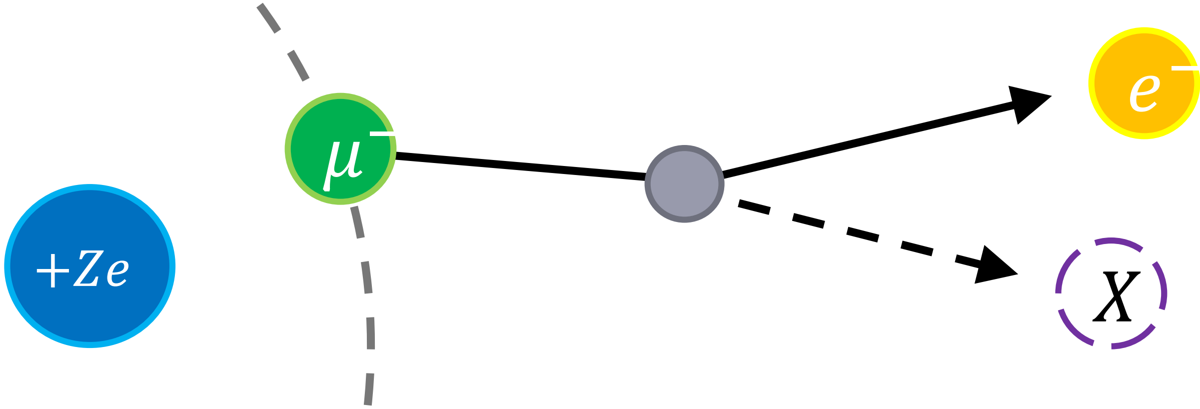
14th June 2019
@ Exploration of Particle Physics and Cosmology with Neutrinos Workshop

$\mu^- \to e^- X$ in muonic atom



Yuichi Uesaka (Saitama U.)

Contents

- charged lepton flavor violation & light new particles
- searches for $\mu \to e + X(invisible)$
- $\mu^- \to e^- X$ in muonic atom
  - Advantages of muonic atom
  - Formulation for e^- spectrum
  - Numerical results & discussion
- summary

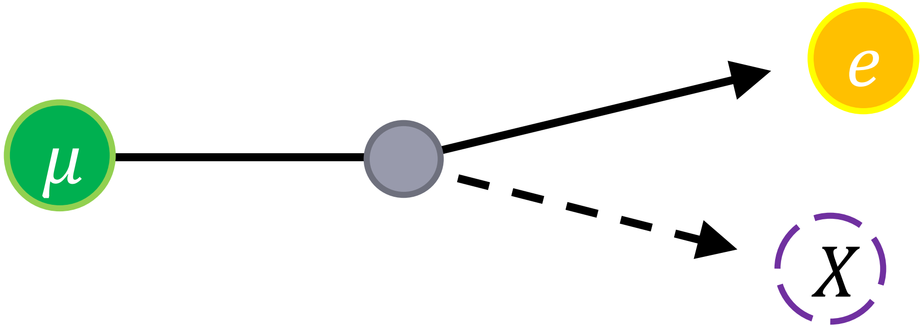
Charged Lepton Flavor Violation (CLFV)

Mode	Upper bound	Experiment (Year)
$\mu^+ \to e^+\gamma$	4.2×10^{-13}	MEG (2016)
$\mu^+ \to e^+e^+e^-$	1.0×10^{-12}	SINDRUM (1988)
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$	7×10^{-13}	SINDRUM II (2006)
$\mu^+ \to e^+X, X \to \mathrm{inv.}$	$O(10^{-5})$	TWIST (2015)
$\mu^+ \to e^+\gamma X, X \to \mathrm{inv.}$	$O(10^{-9})$	Crystal Box (1988)
$\mu^+ \to e^+X, X \to e^+e^-$	$O(10^{-12})$	SINDRUM (1986)
$\mu^+ \to e^+X, X \to \gamma\gamma$	$O(10^{-10})$	MEG (2012)
$\tau \to eX(\mu X), X \to \mathrm{inv.}$	$O(10^{-2})$	ARGUS (1995)

Light invisible X with CLFV

Properties of an unknown boson X

- ✓ light ($m_X < m_\mu$)
- ✓ neutral
- ✓ with μ-e-X coupling



➢ theoretical examples of X

- light (pseudo-)scalar : **majoron, familon, axion(-like) particle, …**
- **light gauge boson**

Example : Majoron

- Singlet Majoron model

Y. Chikashige, R.N. Mohapatra, & R.D. Peccei, PLB**98** (1981) 265.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N}_R\gamma^\mu\partial_\mu N_R + \left(\partial_\mu\sigma\right)^\dagger(\partial^\mu\sigma) - V(\sigma)$$
$$- \left(\overline{L}yN_RH + \frac{1}{2}\overline{N}_R^c\lambda N_R\sigma + \mathrm{h.c.}\right)$$

N_R : right-handed neutrino
σ : scalar with $L = -2$

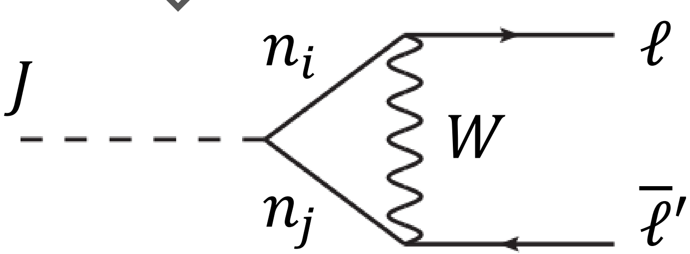
SSB of lepton #

$$\sigma(x) = f + \rho(x) + iJ(x)$$

J : majoron
(NG boson of lepton #)

- **majorana mass of neutrino**
- **interaction of majoron with neutrino**

- **CLFV coupling at one loop !**



n_i : Majorana neutrino mass eigenstate

$$K \equiv \frac{m_D m_D^\dagger}{vf}$$

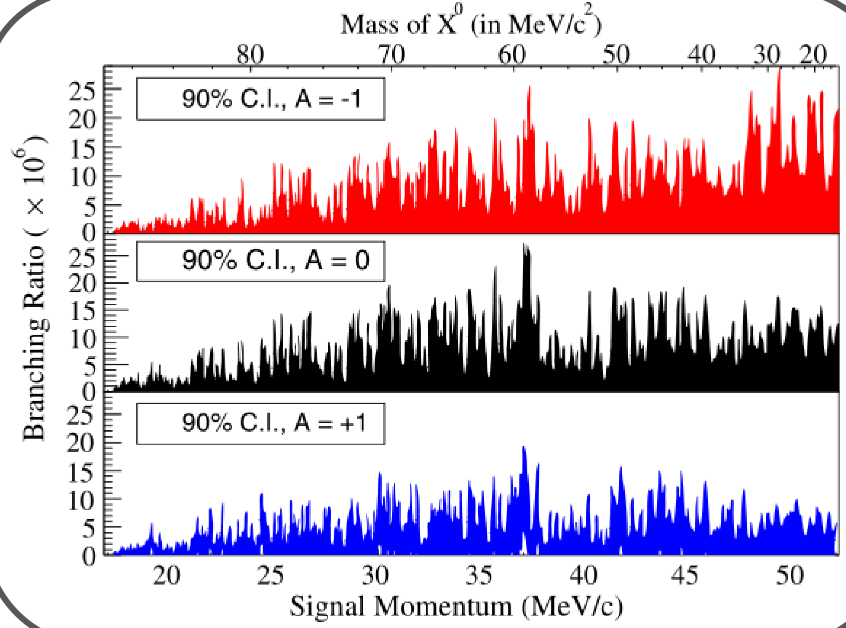
$$\mathcal{L}_{J\ell'\ell} \simeq \frac{im_\ell}{8\pi v} K_{\ell'\ell} J\overline{\ell'}P_R\ell$$

for $m_\ell \gg m_{\ell'}$ ($\ell \neq \ell'$)

$\mu^+ \to e^+ X$ searches $m_X < m_\mu$

- A. Jodidio *et al.* PRD **34**, 1967 (1986).
  - 1.8×10^7 μ^+ that was highly polarized
  - search for e^+ emitted in opposite direction for μ^+ polarization
  - $\mathrm{Br}(\mu^+ \to e^+ X) < 2.6 \times 10^{-6}$ for $m_X = 0$

- TWIST Collab.
  PRD **91**, 052020 (2015).
  - 5.8×10^8 μ^+
  - for various m_X
    & various angular property
    ($d\Gamma/d\cos\theta \propto 1 - AP_\mu \cos\theta$)
  - $\mathrm{Br} < 2.1 \times 10^{-5}$ ($m_X = 0, A = 0$)



- Mu3e Collab. A. Schöning, Talk at Flavour and Dark Matter Workshop, Heidelberg, September 28 (2017).
  - $\mathrm{Br} < 10^{-8}$ (for $25\mathrm{MeV} < m_X < 95\mathrm{MeV}$)

$\mu^- \to e^- X$ in a muonic atom

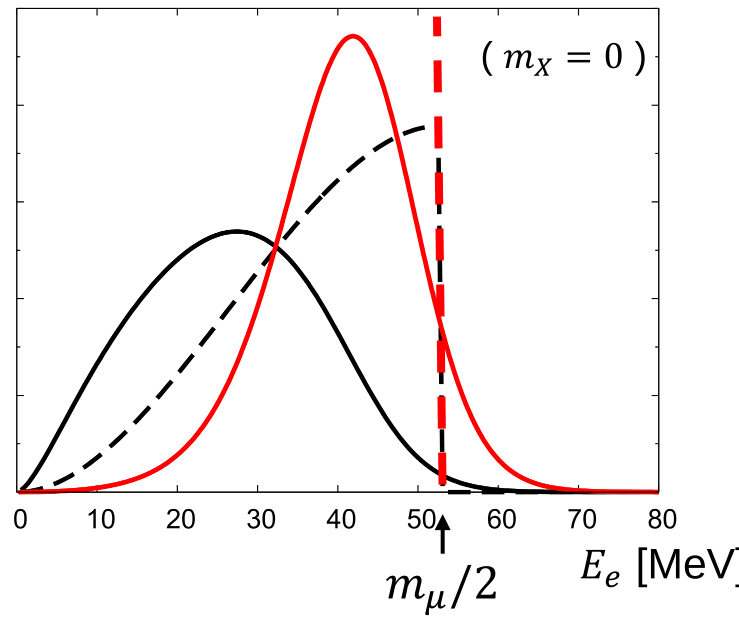
cf. X. G. i Tormo *et al.*, PRD **84**, 113010 (2011).
& H. Natori, Talk at 73th JPS meeting (2018).

Advantages over free muon decay

1. less background

- - - : $\mu^+ \to e^+ X$ (free)
- - - : $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ (free)
—— : $\mu^- \to e^- X$ (μ-gold)
—— : $\mu^- \to e^- \bar{\nu}_e \nu_\mu$ (μ-gold)

shape of electron spectrum



- different peak positions of signal & BG

2. more information : "spectrum", "dependence on nucleus", …

3. huge # of muonic atoms in coming experiments (COMET, Mu2e, DeeMe)

Disadvantages

✓ non-monochromatic signal

✓ shorter life time of muonic atom

Spectrum near end-point (rough estimation)

DIO with two neutrino emission $\mathcal{L} = G\left(\overline{\mu}\gamma_\alpha \nu_\mu\right)\left(\overline{\nu_e}\gamma^\alpha e\right)$

(Decay In Orbit)

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e} \propto \int \frac{d^3 p_\nu}{E_\nu}\frac{d^3 \overline{p}_\nu}{\overline{E}_\nu}\delta\left(E_\nu + \overline{E}_\nu + E_e - E_{tot}\right)\cdots p_\nu \cdots \overline{p}_\nu$$

$$\Delta \equiv \frac{E_{tot} - E_e}{m_\mu}$$

$\sim \Delta^5$ near end-point

DIO with one boson emission $\mathcal{L} = g(\overline{\mu}\gamma_\alpha e)\partial^\alpha X$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e} \propto \int \frac{d^3 p_X}{E_X}\delta\left(E_\nu + \overline{E}_\nu + E_e - E_{tot}\right) \left|\cdots p_X\right|^2$$

$\sim \Delta^3$ near end-point

Investigation of e^- spectrum near **end-point** could be a good probe for $\mu^- \to e^- X$.

⇨ Need to take into account
- relativistic effect for bound μ^-,
- distortion of emitted e^- in Coulomb potential,
- finite size of nucleus, nuclear recoil, …

Previous work

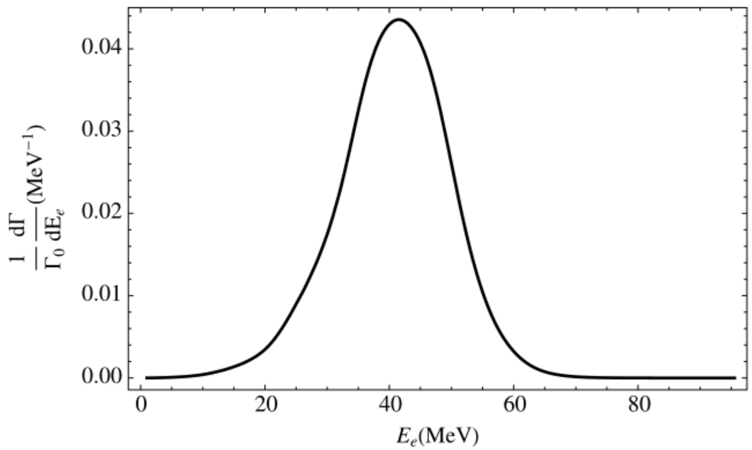
X. G. i Tormo *et al*., PRD **84**, 113010 (2011).

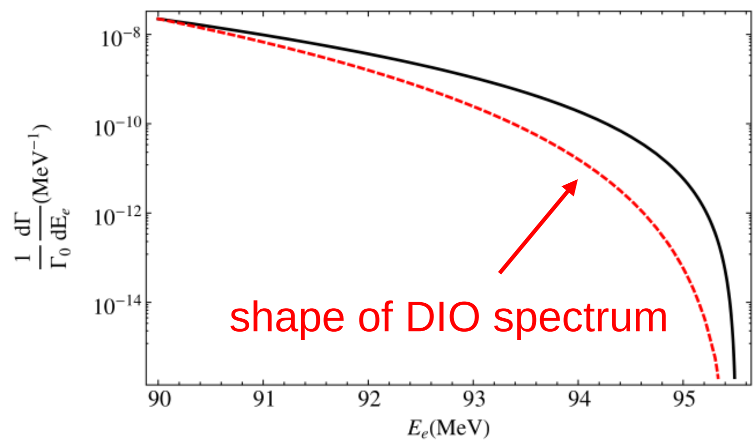
- assuming that massless X has yukawa-type CLFV interaction

$$\mathcal{L}_I = g(\overline{\mu}e)X$$

(g : coupling)

electron spectrum of $\mu^- \to e^- X$ (gold)





- ✓ The result of the past μ-e conv. corresponds to $\mathrm{Br}(\mu \to eX) < 3 \times 10^{-3}$.
- ✓ Sensitivity of COMET & Mu2e : $\mathrm{Br}(\mu \to eX) \sim 2 \times 10^{-5}$

same level as the current limit of free μ^+ search ($\sim 10^{-5}$)

Aim of this work

$\mu^- \to e^- X$ in a muonic atom

X. G. i Tormo *et al.*

CLFV interaction : $\mathcal{L}_I = g(\overline{\mu} e)X$

⇩

This work

✓ various possibilities of CLFV interaction

If the shape of e^- spectrum depends on CLFV interaction,

we could determine the new physics model by observation.

Effective models

A. **Scalar *X***

- <u>yukawa coupling</u> (e.g. majoron induced by R-parity violation, …)

already analyzed by X. G. i Tormo *et al*., PRD **84**, 113010 (2011).

$$\mathcal{L}_{S0} = g_{S0}(\bar{e}\mu)X + [H.c.]$$

- <u>derivative coupling</u> (e.g. majoron, familon, axion, …)

$$\mathcal{L}_{S1} = \frac{g_{S1}}{\Lambda_{S1}}(\bar{e}\gamma_\alpha\mu)\partial^\alpha X + [H.c.]$$

B. **Vector *X***

$$\mathcal{L}_{V0} = g_{V0}(\bar{e}\gamma_\alpha\mu)X^\alpha + [H.c.]$$ (for only massive *X*)

- <u>dipole coupling</u>

$$\mathcal{L}_{V1} = \frac{g_{V1}}{\Lambda_{V1}}(\bar{e}\sigma_{\alpha\beta}\mu)X^{\alpha\beta} + [H.c.]$$

$$X^{\alpha\beta} = \partial^\alpha X^\beta - \partial^\beta X^\alpha$$

Effective models

A. **Scalar *X***

- yukawa coupling (e.g. majoron induced by R-parity violation, …)

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$$\mathcal{L}_{S1} = \frac{g_{S1}}{\Lambda_{S1}}(\bar{e}\gamma_\alpha\mu)\partial^\alpha X + [H.c.]$$

B. **Vector *X***

$$\mathcal{L}_{V0} = g_{V0}(\bar{e}\gamma_\alpha\mu)X^\alpha + [H.c.]$$ (for only massive *X*)

- dipole coupling

$$\mathcal{L}_{V1} = \frac{g_{V1}}{\Lambda_{V1}}(\bar{e}\sigma_{\alpha\beta}\mu)X^{\alpha\beta} + [H.c.]$$

$$X^{\alpha\beta} = \partial^\alpha X^\beta - \partial^\beta X^\alpha$$

Formulation for decay rate

$$\Gamma = \int \frac{d^3p_e}{(2\pi)^3 2E_e} \frac{d^3p_X}{(2\pi)^3 2E_X} (2\pi)\delta\big(m_\mu - E_e - E_X\big) \times \sum_{spins} \left|\langle \psi_e^{s_e}(\boldsymbol{p}_e)\phi_X^{s_X}(\boldsymbol{p}_X)|\mathcal{L}|\psi_\mu^{s_\mu}(1S)\rangle\right|^2$$

partial wave expansion for the electron in the final state

$$\psi_e^{p,s} = \sum_{\kappa,\mu,m} 4\pi\, i^{l_\kappa}(l_\kappa, m, 1/2, s|j_\kappa, \mu) Y^*_{l_\kappa,m}(\hat{p}) e^{-i\delta_\kappa} \psi_p^{\kappa,\mu}$$

Dirac eq. for radial wave functions

$$\frac{dg_\kappa(r)}{dr} + \frac{1+\kappa}{r} g_\kappa(r) - \big(E + m + e\phi(r)\big) f_\kappa(r) = 0$$

$$\frac{df_\kappa(r)}{dr} + \frac{1-\kappa}{r} f_\kappa(r) + \big(E - m + e\phi(r)\big) g_\kappa(r) = 0$$

$$\psi_p^{\kappa,\mu}(\boldsymbol{r}) = \begin{pmatrix} g_\kappa(r)\chi_\kappa^\mu(\hat{r}) \\ i f_\kappa(r)\chi_{-\kappa}^\mu(\hat{r}) \end{pmatrix}$$

ϕ : nuclear Coulomb potential

Electron spectrum

◆ yukawa coupling

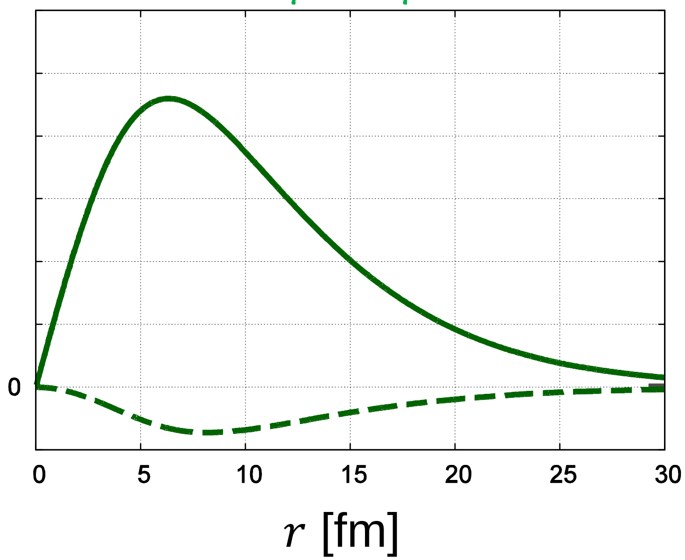
$$\frac{d\Gamma}{dE_e} = \frac{g_{S0}^2}{4\pi^2}\frac{p_e p_X}{m_\mu^2}\sum_\kappa (2j_\kappa + 1)|I_\kappa|^2$$

κ : angular momentum of e^-

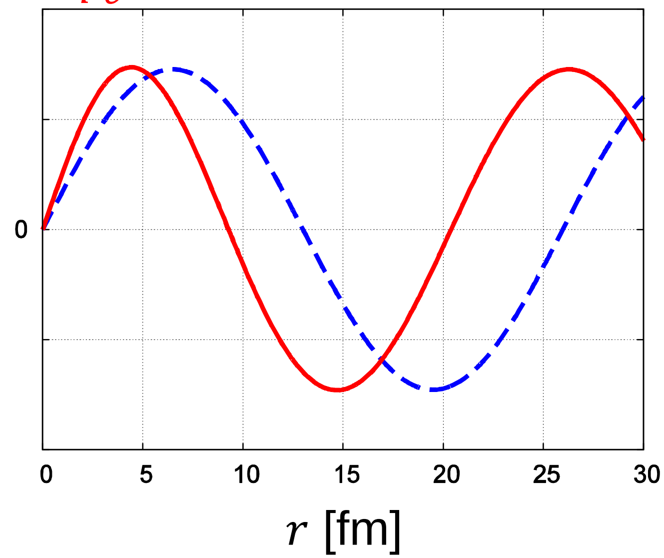
$$I_\kappa = m_\mu \int_0^\infty dr r^2 j_{l_\kappa}(p_X r)\{g_{p_e}^\kappa(r) g_\mu^{1s}(r) - f_{p_e}^\kappa(r) f_\mu^{1s}(r)\}$$

^{208}Pb

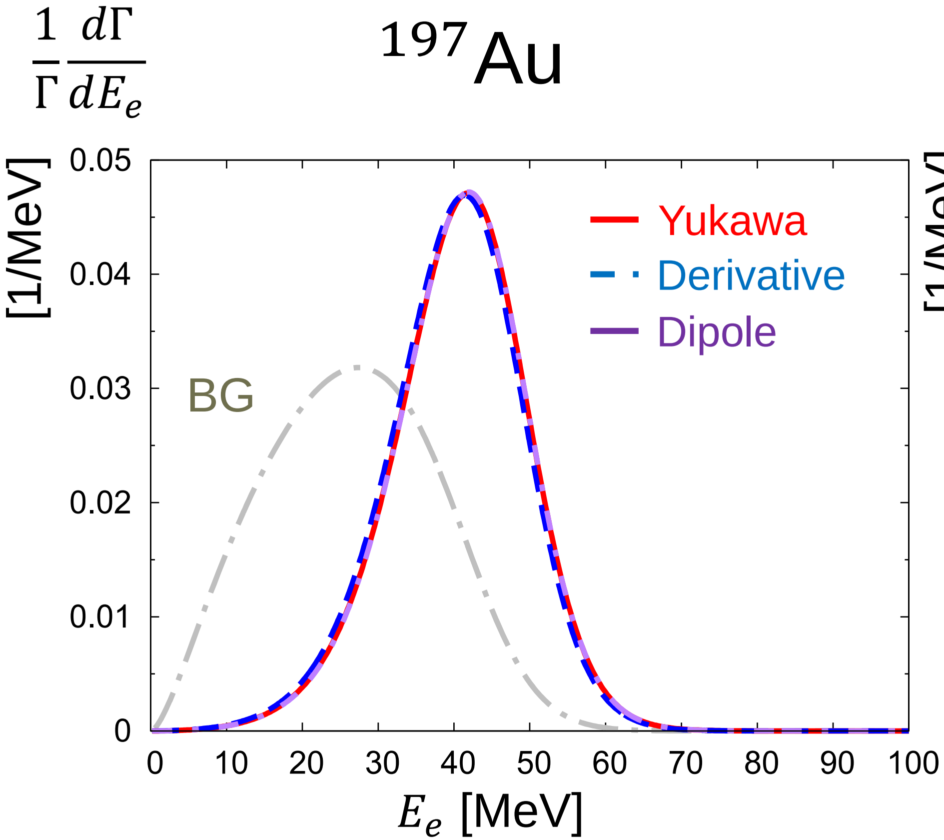
$r g_\mu^{1s}, r f_\mu^{1s}$

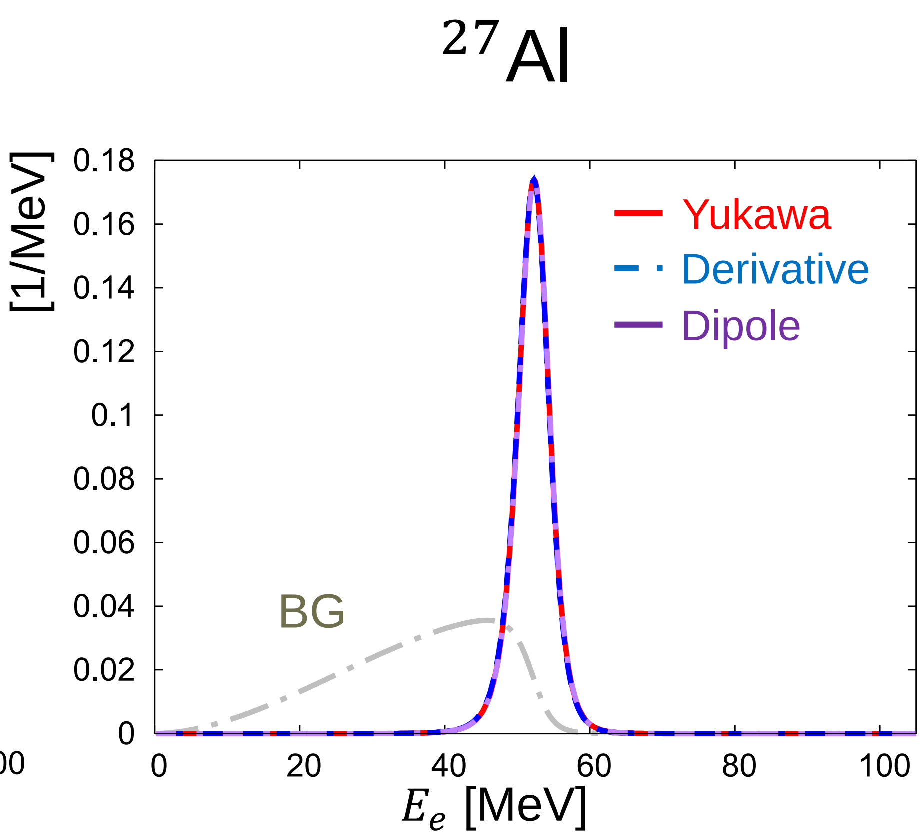


$r g_{p_e=48\mathrm{MeV}}^{\kappa=-1}, r j_0(48\mathrm{MeV} \times r)$



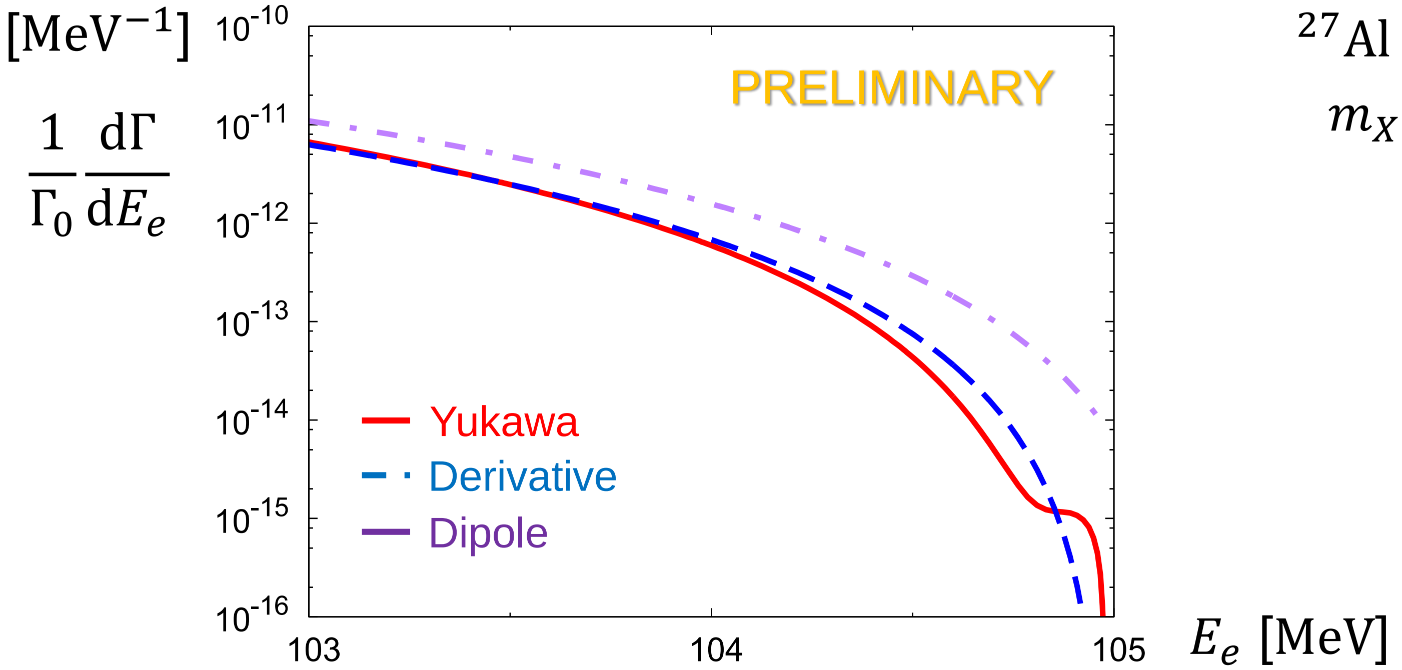
e^- spectrum ($m_X = 0$)





- Spectrum does not strongly depend on properties of X.
- The sharper peak is obtained for the lighter nucleus.

Spectrum near end-point



^{27}Al target

$m_X = 0$

$$\frac{m_\mu}{\Gamma_0}\frac{d\Gamma}{dE_e} = \sum_i a_i \Delta^i$$

$$\Delta = \frac{E_{tot} - E_e}{m_\mu}$$

	Yukawa	Derivative	Dipole
a_1	3.4×10^{-10}	8.4×10^{-16}	3.0×10^{-9}
a_2	-3.1×10^{-7}	-2.3×10^{-12}	-2.6×10^{-7}
a_3	9.7×10^{-5}	8.1×10^{-5}	3.3×10^{-4}
a_4	1.2×10^{-3}	8.7×10^{-4}	-2.8×10^{-2}

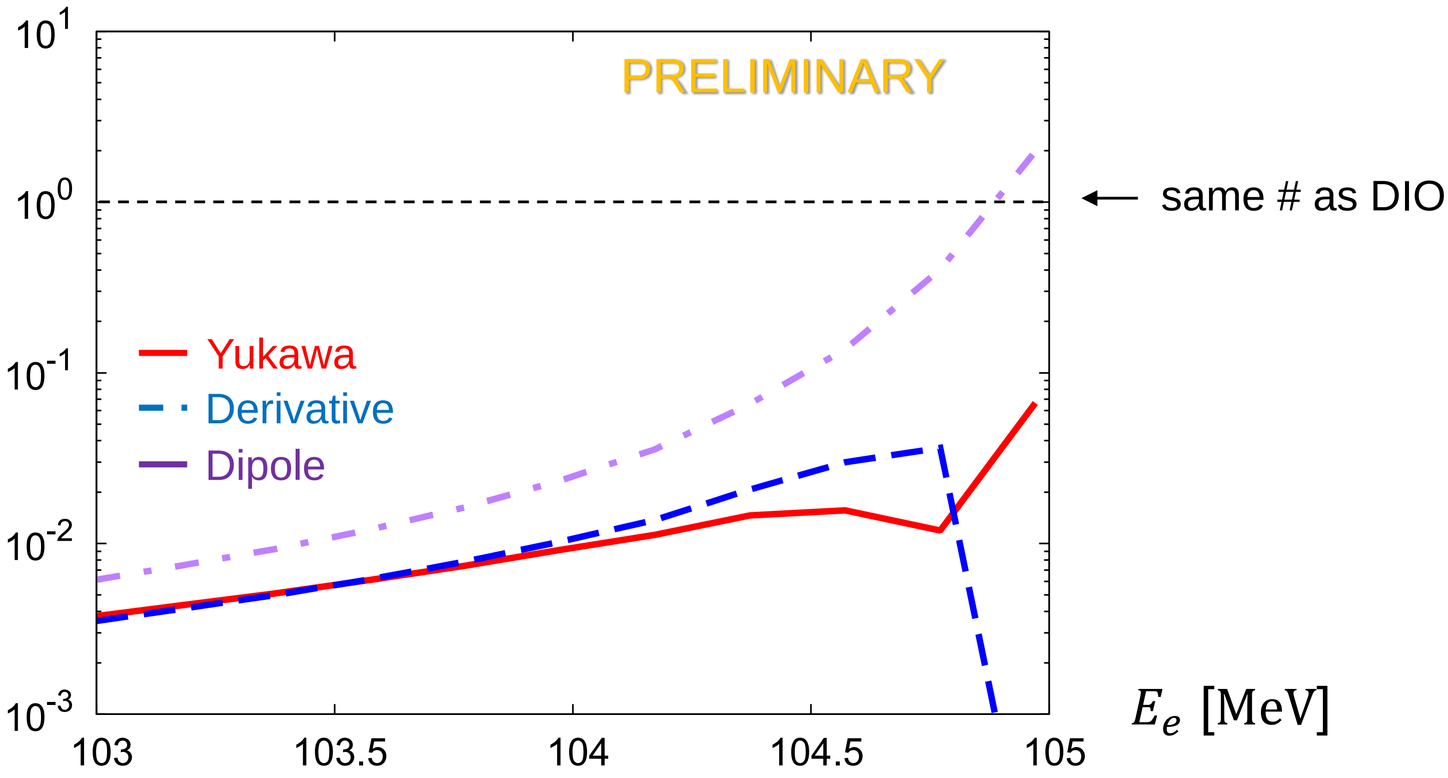
Ratio to background

$\mathrm{Br}(\mu^+ \to e^+ X) < 2.6 \times 10^{-6}$

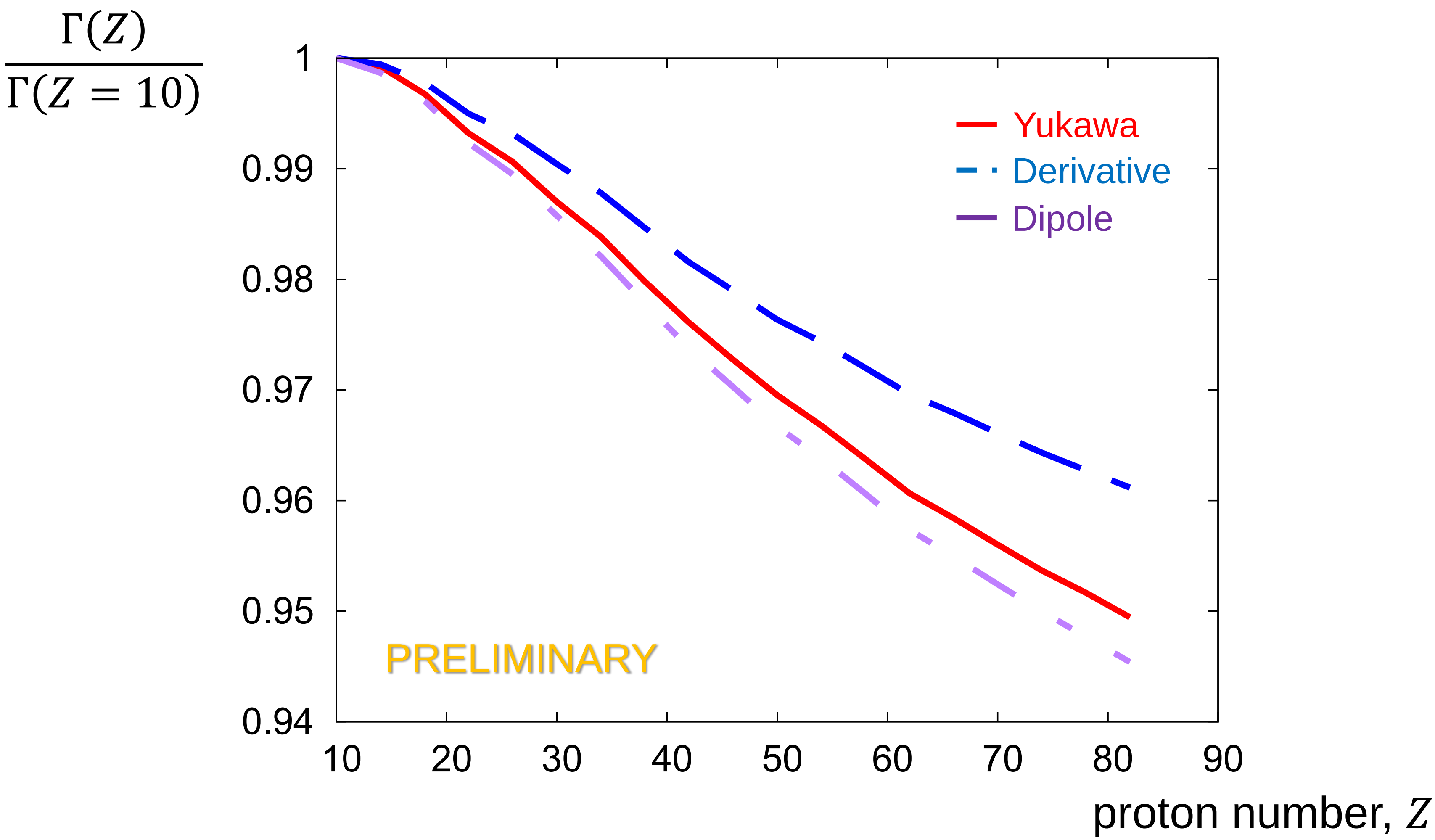
$$\frac{\mathrm{d}\Gamma_{\mu\to eX}}{\mathrm{d}E_e} \Big/ \frac{\mathrm{d}\Gamma_{\mu\to e\nu\nu}}{\mathrm{d}E_e}$$ (allowed maximum)

$^{27}\mathrm{Al}$ target

$m_X = 0$



Nuclear dependence ($m_X = 0$)



Summary

- $\mu^- \to e^- X$ in a muonic atom
  - ✓ Promising probe of a light neutral boson with CLFV
    (e.g. majoron)
  - ✓ Advantages over free muon
    - less background
    - more information (shape of spectrum, Z-dependence, …)
    - many muonic atoms in coming experiments (COMET, Mu2e, DeeMe)
  - ✓ Findings in e^- spectrum
    - the rough shape does not depend on the type of CLFV interaction
    - dipole-case : large tail
    - yukawa-case : characteristic behavior near endpoint (doubtful ?)
  - ✓ Detailed simulation is in progress with members of COMET