# *A New Idea for Charged Lepton Flavor Violation Using a Muonic Atom*

**Phys.Rev.Lett.105:121601,2010**

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1. Introduction
2. A new idea for LFV experiment $\mu e \to ee$
   2.1 An idea
   2.2 Rough Estimate
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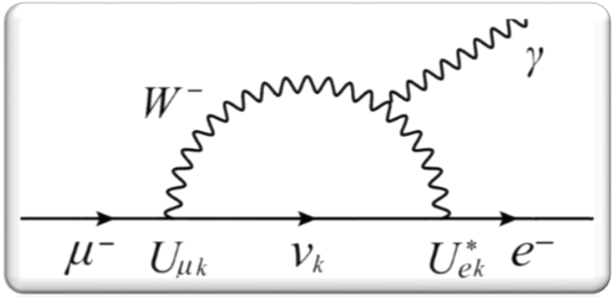
3. Towards a precise estimate
4. Summary

# 1. Lepton Flavor Violation and new Physics

Kuno & Okada, REVIEWS OF MODERN PHYSICS, VOLUME 73, JANUARY 2001
COMET Conceptual Report, KEK Report 2009-10 (2009); http://comet.phys.sci.osaka-u.ac.jp/
Report of Working Group 3 of the CERN Workshop "Flavour in the era of the LHC", arXiV0801.1826

## Standard Model (SM)

Charged Lepton Flavour Violation (LFV) through Lepton Mixing in the neutrino oscillation




But …

$$\mathrm{BR}(\mu \to e\gamma) \sim \left(\frac{\delta m_\nu^2}{m_W^2}\right)^2 < 10^{-54}$$

⇨ Invisible, eternally

Strong suppression of FCNC by GIM

Detection of the LFV signal

⇨ Apparent evidence for beyond the SM

Indeed, in physics beyond SM,

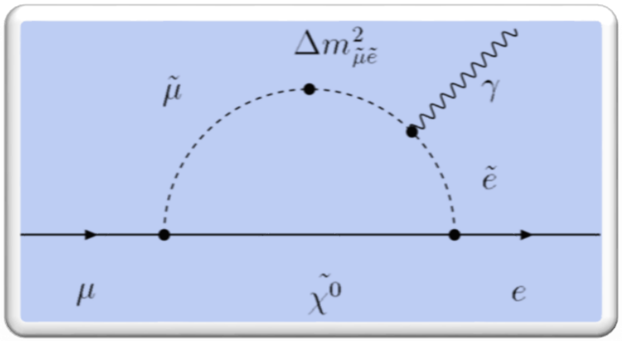
Large FCNC is expected

Particularly Combining with neutrino oscillation
Large FCNC in charged lepton is expected
(must appear ??)

## *e.g.* a supersymmetric model

Enhancement of LFV
through the slepton mixing

⇨ Detectable at future experiments




**Two or more flavors are needed to observe cLFV**

⇨ **Search for LFV with muon is inevitable**

# LFV from muon decay

Upper limit on Br

$$\mu^+ \to e^+\gamma \qquad < \qquad 2.4\times10^{-12}$$

$$\mu^+ \to e^+e^+e^- \qquad < \qquad 1.0\times10^{-12}$$

$$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti} \qquad < \qquad 6.1\times10^{-13}$$

$$\mu^-\mathrm{Au} \to e^-\mathrm{Au} \qquad < \qquad 7\times10^{-13}$$

MEG experiment updates/discovers(?)

$$\mu^+ \to e^+\gamma$$

COMET/Mu2E will discover(?)

$$\mu^+ \to e$$

In near future

# 2. A new idea for LFV experiment μ e -> ee

Phys.Rev.Lett.105:121601,2010,Koike,Kuno,Sato,Yamanaka

New idea for cLFV search

$\mu^- e^- \longrightarrow e^- e^-$ in muonic atom

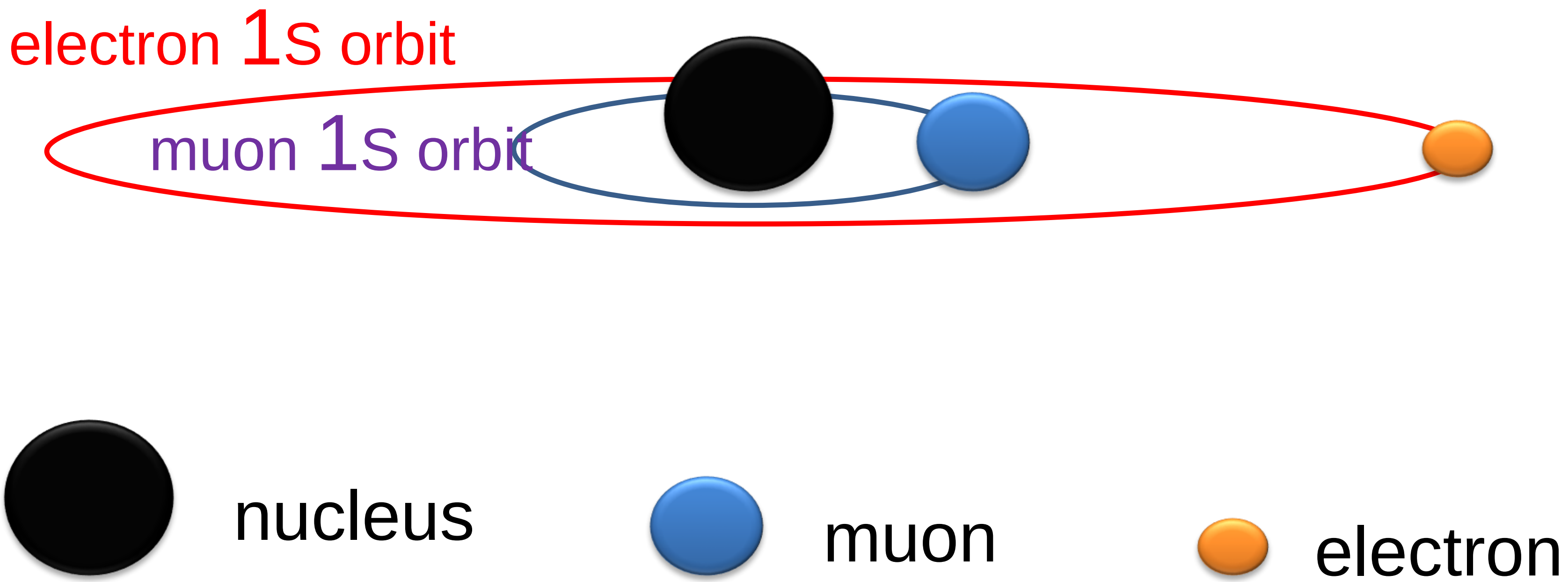
- Why ?
  - After discovery , we need to disentangle effects from several operators to distinguish physics beyond SM

$$
\begin{aligned}
\mathcal{L}_{\mu^- e^- \to e^- e^-} = -\frac{4G_F}{\sqrt{2}} \Big[ & m_\mu A_R\, \overline{\mu_R} \sigma^{\mu\nu} e_L F_{\mu\nu} + m_\mu A_L\, \overline{\mu_L} \sigma^{\mu\nu} e_R F_{\mu\nu} \\
& + g_1 (\overline{\mu_R} e_L)(\overline{e_R} e_L) + g_2 (\overline{\mu_L} e_R)(\overline{e_L} e_R) \\
& + g_3 (\overline{\mu_R} \gamma^\mu e_R)(\overline{e_R} \gamma_\mu e_R) + g_4 (\overline{\mu_L} \gamma^\mu e_L)(\overline{e_L} \gamma_\mu e_L) \\
& + g_5 (\overline{\mu_R} \gamma^\mu e_R)(\overline{e_L} \gamma_\mu e_L) + g_6 (\overline{\mu_L} \gamma^\mu e_L)(\overline{e_R} \gamma_\mu e_R) + (\mathrm{H.c.}) \Big]
\end{aligned}
$$

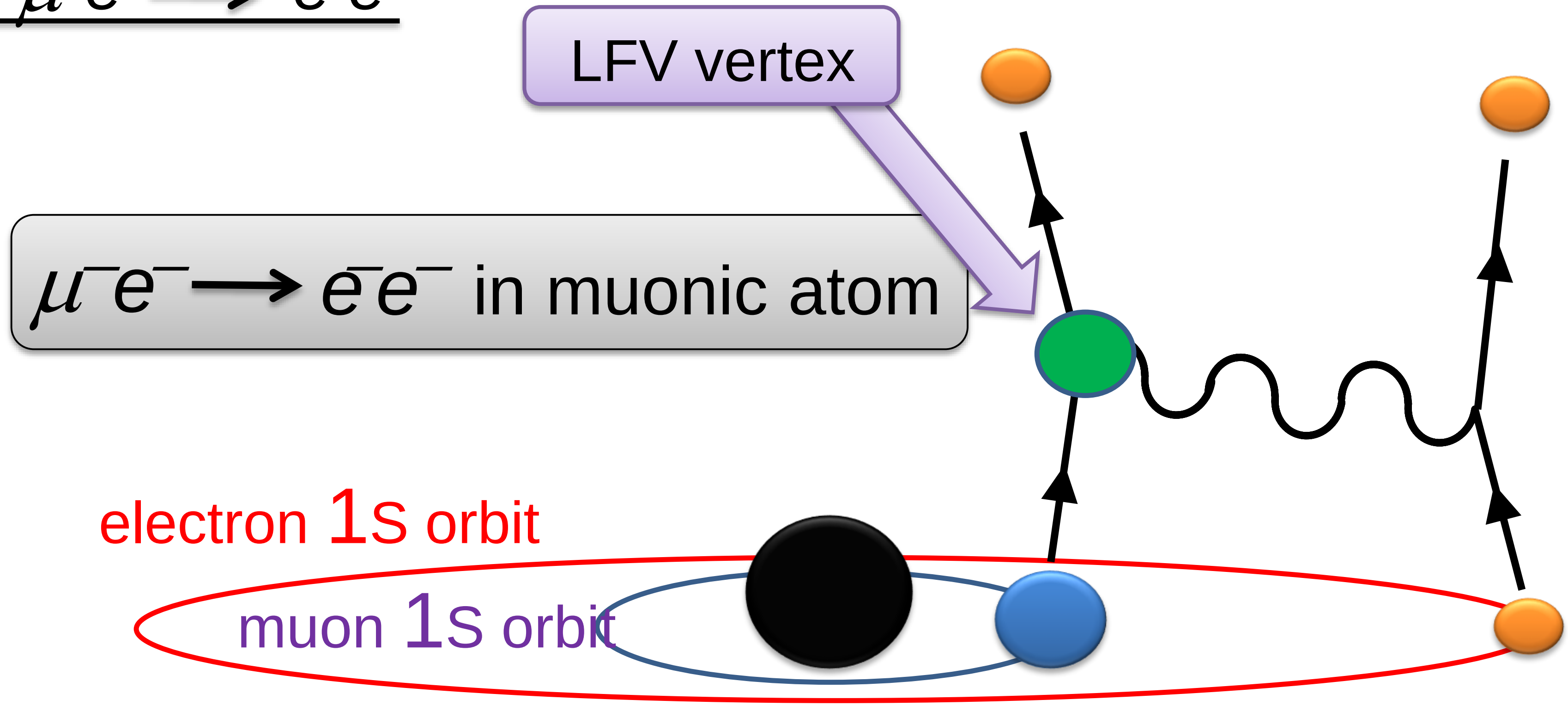
Effective interaction for μ→eγ, μ→3e,μe→ee. μe conversion, ee replaced by qq

# 2.1 An idea

Muonic atom



## $\mu\, e \longrightarrow e\, e$

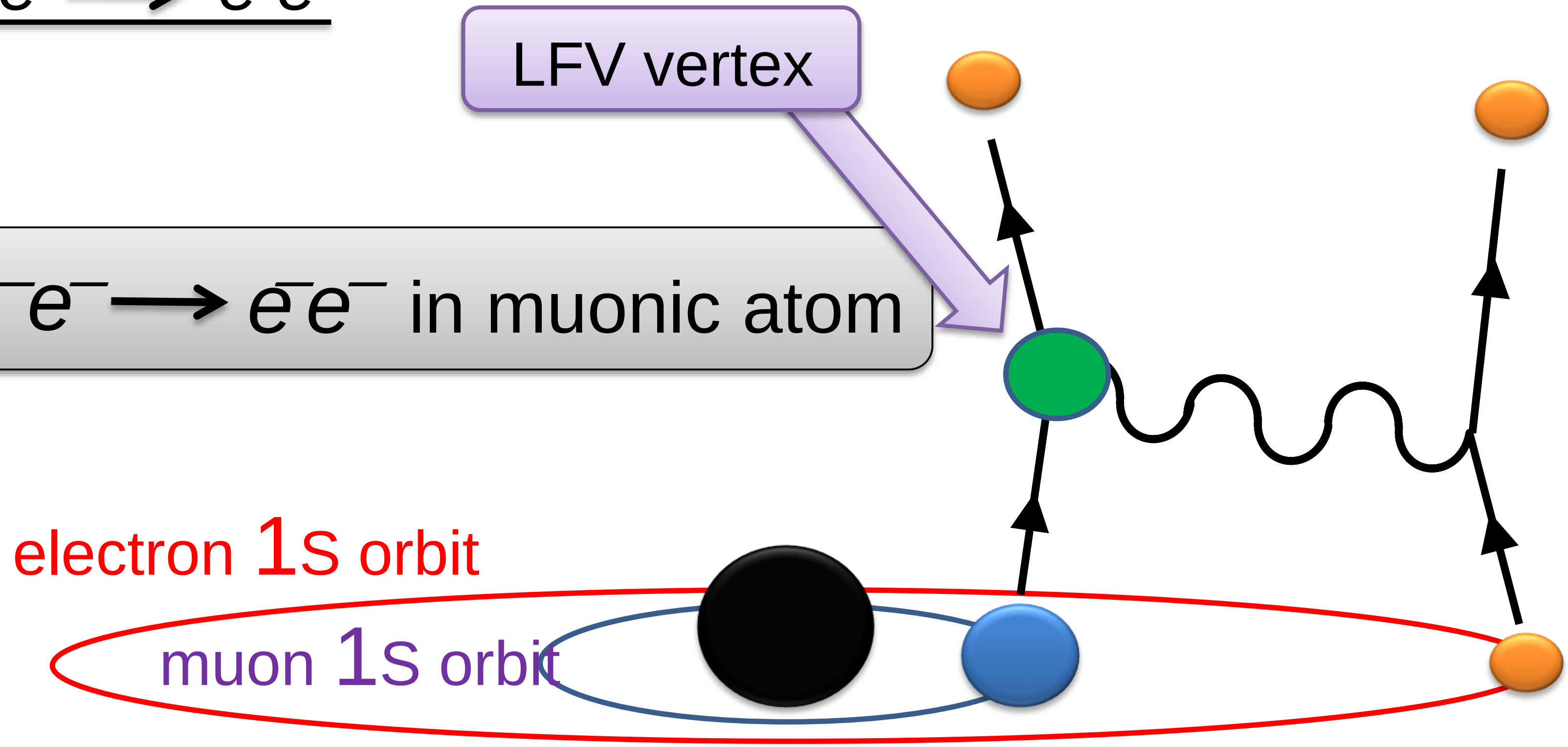



Interaction rate, (approximately, same as beta capture)

$$\Gamma(\mu^- e^- \rightarrow e^- e^-; Z) = 2\sigma v_{\mathrm{rel}} \left|\psi^{(e)}_{1S}(0; Z-1)\right|^2$$

## $\mu\, e \longrightarrow e\, e$

$\mu^- e^- \longrightarrow e^- e^-$ in muonic atom

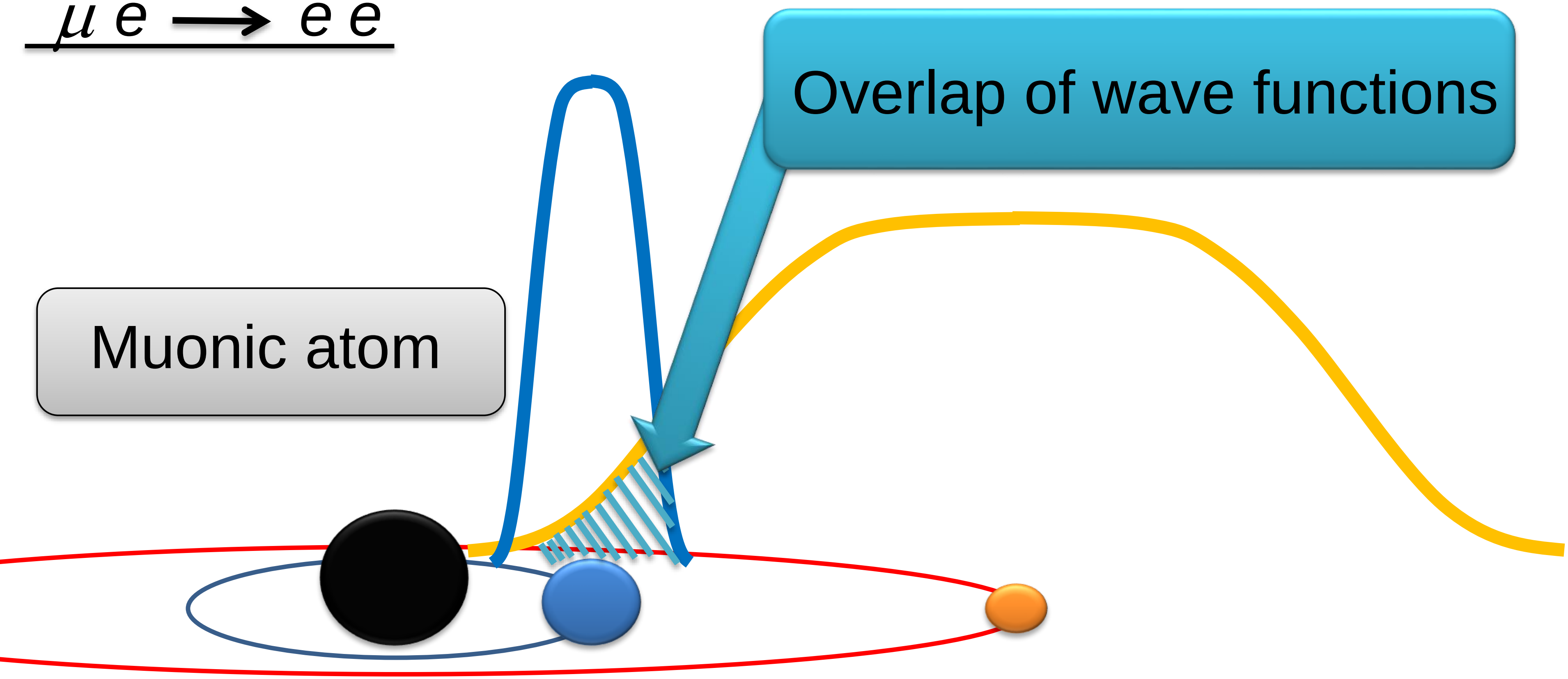



Interaction rate, (approximately, same as beta capture)

$$\Gamma(\mu^- e^- \to e^- e^-; Z) = 2\sigma v_{\mathrm{rel}} \left|\psi^{(\mathrm{e})}_{1\mathrm{S}}(0; Z-1)\right|^2$$

Overlap of wave function of $\mu$ and $e$

## $\mu e \longrightarrow e e$




Approximation

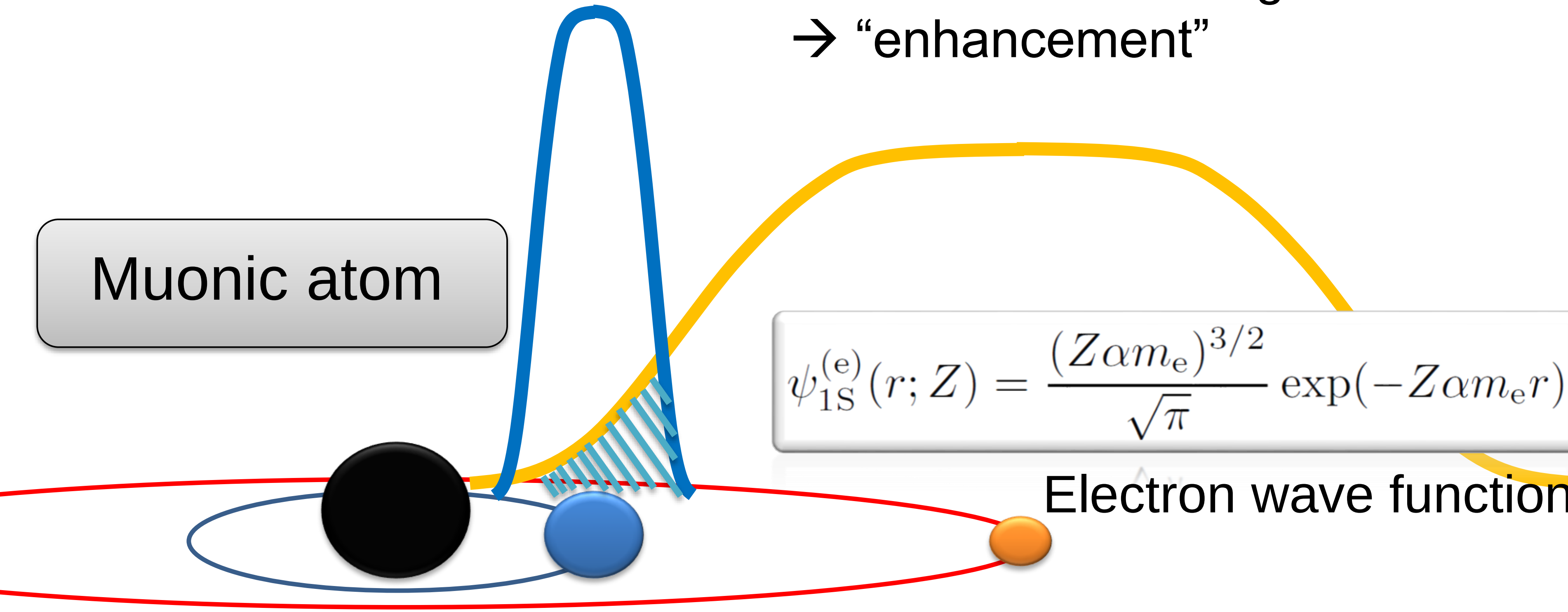
Muon localization at nucleus position $\left( \because \ m_e \ll m_\mu \right)$

⇨ Overlap = electron wave function at nucleus

$\underline{\mu\, e \longrightarrow e\, e}$

Attracted more with higher Z

→ "enhancement"




$$\psi^{(\mathrm{e})}_{1\mathrm{S}}(r;Z) = \frac{(Z\alpha m_{\mathrm{e}})^{3/2}}{\sqrt{\pi}} \exp(-Z\alpha m_{\mathrm{e}} r)$$

r : radial coordinate (distance from nucleus)

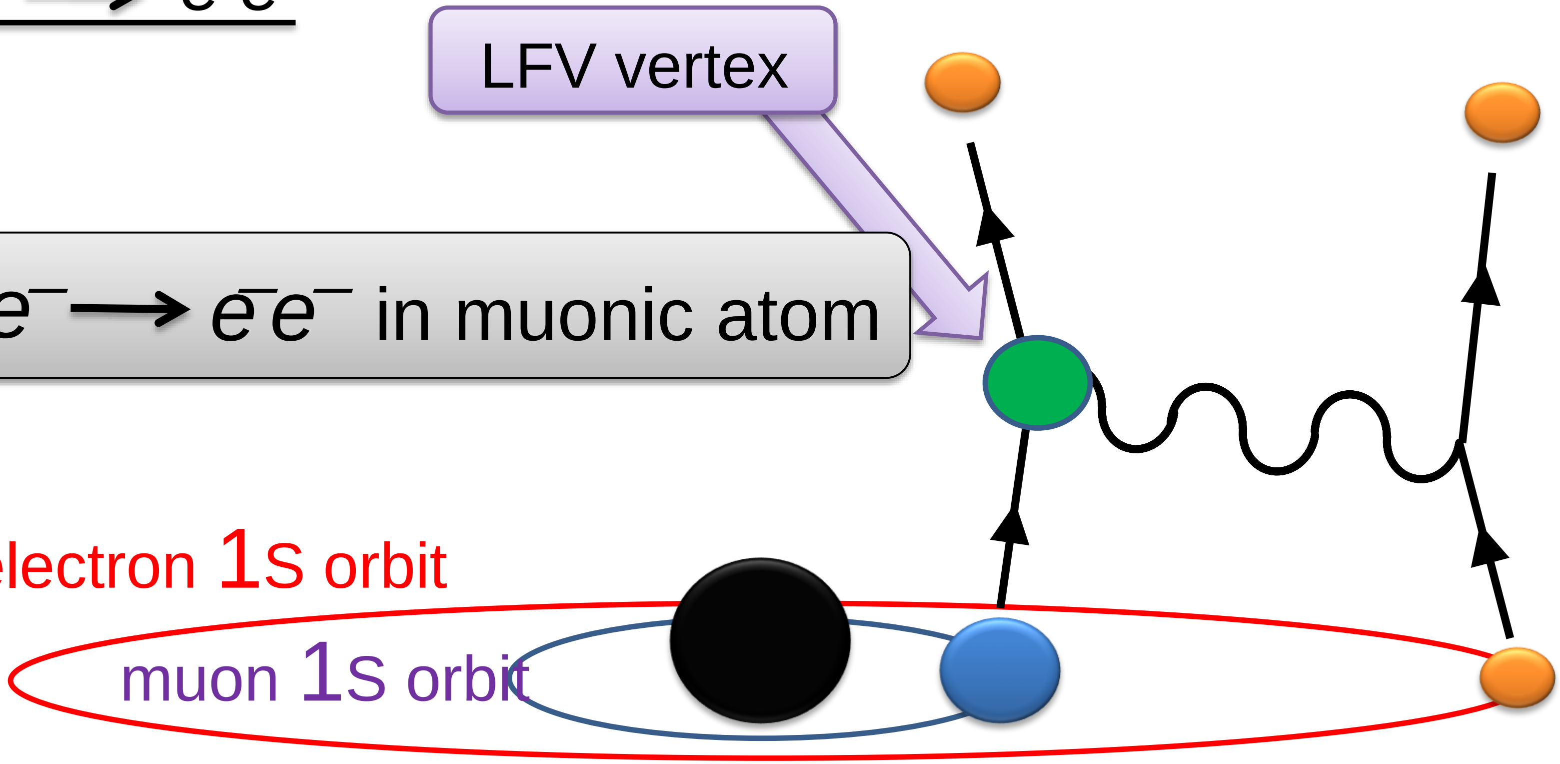
Z : atomic number of nucleus in muonic atom

Overlap of wave functions

$$\left|\psi^{(\mathrm{e})}_{1\mathrm{S}}(0;Z-1)\right|^2$$

## $\mu\, e \longrightarrow e\, e$

$\mu^- e^- \longrightarrow e^- e^-$ in muonic atom




Interaction rate

$$\Gamma(\mu^- e^- \to e^- e^-; Z) = 2\sigma v_{\rm rel} |\psi_{1S}^{(e)}(0; Z-1)|^2$$

Cross section for elemental interaction

# 2.2 Rough Estimate

Effective Lagrangian [ Y. Kuno and Y. Okada Rev. Mod. Phys. **73** (2001) ]

$$\mathcal{L}_{\mu^- e^- \to e^- e^-} = -\frac{4G_\mathrm{F}}{\sqrt{2}} \Big[ m_\mu A_\mathrm{R}\, \overline{\mu_\mathrm{R}} \sigma^{\mu\nu} e_\mathrm{L} F_{\mu\nu} + m_\mu A_\mathrm{L}\, \overline{\mu_\mathrm{L}} \sigma^{\mu\nu} e_\mathrm{R} F_{\mu\nu}$$
$$+ g_1 (\overline{\mu_\mathrm{R}} e_\mathrm{L})(\overline{e_\mathrm{R}} e_\mathrm{L}) + g_2 (\overline{\mu_\mathrm{L}} e_\mathrm{R})(\overline{e_\mathrm{L}} e_\mathrm{R})$$
$$+ g_3 (\overline{\mu_\mathrm{R}} \gamma^\mu e_\mathrm{R})(\overline{e_\mathrm{R}} \gamma_\mu e_\mathrm{R}) + g_4 (\overline{\mu_\mathrm{L}} \gamma^\mu e_\mathrm{L})(\overline{e_\mathrm{L}} \gamma_\mu e_\mathrm{L})$$
$$+ g_5 (\overline{\mu_\mathrm{R}} \gamma^\mu e_\mathrm{R})(\overline{e_\mathrm{L}} \gamma_\mu e_\mathrm{L}) + g_6 (\overline{\mu_\mathrm{L}} \gamma^\mu e_\mathrm{L})(\overline{e_\mathrm{R}} \gamma_\mu e_\mathrm{R}) + (\mathrm{H.c.}) \Big]$$

cLFV effective coupling constant

$A_\mathrm{R}$ $A_\mathrm{L}$ $g_1$ $g_2$ $g_3$ $g_4$ $g_5$ $g_6$

→ Sensitive to the structure of new physics

# $\mu\, e \longrightarrow e\, e$

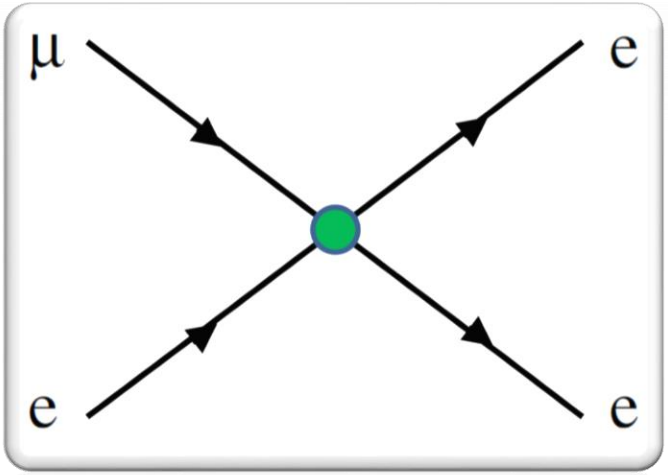
Effective Lagrangian [ Y. Kuno and Y. Okada Rev. Mod. Phys. **73** (2001) ]

$$\mathcal{L}_{\mu^- e^- \to e^- e^-} = -\frac{4G_F}{\sqrt{2}}\Big[ m_\mu A_R\, \overline{\mu_R} \sigma^{\mu\nu} e_L F_{\mu\nu} + m_\mu A_L\, \overline{\mu_L} \sigma^{\mu\nu} e_R F_{\mu\nu}$$

$$+ g_1 (\overline{\mu_R} e_L)(\overline{e_R} e_L) + g_2 (\overline{\mu_L} e_R)(\overline{e_L} e_R)$$

$$+ g_3 (\overline{\mu_R} \gamma^\mu e_R)(\overline{e_R} \gamma_\mu e_R) + g_4 (\overline{\mu_L} \gamma^\mu e_L)(\overline{e_L} \gamma_\mu e_L)$$

$$+ g_5 (\overline{\mu_R} \gamma^\mu e_R)(\overline{e_L} \gamma_\mu e_L) + g_6 (\overline{\mu_L} \gamma^\mu e_L)(\overline{e_R} \gamma_\mu e_R) + (\mathrm{H.c.})\Big]$$




4-Fermi interaction type

$\underline{\mu\, e \longrightarrow e\, e}$

# 4-Fermi interaction dominant case

## Branching ratio

$$\mathrm{Br}(\mu^- e^- \to e^- e^-) \equiv \tilde{\tau}_\mu \Gamma(\mu^- e^- \to e^- e^-)$$
$$= 24\pi (Z-1)^3 \alpha^3 \left(\frac{m_e}{m_\mu}\right)^3 \frac{\tilde{\tau}_\mu}{\tau_\mu} G$$
$$= (3.31 \times 10^{-12})(Z-1)^3 (\tilde{\tau}_\mu / \tau_\mu) G$$

$\tau_\mu$ Lifetime of free muon ($2.197\times10^{-6}$ s)

$\tilde{\tau}_\mu$ Lifetime of bound muon $\begin{pmatrix} 2.19\times10^{-6}\ \text{s} & \text{for } {}^{1}\text{H} \\ (7-8)\times10^{-8}\ \text{s} & \text{for } {}^{238}\text{U} \end{pmatrix}$

$\underline{\mu\, e \longrightarrow e\, e}$

## 4-Fermi interaction dominant case

Branching ratio

$$\mathrm{Br}(\mu^- e^- \to e^- e^-) \equiv \tilde{\tau}_\mu \Gamma(\mu^- e^- \to e^- e^-)$$
$$= 24\pi(Z-1)^3\alpha^3\left(\frac{m_e}{m_\mu}\right)^3 \frac{\tilde{\tau}_\mu}{\tau_\mu} G$$
$$= (3.31\times 10^{-12})(Z-1)^3(\tilde{\tau}_\mu/\tau_\mu)G$$

$$G \equiv G_{12} + 16G_{34} + 4G_{56} + 8G'_{14} + 8G'_{23} - 8G'_{56}$$

$$G_{ij} \equiv |g_i|^2 + |g_j|^2$$

$$G'_{ij} \equiv \mathrm{Re}\left(g_i^* g_j\right)$$

$\mu\, e \longrightarrow e\, e$

# 4-Fermi interaction dominant case

Branching ratio
( $\mu \longrightarrow e\, e\, e$ )

$$\mathrm{Br}(\mu^+ \to \mathrm{e}^+\mathrm{e}^+\mathrm{e}^-) = \frac{1}{8}(G_{12} + 16G_{34} + 8G_{56})$$

Comparison two BRs $\Rightarrow$ probe for CP violating

$$G \equiv G_{12} + 16G_{34} + 4G_{56} + 8G'_{14} + 8G'_{23} - 8G'_{56}$$

$$G_{ij} \equiv |g_i|^2 + |g_j|^2$$

$$G'_{ij} \equiv \mathrm{Re}\,(g_i^* g_j)$$

$\mu\, e \longrightarrow e\, e$

# 4-Fermi interaction dominant case

Branching ratio

$$\mathrm{Br}(\mu^- e^- \to e^- e^-) \equiv \tilde{\tau}_\mu \Gamma(\mu^- e^- \to e^- e^-)$$
$$= 24\pi (Z-1)^3 \alpha^3 \left(\frac{m_e}{m_\mu}\right)^3 \frac{\tilde{\tau}_\mu}{\tau_\mu} G$$
$$= (3.31 \times 10^{-12})(Z-1)^3(\tilde{\tau}_\mu/\tau_\mu)G$$

Enhancement factor from overlap of wave functions

$\left[\because\right.$ Positive charge attracts muon and electron toward the nucleus position. $\left.\right]$

⇒ Notable advantage for heavy nuclei

# $\mu\, e \longrightarrow e\, e$

## Effective Lagrangian

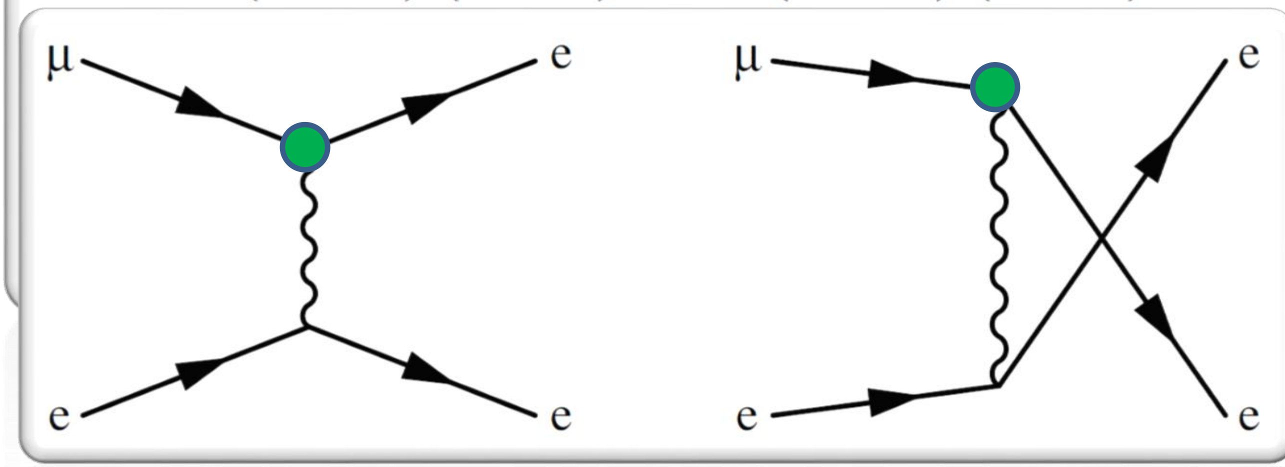
[ Y. Kuno and Y. Okada Rev. Mod. Phys. **73** (2001) ]

$$\mathcal{L}_{\mu^-e^-\to e^-e^-} = -\frac{4G_F}{\sqrt{2}}\Big[m_\mu A_R\,\overline{\mu_R}\sigma^{\mu\nu}e_L F_{\mu\nu} + m_\mu A_L\,\overline{\mu_L}\sigma^{\mu\nu}e_R F_{\mu\nu}$$

$$+\, g_1(\overline{\mu_R}e_L)(\overline{e_R}e_L) + g_2(\overline{\mu_L}e_R)(\overline{e_L}e_R)$$

$$\mu e_L)$$

$$\mu e_R) + (\mathrm{H.c.})\Big]$$




Photonic interaction type

$\mu\, e \longrightarrow e\, e$

# Photonic interaction dominant case

## Branching ratio

$$
\begin{aligned}
&\mathrm{Br}(\mu^- \mathrm{e}^- \to \mathrm{e}^- \mathrm{e}^-) \\
&= 1536\pi^2 (Z-1)^3 \alpha^4 \left(|A_\mathrm{R}|^2 + |A_\mathrm{L}|^2\right) \frac{m_\mathrm{e}}{m_\mu} \frac{\tilde{\tau}_\mu}{\tau_\mu} \\
&= 2.08 \times 10^{-9} (Z-1)^3 \left(|A_\mathrm{R}|^2 + |A_\mathrm{L}|^2\right) (\tilde{\tau}_\mu / \tau_\mu)
\end{aligned}
$$

Photon propagator
in non-relativistic limit

$$\frac{1}{q^2} \simeq \frac{1}{m_\mu m_e}$$

⇨ Enhancement factor
compared with 4-Fermi case

$$\frac{m_\mu^2}{m_e^2}$$

## $\mu\, e \longrightarrow e\, e$

Case : same order cLFV coupling

$$A_{L(R)} \simeq g_i \quad \left( i = 1, 2, \ldots 6 \right)$$

Ratio between photonic and 4-Fermi cross section

$$\sigma v_{\mathrm{photonic}} \sim \alpha \frac{m_\mu^2}{m_e^2} \times \sigma v_{\mathrm{4Fermi}} \sim 10^3 \times \sigma v_{\mathrm{4Fermi}}$$

One of the distinct features for the process

# 2.3 Discovery Reach

Upper limit estimate for BR( $\mu^- e^- \longrightarrow e^- e^-$ )

Taking ratio of the BR to other cLFV BR

4-Fermi interaction dominant case

$$\frac{\mathrm{Br}(\mu^- \mathrm{e}^- \to \mathrm{e}^- \mathrm{e}^-)}{\mathrm{Br}(\mu^+ \to \mathrm{e}^+ \mathrm{e}^+ \mathrm{e}^-)}$$

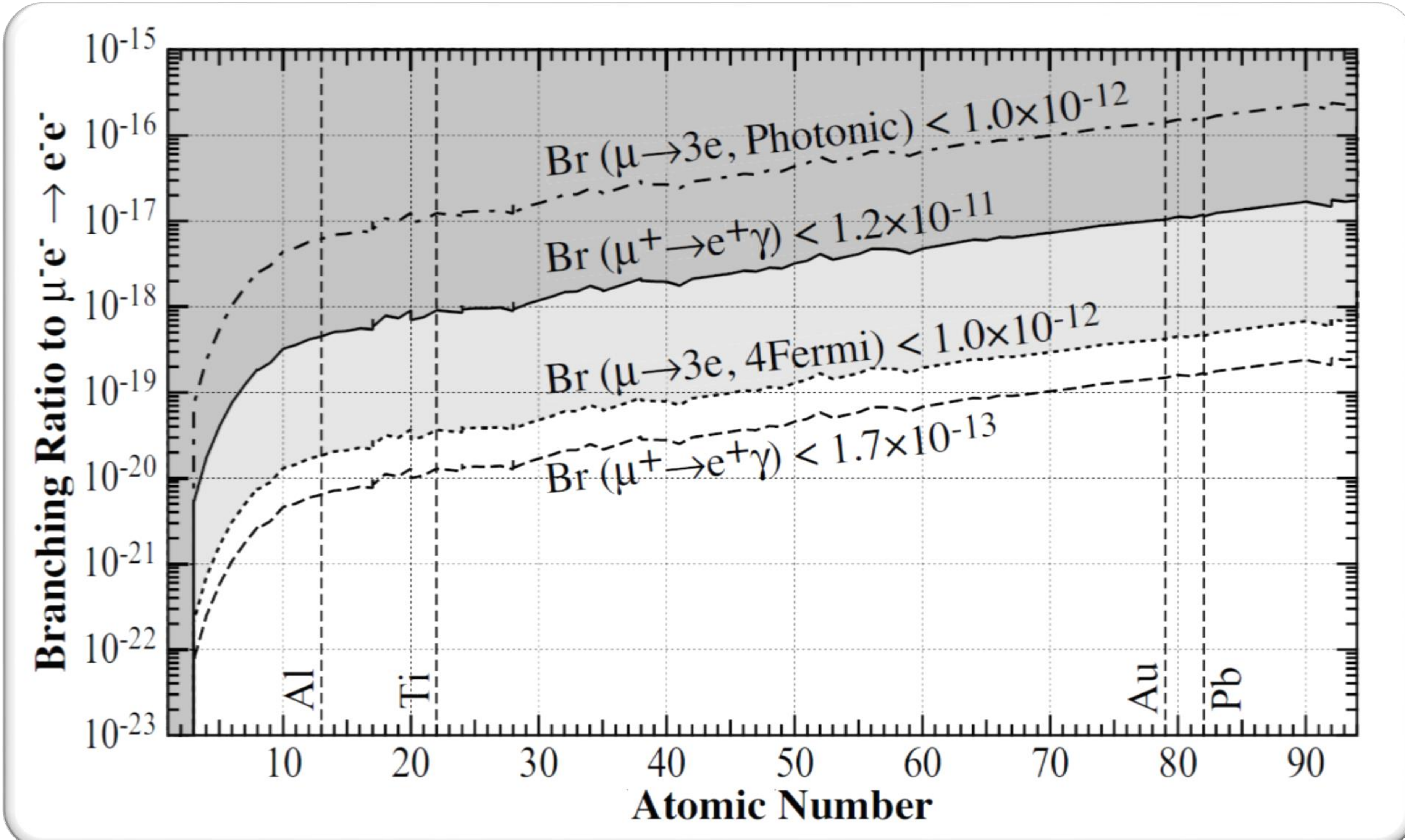
assuming $G/(G_{12}+16G_{34}+8G_{56})$ ~ O(1)

Photonic interaction dominant case

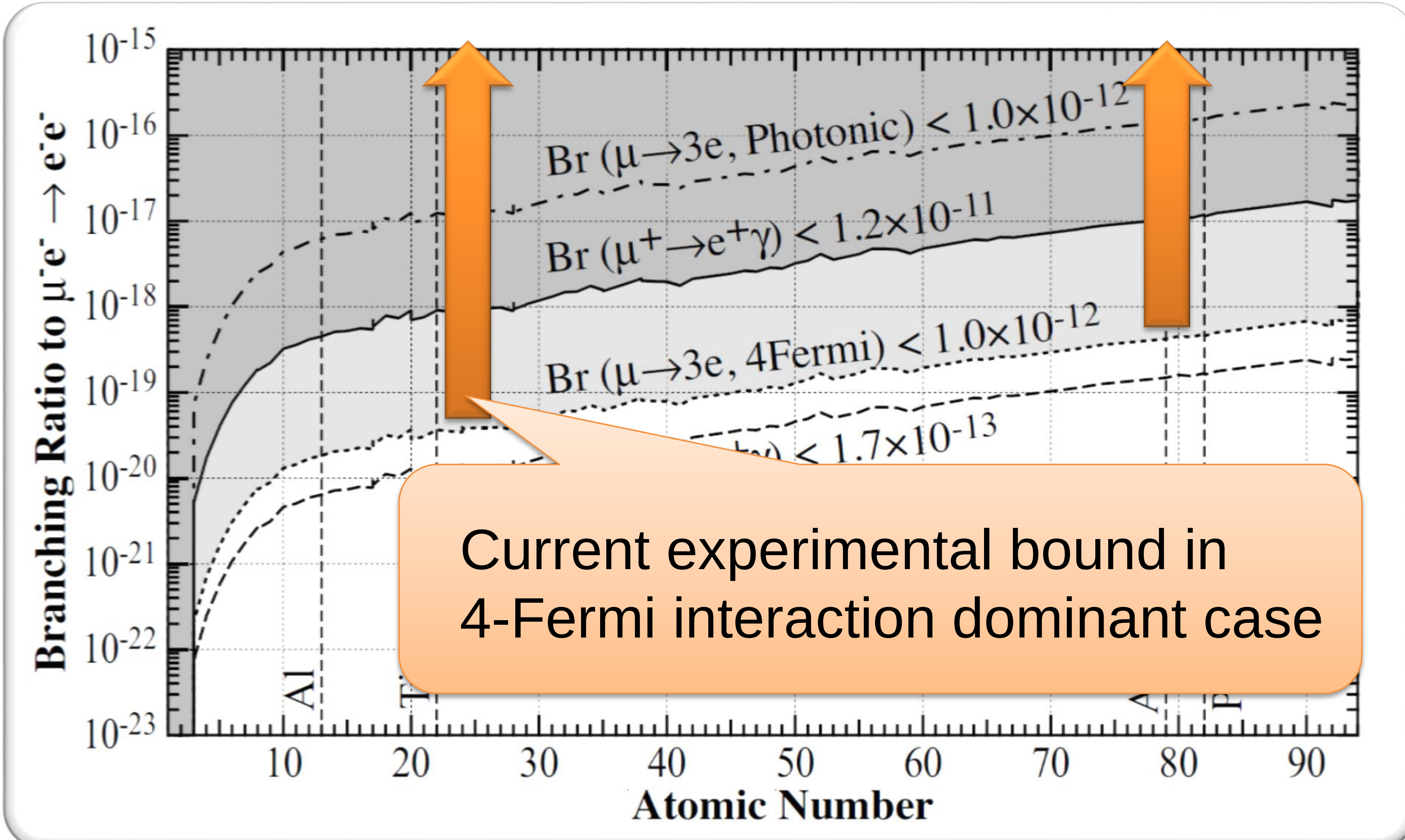
$$\frac{\mathrm{Br}(\mu^- \mathrm{e}^- \to \mathrm{e}^- \mathrm{e}^-)}{\mathrm{Br}(\mu^+ \to \mathrm{e}^+ \mathrm{e}^+ \mathrm{e}^-)} \qquad \frac{\mathrm{Br}(\mu^- \mathrm{e}^- \to \mathrm{e}^- \mathrm{e}^-)}{\mathrm{Br}(\mu^+ \to \mathrm{e}^+ \gamma)}$$

These ratios are independent on cLFV effective coupling

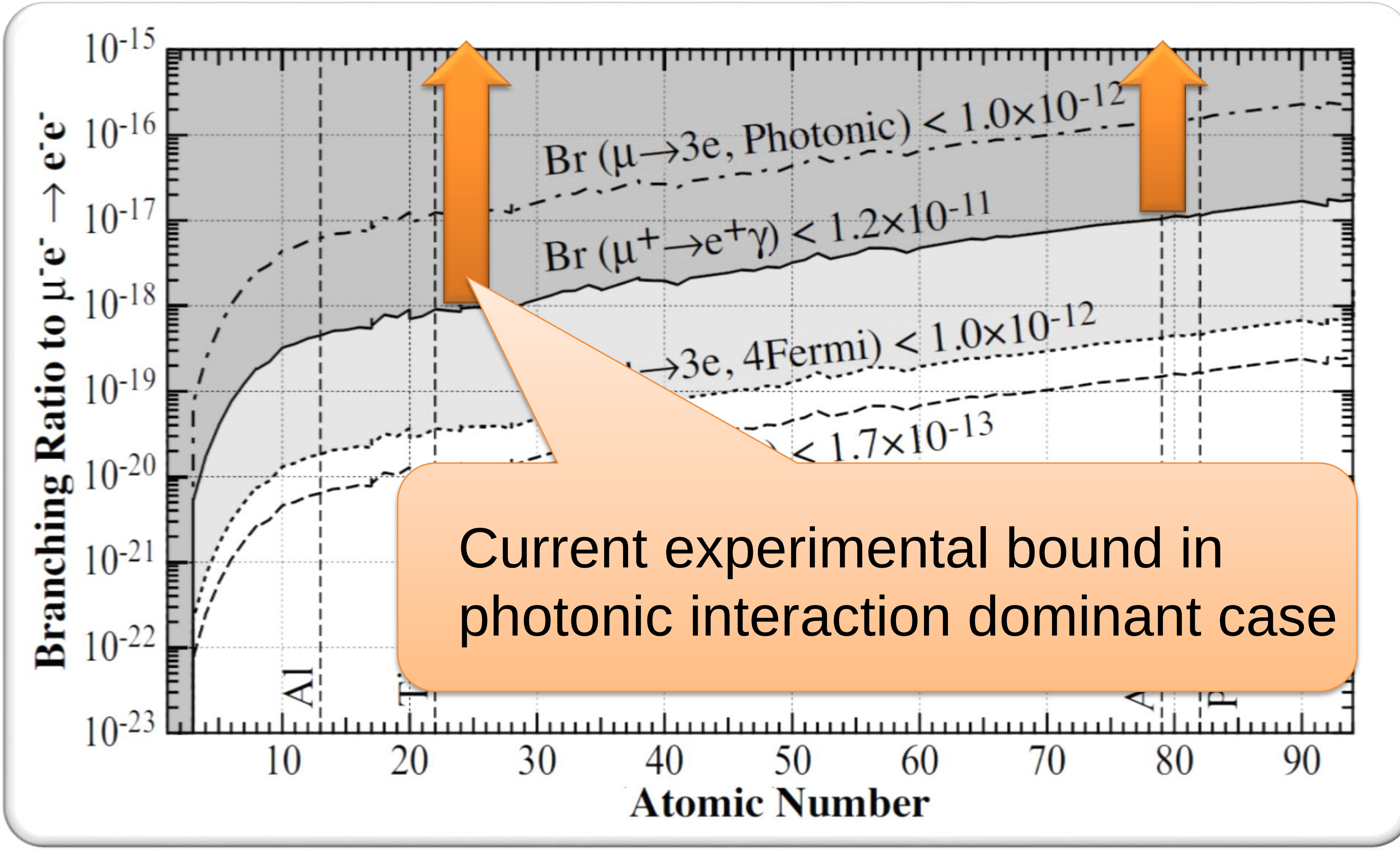
# Discovery reach



## Discovery reach



# Discovery reach



# Discovery reach

| Project | Intensity Reach |
| --- | --- |
| COMET / PRISM | $10^{18} - 10^{19}$ μ/year |
| ν factories | $10^{21}$ μ/year |

With these number of muons the process will be seen !!

# 3 Towards a Precise Estimate

- Out-going electron is also attracted
  - → Enhancement of the rate
- Bound electron is more concentrated for relativistic wave fn.
  - → Enhancement of the rate
- Nuclei is not a point charge
  - → Solve Dirac Eq. numerically

For trial, uniform charge density is assumed

$$
\begin{aligned}
V(r) &= -\frac{Z\alpha}{R}\left(\frac{3}{2}-\frac{1}{2}\frac{r^2}{R^2}\right) \quad \text{for} \quad r<R \\
&= -\frac{Z\alpha}{r} \quad \text{for} \quad r>R
\end{aligned}
$$

$$R = 1.2A^{1/3}\text{fm}$$

# Enhancement of the rate for contact interaction

Preliminary

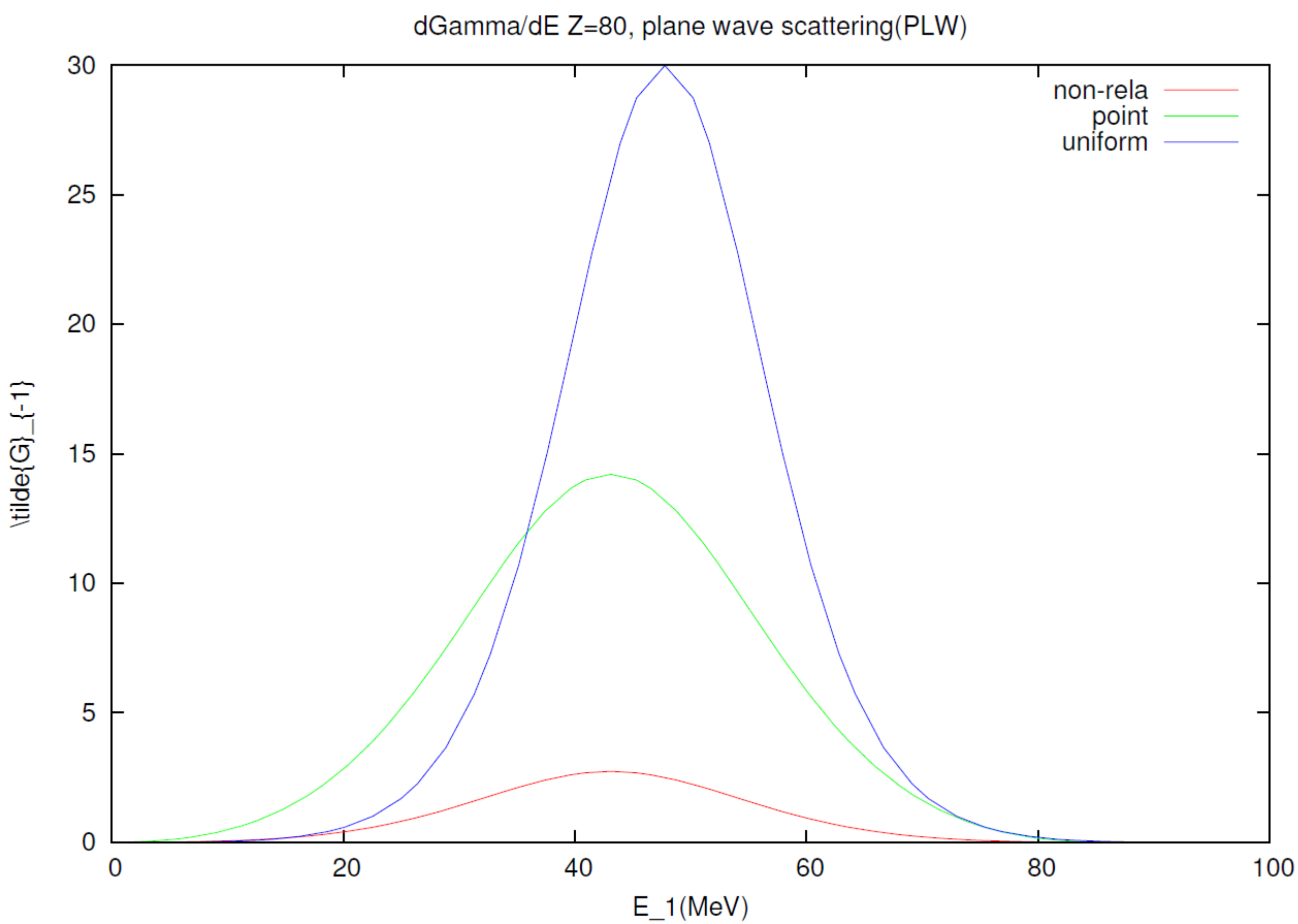
| $Z, A = 2Z$ | Point colomb | Uniform |
|---|---|---|
| 40 | 1.86 | 1.70 |
| 80 | 16.1 | 6.62 |
| 90 | 39.1 | 10.5 |
| 100 | 118 | 17.4 |

Coulomb force does not change chirality and hence same factorization for g's holds

Branching ratio can be

$$10^{-17}$$

# Energy distribution



# 4. Summary

Phys.Rev.Lett.105:121601,2010

- New LFV process $\boxed{\mu^- e^- \longrightarrow e^- e^- \text{ in muonic atom}}$
- Clean signal (2 electrons with total E = $E_\mu$)
- Interaction rate $\boxed{\Gamma(\mu^- e^- \to e^- e^-; Z) \sim (Z-1)^3}$

Or more !!

⇒ Advantage : Large nucleus

- Detectable in on-going or future experiments

⇒ We wish to observe LFV in the process

- Precise Calculation is necessary !!
  Wait for a while !!

- What is target ?

  Flavor violation between $\mu$ and $e$

- What is advantage ?

  - Sensitive to both photonic dipole cLFV operator and 4-Fermi contact cLFV operator

  - Clean signal **[** almost back-to-back dielectron **]**

- Can we measure it at COMET-I ?

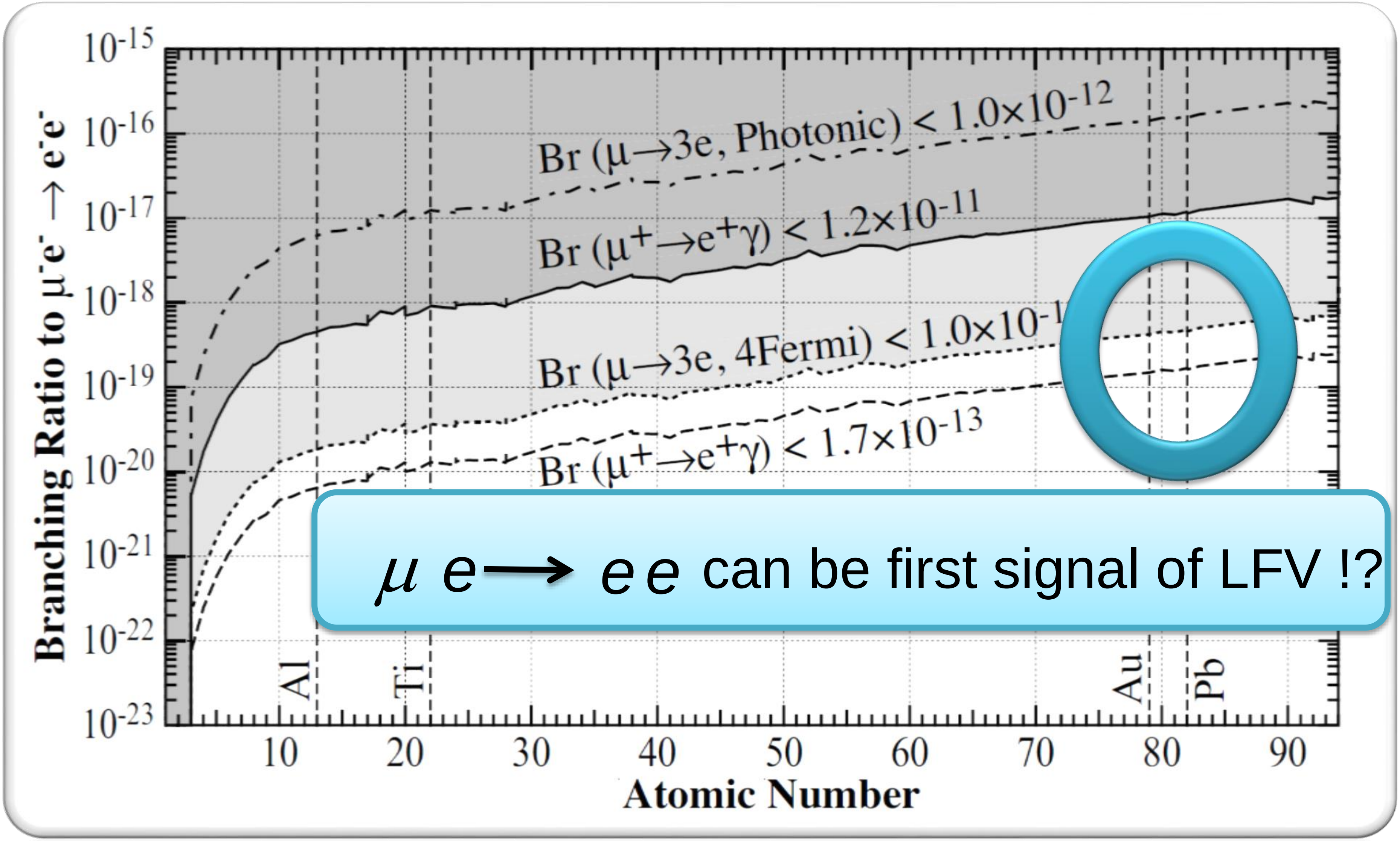
# Discovery reach

| Collaboration | Searching for | Intensity |
|---|---|---|
| MEG | $\mu \to e\gamma$ | $10^{7.5}\ \mu/s$ |
| MUSIC | $\mu \to 3e$ | $10^{8}\ \mu/s$ |
| COMET | $\mu^- N \to e^- N$ | $10^{11}\ \mu/s$ |
| Mu2E (E973) | $\mu^- N \to e^- N$ | $10^{11}\ \mu/s$ |
| PRISM | $\mu^- N \to e^- N$ | $10^{12}\ \mu/s$ |

For run-time 1 year~ $3 \times 10^{7}$ s

$10^{18}$-$10^{19}$ muon at COMET experiment

# Discovery reach



COMET

COMET (COherent Muon Electron Transittion)

http://comet.phys.sci.osaka-u.ac.jp/

- Br for cLFV processes are quite model dependent
- Need other experiment(s) with

  different physics process (with better sensitivity)!

  independently on MEG result
- COMET (COherent Muon Electron Transittion)
  - Submitted a proposal to J-PARC in 2008 and a CDR in 2009,
  - and obtained Stage-1 approval in July 2009

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# COMET Collaboration List

**84 people from 20 institutes ( August 2011 )**

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