Lepton flavor violating radiative decays in EW-scale ν_R model: an update

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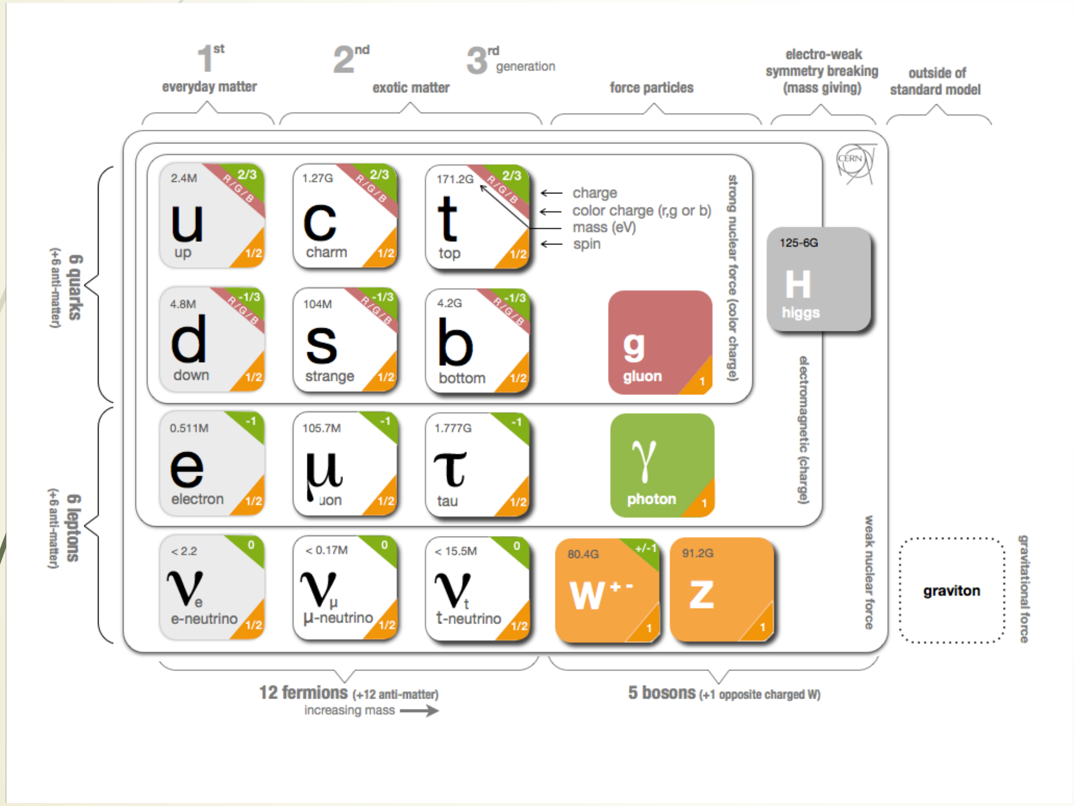
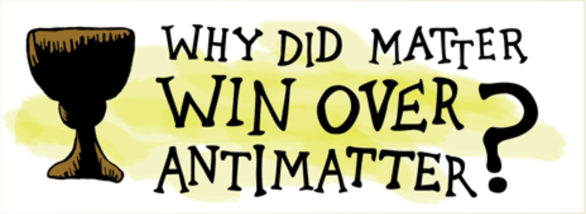
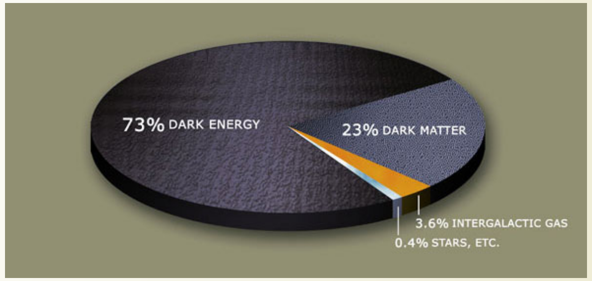
Outline

- Motivation
- Review of EW-scale ν_R model
- The calculation LFV process in EW-scale ν_R model
- Numerical analysis
- Implications
- Conclusions

- The standard model can explain almost of experiment results
- However there are many undetermined parameters and issues







Origin of Mass

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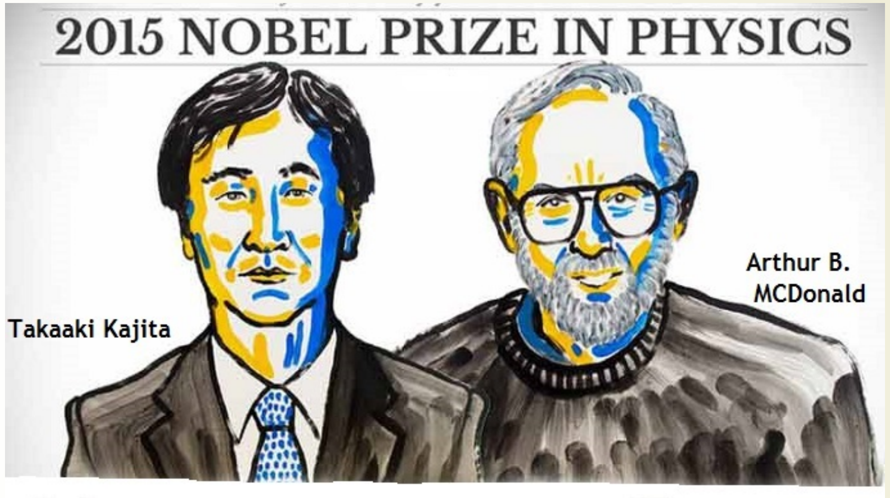
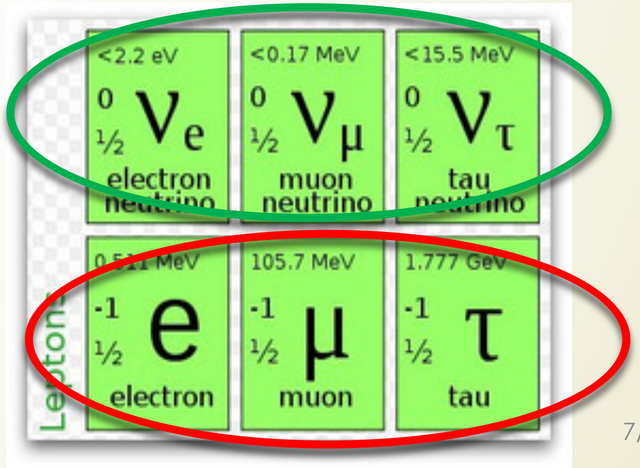
- The flavor puzzle is one of the main unresolved problems of particle physics



- 2015 Nobel prize for **<u>Neutral</u>** <u>lepton flavour violation</u> = **Neutrino oscillation**

- No observable of charged lepton flavour violation in SM

- Could we have a prize for **<u>charged</u>** <u>lepton flavour violation (cLFV)</u>? (if it is observed)



Beyond Standard Model!

- cLFV Current experiment bounds and future sensitivity

cLFV Process	Present Bound	Future Sensitivity
$\mu \to e\gamma$	5.7×10^{-13} (MEG 2013) 4.2×10^{-13} (MEG 2016)	4×10^{-14} (MEG II)
$\tau \to e\gamma$	3.3×10^{-8} (B-factory)	3×10^{-9} (Supper B-factory)
$\tau \to \mu\gamma$	4.4×10^{-8} (B-factory)	3×10^{-9} (Supper B factory)
$\mu \to eee$	4.3×10^{-12} (SINDRUM)	$\sim10^{-16}$ (PSI, MUSIC)
$\mu + Ti \to e + Ti$	4.3×10^{-12} (SINDRUM II)	$\sim10^{-18}$ (PRISM)
$\mu + Au \to e + Au$	7.0×10^{-13} (SINDRUM II)	----
$\mu + Pb \to e + Pb$	4.6×10^{-11} (SINDRUM II)	----
$\mu + SiC \to e + SiC$	----	$\sim10^{-14}$ (DeeMe)
$\mu + Al \to e + Al$	----	$\sim7\times10^{-17}$ (Mu2e) $\sim10^{-16}$ (COMET)

Non-sterile Electroweak-scale Right-handed Neutrino Model (EWνR Model) *[P.Q Hung 2007]*

- Gauge sector

$$SU(3)_C \times SU(2) \times U(1)_Y$$

- Fermions sector

Leptons

$$l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \leftrightarrow l_R^M = \begin{pmatrix} \nu_R \\ e_R^M \end{pmatrix}$$

$$e_R \leftrightarrow e_L^M$$

Quarks

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \leftrightarrow q_R^M = \begin{pmatrix} u_R^M \\ d_R^M \end{pmatrix}$$

$$u_R, d_R \leftrightarrow u_L^M, d_L^M$$

Scalars sector

- **2 Higgs Doublets:**

One only couples to SM fermions:

$$\Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \text{ with } \langle \phi_2^0 \rangle = v_2/\sqrt{2}.$$

While another doublet couples only to Mirror fermions:

$$\Phi_{2M} = \begin{pmatrix} \phi_{2M}^+ \\ \phi_{2M}^0 \end{pmatrix} \text{ with } \langle \phi_{2M}^0 \rangle = v_{2M}/\sqrt{2}.$$

Scalar sector

- **One complex Higgs triplet** with Y/2 = 1

$$\tilde{\chi} = \frac{1}{\sqrt{2}} \vec{\tau}.\vec{\chi} = \begin{pmatrix} \frac{1}{\sqrt{2}} \chi^{+} & \chi^{++} \\ \chi^{0} & -\frac{1}{\sqrt{2}} \chi^{+} \end{pmatrix}$$

$$\begin{aligned} L_M &= g_M \left(l_R^{M,T} \, \sigma_2 \right) \left(i \, \tau_2 \, \tilde{\chi} \right) \, l_R^M \\ &= g_M \, \nu_R^T \, \sigma_2 \, \nu_R \, \chi^o - \frac{1}{\sqrt{2}} \nu_R^T \, \sigma_2 \, e_R^M \, \chi^+ + \ldots \end{aligned}$$

With $\langle \chi^o \rangle = v_M \sim \Lambda_{EW}$, then the Majorana mass of right-handed neutrino is $M_R = g_M v_M \sim \Lambda_{EW}$ if the coupling is in order of 1

Scalar sector

- **One real Higgs triplet** with Y/2 = 0

$$\xi\ (Y/2=0) = (\xi^{+}, \xi^{0}, \xi^{-})$$

With $\langle \xi^{o} \rangle = \langle \chi^{o} \rangle = v_M$ then the **Custodial symmetry** is restored $(\rho = 1)$
(Chanowitz, Golden and Georgi, Machacek)

- **Four Higgs singlets** by using A4 symmetry: one A4 singlet ϕ_{0S} and three A4 triplets ϕ_{iS} with *i=1,2,3*

$$\mathcal{L}_S = -\bar{l}_L\, U^{\dagger}_{\rm PMNS}\, \tilde{M}_{\phi}\, U^{M}_{\rm PMNS} l^{M}_{R} - \bar{l}_R\, U'^{\dagger}_{\rm PMNS}\, \tilde{M}'_{\phi}\, U'^{M}_{\rm PMNS} l^{M}_{L} + {\rm H.c.}$$

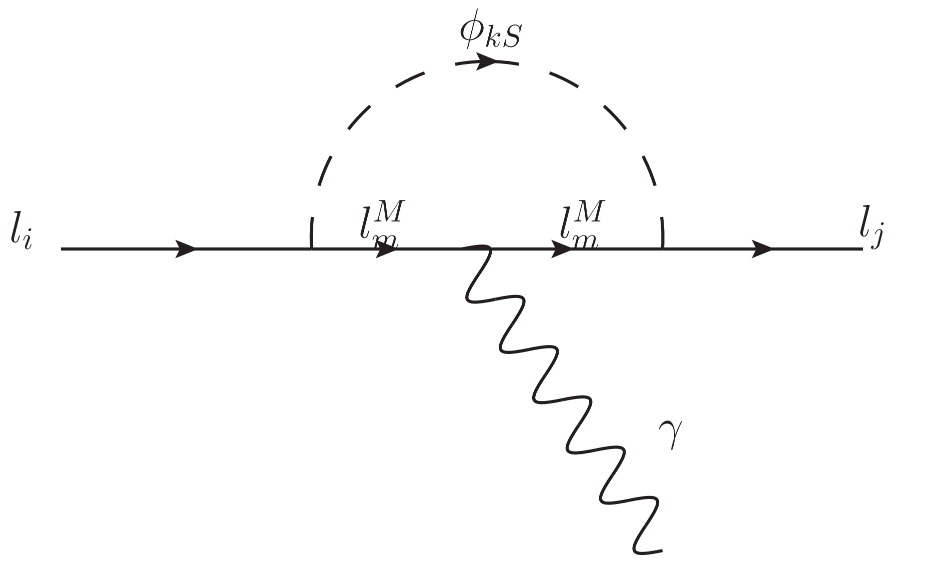
Where:

$$\tilde{M}_{\phi} = U_{CW} \begin{pmatrix} g_{0S}\phi_{0S} & g_{1S}\phi_{3S} & g_{2S}\phi_{2S} \\ g_{2S}\phi_{3S} & g_{0S}\phi_{0S} & g_{1S}\phi_{1S} \\ g_{1S}\phi_{2S} & g_{2S}\phi_{1S} & g_{0S}\phi_{0S} \end{pmatrix} U^{\dagger}_{CW}\,.$$

$$\tilde{M}'_{\phi} = \tilde{M}_{\phi}(g_{0S} \to g'_{0S}\,, g_{1S} \to g'_{1S}\,, g_{2S} \to g'_{2S})$$

- Process $l_i \to l_j + \gamma$

$$\mathcal{L}^{A_4}_{\text{Charged},S} = -\sum_{k=0}^{3}\sum_{i,m=1}^{3}\left(\overline{l_{Li}}\,\mathcal{U}^{L\,k}_{im}\,l^M_{Rm} + \overline{l_{Ri}}\,\mathcal{U}^{R\,k}_{im}\,l^M_{Lm}\right)\phi_{Sk} + \text{H.c.}$$

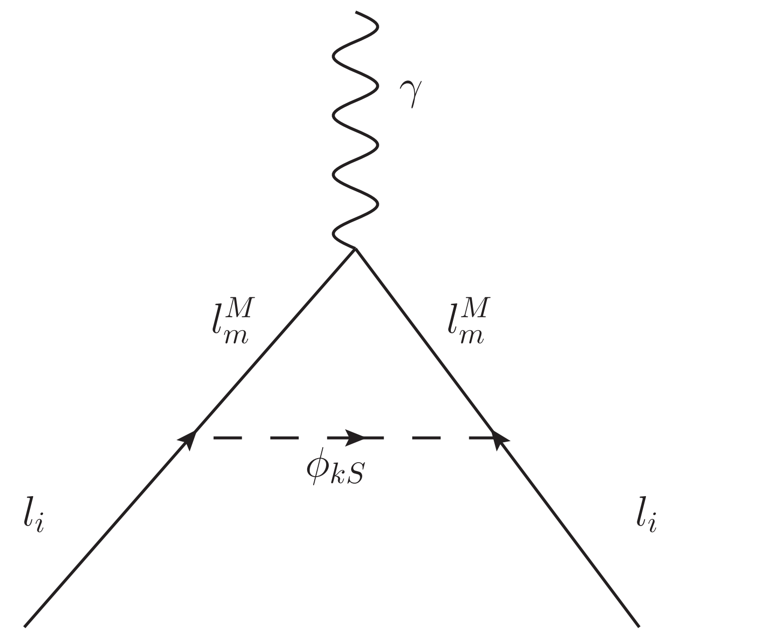


$$\Gamma\left(l_i \to l_j\gamma\right) = \frac{1}{16\pi}m^3_{l_i}\left(1-\frac{m^2_{l_j}}{m^2_{l_i}}\right)^3\left(|C^{ij}_L|^2+|C^{ij}_R|^2\right)$$

Magnetic Dipole Moment

$$\mathcal{L}^{A_4}_{\text{Charged},S} = -\sum_{k=0}^{3}\sum_{i,m=1}^{3}\left(\overline{l_{Li}}\,\mathcal{U}^{L\,k}_{im}\,l^{M}_{Rm} + \overline{l_{Ri}}\,\mathcal{U}^{R\,k}_{im}\,l^{M}_{Lm}\right)\phi_{Sk} + \text{H.c.}$$

$$\Delta a_{l_i} = \frac{2m_{l_i}}{e}\left(\frac{C^{ii}_L + C^{ii}_R}{2}\right)$$



Numerical Analysis

– Scenario 1

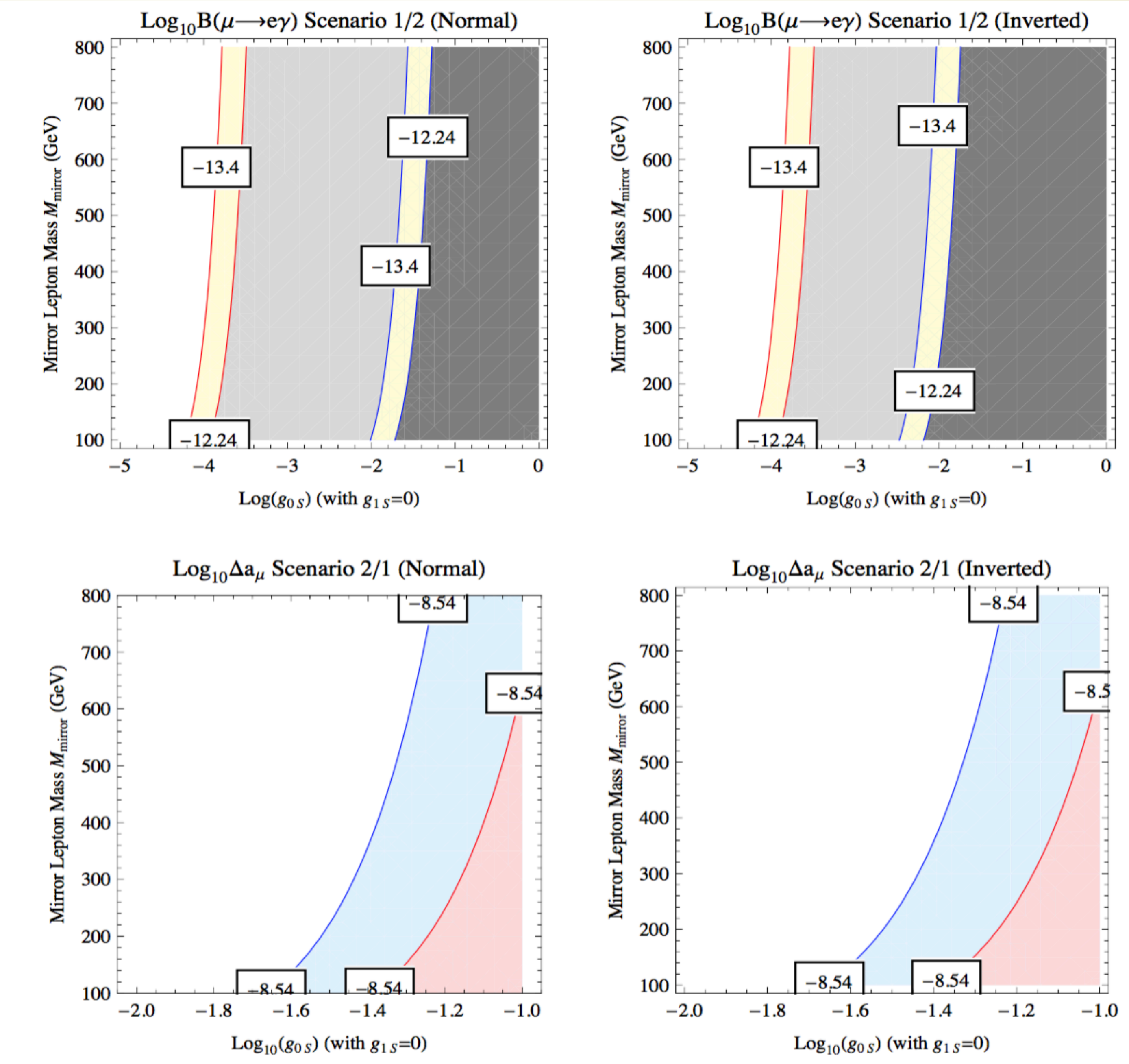
$$U^{lM}_{\text{PMNS}} = U'_{\text{PMNS}} = U'^{lM}_{\text{PMNS}} = U^{\dagger}_{CW}$$

– Scenario 2

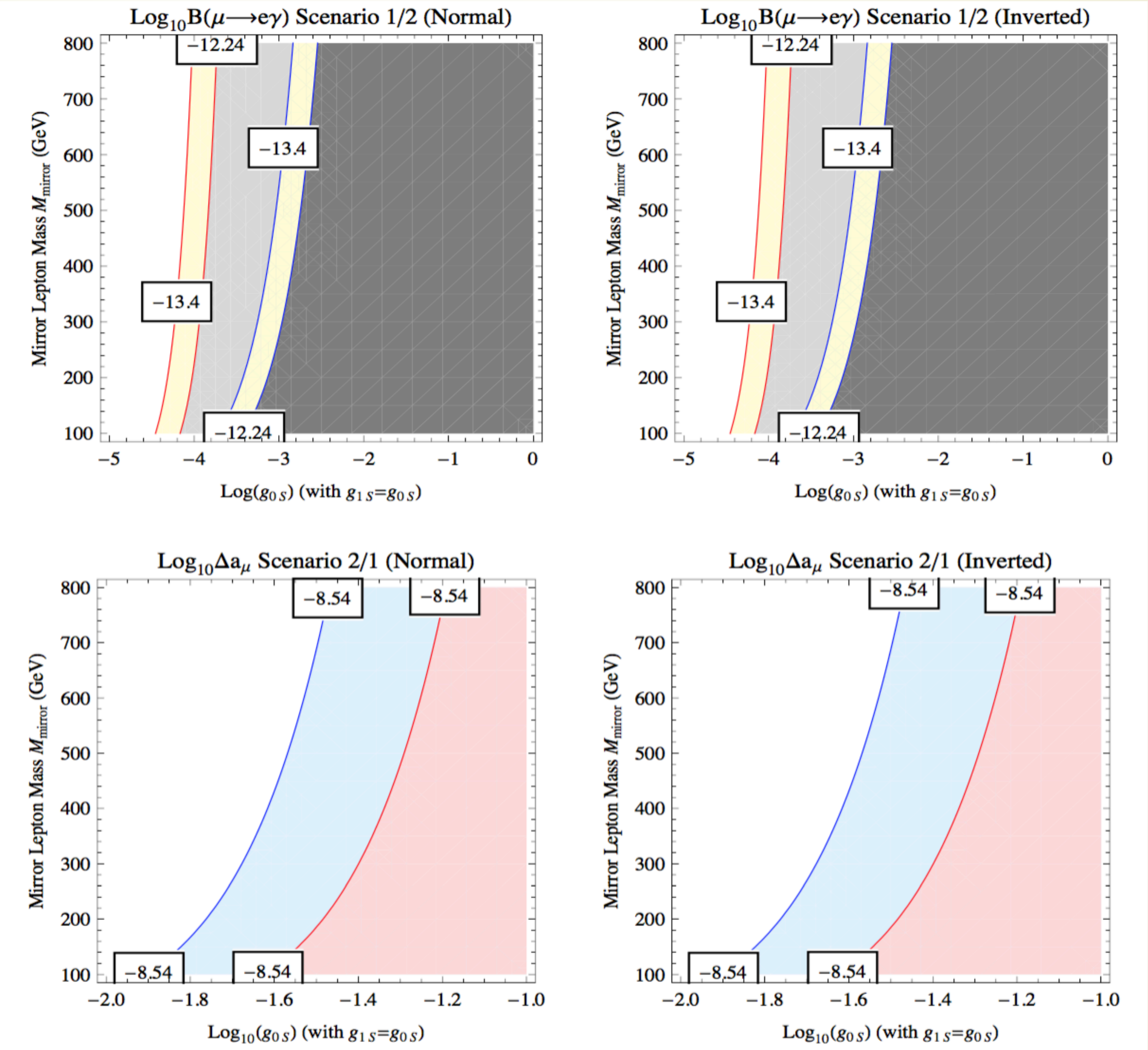
$$U^{lM}_{\text{PMNS}} = U'_{\text{PMNS}} = U'^{lM}_{\text{PMNS}} = U_{\text{PMNS}}$$

$$U_{CW} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix}$$

$g_{0S} \neq 0, \;\; g_{1S} = 0.$



$$g_{1S} = g_{0S}.$$


Log10B(μ⟶eγ) Scenario 1/2 (Normal)
Log10B(μ⟶eγ) Scenario 1/2 (Inverted)
−12.24
−13.4
Mirror Lepton Mass Mmirror (GeV)
Log(g0 S) (with g1 S=g0 S)
Log10Δaμ Scenario 2/1 (Normal)
Log10Δaμ Scenario 2/1 (Inverted)
−8.54
Log10(g0 S) (with g1 S=g0 S)

Discussion

- The LFV process $\mu \to e + \gamma$ is more sensitive to the couplings by almost two order of magnitudes as compared with the anomalous magnetic moment of the muon

- For scenario 1, both the branching ratio of $\mu \to e + \gamma$ and the muon anomalous magnetic moment do not depend sensitively on the normal or inverted neutrino mass hierarchies for the cases of the couplings.

- However, for Scenario 2, there is slightly different between normal and inverted cases. These differences depend on these couplings, for $g1S \geq 0.5 \times g0S$, these differences diminish.

- The sensitivity of the couplings in the B($\mu \to e + \gamma$) has been weakened by one to two order of magnitudes for scenario 2 as compared to scenario 1, while for the muon anomalous magnetic moment it stays more or less the same.

Implications

- The search for mirror leptons

$$l_{Ri}^{M} \rightarrow l_{Lj} + \phi_{kS}$$

The decay length will depend on the magnitude of the Yukawa couplings as well as on the various mixing parameters

- VEV of the singlet Higgs fields

With constraints from $\mu \rightarrow e\,\gamma$ imply $g_{0S} < 10^{-3}$ → singlet VEV up to O(100 MeV)

Conclusions

- Search for cLFV would provide one of the best opportunities to find new physics beyond the Standard Model
- The Electroweak-scale Right-handed neutrino Model has a number of phenomenological implications which could be explored experimentally in the near future.
- We calculated the cLFV processes ($\mu \rightarrow e + \gamma$) as well as anomalous magnetic dipole moment in framework of an extended of Electroweak-scale Right-handed neutrino Model
- By the recent and future expectation data we imposed constraints on the parameter space of the EW-scale ν_R model

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Thank You!

Backup slides

Lagrangian

$$\mathcal{L}_S = -\bar{l}_L\, U^{\dagger}_{\rm PMNS}\, \tilde{M}_\phi\, U^{M}_{\rm PMNS} l^M_R - \bar{l}_R\, U'^{\dagger}_{\rm PMNS}\, \tilde{M}'_\phi\, U'^{M}_{\rm PMNS} l^M_L + {\rm H.c.}$$

$$\tilde{M}_\phi = U^\dagger_\nu M_\phi U_\nu\,,$$

$$U'_{\rm PMNS} = U^\dagger_\nu U^l_R\,,$$

$$U^M_{\rm PMNS} = U^\dagger_\nu U^{l^M}_R\,.$$

$$U'^M_{\rm PMNS} = U^\dagger_\nu U^{l^M}_L\,,$$

TABLE I. Matrix elements for $M^k (k = 0, 1, 2, 3)$.

M^k_{jn}	Value
$M^0_{12}, M^0_{13}, M^0_{21}, M^0_{23}, M^0_{31}, M^0_{32}$	0
$M^0_{11}, M^0_{22}, M^0_{33}$	g_{0S}
$M^1_{11}, M^2_{11}, M^3_{11}$	$\frac{2}{3}\text{Re}\,(g_{1S})$
$M^1_{22}, M^2_{22}, M^3_{22}$	$\frac{2}{3}\text{Re}\,(\omega^* g_{1S})$
$M^1_{33}, M^2_{33}, M^3_{33}$	$\frac{2}{3}\text{Re}\,(\omega g_{1S})$
M^1_{12}, M^1_{21}	$\frac{2}{3}\text{Re}\,(\omega g_{1S})$
M^2_{12}, M^3_{21}	$\frac{1}{3}\,(g_{1S} + \omega g^*_{1S})$
M^3_{12}, M^2_{21}	$\frac{1}{3}\,(g^*_{1S} + \omega^* g_{1S})$
M^1_{13}, M^1_{31}	$\frac{2}{3}\text{Re}\,(\omega^* g_{1S})$
M^2_{13}, M^3_{31}	$\frac{1}{3}\,(g_{1S} + \omega^* g^*_{1S})$
M^3_{13}, M^2_{31}	$\frac{1}{3}\,(g^*_{1S} + \omega g_{1S})$
M^1_{23}, M^1_{32}	$\frac{2}{3}\text{Re}\,(g_{1S})$
M^2_{23}, M^3_{32}	$\frac{2\omega^*}{3}\text{Re}\,(g_{1S})$
M^3_{23}, M^2_{32}	$\frac{2\omega}{3}\text{Re}\,(g_{1S})$

The above construction can be straightforwardly generalized for the right-handed leptons and left-handed mirror leptons. Hence the total $\mathcal{L}_S$ becomes

$$\mathcal{L}_S = -\bar{l}_L\, U^{\dagger}_{\text{PMNS}}\, \tilde{M}_\phi\, U^{M}_{\text{PMNS}} l^M_R - \bar{l}_R\, U'^{\dagger}_{\text{PMNS}}\, \tilde{M}'_\phi\, U'^{M}_{\text{PMNS}} l^M_L + \text{H.c.}$$

$$U'_{\text{PMNS}} = U^{\dagger}_{\nu} U^{l}_{R}\,,$$

$$U'^{M}_{\text{PMNS}} = U^{\dagger}_{\nu} U^{l^M}_{L}\,,$$

$$C_L^{ij} = +\frac{e}{16\pi^2}\sum_{k=0}^{3}\sum_{m=1}^{3}\left\{\frac{1}{m^2_{l^M_m}}\left[m_i\mathcal{U}^{R\,k}_{jm}\left(\mathcal{U}^{R\,k}_{im}\right)^* + m_j\mathcal{U}^{L\,k}_{jm}\left(\mathcal{U}^{L\,k}_{im}\right)^*\right]\mathcal{I}\left(\frac{m^2_{\phi_{kS}}}{m^2_{l^M_m}}\right)\right.$$
$$\left. + \frac{1}{m_{l^M_m}}\mathcal{U}^{R\,k}_{jm}\left(\mathcal{U}^{L\,k}_{im}\right)^*\mathcal{J}\left(\frac{m^2_{\phi_{kS}}}{m^2_{l^M_m}}\right)\right\} ,$$

$$C_R^{ij} = +\frac{e}{16\pi^2}\sum_{k=0}^{3}\sum_{m=1}^{3}\left\{\frac{1}{m^2_{l^M_m}}\left[m_i\mathcal{U}^{L\,k}_{jm}\left(\mathcal{U}^{L\,k}_{im}\right)^* + m_j\mathcal{U}^{R\,k}_{jm}\left(\mathcal{U}^{R\,k}_{im}\right)^*\right]\mathcal{I}\left(\frac{m^2_{\phi_{kS}}}{m^2_{l^M_m}}\right)\right.$$
$$\left. + \frac{1}{m_{l^M_m}}\mathcal{U}^{L\,k}_{jm}\left(\mathcal{U}^{R\,k}_{im}\right)^*\mathcal{J}\left(\frac{m^2_{\phi_{kS}}}{m^2_{l^M_m}}\right)\right\} .$$

- **Gauge group of Left-Right models:**

$$SU(3)_C \times SU(2)_L \times SU(e)_R \times U(1)_{B-L} \qquad (2)$$

- From the gauge groups described above, one notices that the EW-scale ν_R model is characterized by a single symmetry breaking scale: $\Lambda_{EW} \sim 246$ GeV and the Left-Right model is characterized by two symmetry breaking scales: $\Lambda_L \sim \Lambda_{EW}$ and $\Lambda_R \gg \Lambda_L$ which is unknown experimentally but which is constrained to be larger than approximately 3 TeV.

From 1606.08502

- **Fermions in Left-Right models:**

$$SU(2)_L\colon\ l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix};$$

$$SU(2)_R\colon\ l_R = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}.$$

$$SU(2)_L\colon\ q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix};$$

$$SU(2)_R\colon\ q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix}.$$

From 1606.08502

which are produced e.g. in processes such as

$$q + \bar{q} \rightarrow Z \rightarrow \nu_R + \nu_R \,. \tag{1}$$

Since ν_R's are Majorana particles, they can have transitions such as $\nu_R \rightarrow l_R^{M,\mp} + W^{\pm}$. A heavier ν_R can decay into a lighter l_R^M and one can have

$$\begin{aligned} \nu_R + \nu_R &\rightarrow l_R^{M,\mp} + l_R^{M,\mp} + W^{\pm} + W^{\pm} \\ &\rightarrow l_L^{\mp} + l_L^{\mp} + W^{\pm} + W^{\pm} + \phi_S + \phi_S \,, \end{aligned} \tag{2}$$

where $l_R^{M,\mp} \rightarrow l_L^{\mp} + \phi_S$ and where ϕ_S, the singlet scalar field in the model, would constitute the missing energy.