Probing $\mu e\gamma\gamma$ contact interaction with $\mu \to e$ conversion

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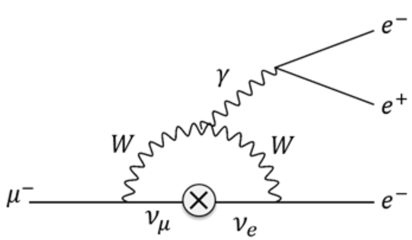
S. Davidson, Y. Kuno, Y. Uesaka, M.Y., PRD102 (2020)

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

Lepton Flavor Violation (LFV):
Clear evidence of new physics scenarios

One of the most promising LFV process:
$\mu \rightarrow e$ conversion in nuclei

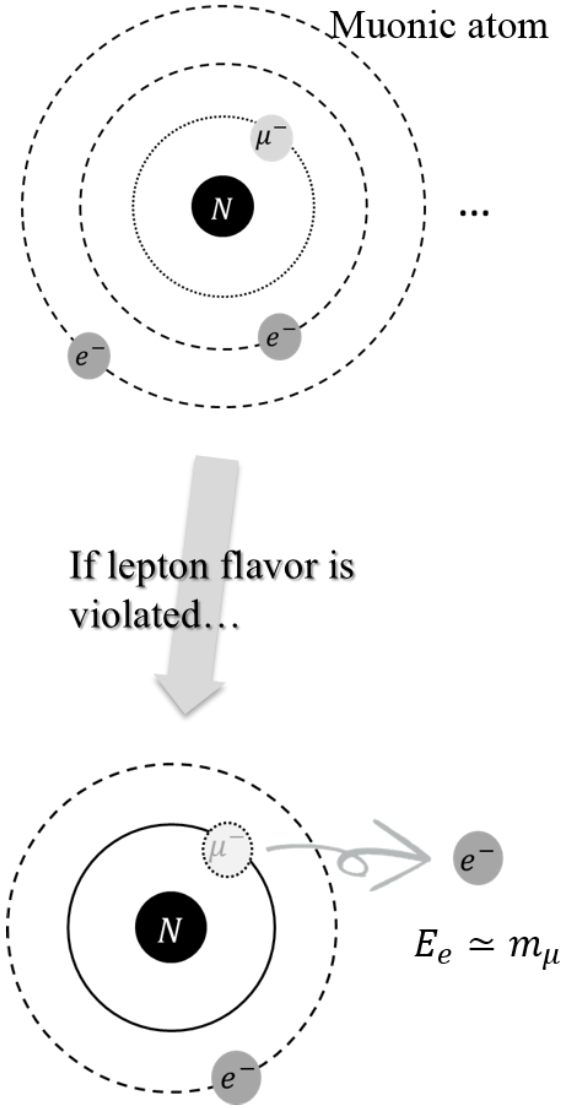
- ☐ Clean signal
- ☐ Versatile and sensitive probe
- ☐ Synergy with LHC/DIS experiments



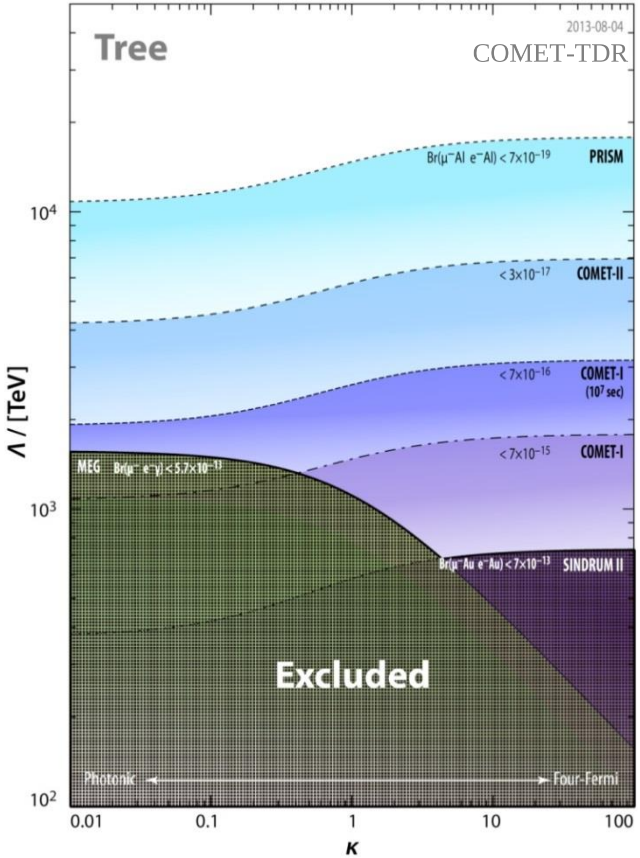
$\mathrm{BR} \simeq 7.4 \times 10^{-55}$

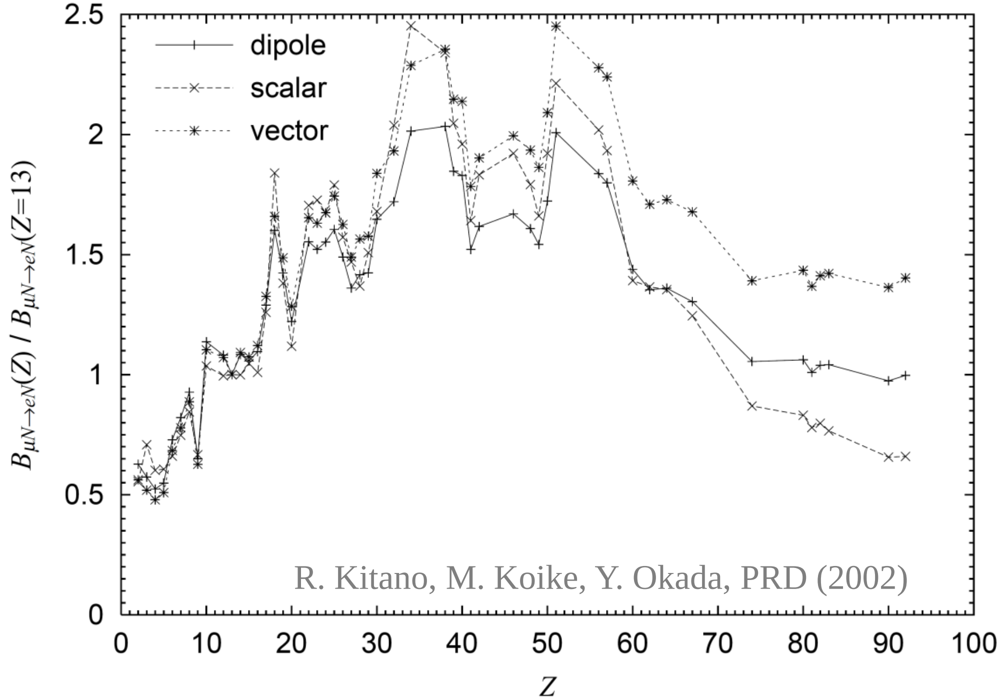
Too small to access experimentally

S. Petcov, Sov. J. Nucl. Phys. (1977)
G. Hernandez-Tome, et al, EPJC (2019)

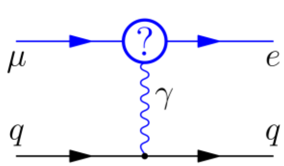


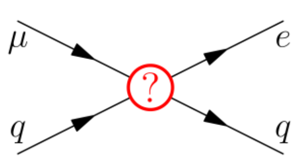
Versatile and sensitive prove to LFV operators





$$\mathcal{L} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_{\mathrm{R}}\sigma^{\mu\nu}e_{\mathrm{L}}F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}\left(\bar{\mu}_{\mathrm{L}}\gamma^{\mu}e_{\mathrm{L}}\right)\left(\bar{q}_{\mathrm{L}}\gamma_{\mu}q_{\mathrm{L}}\right)$$





It is not only a discovery channel, also has the potential to identify the types of LFV operator

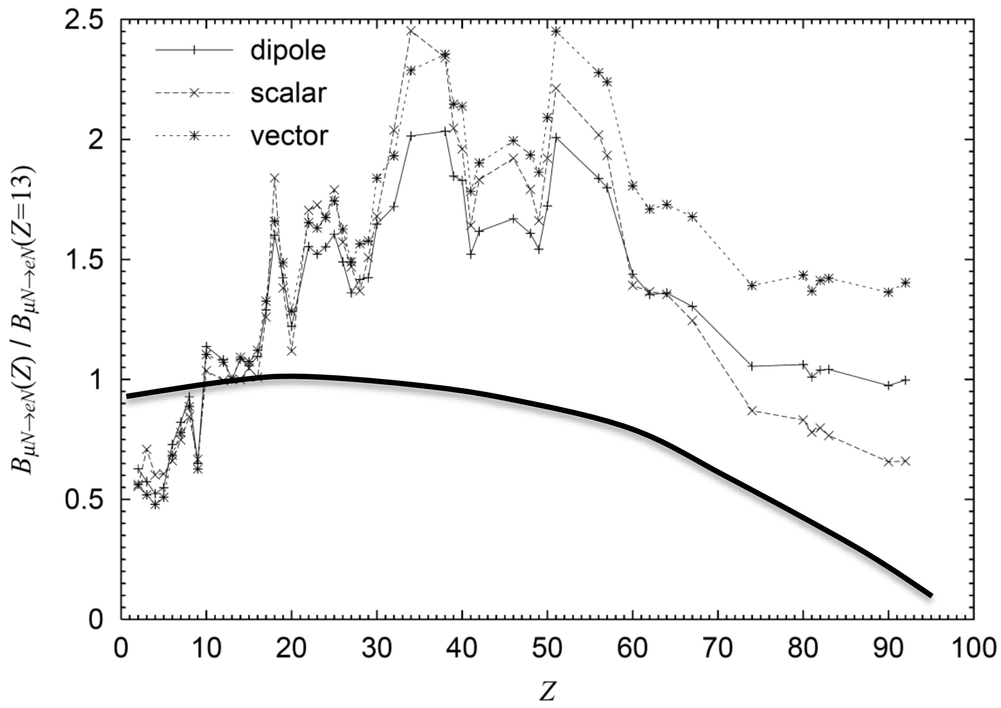
Unknown *Z* dependence

COMET/DeeMe/Mu2e experiments will search for $\mu \to e$ convesion **<u>with different targets</u>**

If : unknown Z dependence is observed

How to interpret the results?

Erroneous measurement?
Miscalculation??
or something???



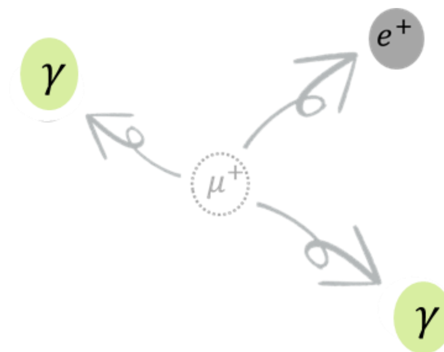
Complete all of types of LFV ope. to evade such confusion

LFV operator $\bar{e}\mu FF$

An LFV operator from new physics scenarios

L. Calibbi, D. Redigolo, R. Ziegler, J. Zupan, 2006.04795,
J. Heeck and H. H. Patel, PRD100 (2019), etc.

$$\mathcal{L} = \frac{1}{v^3}\left(C_{FF,L}\bar{e}P_L\mu F_{\alpha\beta}F^{\alpha\beta} + C_{FF,R}\bar{e}P_R\mu F_{\alpha\beta}F^{\alpha\beta}\right)$$
$$\propto C_{FF,L}\,\bar{e}P_L\mu\gamma\gamma + C_{FF,R}\,\bar{e}P_R\mu\gamma\gamma$$



LFV process : $\mu \to e\gamma\gamma$

Experimental bound

$$\mathrm{BR}(\mu \to e\gamma\gamma) \leq 7.2 \times 10^{-11}$$

Crystal Box Experiment, PRD38 (1988)

Bound on couplings

$$|C_{FF,L}|^2 + |C_{FF,R}|^2 \leq 2.2 \times 10^{-2}$$

J.D.Bowman, T.P.Cheng, L.F.Li, H.S.Matis, PRL41 (1978)

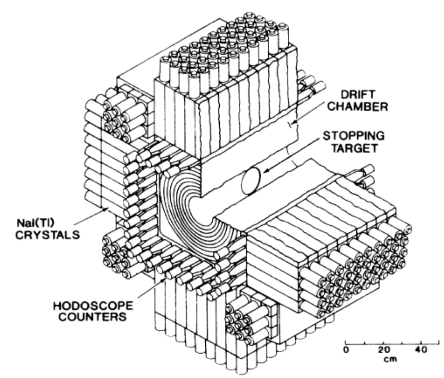


FIG. 2. A schematic cutaway diagram of the Crystal Box detector.

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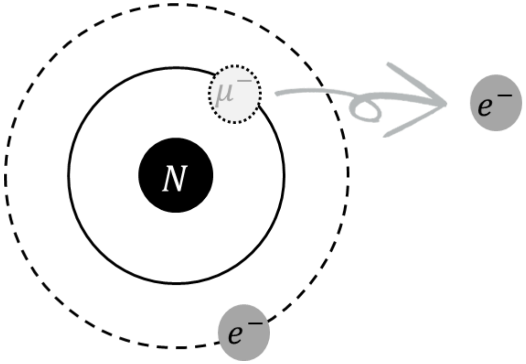

LFV process : $\mu \rightarrow e$ conversion

Experimental bound

$\mathrm{BR}(\mu \rightarrow e \text{ conv.}) \leq 7 \times 10^{-13}$

SINDRUM-II, EPJC47 (2006)

Bound on couplings

$|C_{FF,L}|^2 + |C_{FF,R}|^2 \leq ???$

LFV operator $\bar{e}\mu FF$

An LFV operator from new physics scenarios

L. Calibbi, D. Redigolo, R. Ziegler, J. Zupan, 2006.04795,
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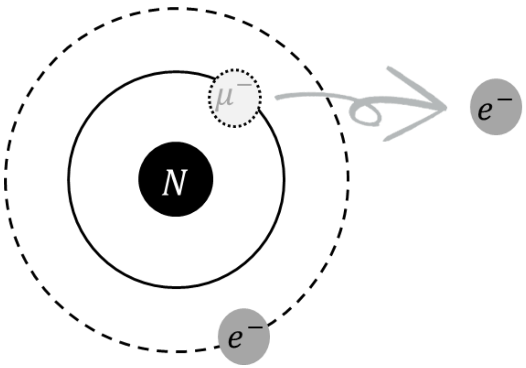
$$\propto C_{FF,L}\,\bar{e}P_L\mu\gamma\gamma + C_{FF,R}\,\bar{e}P_R\mu\gamma\gamma$$

LFV process : $\mu \to e$ conversion



Experimental bound

$\mathrm{BR}(\mu \to e\ \mathrm{conv.}) \leq 7 \times 10^{-13}$

SINDRUM-II, EPJC47 (2006)

Bound on couplings

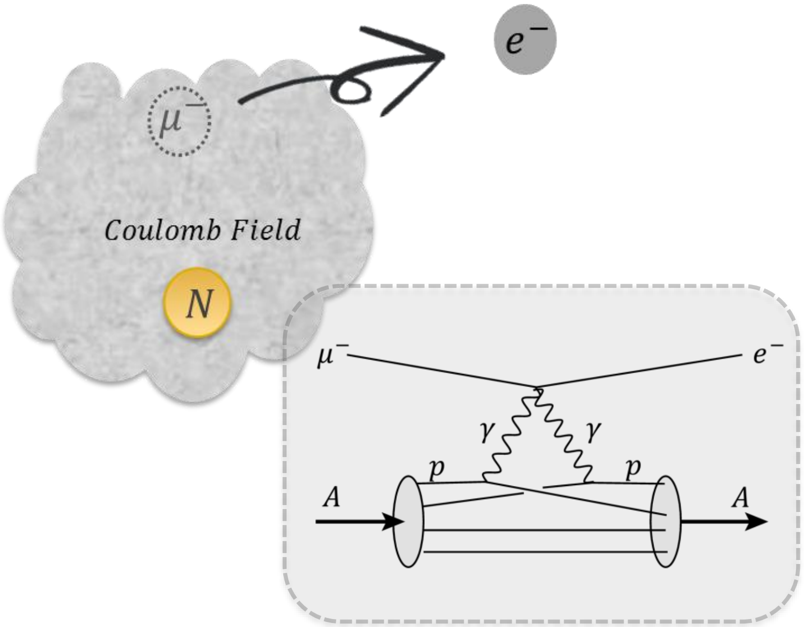
$|C_{\mathrm{FF,L}}|^2 + |C_{\mathrm{FF,R}}|^2 \leq ???$

Aim of this work

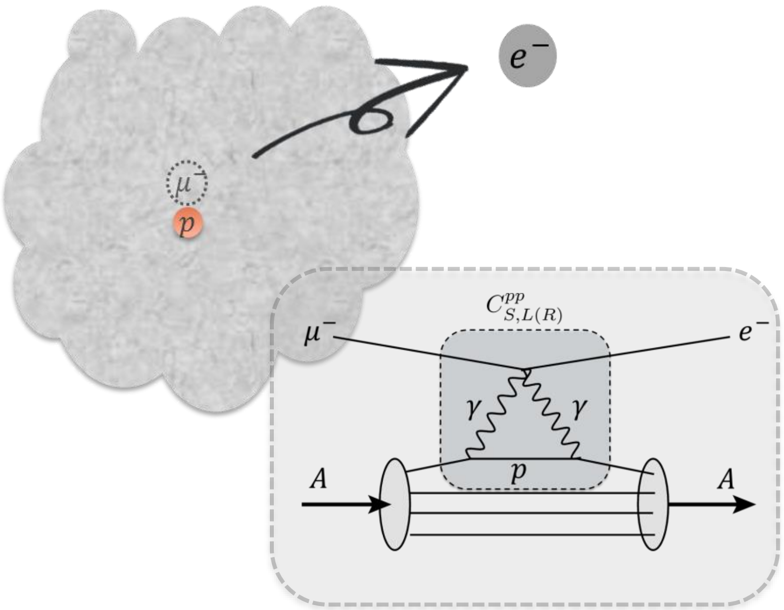
- ☐ How sensitive to $\bar{e}\mu FF$ is $\mu \to e$ conv.?
- ☐ What is target dependence of conv. rate?

Subprocesses of $\mu \to e$ conversion via $\bar{e}\mu FF$

Conversion in the classical electric field
@ momentum transfer $\sim m_\mu$



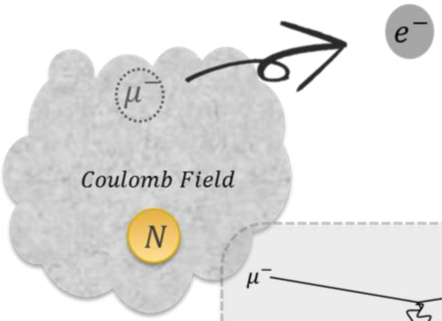
Conversion via the effective scalar ope.
@ momentum transfer $\gtrsim m_p$

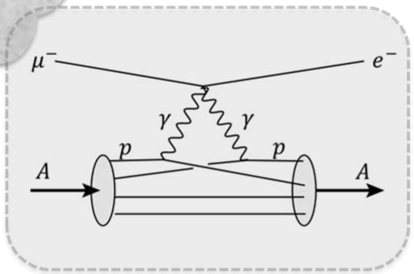


Rate ∝ (overlap of $\mu, e,$ and E^2) ∝ Z^2

Rate ∝ (overlap of $\mu, e,$ and p) ∝ Z

$\mu \to e$ conversion in the classical electric field





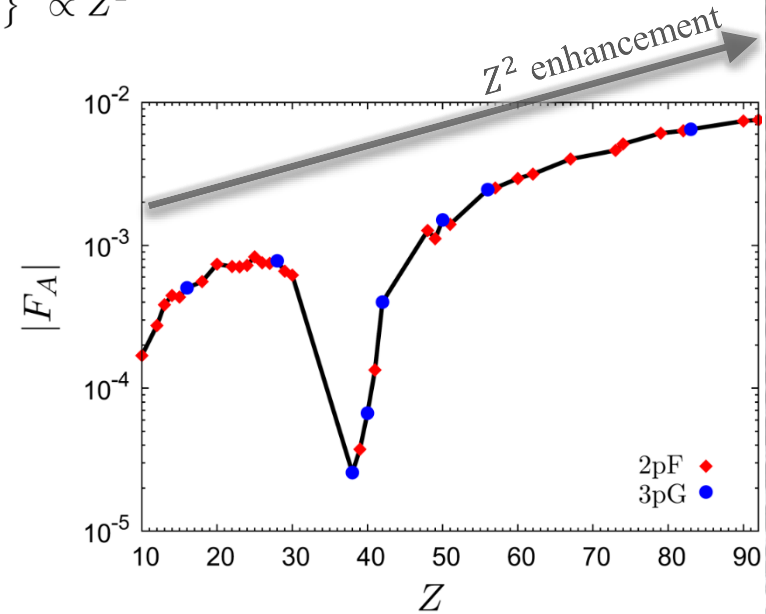
LFV operator

$$\mathcal{L} = \frac{1}{v^3}\left(C_{FF,L}\bar{e}P_L\mu F_{\alpha\beta}F^{\alpha\beta} + C_{FF,R}\bar{e}P_R\mu F_{\alpha\beta}F^{\alpha\beta}\right)$$

Amplitude

$$\mathcal{M} = \frac{1}{v^3}\int d^3r\,\bar{\psi}_e\left(C_{FF,L}P_L + C_{FF,R}P_R\right)\psi_\mu^{1s}\,\langle N|F_{\alpha\beta}F^{\alpha\beta}|N\rangle$$

$$\propto -2\{E(r)\}^2 \propto Z^2$$



Conversion probability

$$\Gamma_{\rm conv} = 16G_F^2 m_\mu^5\,|F_A|^2\left(\frac{m_\mu}{v}\right)^2 \times\left(|C_{FF,L}+C_{FF,R}|^2 + |C_{FF,L}-C_{FF,R}|^2\right)$$

Overlap of wave functions
and electric field

$\mu \to e$ conversion in the classical electric field

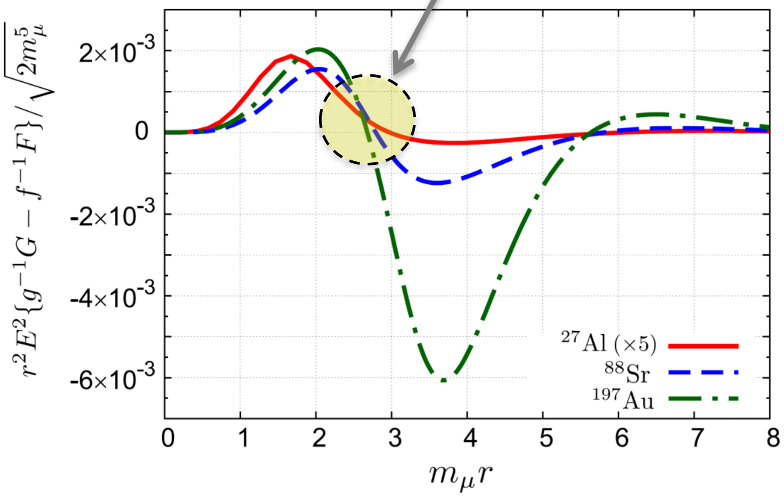
Radial wave func. of μ

Radial wave func. of e

$$F_A = \frac{1}{\sqrt{2m_\mu^7}} \int drr^2 E^2(r) \left[g^{-1}(r)G(r) - f^{-1}(r)F(r) \right]$$

Accidental cancellation between ***E^2*-boosted wave functions inside electron 1st node** and **wave functions outside the 1st node**

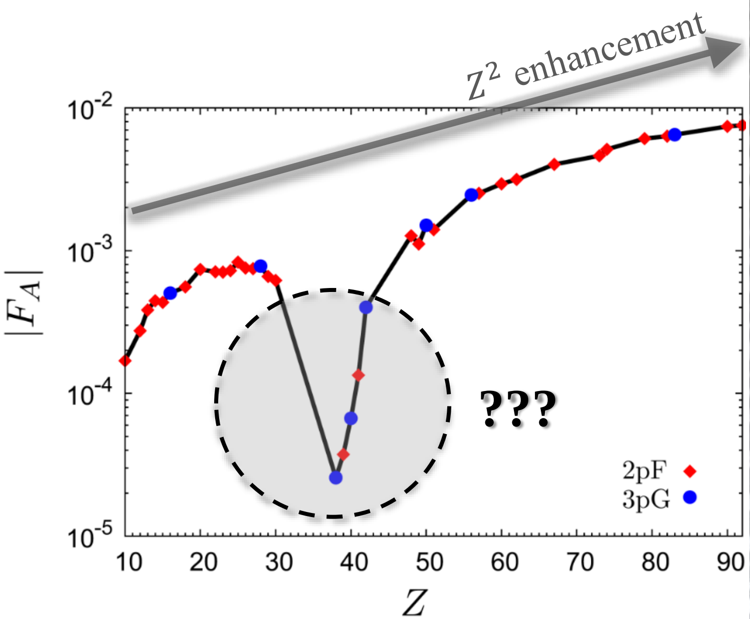
1st node $= \pi/E_e \simeq \pi/m_\mu$



Conversion probability

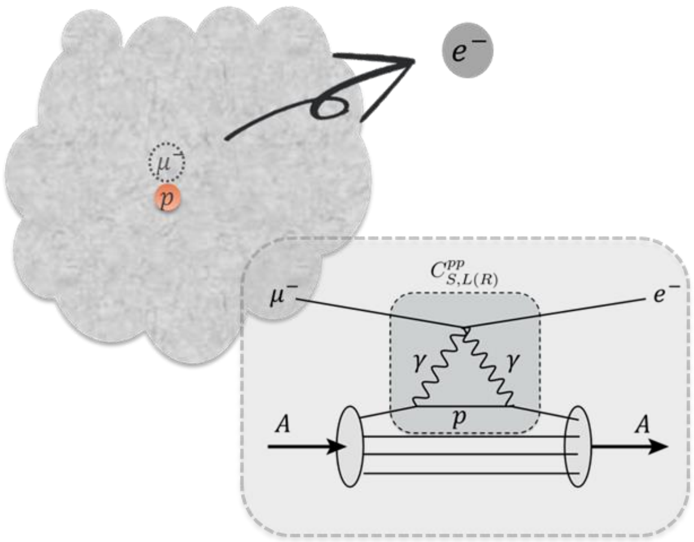
$$\Gamma_{\rm conv} = 16G_F^2 m_\mu^5 \, |F_A|^2 \left(\frac{m_\mu}{v}\right)^2$$
$$\times \left(|C_{FF,L} + C_{FF,R}|^2 + |C_{FF,L} - C_{FF,R}|^2 \right)$$

Overlap of wave functions
and electric field



$\mu \to e$ conversion via the effective scalar operator

Off-shell photon@momentum transfer $\gtrsim m_p$



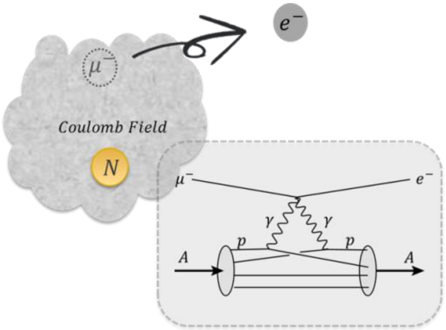
Effective scalar operator

$$\mathcal{O}^{pp}_{S,L(R)} = C_{S,L(R)}\big(\bar{e}P_{L(R)}\mu\big)\big(\bar{\psi}_p P_{L(R)}\psi_p\big)$$

Effective coefficient in the RGE of QED

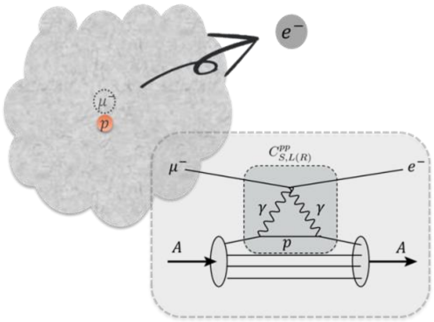
$$\begin{aligned} C^{pp}_{S,L(R)} &= -\frac{6\alpha_{\rm em} m_p}{\pi v}\ln\Big(\frac{2\,\mathrm{GeV}}{m_\mu}\Big) C_{FF,L(R)} \\ &= -2.26\times 10^{-4} C_{FF,L(R)} \end{aligned}$$

Total branching ratio for $\bar{e}\mu FF$ operator



BR for the $\bar{e}\mu FF$ operator

$$\frac{BR\,(\mu A \to eA)}{|C_{FF,L}|^2 + |C_{FF,R}|^2} = \begin{cases} 6.6 \times 10^{-9}\,|+1 + 15\,|^2 & \text{for } ^{27}\text{Al} \\ 9.1 \times 10^{-8}\,|-1 + 3.8\,|^2 & \text{for } ^{197}\text{Au} \end{cases}$$



(Loop contribution) > (Tree contribution)???

Reason : $\left(\text{overlap with proton } S_A^{(p)}\right)$ > (overlap with electric field F_A)

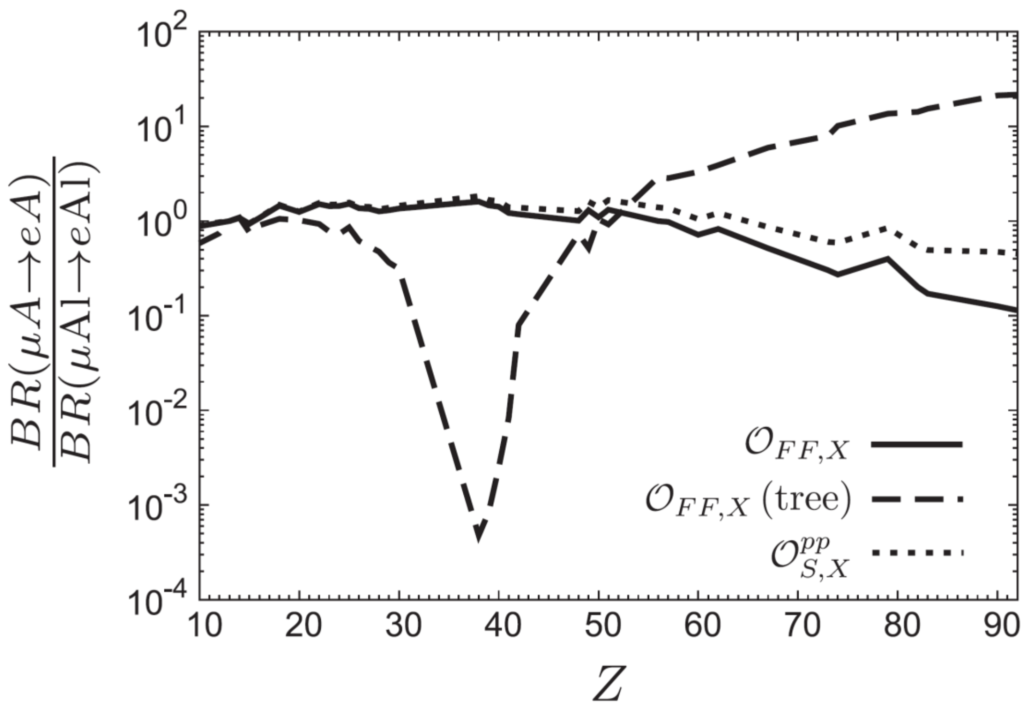
$$\left|\frac{F_A}{S_A^{(p)}}\right| \simeq \frac{2m_\mu^{-1}\left[Ze/(4\pi R^2)\right]^2}{Z\,(4\pi R^3/3)^{-1}} = \frac{2Z\alpha}{3m_\mu R} \simeq \begin{cases} 0.02 & \text{for } ^{27}\text{Al} \\ 0.06 & \text{for } ^{197}\text{Au} \end{cases}$$

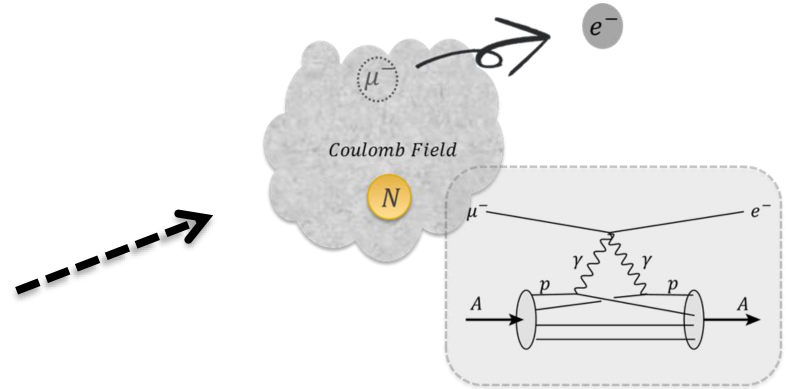
Approximation

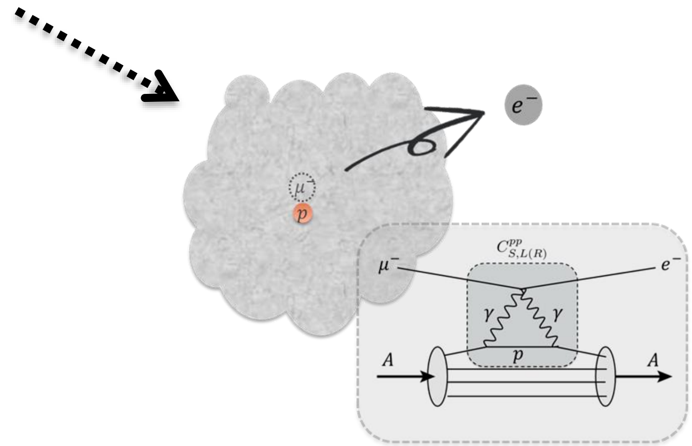
Nuclear electric field $\left|\vec{E}(r)\right| \simeq \dfrac{Ze}{4\pi R^2}$ $\because$ $E(r)$ is maximized at $r \sim R$ (R: nuclear radius)

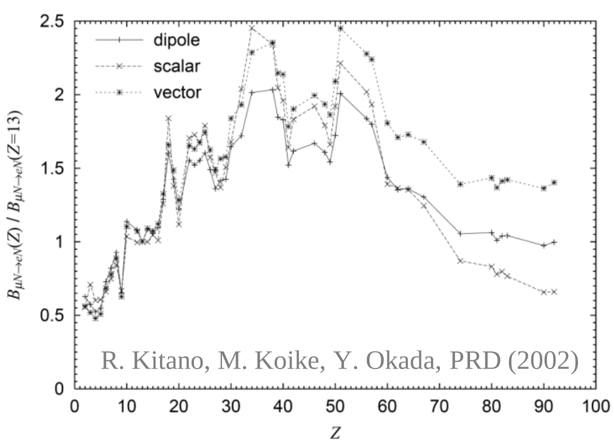
Proton density $\rho \simeq Z\left(\dfrac{4\pi R^3}{3}\right)^{-1}$ $\because$ Assuming a uniform distribution

Target dependence of BR









R. Kitano, M. Koike, Y. Okada, PRD (2002)

- Conversion in the electric field $\propto Z^2$
- Two subprocesses destructively contribute at high-Z
- Different Z dependence from other types of operators

Constraint on the $\bar{e}\mu FF$ interaction

Current constraint on $\bar{e}\mu FF$ coupling

Coefficient	Constraint	Process
$\lvert C_{FF,X} + im_\mu C_{VFF,Y}/(4v)\rvert$	$<2.2 \times 10^{-2}$	$\mathrm{BR}(\mu \to e\gamma\gamma) < 7.2 \times 10^{-11}$
$\lvert C_{F\tilde{F},X} + im_\mu C_{VF\tilde{F},Y}/(4v)\rvert$	$<2.2 \times 10^{-2}$	$\mathrm{BR}(\mu \to e\gamma\gamma) < 7.2 \times 10^{-11}$
$\lvert \ldots + C_{FF,X}\rvert$	$<1.0 \times 10^{-3}$	$\mathrm{BR}(\mu\mathrm{Au} \to e\mathrm{Au}) < 7 \times 10^{-13}$

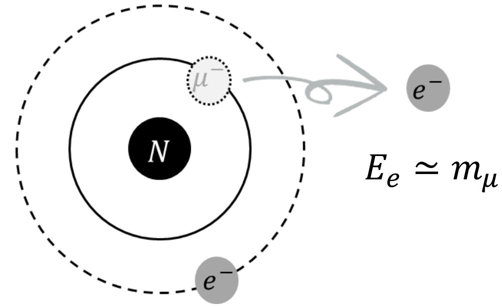
- ***μ → e* conversion set the most stringent constraint!**

- COMET/Mu2e sensitivity

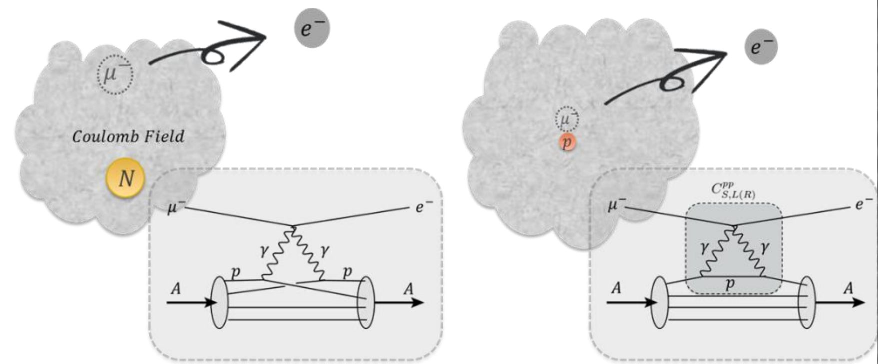
$$C_{FF,L(R)} \leq 7.6 \times 10^{-6} \left(\frac{\mathrm{BR}(\mu\mathrm{Al} \to \mathrm{eAl})}{10^{-16}} \right)^{1/2}$$

- Sensitive to the LFV mediator which dominantly couples with heavy flavors, like Higgs

Summary



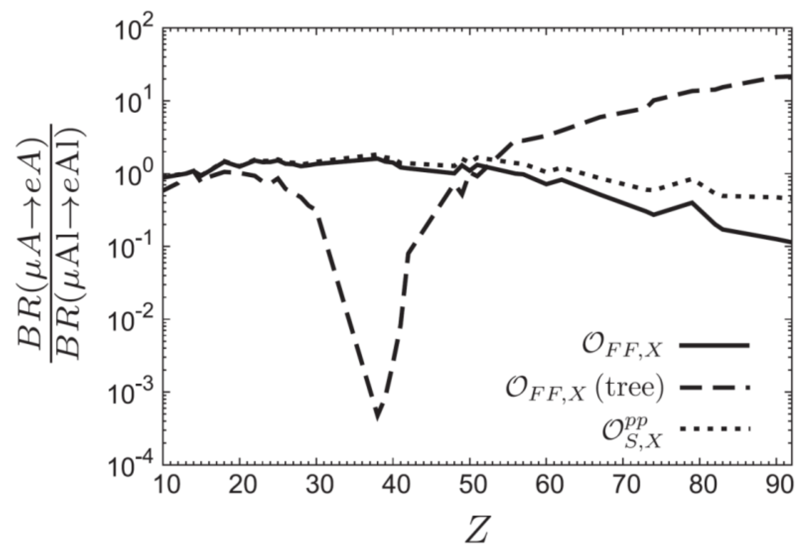
- $\underline{\mu \to e \text{ conversion}}$: Not only a discovery channel, also has the potential to identify the LFV operator



- Complete all of types of LFV ope. to avoid the confusion from unknown Z dependence of $\mu \to e$ conversion rate

- **$\mu \to e$ conversion via $\bar{e}\mu\gamma\gamma$ operator**

- $\mu \to e$ conversion set the most stringent constraint on the $\bar{e}\mu\gamma\gamma$ operator



- Different Z dependence from other types of LFV operators