Lepton Flavor
and
Neutrino Oscillation

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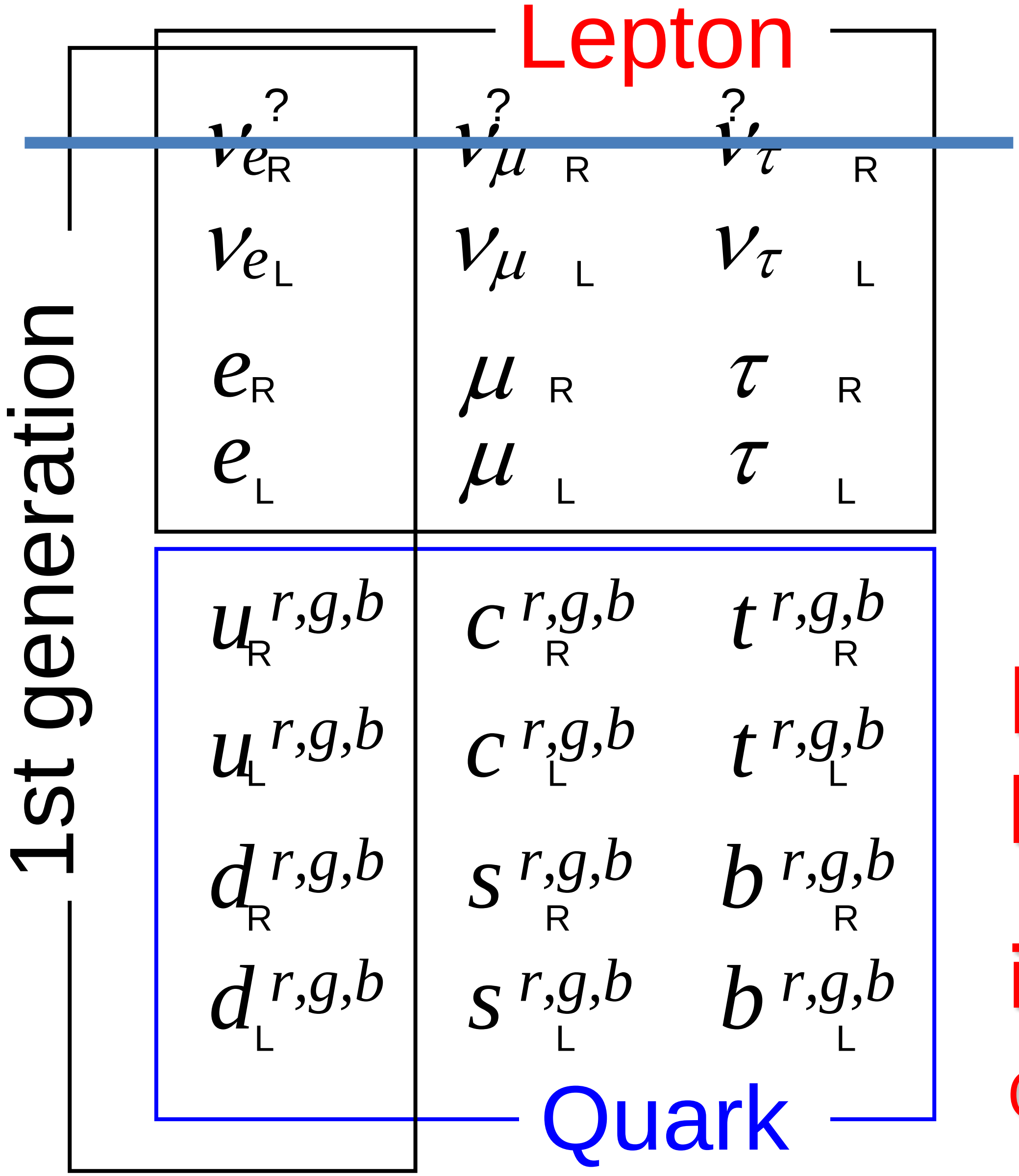
1.Introduction ～ Lepton Flavor in SM

The Standard Model



Lepton

~~$\nu_{e_R}^{?}$~~	~~$\nu_{\mu\,R}^{?}$~~	~~$\nu_{\tau\,R}^{?}$~~
ν_{e_L}	$\nu_{\mu\,L}$	$\nu_{\tau\,L}$
e_R	μ_R	τ_R
e_L	μ_L	τ_L
$u_R^{r,g,b}$	$c_R^{r,g,b}$	$t_R^{r,g,b}$
$u_L^{r,g,b}$	$c_L^{r,g,b}$	$t_L^{r,g,b}$
$d_R^{r,g,b}$	$s_R^{r,g,b}$	$b_R^{r,g,b}$
$d_L^{r,g,b}$	$s_L^{r,g,b}$	$b_L^{r,g,b}$

Quark

1st generation

+Higgs boson H

Chiral Thoery

- No RH neutrino
- L<->R nonsymmetric

⇒

Lepton Flavor (e-like, μ -like, τ -like)

is exact symmetry and conserved

Lepton Flavor in SM

Conserved “Charge” resulting from massless neutrinos

Electron, muon, tau number

$L_e \quad L_\mu \quad L_\tau$

	e^-	ν_e	μ^-	ν_μ	τ^-	ν_τ
L_e	1	1				
L_μ			1	1		
L_τ					1	1

Opposite(-1) for anti particles

Example of conservation

$$\pi^- \rightarrow \mu^- \quad \bar{\nu}_\mu$$

$$L_\mu \quad 0 \quad = \quad 1 + (-1)$$

Derivation of lepton flavor charge

Lepton Part Only

$$L_i = \begin{pmatrix} \nu_{Li} \\ e_{Li} \end{pmatrix}, \quad e_{Ri}, \quad (i = 1, 2, 3)$$

Kinetic Part

$$\mathcal{L}_k = \bar{L}_i i \not{D}_L L_i + \bar{e}_{Ri} i \not{D}_R e_{Ri}$$

$$D_{L\mu} = \begin{pmatrix} \partial_\mu + \frac{i}{2} g_1 B_\mu - g_2 \frac{i}{2} W^0_\mu, & g_2 \frac{i}{\sqrt{2}} W^+_\mu \\ g_2 \frac{i}{\sqrt{2}} W^-_\mu, & \partial_\mu + \frac{i}{2} g_1 B_\mu + \frac{i}{2} g_2 W^0_\mu \end{pmatrix}$$

$$D_{R\mu} = \partial_\mu + i g_1 B_\mu$$

$$\mathcal{L}_k = \mathcal{L}_{k,diag} + \mathcal{L}_{k,W}$$

$$\mathcal{L}_{k,diag} = \bar{\Phi}_j i \not{D}_j \Phi_j$$

$$D_{\mu j =}\partial_\mu - ieQ_j A_\mu - ig_Z(T_{j3} - Q_j \sin^2\theta_w) Z_\mu \quad 3 \times 3$$

$$\Phi_j = \{\nu_L, e_L, e_R\}$$

Sum of 3 species of Weyl sprinors

Invariant under **3** independent unitary transformation

$$U_l \quad , \qquad l = \nu_L,\ e_L,\ e_R, \quad 3 \times 3 \ \mathrm{UnitaryMatrix}$$

$$l \quad \to \quad U_l l \ (e_{Li} \to (U_{e_L} e_L)_i \qquad) \quad U_l$$ independent

$$\mathcal{L}_{k,W} = ig_2\frac{1}{\sqrt{2}}W_\mu^+\bar{\nu}_{Li}\gamma_\mu e_{Li} \ + \ h.c.$$

To make it invariant $U_{\nu_L} = U_{e_L}$ Is necessary. Reduction of symmetry

Higgs Part

$$\mathcal{L}_H = Y_{ij}\bar{L}_i e_{Rj} + h.c.$$

Y_{ij} **3 × 3 complex :: diagonalized by 2 unitary matrices**

$$Y_{ij} \longrightarrow Y_{diag} = \mathrm{diag}\{y_e, y_\mu, y_\tau\} = U_L Y_{ij} U_R^\dagger$$

$$L_\alpha \equiv U_{L\alpha i}L_i = \begin{pmatrix} U_{L\alpha i}\nu_{Li} \\ U_{L\alpha i}e_{Li} \end{pmatrix}, \quad e_{R\alpha} \equiv U_{Ri}E_{Ri}, \quad \alpha = e, \mu, \tau$$

➡
$$\begin{aligned} \mathcal{L}_H &= Y_\alpha \bar{L}_\alpha e_{R\alpha} + h.c. \\ &= h^+\left(y_e\bar{\nu}_{eL}e_R + y_\mu\bar{\nu}_{\mu L}\mu_R + y_\tau\bar{\nu}_{\tau L}\tau_R\right) \\ &\quad + h^0\left(y_e\bar{e}_L e_R + y_\mu\bar{\mu}_L\mu_R + y_\tau\bar{\tau}_L\tau_R\right) + h.c. \end{aligned}$$

Since $U_{\nu_L} = U_{e_L}$ kinetic term is invariant

$$\mathcal{L}_{k,diag} = \bar{\Phi}_\alpha i\not{D}\Phi_\alpha \qquad \Phi_\alpha = \{\nu_{\alpha L}, e_{\alpha L}, e_{\alpha R}\}$$

$$\mathcal{L}_{k,W} = ig_2\frac{1}{\sqrt{2}}W_\mu^+\bar{\nu}_{\alpha L}\gamma_\mu e_{\alpha L} \ + \ h.c.$$

Kinetic terms under flavor basis !!

Residual symmetry ： ： Lepton Flavor

$$\Phi_\alpha = \{\nu_{L\alpha}, e_{L\alpha}, e_{R\alpha}\} \quad \alpha = e, \mu, \tau$$

Paired with same flavor
→Lagrangian is invariant under phase shift of each flavor
→**Lepton flavor conservation**

e.g $$\{e'_L, e'_R, \nu'_{eL}\} = \exp\{-i\theta_e\}\{e_L, e_R, \nu_{eL}\}$$

Phase transformation of electron flavor

$$\begin{aligned} \mathcal{L}'_{k,W} &= ig_2 \frac{1}{\sqrt{2}} W^+_\mu \bar{\nu}'_e \gamma_\mu e'_L \ + \ h.c. \\ &= ig_2 \frac{1}{\sqrt{2}} W^+_\mu \bar{\nu}_e e^{i\theta} \gamma_\mu e^{-i\theta} e_L + h.c = \mathcal{L}_{k,W} \end{aligned}$$

From Noether’s theorem Consered current exists

In each flavor the conserved current is given by

$$j^\mu_\alpha = \bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\alpha} + \bar{e}_{L\alpha}\gamma^\mu e_{L\alpha} + \bar{e}_{R\alpha}\gamma^\mu e_{R\alpha}$$

“Charge” is expressed as follows and it conserve

$$Q_\alpha = \int d^3x j^0_\alpha$$

For example $\alpha = e$, that is, electron flavor charge is given in terms of creation and annihilation operators of electrons

$$Q_e = L_e = \int d^3p \sum_{l=\nu_{eL}, e_L, e_R} b_l^\dagger(\mathbf{p}) b_l(\mathbf{p}) - d_l^\dagger(\mathbf{p}) d_l(\mathbf{p})$$

$$b^\dagger b \qquad \text{number operator for particle}$$

$$d^\dagger d \qquad \text{number operator for anti} - \text{particle}$$

Electron and electron neutrino $L_e = +1$

Positron and anti-electron neutrino $L_e = -1$

Similarly muon and tau flavor charge $L_\mu, \; L_\tau$ is defined.

Lepton Flavor is conserved under SM

Electron, muon, tau number

L_e L_μ L_τ

	e^-	ν_e	μ^-	ν_μ	τ^-	ν_τ
L_e	1	1				
L_μ			1	1		
L_τ					1	1

Opposite(-1) for anti particles

If SM is correct,
in all process, these numbers are conserved

⇔ **Contraposition**

If non-conserved is found, SM is not correct

With additional particles and hence additional operator in Lagrangian,

in general, under the transformation

$$\{\alpha'_L, \alpha'_R, \nu'_{\alpha L}\} = \exp\{-i\theta_\alpha\}\{\alpha_L, \alpha_R, \nu_{\alpha L}\} \quad \alpha = e, \mu, \tau$$

+ appropriate transformation for extra particles

Lagrangian is not invariant

→Lepton flavor cannot be defined

→Lepton flavor " charge" defined under SM Lagrangian

cannot be conserved

Status of LFV with charged lepton

$$\mu^- \rightarrow e^- \quad \gamma$$

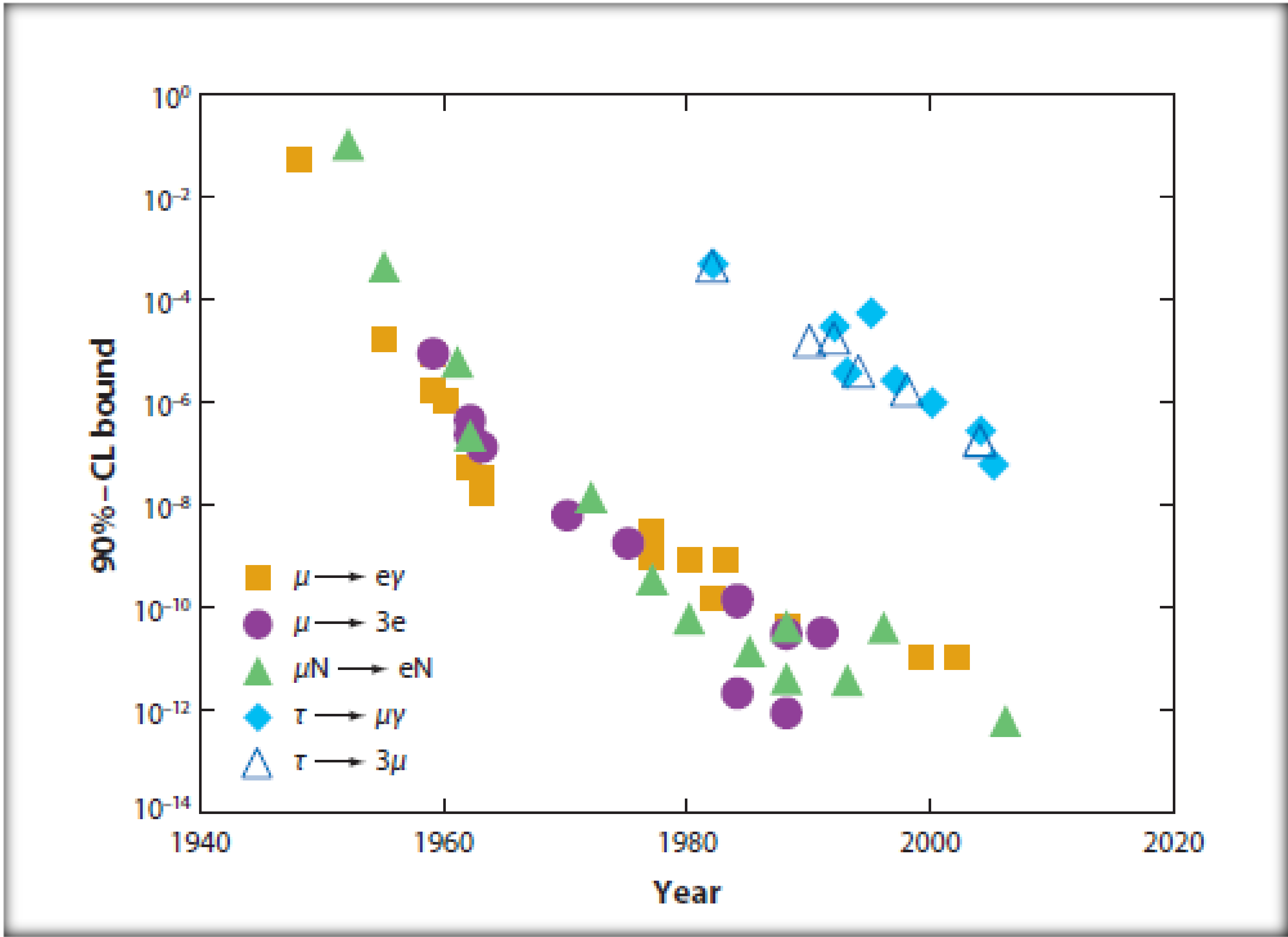
$$L_\mu \quad 1 \quad = \quad 0 + 0$$

$$L_e \quad 0 \quad = \quad 1 + 0$$

No observation of CLFV

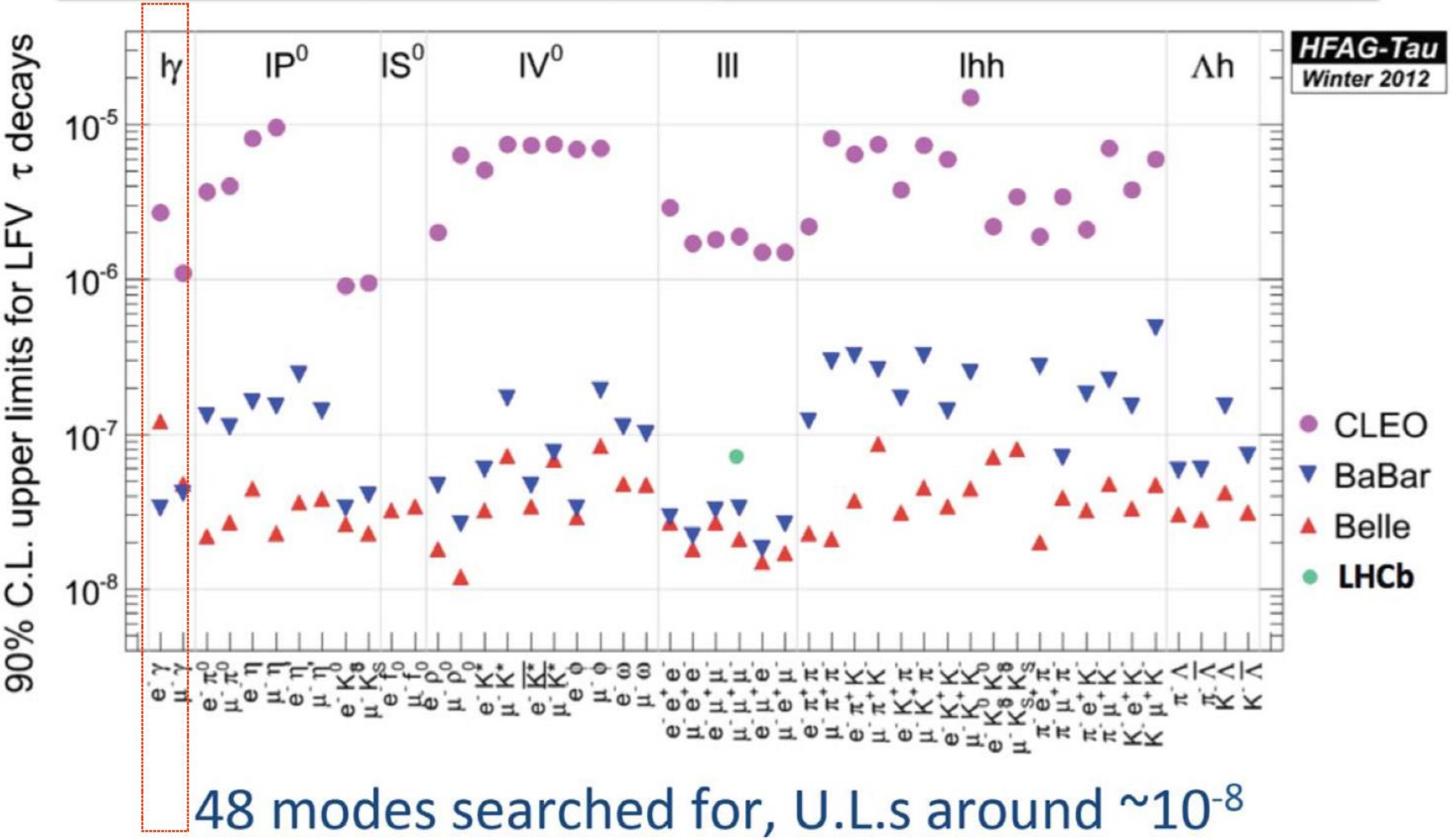
➡

No doubt on SM from CLFV



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

τ decay



48 modes searched for, U.L.s around ~10^{-8}

2. Lepton flavor violation

$$\{\alpha'_L, \alpha'_R, \nu'_{\alpha L}\} = \exp\{-i\theta_\alpha\}\{\alpha_L, \alpha_R, \nu_{\alpha L}\} \quad \alpha = e, \mu, \tau$$

For LF to be defined, Lagrangian must be invariant under this transformation with appropriate transformation on extra particles

If new Lagrangian is not invariant
→Lepton flavor cannot be defined
→Lepton flavor " charge" as defined under SM Lagrangian cannot be conserved

Simplest example

Neutrino mass term with RH neutrinos (SM singlets) ν_{Ra} :: Dirac mass term

$$\mathcal{L}_H + = \tilde{H}\tilde{Y}_{\alpha a}\bar{L}_\alpha \nu_{Ra} + h.c$$

Flavor basis α is fixed by charge lepton mass.
We cannot rotate lepton doublet.

If nature choose $Y_{\alpha i}$ to be diagonalized by rotating ν_{Ra}, $\nu_{R\alpha} \equiv U_{R\alpha a}\nu_{Ra}$

Then $\mathcal{L}_H + = \tilde{H}\tilde{Y}_\alpha \bar{L}_\alpha \nu_{R\alpha}$, and hence LF is defined as a result of

$$\{\alpha'_L, , \alpha'_R, \nu'_{L\alpha}, \nu'_{R\alpha}\} = \exp\{-i\theta_\alpha\}\{\alpha_L, , \alpha_R, \nu_{L\alpha}, \nu_{R\alpha}\}$$

Appropriate transformation

In general, we need by unitary transformation to get mass basis for neutrino

$$\tilde{Y}_{\alpha a} \to \mathrm{diag}\{\tilde{Y}_i\} = U^{\dagger}_{MNS} \tilde{Y}_{\alpha a} U^{\dagger}_{R}$$

→Lepton flavor cannot be defined

→Lepton flavor “ charge” as defined under SM Lagrangian cannot be conserved

$$\tilde{H} \tilde{Y}_{\alpha a} \bar{L}_{\alpha} \nu_{Ra} = h^0 \tilde{Y}_i \bar{\nu}_{Li} \nu_{Ri} + h^- \tilde{Y}_{\alpha i} \bar{\alpha}_L \nu_{Ri}$$

Diagonalized mass

In another words flavor basis do not coincide with mass basis $\nu_{L\alpha} \neq \nu_{Li}$

Interaction with W boson、

$$W^+_{\mu} \bar{\nu}_{\alpha L} \gamma_{\mu} e_{\alpha L} = W^+_{\mu} \bar{\nu}_{Li} U^{\dagger}_{MNS} \gamma_{\mu} e_{\alpha L}$$

Mass base mix with each other. ->Flavor changing processes appear

seed of neutrino oscillation

Incidentally, dirac mass terms, in general, conserve

lepton number

$$L_e + \quad L_\mu + \quad L_\tau \quad\quad L$$

$$\mu^- \to e^- \quad \gamma$$ can happen

$$L \quad 1 \quad = \quad 1 + 0$$

Lepton number = A part of particle number

= (particle =1 & antiparticle=-1)

c.f. Majorana mass term leads lepton number (in general particle number) violation

➡ neutrinoless double beta decay

$\mu^- \to e^+$

not necessary neutrino majorana mass term

3. Neutrino oscillation

In SM, neutrino flavor is defined with paired charged lepton

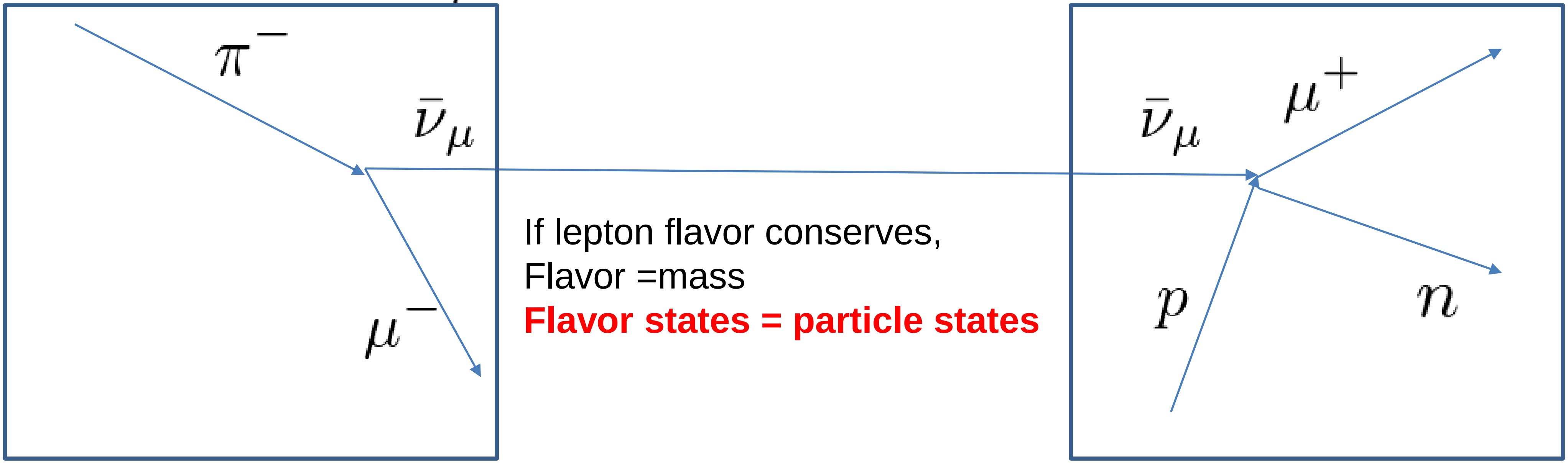
Beta decay, electron is emitted (Le=1) = anti-electron neutrino emitted (Le=-1)
→electron number 0=1+(-1)

$$n \to p + e^- + \bar{\nu}_e$$

$$L_e \ :: \ 0 = 0 + 1 + (-1)$$

Neutrino oscillation

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$



If lepton flavor conserves,
Flavor =mass
Flavor states = particle states

creation

as a whole

detection

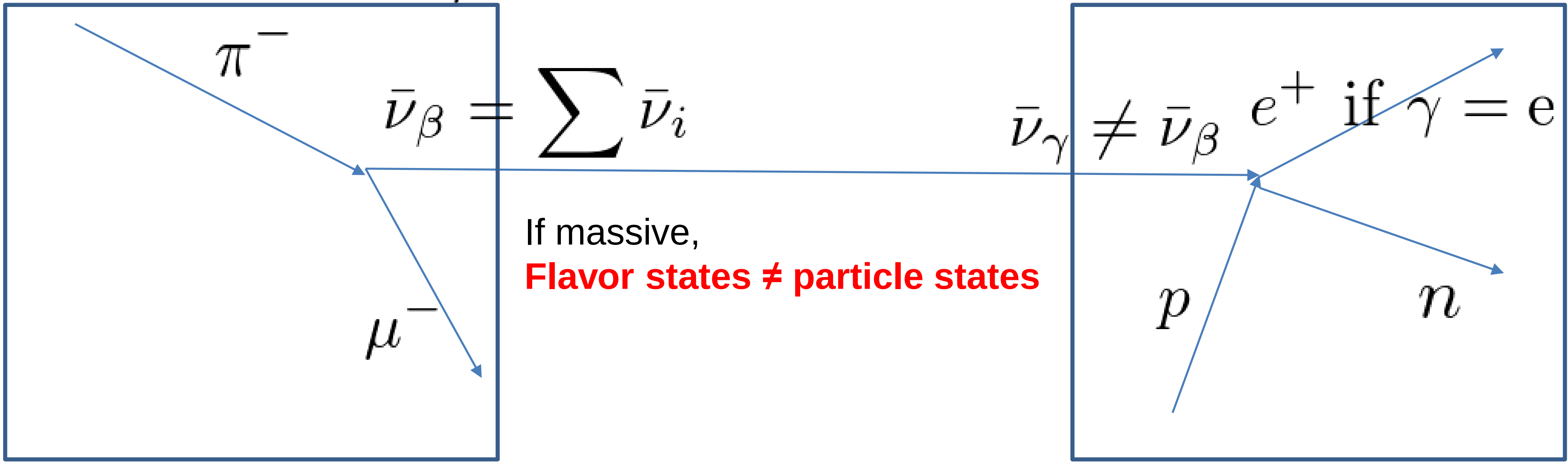
$$\pi^- + p^+ \to \mu^- + \mu^+ + n$$

$$L_\mu \ :: \ 0 + 0 \quad = \quad 1 + (-1)$$

If neutrino is massive,

Neutrino oscillation

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$



$$\bar{\nu}_\beta = \sum \bar{\nu}_i$$

$$\bar{\nu}_\gamma \neq \bar{\nu}_\beta \quad e^+ \text{ if } \gamma = \mathrm{e}$$

If massive,
Flavor states ≠ particle states

creation

detection

as a whole

$$\pi^- + p^+ \to \mu^- + e^+ + n$$

$$L_e :: 0 + 0 = 0 + (-1)$$

$$L_\mu :: 0 + 0 = 1 + (0)$$

LFV!! Logically SM is incorrect !!

To insist it is due to neutrino oscillation, more information has been accumulated

If neutrino is massive,

Maki,Nakagawa,Sakata

Flavor eigenstate $\neq$ Mass eigenstate

Interaction state Particle state

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\alpha i} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Propagation of nuetrinos： As a particle = mass eigenstate

Creation of neutrinos : week interaction accompanied with partner charged lepton Superposition of mass eigenstates

⇒ Multiple propagation of neutrinos

Quantum interference

＝ Neutrino Oscillation

Reactor Neutrino Example

Two flavor
approximation

electron neutrino is emitted

$$\nu^f(0) = \nu_e = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

incidentally $\nu_\mu = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

At a distance $L = t$ survival probability of ν_e

$$P_{\nu_e \to \nu_e} = |\nu_e^\dagger \nu^f(L)|^2 = 1 - \sin^2 2\theta \sin 2\frac{\delta m^2 L}{4E}$$

Quantum interference（oscillation）

$$\to 1 - \frac{1}{2}\sin^2 2\theta$$

$\text{Large } \delta m^2 \text{and/or Low } E$

$$= \cos^4\theta + \sin^4\theta$$

Quantum effect disapper

Merely transition

$$\nu_e \xrightarrow{\cos\theta} \nu_1 \xrightarrow{\cos\theta} \nu_e$$

Ampitude of this transition $\cos^2\theta$

Similarly sin^2θ for 2nd state

incidentally $P_{\nu_e \to \nu_\mu} = |(0,1)\nu^f(x)|^2 = \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4E}$

As a result,

We have to explain neutrino masses and lepton mixings → Lepton Flavor Violation

Neutrinos

★ Neutral (Electromagnetic and color), real under SU(2)

★ Tiny mass (also mass pattern)

○Neutral :: two types of mass term

Dirac : “partner” is necessary. It is neutral (= no charge) under **SM**

so-called Right-Handed(RH) neutrino ν_R . Higgs doublet can be reused

$$yH\bar{\nu}_R L \supset m\bar{\nu}_R\nu_L$$

Majorana : self mass term. Within **renormalizable**, we need to introduce SU(2) tri ϕ

$$y\phi L^T C L \supset \nu_L^T C\nu_L$$

If **nonrenormalizable,** with cutoff without new particle

$$\frac{h_{ij}}{2\Lambda}(HL_i)(HL_j)$$

though Λ indicates new physics = new particle

For example, ν_R majorana mass can be new scale Λ. It is singlet **under SM**

$$M\,\nu_R^T C \nu_R$$ Is allowed

With Dirac mass term $m\bar{\nu}_R\nu_L$, we have mass term for **neutral particle under**

$$(\nu_{L,}\quad \nu_R^C)\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_R^C \end{pmatrix}$$

Eigenstate values are neutrino masses. Especially $m << M$

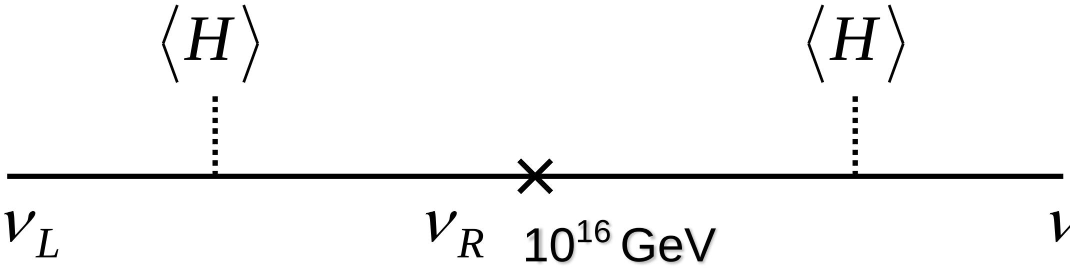
$$\frac{-m^2}{M}, M$$

Seesaw

Particle states ν_L ν_R

Gell-mann *et al*, *Yanagida*

Λ Is RH neutrino Majorana masses. Graphycally

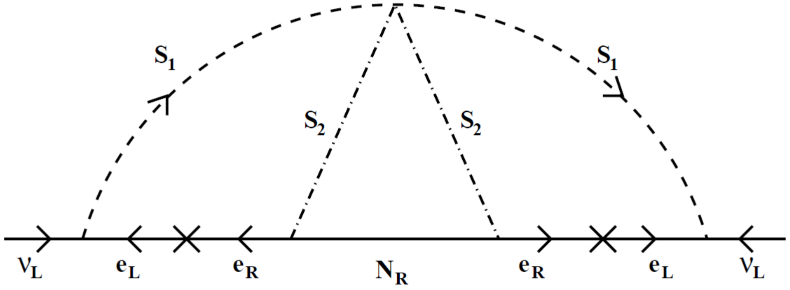


$$m_\nu = \frac{(100)^2}{10^{16}} \sim 10^{-12}\,\mathrm{GeV} \sim 10^{-3}\,\mathrm{eV}$$

$m << M$ Is not necessary. Different type of models

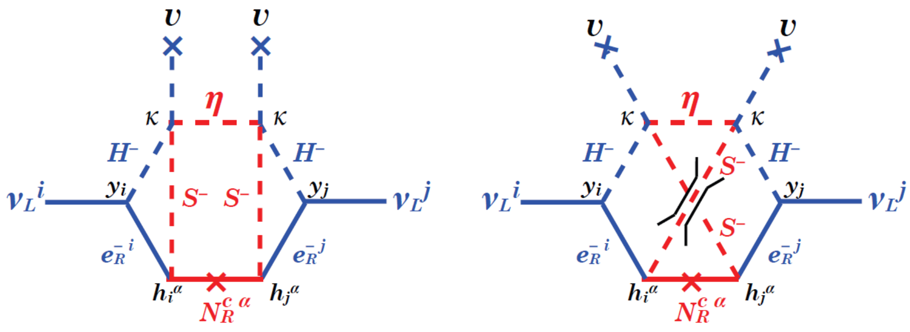
Another example = loop correction   Zee model・radiative seesaw

Krauss *etal*



Majorana mass term for left-handed neutrinos

Aoki *etal*



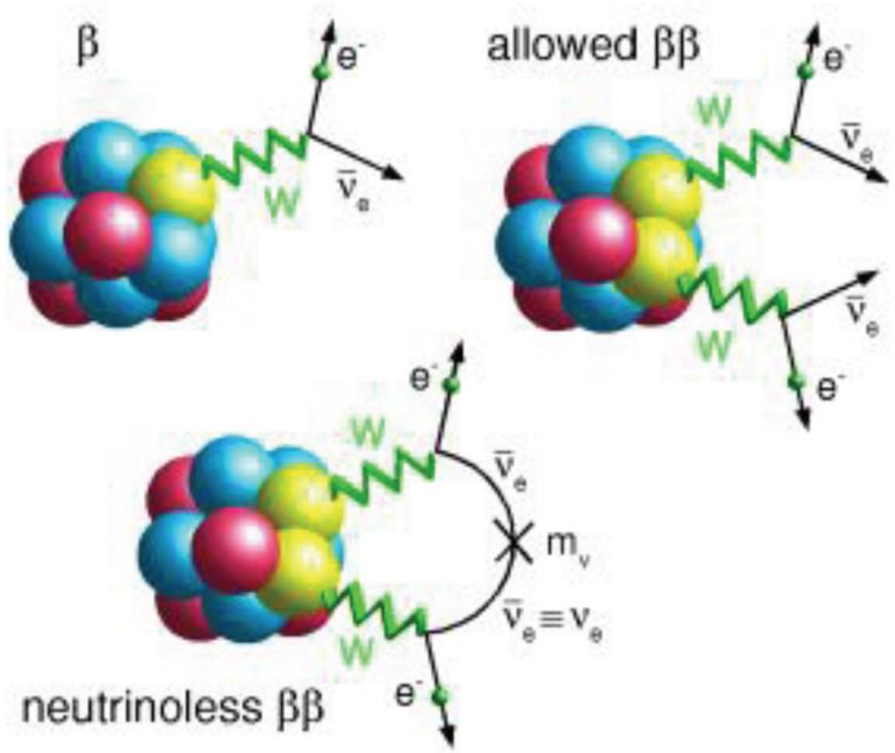
$$\frac{h_{ij}}{2\Lambda}(HL_i)(HL_j)$$

○ Majorana mass term

"violates"
Not only Lepton Flavor
But also Lepton Number

➡ Lepton number changing process

Ecample



Romanino

$$(A, Z) \to (A, Z+2) + 2e$$

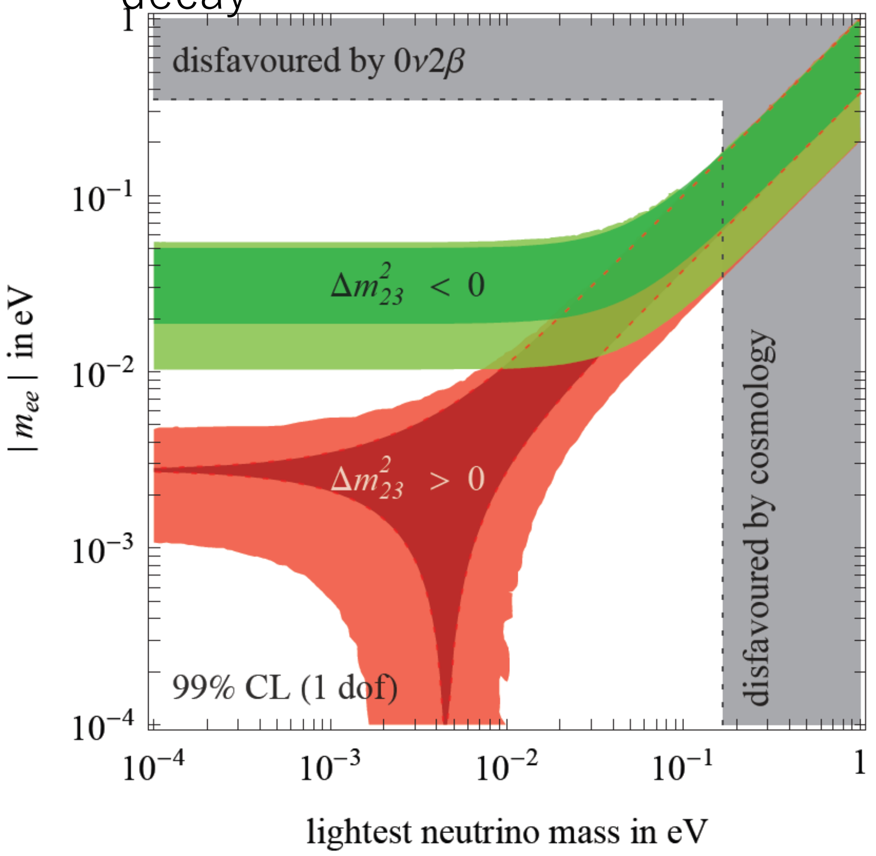
$$(0\nu 2\beta)\ \text{decay}$$

$$m_{ee} = U_{eh}^2 m_h = c_{13}^2(m_1 c_{12}^2 + m_2 s_{12}^2 e^{2i\alpha}) + m_3 s_{13}^2 e^{2i\beta'}$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}s^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}s^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

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

m_{ee} prediction from neutrino oscillation and constraint from Neutrinoless double beta decay



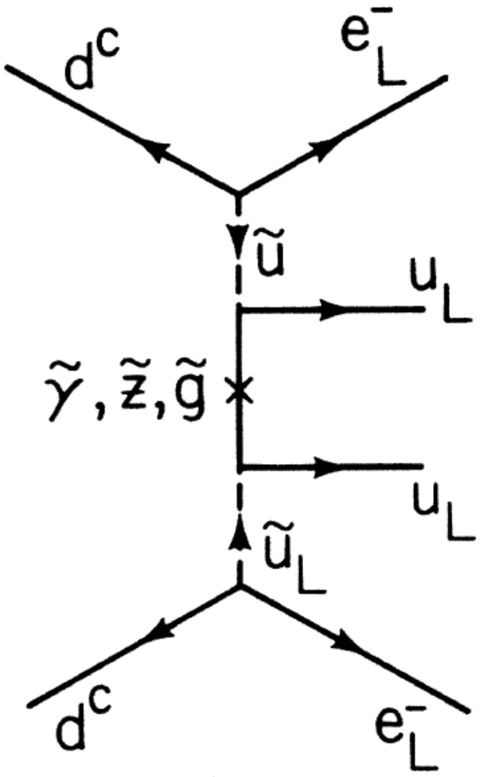
Two kinds of prediction from neutrino oscillation
Normal hierarchy (NH) and inverted hierarchy (IH)

Note

" Majorana mass for left-handed neutrino
→neutrinoless double beta decay "

Always holds
but conversion
is not true !!

Example from
SUSY



Lepton flavor violation and particle number violation has different origin !!!

$\lambda'_{ijk} L_i Q_j D^c_k$

Majorana mass term ≠ neutral
Majorana mass term = real representation,
can be charged

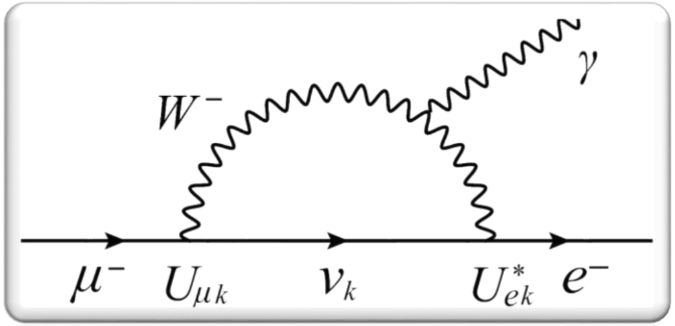
Mohapatra 1986

4.Charged Lepton Flavor violation

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 …

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

Invisible, eternally

Strong suppression of FCNC by GIM

Detection of the LFV signal

Clear evidence for beyond SM

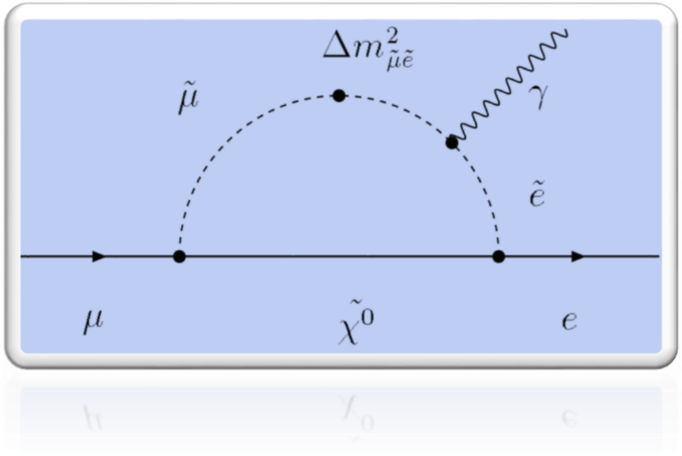
Indeed, in physics beyond SM,

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

$$\mu^+ \to e^+\gamma \quad < 4.2 \times 10^{-13}$$

$$\mu^+ \to e^+e^+e^- < 1.0 \times 10^{-12}$$

$$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti} < 6.1 \times 10^{-13}$$

$$\mu^-\mathrm{Au} \to e^-\mathrm{Au} < 7 \times 10^{-13}$$

$$\mu^+e^- \to \mu^-e^+ < 8.3 \times 10^{-11}$$

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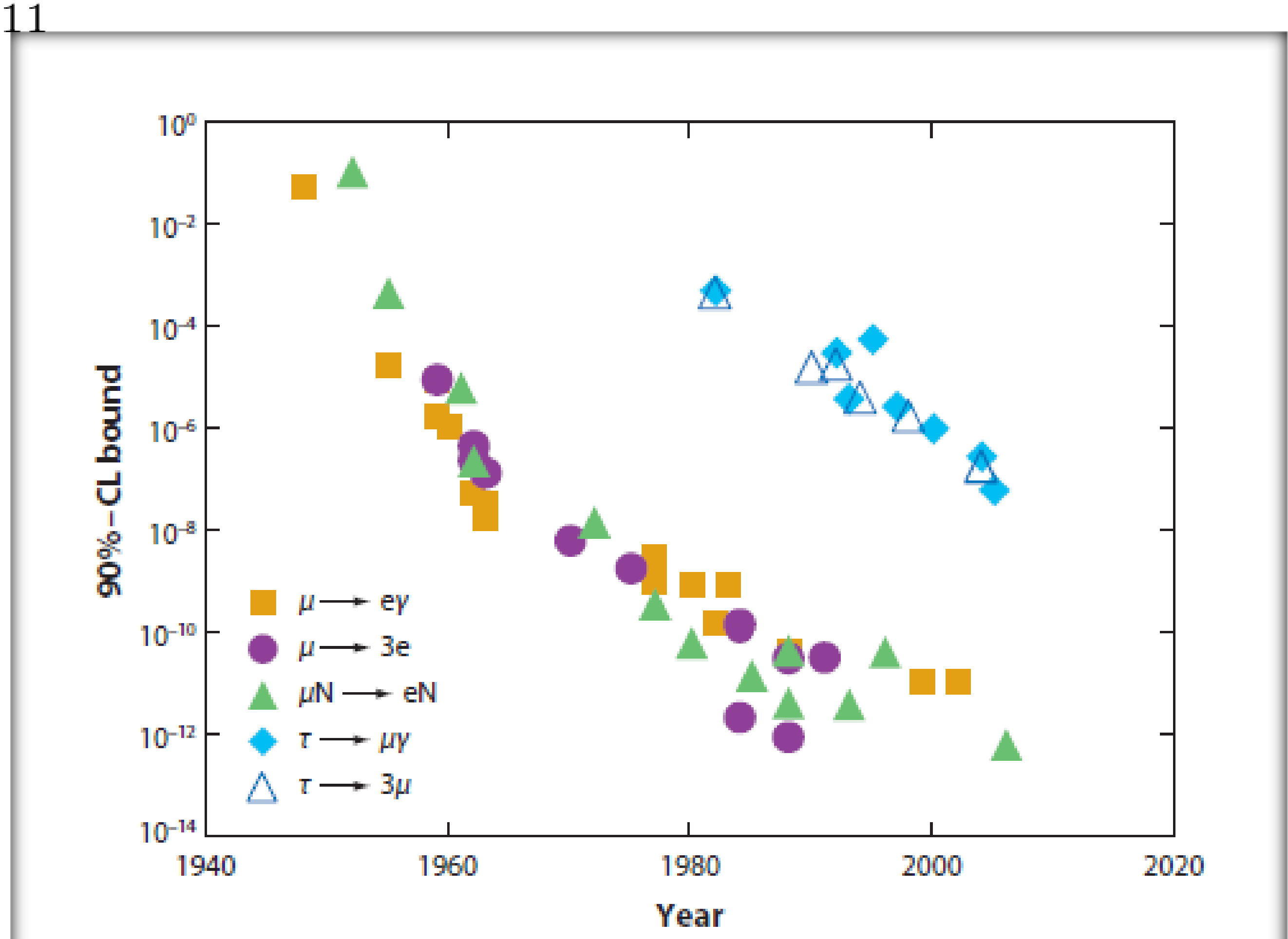
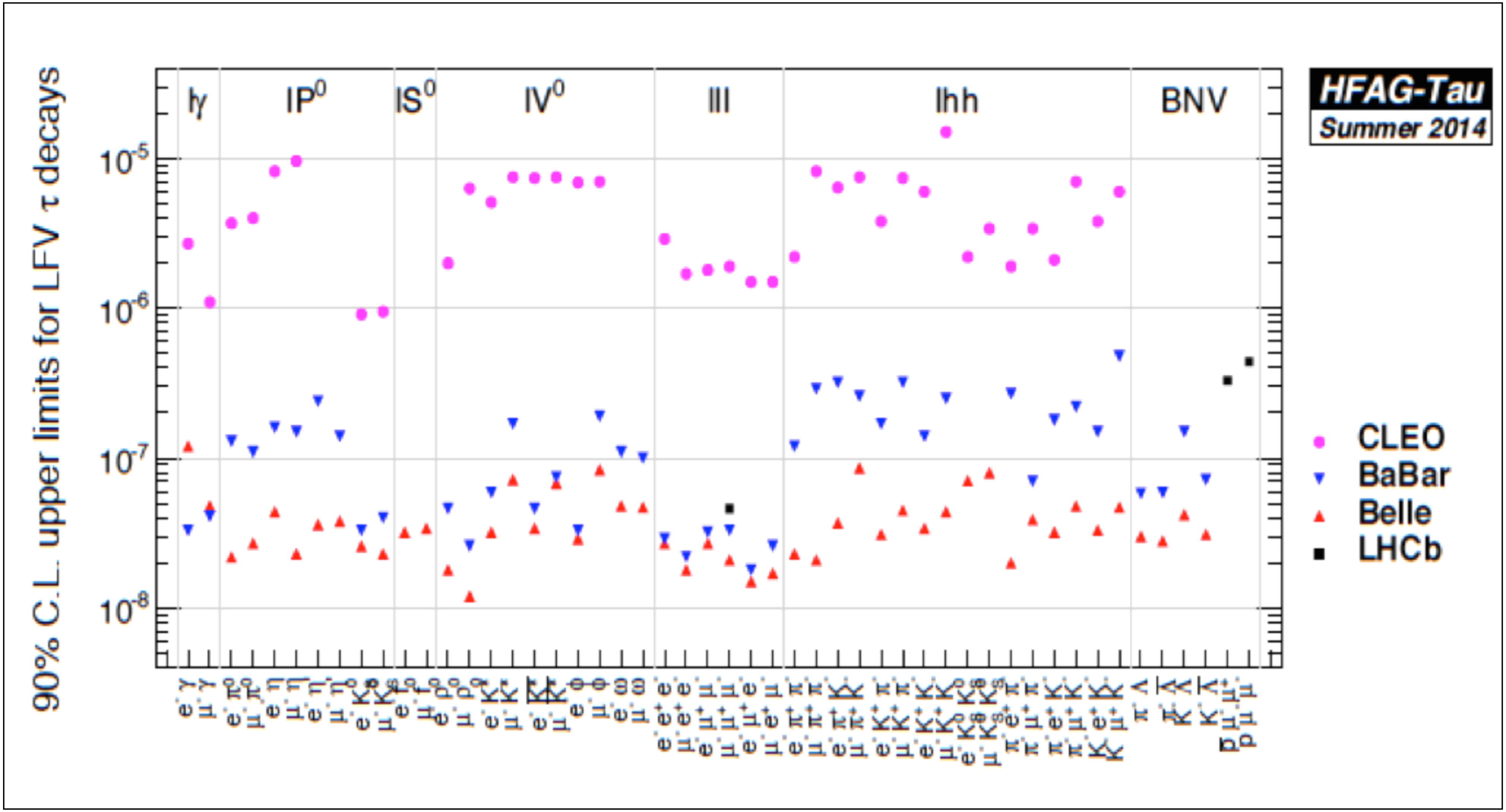
W. J. Marciano, T.Mori, and J. M. Roney

Long history



cLFV from tau decay



Upper bound ~ 1/# of taus

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

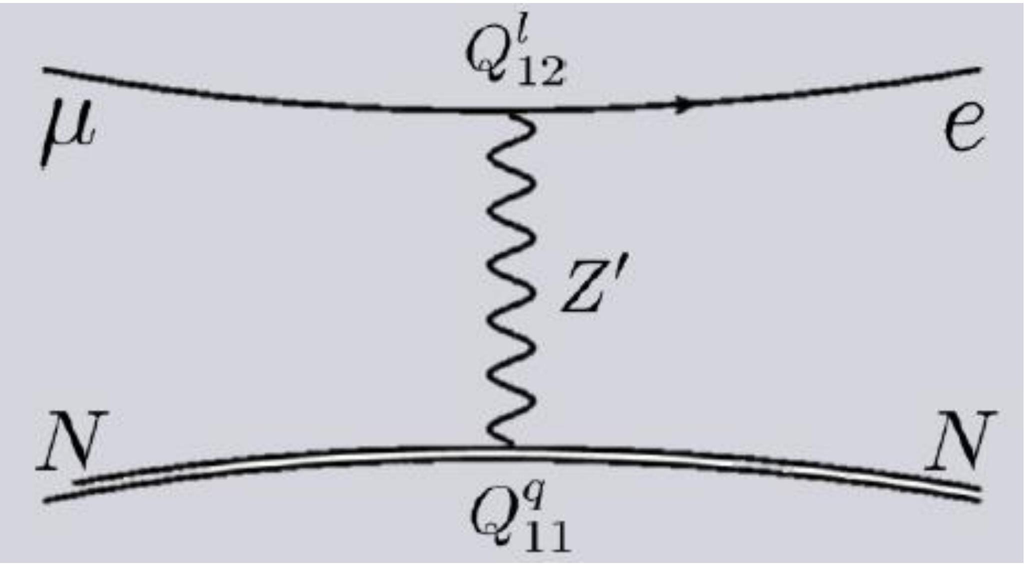
~ α smaller than μ->eγ

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

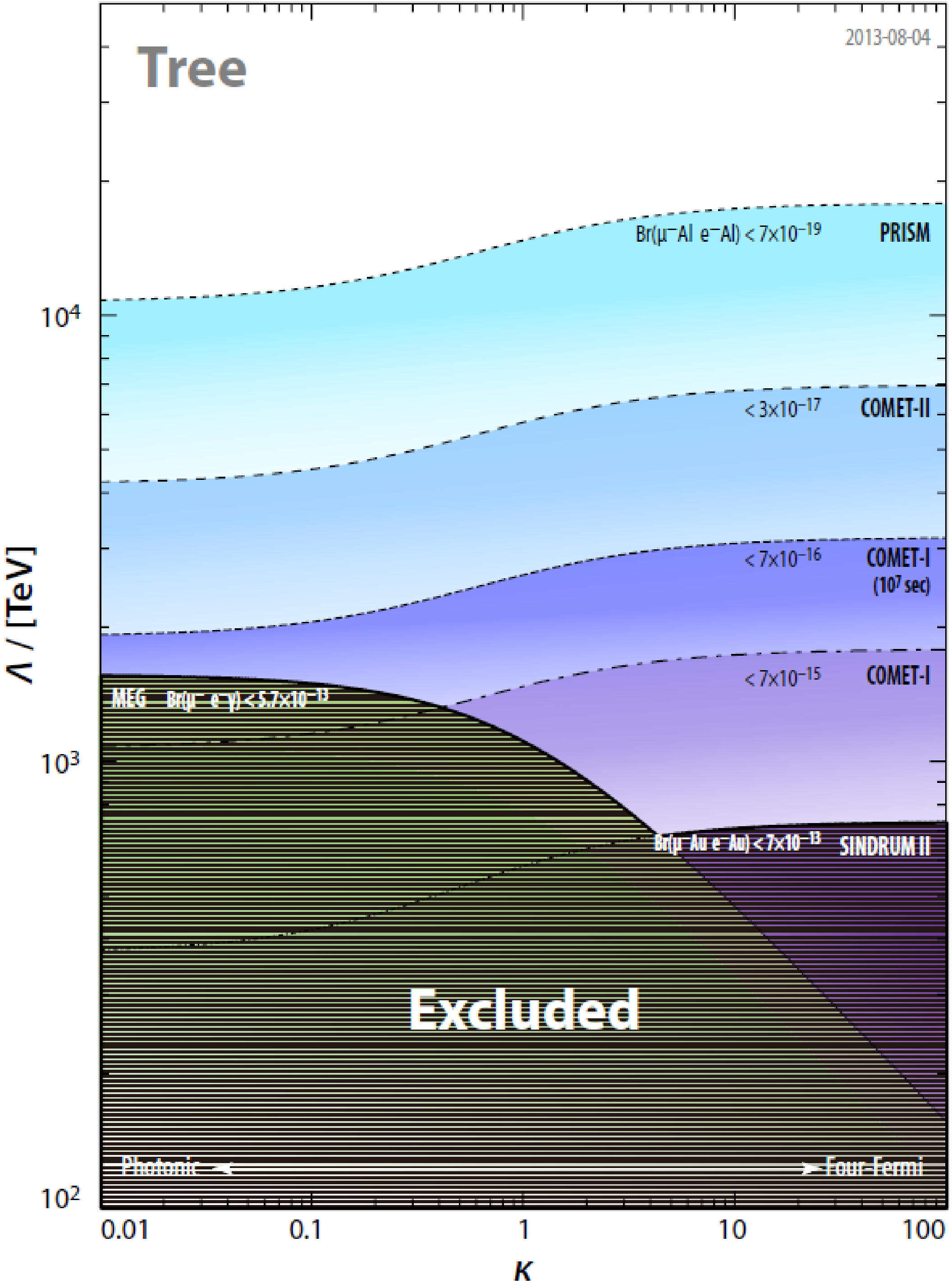
We can parameterize the relative strength

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

$\kappa \sim$ 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

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

irrelevant

cLFV Interaction

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-

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

Different Q's !!

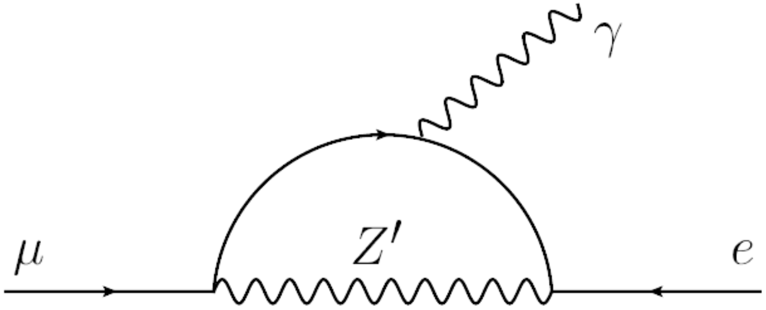


Figure 2: $\mu^+ \to e^+ \gamma$ in the Z' models.

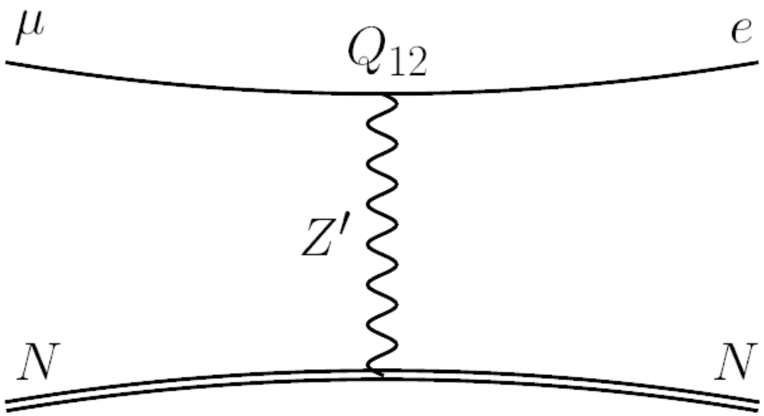
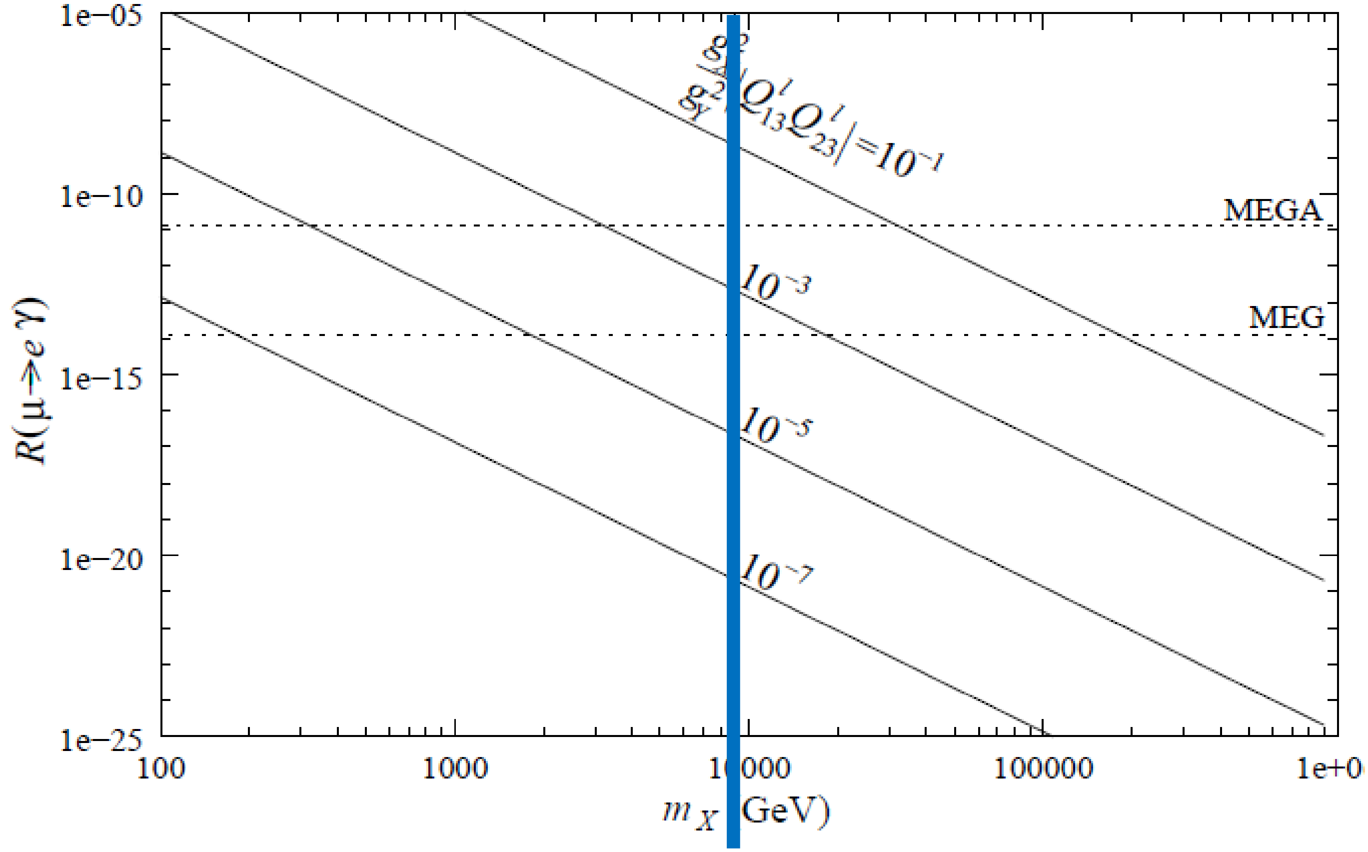


Figure 3: Non-photonic diagram of $\mu^- - e^-$ conversion in the Z' models.

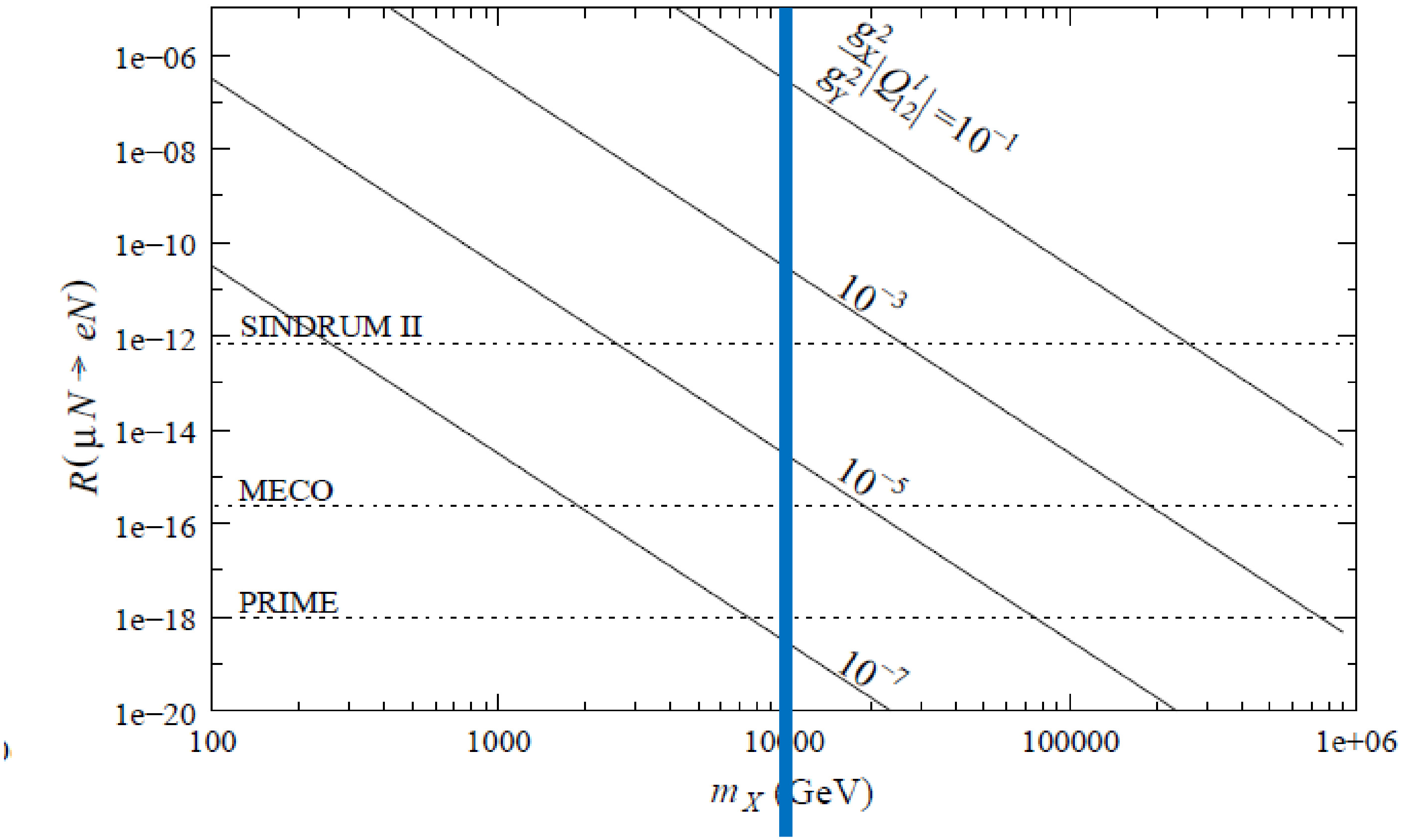


10TeV

Brandon Murakami

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

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



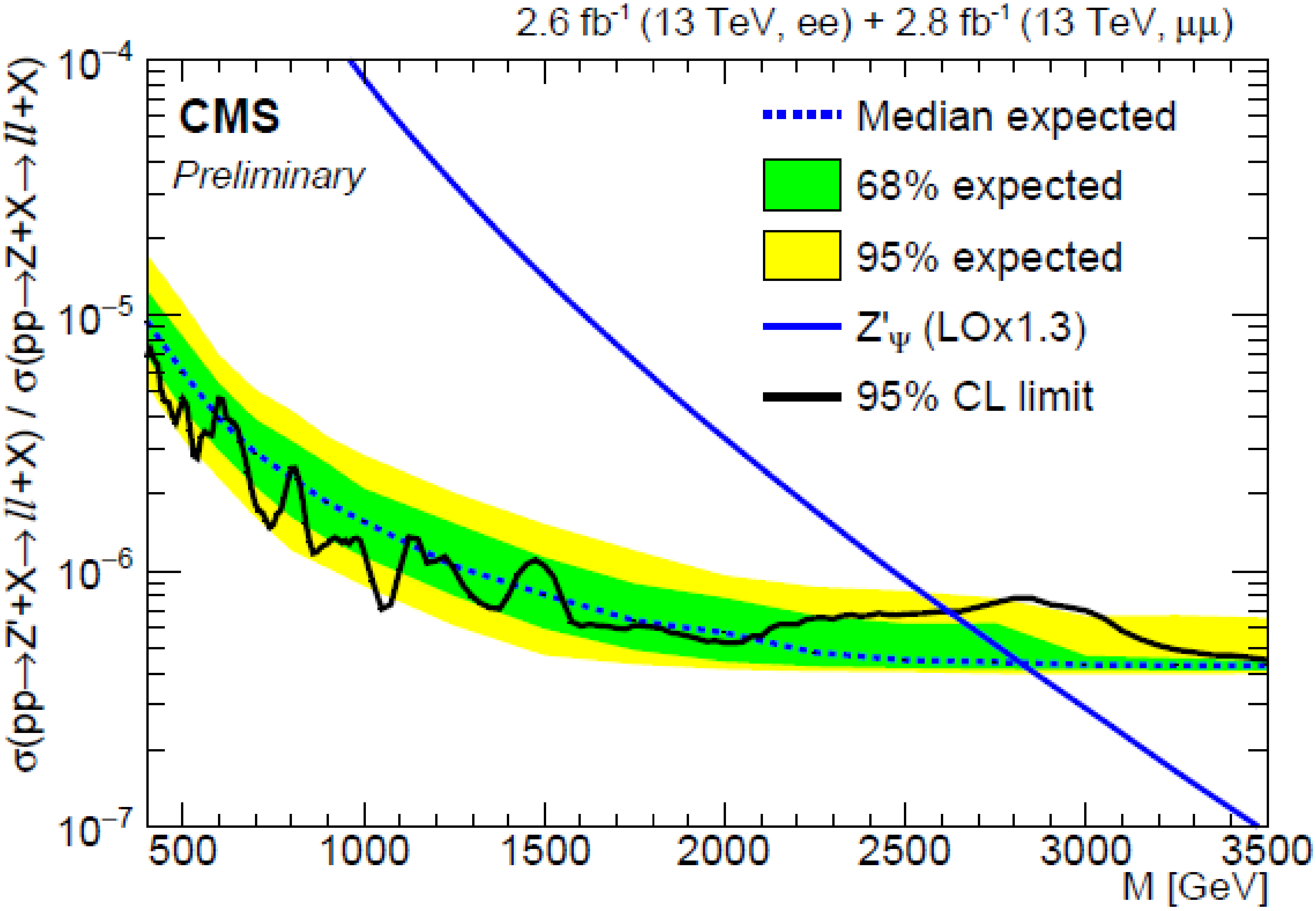
Brandon
Murakami

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

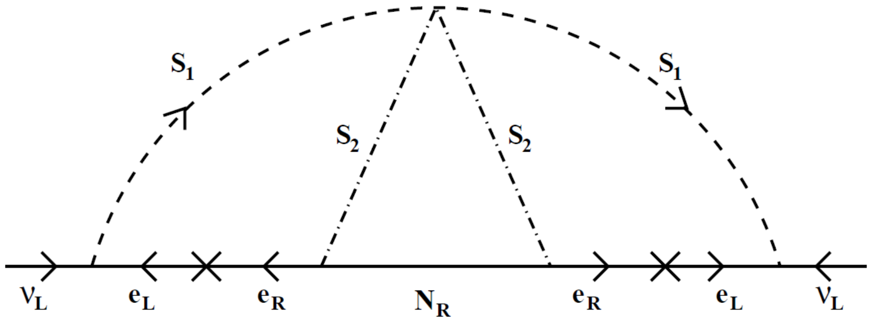
SUSY :: Still main target!?

2< doublet higgs :: SUSY is restricted version

{ Higgs triplet :: doubly charged

Radiative generation of neutrino masses

Krauss *etal*



sometimes doubly charged

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

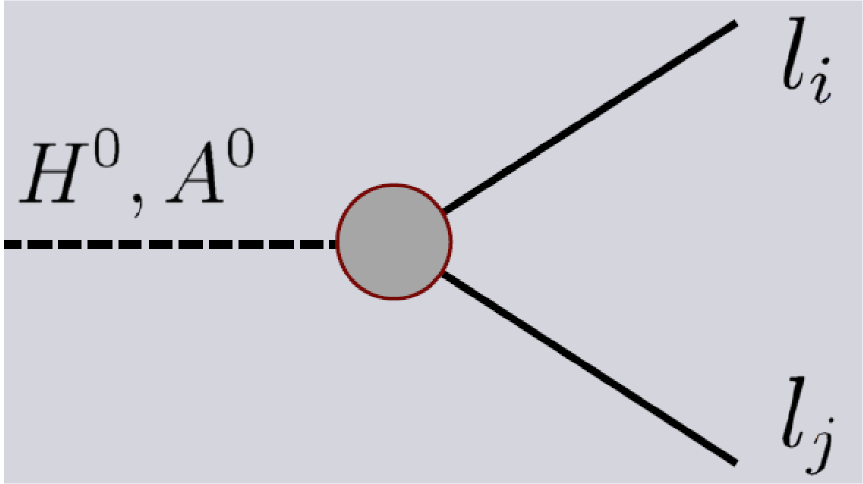
Is more relevant

SUSY

Neutral scalar : Heavy neutral higgs , sneutrino

With R-Parity

Scalar (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

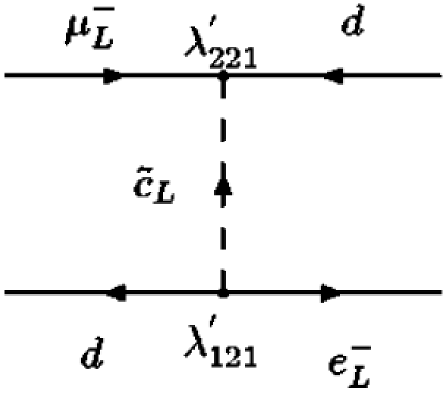
Furthermore, these higgses are probably very heavy

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 $\mu \rightarrow e + \gamma$

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

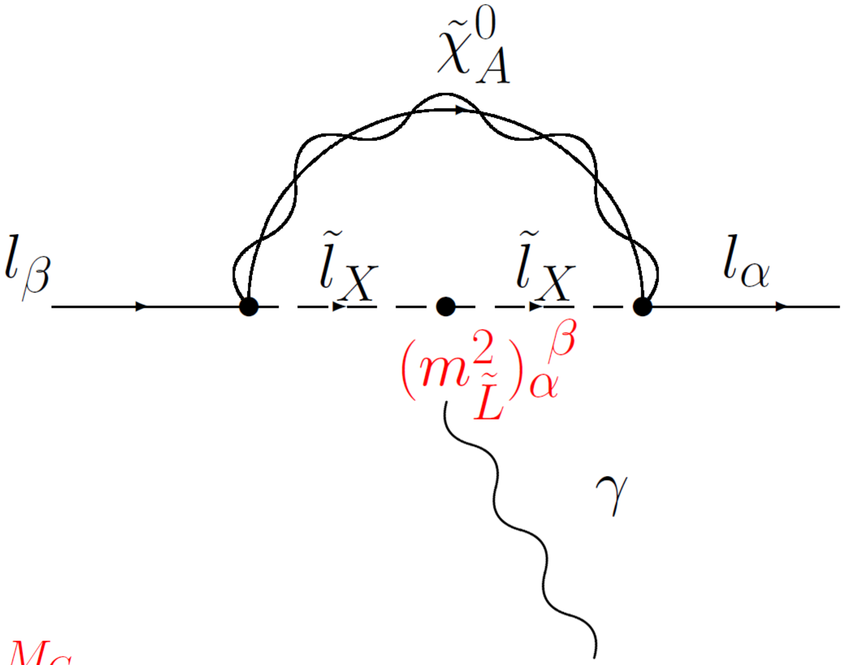
$$m^2_{\tilde{l}} = \begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}}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

CMSSM + RH neutrino

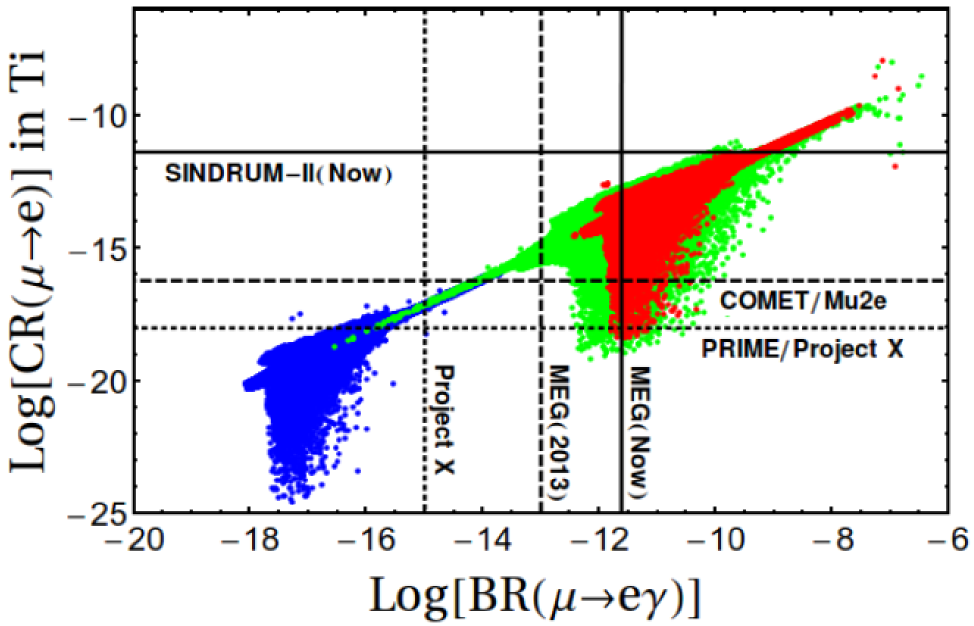
Most exhaustedly studied

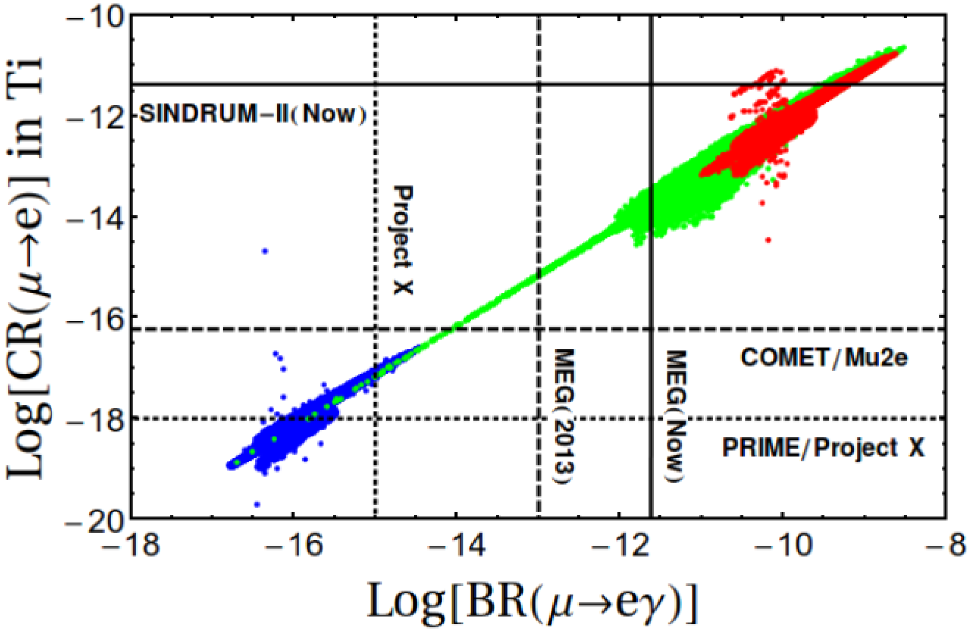
$$W = f_\nu^{i\beta} \bar{N}_i L_\beta H_u$$

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



Dipole dominant





1207.7227   Calibbi *et al*

5.Summary

Lepton Flavor

Exact Symmetry in the Standard Model

If SM is correct then LF conserves

<-->

LFV then SM is not correct

Neutrino Oscillation

Manifestation of Lepton Flavor Violation

-->

SM must be extended so that neutrinos are massive

Neutrino masses

Dirac or Majorana? Tree or Indused?

If Majorana --> Lepton Number is also violated

neutrinoless double beta decay, $\mu^- \to e^+$in muonic atom

Charged Lepton Flavor Violation

SU(2) connection indicates LFV in Charged lepton

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

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

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

E.g.

R–parity violating SUSY gives such a situation

☑ 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

$$\mathcal{W}_{\not{R}} = \lambda_{ijk}L_iL_jE^c_k + \lambda'_{ijk}L_iQ_jD^c_k + \lambda''_{ijk}U^c_iD^c_jD^c_k$$

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

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

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

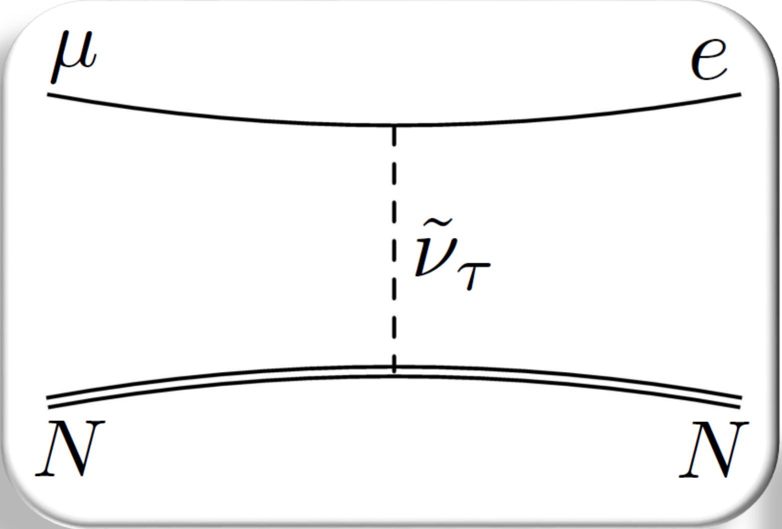
$$\lambda'_{ijj} \gg \lambda'_{ijk} \quad (j \neq k)$$

☑ RPV terms in superpotential in SUSY

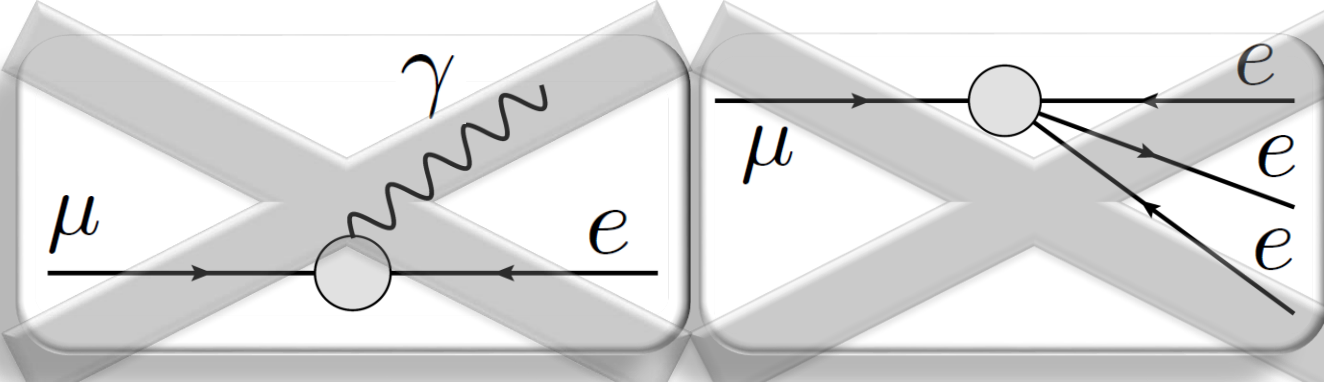
$$\mathcal{W}_{\not R} = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \xcancel{\lambda''_{ijk} U^c_i D^c_j D^c_k}$$

Exotic processes in the scenario

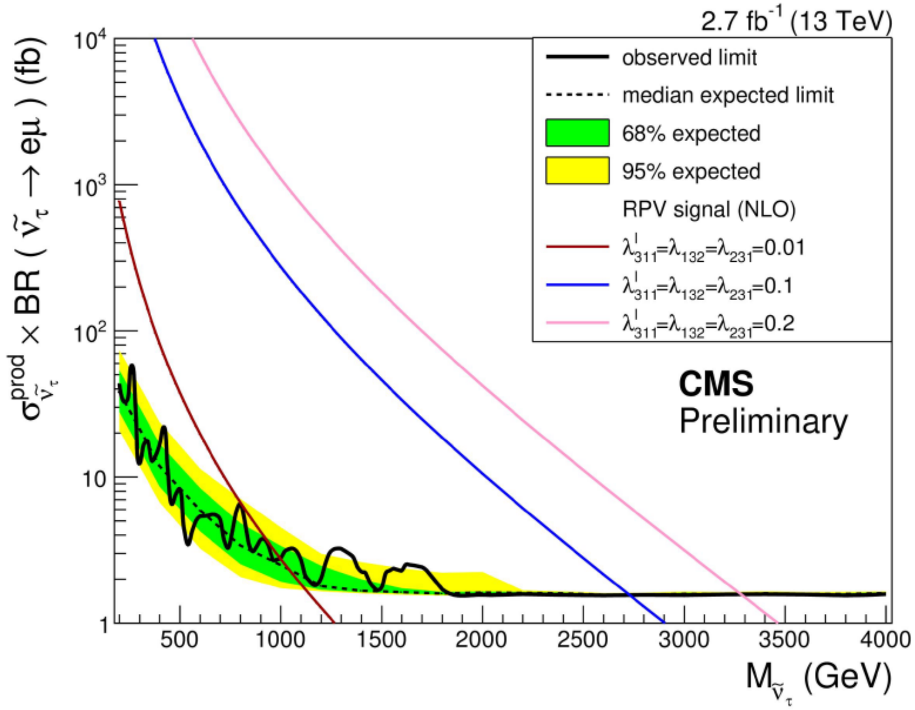
$$\begin{aligned}\mathcal{L}_{\mathrm{RPV}} = 2\{\, &\lambda_{312}\tilde{\nu}_\tau \bar{\mu}_R e_L + \lambda_{321}\tilde{\nu}_\tau \bar{e}_R \mu_L + \lambda_{132}\tilde{\tau}_L \bar{\mu}_R \nu_e + \lambda_{231}\tilde{\tau}_L \bar{e}_R \nu_\mu \,\} \\ &+ \{\, \lambda'_{311}\big(\tilde{\nu}_\tau \bar{d}_R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

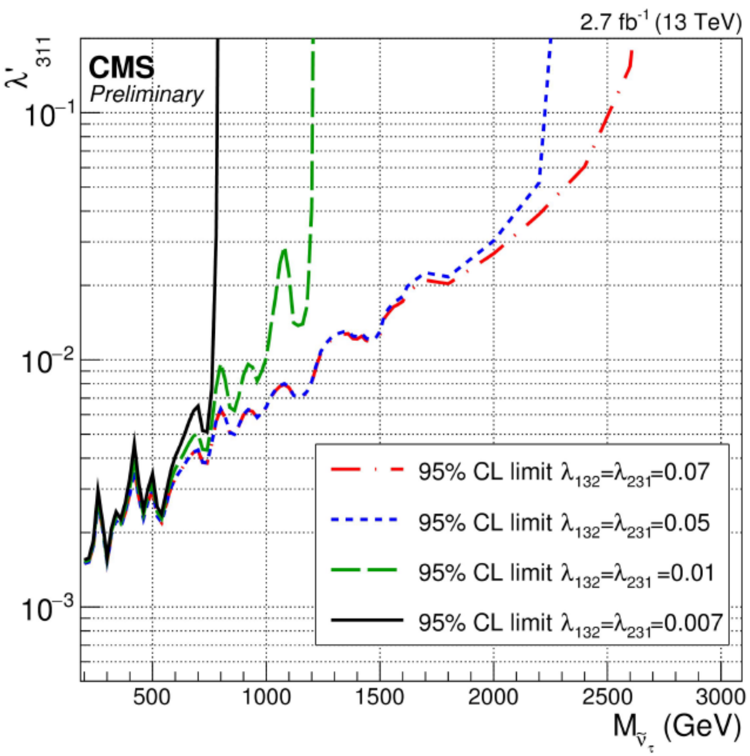


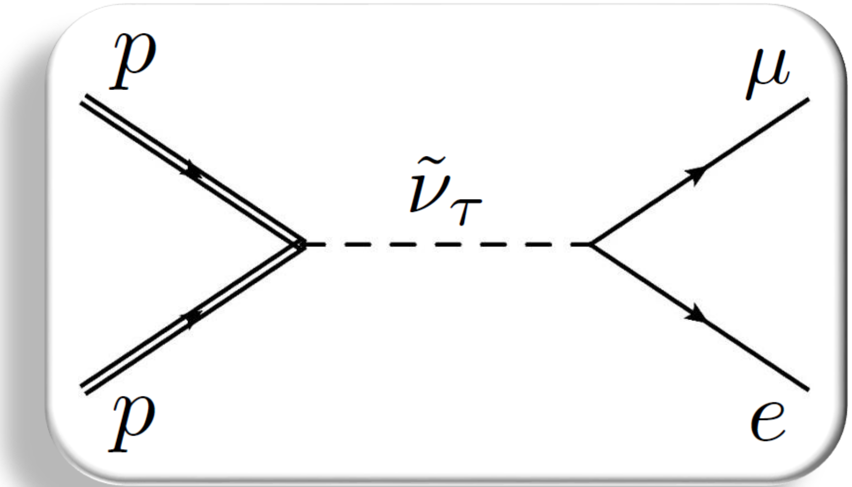
- ☑ μ-e conversion@tree level
- ☑ Negligible rates of other cLFV processes



Current bound for the scalar with LFV





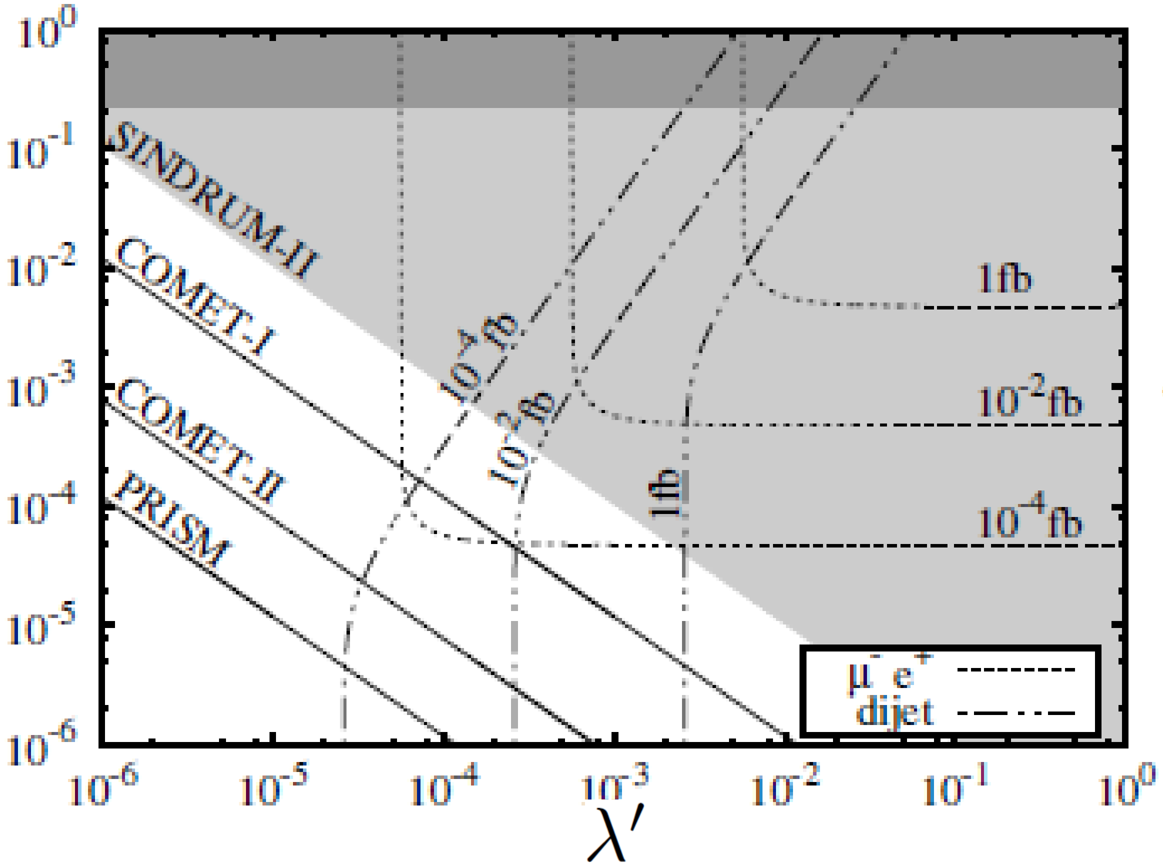


Correlations of distinctive signals

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

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

- sneutrino mass $m_{\tilde{\nu}_\tau} = 1\mathrm{TeV}$
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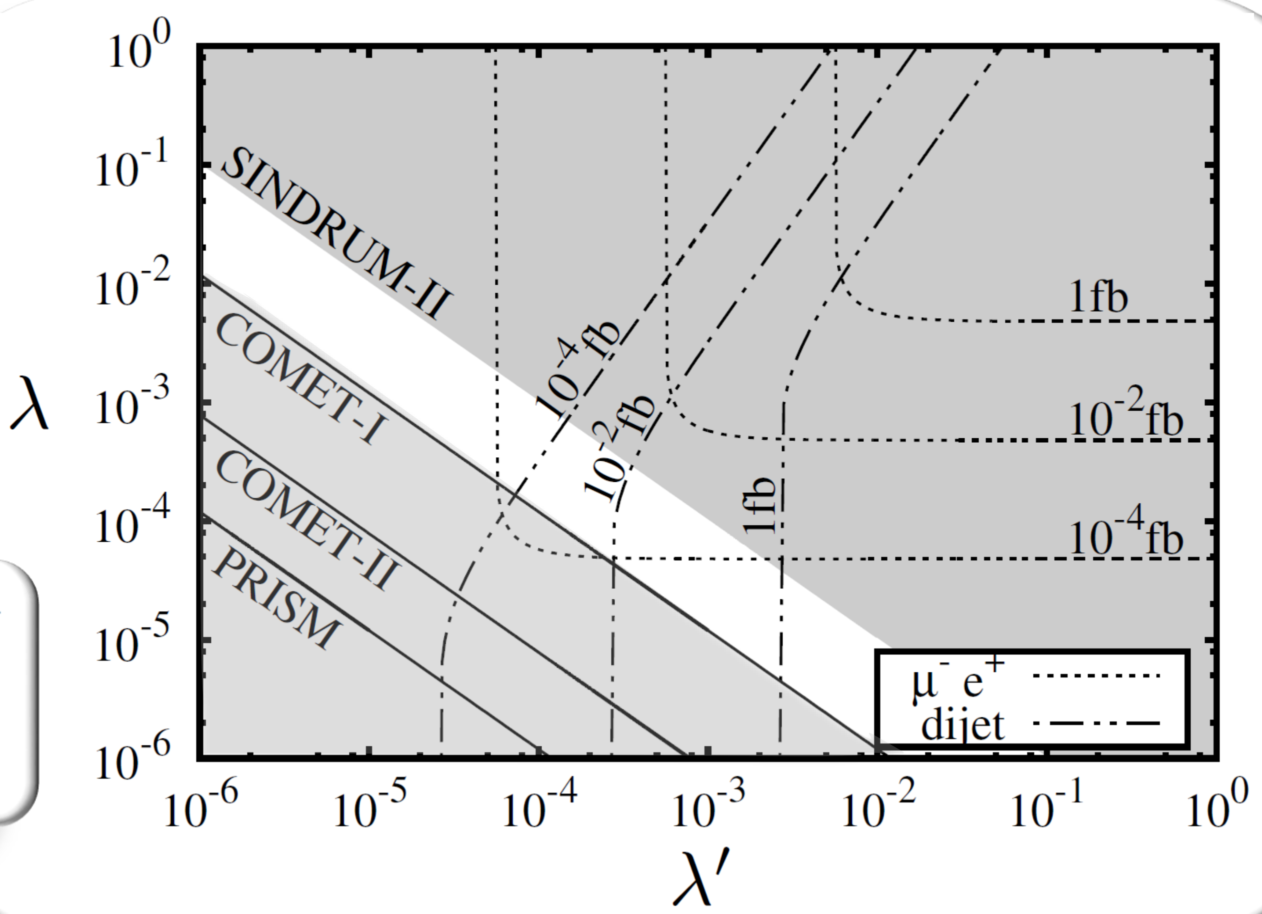


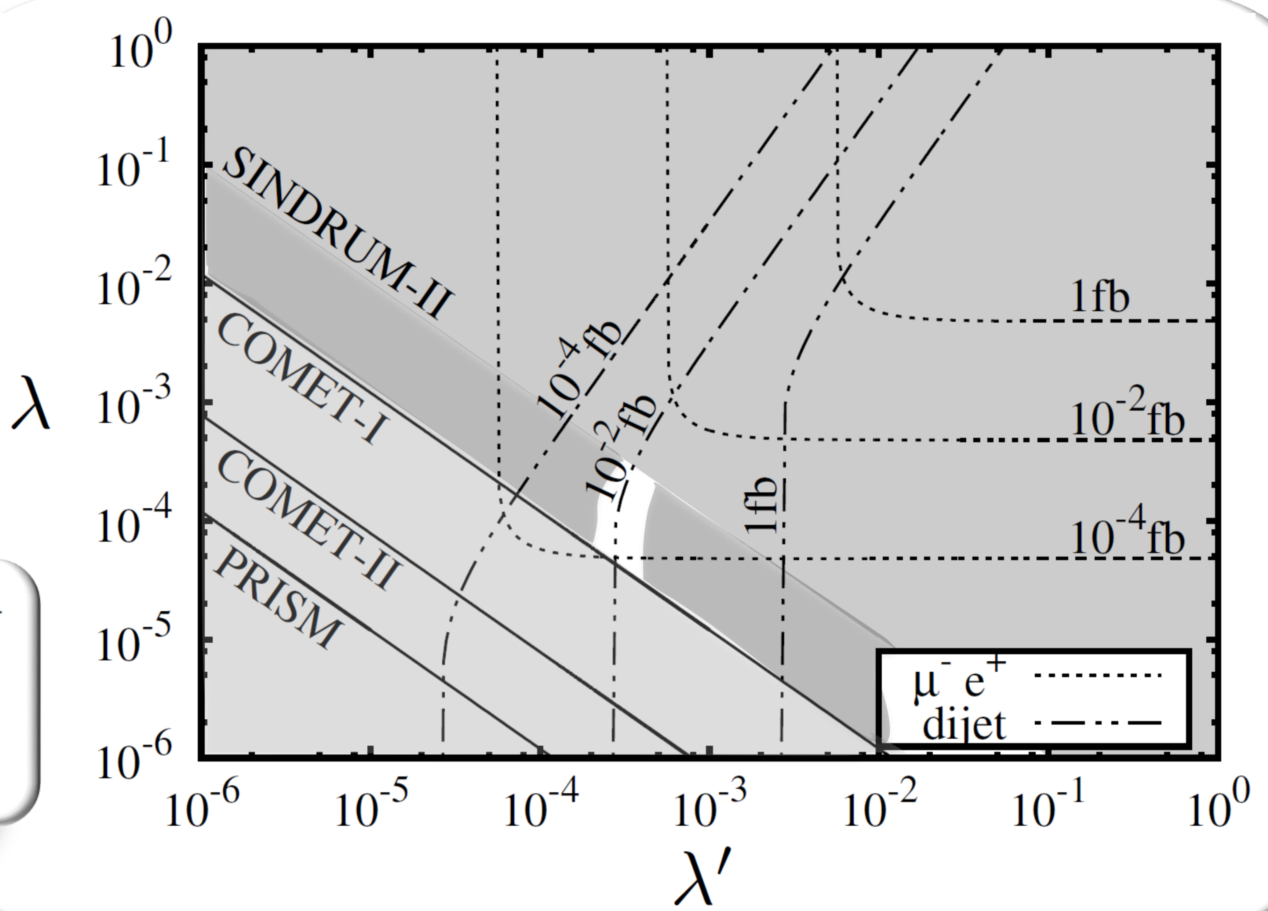
☑ COMET/DeeMe found m−e conversion → white band

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

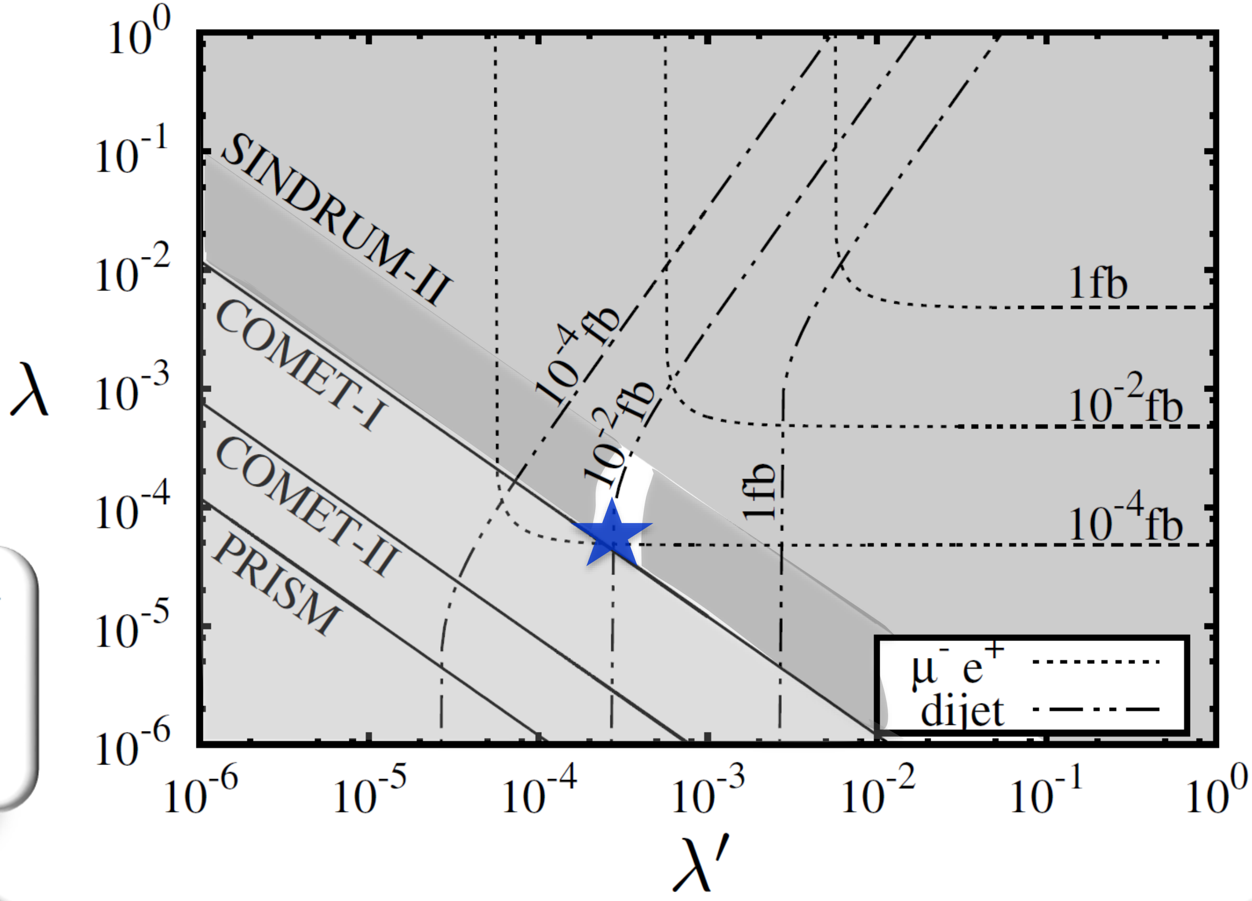
☑ Dijet resonance is found with 10 fb^{-2} → white small region

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 ?