Lepton Flavor Violating Processes in Mirror Fermion Models (with Non-Sterile Electroweak Scale ν_R)

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Ref:
(1) PQ Hung, T. Le, V. Q. Tran, TCY, arXiv:1508.07016 and work in progress
(2) Chang, Nugroho, TCY, work in progress

References

- ...
- Kuno and Okada, RMP73, (2001) 151
- Kitano, Koike and Okada, PRD66, 096002 (2002)
- Dinh, Ibarra, Molinaro and Petcov,
  JHEP08 (2012) 125, arXiv:1205.4671
- Harnik, Kopp and Zupan,
  JHEP03 (2013) 026, arXiv:1209.1397v3
- Glashow, Guadagnoli and Lane, PRL 114 (2015) 091801, arXiv:1411.0565
- ...

Introduction

Non-Sterile EW scale ν_R model (Minimal Version)

PQ Hung, PLB 649 (2007)

- Gauge Group - Same as Standard Model
- Leptons

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

$$e_R \longleftrightarrow e_L^M$$

- Quarks

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

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

- Higgses (With Custodial Symmetry)

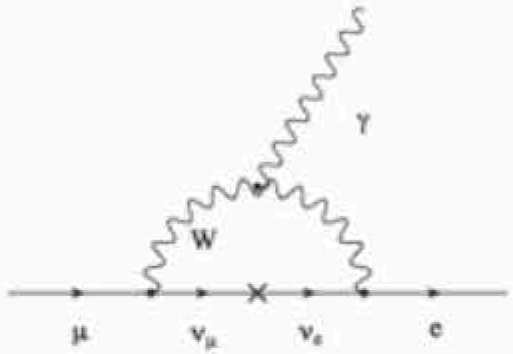
$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix} \qquad \chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \xi^+ \\ \chi^{--} & \xi^- & \chi^{0*} \end{pmatrix} \qquad \phi_S$$

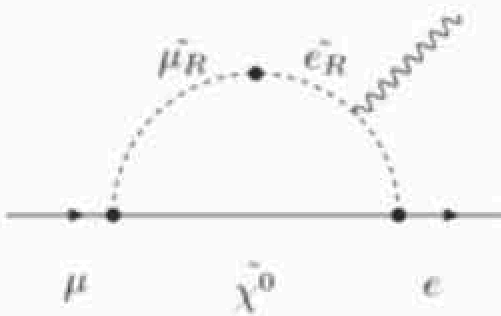
$(2, Y = 1/2)$ $\tilde{\chi}\,(3, Y = 1/2)$ $\xi\,(3, Y = 0)$ $(1, Y = 0)$

Georgi-Machacek

Motivations of Mirror Fermion Model

- Motivation of the original model
  - LFV processes to probe for new physics (SM contributions are minuscule!)
  - Electroweak scale non-sterile ν_R ('Testable' Seesaw Mechanism)
  - Parity Restoration (at high energies)
  - Non-perturbative (Lattice) formulation of SM (e.g. to study 1st Phase Transition etc)
  - Left mirrors Right (fermions)
  - Embed-able into GUT like E_6





- Two Extensions
  - Mirror Higgs doublet was introduced to accommodate the 125 GeV scalar resonance observed at LHC [Hoang, Hung, Kamat, 1412.0343]
  - Introduce a A_4 triplet of scalar singlets $\{\phi_{Si}\}$ to account for lepton mixing effects and provide a possible explanation why U_{PMNS} is so different from V_{CKM} [Hung and Le, 1501.02538]

Neutrino Masses in EW scale ν_R Model

- Majorana Mass from Triplet

$$\mathcal{L}_M = g_M l_R^{M,T} \sigma_2 \tau_2 \tilde{\chi}\, l_R^M$$
$$= g_M \nu_R^T \sigma_2 \nu_R \chi^0 + \cdots$$
$$\to M_R \nu_R^T \sigma_2 \nu_R + \cdots$$
$$\text{with } M_R = g_M \langle \chi_0 \rangle = g_M v_M \geq M_Z/2 \approx 46\,\text{GeV}$$

(As interesting as high scale case!)
[Minkowski; Gell-Mann, Ramond, Slansky; Yanagida;...]

- Dirac Mass from Singlet

$$\mathcal{L}_S = g_{Sl} \bar{l}_L \phi_S l_R^M + \text{H.c.}$$
$$= g_{Sl} \overline{\nu}_L \phi_S \nu_R + \cdots + \text{H.c.}$$
$$\to M_D \overline{\nu}_L \nu_R + \cdots + \text{H.c.}$$
$$\text{with } M_D = g_{Sl} \langle \phi_S \rangle = g_{Sl} v_S$$

(Not necessarily related to EW scale!)

- Light Neutrinos (See-Saw)

$$m_\nu = \frac{M_D^2}{M_R} < \mathcal{O}(\text{eV})$$

$\sum m_\nu < 0.23\,\text{eV}$ [Planck 2015]

If $g_{Sl} \sim \mathcal{O}(1)$, then $v_S \sim \mathcal{O}(10^{5-6}\,\text{eV})$;

If $g_{Sl} \sim \mathcal{O}(10^{-6})$, then $v_S \sim \mathcal{O}(\Lambda_{EW} \sim 246\,\text{GeV})$.

Charged Leptons

- The Yukawas

$$\mathcal{L}_{\text{charged leptons}} = g_{Sl}\bar{e}_L\phi_S e_R^M + g'_{Sl}\bar{e}_R\phi_S e_L^M + \text{H.c.}$$

- In terms of mass eigenstates

$$e_L \to U_L^l e_L\,,\; e_R^M \to U_R^{l^M} e_R^M$$

$$e_R \to U_R^l e_R\,,\; e_L^M \to U_L^{l^M} e_L^M$$

$$\mathcal{L}_{\text{charged leptons}} = \bar{e}_L U^L e_R^M \phi_S + \bar{e}_R U^R e_L^M \phi_S + \text{H.c.}$$

$$U^L = (U_L^l)^\dagger g_{Sl} U_R^{l^M} = (U_L^l)^\dagger \left(\frac{M_D}{v_S}\right) U_R^{l^M} \qquad \text{(Doublet)}$$

$$U^R = (U_R^l)^\dagger g'_{Sl} U_L^{l^M} \qquad \text{(Singlet)}$$

- U^L and U^R provide the deep connection of Dirac neutrino mass matrix and lepton flavor violation processes!
- Indeed, $\mu\to e\gamma$ and $\tau\to\mu\gamma$ were analyzed by Hung some time ago (PLB 659, 2008). Mirror leptons and singlet in the loop; SM loops are small in general.

Further Extension: A_4 Model of Neutrino Masses

- Recently, the minimal model has been extended to include a A_4 symmetry in the neutrino sector (Hung & Le, arXiv:1501.02538).
- Instead of one, four Higgs singlets were introduced.

Field	$(\nu, l)_L$	$(\nu, l^M)_R$	e_R	e_L^M	ϕ_{0S}	$\tilde{\phi}_S$	Φ_2
A_4	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{1}$	$\underline{3}$	$\underline{1}$

- A_4 multiplication rule

$$\begin{aligned}\underline{3} \times \underline{3} &= \underline{1}(11 + 22 + 33) + \underline{1}'(11 + \omega^2 22 + \omega 33) + \underline{1}''(11 + \omega 22 + \omega^2 33) \\ &+ \underline{3}(23, 31, 12) + \underline{3}(32, 13, 21)\end{aligned}$$

- Three Yukawa couplings are now possible for the neutrino Dirac mass

$$\mathcal{L}_S = -\overline{l_L^0}\left(g_{0S}\phi_{0S} + g_{1S}\tilde{\phi}_S + g_{2S}\tilde{\phi}_S\right) l_R^{M,0} + \text{H.c.}$$
$$\underline{3} \otimes (\quad \underline{1} \quad \underline{3} \quad \underline{3} \quad) \, \underline{3}$$

where g_{1S} and g_{2S} terms are the two possible ways that the triplet singlet couples to the product of lepton doublet and mirror lepton doublet. However $(g_{2S})^* = g_{1S}$ from reality of the mass eigenvalues! Note that these couplings are just complex numbers!

- Similar Yukawa couplings for right-handed SM singlets can be written down with three new Yukawa couplings g'_{0S}, g'_{1S}, and g'_{2S}.
- Provides a possible explanation why U_{PMNS} is so different from V_{CKM}.

More Details of the Extension - I

- From the A4 multiplication rules, we have

$$\mathcal{L}_S = -\overline{l_L^0}\left(g_{0S}\phi_{0S} + g_{1S}\tilde{\phi}_S + g_{2S}\tilde{\phi}_S\right) l_R^{M,0} + \text{H.c.}$$
$$= -\overline{l_L^0} M_\phi l_R^{M,0} + \text{H.c.}$$

where

$$M_\phi = \begin{pmatrix} g_{0S}\phi_{0S} & g_{1S}\phi_{3S} & g_{2S}\phi_{2S} \\ g_{2S}\phi_{3S} & g_{0S}\phi_{0S} & g_{1S}\phi_{1S} \\ g_{1S}\phi_{2S} & g_{2S}\phi_{1S} & g_{0S}\phi_{0S} \end{pmatrix} \longrightarrow M_\nu^D = \begin{pmatrix} g_{0S}v_0 & g_{1S}v_3 & g_{2S}v_2 \\ g_{2S}v_3 & g_{0S}v_0 & g_{1S}v_1 \\ g_{1S}v_2 & g_{2S}v_1 & g_{0S}v_0 \end{pmatrix}$$

- Using $v_0 = \langle\phi_{0S}\rangle$, $v_i = \langle\phi_{iS}\rangle = v$, we diagonalize M_ν^D

$$U_\nu^\dagger M_\nu^D U_\nu = \begin{pmatrix} m_{1D} & 0 & 0 \\ 0 & m_{2D} & 0 \\ 0 & 0 & m_{3D} \end{pmatrix},$$

In many popular A4 models, one has

$$U_{CW} \to U_{lL}$$

Cabibbo (1978), Wolfenstein (1978)

$$U_\nu = U_{CW}^\dagger$$

to exhibit CP violation in neutrino oscillations!

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

$$U_{\nu_L} = U_{\nu_R} = U_\nu$$

$$\omega = e^{2\pi i/3}$$

More Details of the Extension - II

- In the mass eigenstates,

$$l_L^0 = U_L^l l_L \quad , l_R^{M,0} = U_R^{l^M} l_R^M$$

the interaction becomes

$$\mathcal{L}_S = -\bar{l}_L U_L^{l\dagger} U_\nu U_\nu^\dagger M_\phi U_\nu U_\nu^\dagger U_R^{l^M} l_R^M + \text{H.c.}$$

$$= -\bar{l}_L U_{\text{PMNS}}^\dagger \tilde{M}_\phi U_{\text{PMNS}}^M l_R^M + \text{H.c.} \; ,$$

where

$$\tilde{M}_\phi = U_\nu^\dagger M_\phi U_\nu \; , \quad U_{\text{PMNS}} = U_\nu^\dagger U_L^l \quad \text{and} \quad U_{\text{PMNS}}^M = U_\nu^\dagger U_R^{l^M}$$

- Including the SM right-handed singlets and mirror left-handed doublets, the interaction is

$$\mathcal{L}_S = -\bar{l}_L U_{\text{PMNS}}^\dagger \tilde{M}_\phi U_{\text{PMNS}}^M l_R^M - \bar{l}_R U_{\text{PMNS}}'^\dagger \tilde{M}_\phi' U_{\text{PMNS}}'^M l_L^M + \text{H.c.}$$

$$= -\sum_{i,m,k} (\mathcal{U}_{im}^{L\,k} \bar{l}_{Li} \phi_{kS} l_{Rm}^M + \mathcal{U}_{im}^{R\,k} \bar{l}_{Ri} \phi_{kS} l_{Lm}^M) + \text{H.c.}$$

where $U_{\text{PMNS}}' = U_\nu^\dagger U_R^l$, $U_{\text{PMNS}}'^M = U_\nu^\dagger U_L^{l^M}$, and $l_R^0 = U_R^l l_R$, $l_L^{M,0} = U_L^{l^M} l_L^M$.

$\tilde{M}_\phi' = U_\nu^\dagger M_\phi' U_\nu$ $\quad$ M_ϕ' same as M_ϕ with $g_{0S} \to g_{0S}'$, $g_{1S} \to g_{1S}'$, $g_{2S} \to g_{2S}'$.

The Yukawa Couplings $\mathcal{U}^L$ & $\mathcal{U}^R$

$$\mathcal{U}^{L\,k}_{im} = \sum_{j,n=1}^{3} \left(\left(U^l_L\right)^\dagger \cdot U_\nu \right)_{ij} M^k_{jn} \left(U^\dagger_\nu \cdot U^{l^M}_R \right)_{nm} ,$$
$$\equiv \sum_{j,n=1}^{3} \left(U^\dagger_{\text{PMNS}} \right)_{ij} M^k_{jn} \left(U^{l^M}_{\text{PMNS}} \right)_{nm} ,$$
$$= \left(U^\dagger_{\text{PMNS}} \cdot M^k \cdot U^{l^M}_{\text{PMNS}} \right)_{im} ,$$

$$\mathcal{U}^{R\,k}_{im} = \sum_{j,n=1}^{3} \left(\left(U^l_R\right)^\dagger \cdot U_\nu \right)_{ij} M'^k_{jn} \left(U^\dagger_\nu \cdot U^{l^M}_L \right)_{nm} ,$$
$$\equiv \sum_{j,n=1}^{3} \left(U'^\dagger_{\text{PMNS}} \right)_{ij} M'^k_{jn} \left(U'^{l^M}_{\text{PMNS}} \right)_{nm} ,$$
$$= \left(U'^\dagger_{\text{PMNS}} \cdot M'^k \cdot U'^{l^M}_{\text{PMNS}} \right)_{im} .$$

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

$$\omega = e^{2\pi i/3}$$

- M^k is given by

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

- M'^k can be obtained from M^k with $g_{0S} \rightarrow g'_{0S}$ and $g_{1S} \rightarrow g'_{1S}$

- Yukawa couplings $\mathcal{U}^L$, $\mathcal{U}^R$ contain 4 different PMNS-type mixing effects and information about A_4 symmetry in the lepton sector

$U_{\mathrm{PMNS}} = (U_\nu)^\dagger U_{lL}$

- Standard Parameterization

$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \cdot P \qquad P = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

Mixing Parameters	Normal Hierarchy	Inverted Hierarchy
$\sin^2\theta_{12}$	0.308 ± 0.017	0.308 ± 0.017
$\sin^2\theta_{23}$	$0.437^{+0.033}_{-0.023}$	$0.455^{+0.139}_{-0.031}$
$\sin^2\theta_{13}$	$0.0234^{+0.0020}_{-0.0019}$	$0.024^{+0.0019}_{-0.0022}$
δ/π	$1.39^{+0.38}_{-0.27}$	$1.31^{+0.29}_{-0.33}$
$\delta m^2 = m_2^2 - m_1^2$	$(7.54^{+0.26}_{-0.22}) \times 10^{-5}\mathrm{eV}^2$	$(7.54^{+0.26}_{-0.22}) \times 10^{-5}\mathrm{eV}^2$
$\Delta m^2 = \lvert m_3^2 - (m_1^2 + m_2^2)/2\rvert$	$(2.43 \pm 0.06) \times 10^{-3}\mathrm{eV}^2$	$(2.38 \pm 0.06) \times 10^{-3}\mathrm{eV}^2$

- Capozzi, Fogli, Lisi, Marrone, Montanino, and Palazzo, PRD 89, 093018 (2014) [arXiv:1312.2878]

$$U^{\mathrm{NH}}_{\mathrm{PMNS}} = \begin{pmatrix} 0.8221 & 0.5484 & -0.0518 + 0.1439i \\ -0.3879 + 0.07915i & 0.6432 + 0.0528i & 0.6533 \\ 0.3992 + 0.08984i & -0.5283 + 0.05993i & 0.7415 \end{pmatrix}$$

$$U^{\mathrm{IH}}_{\mathrm{PMNS}} = \begin{pmatrix} 0.8218 & 0.5483 & -0.08708 + 0.1281i \\ -0.3608 + 0.0719i & 0.6467 + 0.04796i & 0.6664 \\ 0.4278 + 0.07869i & -0.5254 + 0.0525i & 0.7293 \end{pmatrix}$$

Calculations

- Early calculation of $\mu \rightarrow e\gamma$ and $\tau \rightarrow \mu\gamma$ in the minimal model was done back in 2008 [PQ Hung, PLB 659 (2008)].
- Here we perform an updated analysis in the extended model with A_4 symmetry.
- Current Limit (April, 2013)
  $B(\mu^+ \rightarrow e^+\gamma) \leqq 5.7\times10^{-13}$ (90%CL)
- MEG-II Short Term Upgrade
  Engineering Run - End of 2015
  Physics Run - 2016
- Expected upper limit 4×10^{-14}
  - an order of magnitude improvement!

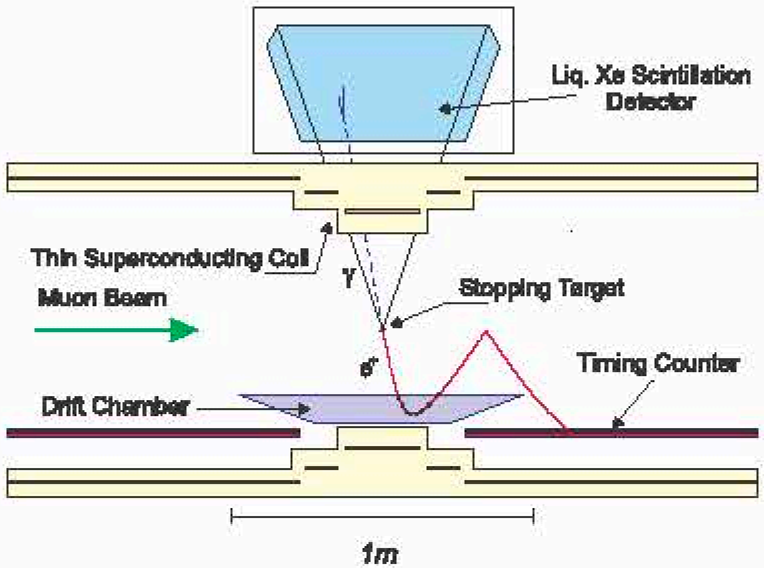


Figure 1: The MEG detector.

The Invariant Amplitude

$$M(l_i^-(p) \to l_j^-(p')\gamma(q)) = \bar{u}_j(p') i\sigma^{\mu\nu} q_\nu [C_L^{ij} L + C_R^{ij} R] u_i(p) \epsilon_\mu^*(q)$$

$$C_L^{ij} = +\frac{e}{16\pi^2} \sum_{k=0}^{3} \sum_{m=1}^{3} \left\{ \frac{1}{m_{l_m^M}^2} \left[m_i \mathcal{U}_{jm}^{Rk} \left(\mathcal{U}_{im}^{Rk}\right)^* + m_j \mathcal{U}_{jm}^{Lk} \left(\mathcal{U}_{im}^{Lk}\right)^* \right] \mathcal{I}\left(\frac{m_{\phi_{Sk}}^2}{m_{l_m^M}^2}\right) + \frac{1}{m_{l_m^M}} \mathcal{U}_{jm}^{Rk} \left(\mathcal{U}_{im}^{Lk}\right)^* \mathcal{J}\left(\frac{m_{\phi_{Sk}}^2}{m_{l_m^M}^2}\right) \right\} ,$$

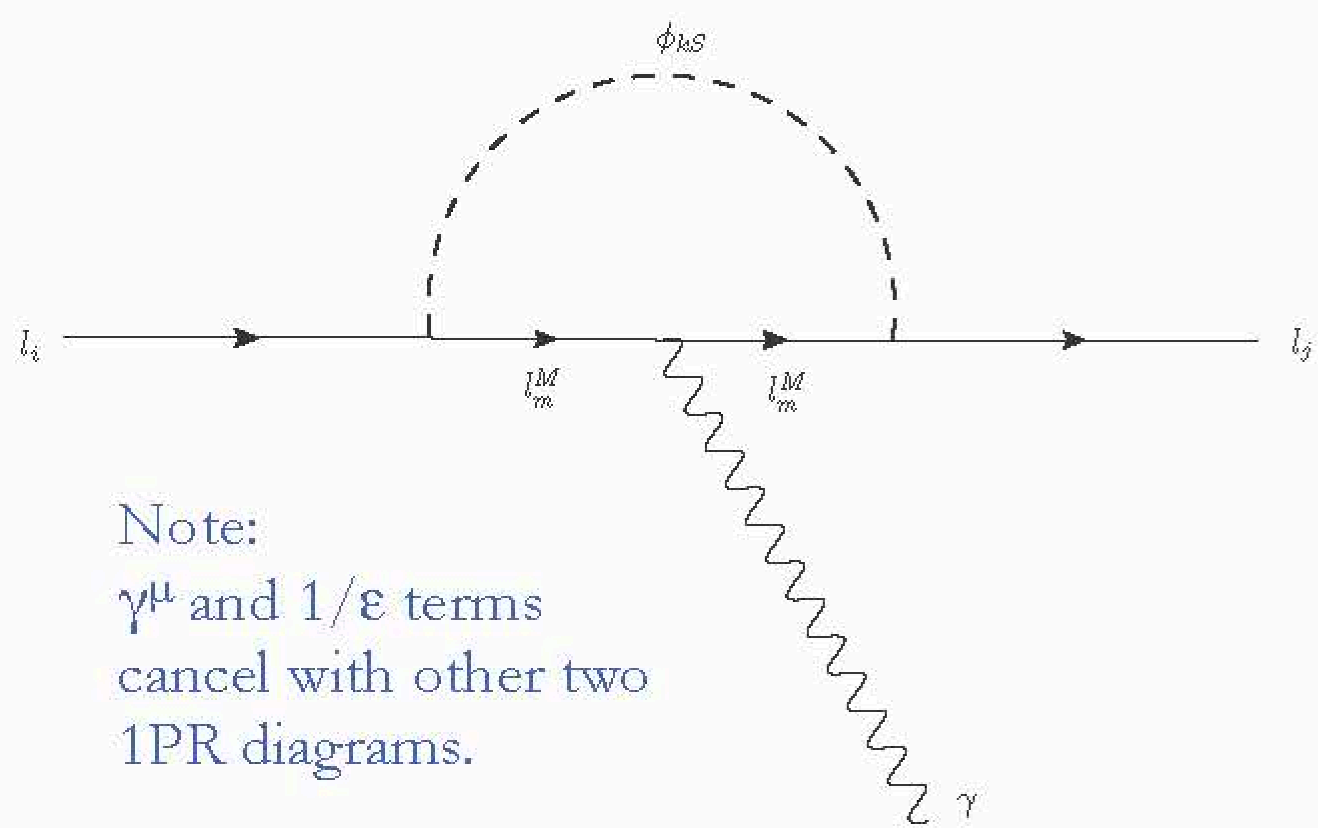
$$C_R^{ij} = +\frac{e}{16\pi^2} \sum_{k=0}^{3} \sum_{m=1}^{3} \left\{ \frac{1}{m_{l_m^M}^2} \left[m_i \mathcal{U}_{jm}^{Lk} \left(\mathcal{U}_{im}^{Lk}\right)^* + m_j \mathcal{U}_{jm}^{Rk} \left(\mathcal{U}_{im}^{Rk}\right)^* \right] \mathcal{I}\left(\frac{m_{\phi_{Sk}}^2}{m_{l_m^M}^2}\right) + \frac{1}{m_{l_m^M}} \mathcal{U}_{jm}^{Lk} \left(\mathcal{U}_{im}^{Rk}\right)^* \mathcal{J}\left(\frac{m_{\phi_{Sk}}^2}{m_{l_m^M}^2}\right) \right\}$$

- $\mathcal{I}$ and $\mathcal{J}$ (Ignoring m_i and m_j)

$$\mathcal{I}(r) = \frac{1}{12(1-r)^4}\left[-6r^2 \log r + r(2r^2 + 3r - 6) + 1\right]$$

$$\mathcal{J}(r) = \frac{1}{2(1-r)^3}\left[-2r^2 \log r + r(3r - 4) + 1\right] .$$

- $\mathcal{U}^L$ and $\mathcal{U}^R$ mix different families of charged leptons with those of the mirror leptons (see below)



Note:
γ^μ and $1/\varepsilon$ terms cancel with other two 1PR diagrams.

3 Observables (1 Stone 3 Birds)

- LFV Radiative Decay Rate

$$\Gamma\left(l_i \to l_j \gamma\right) = \frac{1}{16\pi} m_{l_i}^3 \left(1 - \frac{m_{l_j}^2}{m_{l_i}^2}\right)^3 \left(|C_L^{ij}|^2 + |C_R^{ij}|^2\right)$$

- Anomalous Magnetic Moment

$$\Delta a_{l_i} = \frac{2m_{l_i}}{e}\left(\frac{C_L^{ii} + C_R^{ii}}{2}\right)$$

$$= +\frac{1}{16\pi^2}\left\{\sum_{k=0}^{3}\sum_{m=1}^{3} 2\left(|\mathcal{U}_{im}^{L\,k}|^2 + |\mathcal{U}_{im}^{R\,k}|^2\right)\frac{m_{l_i}^2}{m_{l_m^M}^2}\mathcal{I}\left(\frac{m_{\phi_{Sk}}^2}{m_{l_m^M}^2}\right) + \sum_{k=0}^{3}\sum_{m=1}^{3} \mathrm{Re}\left(\mathcal{U}_{im}^{L\,k}\left(\mathcal{U}_{im}^{R\,k}\right)^*\right)\frac{m_{l_i}}{m_{l_m^M}}\mathcal{J}\left(\frac{m_{\phi_{Sk}}^2}{m_{l_m^M}^2}\right)\right\}$$

- Electric Dipole Moment

$$d_{l_i} = \frac{i}{2}\left(C_L^{ii} - C_R^{ii}\right) \quad ,$$

$$= +\frac{e}{16\pi^2}\sum_{k=0}^{3}\sum_{m=1}^{3}\frac{1}{m_{l_m^M}}\mathrm{Im}\left(\mathcal{U}_{im}^{L\,k}\left(\mathcal{U}_{im}^{R\,k}\right)^*\right)\mathcal{J}\left(\frac{m_{\phi_{Sk}}^2}{m_{l_m^M}^2}\right)$$

Numerical Results

- Assumption
  - Higgs Singlet Masses $m_{\phi_{Sk}} \sim 10\,\mathrm{MeV}$
  - Mirror Charged Lepton Masses

$$m_{l^M_m} = M_{mirror} + \delta_m \qquad M_{mirror} \sim 100 \text{ to } 800 \text{ GeV}$$

  - Yukawa Coupling Constants

$$g_{0S}, g_{1S}, g'_{0S}, g'_{1S} \text{ are all real!}$$

  - Mixing Matrices

Scenario 1 : $U^{l^M}_{PMNS} = U'_{PMNS} = U'^{l^M}_{PMNS} = U^{\dagger}_{CW}$

Scenario 2 : $U^{l^M}_{PMNS} = U'_{PMNS} = U'^{l^M}_{PMNS} = U_{PMNS}$

Scenario 1/2

Branching Ratio Contour on Coupling and Mirror Lepton Mass Space (g_{0S}, M_{mirror})

$$g'_{0S} = g_{0S}$$
$$g'_{1S} = g_{1S} = 0$$

$B(\mu^+ \to e^+\gamma) \leq 5.7 \times 10^{-13}(90\%\text{CL})$ $\Delta a_\mu = 288 \times 10^{-11}$

Scenario 1/2

Branching Ratio Contour on Coupling and Mirror Lepton Mass Space (g_{0S}, M_{mirror})

$$g_{1S} = 10^{-2} \cdot g_{0S}$$
$$g'_{0S} = g_{0S}$$
$$g'_{1S} = g_{1S}$$

$B(\mu^+ \to e^+\gamma) \leq 5.7 \times 10^{-13}(90\%\mathrm{CL})$

$\Delta a_\mu = 288 \times 10^{-11}$

Scenario 1/2

Branching Ratio Contour on Coupling and Mirror Lepton Mass Space (g_{0S}, M_{mirror})

$$g_{1S} = 10^{-1} \cdot g_{0S}$$
$$g'_{0S} = g_{0S}$$
$$g'_{1S} = g_{1S}$$

$B(\mu^+ \to e^+\gamma) \leq 5.7 \times 10^{-13}(90\%\text{CL})$ $\Delta a_\mu = 288 \times 10^{-11}$

Scenario 1/2

Branching Ratio Contour on Coupling and Mirror Lepton Mass Space (g_{0S}, M_{mirror})

$$g_{1S} = 0.5 \cdot g_{0S}$$
$$g'_{0S} = g_{0S}$$
$$g'_{1S} = g_{1S}$$

$B(\mu^+ \to e^+\gamma) \leq 5.7 \times 10^{-13}(90\%CL)$ $\Delta a_\mu = 288 \times 10^{-11}$

Scenario 1/2

Branching Ratio Contour on Coupling and Mirror Lepton Mass Space ($g_{0S} = g_{1S}$, M_{mirror})

$$g'_{0S} = g_{0S} = g'_{1S} = g_{1S}$$

$B(\mu^+ \to e^+\gamma) \leq 5.7 \times 10^{-13}(90\%\mathrm{CL})$ $\Delta a_\mu = 288 \times 10^{-11}$

Scenario 1/2

Branching Ratio Contour on Coupling and Mirror Lepton Mass Space (g_{1S}, M_{mirror})

$$g'_{0S} = g_{0S} = 0$$
$$g'_{1S} = g_{1S}$$

$B(\mu^+ \to e^+\gamma) \leq 5.7 \times 10^{-13}(90\%\mathrm{CL})$ $\Delta a_\mu = 288 \times 10^{-11}$

Discussions

- In the same mass range of the mirror leptons the LFV process $\mu \to e\,\gamma$ is more sensitive to the couplings by almost 2 orders of magnitudes as compared to Δa_μ.

- As one turns on the A_4 triplet couplings, the contours of $Log_{10}(\mu \to e\,\gamma)$ are shifting toward to the left, indicating the role of the triplet singlets becomes more relevant and thus the constraints on the parameter space becomes more stringent from the current MEG limit.

- The sensitivity of the couplings in the $B(\mu \to e\,\gamma)$ has been weakened by one to two orders of magnitudes for scenario 2 as compared to scenario 1. However, this sensitivity is not present for Δa_μ.

- As one slowly turns on the A_4 triplet couplings $g_{1S} = 0$ to $10^{-1} g_{0S}$, the red contours of $Log_{10}(\mu \to e\,\gamma)$ of scenario 1 remains the same when comparing NH versus IH, while the blue contours of scenario 2 move toward to the left. This indicates some differences between NH and IH of neutrino masses for scenario 2. However, for $g_{1S} > 0.5 g_{0S}$, these differences disappear! There features are not there for Δa_μ!

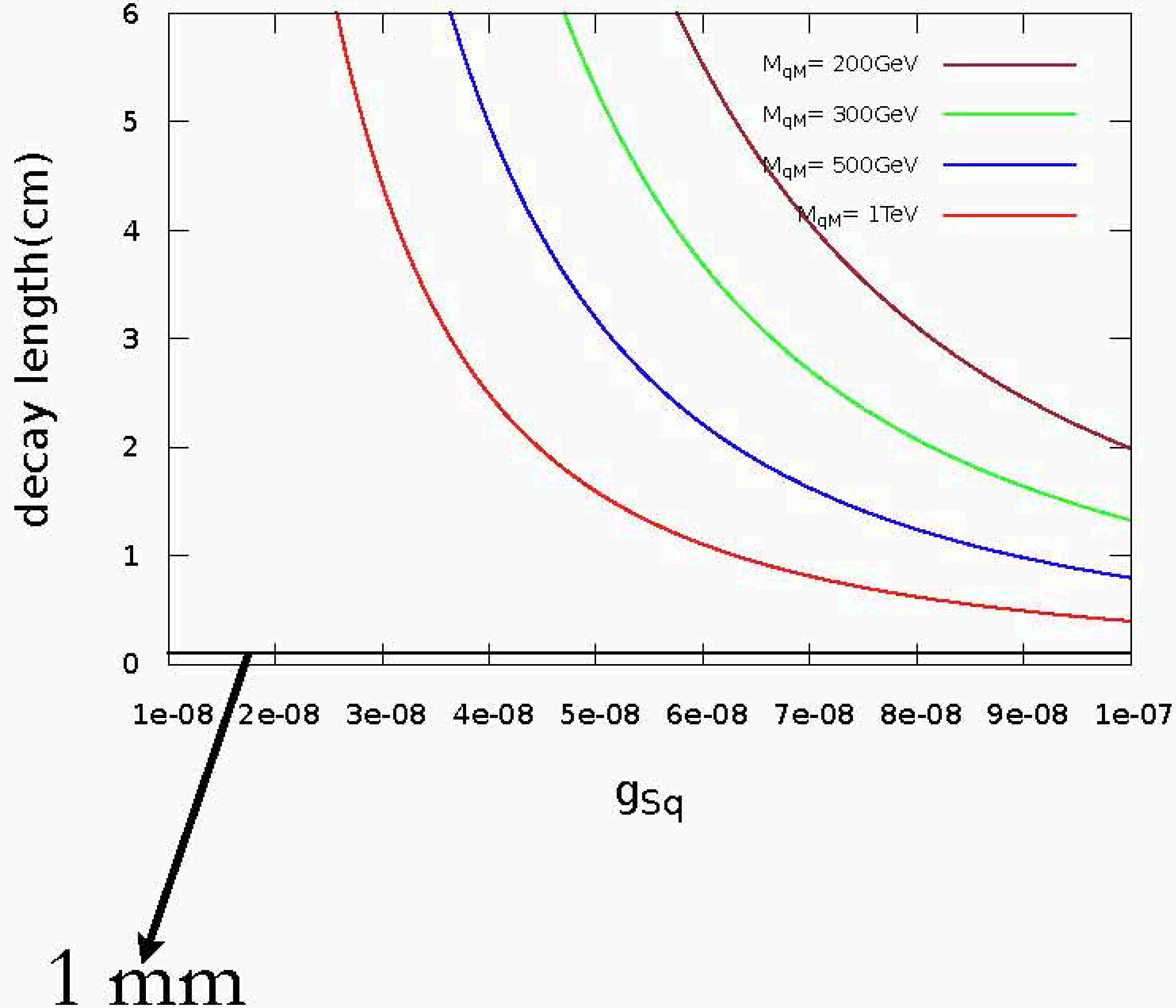
- Due to the smallness of the couplings, decay length of the mirror leptons (or quarks) which depends on the product of the couplings and the mixing parameters will probably decay outside the beam pipe, which may lead to displaced vertices at the collider.

OSU-HEP-15-06

The search for mirror quarks at the LHC

Shreyashi Chakdar[1,2],* K. Ghosh[1],† V. Hoang[2],‡ P. Q. Hung[2,3],§ and S. Nandi[1]¶

- Decay length of mirror quark
- Above 1 mm black line, significantly different than the decay length coming from the b-quark displaced vertices



Summary

- Updated analysis on $\mu \to e\gamma$ and Δa_μ in non-sterile EW-scale ν_R model with A_4 symmetry (necessarily broken in charged lepton sector) were presented. It links LFV processes with U_{PMNS} in the neutrino sector which is quite distinct from many other models.
- Current MEG limit on $B(\mu \to e\gamma)$ imposes constraints on the mirror lepton masses and Yukawa couplings. Projected limit will put even more interesting constraints on the model.
- Predictions of $B(\mu \to e\gamma)$ in the extended model with A_4 symmetry are slightly sensitive to the neutrino mass hierarchy in scenarios 2 but not scenario 1. However, Δa_μ is not sensitive to the mass hierarchies.
- Regions allowed by Δa_μ excluded by current limit of $B(\mu \to e\gamma)$!
- Work in progress:
  $h \to \tau\mu$, τe versus $\tau \to \mu\gamma$, $e\gamma$
  μe conversion in nuclei
  $t \to c(\gamma, Z, g, h)$

LFV Higgs Decay

[Chang, Nugroho, TCY, in progress]

- Experimental Status

CMS [1]:

$$\mathrm{Br}(h \to \tau\mu) = 0.84^{+0.39}_{-0.37}\% \quad [\text{Best Fit}] \,,$$
$$< 1.51\% \qquad [95\% \text{ CL}] \,.$$

Theoretical limit [12]:

$$\mathrm{Br}(h \to \tau e) < 13\% \quad [95\% \text{ CL}] \,.$$

BaBar experiment 90% C.L. [3]:

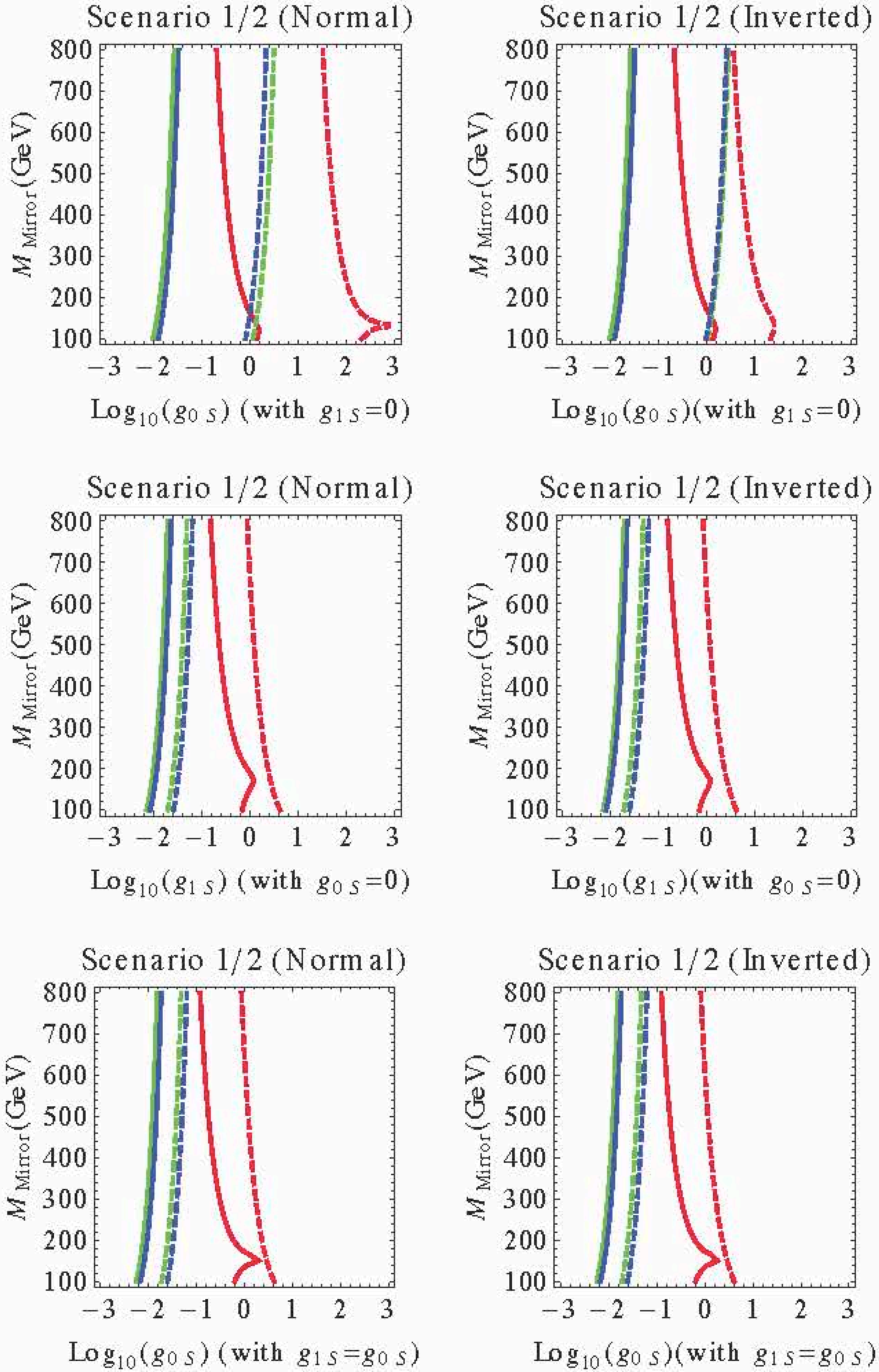
$$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \times 10^{-8} \,,$$
$$\mathrm{Br}(\tau \to e\gamma) < 3.3 \times 10^{-8} \,.$$

Preliminary Results

$Br(h \to \tau\mu) < 1.51\%$

$Br(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$

$Br(\tau \to e\gamma) < 3.3 \times 10^{-8}$



Preliminary Results

$\mathrm{Br}(h \to \tau\mu) < 1.51\%$

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

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Thank You