Charged Lepton Flavor Violation

SATO, Joe

(Saitama University)

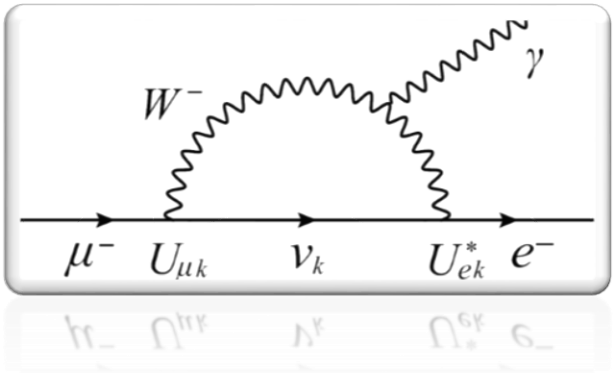
July14 Quy Nhon Vietnam

1.Introduction

Lepton Flavor is exact symmetry in SM

as long as neutrinos are massless

Charged Lepton Flavor Violation (cLFV) through Lepton Mixing in the neutrino oscillation



But … $\mathrm{BR}(\mu \to e\gamma) \sim \left(\frac{\delta m^2_\nu}{m^2_W}\right)^2 < 10^{-54}$ ⇒ Invisible, eternally

Strong suppression of FCNC by GIM

Detection of the LFV signal ⇒ Clear evidence for beyond SM

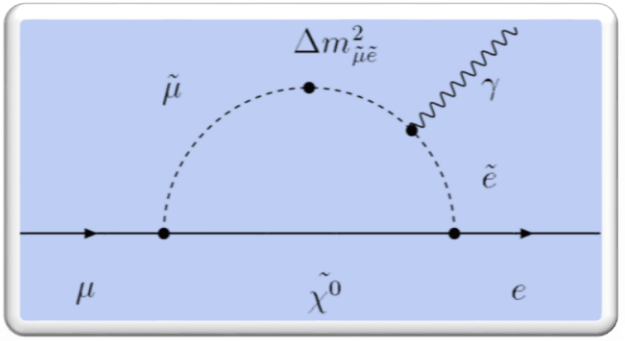
Indeed, in physics beyond SM,

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

⇨ **Search for LFV with charged lepton is inevitable**

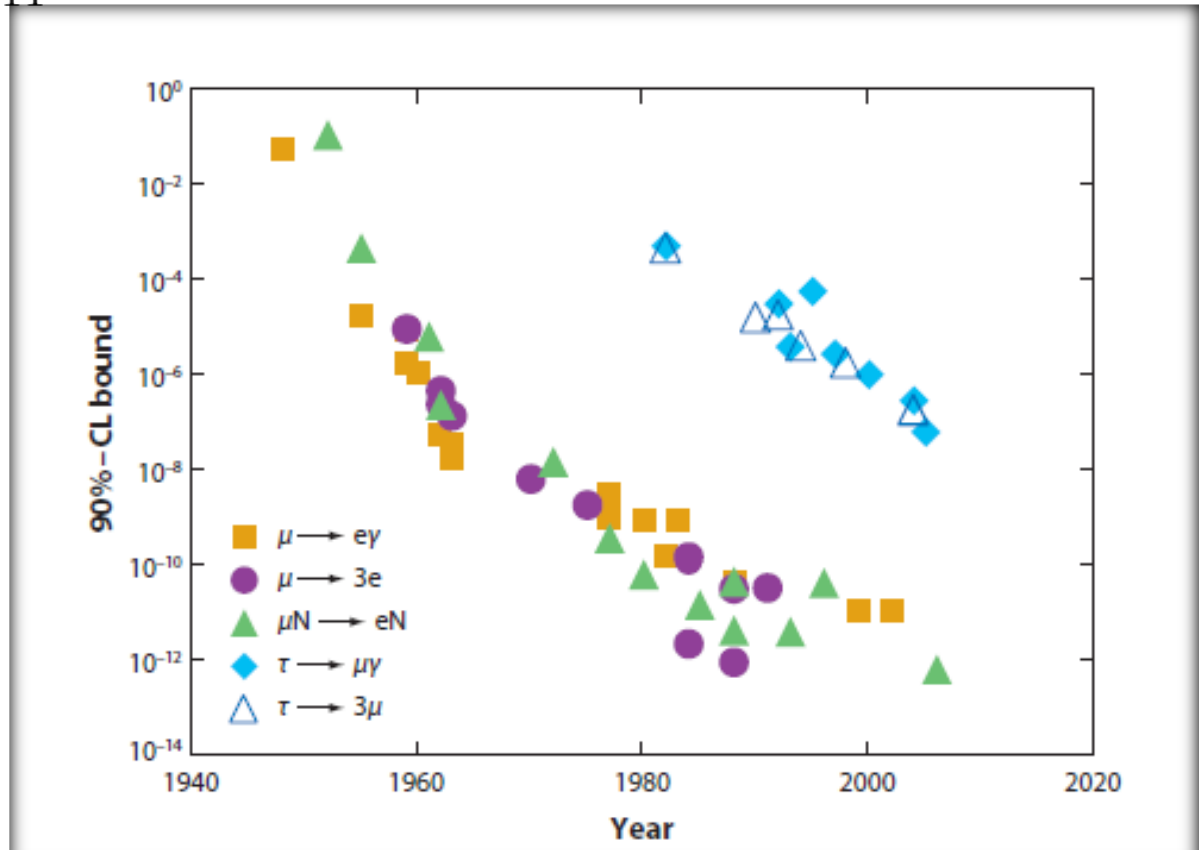
cLFV from muon decay

Upper limit on Br

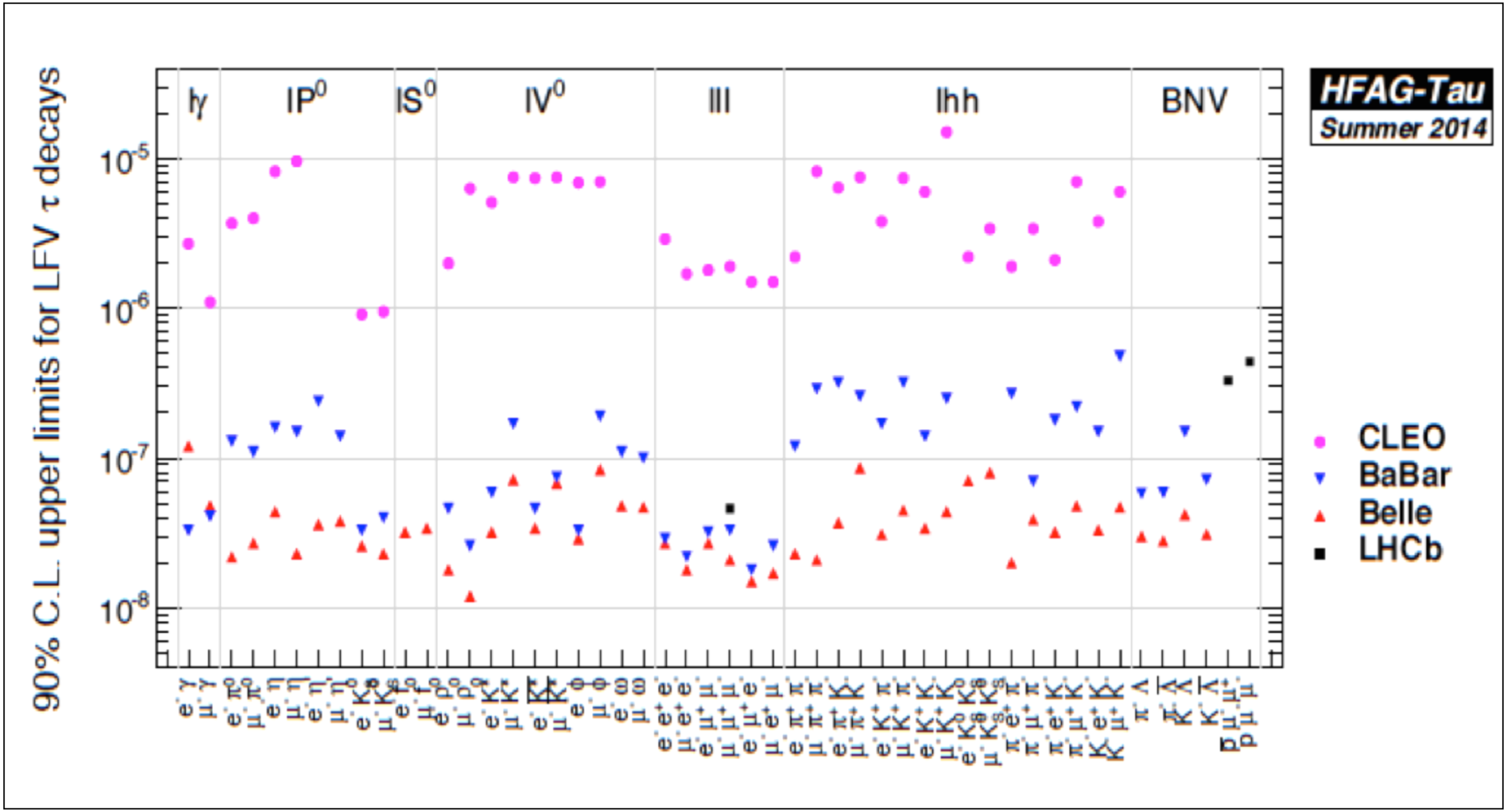
$$\mu^+ \to e^+\gamma \quad < 4.2 \times 10^{-13}$$
$$\mu^+ \to e^+e^+e^- < 1.0 \times 10^{-12}$$
$$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti} < 6.1 \times 10^{-13}$$
$$\mu^-\mathrm{Au} \to e^-\mathrm{Au} < 7 \times 10^{-13}$$
$$\mu^+e^- \to \mu^-e^+ < 8.3 \times 10^{-11}$$

Annu. Ref. Nucl. Part. Sci. 2008. 58:315-41
W. J. Marciano, T.Mori, and J. M. Roney

Long history



cLFV from tau decay



Upper bound ~ 1/# of taus

(New?) particle with LFV

SM Particle

$$Z \to ll' < O(10^{-6}) \text{ for } e\mu, O(10^{-5}) \text{ for } l\tau$$
$$H \to ll' < O(1\%)$$
$$\text{or} \quad \mathrm{Br}(H \to \mu\tau) = 0.84 \pm 0.39\%$$

New(?) Particle with LFV

Z' from Extra dim/extra U(1) models

Neutral scalar, e.g. scalar neutrino in SSM

No signals yet even with LHC

2.Effective operators for CLFV

A) Loop vs Tree

$\mu^+ \to e^+\gamma$ :: Loop only, dipole

Gauge Symmetry forbids tree contribution

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

$\mu^- N \to e^- N$

:: Loop and Tree

e.g. Loop = dipole + quark bilinear = $\mu^- N \to e^- N$

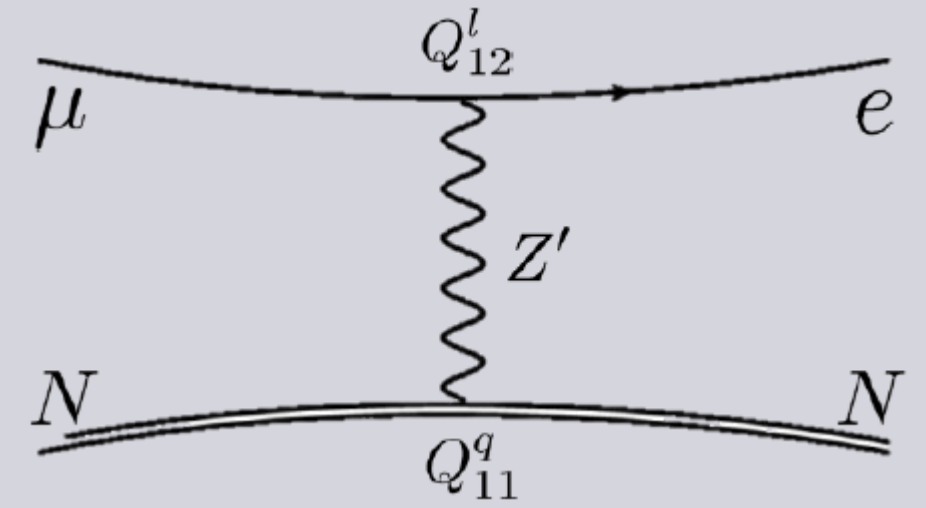
$\sim$ α smaller than μ->eγ

Tree :: singlet particle is necessary for conversion!

Charge 2 is OK for μ -> 3e

Leptoquark is OK for μ -> e

Tree, e.g.



No direct relation with MEG
NO suppression

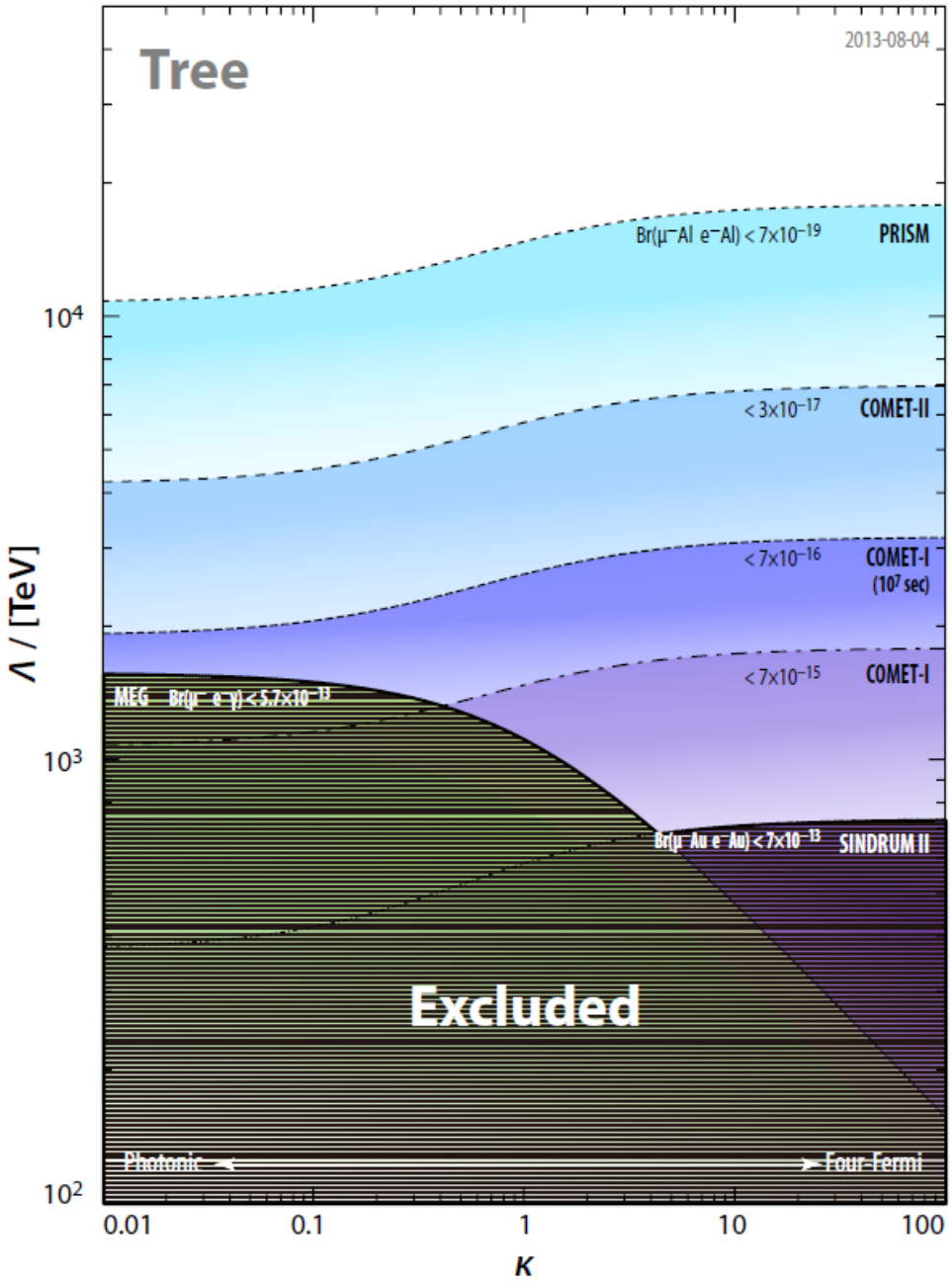
We can parameterize the relative strength

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

$\kappa \sim$ α :: dipole type, say SUSY with R parity

In general, Model Dependent

MEG



PRISM

COMET Phase-II

COMET Phase-I

B) Vector vs Scalar

cLFV is mediated by new particle(s)

Vector Boson ::

Boson with broken gauge

So-called Z' Model, Extra U(1) from SO(10) GUT

Kaluza-Klein mode of gauge

Higher dimensional models have massive modes of gauge bosons

Scalar Boson ::

From symmetry = SUSY

Extension of Higgs :: more 2plet, 3plet for nu mass

Explanation for new physics

Vector type interaction

If Vector boson has no charge

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

can occur at tree level

in a wide sense Z' model

$\mu^+ \to e^+\gamma \Longleftrightarrow \mu^- N \to e^- N$

irrelevant

cLFV Interaction

$$\frac{g_{Z'}}{\sin\theta_W}\bar{l}_i Q_{ij}\gamma^\mu l_j Z'_\mu$$

Experiment type	Charges probed
$\mu^- N \to e^- N$	Q_{12}
$\mu^+ \to e^+\gamma$	$Q_{13}Q_{23}$ (and all others)
$\mu^+ \to e^+e^-e^+$	$Q_{11}Q_{12}$
$e^+e^- \to \mu^+\tau^-(\mu^-\tau^+)$	$Q_{11}Q_{23}$ $(Q_{12}Q_{13})$
$e^+e^- \to \mu^+\mu^-$	$Q_{11}Q_{22}$ (Q_{12})
muon $g-2$	Q_{23} $(Q_{21}Q_{22})$

Table 1: The CFLV experiments and the corresponding Z' charges probed at lowest order pro-

Different Q's !!

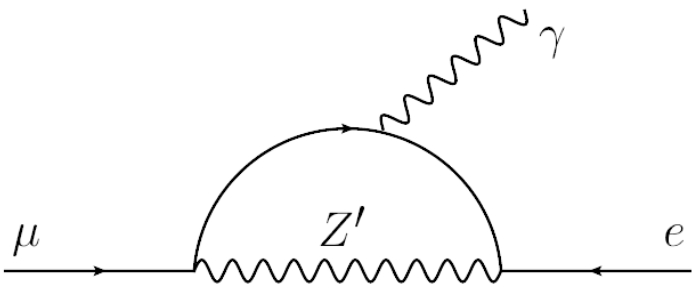


Figure 2: $\mu^+ \to e^+\gamma$ in the Z' models.

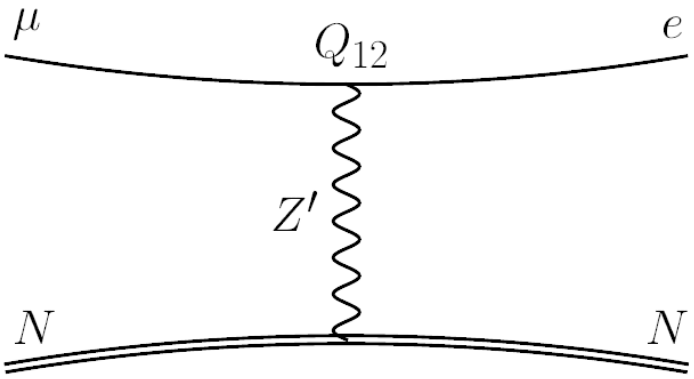
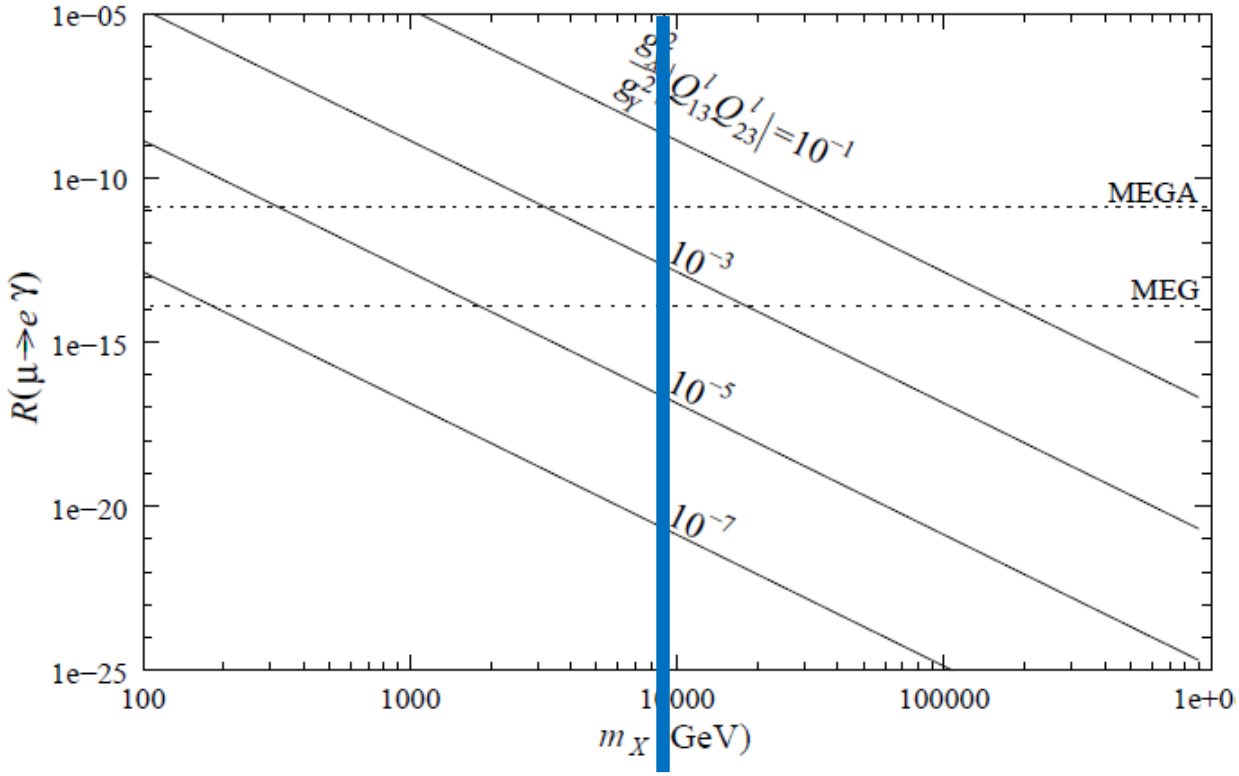


Figure 3: Non-photonic diagram of $\mu^- - e^-$ conversion in the Z' models.

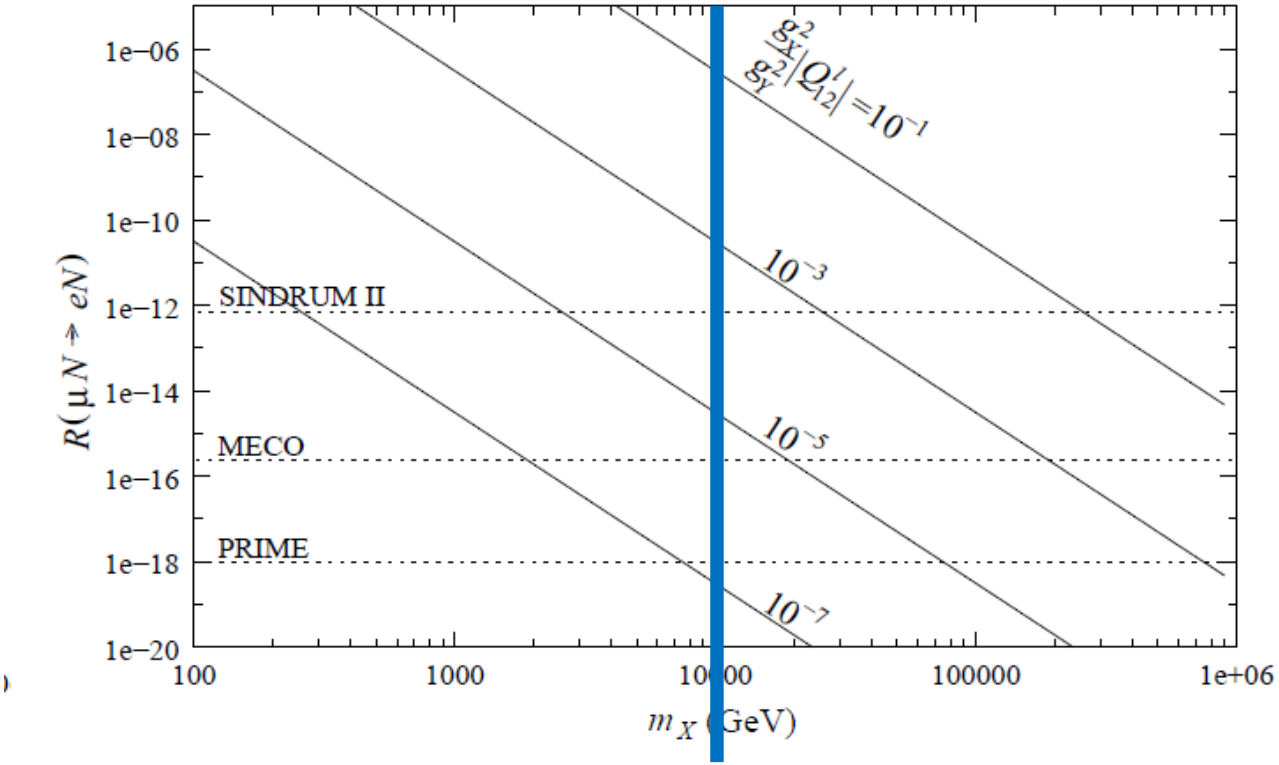


Brandon Murakami

10TeV

Figure 4: Constraint of Z' by the current search for $\mu^+ \to e^+\gamma$.

$$B(\mu \to e\gamma) = 1.3 \times 10^{-13} \left(\frac{g_x}{g_Y}\right)^4 \left(\frac{Q_{13}Q_{23}}{10^{-5}}\right)^2 \left(\frac{1\text{TeV}}{m_{Z'}}\right)^4$$



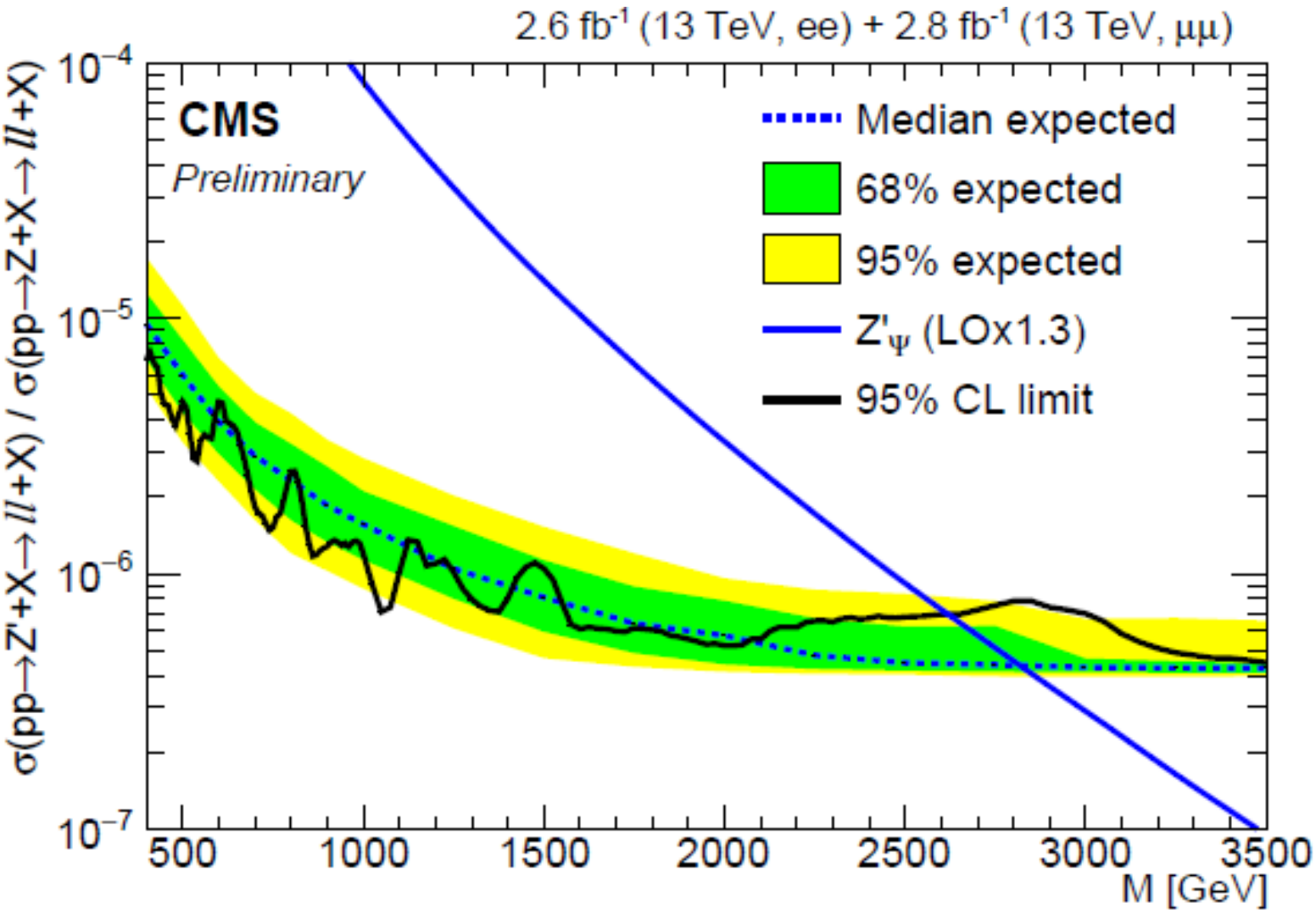
Brandon Murakami

10TeV

Figure 5: Constraint of Z' by the current search for $\mu^- - e^-$ conversion.

$$B(\mu N \to eN) = 3.1 \times 10^{-11} \left(\frac{g_{Z'}}{g_Y}\right)^4 \left(\frac{Q_{12}}{10^{-5}}\right)^2 \left(\frac{1\ \text{TeV}}{m_{Z'}}\right)^4$$

Direct Search at LHC ,excluded < 3TeV



Scalar type

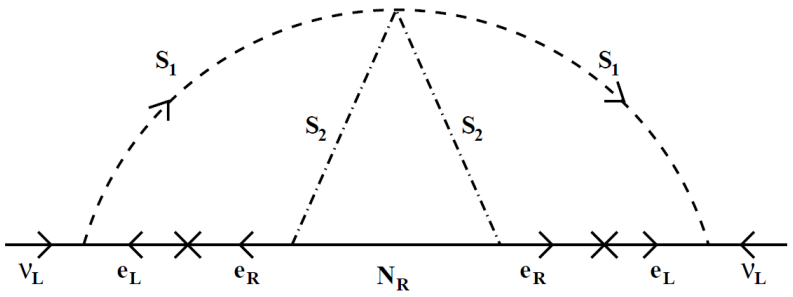
SUSY :: Still main target!?

2< doublet higgs :: SUSY is restricted version

{ Higgs triplet :: doubly charged

Radiative generation of neutrino masses

Krauss *etal*



sometimes doubly charged

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

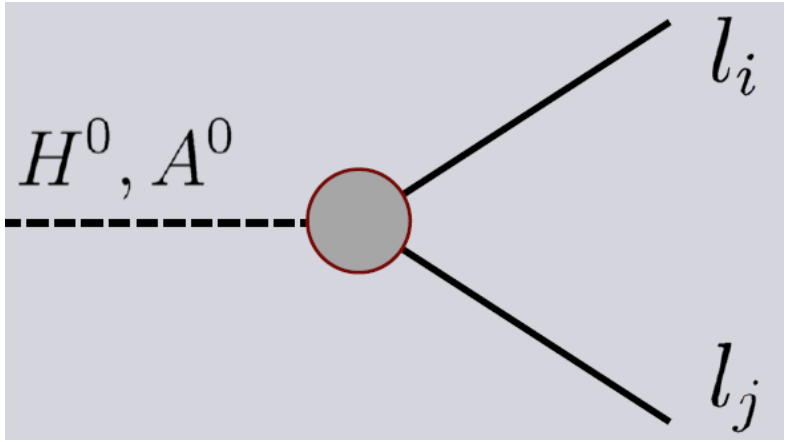
Is more relevant

SUSY

Neutral scalar : Heavy neutral higgs , sneutrino

With R-Parity

Higgs can contribute at tree level



Naïve 2< doublets, this coupling can be large, though…

In SUSY , slepton mixing must be contributed , that is, the couplings has same or less magnitude as dipole

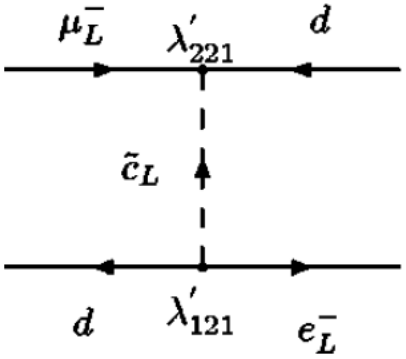
Furthermore, these higgses are probably very heavy

If R parity is broken,

$$W_{RPV}=\frac{\lambda_{ijk}}{2}L_iL_j\overline{E}_k+\lambda'_{ijk}L_iQ_j\overline{D}_k+\lambda''_{ijk}\overline{U}_i\overline{D}_j\overline{D}_k+\mu'_iL_iH_u$$

Tree contribution may dominate for $\mu - e$ conversion

Leptoquark



While $\mu \to e + \gamma$

Induced by loop

distinction of models

Andre´ de Gouveˆa, Smaragda Lola, and Kazuhiro Tobe

	$\frac{\mathrm{Br}(\mu\to e\gamma)}{\mathrm{Br}(\mu\to 3e)}$	$\frac{\mathrm{R}(\mu\to e \text{ in Ti})}{\mathrm{Br}(\mu\to 3e)}$	A_P	A_{P_1}	A_{P_2}	A_{P_1}/A_{P_2}
$\lambda'_{121}\lambda'_{221}$	1.1	2×10^5	-100%	-26%	-5%	5.6
MSSM with ν_R	1.6×10^2	0.92	-100%	10%	17%	0.6

Orthodox scenario

Source of LFV
=
Slepton mixing

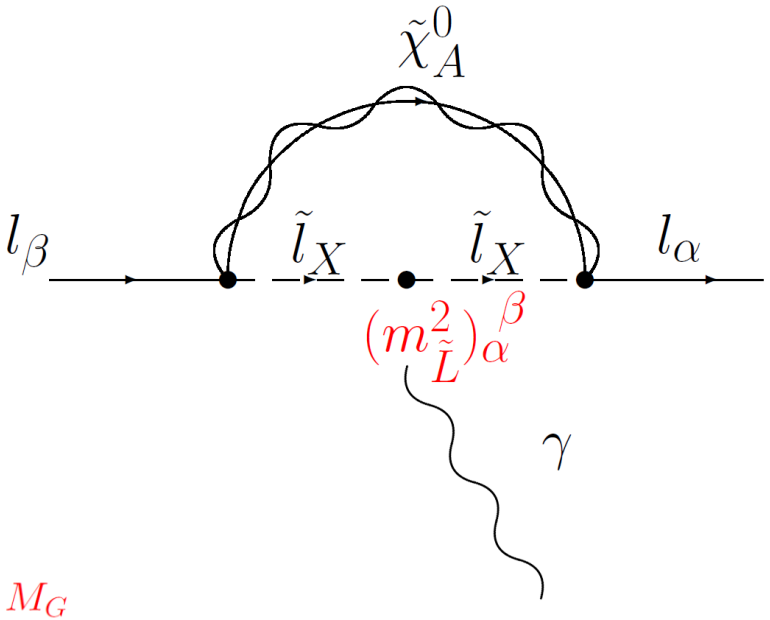
$$m_{\tilde{l}}^2 = \begin{pmatrix} m_{\tilde{e}\tilde{e}}^2 & \Delta m_{\tilde{e}\tilde{\mu}}^2 & \Delta m_{\tilde{e}\tilde{\tau}}^2 \\ \Delta m_{\tilde{\mu}\tilde{e}}^2 & m_{\tilde{\mu}\tilde{\mu}}^2 & \Delta m_{\tilde{\mu}\tilde{\tau}}^2 \\ \Delta m_{\tilde{\tau}\tilde{e}}^2 & \Delta m_{\tilde{\tau}\tilde{\mu}}^2 & m_{\tilde{\tau}\tilde{\tau}}^2 \end{pmatrix}$$

CMSSM + RH neutrino

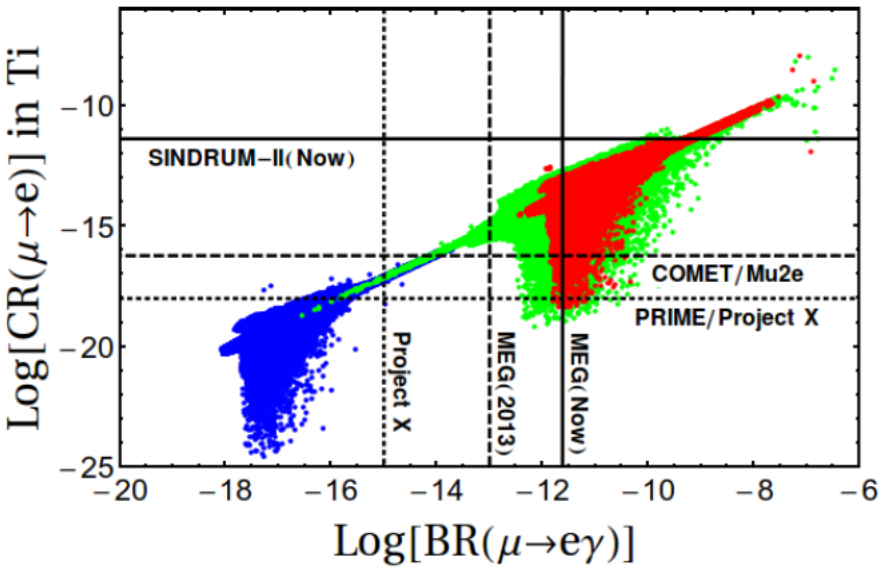
Most exhaustedly studied

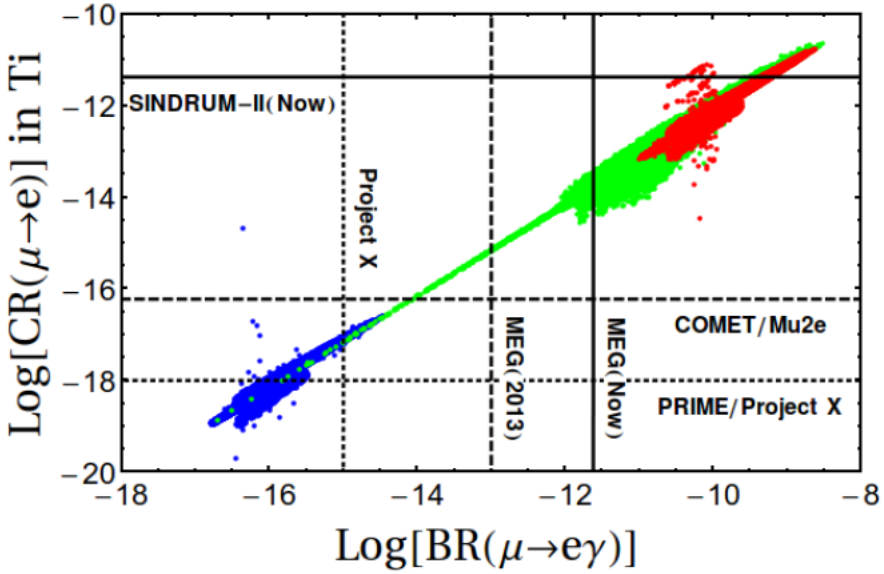
$$W = f_\nu^{i\beta} \bar{N}_i L_\beta H_u$$

$$(m_{\tilde{L}}^2)_\alpha^{\ \beta} \simeq -\frac{(6+a_0^2)m_0^2}{16\pi^2}(f_\nu^\dagger f_\nu)_\alpha^{\ \beta} \log\frac{M_G}{M_R}$$
$$\simeq -\frac{(6+a_0^2)m_0^2}{16\pi^2} U_{\alpha k}^{Dirac} (U^{Dirac*})^{\beta k} |f_{\nu k}|^2 \log\frac{M_G}{M_R}$$



Dipole dominant





1207.7227 Calibbi *et al*

3.Connection among CLFVs
an Example

J.S & M.Yamanaka
Phys. Rev. D91 055018-1-17, 2015

MEGII experiment updates/discovers(?)

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

COMET/DeeMe/Mu2E will discover(?)

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

In near future

Sensitivity is same.

If COMET find CLFV first then …?

μ-e conversion and then ?

If μ-e conversion is found, while other cLFV processes will never be found

E.g.

R-parity violating SUSY gives such a situation

Tree contribution for CLFV
Scalar/Vector with LFV
Direct coupling with qq and μ-e

- ☑ No correlations among cLFVs
- ☑ How to confirm the scenario?

Aim of this work

To find out distinctive signals to discriminate the scenario and other new physics models

To show the feasibility to determine the parameters in the RPV scenario through observing the signals

How to confirm a model?

R-parity violating SUSY

- ☑ Candidate of new physics: R−parity violating SUSY
- ☑ Consistent with experimental/theoretical status
  - New physics is required to cancel Higgs quadratic divergence
  - TeV scale SUSY predicts grand unification of interactions
  - So far no typical SUSY signals have been observed
- ☑ RPV terms in superpotential in SUSY

Omit the term to avoid proton decay

$$\mathcal{W}_{\not R} = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k$$

Offers LFV Scalar

Framework of our scenario

Naturally realized by RG evoltion
with universal masses@GUT scale

- ☑ Slepton contribution to RPV: only 3rd generation

- ☑ Different generation of left– and right–handed leptons
  λ_{ijk} (i $\neq$k and j $\neq$k)

Assumption to realize
the interesting situation

- ☑ RPV terms in superpotential in SUSY

$$\mathcal{W}_{\not R} = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k$$

Framework of our scenario

Naturally realized unless we introduce additional sources of flavor violation

- ☑ For quarks, flavor diagonal components are much larger than off-diagonal components

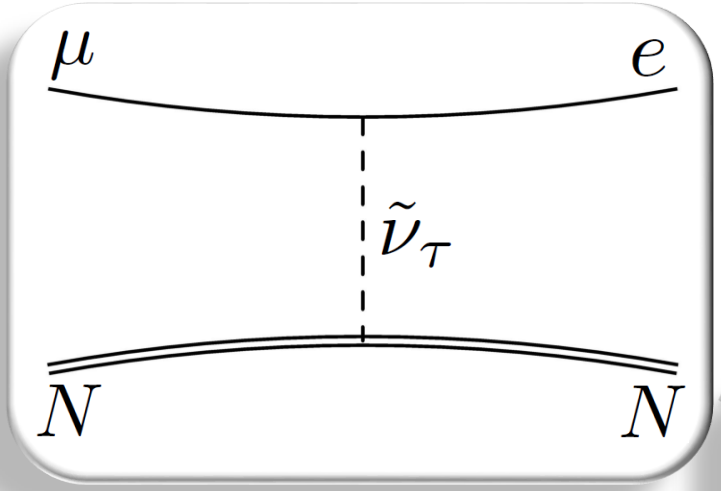
$$\lambda'_{ijj} \gg \lambda'_{ijk} \quad (j \neq k)$$

- ☑ RPV terms in superpotential in SUSY

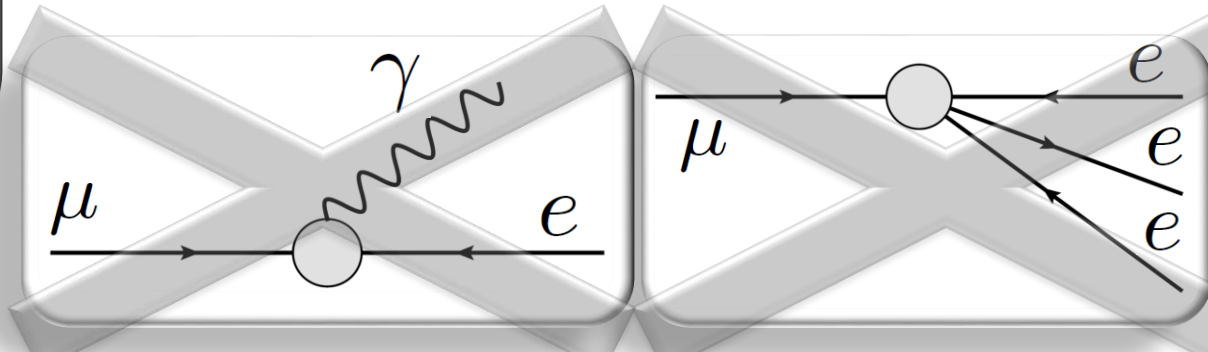
$$\mathcal{W}_{\not R} = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k$$

Exotic processes in the scenario

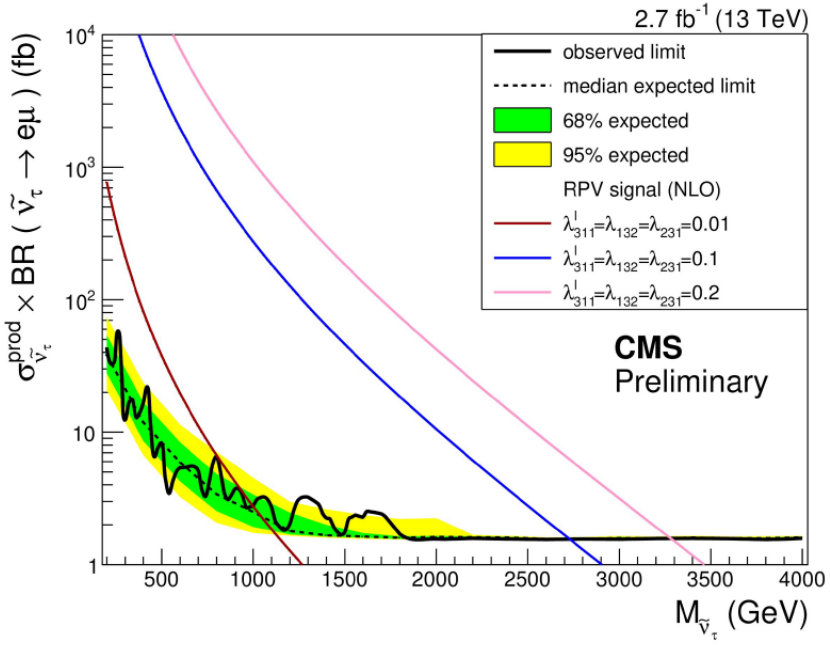
$$\mathcal{L}_{\rm RPV} = 2\{\,\lambda_{312}\tilde{\nu}_\tau\bar{\mu}_R e_L + \lambda_{321}\tilde{\nu}_\tau\bar{e}_R\mu_L + \lambda_{132}\tilde{\tau}_L\bar{\mu}_R\nu_e + \lambda_{231}\tilde{\tau}_L\bar{e}_R\nu_\mu\,\}$$
$$+\{\,\lambda'_{311}(\tilde{\nu}_\tau\bar{d}_R d_L - \tilde{\tau}_L\bar{d}_R u_L) + \lambda'_{322}(\tilde{\nu}_\tau\bar{s}_R s_L - \tilde{\tau}_L\bar{s}_R c_L)$$
$$+\lambda'_{333}(\tilde{\nu}_\tau\bar{b}_R b_L - \tilde{\tau}_L\bar{b}_R t_L)\,\} + \text{h.c.}$$

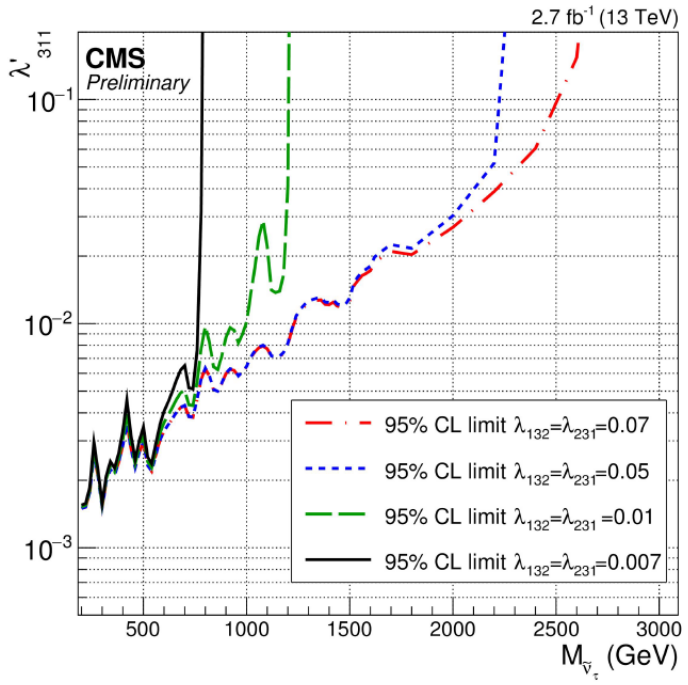


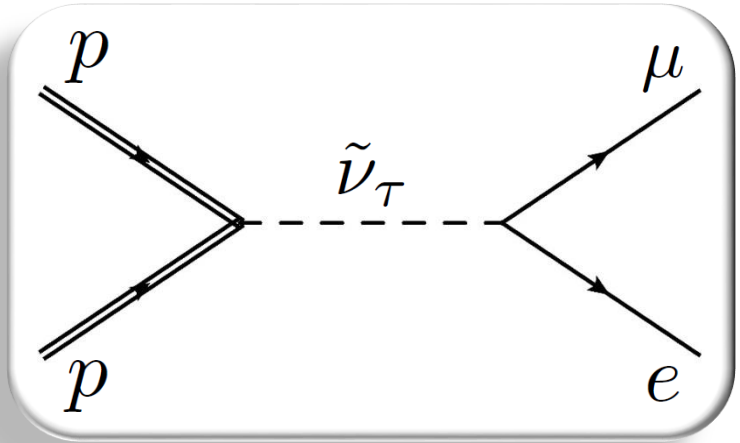
- ☑ μ-e conversion@tree level
- ☑ Negligible rates of other cLFV processes



Current bound for the scalar with LFV





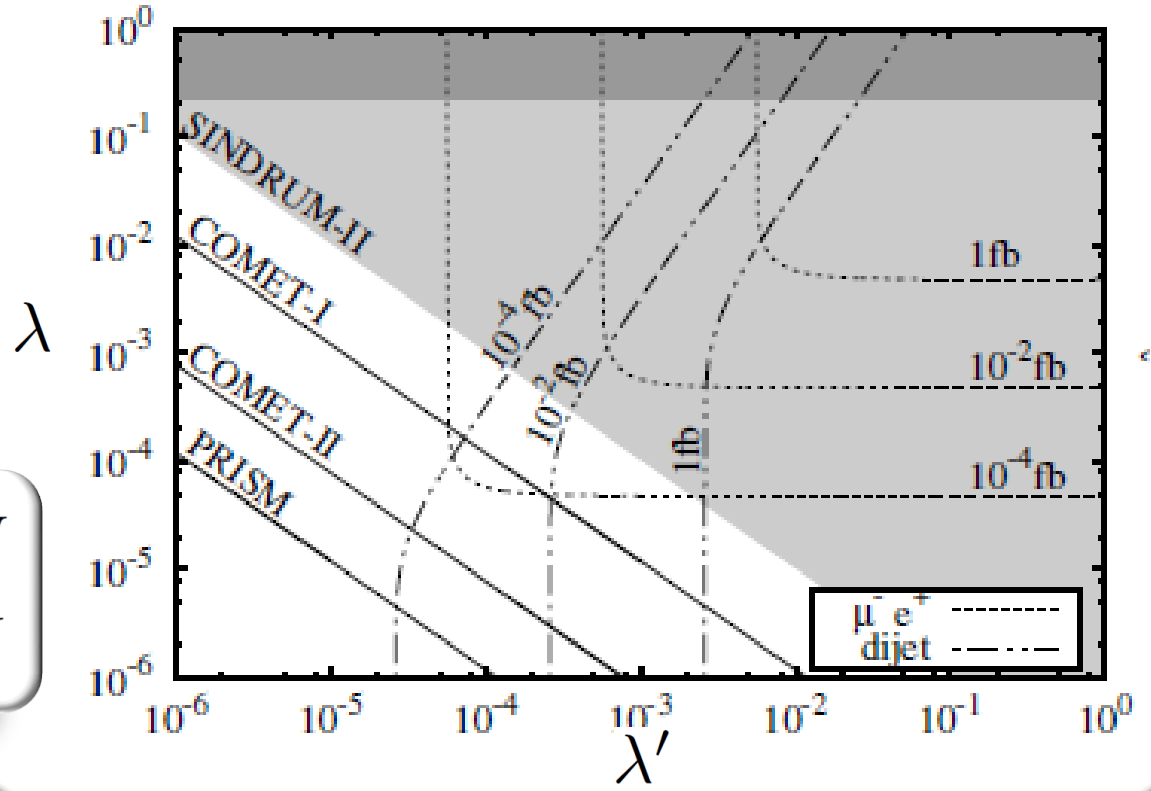


Correlations of distinctive signals

Contour plot of

- $\mathrm{BR}(\mu^- + N \to e^- + N)$
- $\sigma(pp \to \mu\bar{e})$
- $\sigma(pp \to jj)$

- sneutrino mass $m_{\tilde{\nu}_\tau} = 1\mathrm{TeV}$
- collision energy $\sqrt{s} = 14\mathrm{TeV}$



☑ μ-e conversion search is a strong tool for exploring RPV

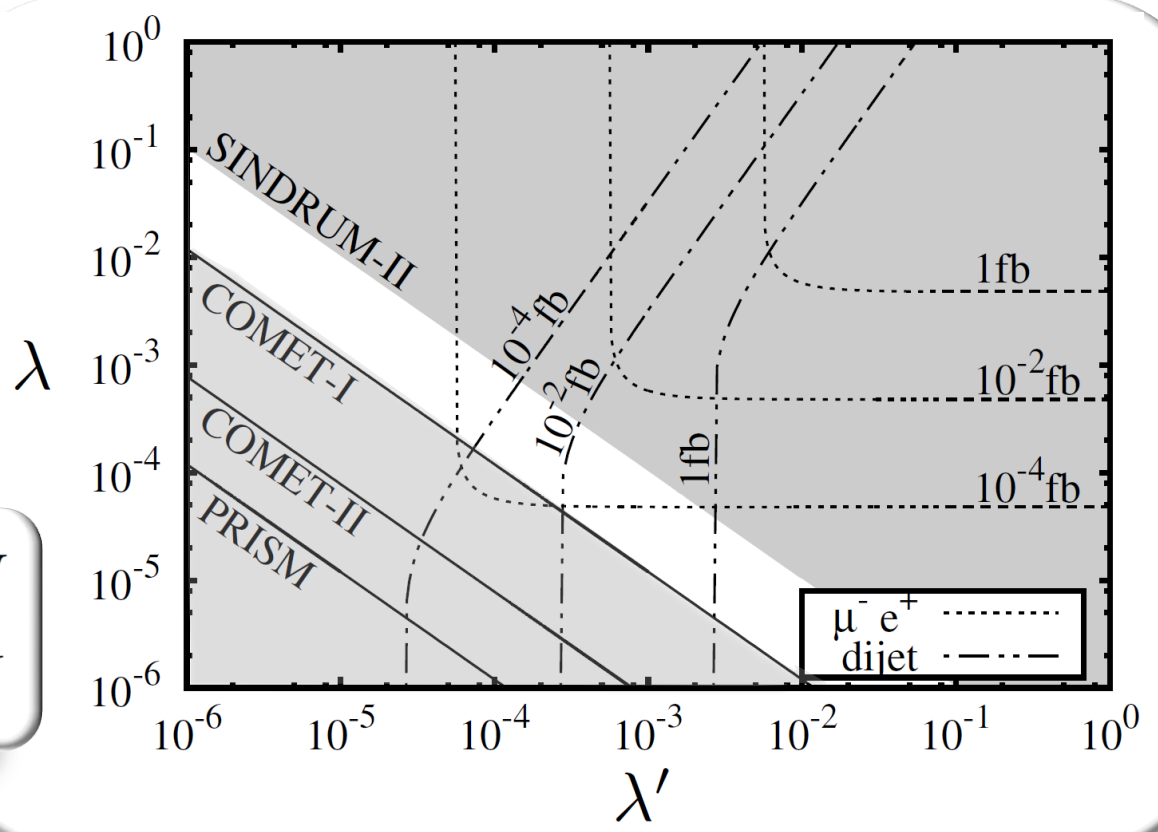
☑ PRISM explores all parameter space wherein LHC can survey

Correlations of distinctive signals

Contour plot of

- $\mathrm{BR}(\mu^- + N \to e^- + N)$
- $\sigma(pp \to \mu\bar{e})$
- $\sigma(pp \to jj)$

- sneutrino mass $m_{\tilde{\nu}_\tau} = 1\mathrm{TeV}$
- collision energy $\sqrt{s} = 14\mathrm{TeV}$



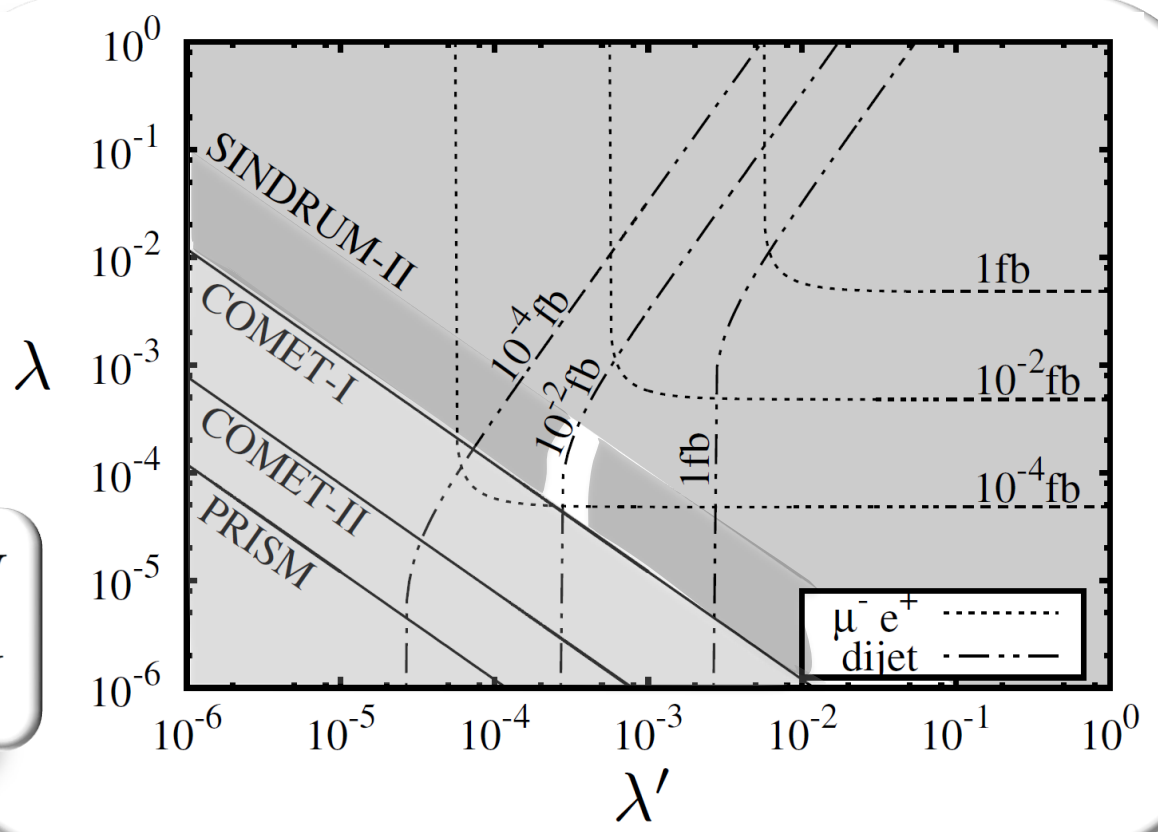
☑ COMET/DeeMe found m−e conversion ➡ white band

Correlations of distinctive signals

Contour plot of

- $\mathrm{BR}(\mu^- + N \to e^- + N)$
- $\sigma(pp \to \mu\bar{e})$
- $\sigma(pp \to jj)$

- sneutrino mass $m_{\tilde{\nu}_\tau} = 1\mathrm{TeV}$
- collision energy $\sqrt{s} = 14\mathrm{TeV}$



☑ COMET/DeeMe found m−e conversion ➡ white band

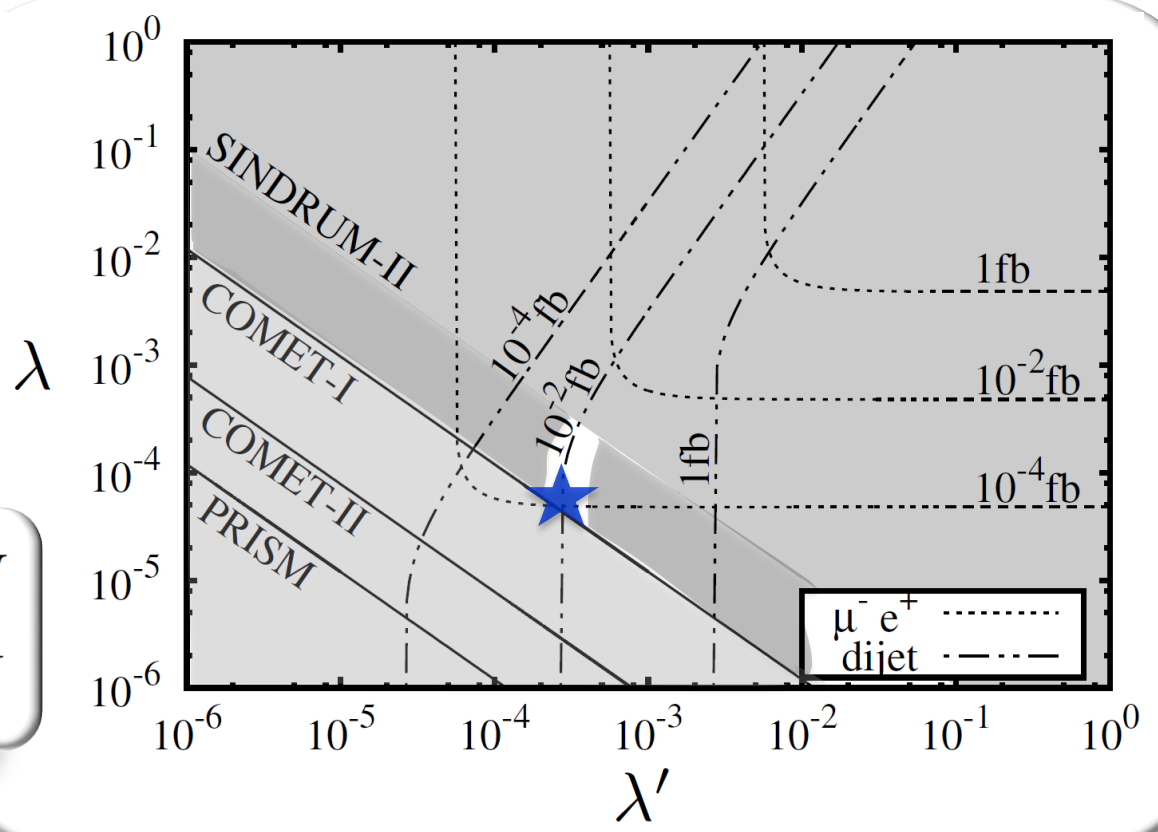
☑ Dijet resonance is found with 10 fb^{-2} ➡ white small region

Correlations of distinctive signals

Contour plot of

- $\mathrm{BR}(\mu^- + N \to e^- + N)$
- $\sigma(pp \to \mu\bar{e})$
- $\sigma(pp \to jj)$

- sneutrino mass $m_{\tilde{\nu}_\tau} = 1\mathrm{TeV}$
- collision energy $\sqrt{s} = 14\mathrm{TeV}$



☑ $\mu\bar{e}$ resonance is found with 10 fb^{-4} ➡ blue star point

☑ J-PARC and LHC precisely determine the RPV parameters!

More on coupling discrimination

- Non Standard Interaction

Pion decay in scalar channel – chiral enhancement

Exotic decay $\pi^+ \to \mu^+ \nu_e$

$$\epsilon^S_{\mu e} = \sqrt{2} \frac{m_\pi^2}{m_\mu m} \frac{\lambda^*_{312} \lambda'_{311}}{G_F m^2_{\tilde{\tau}}}$$

312 : LH electron only

- ILC with polarization

LHC signal is same for 312(LH e) and 321 (RH e)

Can you distinguish them ?

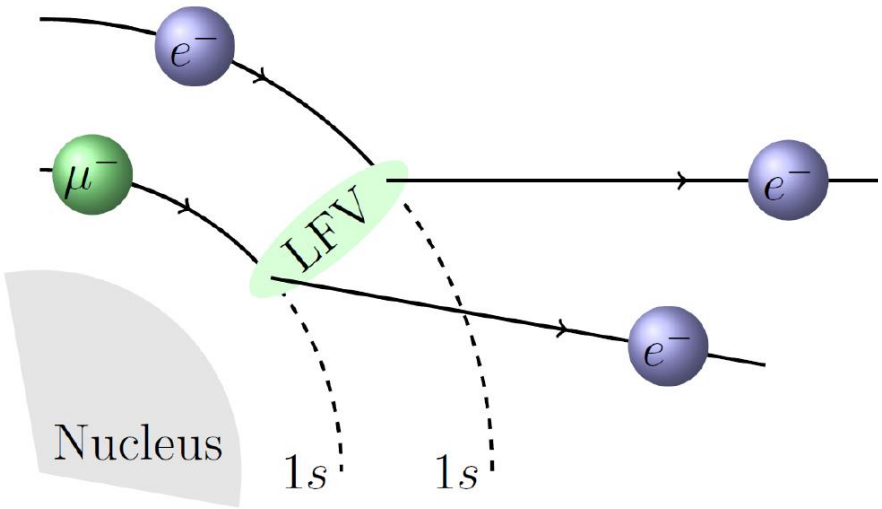
4.Another idea for CLFV with muon

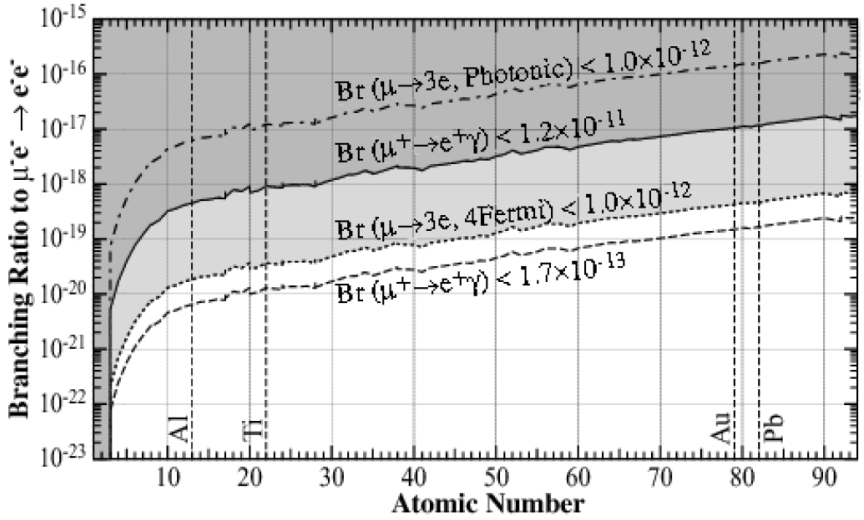
M.Koike,Y.Kuno,J.S., M.Yamanaka, Phys. Rev. Lett. 105, 121601 (2010)
Y.Uesaka, Y.Kuno,J.S., T.Sato, M.Yamanaka, Phys. Rev. D93 076006-1-8, 2016

$$\mu^- + e^- \to e^- + e^- \textbf{ in orbits}$$

Same lagrangian for muon LFV

$$\mathrm{Br}(\mu^- e^- \to e^- e^-) = 3.3 \cdot 10^{-12} \times (Z-1)^3 \left(\frac{\tilde{\tau}_\mu}{\tau_\mu}\right) G$$





5.Summary

Charged Lepton Flavor Violation

Clean signal for Physics beyond the Standard Model

Not observed yet though many searches have been done

Muon decay , Tau decay, LFV in final state(decay product)

Classification of new physics

Tree vs Loop : $\mu^+ \to e^+\gamma$:always loop effect

Scalar vs Vector

Model dependence

Most precise measurements with muon

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

Which one will be observed first?

Example of model dependent analysis with other signals

New CLFV mode? $\mu^- + e^- \to e^- + e^-$ **in orbits**