Lambda^4}\left|\sum_Y C_Y^N W_Y^N\right|^2$$

e.g., $W_S^p \sim \int d^3x\, \bar{\psi}_e P_\alpha \psi_\mu Z \rho^{(p)}$

Nuclear Response Functions

Theoretical Analysis

Kitano, et al, PRD66(2002)09600
Cirigliano, et al, PRD80(2009)013002

Scale

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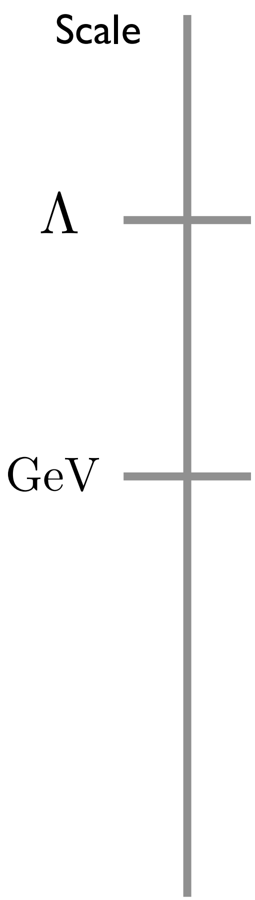
e.g., $W^p_S \sim \int d^3x\, \bar{\psi}_e P_\alpha \psi_\mu Z\rho^{(p)}$

Solutions to the Dirac equations

Theoretical Analysis

Kitano, et al, PRD66(2002)09600
Cirigliano, et al, PRD80(2009)013002



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- Various Lattice QCD results $\sigma_{\pi N}\ [\mathrm{MeV}] = \frac{1}{2}\langle N|(m_u + m_d)(\bar{u}u + \bar{d}d)|N\rangle$

Alexandrou 2014	Hoferichter 2015	Yang 2016	Rajan 2021
65(13)	59.1(3.5)	40(4)	59.6(7.4)

Theoretical Analysis

Kitano, et al, PRD66(2002)09600
Cirigliano, et al, PRD80(2009)013002

Scale

Λ

GeV

CLFV interactions in BSM physics

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Alexandrou 2014	Hoferichter 2015	Yang 2016	Rajan 2021
65(13)	59.1(3.5)	40(4)	59.6(7.4)

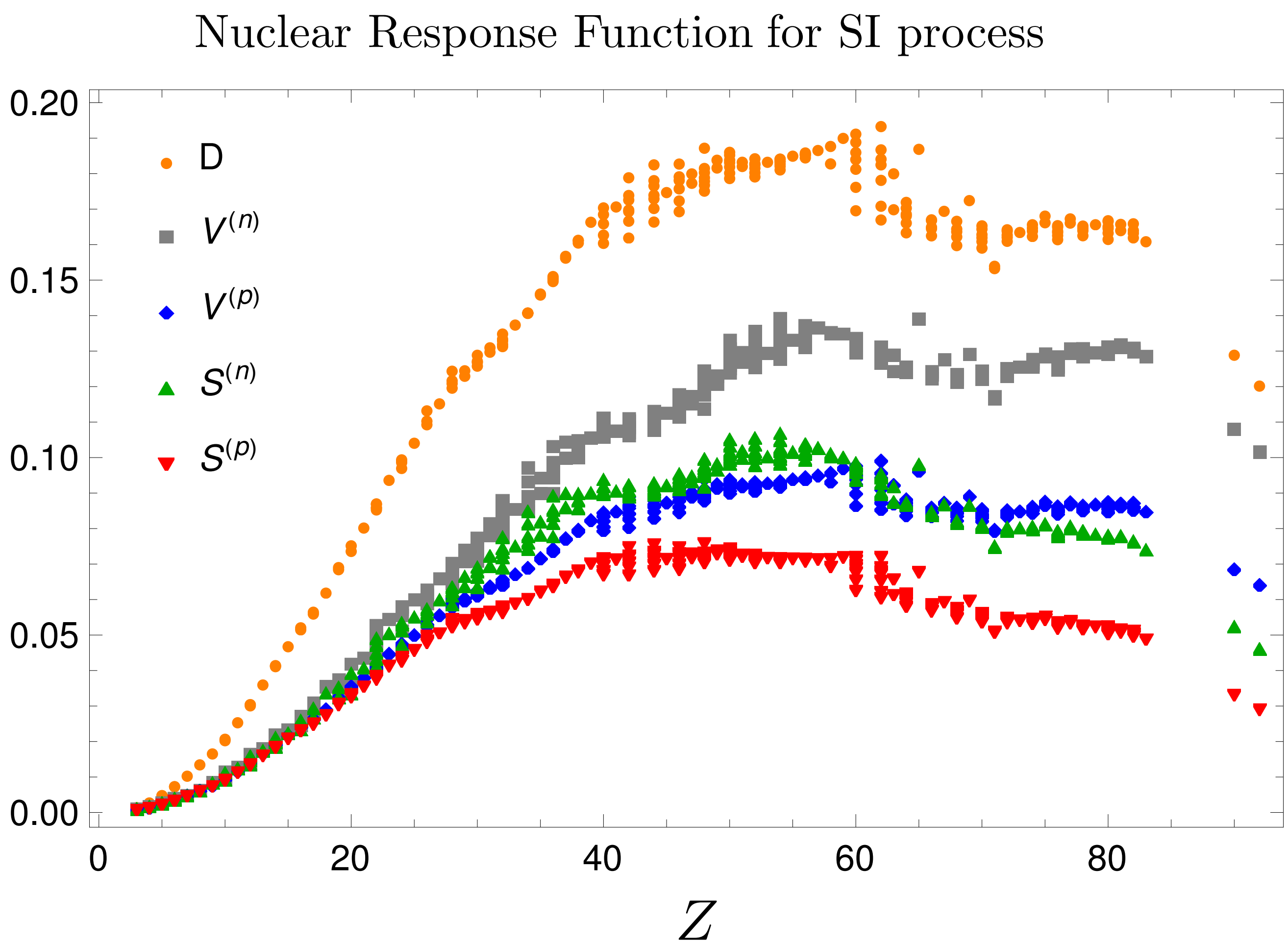
- Uncertainty in nucleon density $\int_0^\infty dr\ 4\pi r^2 \rho^{(p,n)} = 1$

~ 5% for light Z nuclei and ~10% for heavy Z (worse for neutron)

J. Heeck et al, Nucl.Phys.B 980 (2022) 115833

Z dependence

J. Heeck et al, Nucl.Phys.B 980 (2022) 115833



Nuclear response functions peak around Z ~ 60, then saturate or decrease for heavy nuclei.

SI vs SD process

SI vs SD

- Spin-independent (SI) process

- Spin-dependent (SD) process

SI vs SD

- Spin-independent (SI) process

Ex) Dipole operator : $\mathcal{L}_{\mathrm{CLFV}}^{\mathrm{SI}} \supset -\frac{m_\mu}{\Lambda^2}\, C_{DY}\, \overline{e_Y}\sigma^{\mu\nu}\mu F_{\mu\nu} + \cdots$

✔ All nucleons participate in the process

$$\mathrm{BR}(\mu \to e)_{\mathrm{SI}} \propto |C_{DY}|^2 Z^2 \quad (Z = 13 \text{ for Al})$$

*rough idea

- Spin-dependent (SD) process

SI vs SD

- Spin-independent (SI) process

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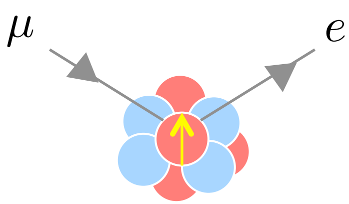


- Spin-dependent (SD) process

Ex) Pseudo-scalar operator: $\mathcal{L}_{\mathrm{CLFV}}^{\mathrm{SD}} \supset -\frac{1}{\Lambda^2} \, C_P \, \overline{e_Y} \mu \, \bar{q} \gamma_5 q + \cdots$

✔ No enhancement, so naively *sub-leading* contribution

$$\mathrm{BR}(\mu \to e)_{\mathrm{SD}} \propto |C_P|^2$$

*Theoretical analysis requires nuclear many body calculations

Recent developments

- Nuclear-level Effective Theory (*both SI and SD interactions)

$$\mathcal{L}_{\mathrm{CLFV}}^{N} \supset c_1 \bar{e}\mu \bar{N} N + c_2 \bar{e}\mu \bar{N} i\gamma_5 N + \cdots$$

$$\Gamma(\mu \to e) = \frac{m_\mu^5}{\Lambda^4} \left| c_i W_i^N \right|^2$$

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

Recent developments

- Nuclear-level Effective Theory (*both SI and SD interactions)

$$\mathcal{L}^{N}_{\mathrm{CLFV}} \supset c_1 \bar{e}\mu \bar{N} N + c_2 \bar{e}\mu \bar{N} i\gamma_5 N + \cdots \quad \Big| \quad \Gamma(\mu \to e) = \frac{m_\mu^5}{\Lambda^4} \left| c_i W_i^N \right|^2$$

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

- Axion-Like Particles (ALP) with LFV interactions

✔ Mass hierarchy and mixing + Strong CP problem

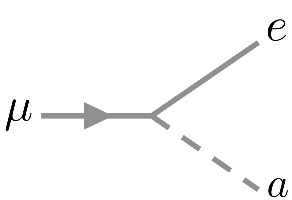
*Light scalar particles originating from spontaneous breaking of global symmetry

Froggatt, Nielsen, NPB147(1979)277, Ema, et al ,JHEP01(2017)096
Calibbi, Goertz, Redigolo, Ziegler, Zupan, PRD95(2017)095009, Cornella, et al, JHEP01(2020)158

$$\mathcal{L} \supset -i\frac{a}{f_a}\left[v_{ij}\bar{f}_i(m_j - m_i)f_j + a_{ij}\bar{f}_i(m_j + m_i)\gamma_5 f_j\right]$$

- Searches for CLFV muon decay into ALP

L. Calibbi, D. Redigolo, R. Ziegler, J. Zupan, JHEP09(2021)173
Y. Jho, et al, JHEP10(2022)029, R. Hill, et al, 2310.00043z

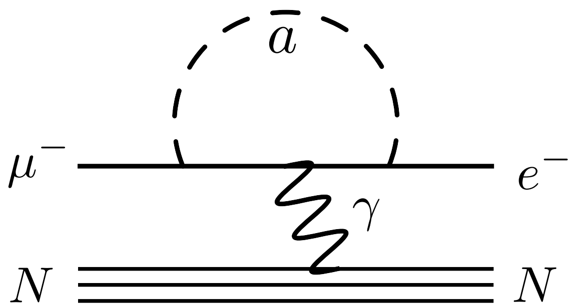


LFV ALP contributions

KF, E. Mereghetti 2307.13076

Previous study considered spin-independent process from ALP interactions:

Photon dipole (JHEP01(2020)158)



$$\mathcal{L}_{\rm CLFV} \supset -\frac{m_\mu}{f_a^2} C_D \; \bar{e}\sigma^{\mu\nu}\mu F_{\mu\nu}$$

One-loop

f_a : ALP decay constant

LFV ALP contributions

KF, E. Mereghetti 2307.13076

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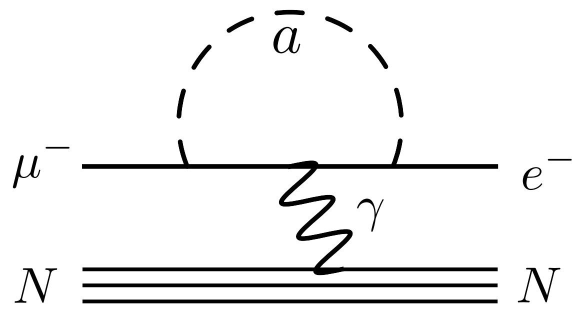
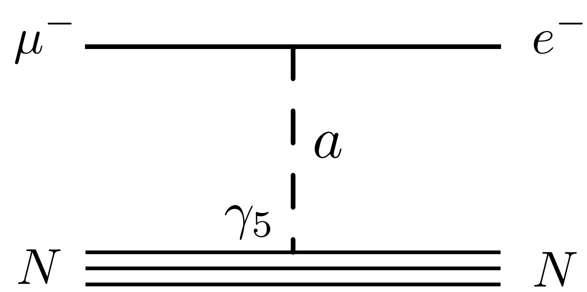


Four-fermion interaction



$$\mathcal{L}_{\rm CLFV} \supset -\frac{m_\mu}{f_a^2} C_D \; \bar{e}\sigma^{\mu\nu}\mu F_{\mu\nu} \qquad -\frac{1}{f_a^2} C_P \; \bar{e}\mu \; \bar{q} i\gamma_5 q$$

One-loop

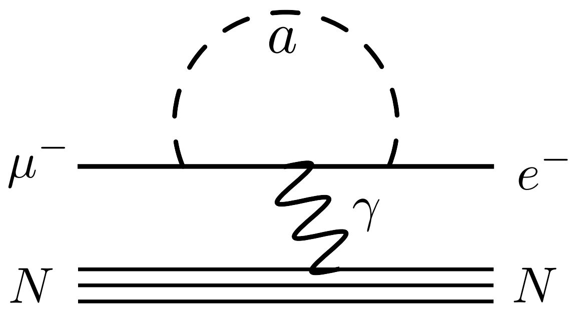
Tree

LFV ALP contributions

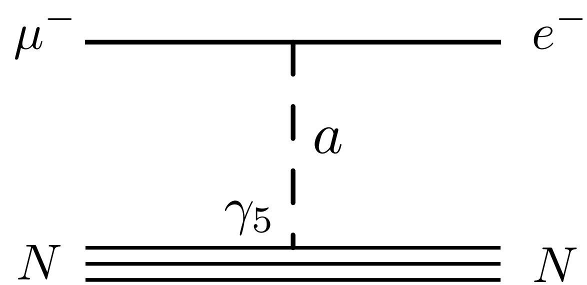
KF, E. Mereghetti 2307.13076

Previous study considered spin-independent process from ALP interactions:

Photon dipole (JHEP01(2020)158)



Four-fermion interaction



$$\mathcal{L}_{\rm CLFV} \supset -\frac{m_\mu}{f_a^2} C_D \; \bar{e}\sigma^{\mu\nu}\mu F_{\mu\nu} \qquad -\frac{1}{f_a^2} C_P \; \bar{e}\mu \; \bar{q} i \gamma_5 q$$

One-loop

Tree

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

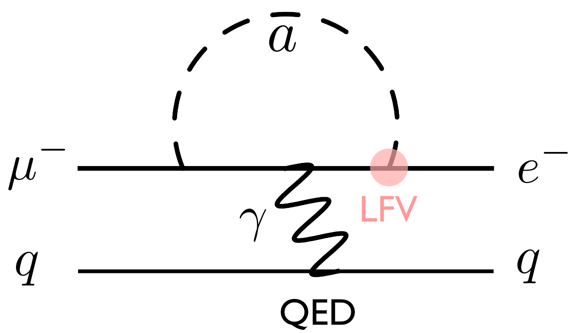
SI vs SD ?

LFV ALP contributions

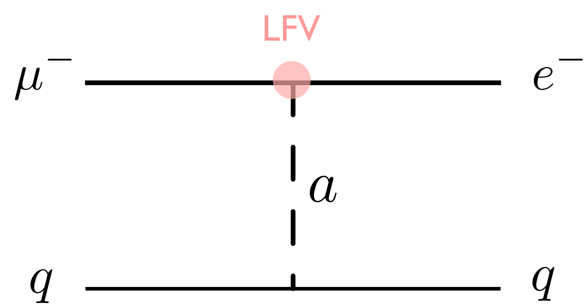
NPB147(1979)277, 1103.62171612.08040, 1612.05492, 1701.07209, 1805.07341, 1909.02029, 2006.04795

$$\mathcal{L}_{\rm ALP} \supset -im_\mu \frac{a}{f_a}\bar{e}(v_{e\mu} + a_{e\mu}\gamma_5)\mu \;\; -m_\mu \frac{a}{f_a}\bar{\mu}i\gamma_5\mu \;\; -m_q \frac{a}{f_a}\bar{q}i\gamma_5 q$$

Photon dipole (purely leptonic)



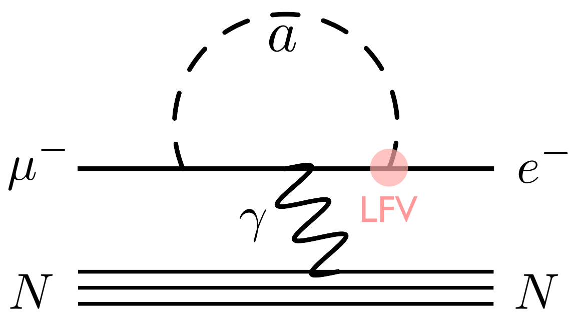
Four-fermion interaction



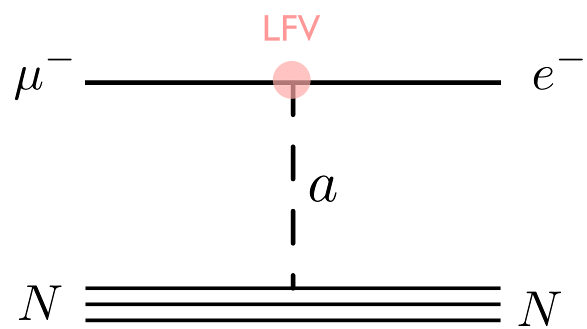
LFV ALP contributions

$$\mathcal{L}_{\rm ALP} \supset -im_\mu \frac{a}{f_a}\bar{e}(v_{e\mu} + a_{e\mu}\gamma_5)\mu \;\; -m_\mu \frac{a}{f_a}\bar{\mu}i\gamma_5\mu \;\;\; -m_q \frac{a}{f_a}\bar{q}i\gamma_5 q$$

Photon dipole



Four-fermion interaction

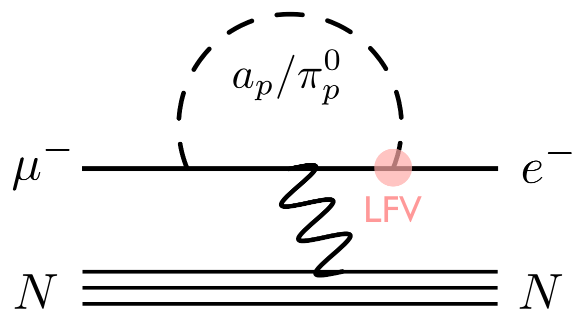


Need nucleon-level interactions : SU(2) Chiral PT with ALPs

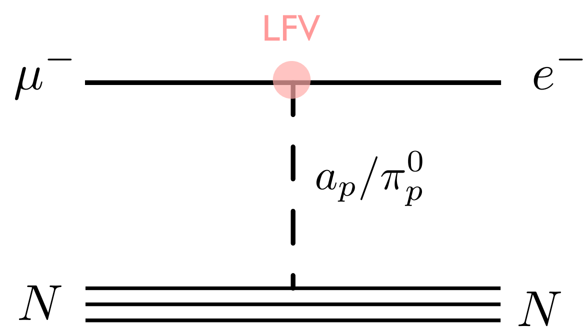
LFV ALP contributions

$$\mathcal{L}_{\mathrm{ALP}} \supset -im_\mu \frac{\cancel{a}}{f_a}\bar{e}(v_{e\mu} + a_{e\mu}\gamma_5)\mu \; -m_\mu \frac{\cancel{a}}{f_a}\bar{\mu}i\gamma_5\mu \qquad a \to (c_\alpha a_p + s_\alpha \pi_p^0)$$

Photon dipole



Four-fermion interaction



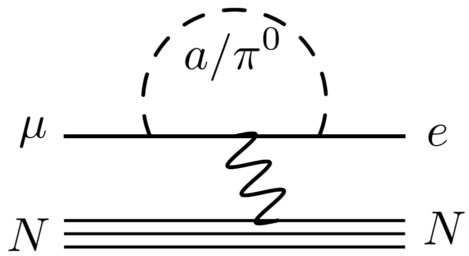
$$\mathcal{L}_{\chi\mathrm{PT}} \supset -g_A \frac{m_N}{f_\pi}\left(c_\alpha \pi_p^0 - s_\alpha a_p\right)\bar{N}i\gamma_5\tau^3 N$$

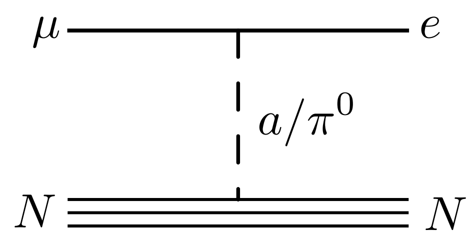
$$g_A = 1.27$$
$$f_\pi = 92.2 \text{ MeV}$$

$$\begin{pmatrix} a \\ \pi^0 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix}\begin{pmatrix} a_p \\ \pi_p^0 \end{pmatrix}$$

$$c_\alpha \approx 1 \quad s_\alpha \approx \frac{f_\pi}{f_a}\frac{m_{\pi^0}^2}{m_{\pi^0}^2 - m_a^2}$$

LFV ALP contributions





$$\Gamma(\mu \to e) \propto \frac{m_\mu^5}{f_a^4} \left(W_D \ |C_D|^2 + \frac{1}{4} \ W_P \ |C_P|^2 \right)$$

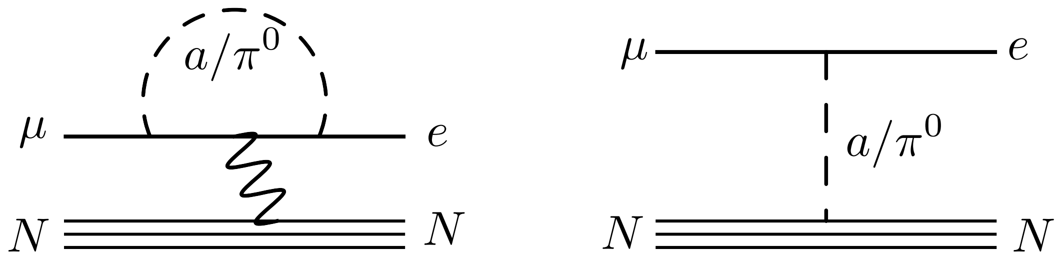
Couplings of nucleon interactions

$$\text{For } m_a \ll m_\mu, \quad C_D \simeq -\frac{\alpha_{\rm em}}{8\pi} \left(a_{e\mu} \pm v_{e\mu}\right) a_{\mu\mu}$$

$$C_P \simeq g_A a_{e\mu}$$

$$\boxed{\frac{|C_P|^2}{|C_D|^2} \sim \frac{g_A^2}{\frac{\alpha_{\rm em}^2}{64\pi^2}} \sim \mathcal{O}(10^7)}$$

LFV ALP contributions



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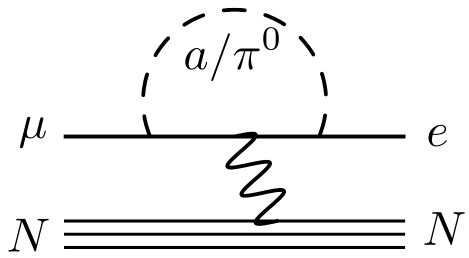
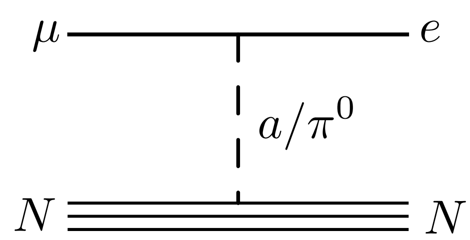
Nuclear response functions

https://github.com/Berkeley-Electroweak-Physics/Mu2e

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

LFV ALP contributions





$$\Gamma(\mu \to e) \propto \frac{m_\mu^5}{f_a^4} \left(W_D \; |C_D|^2 + \frac{1}{4} \; W_P \; |C_P|^2 \right)$$

Nuclear response functions

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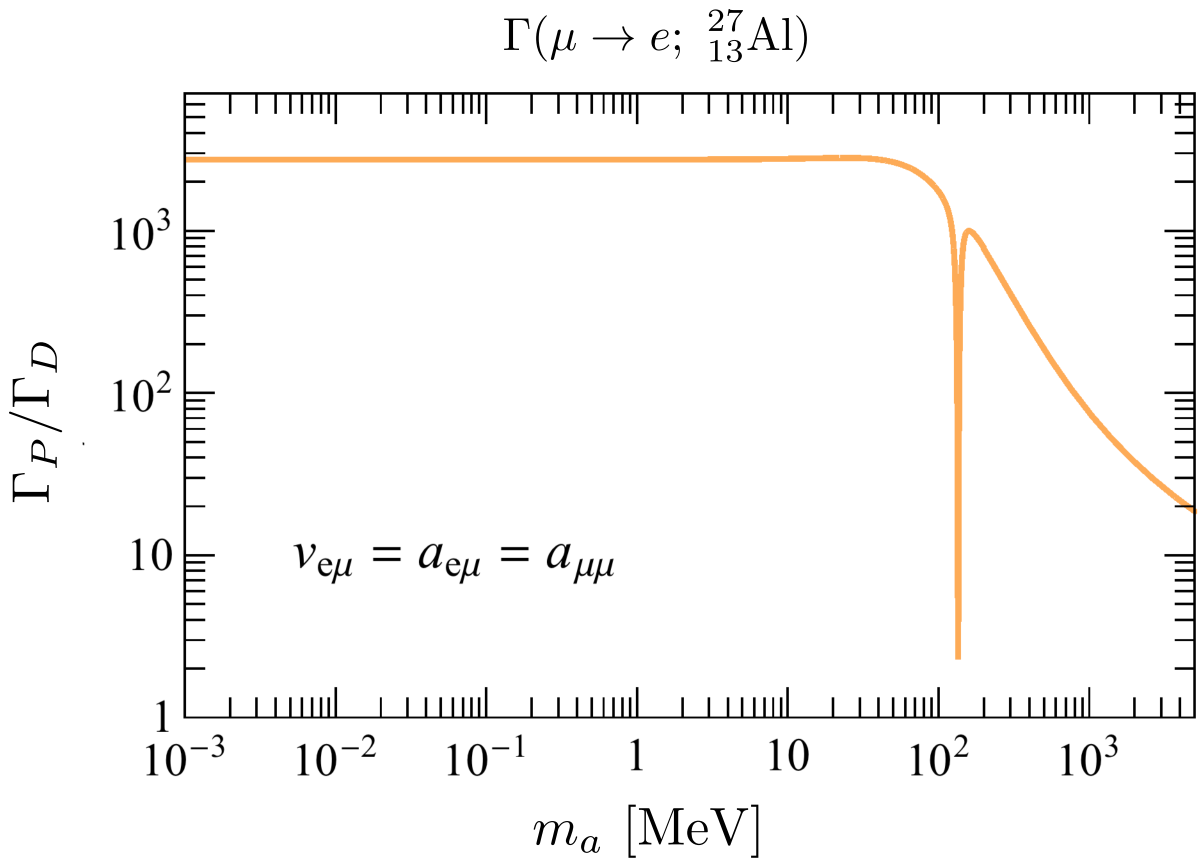
	Target	Abundance [%]	Spin	W_D	W_P
Mu2e COMET	${}^{27}_{13}\mathrm{Al}$	100	$5/2^+$	61.67	9.2×10^{-2}
	${}^{48}_{22}\mathrm{Ti}$	73.72	0^+		
Current	${}^{47}\mathrm{Ti}$	7.44	$5/2^-$	116.3	7.1×10^{-3}
	${}^{49}\mathrm{Ti}$	5.41	$7/2^-$		

Conversion Rate

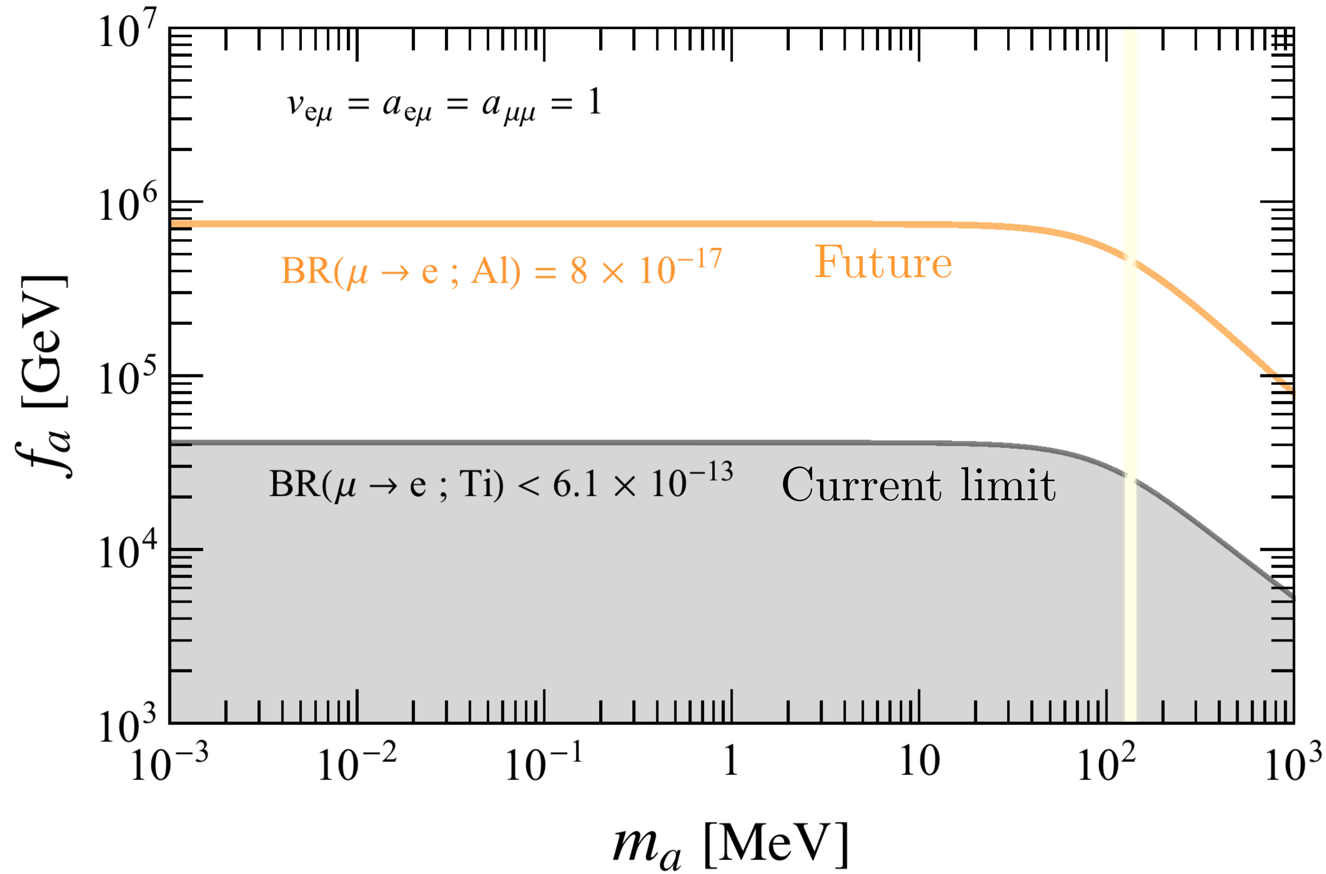
KF, E. Mereghetti 2307.13076



The conversion process is dominated by pseudo-scalar interaction.

Limit on ALP decay constant

KF, E. Mereghetti 2307.13076

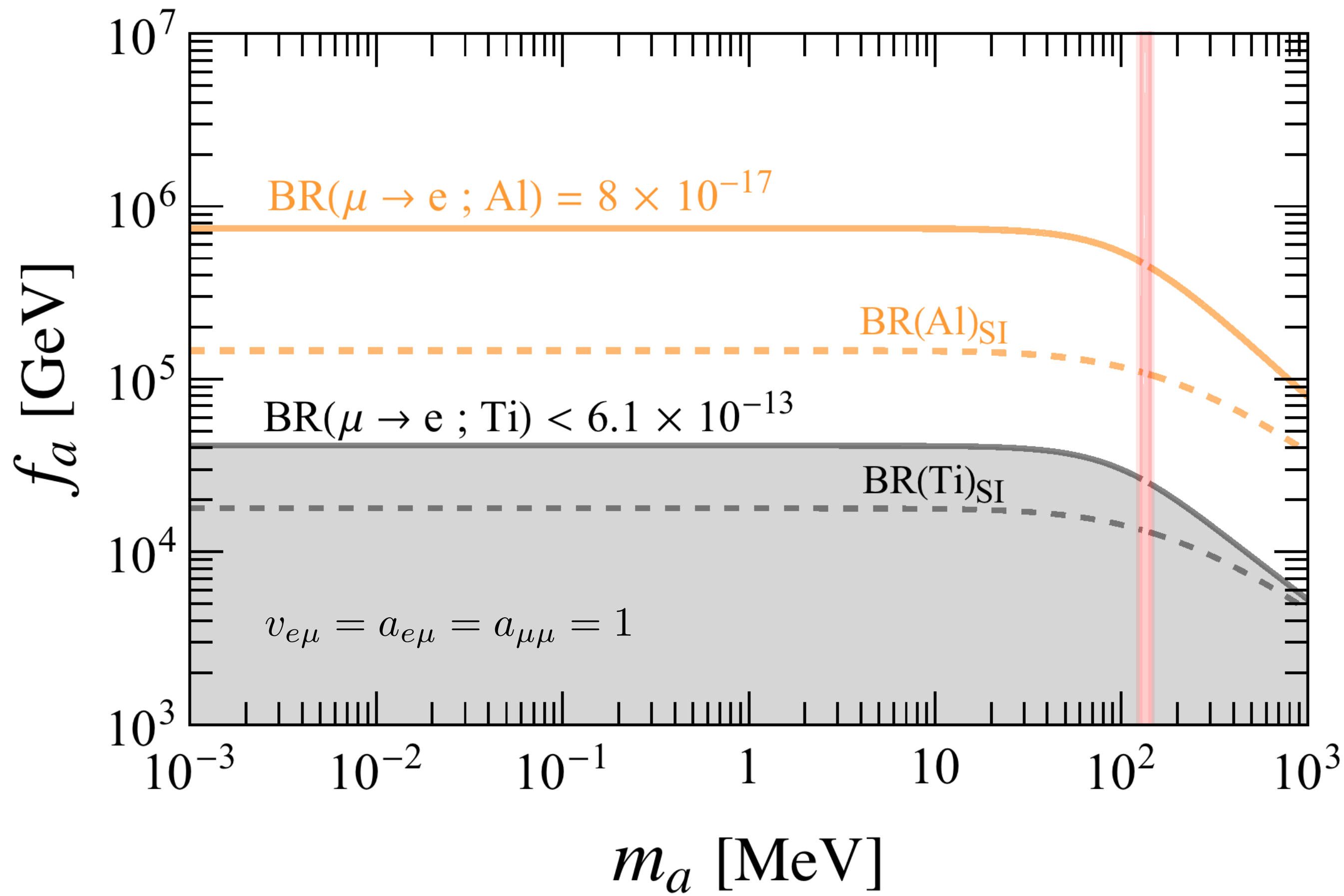


Current : $f_a > O(1-10)$ TeV

Future : $f_a > O(100)$ TeV

Limit on ALP decay constant

KF, E. Mereghetti 2307.13076



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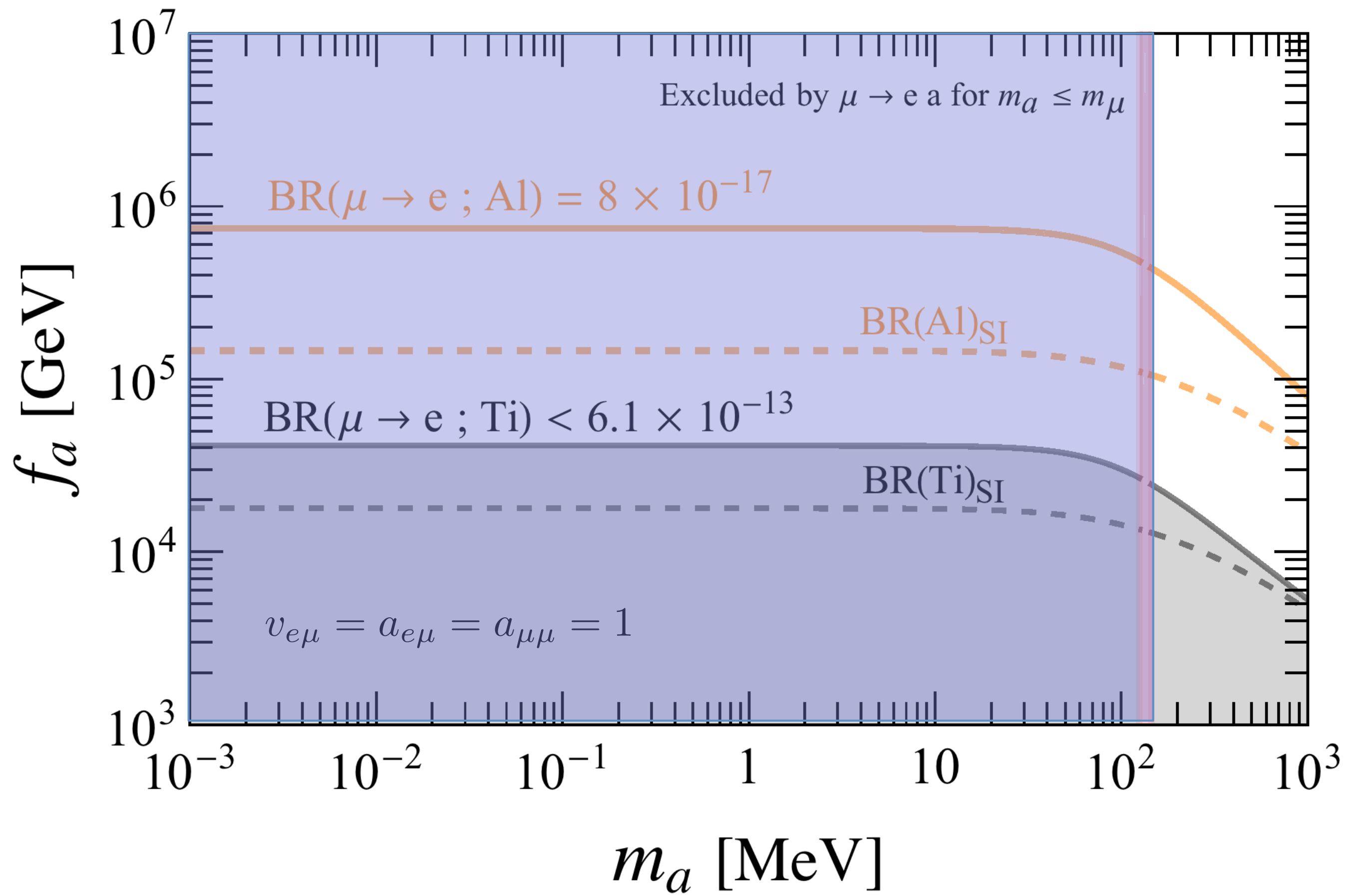


$\mu \to ea$ is open for $m_\mu \gtrsim m_a$

$f_a > \mathcal{O}(10^9)$ GeV

$\mathrm{BR}(\mu \to ea) < 2.6 \times 10^{-6}$

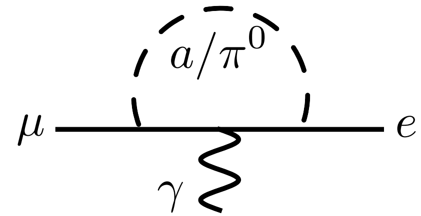
A. Jodidio et al, PRD34(1986)1967
L. Calibbi, D. Redigolo, R. Ziegler, J. Zupan, JHEP09(2021)173

Other constraints

KF, E. Mereghetti 2307.13076

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

MEG II Collaboration, 2310.12614



Other constraints

KF, E. Mereghetti 2307.13076

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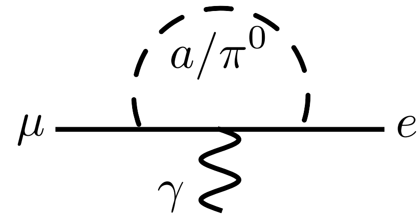
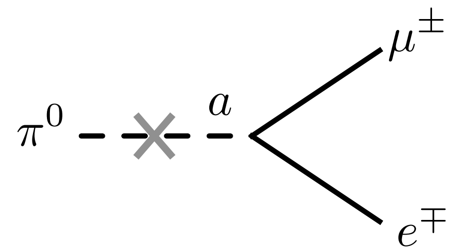
  MEG II Collaboration, 2310.12614

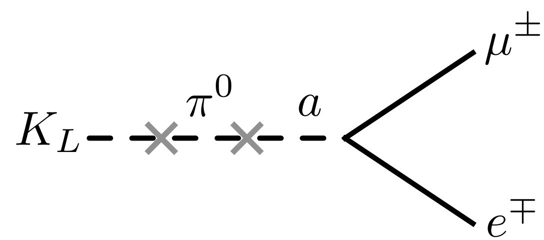


- LFV Pion decay $\mathrm{BR}(\pi^0 \to \mu^\pm e^\mp) < 3.6 \times 10^{-10}$

  KTeV Collaboration, PRL100(2008)131803



- LFV Kaon decays

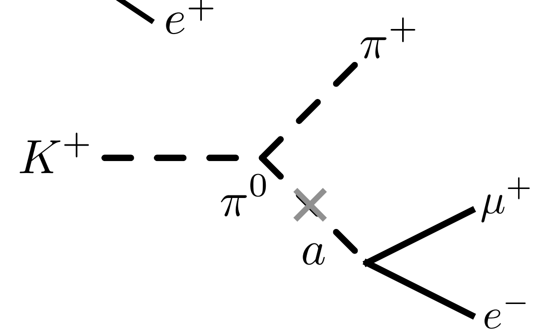


$$\mathrm{BR}(K_L \to \mu^\pm e^\mp) < 4.7 \times 10^{-12}$$

BNL Collaboration, PRL81(1998)573

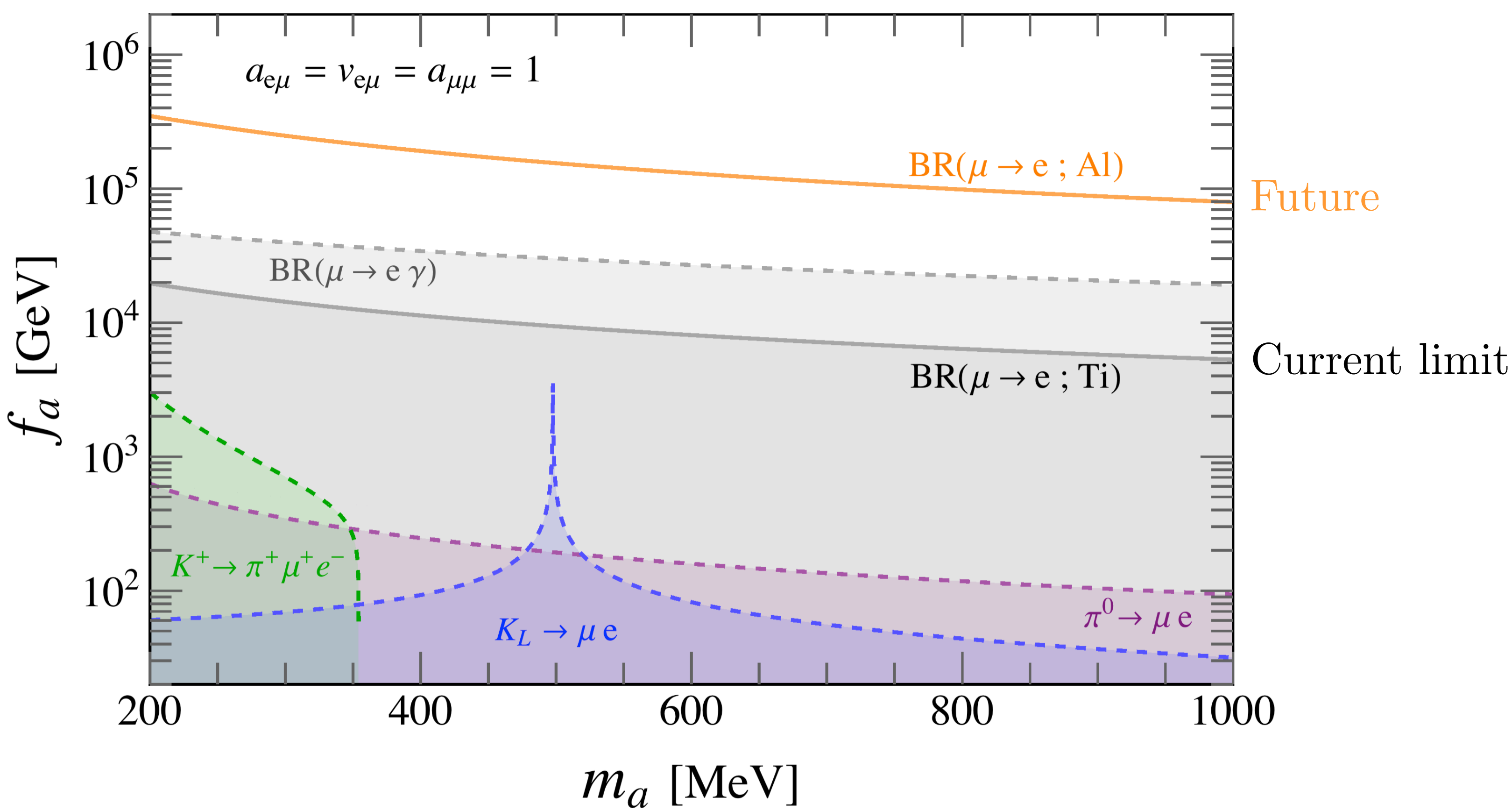
$$\mathrm{BR}(K^+ \to \pi^+\mu^+e^-) < 1.3 \times 10^{-11}$$

PRD72(2005)012005



Limit on ALP decay constant

KF, E. Mereghetti 2307.13076



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

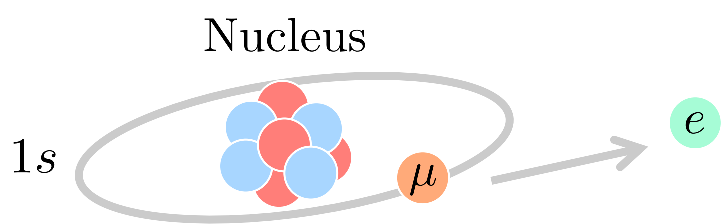
✔ The future mu2e conversion searches have the great potential to probe LFV ALP scenarios!

Summary

Searches for violations of fundamental symmetries and conservation laws

- Powerful Probes of physics beyond the Standard Model (BSM)

Charged Lepton Flavor violation : Mu to E conversion



- 4-orders of magnitude improvements in BR
- SD process can dominate the conversion process in ALP models.
- fa > O(100) TeV can be achieved, complementary role.

Discussion/Outlook : Other ALP couplings and Extension to SU(3) Chiral PT

EIC workshop starting next Monday!

Electroweak and Beyond the Standard Model Physics at the EIC

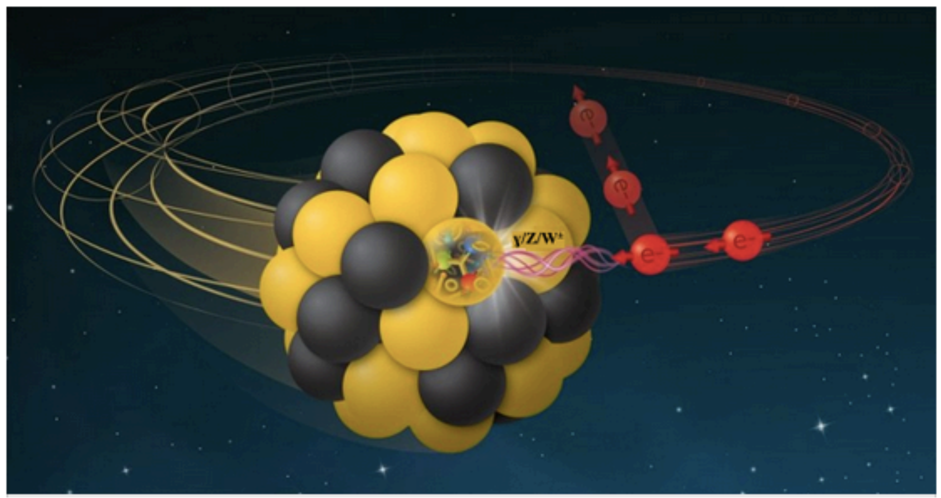
February 12, 2024 - February 16, 2024

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

9 :15 AM Mon : BSM searches at the Intensity Frontier – Theoretical Overbiew by Vincenzo
4 :00 PM Mon : Probing axion-like particles at the EIC in the coherent scattering by Hongkai Liu

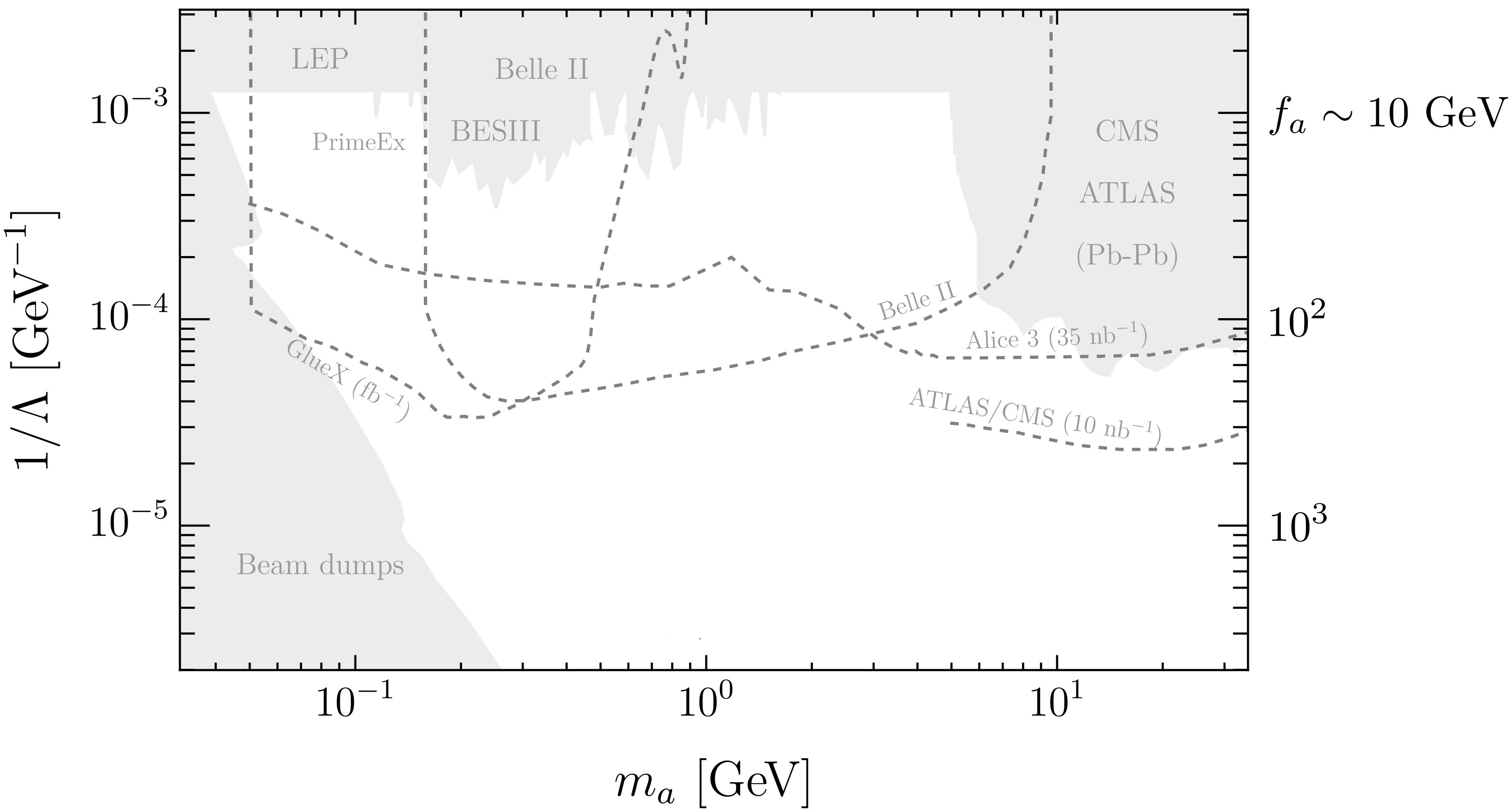
10:00 AM Wed : CLFV at the EIC vs low energy by Emanuele Mereghetti
11: 15 AM Wed : Experimental view on CLFV at the eic in tau decays with muons in the final state by Andrew Hurley
10 :00 AM Thu : Flavor-violating ALPs at the EIC by Ethan Neil

Backup slides

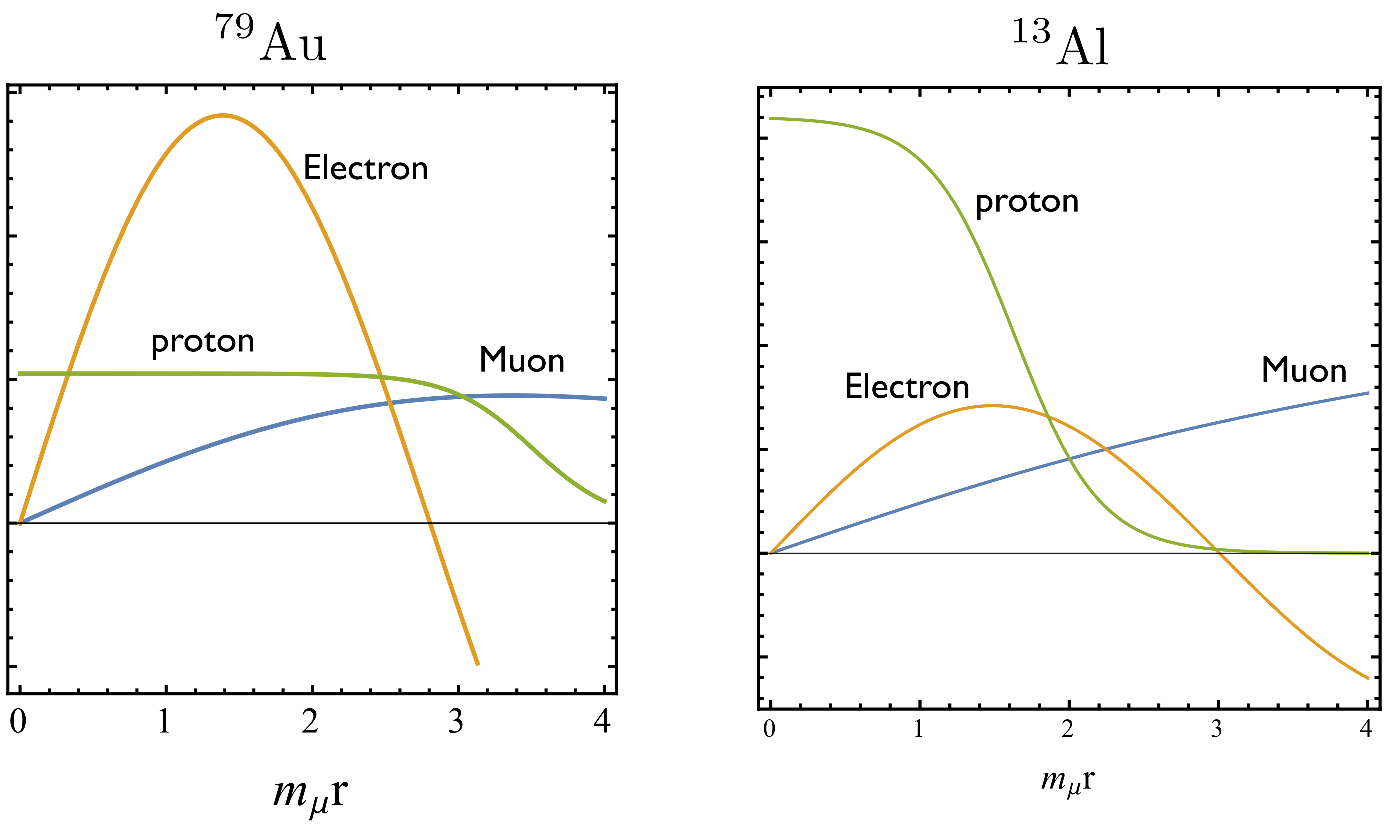
Photon coupling

R. Balkin, et al, 2310.08827

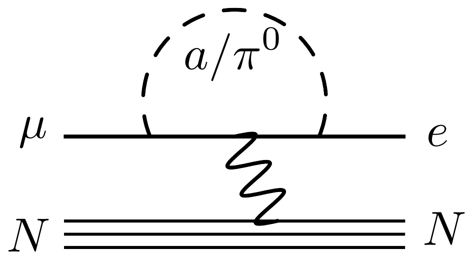
$$\mathcal{L} \supset -\frac{a}{4\Lambda} F\tilde{F}$$

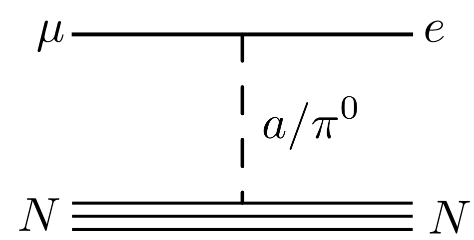


Lepton wave functions



LFV ALP contributions





$$\Gamma(\mu \to e) \propto \frac{m_\mu^5}{f_a^4} \left(W_{MM} |C_D|^2 + \frac{1}{4} W^{11}_{\Sigma''\Sigma''} |C_P|^2 \right)$$

$$\mathcal{O}_D = -\frac{i}{f_a^2} \frac{2}{m_\mu} C_{D\alpha} \bar{e} \sigma^{\mu\nu} P_\alpha \mu q_\mu \; \bar{N} \gamma_\nu \left(\frac{1+\tau^3}{2} \right) N$$

$$\mathcal{O}_P = -\frac{i}{f_a^2} C_P \frac{m_N}{m_\mu} \bar{e} \gamma^5 \mu \; \bar{N} i \gamma^5 \tau^3 N$$

For $m_a \ll m_\mu$, $C_D \simeq -\frac{\alpha_{\rm em}}{8\pi} \left(a_{e\mu} \pm v_{e\mu} \right) a_{\mu\mu}$

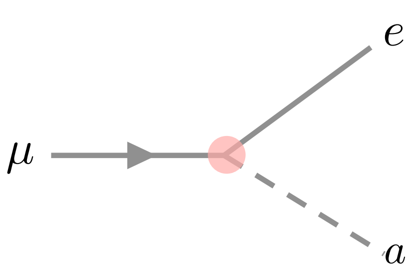
$C_P \simeq g_A a_{e\mu}$

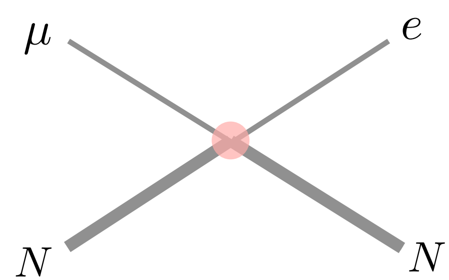
$$\frac{|C_P|^2}{|C_D|^2} \sim \frac{g_A^2}{\frac{\alpha_{\rm em}^2}{64\pi^2}} \sim \mathcal{O}(10^7)$$

Limit on ALP decay constant

KF, E. Mereghetti 2307.13076

$$\Gamma_\mu \sim \Gamma_{\rm capt}({\rm Al}) \sim \mathcal{O}(10^{-16})\ {\rm MeV} \equiv \Gamma$$





$$\mathrm{BR}(\mu \to e a) \sim \frac{m_\mu^3}{\Gamma}\frac{1}{f_a^2} \lesssim \mathcal{O}(10^{-6})$$

$$\frac{m_\mu^3}{\Gamma} \times 10^6 \lesssim f_a^2$$

$$\mathrm{BR}(\mu \to e) \sim \frac{m_\mu^5}{\Gamma}\frac{1}{f_a^4} \lesssim \mathcal{O}(10^{-12})$$

$$\frac{m_\mu^3}{\Gamma} \underbrace{\left(\frac{\Gamma}{m_\mu}\right)^{1/2}}_{10^{-9}} \times 10^6 \lesssim f_a^2$$

Roughly 4-orders of magnitude stronger limit from mu to e a: $f_a > \mathcal{O}(10^9)\ \mathrm{GeV}$

*Focus on $m_a > m_\mu$.