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Title: Searching for muon to electron conversion

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Intended for: I will give a theory seminar talk at INT, University of Washington on February 8th.

Issued: 2024-02-05



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Searching for Muon to Electron Conversion

Kaori Fuyuto

Los Alamos National Laboratory

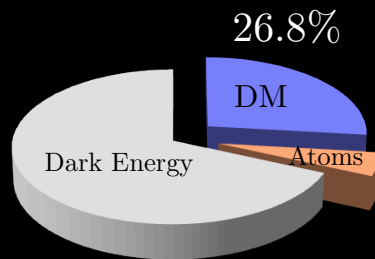


KF, E. Mereghetti, 2307.13076

February 8, 2024 @ INT
U of Washington

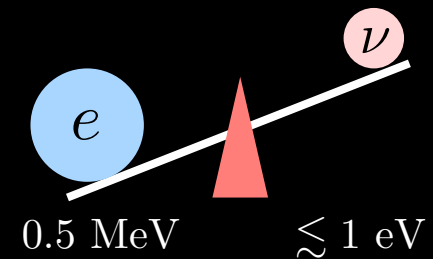
We still don't know much about our Universe.

What is Dark Matter?



The origin of
the present Universe

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

3

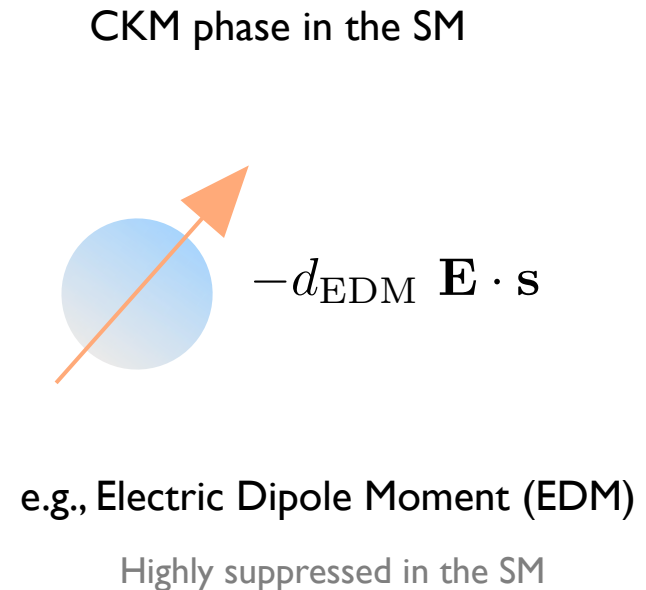
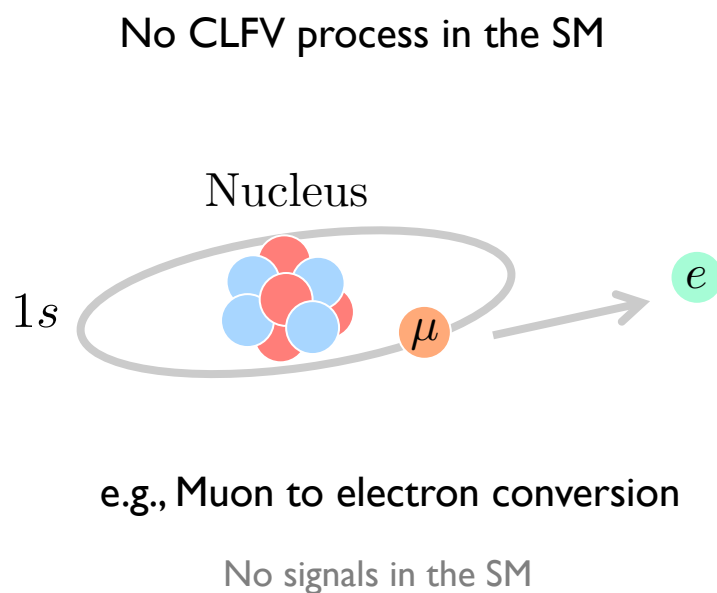
Searches for violations of fundamental symmetries / conservation laws

Fundamental Symmetry Tests

4

Searches for violations of fundamental symmetries / conservation laws

Ex) Lepton Flavor violation and CP violation



Observations of these processes would immediately point to BSM physics.

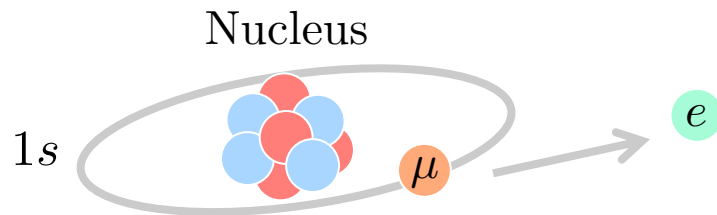
Fundamental Symmetry Tests

5

Searches for violations of fundamental symmetries / conservation laws

Ex) Lepton Flavor violation and CP violation

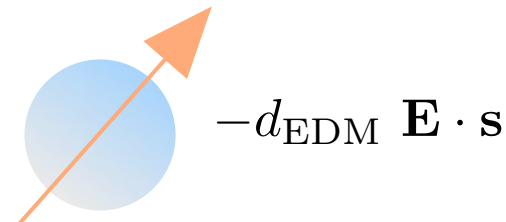
No CLFV process in the SM



e.g., Muon to electron conversion

No signals in the SM

CKM phase in the SM



e.g., Electric Dipole Moment (EDM)

Highly suppressed in the SM

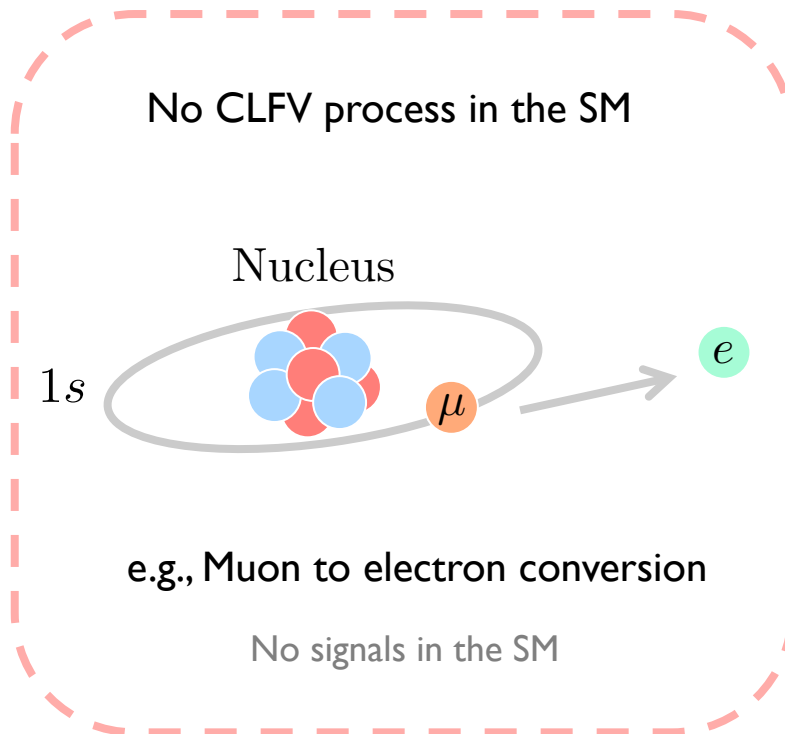
✓ Powerful Probes of physics beyond the Standard Model (BSM)

Fundamental Symmetry Tests

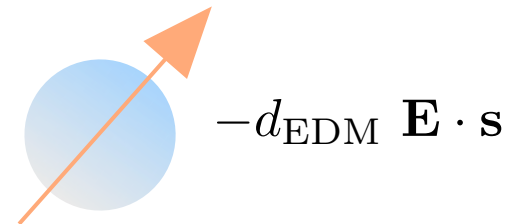
6

Searches for violations of fundamental symmetries / conservation laws

Ex) Lepton Flavor violation and CP violation



CKM phase in the SM



e.g., Electric Dipole Moment (EDM)

Highly suppressed in the SM

Today : CLFV searches

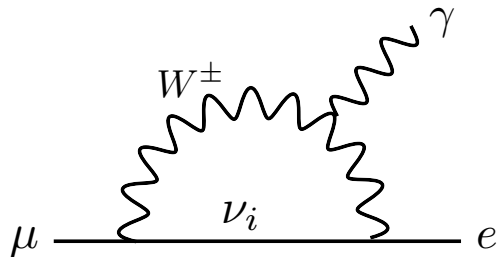


Charged Lepton Flavor Violation

CLFV searches

Searches for CLFV are strong tools to probe BSM physics.

Ex) SM + neutrino mass (vSM)



Petcov '77, Marciano-Sanda '77

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

Dirac or Majorana

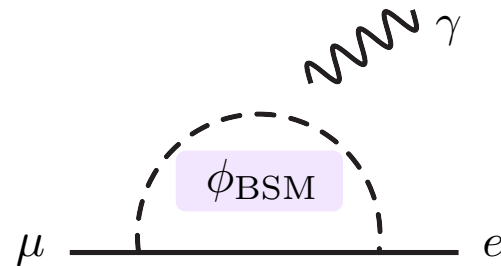
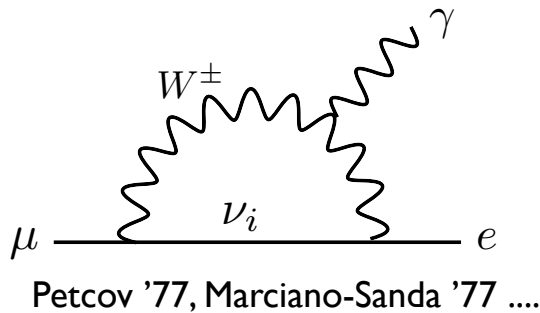
$$\text{Br}(\mu \rightarrow e\gamma) = \frac{3\alpha_{\text{em}}}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{m_W^2} \right|^2 < 10^{-54}$$

Extremely small!

CLFV searches

Searches for CLFV are strong tools to probe BSM physics.

Ex) SM + neutrino mass (vSM)

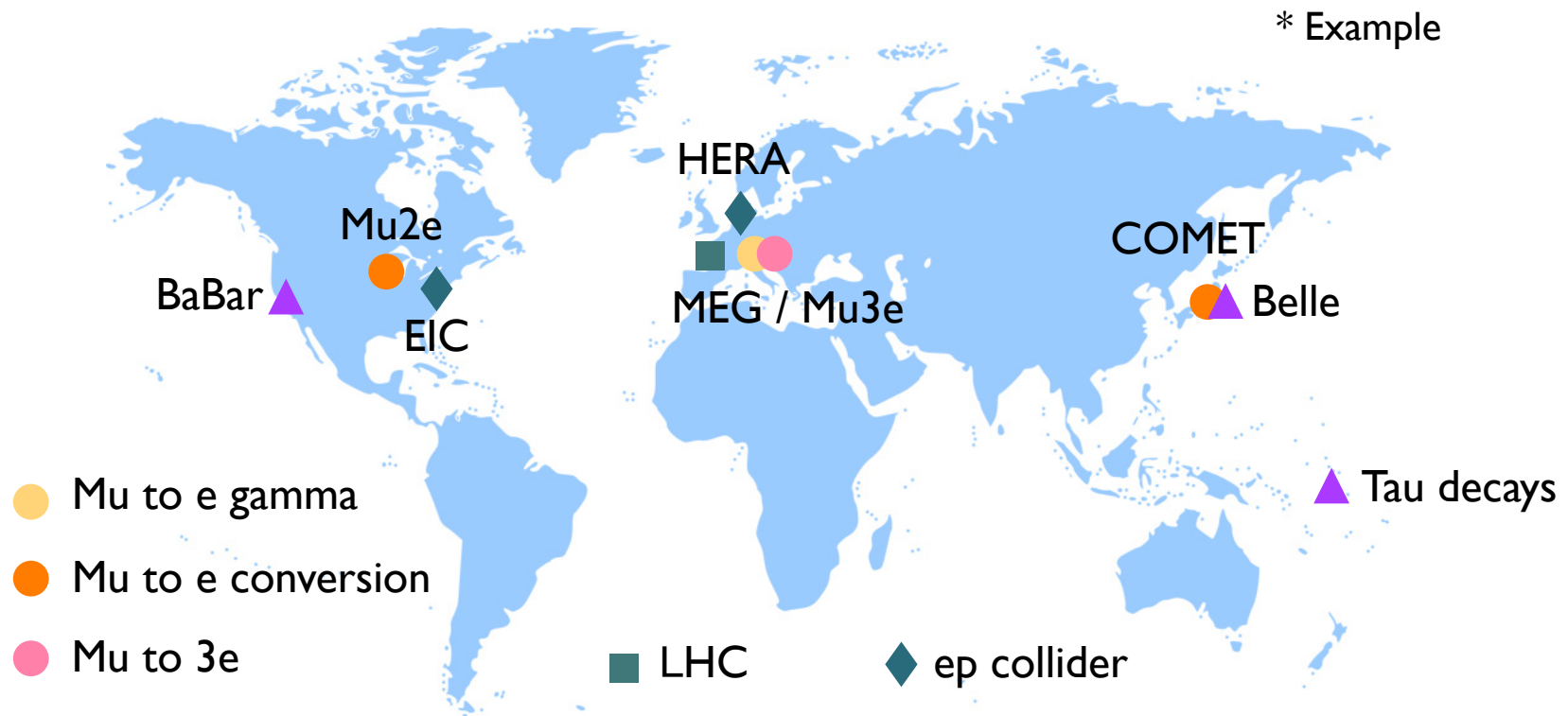


$$\text{Br}(\mu \rightarrow e\gamma) < 10^{-54} \ll \text{Br}(\mu \rightarrow e\gamma)_{\text{BSM}}$$

✓ The Observations of CLFV would point to new physics beyond vSM.

*Underlying mechanism of the neutrino mass.

CLFV searches



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

MEG II Collaboration, 2310.12614

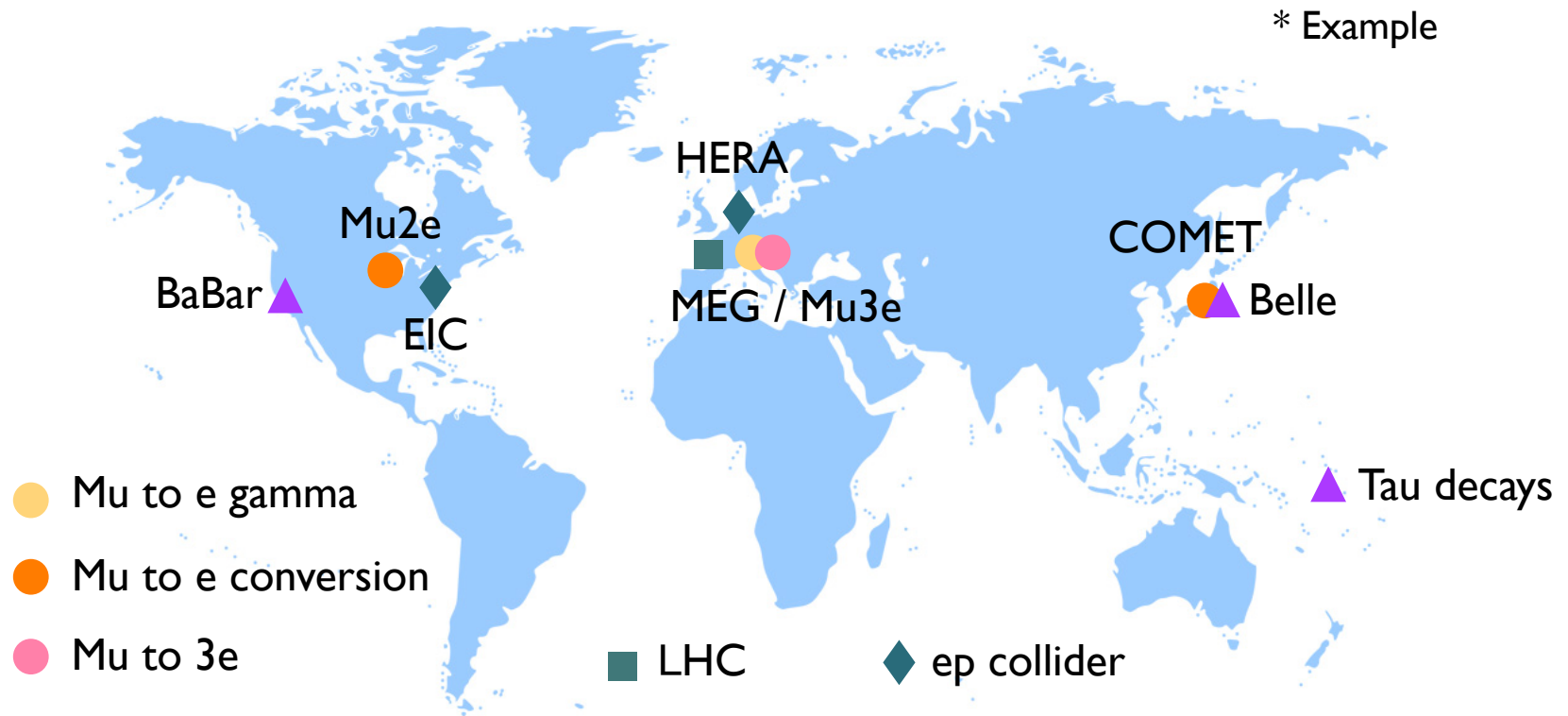
$$\text{BR}(\mu^- \text{ Ti} \rightarrow e^- \text{ Ti}) < 6.1 \times 10^{-13}$$

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

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

*From one-loop contribution

CLFV searches



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

MEG II Collaboration, 2310.12614

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

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

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

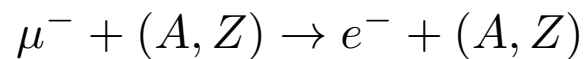
BaBar, PRL104 (2010) 021802

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

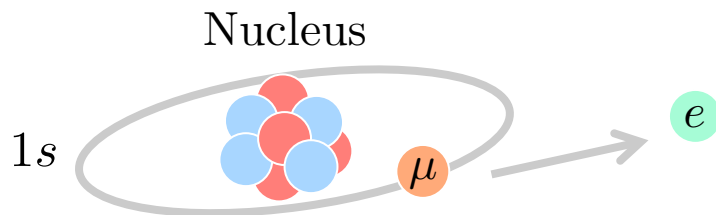
Belle, PLB719 (2013) 346-353

Mu to E conversion

Muon to Electron conversion in Muonic Atom



*Mono-energetic electron



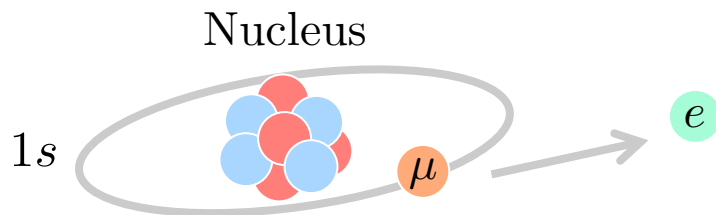
$$E_e \simeq m_\mu - B_\mu$$

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

Mu to E conversion

Muon to Electron conversion in Muonic Atom

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

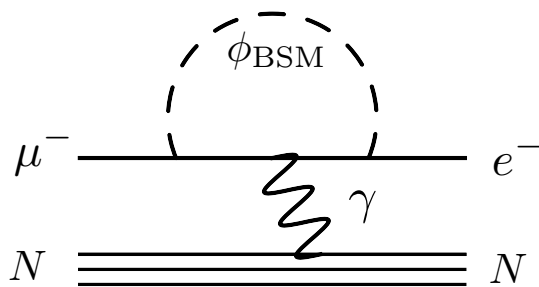


$$E_e \simeq m_\mu - B_\mu$$

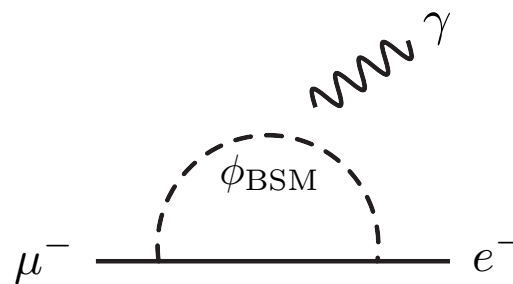
$$B_\mu \simeq \frac{\alpha_{\text{em}}^2 Z^2}{2} m_\mu$$

Ex) Photonic interaction

* Purely leptonic BSM interactions



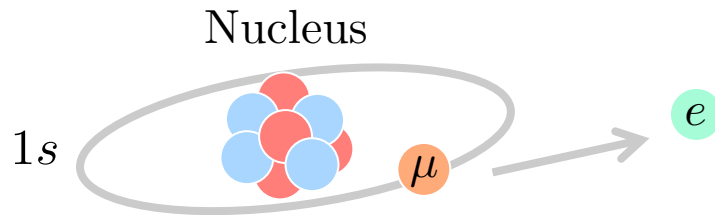
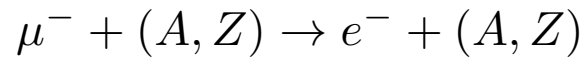
Mu to e conversion



Mu to e gamma

Mu to E conversion

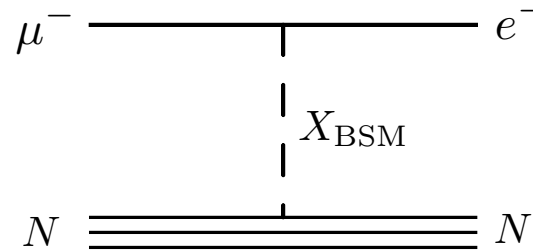
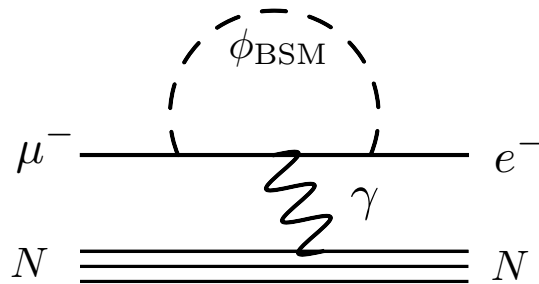
Muon to Electron conversion in Muonic Atom



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

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

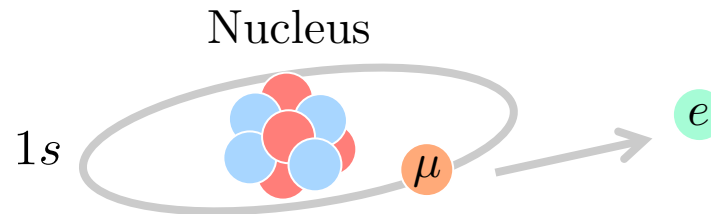
Ex) Photonic- and Non-photonic interaction



✓ Contributions from various CLFV interactions to the conversion process

Mu to E conversion

Muon to Electron conversion in Muonic Atom



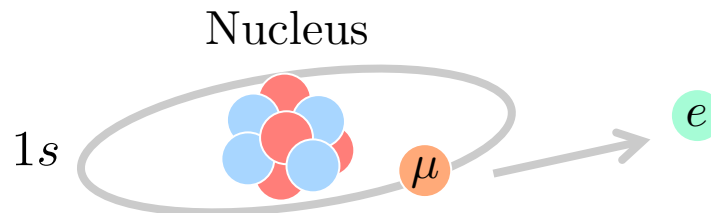
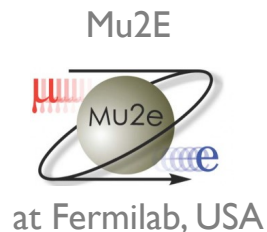
$$\text{BR}(\mu \rightarrow e) = \frac{\Gamma_{\text{conv}}(\mu + (A, Z) \rightarrow e + (A, Z))}{\Gamma_{\text{capt}}(\mu + (A, Z) \rightarrow \nu_{\mu} + (A, Z - 1))}$$

* Capture rate : PRC 35, 2212 (1987)

Process	$\Gamma_{\text{capt}} [10^{-15} \text{ MeV}]$	Upper Bound
$\mu^- + \text{Ti} \rightarrow e^- + \text{Ti}$	1.705	6.1×10^{-13}
$\mu^- + \text{Au} \rightarrow e^- + \text{Au}$	8.603	7×10^{-13}
$\mu^- + \text{Pb} \rightarrow e^- + \text{Pb}$	8.853	4.6×10^{-11}

Mu to E conversion

Muon to Electron conversion in Muonic Atom



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

* Capture rate : PRC 35, 2212 (1987)

Process	$\Gamma_{\text{capt}} [10^{-15} \text{ MeV}]$	Upper Bound
$\mu^- + \text{Ti} \rightarrow e^- + \text{Ti}$	1.705	6.1×10^{-13}
$\mu^- + \text{Au} \rightarrow e^- + \text{Au}$	8.603	7×10^{-13}
$\mu^- + \text{Al} \rightarrow e^- + \text{Al}$	0.463	Expected $\mathcal{O}(10^{-17})$

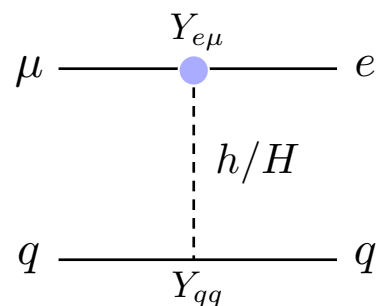
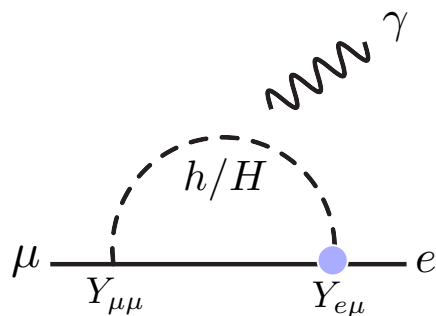
Mu2E
COMET

* Improvement by 4 orders of magnitude

Theoretical Approach

Theoretical Analysis

- CLFV interactions are generated in various BSM models, e.g., 2HDM:



● CLFV coupling

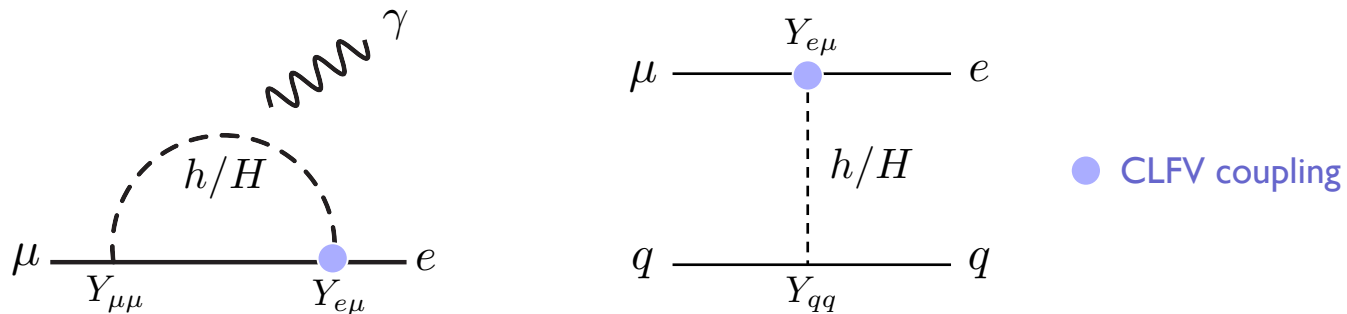
$$\text{Ex)} \quad \mathcal{L}_{\text{CLFV}} = -\frac{m_\mu}{\Lambda^2} C_D \bar{e} \sigma^{\mu\nu} P_R \mu F_{\mu\nu} - \frac{1}{\Lambda^2} C_S \bar{e} P_R \mu \bar{q} q$$

Photon Dipole

Scalar

Theoretical Analysis

- CLFV interactions are generated in various BSM models, e.g., 2HDM:



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

Photon Dipole

Scalar

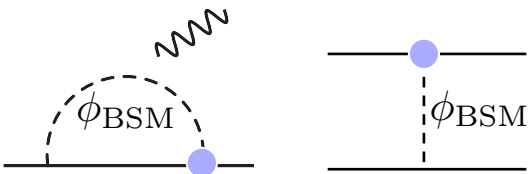
- Model-independent analysis has been comprehensively done (mainly SI interactions).

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).

Scale

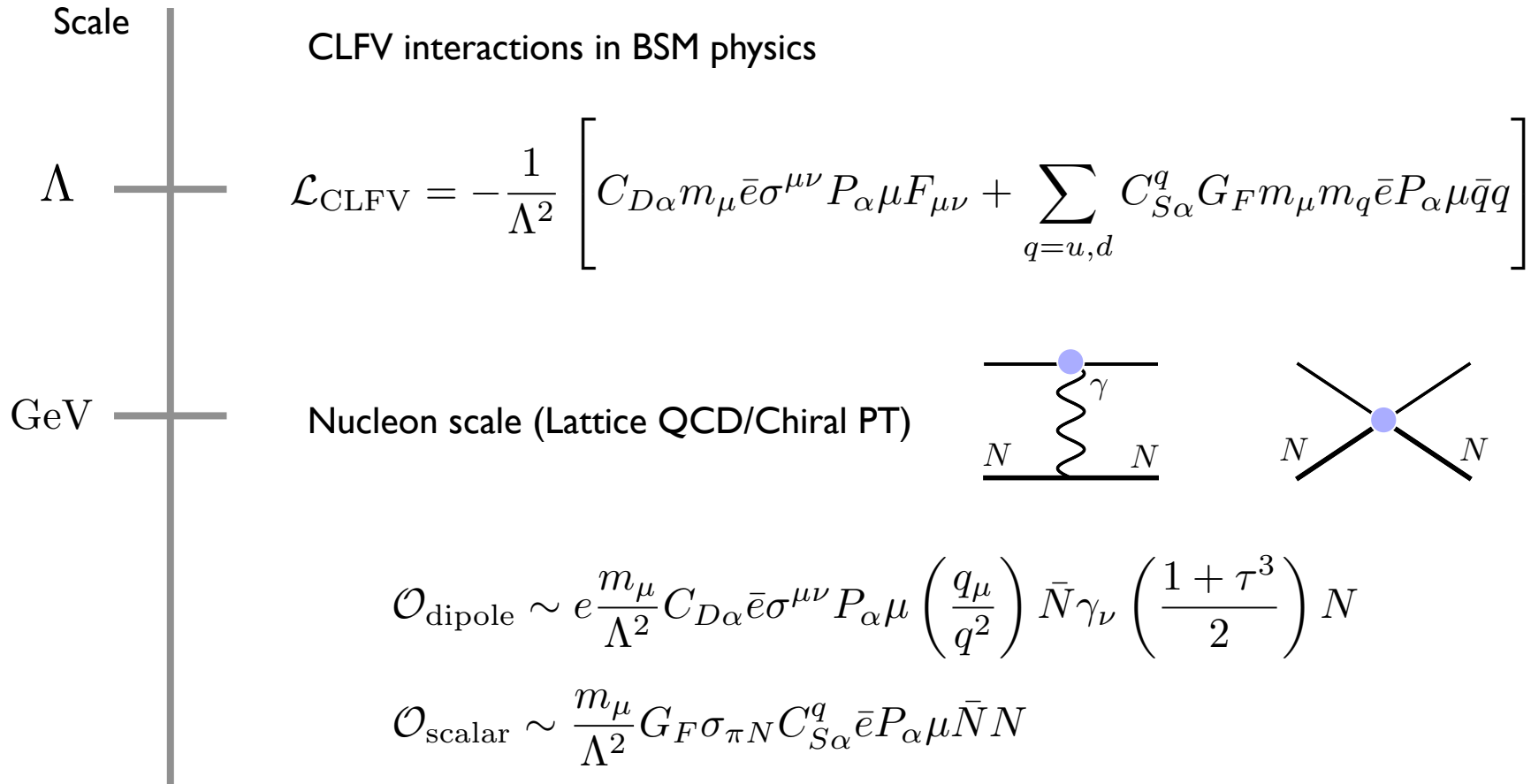
CLFV interactions in BSM physics



Λ

$$\mathcal{L}_{\text{CLFV}} = -\frac{1}{\Lambda^2} \left[C_{D\alpha} m_\mu \bar{e} \sigma^{\mu\nu} P_\alpha \mu F_{\mu\nu} + \sum_{q=u,d} C_{S\alpha}^q G_F m_\mu m_q \bar{e} P_\alpha \mu \bar{q} q \right]$$

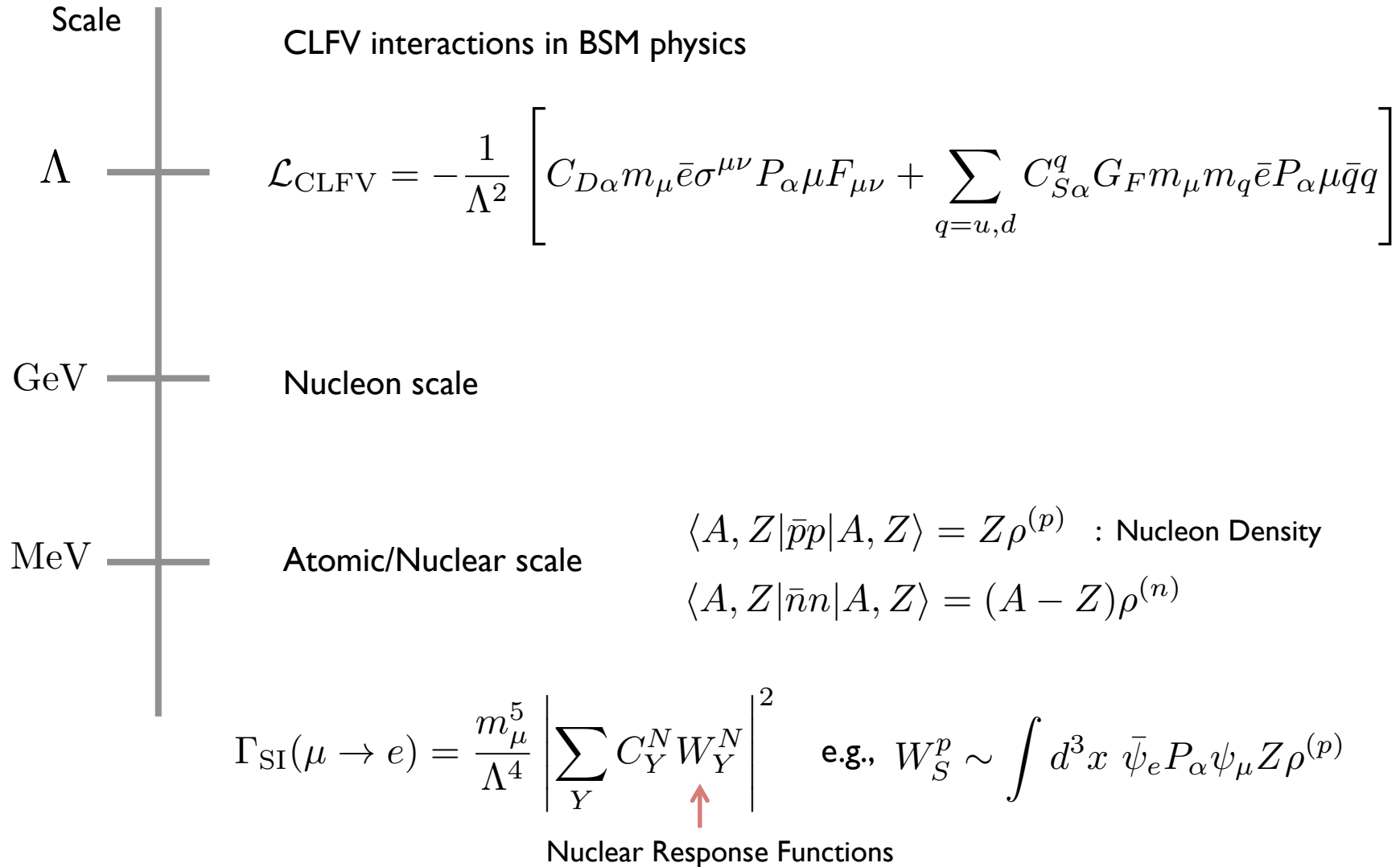
e.g., $\frac{C_D}{\Lambda^2} \sim \frac{e}{(4\pi)^2} \frac{1}{m_\phi^2} Y_{\mu\mu} Y_{e\mu} \quad \frac{C_S}{\Lambda^2} \sim \frac{1}{m_\phi^2} Y_{qq} Y_{e\mu}$



with $N = \begin{pmatrix} p \\ n \end{pmatrix}$ $\sigma_{\pi N} = 59.1(3.5) \text{ MeV}$

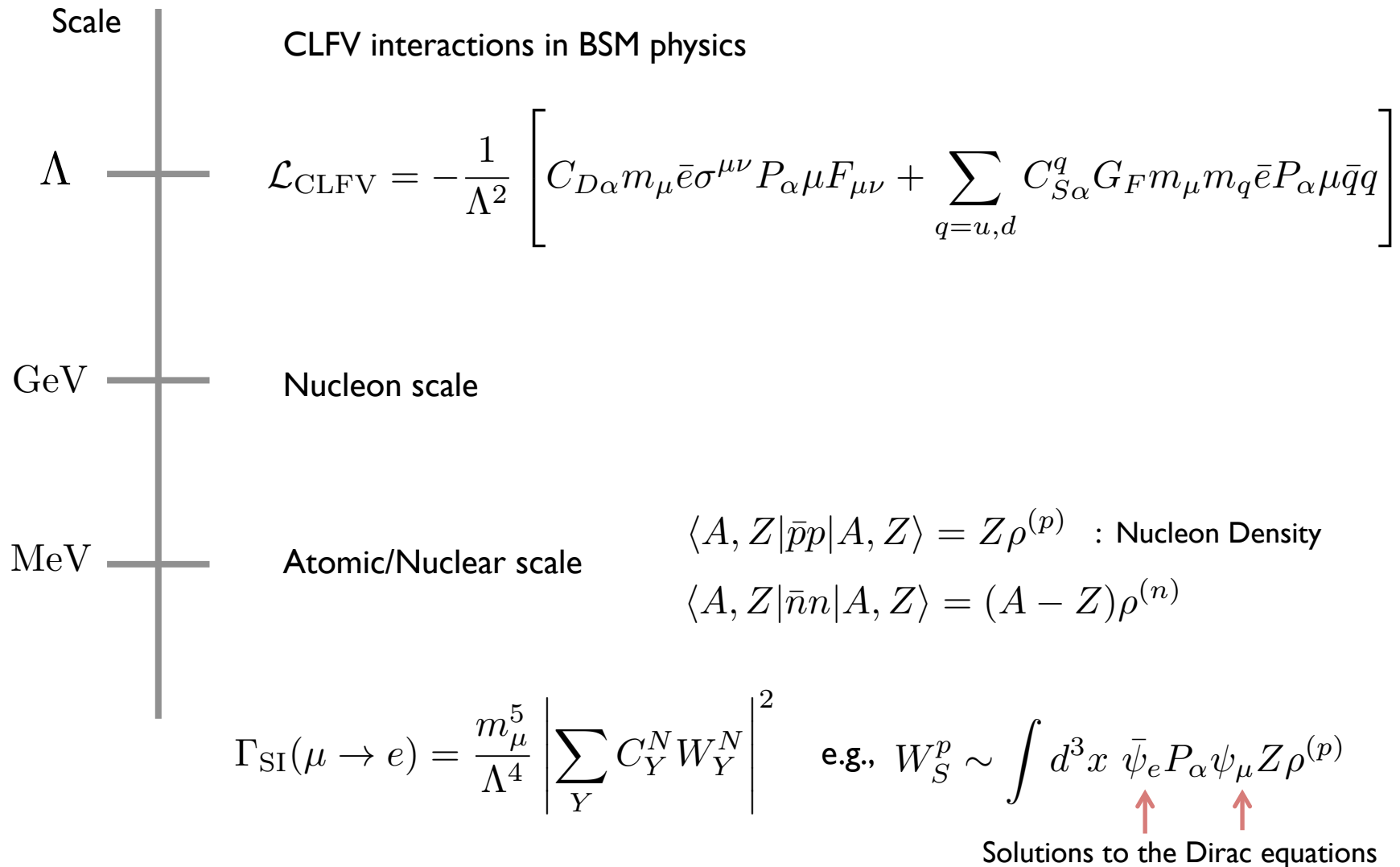
Theoretical Analysis

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



Theoretical Analysis

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



Scale

CLFV interactions in BSM physics

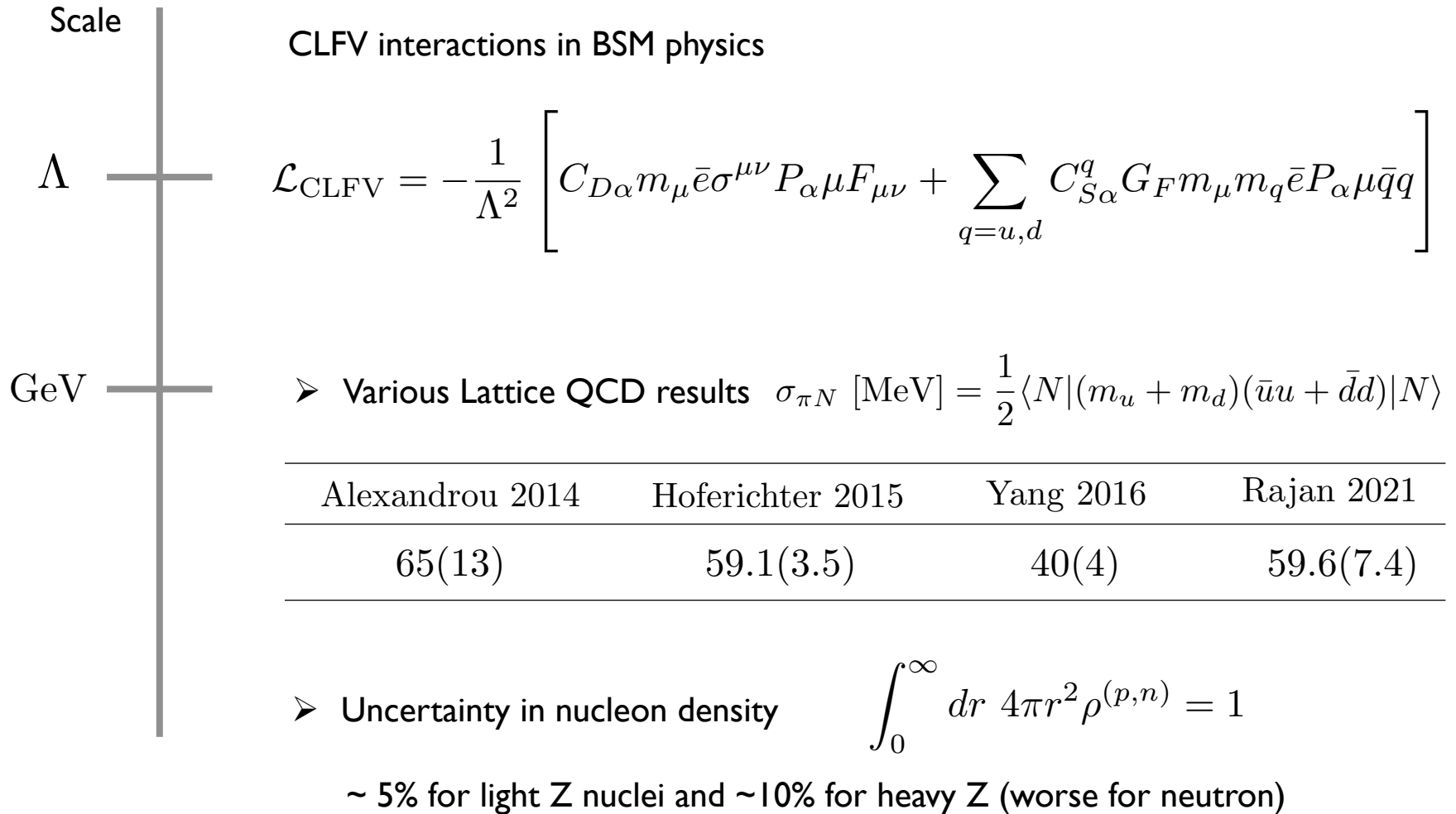
Λ

$$\mathcal{L}_{\text{CLFV}} = -\frac{1}{\Lambda^2} \left[C_{D\alpha} m_\mu \bar{e} \sigma^{\mu\nu} P_\alpha \mu F_{\mu\nu} + \sum_{q=u,d} C_{S\alpha}^q G_F m_\mu m_q \bar{e} P_\alpha \mu \bar{q} q \right]$$

GeV

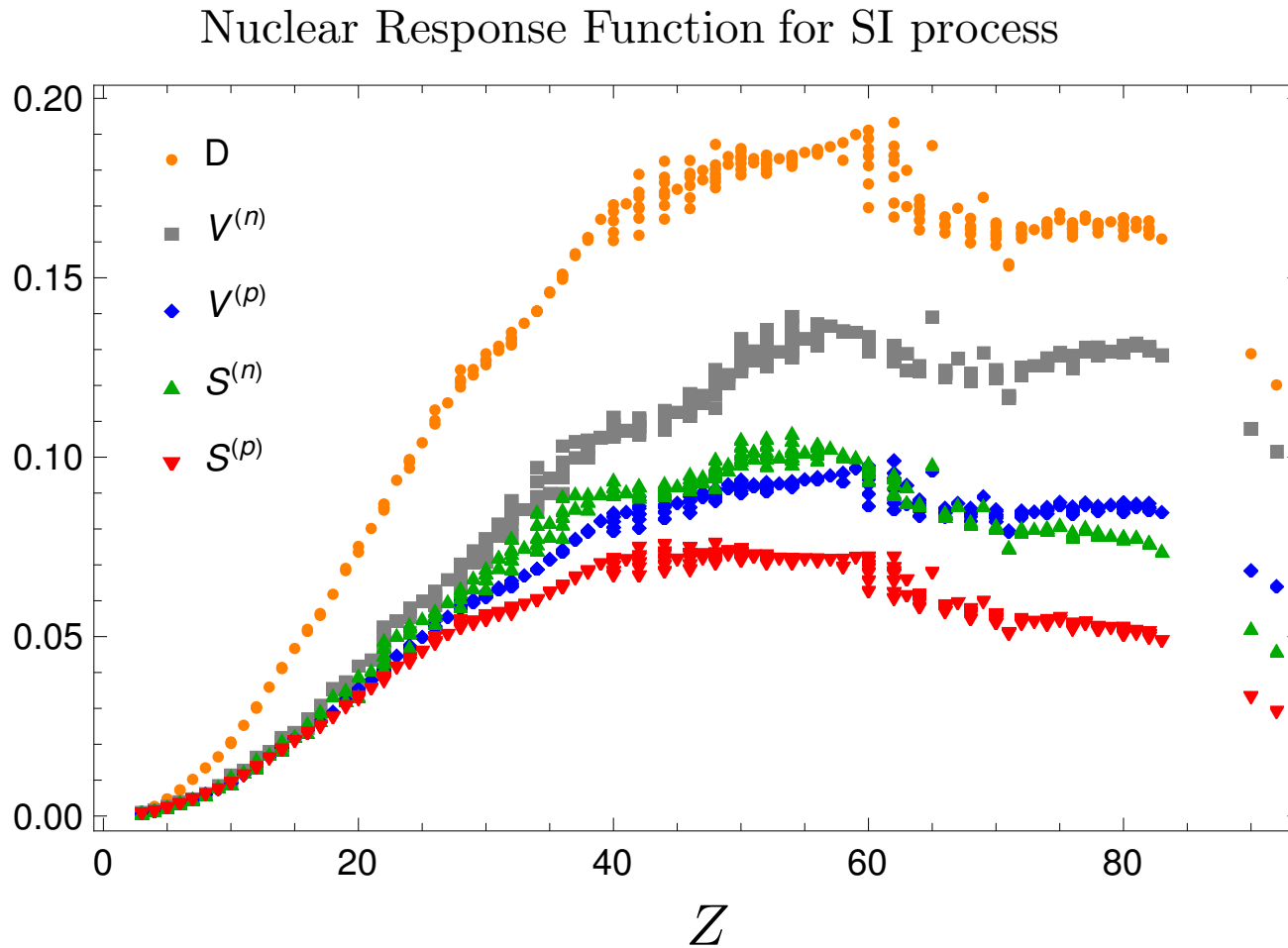
➤ Various Lattice QCD results $\sigma_{\pi N}$ [MeV] = $\frac{1}{2} \langle N | (m_u + m_d) (\bar{u}u + \bar{d}d) | N \rangle$

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



Z dependence

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



Nuclear response functions peak around $Z \sim 60$, 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

$$\text{Ex) Dipole operator : } \mathcal{L}_{\text{CLFV}}^{\text{SI}} \supset -\frac{m_\mu}{\Lambda^2} C_{DY} \bar{e}_Y \sigma^{\mu\nu} \mu F_{\mu\nu} + \dots$$

✓ All nucleons participate in the process

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

*rough idea

- Spin-dependent (SD) process

SI vs SD

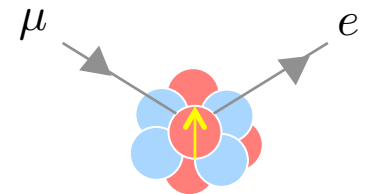
- Spin-independent (SI) process

Ex) Dipole operator : $\mathcal{L}_{\text{CLFV}}^{\text{SI}} \supset -\frac{m_\mu}{\Lambda^2} C_{DY} \bar{e}_Y \sigma^{\mu\nu} \mu F_{\mu\nu} + \dots$

✓ All nucleons participate in the process

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

*rough idea



- Spin-dependent (SD) process

Ex) Pseudo-scalar operator: $\mathcal{L}_{\text{CLFV}}^{\text{SD}} \supset -\frac{1}{\Lambda^2} C_P \bar{e}_Y \mu \bar{q} \gamma_5 q + \dots$

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

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

*Theoretical analysis requires nuclear many body calculations

Recent developments

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

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

Haxton, Rule, McElvain, Ramsey-Musol, PRC 107(2023)035504

Mathematica and Python : <https://github.com/Berkeley-Electroweak-Physics/Mu2e>

Recent developments

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

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

Haxton, Rule, McElvain, Ramsey-Musol, PRC 107(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, NPB 147(1979)277, Ema, et al, JHEP 01(2017)096

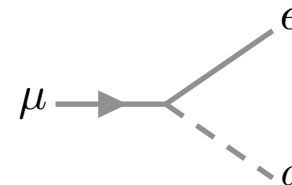
Calibbi, Goertz, Redigolo, **Ziegler**, Zupan, PRD 95(2017)095009, Cornella, et al, JHEP 01(2020)158

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

- Searches for CLFV muon decay into ALP

L. Calibbi, D. Redigolo, **R. Ziegler**, J. Zupan, JHEP 09(2021)173

Y. Jho, et al, JHEP 10(2022)029, R. Hill, et al, 2310.00043z

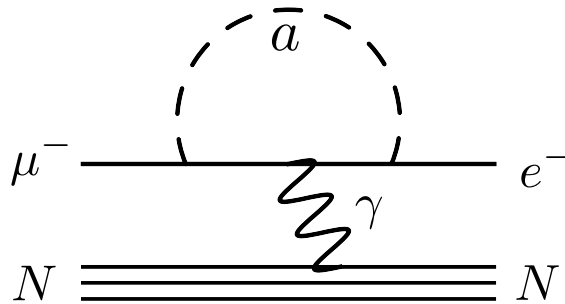


LFV ALP contributions

KF, E. Mereghetti 2307.13076

Previous study considered spin-independent process from ALP interactions:

Photon dipole (JHEP01(2020)158)



$$\mathcal{L}_{\text{CLFV}} \supset -\frac{m_\mu}{f_a^2} C_D \bar{e} \sigma^{\mu\nu} \mu F_{\mu\nu} \quad \Bigg| \quad f_a : \text{ALP decay constant}$$

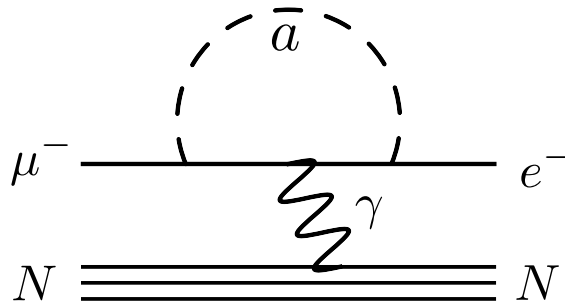
One-loop

LFV ALP contributions

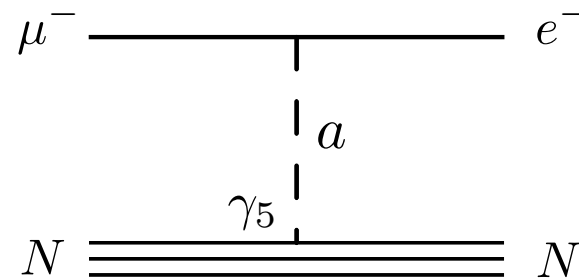
KF, E. Mereghetti 2307.13076

Previous study considered spin-independent process from ALP interactions:

Photon dipole (JHEP01(2020)158)



Four-fermion interaction



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

One-loop

$$-\frac{1}{f_a^2} C_P \bar{e} \mu \bar{q} i \gamma_5 q$$

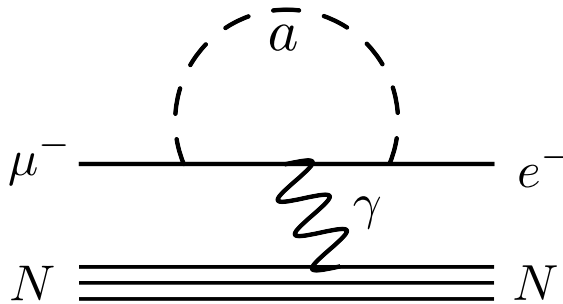
Tree

LFV ALP contributions

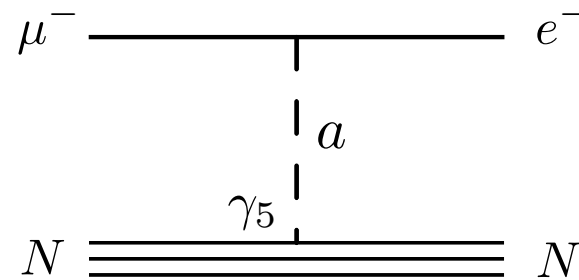
KF, E. Mereghetti 2307.13076

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Four-fermion interaction



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

One-loop

$$-\frac{1}{f_a^2} C_P \bar{e} \mu \bar{q} i \gamma_5 q$$

Tree

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

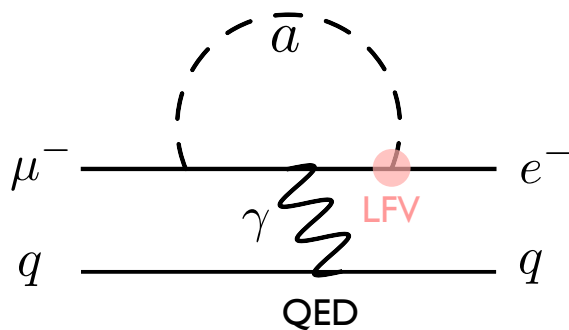
SI vs SD ?

LFV ALP contributions

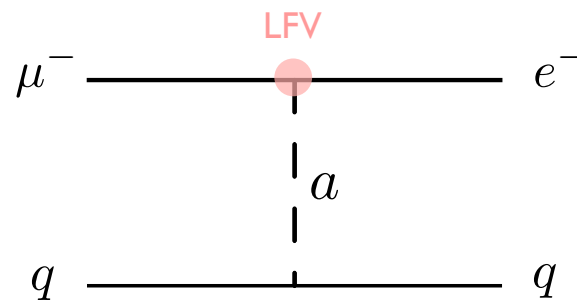
NPB147(1979)277, 1103.62171612.08040, 1612.05492,
1701.07209, 1805.07341, 1909.02029, 2006.04795

$$\mathcal{L}_{\text{ALP}} \supset -im_\mu \frac{a}{f_a} \bar{e}(v_{e\mu} + a_{e\mu}\gamma_5)\mu - m_\mu \frac{a}{f_a} \bar{\mu}i\gamma_5\mu - m_q \frac{a}{f_a} \bar{q}i\gamma_5q$$

Photon dipole (purely leptonic)



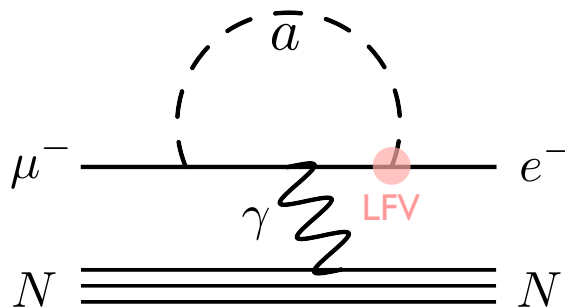
Four-fermion interaction



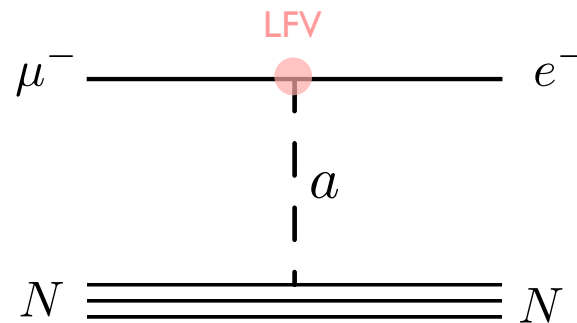
LFV ALP contributions

$$\mathcal{L}_{\text{ALP}} \supset -im_\mu \frac{a}{f_a} \bar{e}(v_{e\mu} + a_{e\mu}\gamma_5)\mu - m_\mu \frac{a}{f_a} \bar{\mu}i\gamma_5\mu - m_q \frac{a}{f_a} \bar{q}i\gamma_5q$$

Photon dipole



Four-fermion interaction

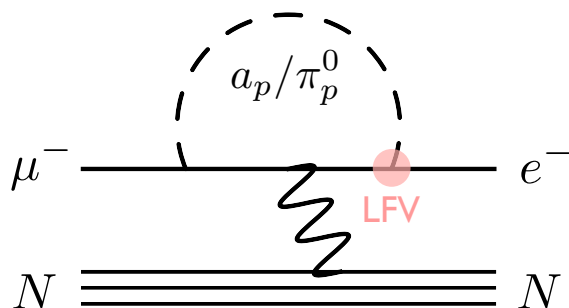


Need nucleon-level interactions : SU(2) Chiral PT with ALPs

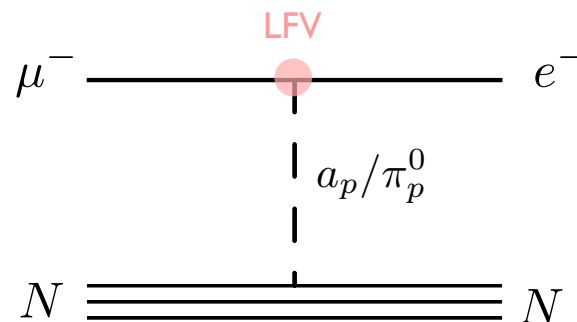
LFV ALP contributions

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

Photon dipole



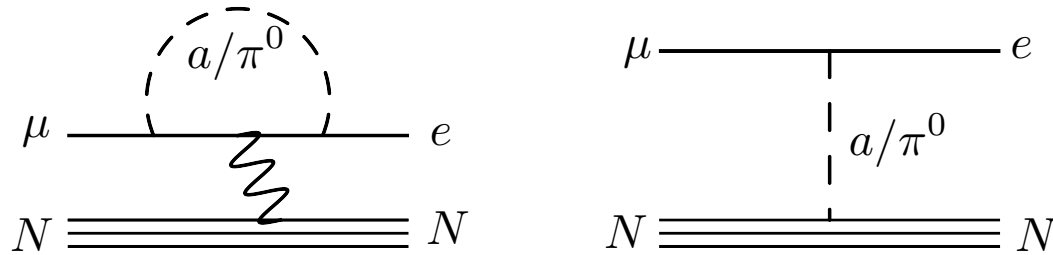
Four-fermion interaction



$$\mathcal{L}_{\chi\text{PT}} \supset -g_A \frac{m_N}{f_\pi} (c_\alpha \pi_p^0 - s_\alpha a_p) \bar{N} i\gamma_5 \tau^3 N \quad \left| \quad \begin{array}{l} g_A = 1.27 \\ f_\pi = 92.2 \text{ MeV} \end{array} \right.$$

$$\begin{pmatrix} a \\ \pi^0 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} a_p \\ \pi_p^0 \end{pmatrix} \quad \left| \quad c_\alpha \approx 1 \quad s_\alpha \approx \frac{f_\pi}{f_a} \frac{m_{\pi^0}^2}{m_{\pi^0}^2 - m_a^2} \right.$$

LFV ALP contributions



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

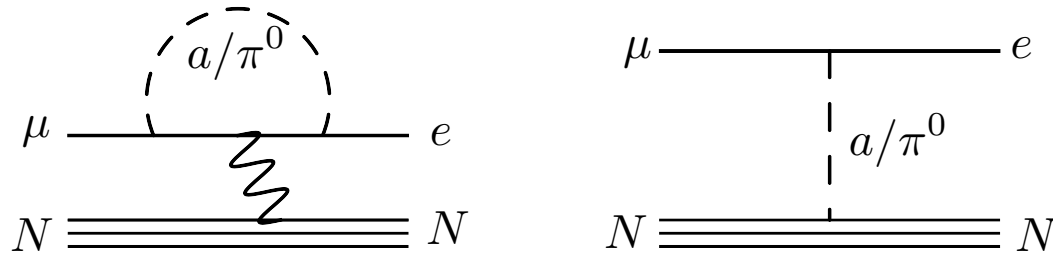
Couplings of nucleon interactions

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

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

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

LFV ALP contributions



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

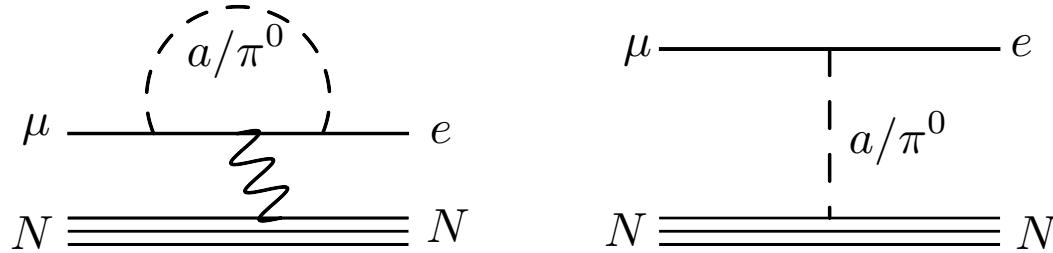
Nuclear response functions

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

Mu2e
COMET

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

LFV ALP contributions



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

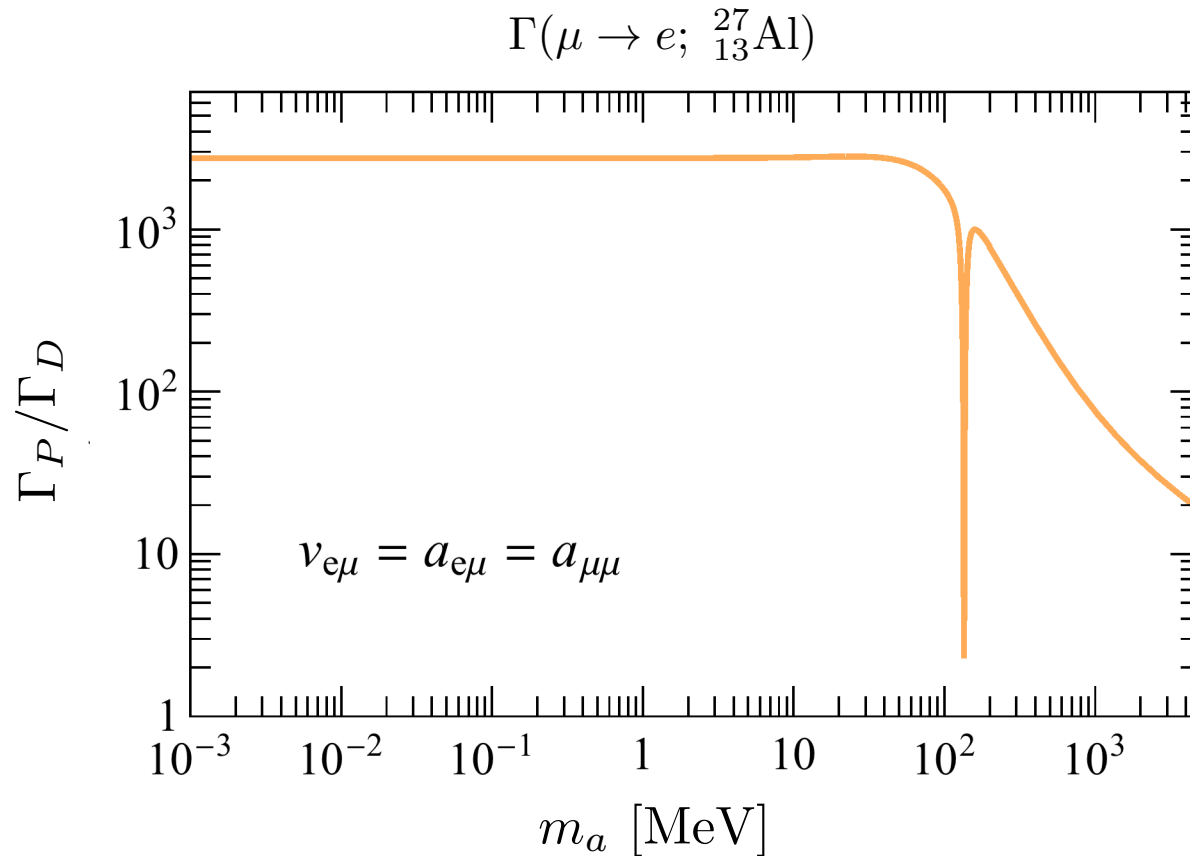
Nuclear response functions

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

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

Conversion Rate

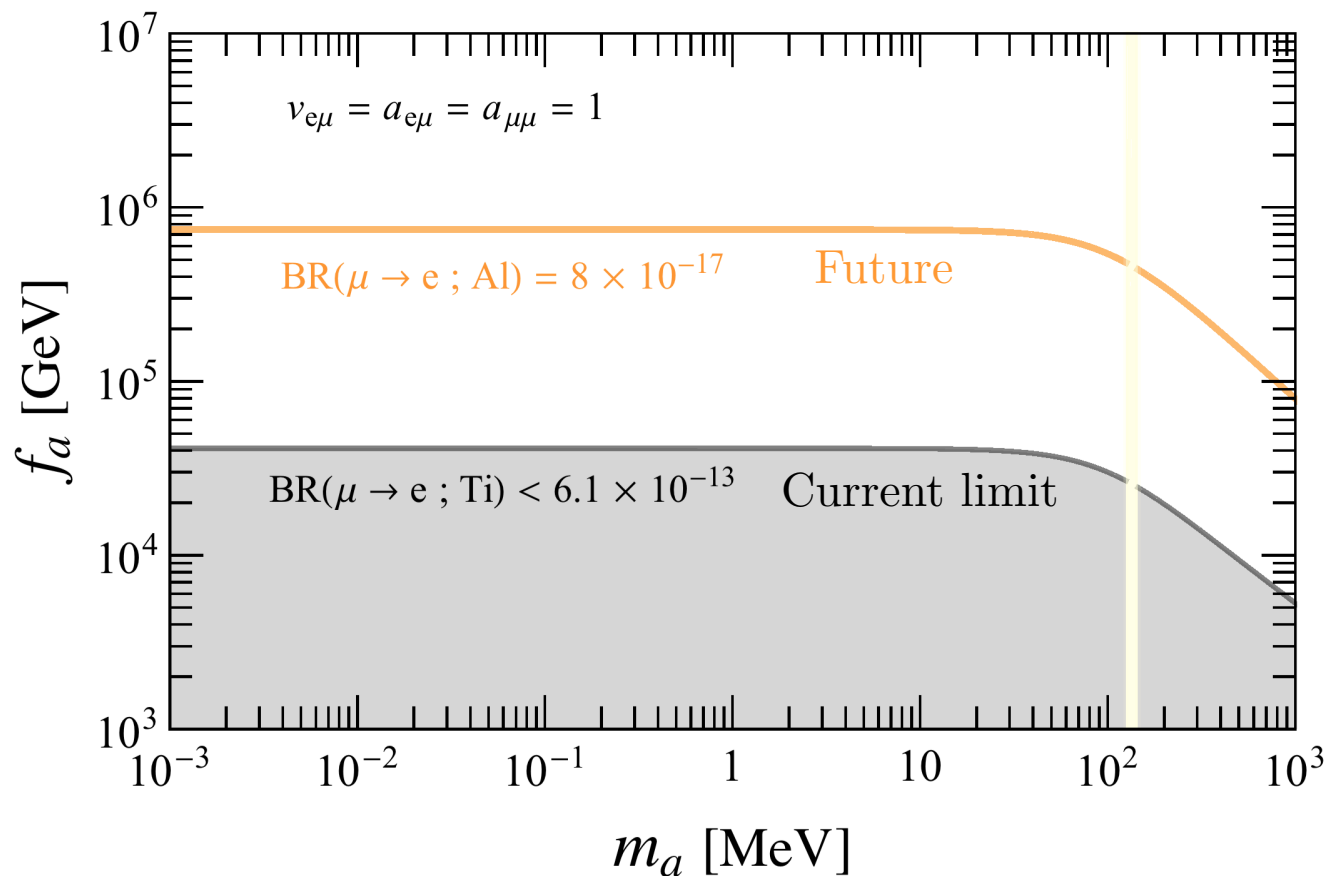
KF, E. Mereghetti 2307.13076



The conversion process is dominated by pseudo-scalar interaction.

Limit on ALP decay constant

KF, E. Mereghetti 2307.13076

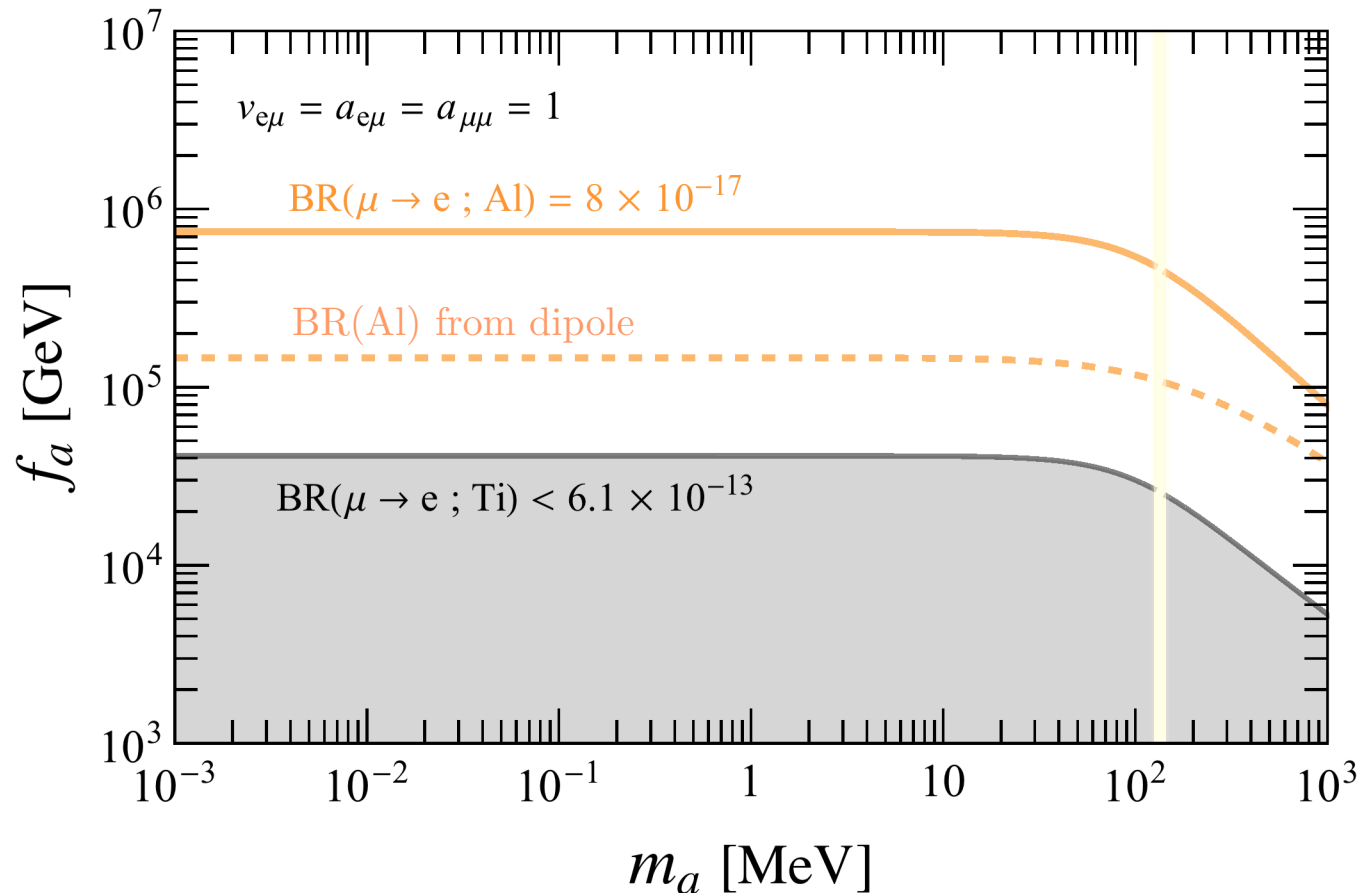


Current : $f_a > O(1 - 10) \text{ TeV}$

Future : $f_a > O(100) \text{ TeV}$

Limit on ALP decay constant

KF, E. Mereghetti 2307.13076

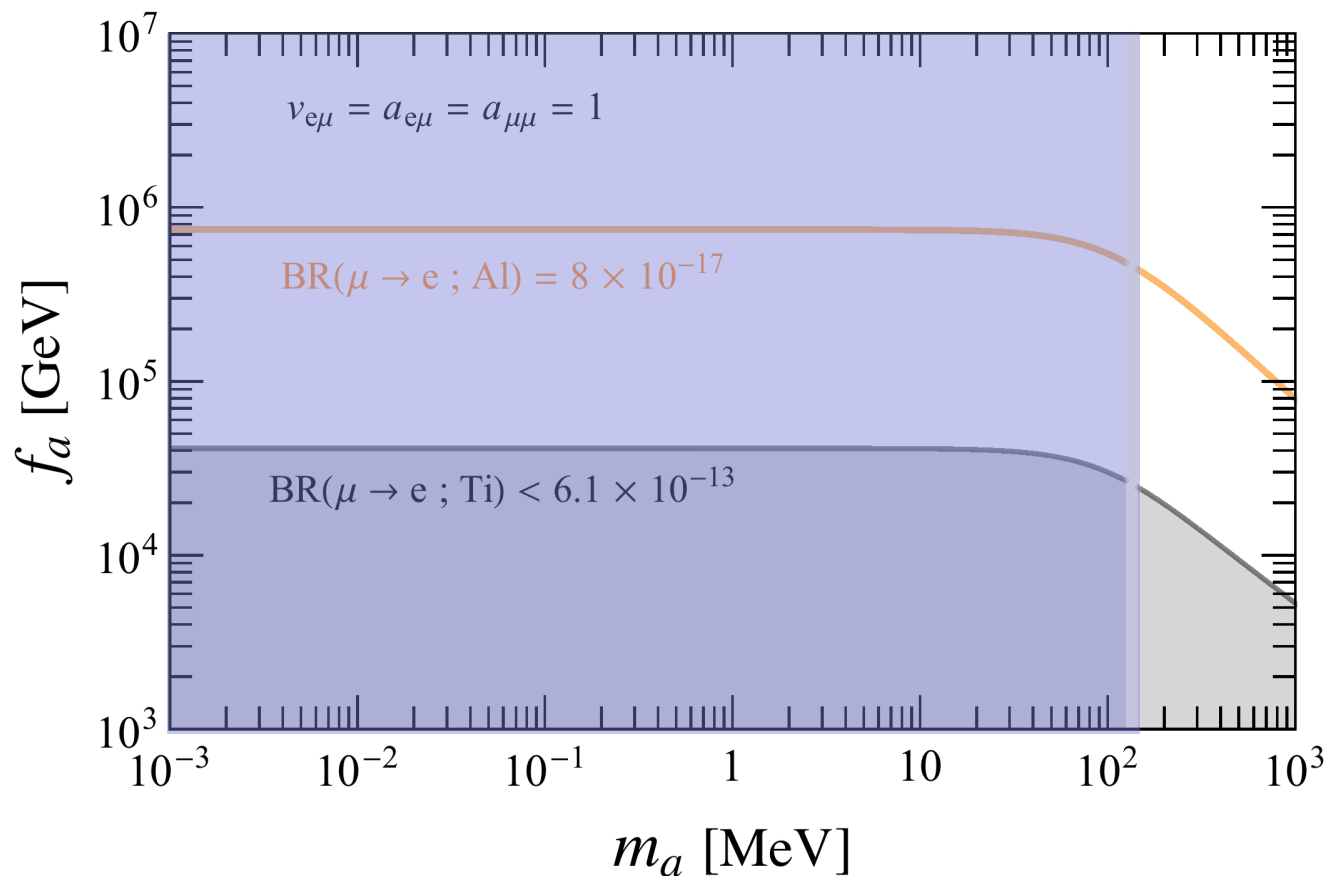


Current : $f_a > O(1 - 10) \text{ TeV}$

Future : $f_a > O(100) \text{ TeV}$

Limit on ALP decay constant

KF, E. Mereghetti 2307.13076



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

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

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

A. Jodidio et al, PRD34(1986)1967

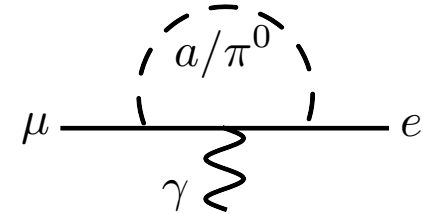
L. Calibbi, D. Redigolo, R. Ziegler, J. Zupan, JHEP09(2021)173

Other constraints

KF, E. Mereghetti 2307.13076

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

MEG II Collaboration, 2310.12614

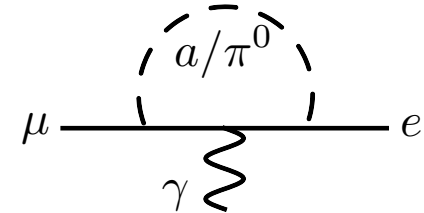


Other constraints

KF, E. Mereghetti 2307.13076

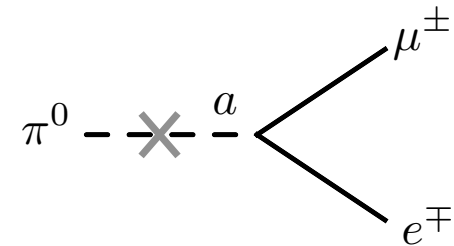
- Mu to E gamma $\text{BR}(\mu^+ \rightarrow e^+ \gamma) < 3.1 \times 10^{-13}$

MEG II Collaboration, 2310.12614



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

KTeV Collaboration, PRL100(2008)131803



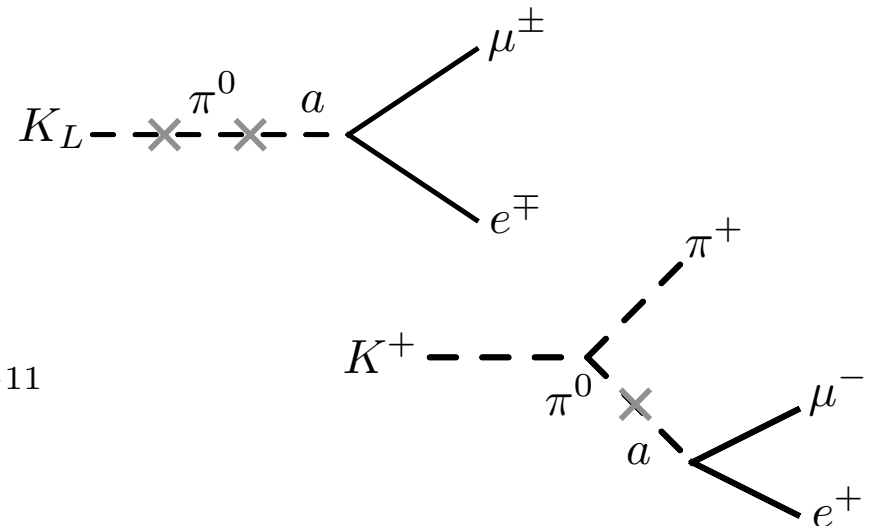
- LFV Kaon decays

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

BNL Collaboration, PRL81(1998)573

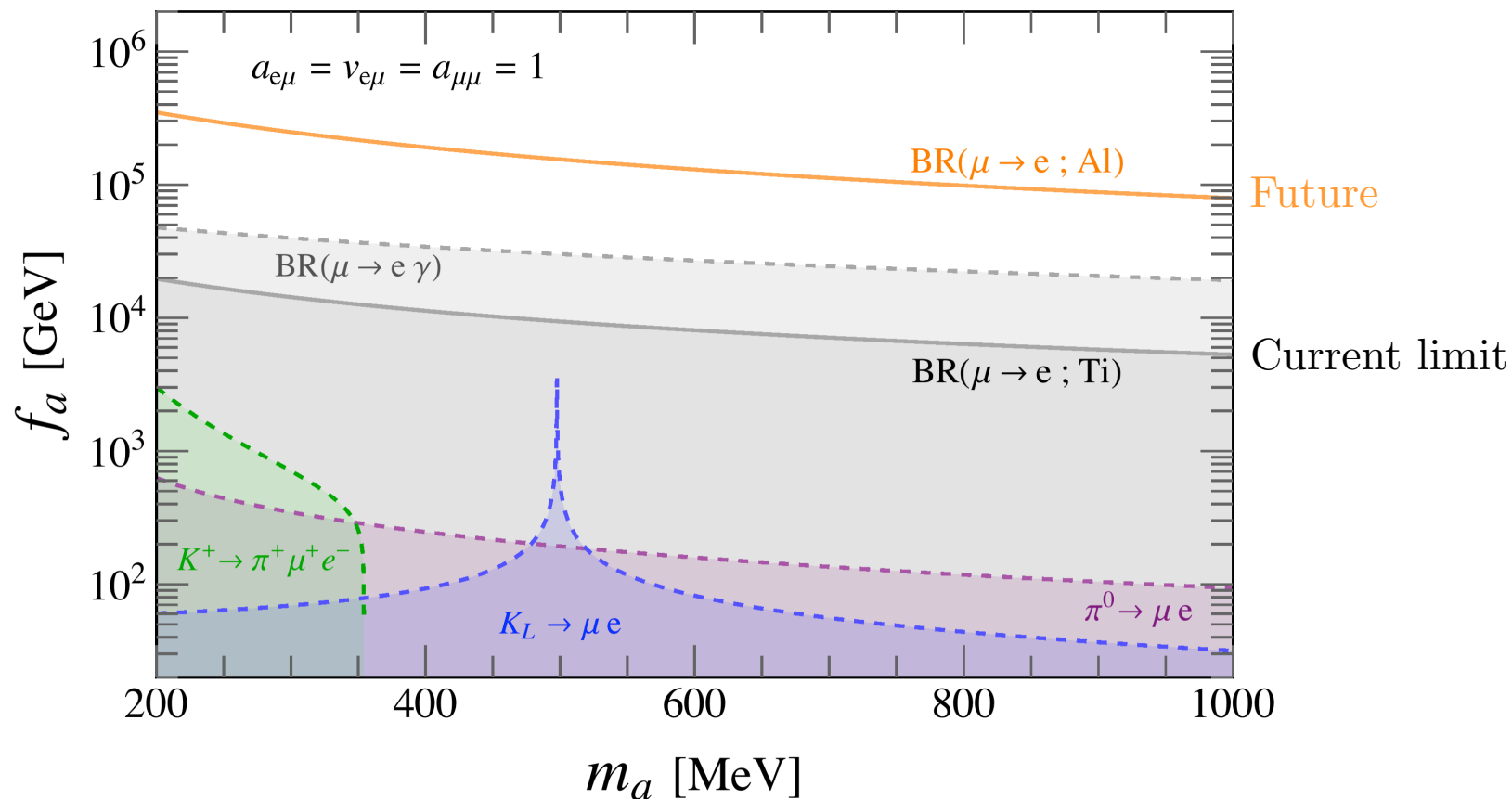
$$\text{BR}(K^+ \rightarrow \pi^+ \mu^+ e^-) < 1.3 \times 10^{-11}$$

PRD72(2005)012005



Limit on ALP decay constant

KF, E. Mereghetti 2307.13076



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

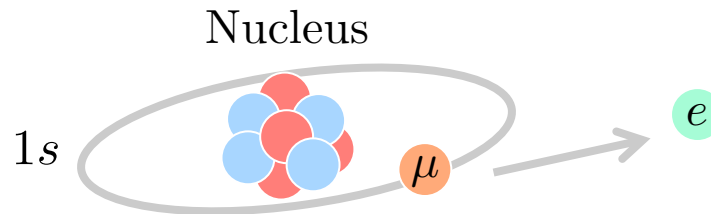
✓ The future mu2e conversion searches have the great potential to probe LFV ALP scenarios!

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.
- $f_a > \mathcal{O}(100)$ TeV can be achieved, complementary role.

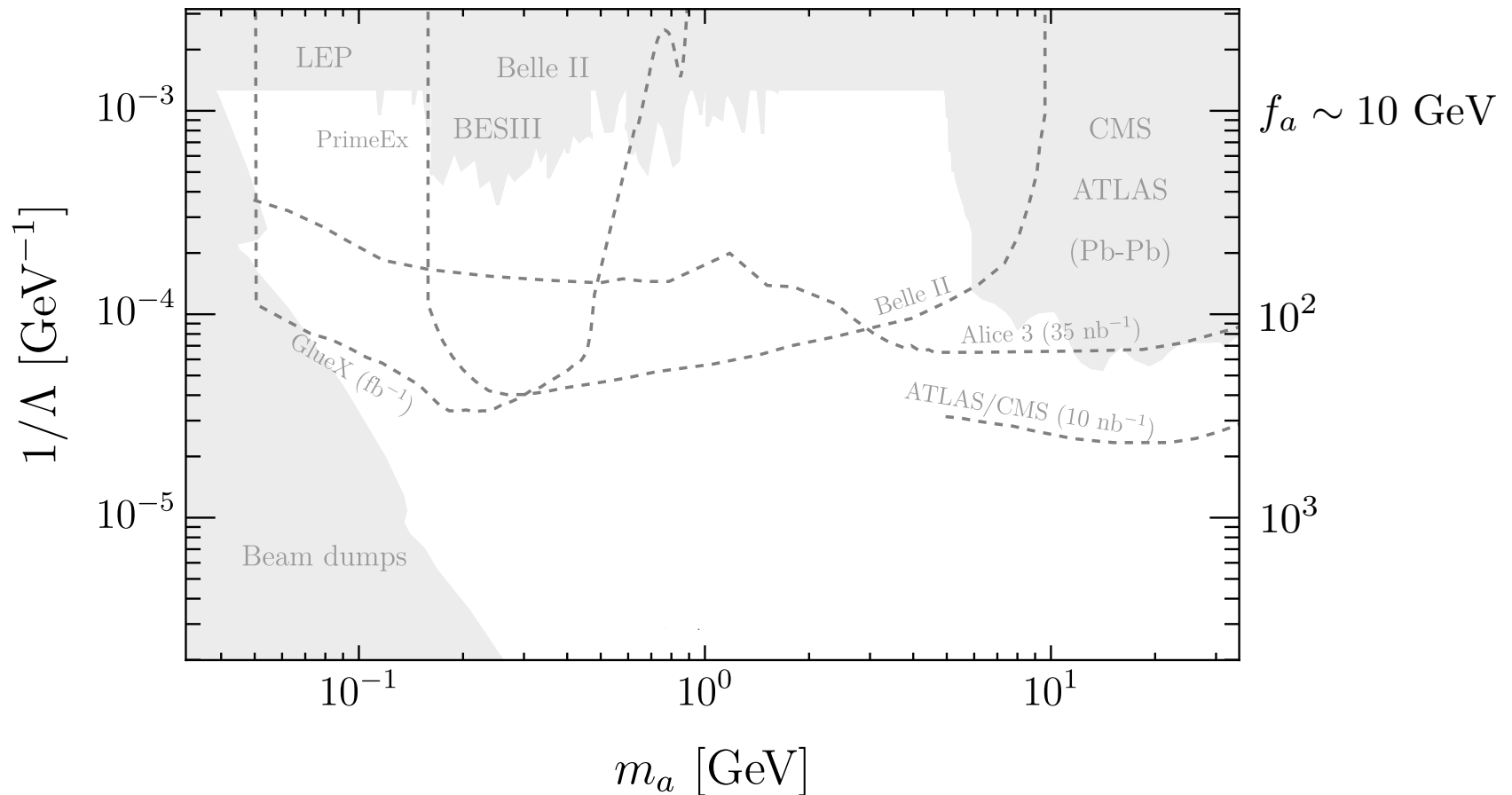
Discussion/Outlook : Other ALP couplings and Extension to SU(3) Chiral PT

Backup slides

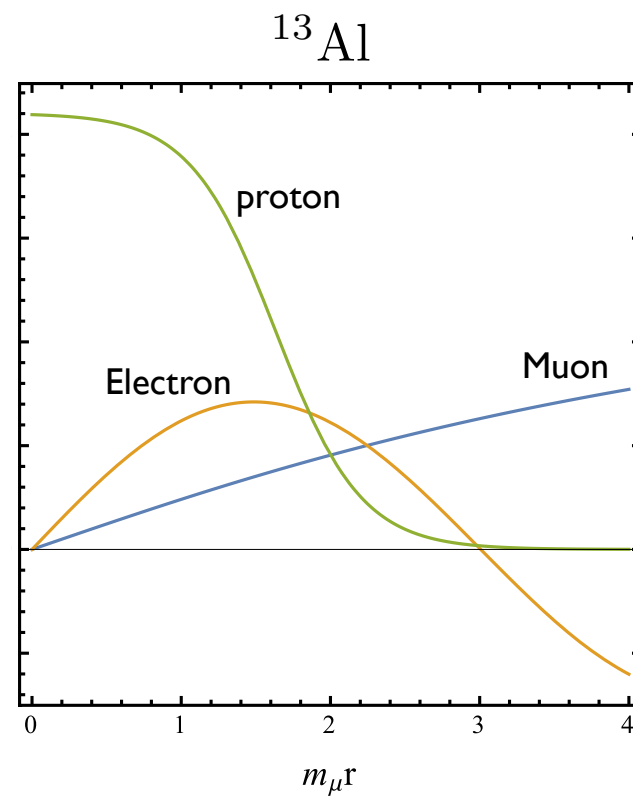
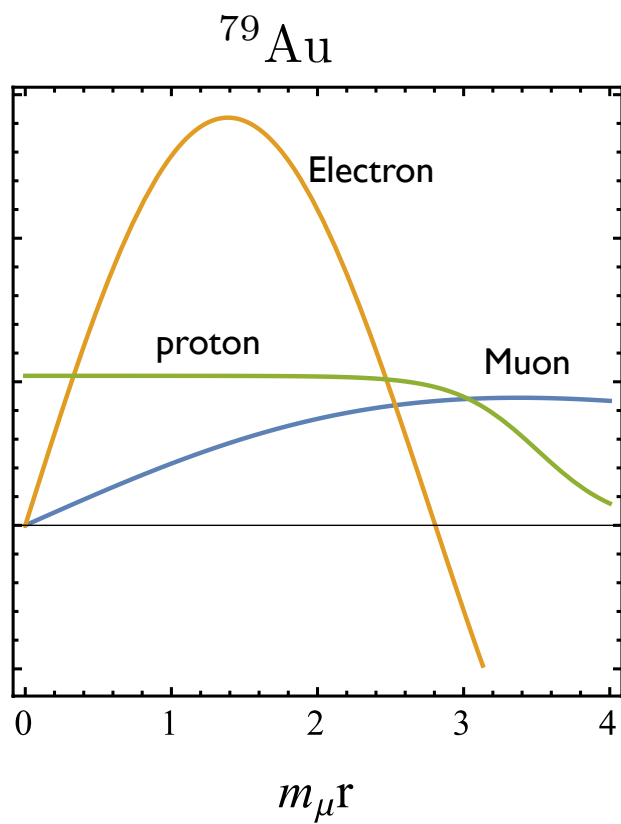
Photon coupling

R. Balkin, et al, 2310.08827

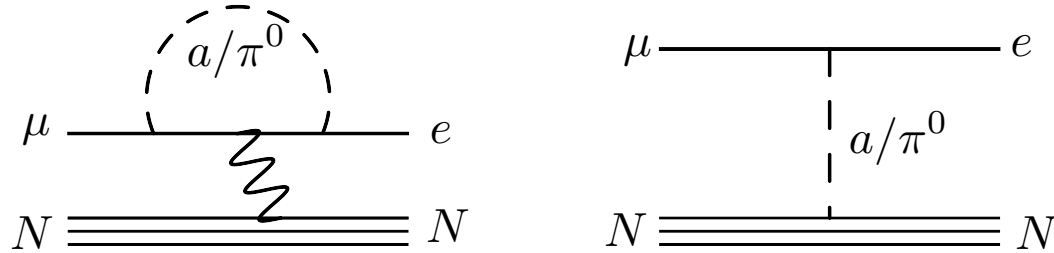
$$\mathcal{L} \supset -\frac{a}{4\Lambda} F \tilde{F}$$



Lepton wave functions



LFV ALP contributions



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

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

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

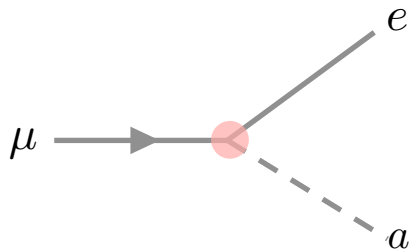
For $m_a \ll m_\mu$, $C_D \simeq -\frac{\alpha_{\text{em}}}{8\pi} (a_{e\mu} \pm v_{e\mu}) a_{\mu\mu}$
 $C_P \simeq g_A a_{e\mu}$

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

Limit on ALP decay constant

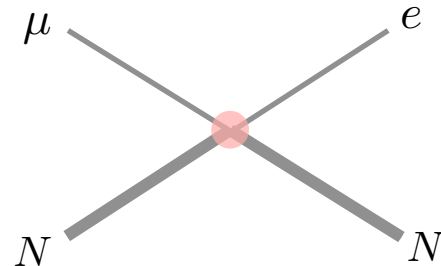
KF, E. Mereghetti 2307.13076

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



$$\text{BR}(\mu \rightarrow ea) \sim \frac{m_\mu^3}{\Gamma} \frac{1}{f_a^2} \lesssim \mathcal{O}(10^{-6})$$

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



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

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

10^{-9}

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

*Focus on $m_a > m_\mu$.