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Overview of Various Charged Lepton-Flavour-Violation and Related Processes

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December 6th, 2019
3rd Workshop on “Physics at the high-intensity hadron accelerator in China”, Dongguan, China

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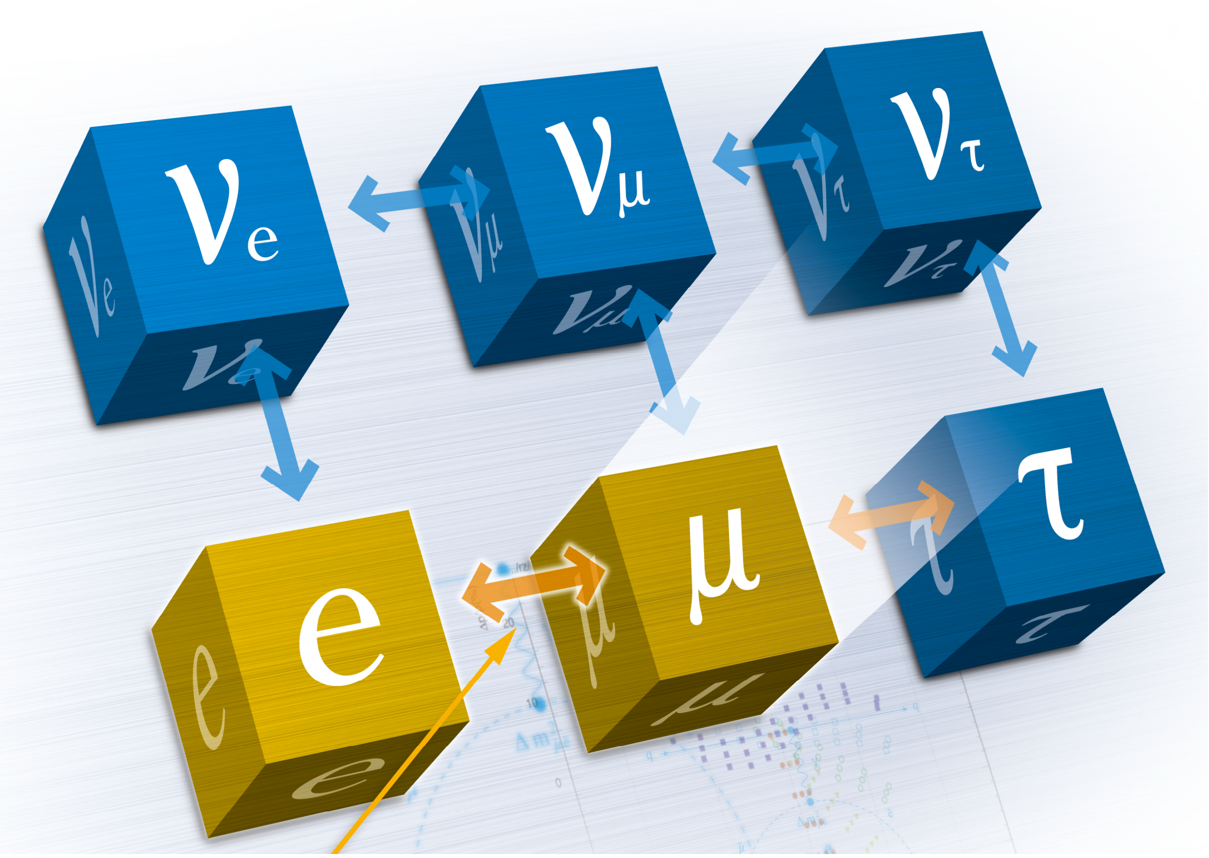
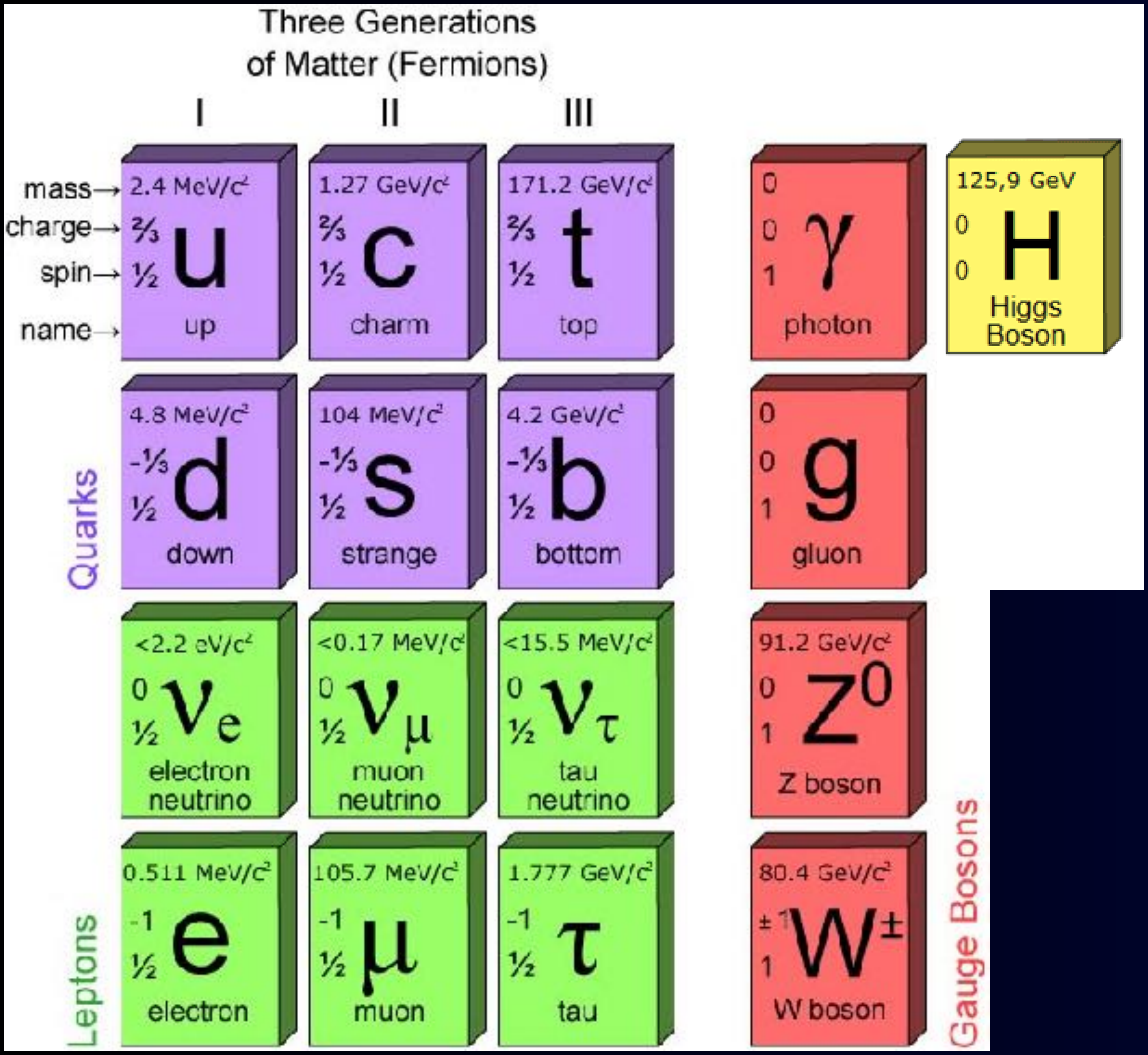
Outline

- Physics Motivation of CLFV
- Golden muon CLFV processes
- More muon CLFV processes
- CLFV of Tau leptons, Z, Higgs and Mesons
- Summary



Physics Motivation of CLFV

The Standard Model



The Standard Model is considered to be incomplete.

ex.

mass and mixing,
strong CP,
dark matter,
baryogenesis,
dark energy

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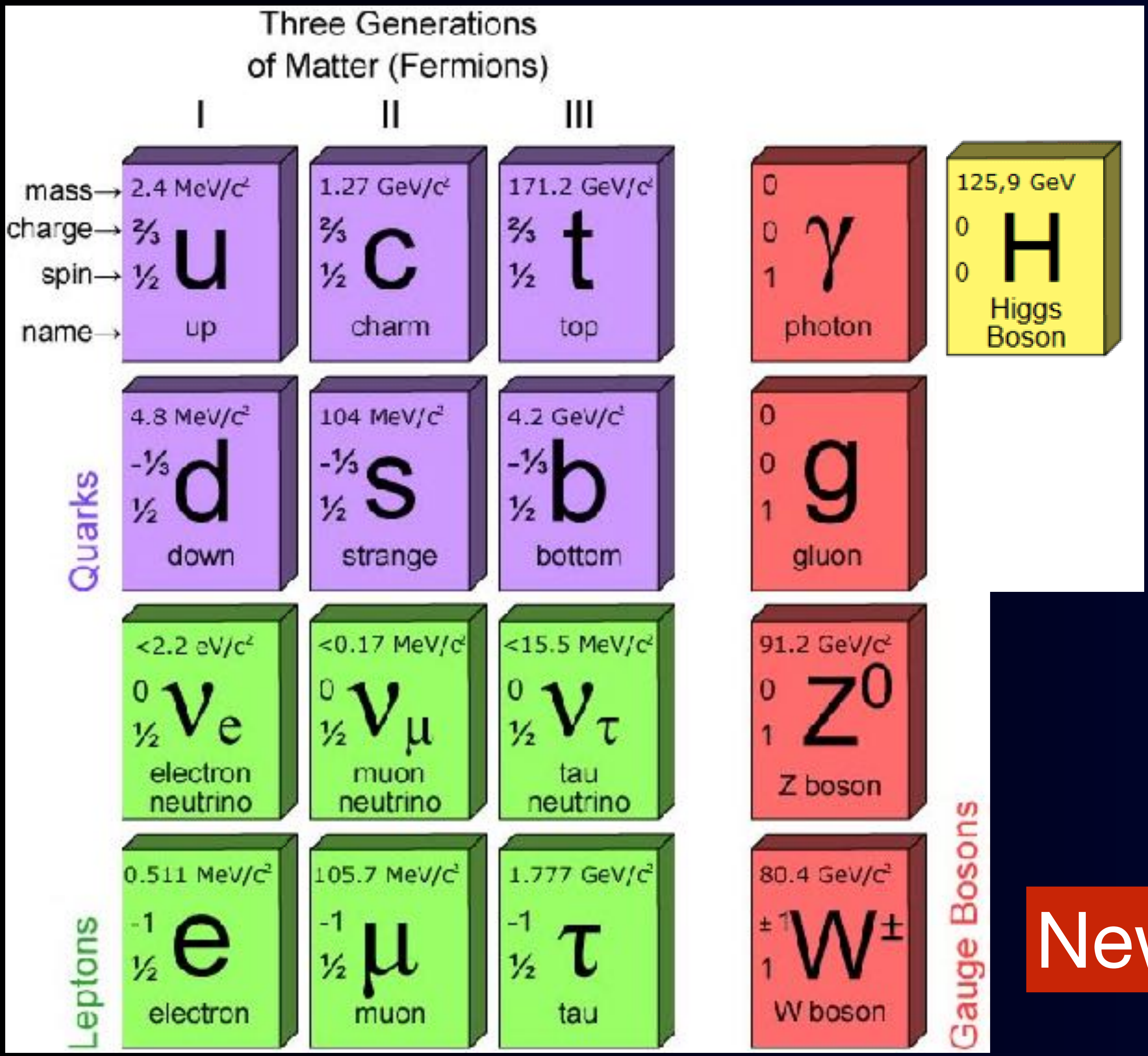

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New Physics is needed.

Sensitivity for BSM with CLFV

Effective Field Theory (EFT) Approach

$$\mathscr{L}_{eff} = \mathscr{L}_{\mathrm{SM}} + \sum_{d>4} \frac{C^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$

Λ is the energy scale of new physics
$C^{(d)}$ is the coupling constant.

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from BR(μ→eγ)<4.2×10^{-13}

$$\frac{C^6}{\Lambda^2}\mathcal{O}^6 \to \frac{C^6}{\Lambda^2}\bar{e}_L\sigma^{\rho\nu}\mu_R\Phi F_{\rho\nu}$$

⬇

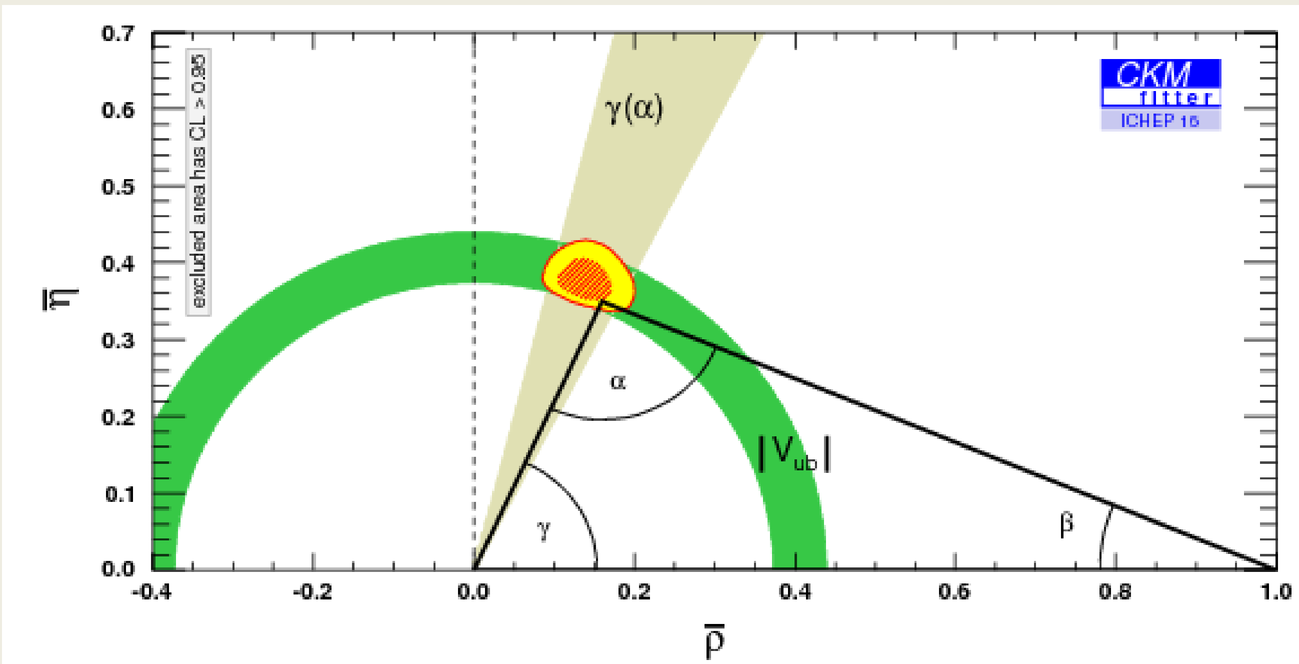
$$\Lambda \sim \mathcal{O}(10^4)\ \text{TeV}$$

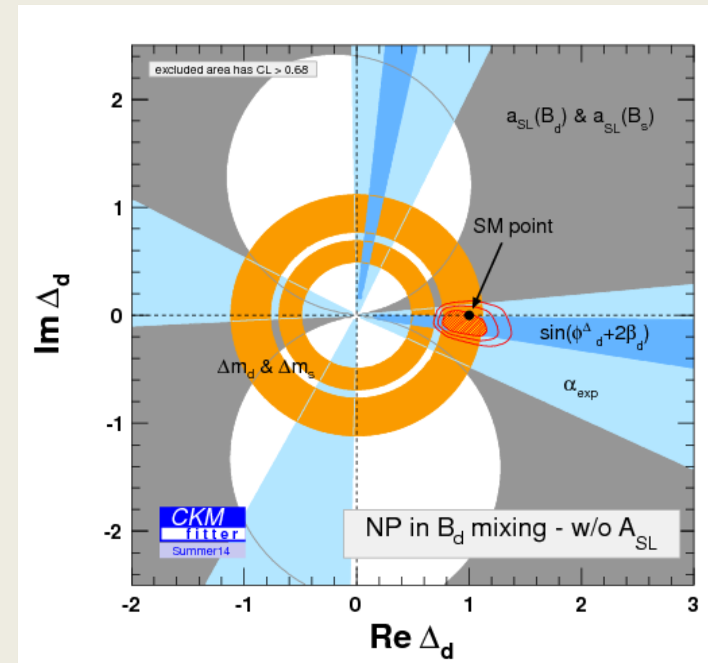
$cf.: \varepsilon_K$

	$\lvert C_a\rvert$ [$\Lambda = 1$ TeV]	Λ (TeV) [$\lvert C_a\rvert = 1$]	CLFV Process
$C_{e\gamma}^{\mu e}$	2.1×10^{-10}	6.8×10^{4}	$\mu\to e\gamma$
$C_{\ell e}^{\mu\mu\mu e,e\mu\mu\mu}$	1.8×10^{-4}	75	$\mu\to e\gamma$ [1-loop]
$C_{\ell e}^{\mu\tau\tau e,e\tau\tau\mu}$	1.0×10^{-5}	312	$\mu\to e\gamma$ [1-loop]
$C_{e\gamma}^{\mu e}$	4.0×10^{-9}	1.6×10^{4}	$\mu\to eee$
$C_{\ell\ell,ee}^{\mu eee}$	2.3×10^{-5}	207	$\mu\to eee$
$C_{\ell e}^{\mu eee,ee\mu e}$	3.3×10^{-5}	174	$\mu\to eee$
$C_{e\gamma}^{\mu e}$	5.2×10^{-9}	1.4×10^{4}	$\mu^-\text{Au}\to e^-\text{Au}$
$C_{\ell q,\ell d,ed}^{e\mu}$	1.8×10^{-6}	745	$\mu^-\text{Au}\to e^-\text{Au}$
$C_{eq}^{e\mu}$	9.2×10^{-7}	1.0×10^{3}	$\mu^-\text{Au}\to e^-\text{Au}$
$C_{\ell u,eu}^{e\mu}$	2.0×10^{-6}	707	$\mu^-\text{Au}\to e^-\text{Au}$

F. Feruglio, P. Paradisi and A. Pattori, Eur. Phys. J. C 75 (2015) no.12, 579
G. M. Pruna and A. Signer, JHEP 1410 (2014) 014

Probing NP with FCNC





ij	Λ [TeV] CPC	Λ [TeV] CPV	Observables
sd	9.8×10^2	1.6×10^4	$\Delta m_K; \epsilon_K$
bd	6.6×10^2	9.3×10^2	$\Delta m_B; S_{\psi K}$
bs	1.4×10^2	2.5×10^2	$\Delta m_{B_s}; S_{\psi\phi}$

Lower bounds on the NP scale in $\frac{1}{\Lambda^2}\,(\overline{q_{Li}}\gamma_\mu q_{Lj})(\overline{q_{Li}}\gamma^\mu q_{Lj})$

from presentation by Yossi Nir (Weizmann Institute) at EPPSU, Granada 2019

Future Sensitivity for BSM with CLFV

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Future planned experiments expecting improvements of >10,000 or more (will be described later) would probe ….

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$$R \propto \frac{1}{\Lambda^4}$$

Future Sensitivity for BSM with CLFV

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1 CLFV would explore scales way beyond the energies that our present and future colliders can directly reach.

Future Sensitivity for BSM with CLFV

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$$R \propto \frac{1}{\Lambda^4}$$

1 CLFV would explore scales way beyond the energies that our present and future colliders can directly reach.

It is crucial in establishing where is the next fundamental scale above the electroweak symmetry breaking.

CLFV in the SM

SM neutrinos

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Neutrino oscillation has been observed.
Lepton mixing in the SM has been established.

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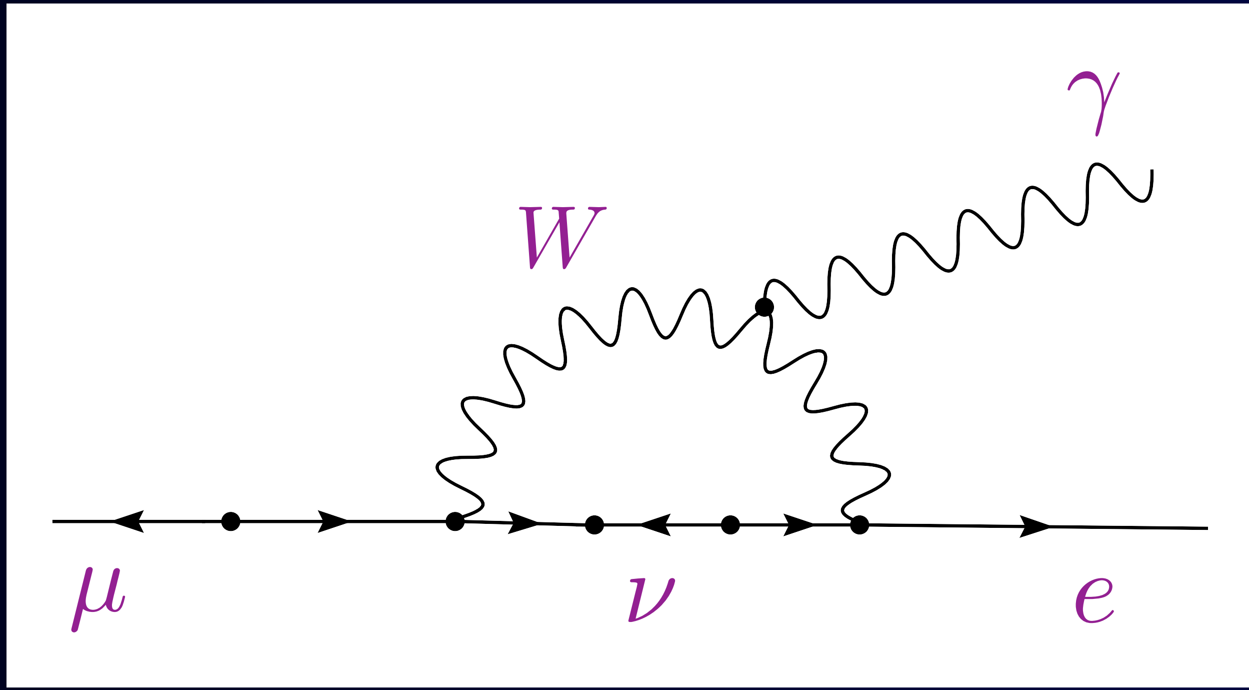

S.T. Petcov, Sov.J. Nucl. Phys. 25 (1977) 340

$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_l (V_{MNS})^*_{\mu l}(V_{MNS})_{el}\frac{m^2_{\nu_l}}{M^2_W}\right|^2$$

BR~O(10^{-54})

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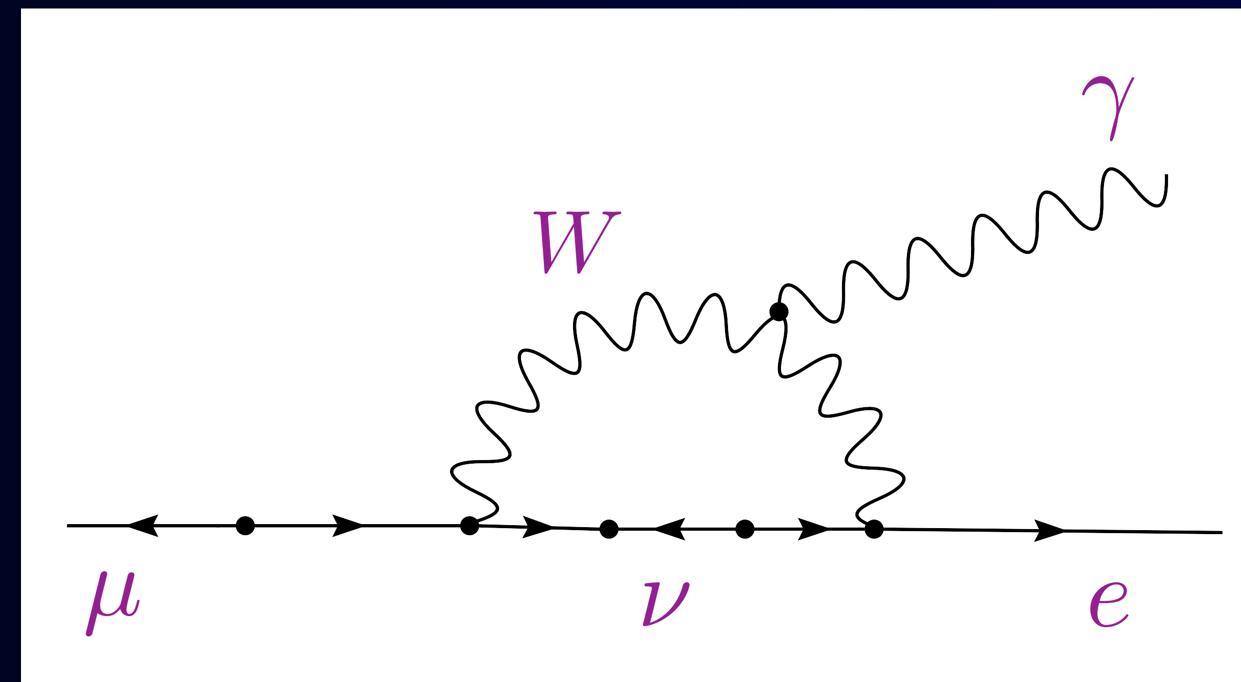

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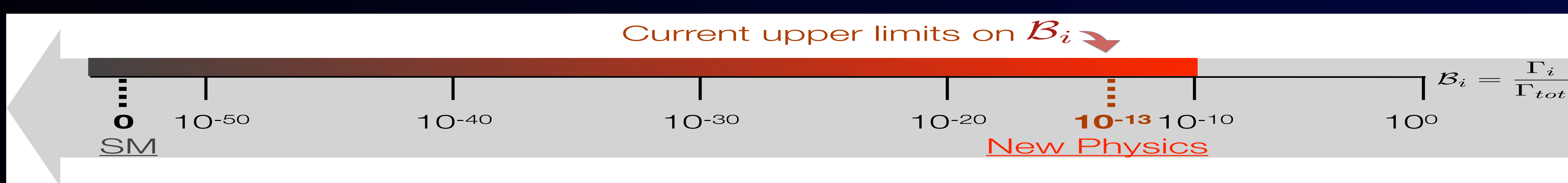

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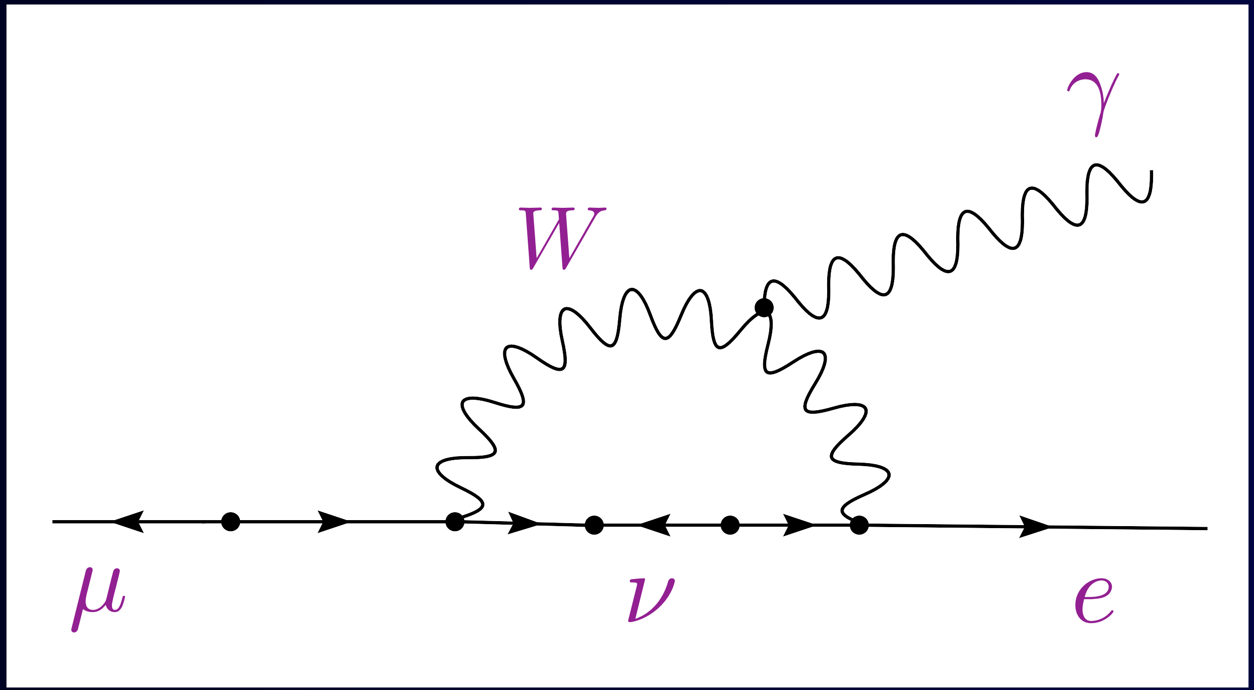

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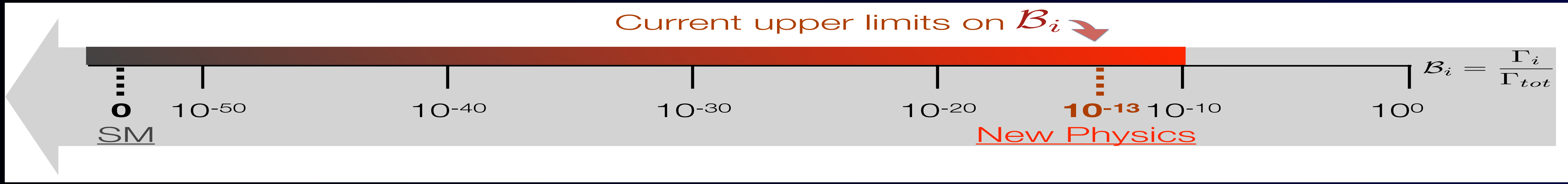

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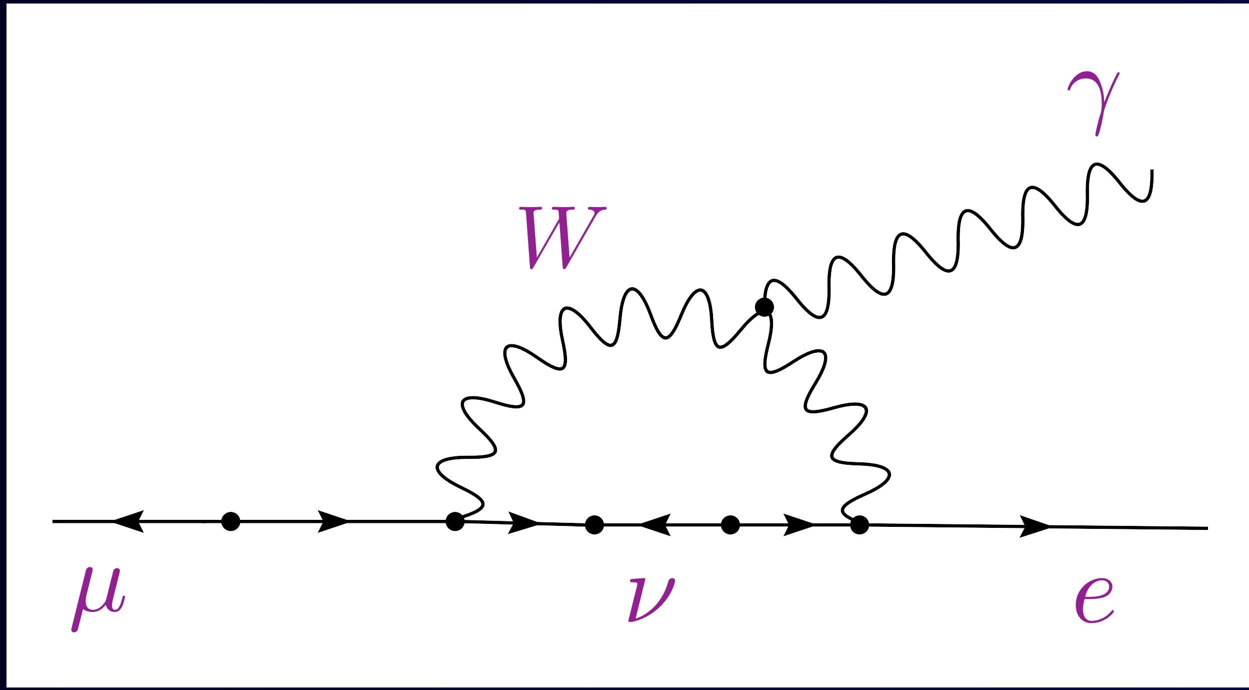

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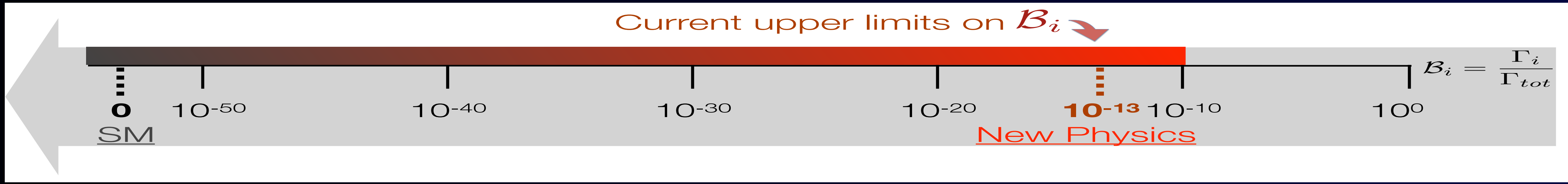
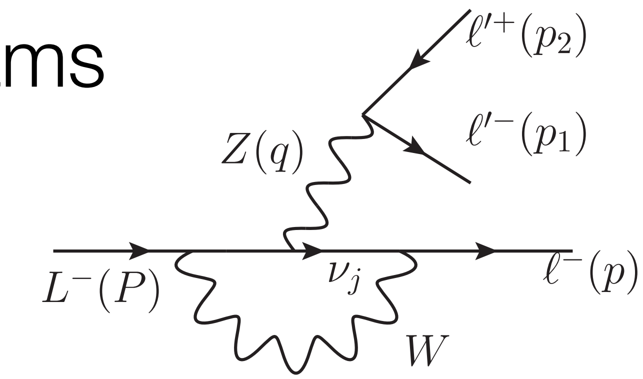


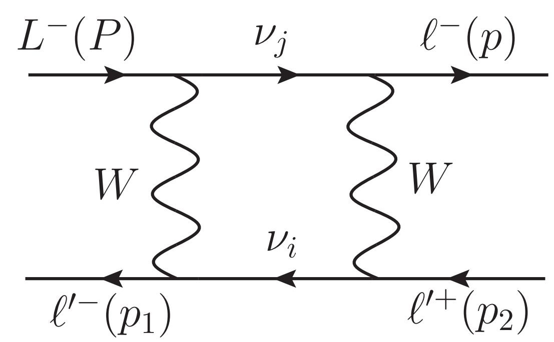
2

CLFV has a large window for BSM without SM backgrounds.

SM Contributions to $L^- \to \ell^-\ell'^+\ell'^-$

Penguin diagrams





Box diagrams

Decay channel	Our Result	Petcov's Result*	Our Result	Petcov's Result*
$\mu^- \to e^-e^+e^-$	$9{,}5 \cdot 10^{-55}$	$1{,}0 \cdot 10^{-53}$	$2{,}1 \cdot 10^{-56}$	$2{,}6 \cdot 10^{-53}$
$\tau^- \to e^-e^+e^-$	$5{,}0 \cdot 10^{-56}$	$1{,}8 \cdot 10^{-54}$	$3{,}6 \cdot 10^{-57}$	$4{,}5 \cdot 10^{-54}$
$\tau^- \to \mu^-\mu^+\mu^-$	$1{,}0 \cdot 10^{-54}$	$3{,}7 \cdot 10^{-53}$	$7{,}6 \cdot 10^{-56}$	$9{,}7 \cdot 10^{-53}$
$\tau^- \to e^-\mu^+\mu^-$	$2{,}9 \cdot 10^{-56}$	$1{,}0 \cdot 10^{-54}$	$1{,}7 \cdot 10^{-57}$	$2{,}2 \cdot 10^{-54}$
$\tau^- \to \mu^-e^+e^-$	$7{,}3 \cdot 10^{-55}$	$2{,}5 \cdot 10^{-53}$	$4{,}0 \cdot 10^{-56}$	$5{,}0 \cdot 10^{-53}$

Total

Decay channel	Our Result	Petcov's Result*
$\mu^- \to e^-e^+e^-$	$7{,}4 \cdot 10^{-55}$	$8{,}5 \cdot 10^{-54}$
$\tau^- \to e^-e^+e^-$	$3{,}2 \cdot 10^{-56}$	$1{,}4 \cdot 10^{-54}$
$\tau^- \to \mu^-\mu^+\mu^-$	$6{,}4 \cdot 10^{-55}$	$3{,}2 \cdot 10^{-53}$
$\tau^- \to e^-\mu^+\mu^-$	$2{,}1 \cdot 10^{-56}$	$9{,}4 \cdot 10^{-55}$
$\tau^- \to \mu^-e^+e^-$	$5{,}2 \cdot 10^{-55}$	$2{,}1 \cdot 10^{-53}$

S. T. Petcov, Sov. J. Nucl. Phys. 25, 340 (1977).
G. Hernandez-Tome, G. Lopez-Castroand P. Roig. ArXiv:1807.0605

“Golden” μ→e CLFV Transition Processes

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$$\mu^+ \rightarrow e^+\gamma$$

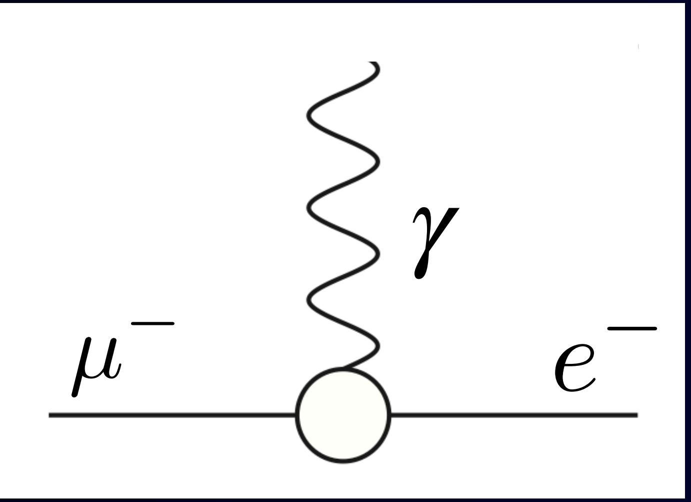
$$\mu^+ \rightarrow e^+e^+e^-$$

$$\mu^- N \rightarrow e^- N$$

“Golden” μ→e CLFV Transition Processes

dipole interaction

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



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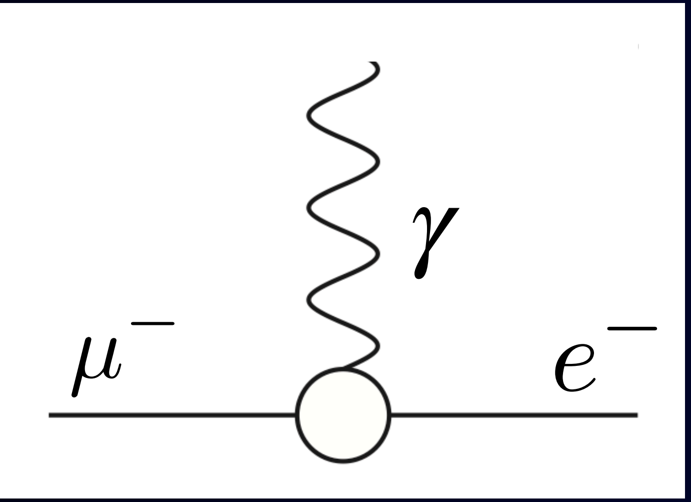
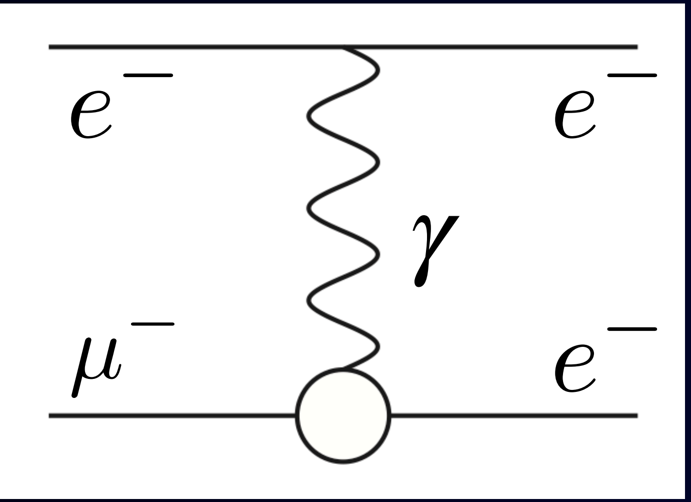
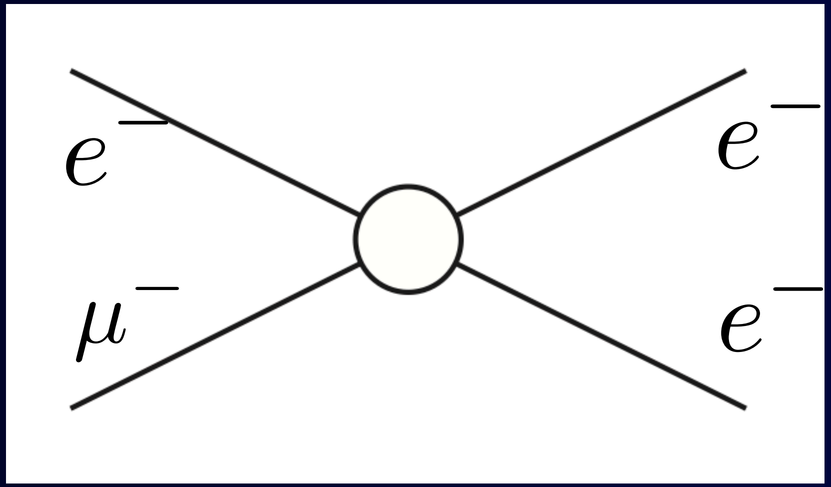


contact interaction

$$\mu^+ \rightarrow e^+e^+e^-$$





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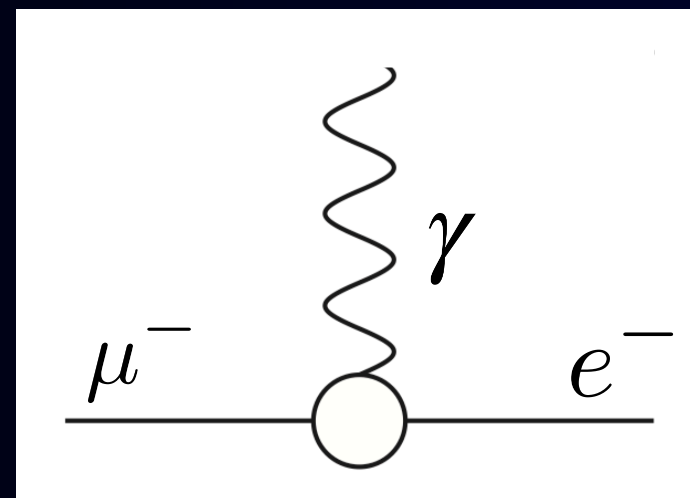

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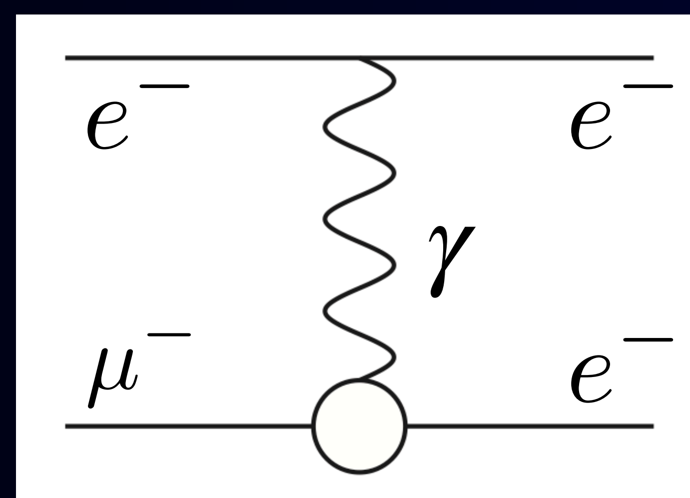

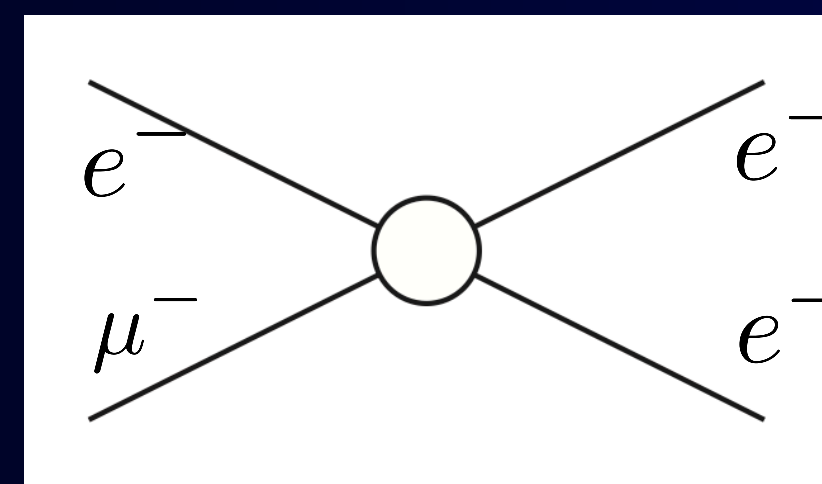

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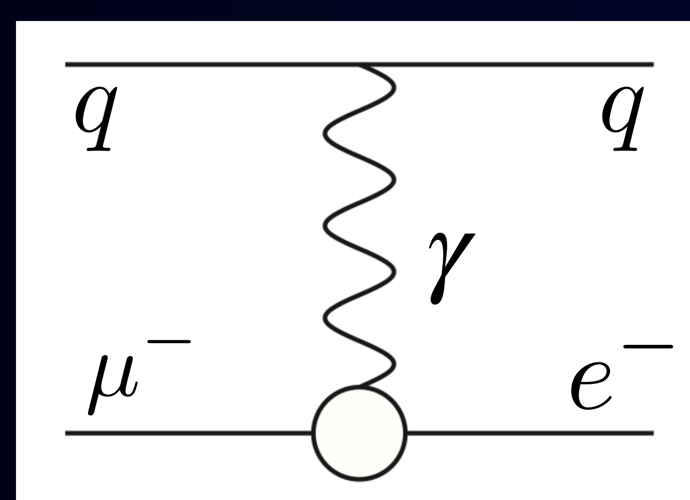
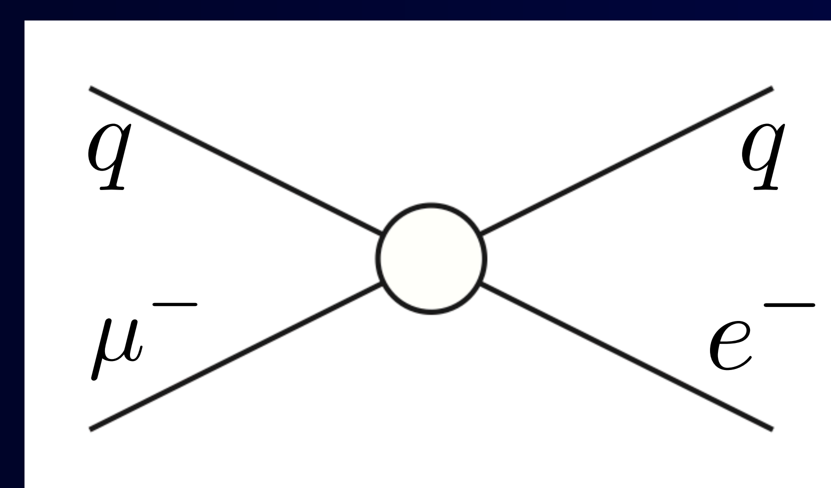


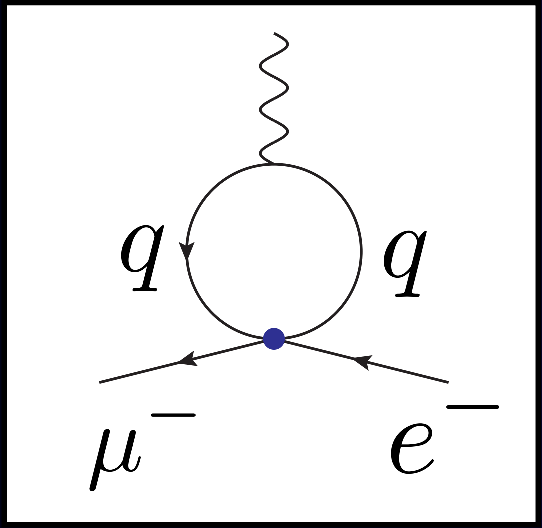


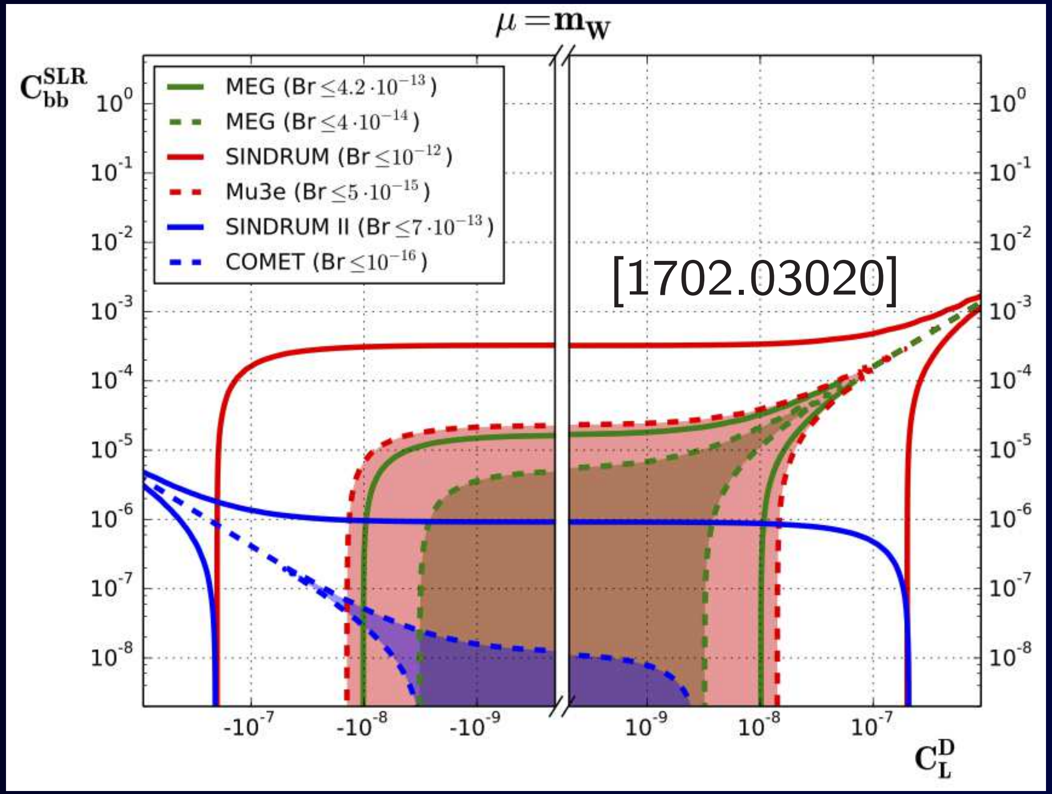
Operator Mixing via RGE

Operator Mixing via RGE

EFT at high physics scale

The operators are mixed in RGE at the experiment scale





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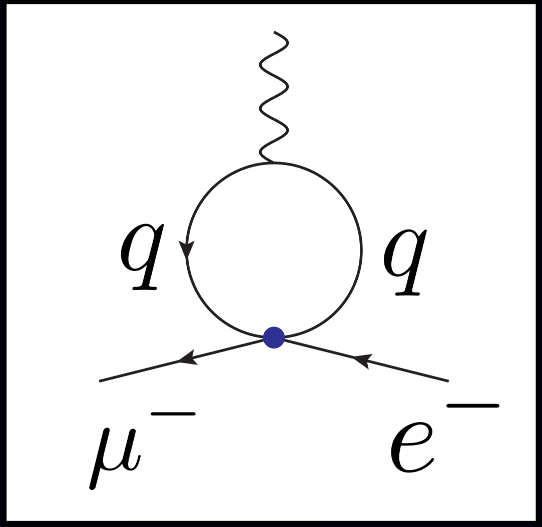
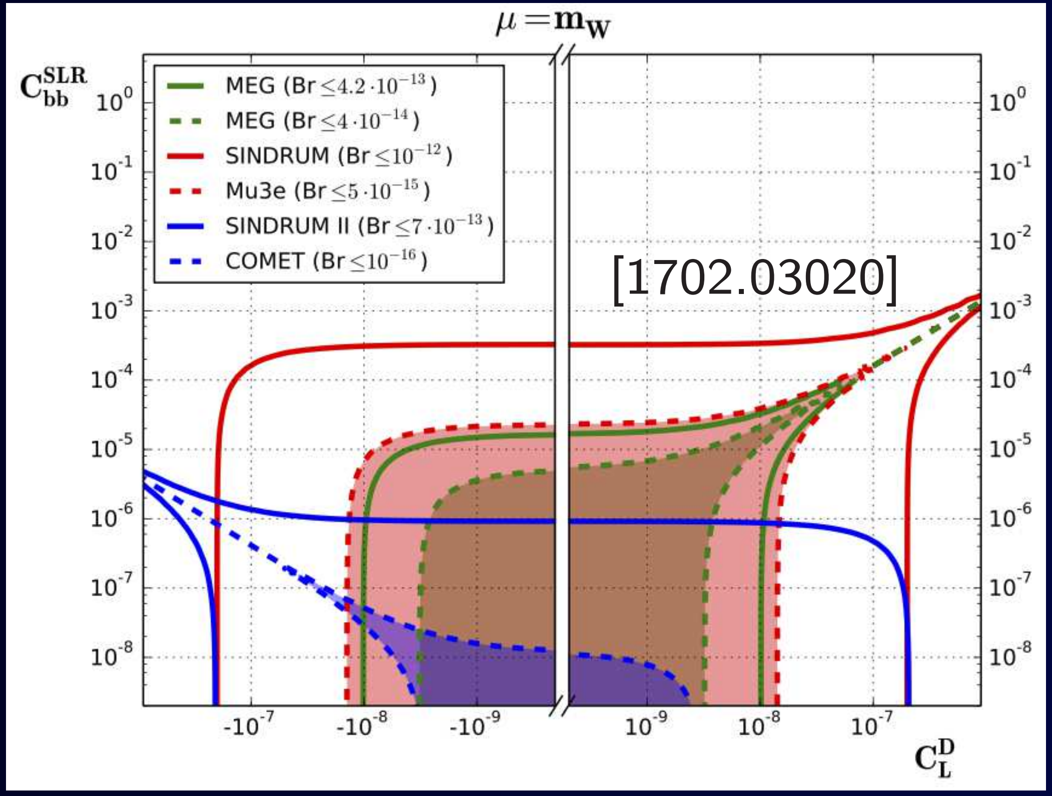




All processes are equally important (not competing).

A. Crivellin, S. Davidson, G.M. Pruna and A. Signer, arXiv:1611.03409

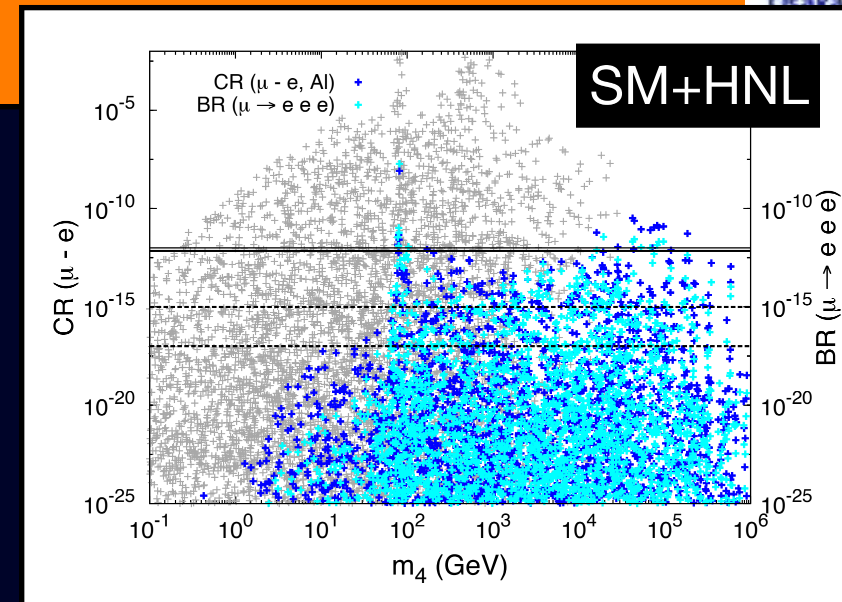
A. Crivellin, S. Davidson, G.M. Pruna and A. Signer, JHEP 117 (2017) no.5

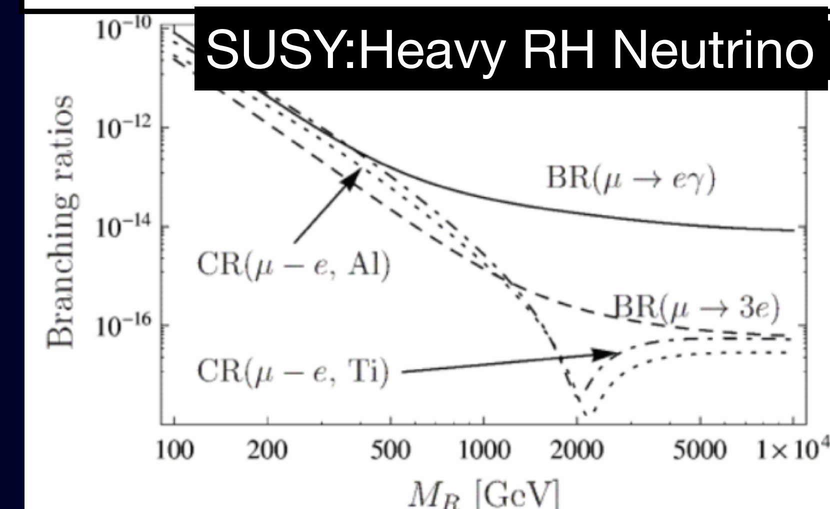
S. Davidson, Eur. Phys. J. C76 (2016) 370

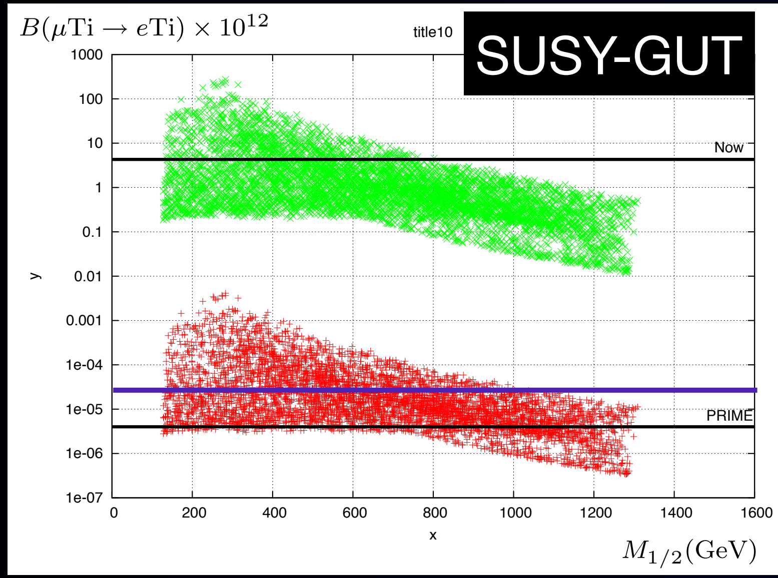
Model dependent CLFV

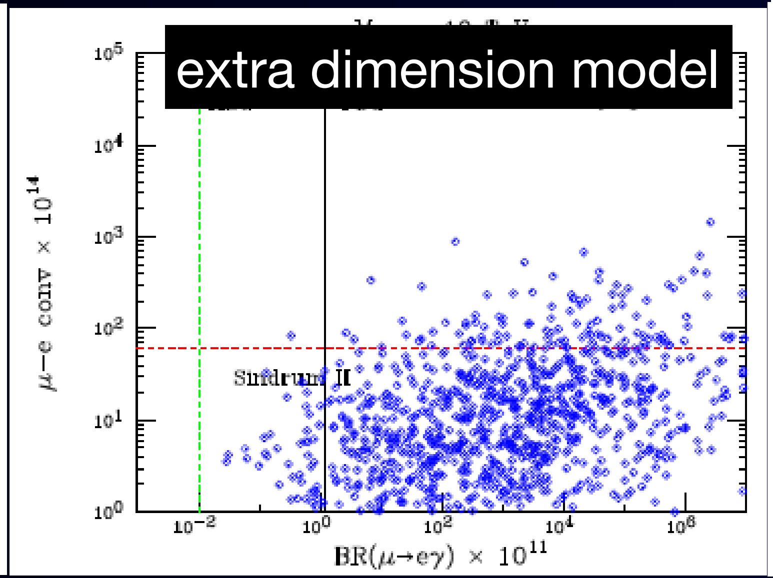
Model dependent CLFV

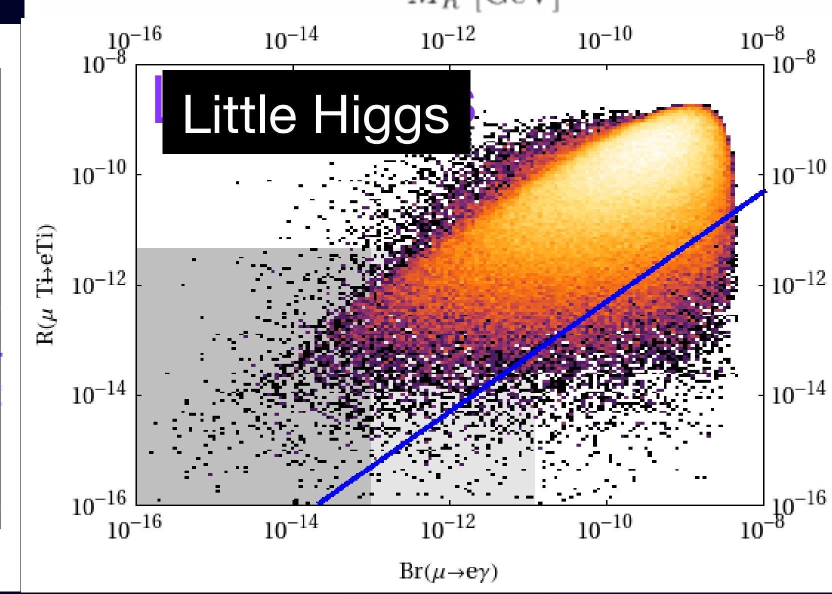
- SM + NHL (neutral heavy lepton)
- large extra dimensions
- extended Higgs sector
- additional vector boson (Z')
- leptoquark
- SUSY-GUT and SUSY seesaw
- R-parity violating SUSY
- low-energy seesaw
- etc. etc.











Muon g-2 Anomaly and Muon CLFV

Muon g-2 Anomaly and Muon CLFV

muon g-2 anomaly

flavour conserving component of the BSM dipole operator

muon CLFV ($\mu \to e\gamma$ etc.)

flavour violating component of the BSM dipole operator

Muon g-2 Anomaly and Muon CLFV

Osaka University

muon g-2 anomaly

flavour conserving component of the BSM dipole operator

muon CLFV ($\mu \to e\gamma$ etc.)

flavour violating component of the BSM dipole operator

If the Muon g-2 anomaly is confirmed, it will establish the presence of a BSM muon interaction which may induce sizable effects of muon CLFV.

M. Lindner, M. Platscher, and F.S. Queiroz, arXiv:161006587

LFUV and LFV

LFUV and LFV

Osaka University

Lepton Flavour Universality Violation (UFUV)

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\, \mu^+\, \mu^-)}{\mathrm{BR}(B \to K^{(*)}\, e^+\, e^-)}$$

neutral current

$$R_{K^{(*)}}^{exp} < R_{K^{(*)}}^{SM}$$

$$R_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\, \tau^-\, \bar{\nu})}{\mathrm{BR}(B \to D^{(*)}\, \ell^-\, \bar{\nu})}$$

charged current

$$R_{D^{(*)}}^{exp} > R_{D^{(*)}}^{SM}$$

Many discussions on the relation between LFUV and CLFV. If confirmed, it might introduce CLFV. in particular, models such as Z' and Leptoquarks.

Golden Muon CLFV

Muon CLFV Processes

- $\mu^+ \to e^+\gamma$
- $\mu^+ \to e^+e^+e^-$
- $\mu^- + N(A,Z) \to e^- + N(A,Z)$
- $\mu^- + N(A,Z) \to e^+ + N(A,Z-2)$
- $\mu^- + N(A,Z) \to \mu^+ + N(A,Z-2)$
- $\mu^+e^- \to \mu^-e^+$
- $\mu^-e^- \to e^-e^-$
- $\mu + N \to \tau + X$
- $\nu_\mu + N \to \tau^+ + X$
- $\mu \to ea$

Muon CLFV Processes

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- $\nu_\mu + N \to \tau^+ + X$
- $\mu \to ea$

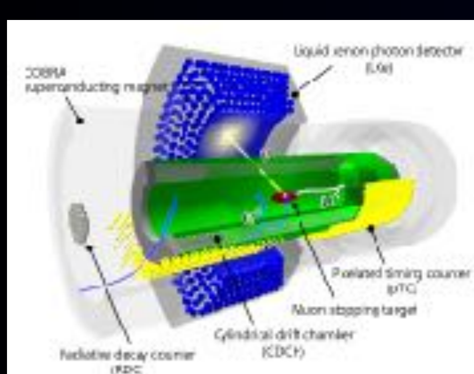
Current Limits of Muon LFV Processes

Current Limits of Muon LFV Processes

	Current upper limit	Future sensitivity
$\mu \to e\gamma$	4.2 x 10^{-13}	~ 4 x 10^{-14}
$\mu \to eee$	1.0 x 10^{-12}	~1.0 x 10^{-16}
$\mu N \to eN'$	7.0 x 10^{-13}	< 10^{-16}

in this workshop

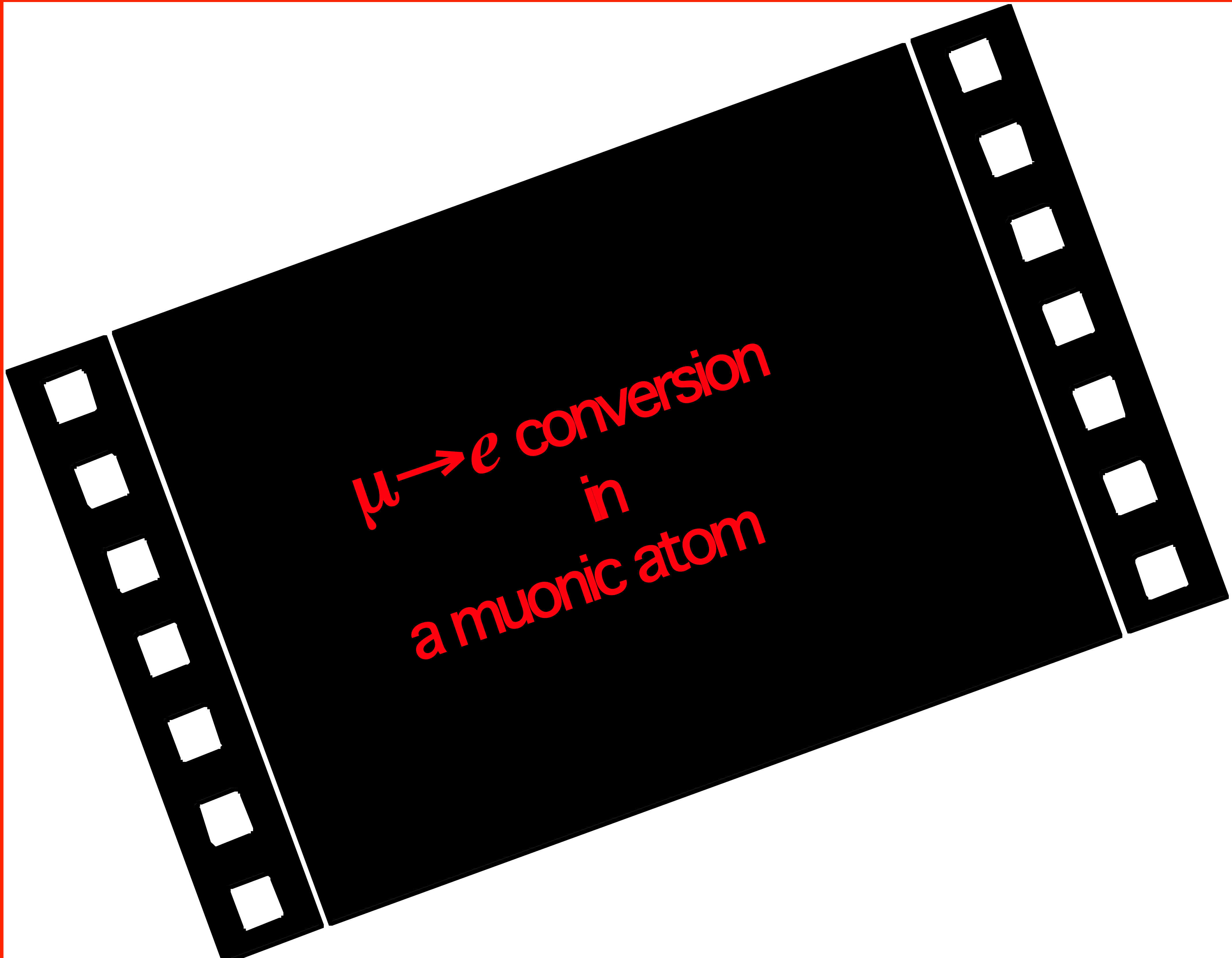
MEG/MEG-II
Stefan Ritz



Mu3e

Mu2e
Wang Ying

COMET
Chen Wu


$\mu \rightarrow e$ conversion
in
a muonic atom

EFT approach for μ→e conversion

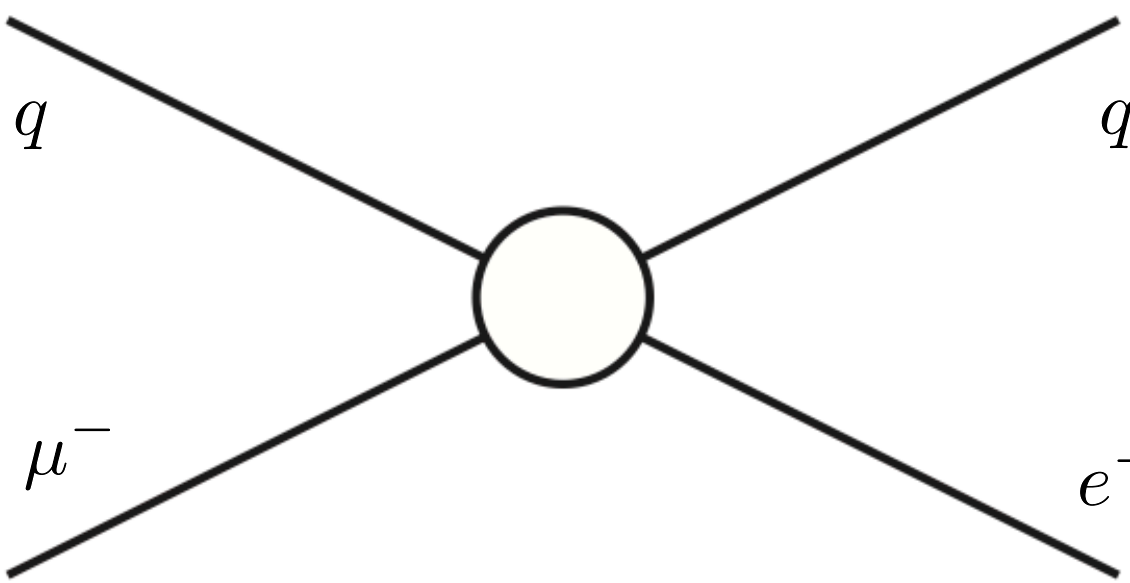
EFT approach for μ→e conversion

$$\mu^- + q \to e^- + q$$

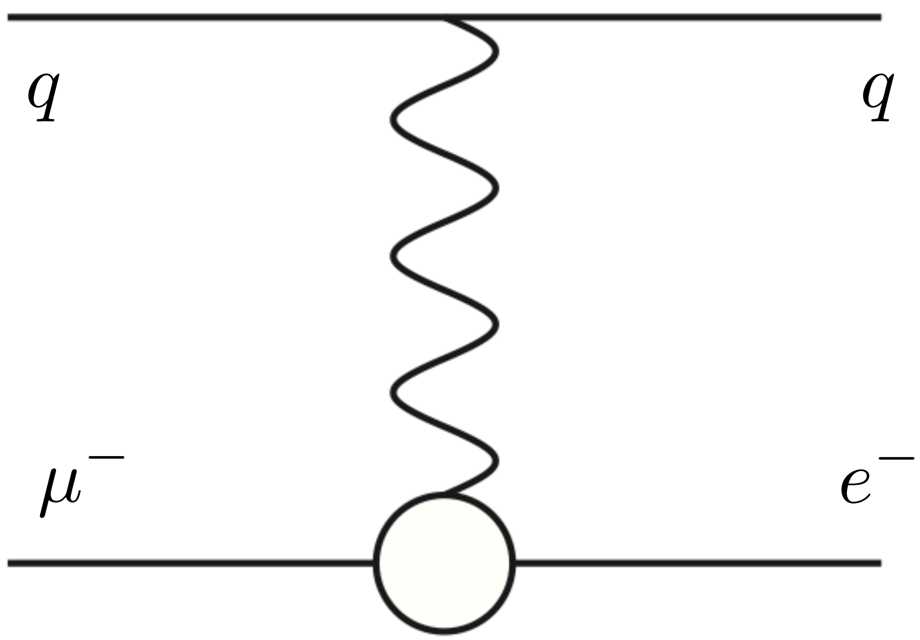
EFT approach for μ→e conversion

$$\mu^- + q \to e^- + q$$

contact interaction



dipole interaction



$$(\overline{e}\Gamma P_Y \mu)(\overline{q}\Gamma q) \quad , \quad q \in \{u, d, s\}$$

$$\Gamma = \{I, \gamma_5, \gamma, \gamma\gamma_5, \sigma\}$$

S, P, V, A, T

dipole (D)

Effective Field Theory for μ→e Conversion

two-lepton and two-nucleon operators and dipole operators

$$
\begin{aligned}
\mathcal{L}_{\mu A\to eA}(\Lambda_{expt}) \quad = \quad & -\frac{4G_F}{\sqrt{2}}\sum_{N=p,n}\Big[m_\mu\left(C_{DL}\overline{e_R}\sigma^{\alpha\beta}\mu_L F_{\alpha\beta}+C_{DR}\overline{e_L}\sigma^{\alpha\beta}\mu_R F_{\alpha\beta}\right) \\
& +\left(\widetilde{C}_{SL}^{(NN)}\overline{e}P_L\mu+\widetilde{C}_{SR}^{(NN)}\overline{e}P_R\mu\right)\overline{N}N \\
& +\left(\widetilde{C}_{P,L}^{(NN)}\overline{e}P_L\mu+\widetilde{C}_{P,R}^{(NN)}\overline{e}P_R\mu\right)\overline{N}\gamma_5 N \\
& +\left(\widetilde{C}_{VL}^{(NN)}\overline{e}\gamma^\alpha P_L\mu+\widetilde{C}_{VR}^{(NN)}\overline{e}\gamma^\alpha P_R\mu\right)\overline{N}\gamma_\alpha N \\
& +\left(\widetilde{C}_{A,L}^{(NN)}\overline{e}\gamma^\alpha P_L\mu+\widetilde{C}_{A,R}^{(NN)}\overline{e}\gamma^\alpha P_R\mu\right)\overline{N}\gamma_\alpha\gamma_5 N \\
& +\left(\widetilde{C}_{Der,L}^{(NN)}\overline{e}\gamma^\alpha P_L\mu+\widetilde{C}_{Der,R}^{(NN)}\overline{e}\gamma^\alpha P_R\mu\right)i(\overline{N}\overleftrightarrow{\partial}_\alpha\gamma_5 N) \\
& +\left(\widetilde{C}_{T,L}^{(NN)}\overline{e}\sigma^{\alpha\beta}P_L\mu+\widetilde{C}_{T,R}^{(NN)}\overline{e}\sigma^{\alpha\beta}P_R\mu\right)\overline{N}\sigma_{\alpha\beta}N+h.c.\Big] \quad .
\end{aligned}
$$

dipole

scalar

pseudo-scalar

vector

axial-vector

(derivative)

tensor

Effective Field Theory for μ→e Conversion

two-lepton and two-nucleon operators and dipole operators

$$\mathcal{L}_{\mu A\to eA}(\Lambda_{expt}) = -\frac{4G_F}{\sqrt{2}}\sum_{N=p,n}\Big[m_\mu\left(C_{DL}\overline{e_R}\sigma^{\alpha\beta}\mu_L F_{\alpha\beta}+C_{DR}\overline{e_L}\sigma^{\alpha\beta}\mu_R F_{\alpha\beta}\right)$$

dipole

scalar
$$+\left(\widetilde{C}^{(NN)}_{SL}\overline{e}P_L\mu+\widetilde{C}^{(NN)}_{SR}\overline{e}P_R\mu\right)\overline{N}N$$

pseudo-scalar
$$+\left(\widetilde{C}^{(NN)}_{P,L}\overline{e}P_L\mu+\widetilde{C}^{(NN)}_{P,R}\overline{e}P_R\mu\right)\overline{N}\gamma_5 N$$

vector
$$+\left(\widetilde{C}^{(NN)}_{VL}\overline{e}\gamma^\alpha P_L\mu+\widetilde{C}^{(NN)}_{VR}\overline{e}\gamma^\alpha P_R\mu\right)\overline{N}\gamma_\alpha N$$

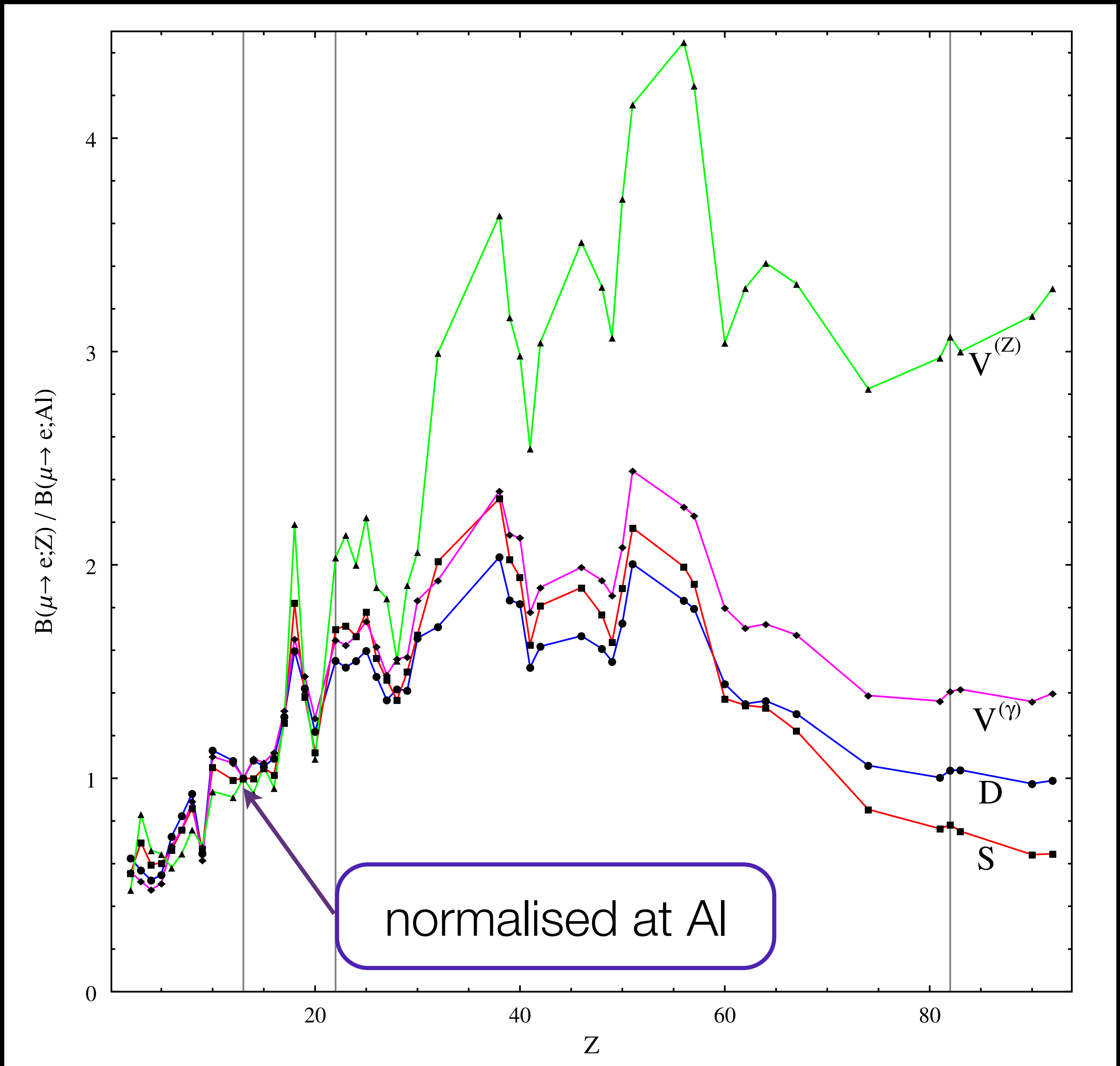
axial-vector
$$+\left(\widetilde{C}^{(NN)}_{A,L}\overline{e}\gamma^\alpha P_L\mu+\widetilde{C}^{(NN)}_{A,R}\overline{e}\gamma^\alpha P_R\mu\right)\overline{N}\gamma_\alpha\gamma_5 N$$

(derivative)
$$+\left(\widetilde{C}^{(NN)}_{Der,L}\overline{e}\gamma^\alpha P_L\mu+\widetilde{C}^{(NN)}_{Der,R}\overline{e}\gamma^\alpha P_R\mu\right)i(\overline{N}\overleftrightarrow{\partial}_\alpha\gamma_5 N)$$

tensor
$$+\left(\widetilde{C}^{(NN)}_{T,L}\overline{e}\sigma^{\alpha\beta}P_L\mu+\widetilde{C}^{(NN)}_{T,R}\overline{e}\sigma^{\alpha\beta}P_R\mu\right)\overline{N}\sigma_{\alpha\beta}N+h.c.\Big] \quad .$$

22 coeff. = 2 (dipole) + 2 (left/right) x 2 (proton/neutron) x 5 (interaction)

Discrimination of the interactions by different targets



vector interaction (with Z boson)	with Z penguin
vector interaction (with photon -charge radius)	left-right models
dipole interaction	SUSY-GUT
scalar interaction	SUSY seesaw

R. Kitano, M. Koike and Y. Okada, Phys.Rev. D66 (2002) 096002; D76 (2007) 059902

V. Cirigliano, R. Kitano, Y. Okada, and P. Tuzon, Phys. Rev. D80 (2009) 013002

Spin Dependent μ-e conversion and Spin Independent μ-e conversion

Spin Dependent μ-e conversion and Spin Independent μ-e conversion

dipole interaction

vector interaction

scalar interaction

Spin independent μ-e Conversion (coherent)

Spin Dependent μ-e conversion and Spin Independent μ-e conversion

dipole interaction

vector interaction

scalar interaction

Spin independent μ-e Conversion (coherent)

Pseudo-scaler interaction

axial vector interaction

tensor interaction

Spin dependent μ-e Conversion (incoherent)

compare zero-spin and non-zero-spin nuclear targets

V. Cirigliano, S. Davidson, YK, Phys. Lett. B 771 (2017) 242

S. Davidson, YK, A. Saporta, Eur. Phys. J. C78 (2018) 109

More Muon CLFV

Muon CLFV Processes

- $\mu^+ \rightarrow e^+\gamma$
- $\mu^+ \rightarrow e^+e^+e^-$
- $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$
- $\mu^- + N(A,Z) \rightarrow e^+ + N(A,Z-2)$
- $\mu^- + N(A,Z) \rightarrow \mu^+ + N(A,Z-2)$
- $\mu^+e^- \rightarrow \mu^-e^+$
- $\mu^-e^- \rightarrow e^-e^-$
- $\mu + N \rightarrow \tau + X$
- $\nu_\mu + N \rightarrow \tau^+ + X$
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μ^- to e^+ conversion in muonic atom

μ^- to e^+ conversion in muonic atom

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$$\mu^- + N(A,Z) \to e^+ + N(A,Z-2)$$

Lepton number violation (LNV) and
Lepton flavour violation (LFV)

Final can be the ground or excited states.

signal signature

$$E_{\mu e^+} = m_\mu - B_\mu - E_{rec} - (M(A,Z-2) - M(A,Z))$$

backgrounds

- radiative muon nuclear capture (RMC)

$$\mu^- + N(A,Z) \to N(A,Z-1) + \nu + \gamma$$

$$E_{RMC} = m_\mu - B_\mu - E_{rec} - (M(A,Z-1) - M(A,Z))$$

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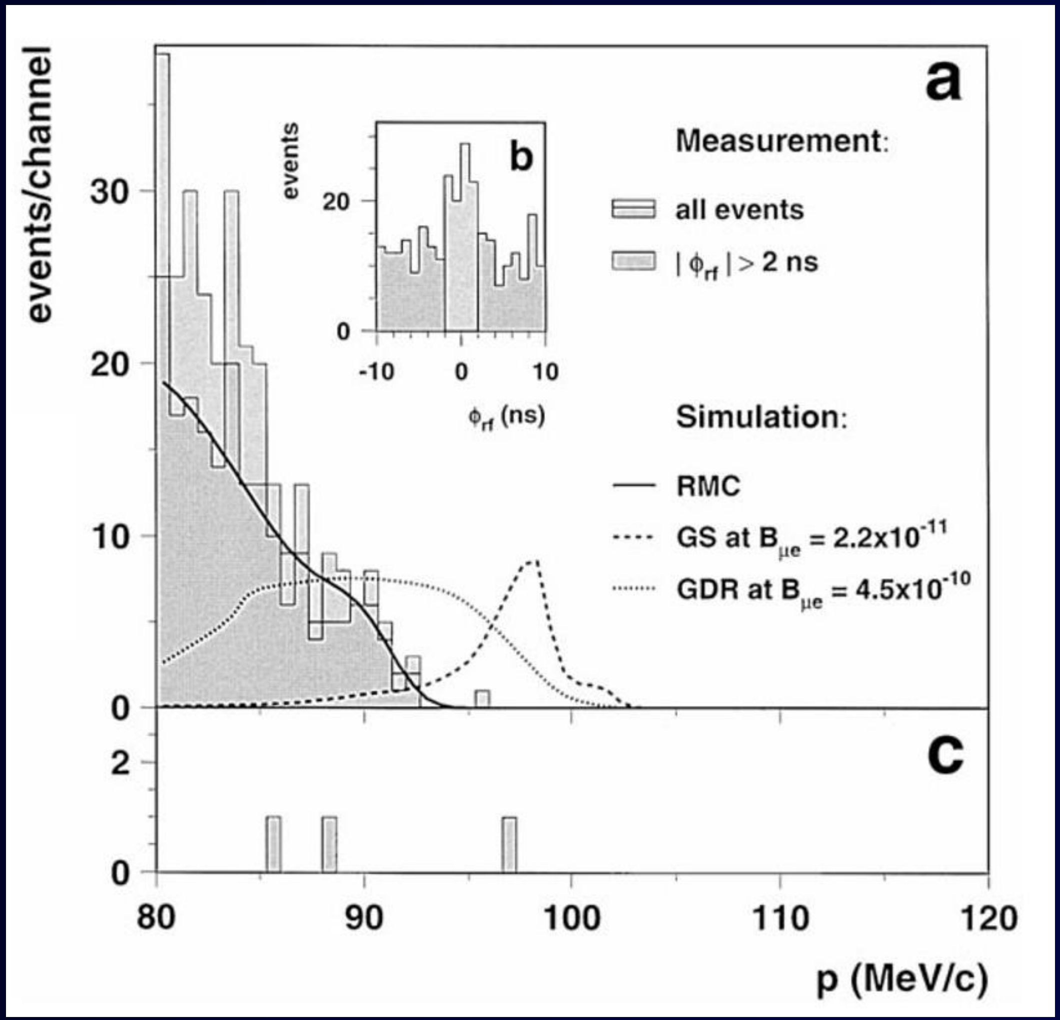

$$\mu^- + \mathrm{Ti} \rightarrow e^+ + \mathrm{Ca(gs)} \leq 1.7\times10^{-12}$$
$$\mu^- + \mathrm{Ti} \rightarrow e^+ + \mathrm{Ca(ex)} \leq 3.6\times10^{-11}$$

J. Kaulard et al. (SINDRUM-II)
Phys. Lett. B422 (1998) 334.

μ^- to e^+ conversion : Target Selection

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μ^- to e^+ conversion : Target Selection

$$\mu^- + N(A,Z) \rightarrow e^+ + N(A,Z-2)$$

Requirement on targets

$$E_{\mu e^+} > E_{RMC} \longrightarrow M(A,Z-1) < M(A,Z-2)$$

Atom	$E_{\mu^- e^+}$ (MeV)	$E_{\mu^- e^-}$ (MeV)	E^{end}_{RMC} (MeV)	N.A. (%)	f_{cap} (%)	τ_{μ^-} (ns)	A_T
^{27}Al	92.30	104.97	101.34	100	61.0	864	0.191
^{32}S	101.80	104.76	102.03	95.0	75.0	555	0.142
^{40}Ca	103.55	104.39	102.06	96.9	85.1	333	0.078
^{48}Ti	98.89	104.18	99.17	73.7	85.3	329	0.076
^{50}Cr	104.06	103.92	101.86	4.4	89.4	234	0.038
^{54}Fe	103.30	103.65	101.93	5.9	90.9	206	0.027
^{58}Ni	104.25	103.36	101.95	68.1	93.1	152	0.009
^{64}Zn	103.10	103.04	101.43	48.3	93.0	159	0.011
^{70}Ge	100.67	102.70	100.02	20.8	92.7	167	0.013

Aluminum (for COMET & Mu2e) is not good.

B. Yeo, YK, M. Lee and K. Zuber, Phys. Rev. D96 (2017) 075027

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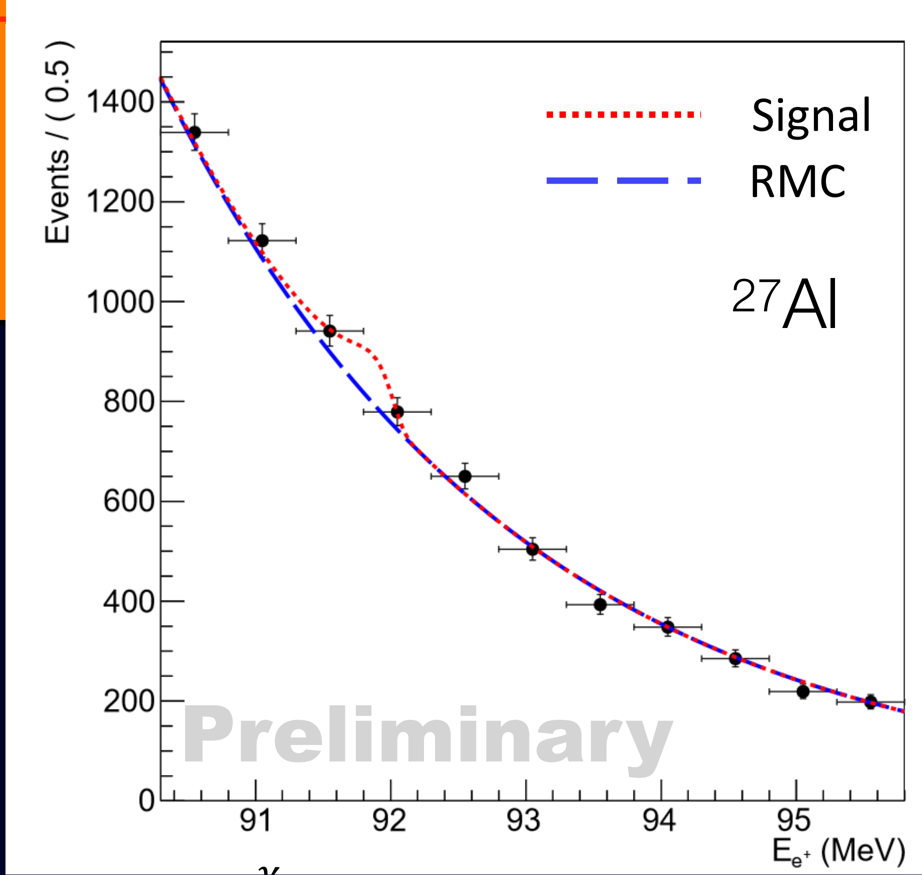
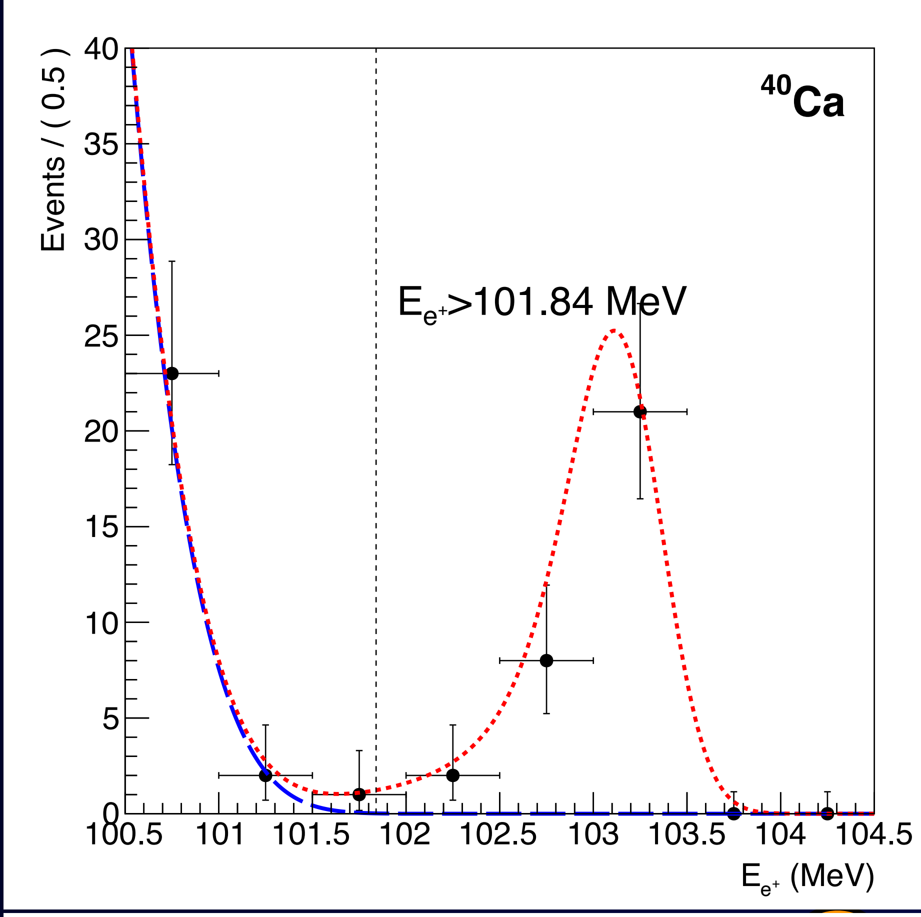
10^{18} muons, signal~1×10^{-12}





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Search for ALP in $\mu \to ea$

Search for ALP in $\mu \to ea$

Osaka University

$\mu \to ea$

a is a light, invisible, new particle with FV coupling to leptons. It could be

: (pseudo)scalar, like
Majoron,
Axion,
Familon

: light gauge boson, Z'

$$\mathcal{L}_{a\ell\ell} = \frac{\partial^\mu a}{2f_a}\left(C^V_{ij}\ \bar{\ell}_i\gamma_\mu\ell_j + C^A_{ij}\ \bar{\ell}_i\gamma_\mu\gamma_5\ell_j\right)$$

$$\Gamma(\ell_i \to \ell_j\, a) = \frac{1}{16\pi}\frac{m^3_{\ell_i}}{F^2_{ij}}\left(1 - \frac{m^2_a}{m^2_{\ell_i}}\right)^2 \qquad F_{ij} \equiv \frac{2f_a}{\sqrt{|C^V_{ij}|^2 + |C^A_{ij}|^2}}$$

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Osaka University

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$$\Gamma(\ell_i \to \ell_j \, a) = \frac{1}{16\pi} \frac{m_{\ell_i}^3}{F_{ij}^2} \left(1 - \frac{m_a^2}{m_{\ell_i}^2} \right)^2 \qquad F_{ij} \equiv \frac{2 f_a}{\sqrt{|C_{ij}^V|^2 + |C_{ij}^A|^2}}$$

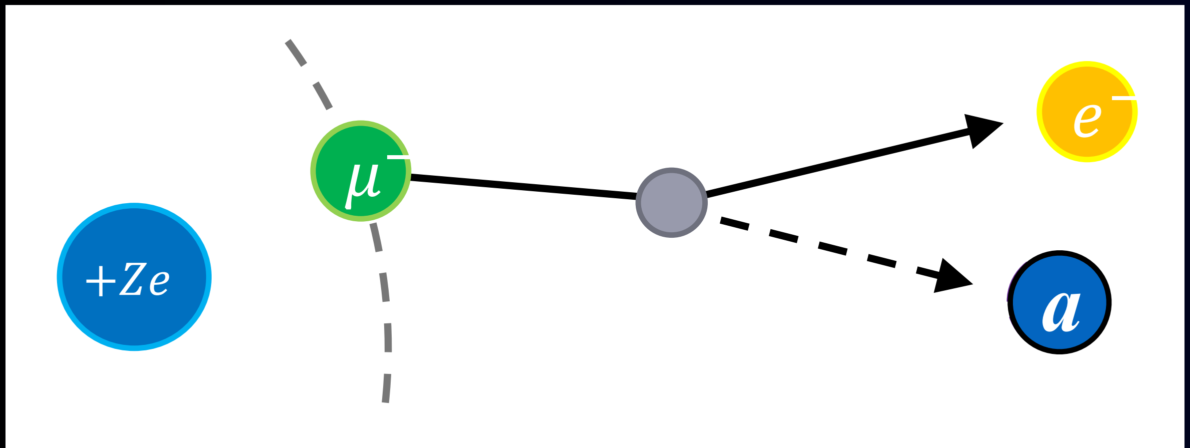
Current Limits and future

- Jodidio et al. (TRIUMF) 1986
  - polarised muons
  - $\mathrm{BR}(\mu^+ \to e^+ a) < 2.6 \times 10^{-6}$
  - $F_{e\mu} > 5.5 \times 10^9\,\mathrm{GeV}$
- TWIST (TRIUMF) 2014
  - Michel Parameters
  - $\mathrm{BR}(\mu^+ \to e^+ a) < 5.8 \times 10^{-5}$
  - $F_{e\mu} > 1.2 \times 10^9\,\mathrm{GeV}$
- Crystal Box (LAMPF) 1988
  - NaI(Tl) crystals
  - $\mathrm{BR}(\mu^+ \to e^+ a\gamma) < 1.1 \times 10^{-9}$
  - $F_{e\mu} > 9.8 \times 10^8\,\mathrm{GeV}$
- Mu3e plan at PSI ($25 < m_a < 90\,\mathrm{MeV}$)
  - $\mathrm{BR}(\mu^+ \to e^+ a) < 10^{-8}$

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

bound $\mu \to ea$

- Advantages
  - background less
  - spectrum shape
    - nucleus dependence
  - many μ-'s as parasite !!!
- Disadvantage
  - not monochromatic



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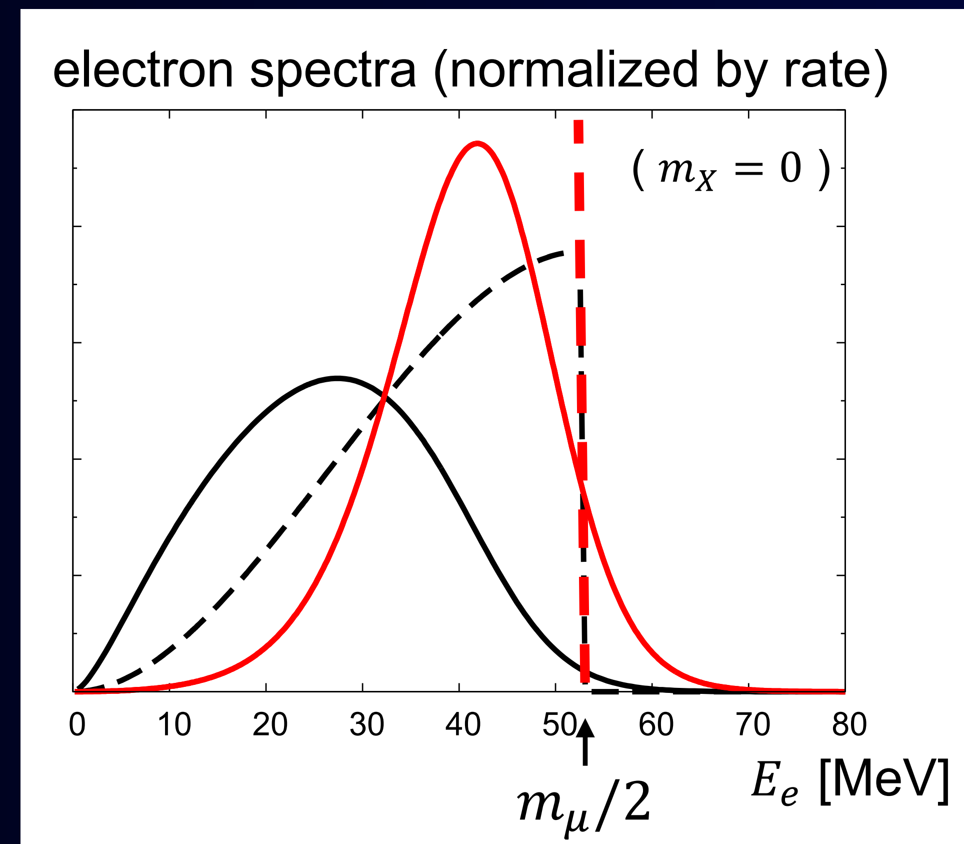
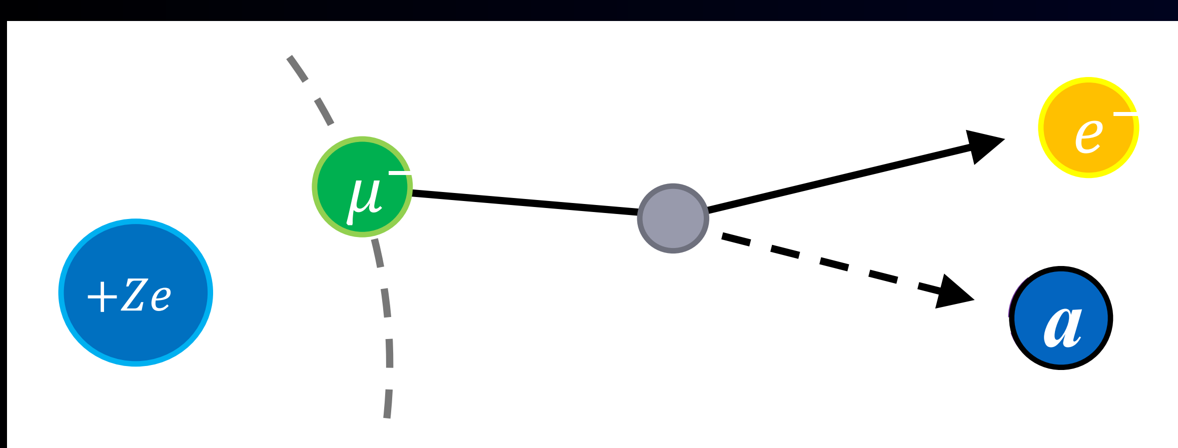
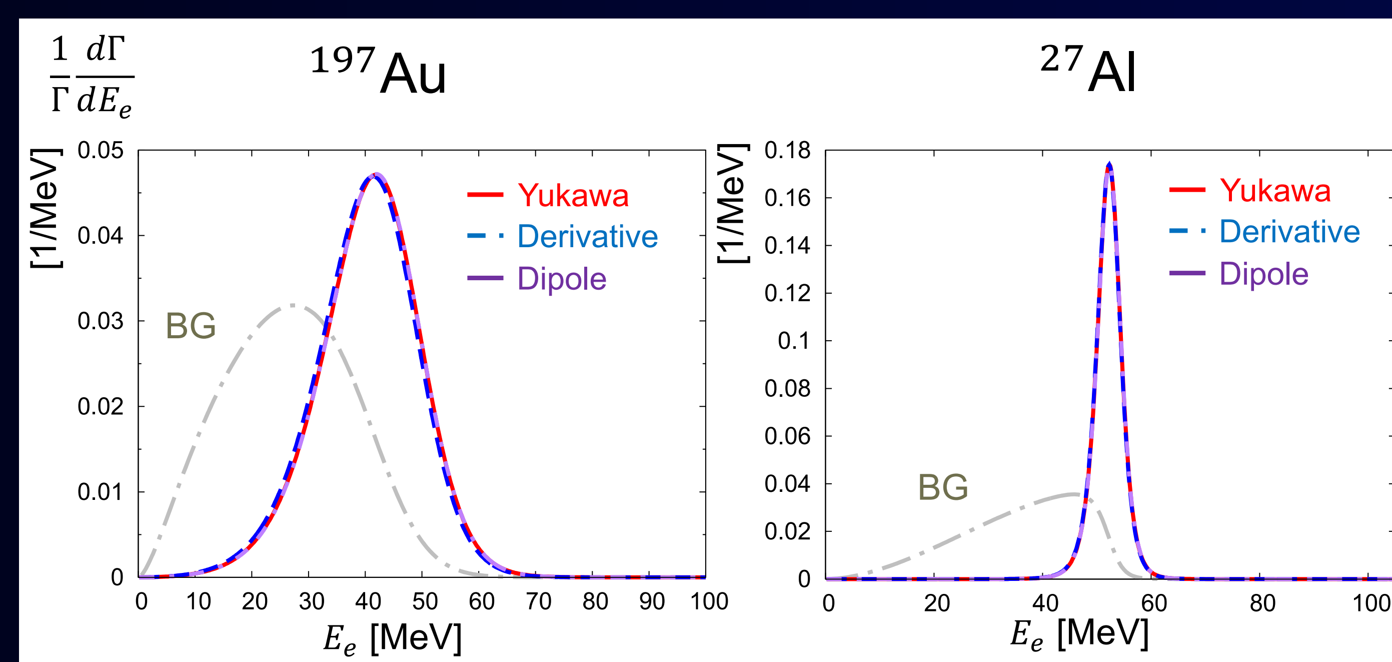


free decay in dashed
bound decay in solid





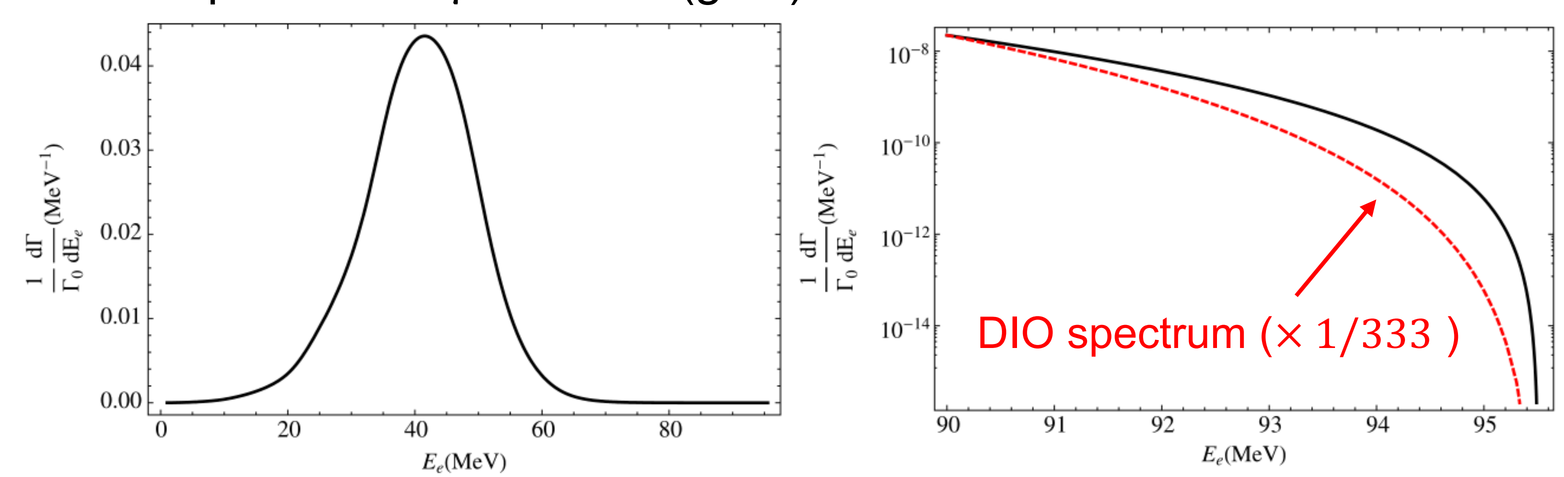
Y. Uesaka, at NuFACT2019

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

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

- Spectrum near the end-point
  - μ-e conversion signal region
  - signal bound $\mu^- \to e^- a \propto \Delta E^3$
  - DIO background $\propto \Delta E^5$
- Past analysis (X.G. i Tormo et al.)
  - use the past μ-e conversion data
  - $\mathrm{BR}(\mu^- \to e^- a) < 3 \times 10^{-3}$

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



X.G. i Tormo, D. Bryman, A. Czarnecki, M. Dowling. Phys. Rev. D84 113010 (2011)

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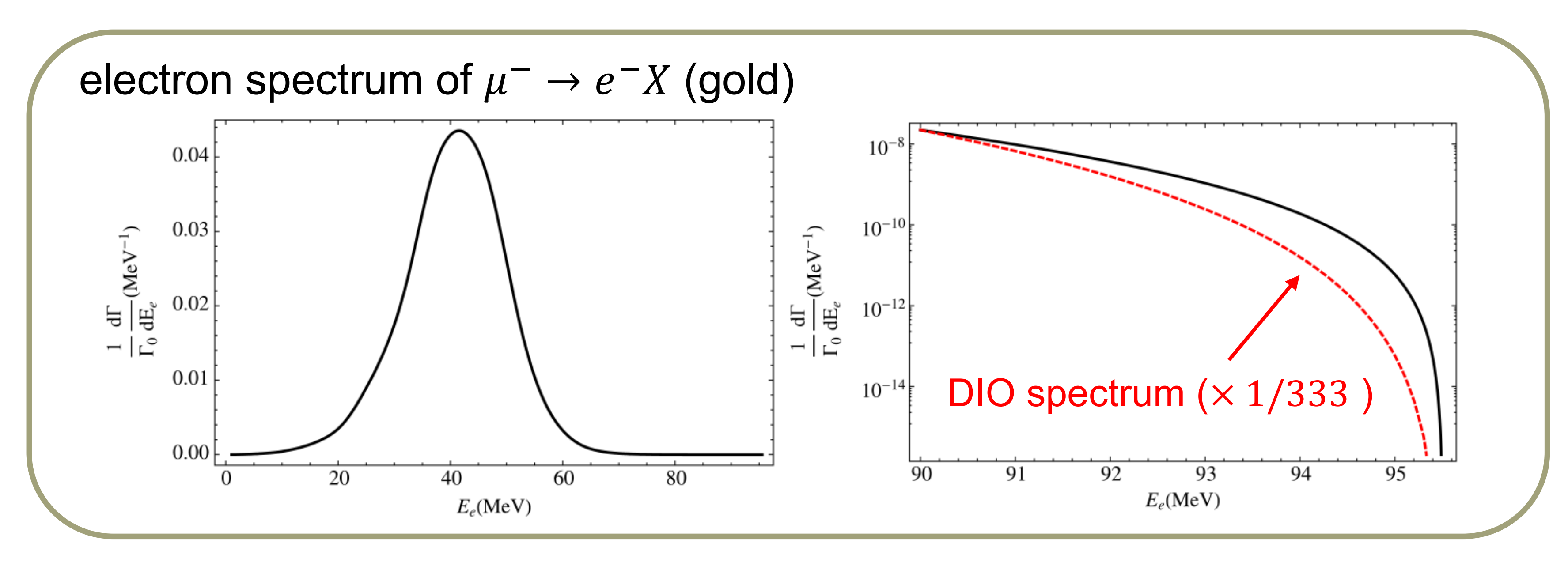
  - use the past μ-e conversion data
  - $\mathrm{BR}(\mu^- \to e^- a) < 3 \times 10^{-3}$
- "Preliminary" estimation at the spectrum at the end point (80 - 105 MeV/c) in COMET Phase-I
  - $\mathrm{BR}(\mu^- \to e^- a) < 3 \times 10^{-6}$
- dedicated measurement at lower energy ?



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CLFV of
Muon Bound States

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Muonium to Antimuonium Conversion
Mu (μ^+e^-) → anti-Mu (μ^-e^+)

data

Future prospects:

- new proposal at CSNS
  - later in this workshop
- new attempt at MUSE/J-PARC ?

Muonium to Antimuonium Conversion
Mu (μ^+e^-) →anti-Mu (μ^-e^+)

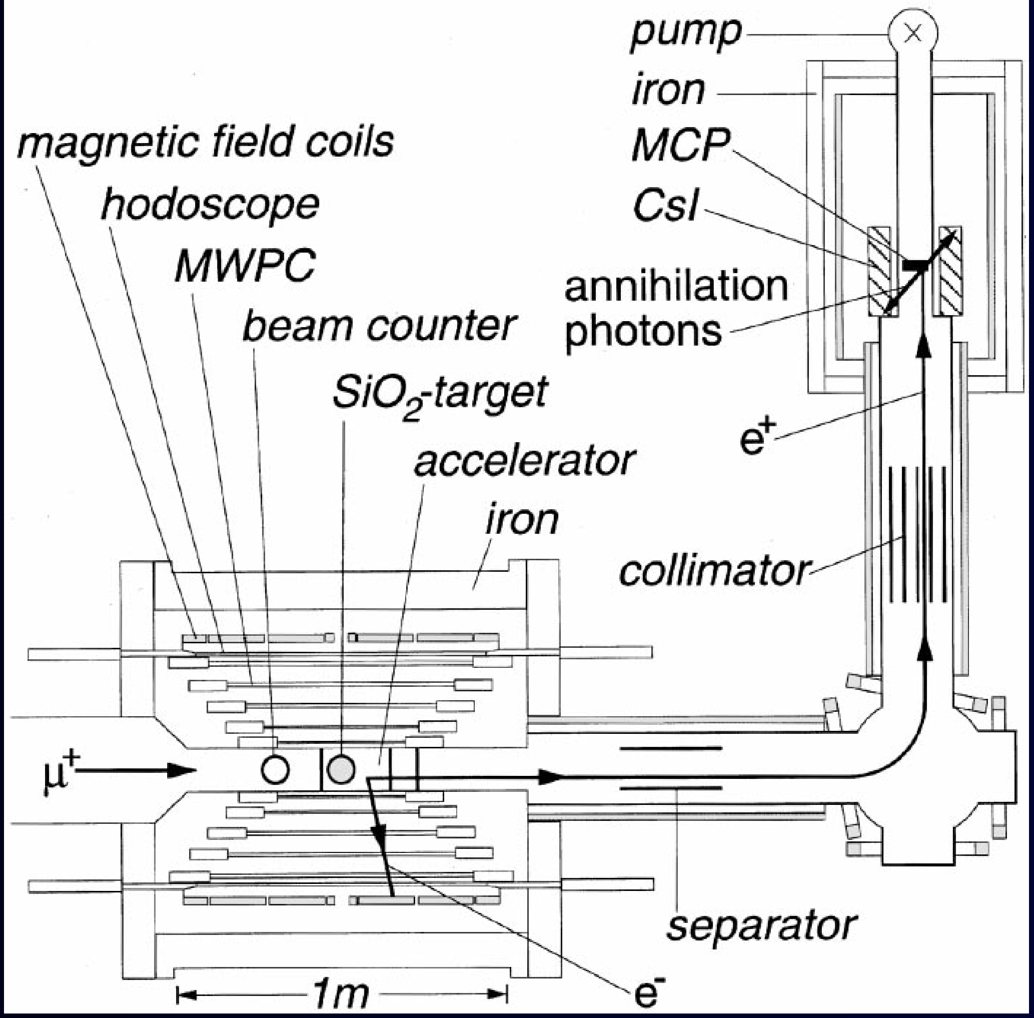
$$\mu^+ + e^- \rightarrow \mu^- + e^+$$

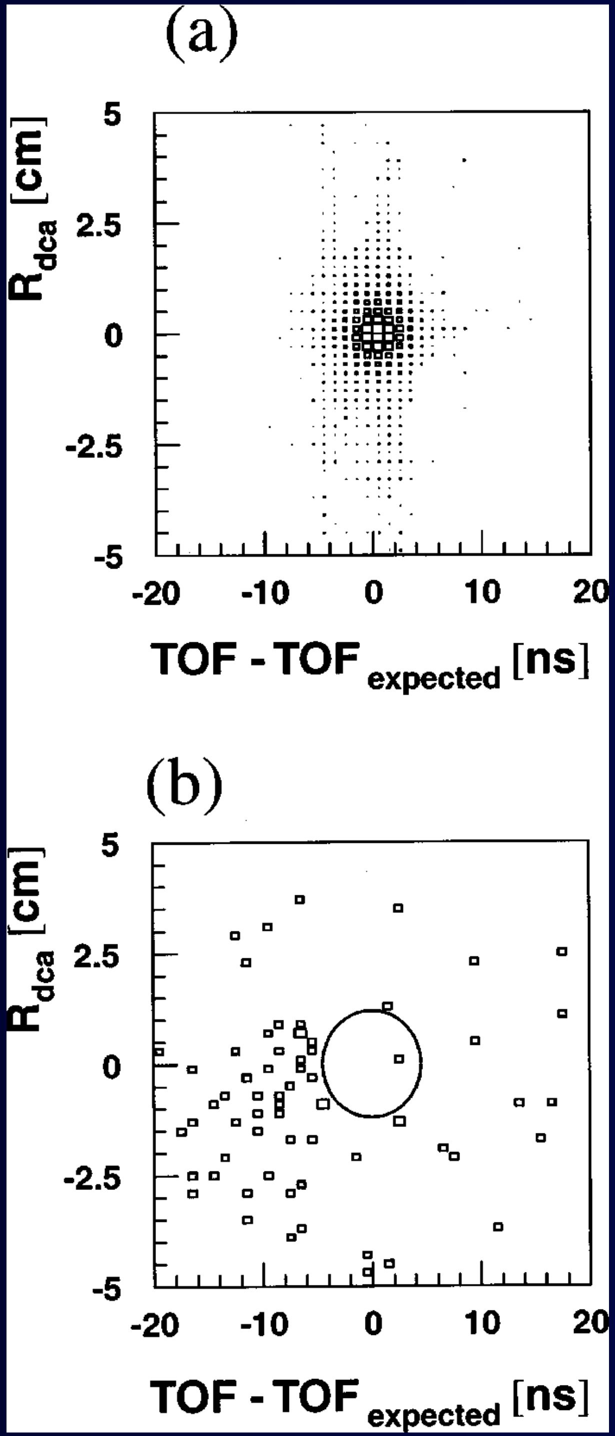
$$|\Delta L_{\mu/e}| = 2$$

- doubly-charged Higgs model etc.
- muonium production in vacuum

previous experiment at PSI (1999)

$$G_{Mu\overline{Mu}} < 3 \times 10^{-3} G_F$$





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Muonium CLFV Decay

$\mu^+ e^- \to \gamma\gamma$ $\mu^+ e^- \to \overline{\nu}_\mu \nu_e$

Muonium CLFV Decay

$$\mu^+ + e^- \rightarrow e^+ + e^- \qquad \mu^+ e^- \rightarrow \gamma\gamma \qquad \mu^+ e^- \rightarrow \overline{\nu}_\mu \nu_e$$

- similar to μ→eee
  - may be useful to distinguish different couplings
  - 2 body final state
- disadvantage
  - poor-wave function overlap between μ and e
    - Coulomb bound state

Muonium CLFV Decay

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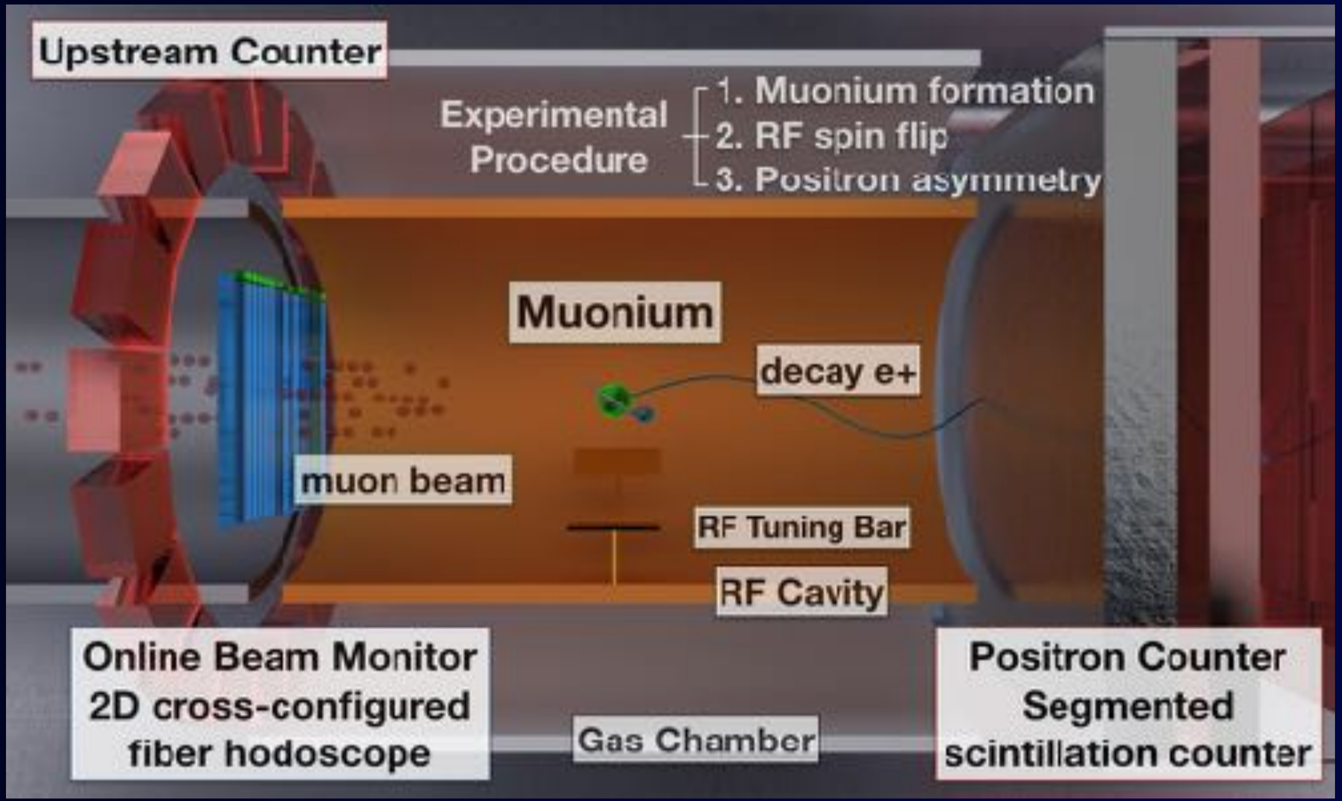
  - may be useful to distinguish different couplings
  - 2 body final state
- disadvantage
  - poor-wave function overlap between μ and e
    - Coulomb bound state

Future prospects:

- no experiments so far
- muonium production in MUSEUM at MUSE @ J-PARC
  - measurement of hyperfine splitting
  - 10^{15} for 2×10^{7} sec

Museum detector @J-PARC



Osaka University

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

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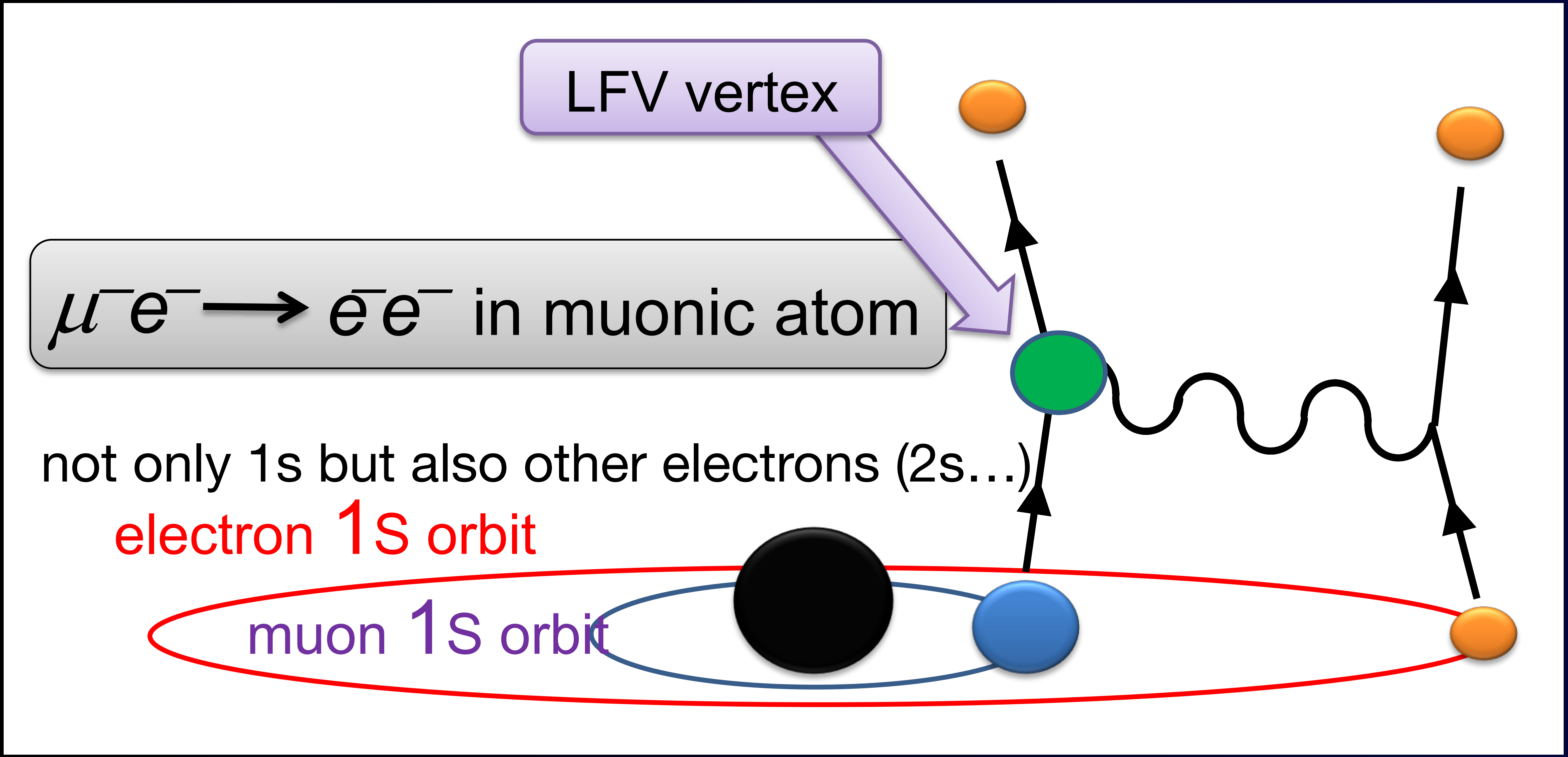
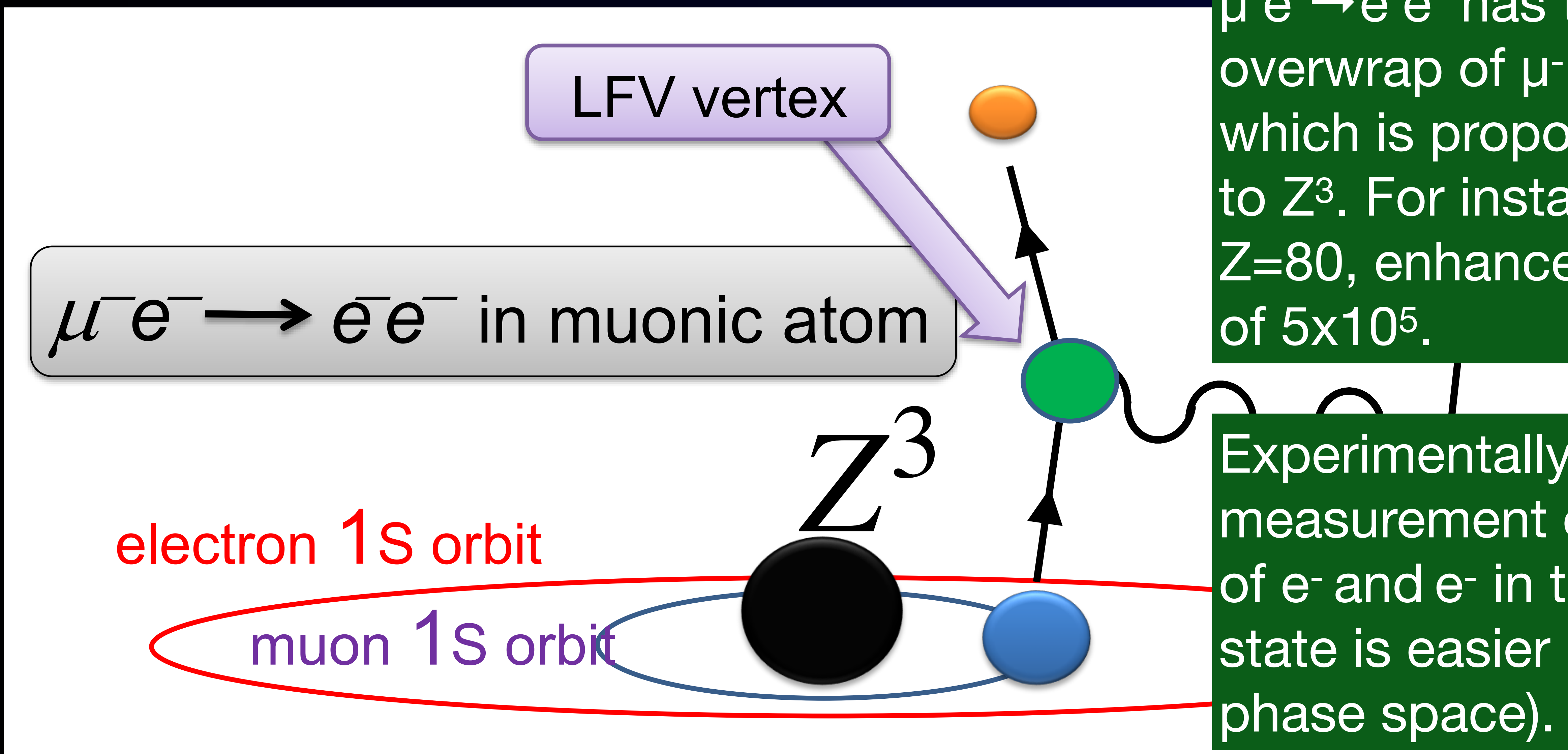


- Original idea

  M. Koike, YK, J. Sato and M. Yamanaka, Phys. Rev. Lett. 105 (2010)

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

$$\mu^- + e^- \to e^- + e^-$$



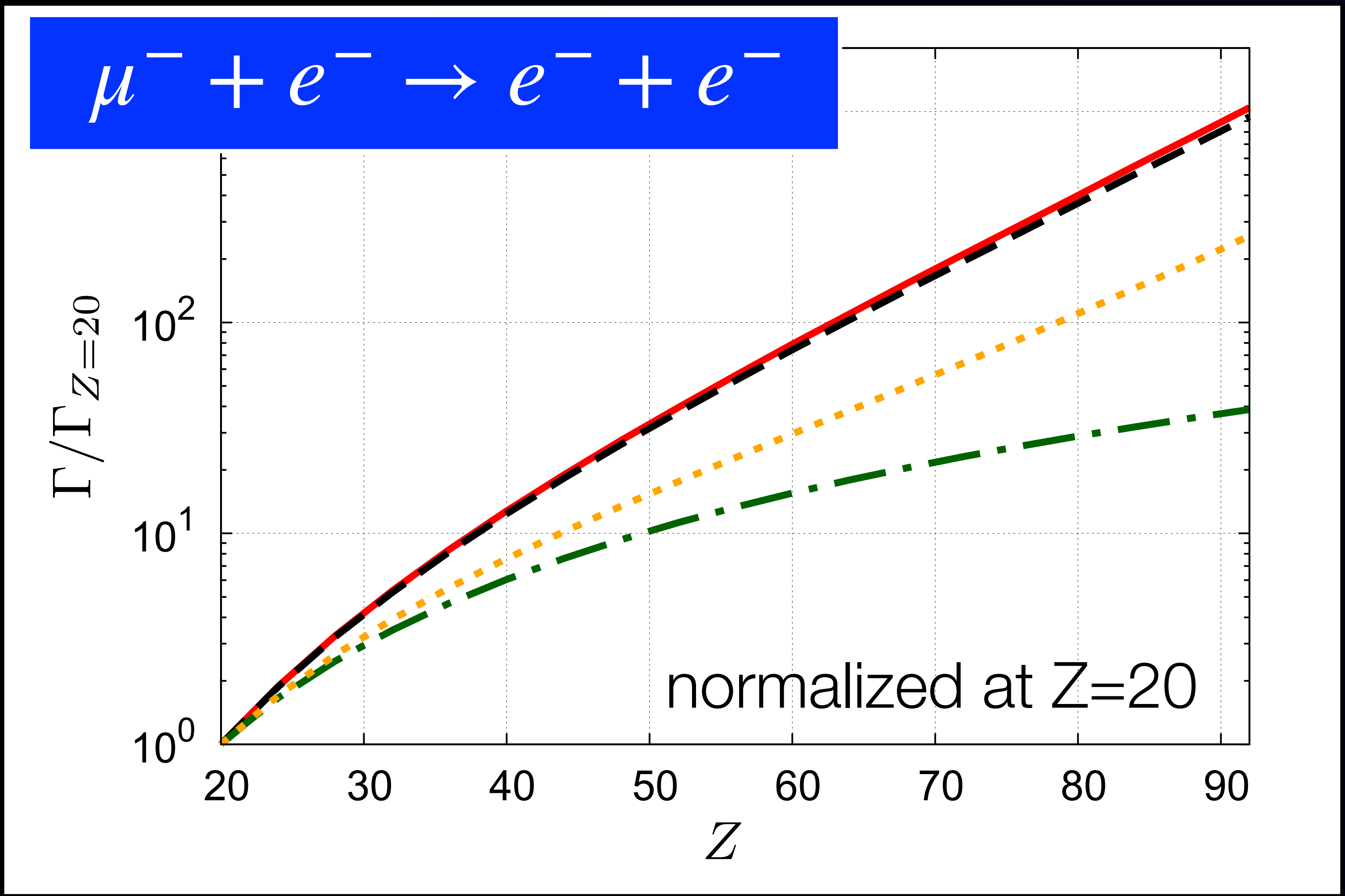
$\mu^- e^- \to e^- e^-$ has the overwrap of μ^- and e^- which is proportional to Z^3. For instance, Z=80, enhancement of 5×10^5.

Experimentally measurement of a pair of e^- and e^- in the final state is easier (larger phase space).

- Original idea

M. Koike, YK, J. Sato and M. Yamanaka, Phys. Rev. Lett. 105 (2010)

$\mu^- + e^- \to e^- + e^-$ in a muonic atom : Z dependence for model discrimination



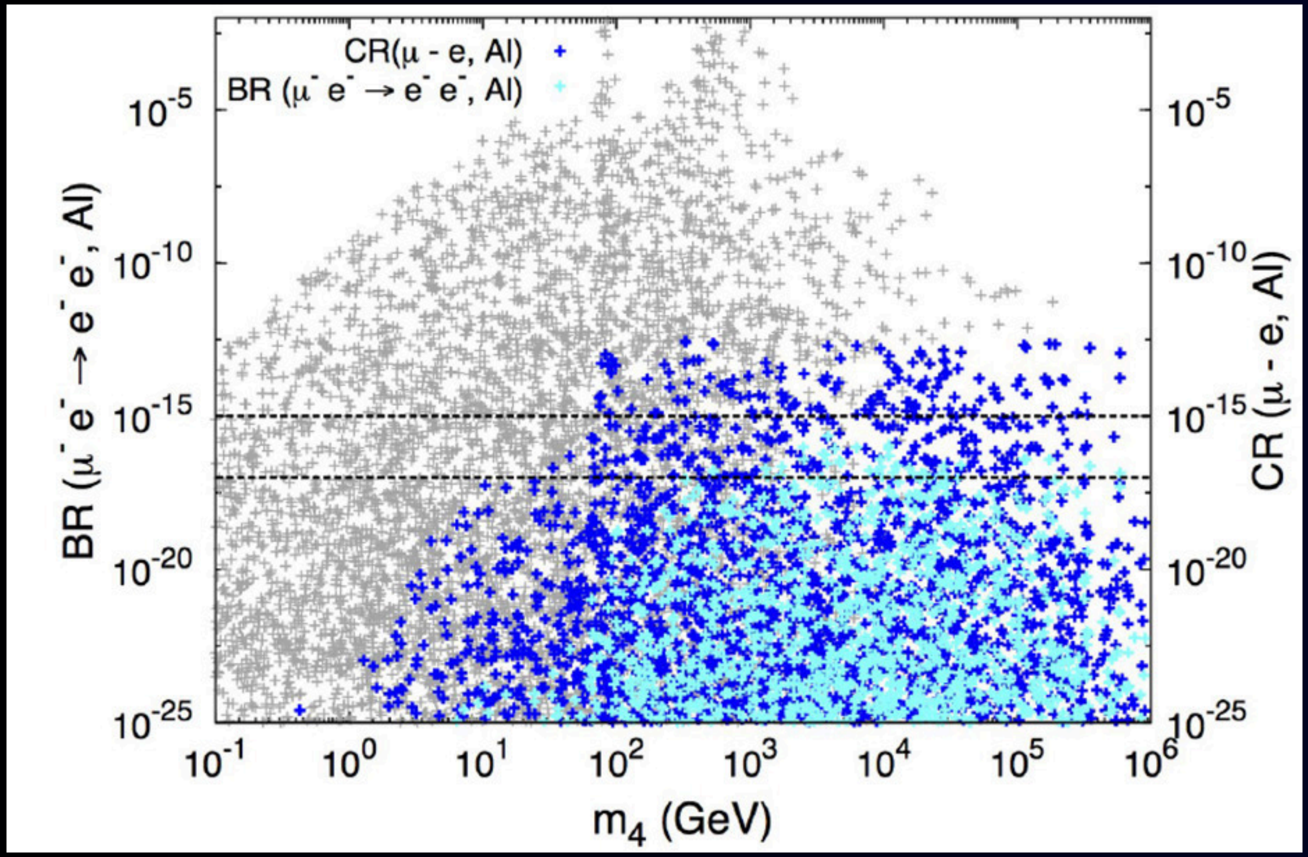
(1) solid red line : contact int. with the same chirality
(2) a dashed black line : contact int. with opposite chirality
(3) a dash-dotted green line : photonic int.
(4) a dotted orange line : mix of contact and photonic int.

- Study of contact interaction with different Z targets
  Y. Uesaka, YK, J. Sato, T. Sato and M. Yamanaka, Phys. Rev. D93 (2016) 076006
- Study of long-distance dipole interaction with different Z targets
  Y. Uesaka, YK, J. Sato, T. Sato and M. Yamanaka, Phys. Rev. D97 (2018) 015017

Heavy Neutral Lepton (HNL) Models for $\mu^- + e^- \to e^- + e^-$ in a muonic atom

Osaka University

(3+1) model

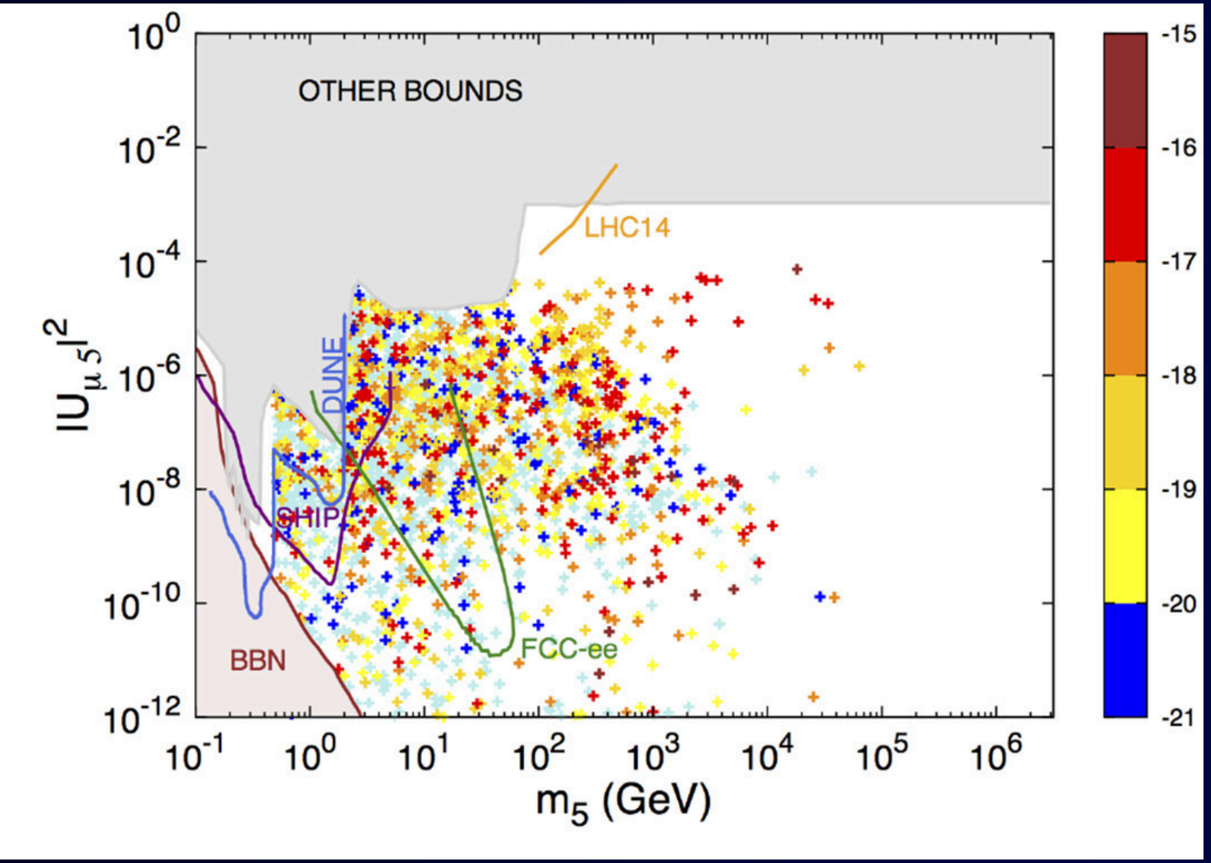


m_4 : HNL mass

cyan points : $\mu^- + e^- \to e^- + e^-$

blue points : $\mu^- + Al \to e^- + Al$

(3+2) model



m_5 : HNL mass

colored points : $Br(\mu^- + e^- \to e^- + e^-)$

A. Abada, V. De Romeri, A.M. Teixeira, JHEP 02 (2016) 083)

Muon CLFV Processes

- $\mu^+ \to e^+\gamma$
- $\mu^+ \to e^+e^+e^-$
- $\mu^- + N(A,Z) \to e^- + N(A,Z)$
- $\mu^- + N(A,Z) \to e^+ + N(A,Z-2)$
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- $\mu^+e^- \to \mu^-e^+$
- $\mu^-e^- \to e^-e^-$
- $\mu + N \to \tau + X$
- $\nu_\mu + N \to \tau^+ + X$
- $\mu \to ea$

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Osaka University

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CLFV Scattering Process

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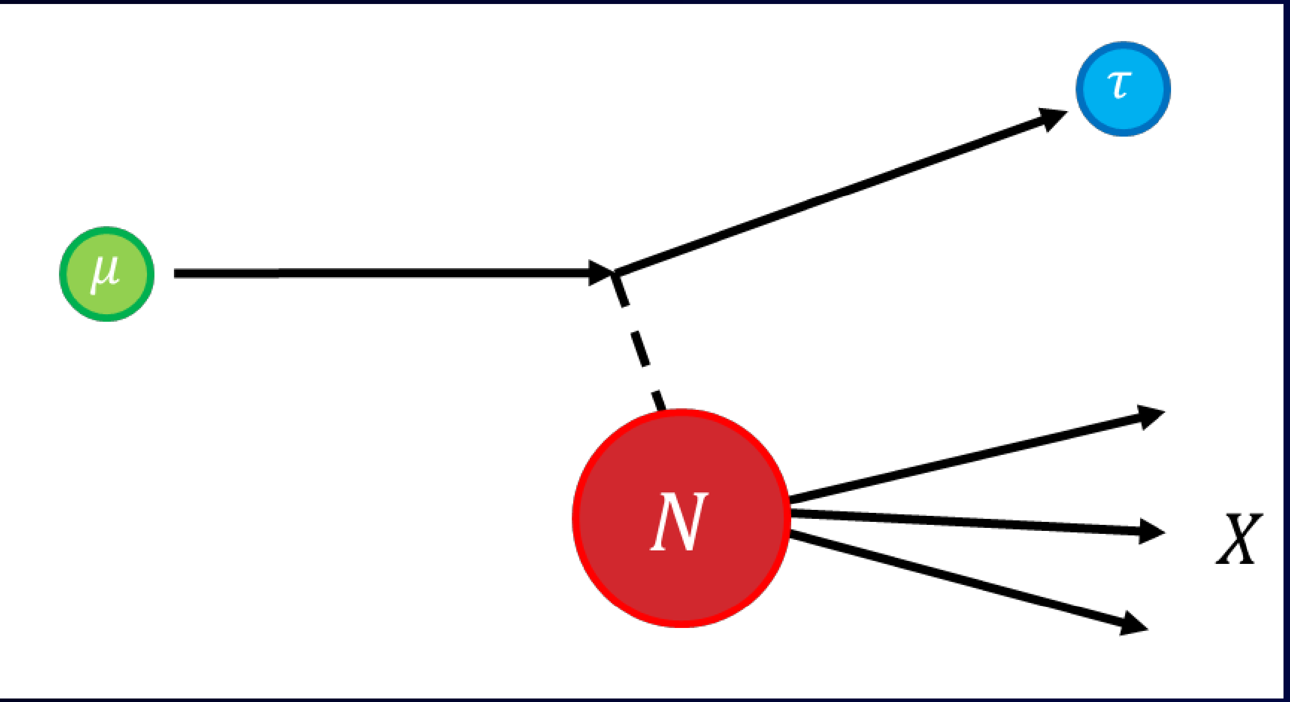
$$\mu + N\ (e + N) \to \tau + X$$

$$m_\mu < m_\tau$$

inelastic scattering (DIS) region with high-intensity and high-energy muon (electron) beams



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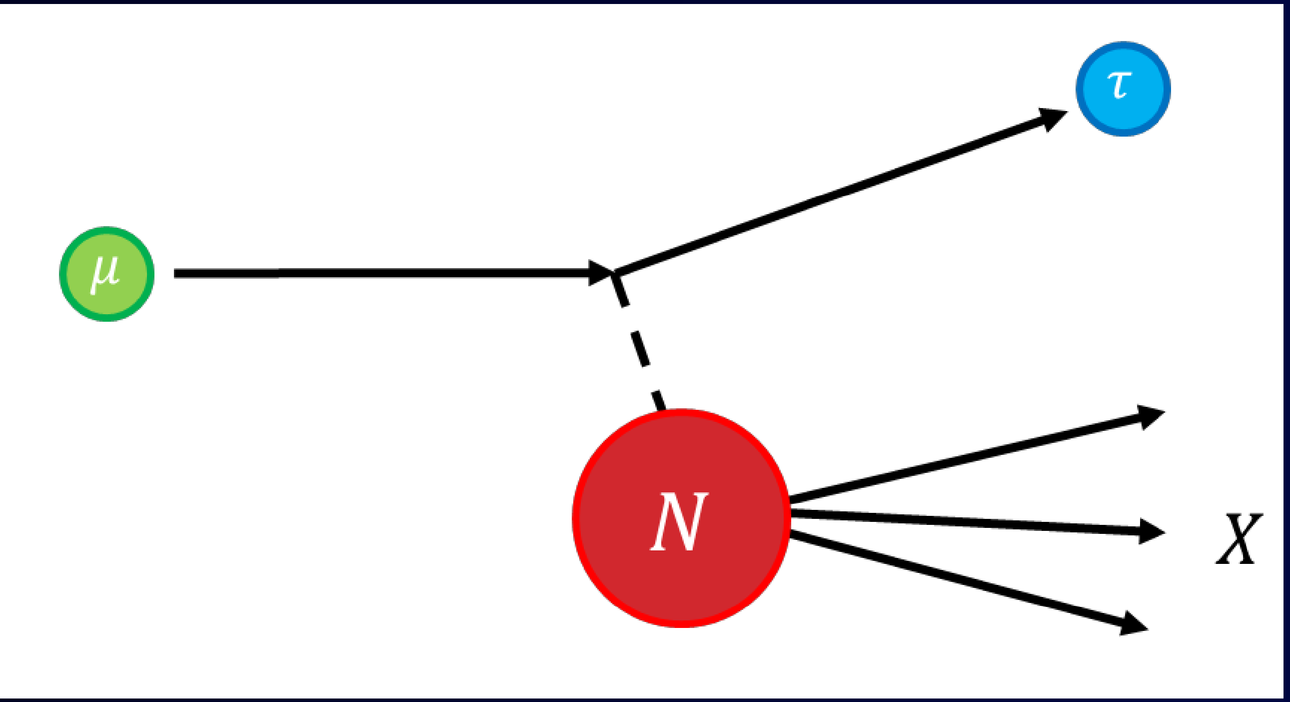

- the search with scattering is less effective than searches with decays (weak interaction cross section ~ 10^{-45} barns at 1MeV)
- scattering cross section increases as incident energy is higher.
- electron beam from ILC (at beam dump) or muon beam from muon collider can be considered.

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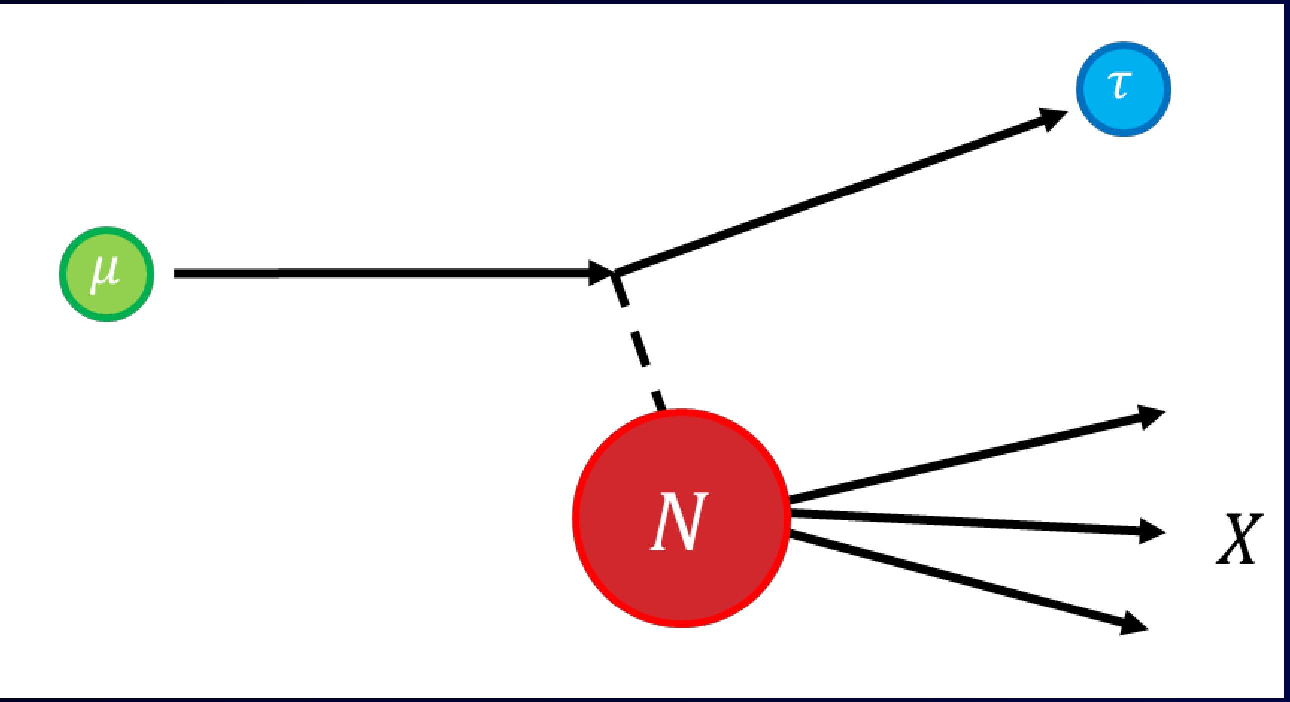

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M. Takeuchi, Y. Uesaka, M. Yamanaka, Phys. Lett. B772 (2017) 279

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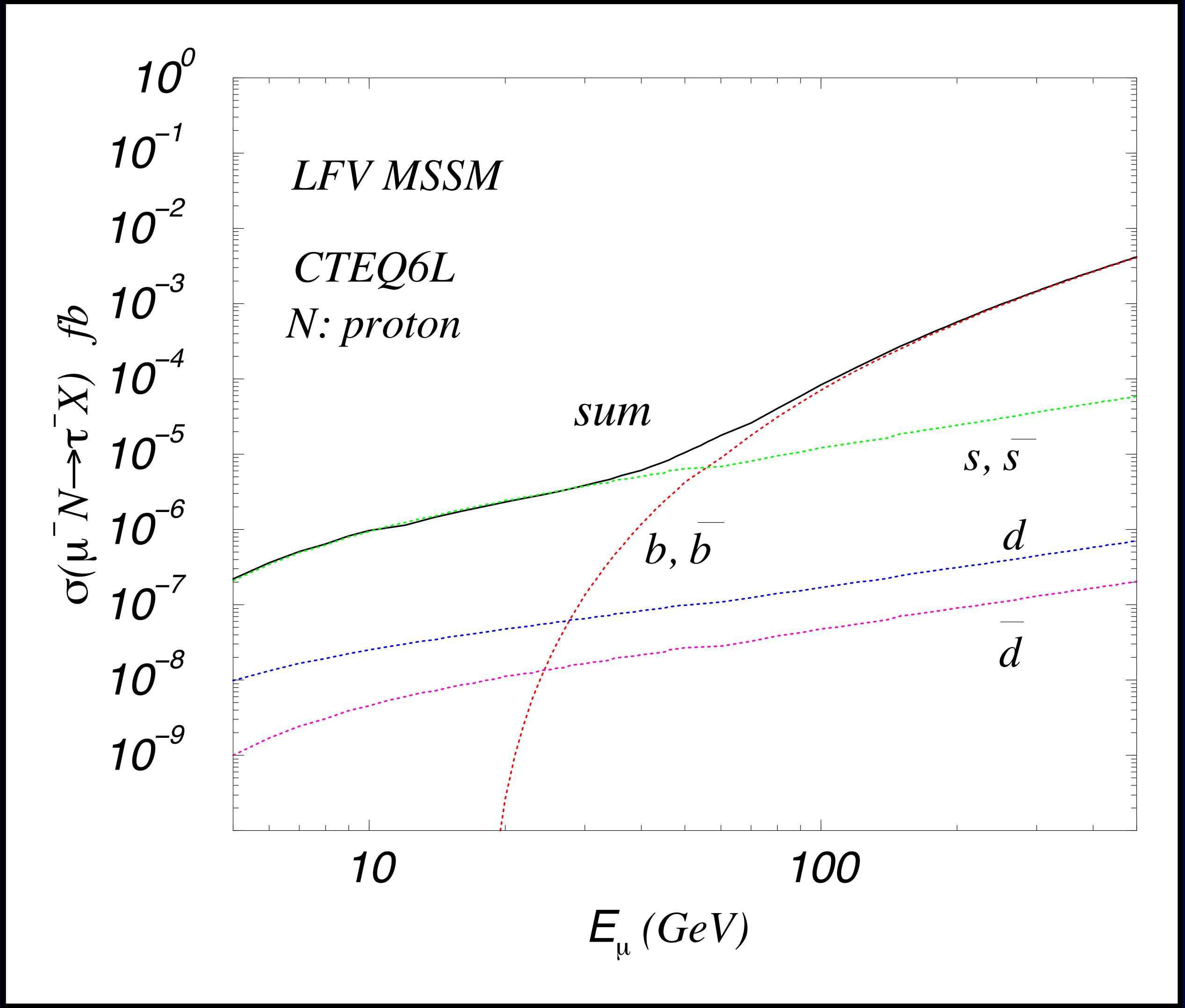
$$\mu + N\ (e + N) \rightarrow \tau + X$$

Minimum supersymmetric model (MSSM) with Higgs mediated LFV coupling

Upper limits from tau decays is given.

$$\tau \rightarrow \mu\eta$$

$\sigma < 10^{-5}$ fb for 50 GeV muons.



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LNV Charged Current Scattering Process

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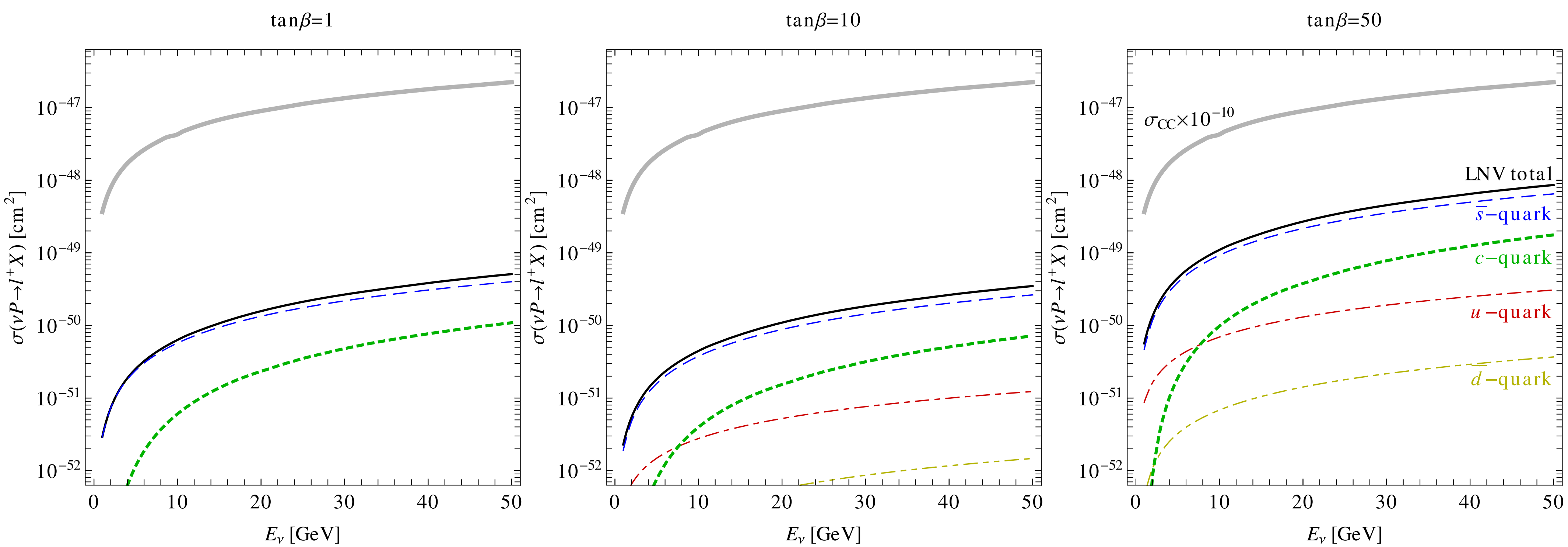
$$\nu_\alpha + N \to \ell_\beta^+ + X$$

LNV LFV charged current (LNV-CC) interaction

- measurement can be made at a neutrino near detector with a magnetic field to identify an electric charge of the charged leptons
- at production like $\pi^+ \to \mu^+ \overline{\nu}_\alpha$
- at detector

$10^{-48}\mathrm{cm}^2$

at 50 GeV



S. Kanemura, YK, and T. Ota, Phys. Lett. B719 (2013) 373

CLFV of Tau Lepton, Z boson, Higgs and Mesons

CLFV of Tau Leptons - radiative and leptonic

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$$\tau^{\pm} \to \ell^{\pm}\gamma$$

- Event Signature
  - energy $E_{\ell\gamma} \sim \sqrt{s}/2$
  - mass $M_{\ell\gamma} \sim M_{\tau}$

$$\mathrm{BR}(\tau \to \mu\gamma) \leq 4.4 \times 10^{-8}$$

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

$$\tau^{\pm} \to \ell_i^{\pm}\ell_j^{\pm}\ell_k^{\mp}$$

- Event Signature
  - energy $E_{3\ell} \sim \sqrt{s}/2$
  - mass $M_{3\ell} \sim M_{\tau}$

3ℓ final state	BR (BaBar)	BR (Belle)
$e^-e^+e^-$	2.9×10^{-8}	2.7×10^{-8}
$\mu^-e^+e^-$	2.2×10^{-8}	1.8×10^{-8}
$\mu^-e^-e^-$	1.8×10^{-8}	1.5×10^{-8}
$e^+\mu^-\mu^-$	2.6×10^{-8}	1.7×10^{-8}
$e^-\mu^+\mu^-$	3.2×10^{-8}	2.7×10^{-8}
$\mu^-\mu^+\mu^-$	3.3×10^{-8}	2.1×10^{-8}

CLFV of Tau Leptons - radiative and leptonic

Osaka University

$$\tau^\pm \to \ell^\pm \gamma$$

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Future prospects at Super KEK-B, Tau-charm factory, LHCb, HL-LHC

$$\mathrm{BR}(\tau \to \ell\gamma) \leq (1-3) \times 10^{-9} \quad \mathrm{BR}(\tau \to 3\ell) \leq (1-2) \times 10^{-10}$$

CLFV of Tau Leptons - semi-leptonic

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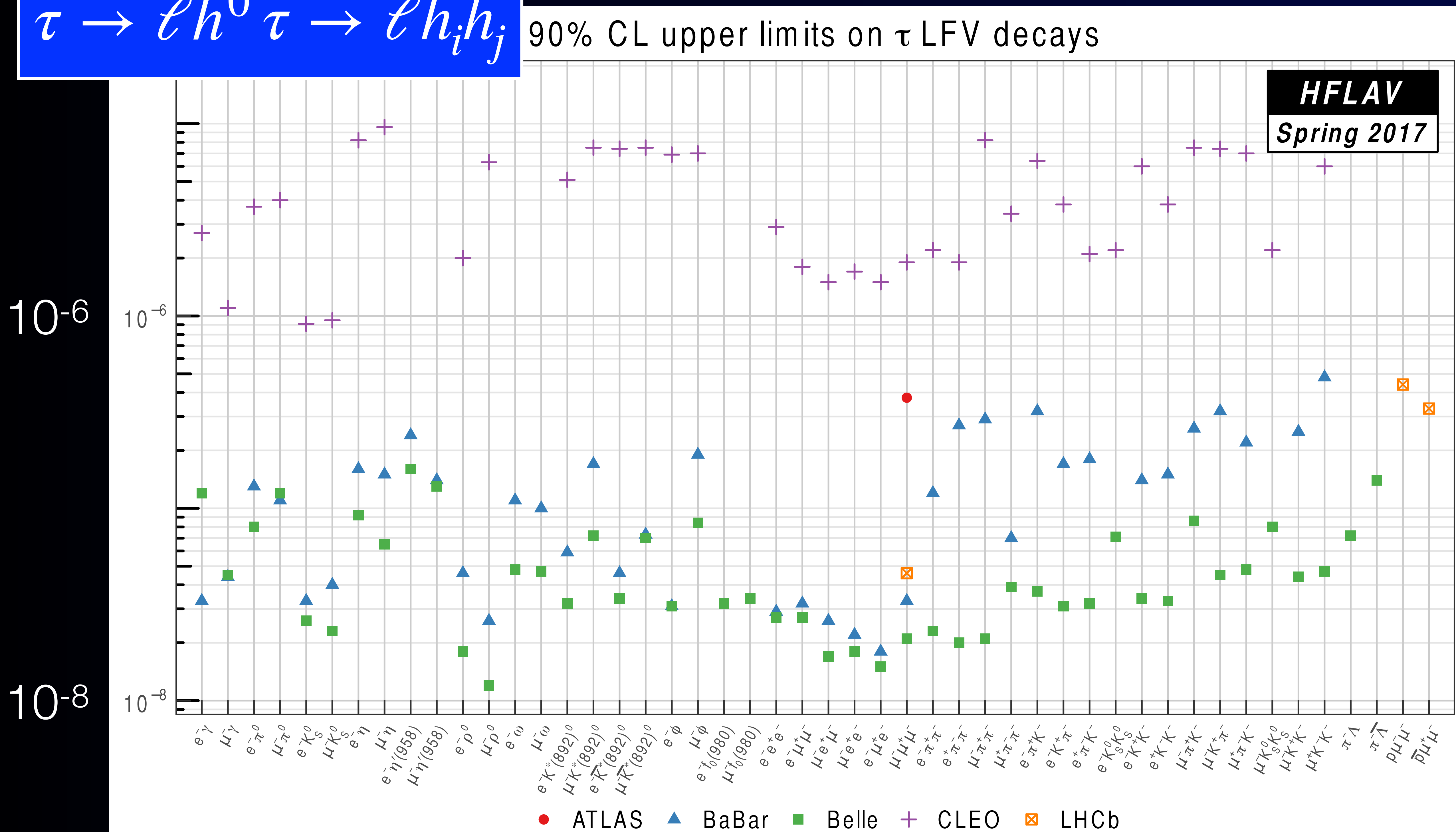
$\tau \to \ell h^0 \quad \tau \to \ell h_i h_j$



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$\mathrm{BR}(Z^0 \to \mu\tau) \le 1.2 \times 10^{-5}$ LEP, (ATLAS, CMS)

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$H^0 \to \ell_i \ell_j$

$\mathrm{BR}(H^0 \to e\mu) \le 0.035\,\%$ CMS (2012)

$\mathrm{BR}(H^0 \to e\tau) \le 0.37\,\%$ CMS (2016)

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Future Prospects

HL-LHC, ILC, FCC-ee, CEPC and others

CLFV of Mesons

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- Lepton flavour violating K decays

$K^+ \to \pi^+\mu^-e^+ : BR < 5.2 \times 10^{-10}$	BNL E865
$K^+ \to \pi^+\mu^+e^- : BR < 1.3 \times 10^{-11}$	BNL E777/E865
$K^0 \to \mu^\pm e^\mp : BR < 4.7 \times 10^{-12}$	BNL E871

- Lepton number violating K decays

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Future Prospects — NA62 ~$O(10^{-11})$

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Thank you!

谢谢

ありがとう!