$\mu - e$ Conversion in the Electroweak-scale Right-handed Neutrino Model

Trinh Le

work done in collaboration with
PQ Hung (UVA), VQ Tran (NTNU), TC Yuan (Academia Sinica)

Quy Nhon, July 12, 2016

Why study $\mu - e$ conversion?

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Challenge?

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Credit: Fermilab Education Office

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Reflecting New Physics

- Observing the process will help to understand why particles change flavors.
- Discovering it is crucial to understand what Physics may lay beyond the Standard Model.

In this talk

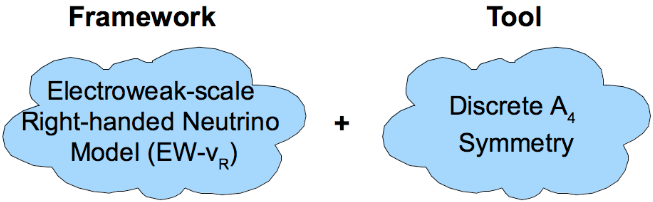
- Study $\mu - e$ conversion as phenomenological implications in a **model of neutrino masses**.
- $\mu - e$ conversion and $\mu \to e\gamma$ might be related to each other under a good approximation that we have established.
- Discuss future searches for $\mu - e$ conversion at Fermilab and J-PARC COMET.

Outline

1. Review
   - EW-ν_R Model
   - A_4 Symmetry
   - A model of neutrino masses
2. $\mu - e$ Conversion Process
3. A link between $\mu - e$ Conversion and $\mu \to e\gamma$
4. Conclusion

Review

Model of neutrino masses[1]



[1] P.Q. Hung, T. Le, JHEP 1509, 001 (2015)

The EW-ν_R Model [2]

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Model in which right-handed neutrinos have Majorana masses of the order of Λ_{EW} naturally. They can be detected at the LHC!

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How?

For naturalness, M_R has to be related to the breaking scale of the SM $\Rightarrow$ ν_R's cannot be a singlet of the SM $\Rightarrow$ Simplest picture: ν_R is a member of a doublet of SU(2) along with a mirror charged lepton also right-handed $\Rightarrow$ Mirror fermions. ν_R's are non-sterile.

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Why?

$M_R \propto O(\Lambda_{EW})$ and $\nu_R \in$ SU(2) doublets $\Rightarrow$ ν_R can be produced at the LHC with electroweak cross sections $\Rightarrow$ Direct evidence for the seesaw mechanism such as same-sign dilepton events coming from ν_R's decays.

[2] P.Q. Hung, 2007

Minimal model

- Gauge group: $SU(3)_C \times SU(2) \times U(1)_Y$

- Model Content (generic notation)

SM:

$$l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} ; \; q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$e_R; \; u_R, \; d_R$

Mirror:

$$l_R^M = \begin{pmatrix} \nu_R \\ e_R^M \end{pmatrix} ; \; q_R^M = \begin{pmatrix} u_R^M \\ d_R^M \end{pmatrix}$$

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Mirror particles are totally different from the SM particles!

Higgs sector: one Higgs doublet Φ_2, two Higgs triplet χ and ξ and one Higgs singlet ϕ_S.

- Majorana mass of ν_R

$$\begin{aligned} L_M &= g_M \left(l_R^{M,T}\ \sigma_2\right)\ (i\ \tau_2\ \tilde{\chi})\ l_R^M \\ &= g_M\ \nu_R^T\ \sigma_2\ \nu_R\ \chi^0 - \frac{1}{\sqrt{2}}\ \nu_R^T\ \sigma_2\ e_R^M\ \chi^+ + \ldots \end{aligned} \tag{1}$$

→ Lepton number is violated

- Dirac mass

$$\begin{aligned} L_S &= g_{Sl}\ \bar{l}_L\ \phi_S\ l_R^M + h.c. \\ &= g_{Sl}\bar{\nu}_L\ \phi_S\ \nu_R + \ldots + h.c. \end{aligned} \tag{2}$$

→ Lepton number is conserved

More details?

See V.Q. Tran, S. Chakdar and A. Aranda talks on EW-ν_R Model

A_4 Symmetry

Why?

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What?

- Non-Abelian discrete group
- Four irreducible representations: **Three** 1-dimension representations called $\underline{1}$, $\underline{1}'$, $\underline{1}''$ and **One** 3-dimension representation called $\underline{3}$

A model of neutrino masses

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- Let us apply A_4 to the neutrino Dirac mass matrix which involves a Higgs singlet ϕ_S. With A_4 symmetry, we have an extension to 4 Higgs singlets $\Rightarrow$ No constraints from the LHC!
- Assignments of the model's content under A_4

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

$$L_S = \bar{l}_L \left(g_{0S}\phi_{0S} + g_{1S}\tilde{\phi}_S + g_{2S}\tilde{\phi}_S\right) l_R^M + h.c. \quad (3)$$

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$$A_4: \quad \underline{3} \otimes (\quad \underline{1} \quad \underline{3} \quad \underline{3}\ )\ \underline{3}$$

Neutrino Dirac mass matrix

$$M_\nu^D = \begin{pmatrix} g_{0S}v_0 & g_{1S}v_3 & g_{2S}v_2 \\ g_{2S}v_3 & g_{0S}v_0 & g_{1S}v_1 \\ g_{1S}v_2 & g_{2S}v_1 & g_{0S}v_0 \end{pmatrix}$$ where $v_{0,1,2,3}$: VEVs of Higgs singlets.

M_ν^D can be diagonalized by

$$U_\nu = U_{CW}^\dagger = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega^2 & \omega \\ 1 & \omega & \omega^2 \end{pmatrix}$$ with $\omega = e^{i2\pi/3}$

U_{CW}: the Cabibbo[3]-Wolfenstein[4] matrix

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Model of neutrino masses (con't)

Not to forget the PMNS

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• *Ansätz* for U_{lL}: use Wolfenstein-like parametrization to have a small deviation from a unit matrix

$$U_{lL} \to U_{lL} = \begin{pmatrix} 1 - \frac{\lambda_l^2}{2} & \lambda_l & A_l \lambda_l^3(\rho_l - i\eta_l) \\ -\lambda_l & 1 - \frac{\lambda_l^2}{2} & A_l \lambda_l^2 \\ A_l \lambda_l^3(1 - \rho_l - i\eta_l) & -A_l \lambda_l^2 & 1 \end{pmatrix} \quad (4)$$

where $A_l,\ \rho_l,\ \eta_l$ are real parameters of O(1).

Photo by Reidar Hahn, Fermilab

SINDRUM II @ PSI

SINDRUM II: $B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$

SINDRUM II: $B(\mu^- + Ti \rightarrow e^- + Ti) < 6.1 \times 10^{-13}$

Projected Sensitivity for
$B(\mu^- + Al \rightarrow e^- + Al)$

→ **Mu2e: 6×10^{-17}**

→ **COMET:3×10^{-17}**

$\mu - e$ Conversion

Effective Lagrangian for $\mu - e$ Conversion

$$\begin{aligned} \mathcal{L}_{\text{eff}} = & - \frac{1}{\Lambda^2}\Big[\Big(C_{DR} m_\mu \bar{e}\sigma^{\alpha\beta}P_L\mu + C_{DL} m_\mu \bar{e}\sigma^{\alpha\beta}P_R\mu\Big) F_{\alpha\beta} \\ & + \sum_{q=u,d,s} \Big(C_{VR}^{(q)}\bar{e}\gamma^\alpha P_R\mu + C_{VL}^{(q)}\bar{e}\gamma^\alpha P_L\mu\Big)\bar{q}\gamma_\alpha q \\ & + \sum_{q=u,d,s} m_\mu m_q G_F \Big(C_{SR}^{(q)}\bar{e}P_R\mu + C_{SL}^{(q)}\bar{e}P_L\mu\Big)\bar{q}q \\ & + m_\mu \left(C_{GQR} G_F \bar{e}P_L\mu + C_{GQL} G_F \bar{e}P_R\mu\right)\frac{\beta_L}{2g_s^3} G^{a\alpha\beta}G^a_{\alpha\beta} + \text{H.c.}\Big]. \end{aligned} \tag{5}$$

where $C_{D(L,R)}$, $C^{(q)}_{V(L,R)}$, $C^{(q)}_{S(L,R)}$ and $C_{GQ(L,R)}$ are dimensionless coupling constants depending on specific LFV model.

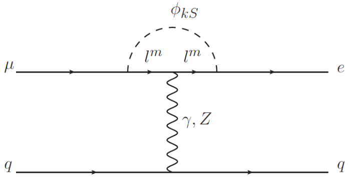
Conversion rate (general formula) [5]

$$\begin{aligned}\Gamma_{\rm conv} \;=\; \frac{m_\mu^5}{4\Lambda^4}\Bigg(\Big| & C_{DR}D + 4\tilde{C}_{VR}^{(p)}V^{(p)} + 4\tilde{C}_{VR}^{(n)}V^{(n)} + \\ & +4G_F m_\mu\left(m_p\tilde{C}_{SR}^{(p)}S^{(p)} + m_n\tilde{C}_{SR}^{(n)}S^{(n)}\right)\Big|^2 \\ + \Big| & C_{DL}D + 4\tilde{C}_{VL}^{(p)}V^{(p)} + 4\tilde{C}_{VL}^{(n)}V^{(n)} + \\ & +4G_F m_\mu\left(m_p\tilde{C}_{SL}^{(p)}S^{(p)} + m_n\tilde{C}_{SL}^{(n)}S^{(n)}\right)\Big|^2\Bigg)\,. \qquad (6)\end{aligned}$$

where D, V, S are overlap integrals of the relativistic wave functions of μ and e in the electric field of nucleus.

[5] R. Kitano, M. Koike, Y. Okada (2007)

Contributions to the conversion rate



Photon and Z boson exchange

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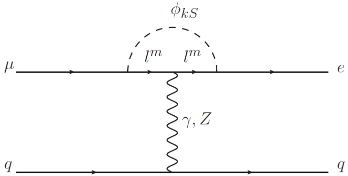

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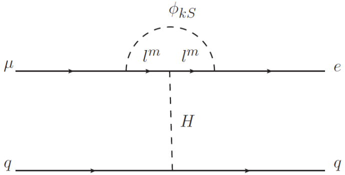

Higgs exchange with light quarks

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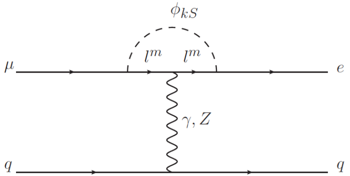

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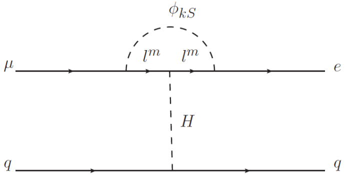

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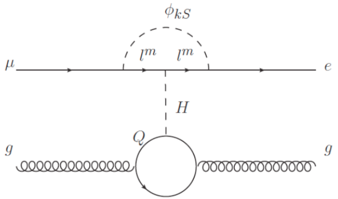

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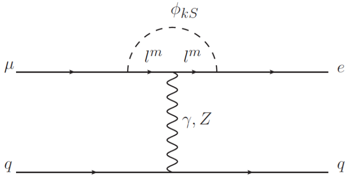

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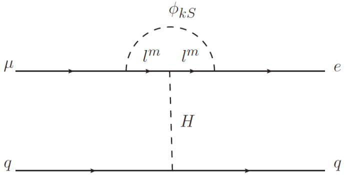

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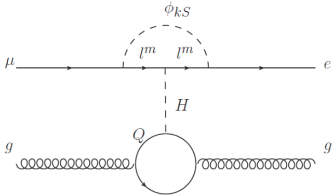

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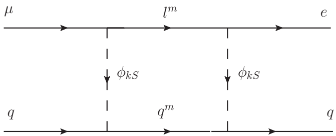
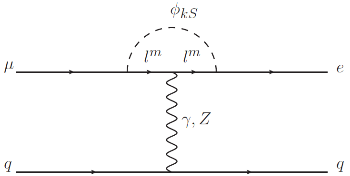


Box diagram

Contributions to the conversion rate



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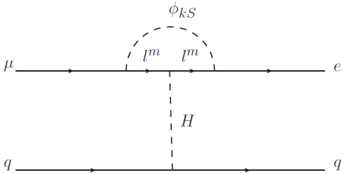

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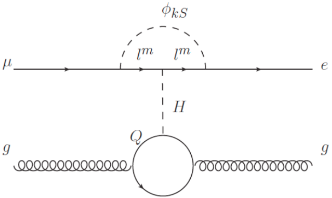

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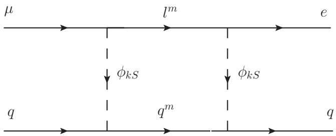

Box diagram

The main contribution comes from γ exchange!

The formula for the conversion rate (from γ contributions ONLY)

$$\Gamma_{\rm conv} \simeq \frac{m_\mu^5}{4\Lambda^4}\left(\left|C_{DR}D + 4\tilde{C}_{VR}^{(p)}V^{(p)} + 4\tilde{C}_{VR}^{(n)}V^{(n)}\right|^2 + \left|C_{DL}D + 4\tilde{C}_{VL}^{(p)}V^{(p)} + 4\tilde{C}_{VL}^{(n)}V^{(n)}\right|^2\right) . \qquad (7)$$

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Question

Is there any relation between $\mu - e$ conversion and $\mu \to e\gamma$?

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$\mu - e$ Conversion and $\mu \to e\gamma$

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$$\Gamma^{\gamma *}_{conv}(q^2 \to 0) \approx \pi D^2 \Gamma^{\gamma} \tag{8}$$

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Nucleus	D	$V^{(p)}$	$V^{(n)}$	$S^{(p)}$	$S^{(n)}$
$^{27}_{13}$Al	0.0362	0.0161	0.0173	0.0155	0.0167
$^{48}_{22}$Ti	0.0864	0.0396	0.0468	0.0368	0.0435
$^{197}_{79}$Au	0.189	0.0974	0.146	0.0614	0.0918
$^{208}_{82}$Pb	0.161	0.0834	0.128	0.0488	0.0749

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So in terms of the branching ratio, we have

$$B_{\mu N \to eN} = \frac{\Gamma^{\gamma *}_{conv}}{\Gamma_{capt}} = \pi D^2 \frac{\Gamma_{\mu}}{\Gamma_{capt}} B_{\mu \to e\gamma} \tag{9}$$

Numerical analysis

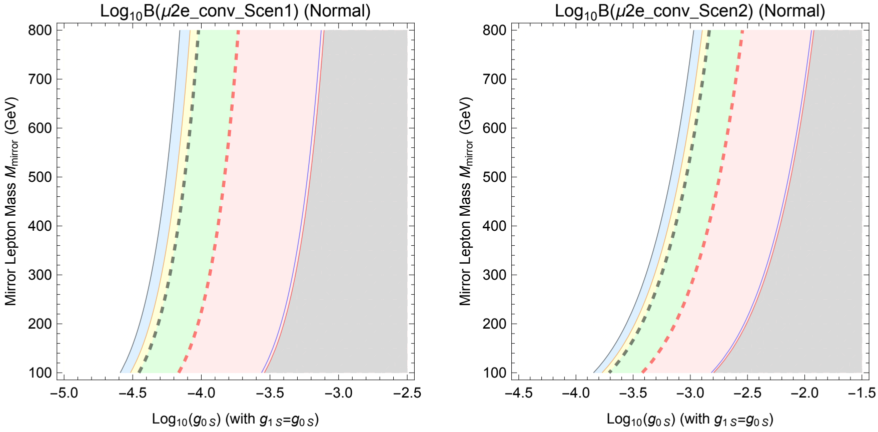

Figure : $g_{0S} = g'_{0S} = g_{1S} = g'_{1S}$.

Let's zoom in

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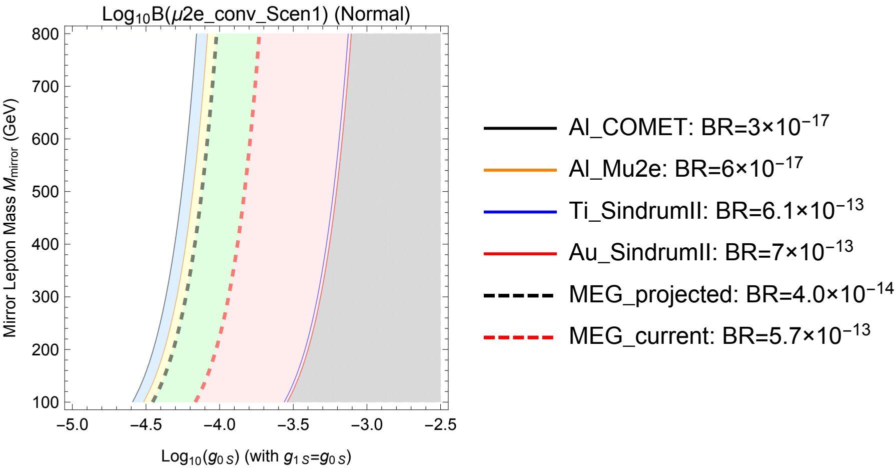
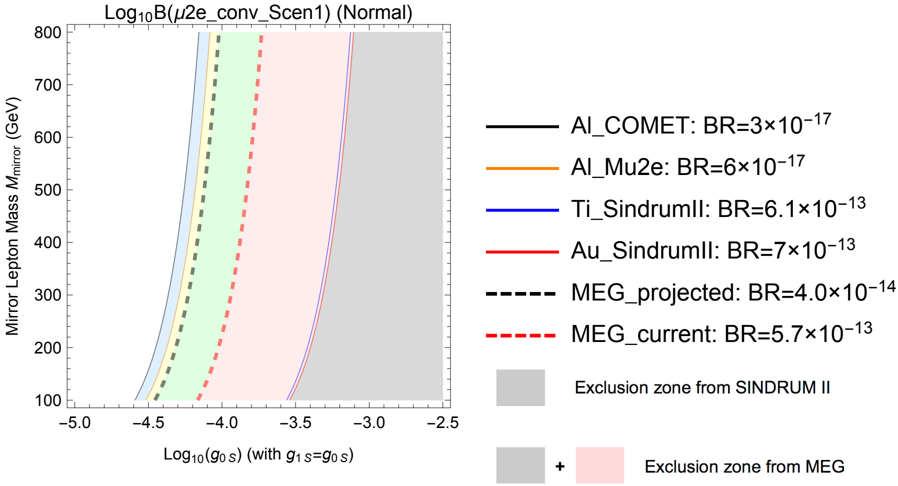

Log10B(μ2e_conv_Scen1) (Normal)
Mirror Lepton Mass Mmirror (GeV)
800
700
600
500
400
300
200
100
−5.0
−4.5
−4.0
−3.5
−3.0
−2.5
Log10(g0 S) (with g1 S=g0 S)
Al_COMET: BR=3×10−17
Al_Mu2e: BR=6×10−17
Ti_SindrumII: BR=6.1×10−13
Au_SindrumII: BR=7×10−13
MEG_projected: BR=4.0×10−14
MEG_current: BR=5.7×10−13

Let's zoom in



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Exclusion zone from SINDRUM II
+
Exclusion zone from MEG

Conclusion

- In our analysis, we are showing that constraints from $\mu - e$ conversion imply Yukawa couplings $< 10^{-3}$.
  - Due to small couplings, searches for mirror particles of this model at the LHC would be quite interesting since they might decay outside the beam pipe and inside silicon vertex detectors (displaced vertices).

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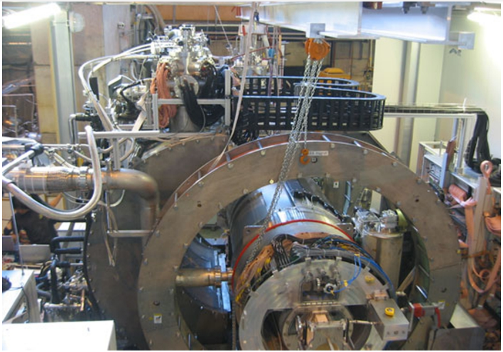
  - Due to small couplings, searches for mirror particles of this model at the LHC would be quite interesting since they might decay outside the beam pipe and inside silicon vertex detectors (displaced vertices).
- We found a relation between $\mu \to e\gamma$ and $\mu \to e$ conversion within a good approximation.
- The current limit from $\mu \to e\gamma$ excludes almost half of the searched region for the branching ratio of $\mu - e$ conversion. Therefore, our work may help to narrow down future searches for $\mu - e$ conversion at Mu2e and J-PARC COMET within this model.

Backup

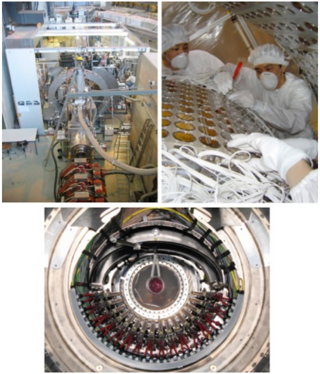
Backup slides

$\mu \to e\gamma$



MEG apparatus by Prof. Saoshi Mihara

MEG Experiment



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$$B(\mu^+ \to e^+ \gamma) < 5.7 \times 10^{-13}$$

Projected Sensitivity = 4.0×10^{-14}

$l_i \to l_j\gamma$

Recall that Model of Neutrino Masses has an A_4-**singlet** ϕ_{0S} and an A_4-**triplet** $\{\phi_{iS}\}$ $(i = 1, 2, 3)$.

Total Yukawa interactions

$$\mathcal{L}_S = -\bar{l}_L\, U^\dagger_{\rm PMNS}\, \tilde{M}_\phi\, U^M_{\rm PMNS} l^M_R - \bar{l}_R\, U'^\dagger_{\rm PMNS}\, \tilde{M}'_\phi\, U'^M_{\rm PMNS} l^M_L + {\rm H.c.} \tag{10}$$

where

- $\tilde{M}_\phi = U^\dagger_\nu M_\phi U_\nu$, $\tilde{M}'_\phi = U^\dagger_\nu M'_\phi U_\nu$ and M'_ϕ is the same as M_ϕ.
- $U_{\rm PMNS} = U^\dagger_\nu U^l_L\,,\; U^M_{\rm PMNS} = U^\dagger_\nu U^{l^M}_R$
- $U'_{\rm PMNS} = U^\dagger_\nu U^l_R\,,\; U'^M_{\rm PMNS} = U^\dagger_\nu U^{l^M}_L$

$l_i \to l_j\gamma$ (con't)

For the process $l_i^-(p) \to l_j^-(p') + \gamma(q)$

- The amplitude

$$\mathcal{M}\left(l_i^- \to l_j^-\gamma\right) = \epsilon_\mu^*(q)\bar{u}_j(p')\left\{i\sigma^{\mu\nu}q_\nu\left[C_L^{ij}P_L + C_R^{ij}P_R\right]\right\}u_i(p) \ , \tag{11}$$

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- The partial width

$$\Gamma\left(l_i \to l_j\gamma\right) = \frac{1}{16\pi}m_{l_i}^3\left(1 - \frac{m_{l_j}^2}{m_{l_i}^2}\right)^3\left(|C_L^{ij}|^2 + |C_R^{ij}|^2\right) \quad . \tag{12}$$

Coefficients

$$C_L^{ij} = +\frac{e}{16\pi^2}\sum_{k=0}^{3}\sum_{m=1}^{3}\left\{\frac{1}{m_{l_m^M}^2}\left[m_i\mathcal{U}_{jm}^{R\,k}\left(\mathcal{U}_{im}^{R\,k}\right)^* + m_j\mathcal{U}_{jm}^{L\,k}\left(\mathcal{U}_{im}^{L\,k}\right)^*\right]\mathcal{I}\left(\frac{m_{\phi_{kS}}^2}{m_{l_m^M}^2}\right) + \frac{1}{m_{l_m^M}}\mathcal{U}_{jm}^{R\,k}\left(\mathcal{U}_{im}^{L\,k}\right)^*\mathcal{J}\left(\frac{m_{\phi_{kS}}^2}{m_{l_m^M}^2}\right)\right\}, \quad (13)$$

$$C_R^{ij} = +\frac{e}{16\pi^2}\sum_{k=0}^{3}\sum_{m=1}^{3}\left\{\frac{1}{m_{l_m^M}^2}\left[m_i\mathcal{U}_{jm}^{L\,k}\left(\mathcal{U}_{im}^{L\,k}\right)^* + m_j\mathcal{U}_{jm}^{R\,k}\left(\mathcal{U}_{im}^{R\,k}\right)^*\right]\mathcal{I}\left(\frac{m_{\phi_{kS}}^2}{m_{l_m^M}^2}\right) + \frac{1}{m_{l_m^M}}\mathcal{U}_{jm}^{L\,k}\left(\mathcal{U}_{im}^{R\,k}\right)^*\mathcal{J}\left(\frac{m_{\phi_{kS}}^2}{m_{l_m^M}^2}\right)\right\}. \quad (14)$$

$l_i \to l_j\gamma$ (con't)

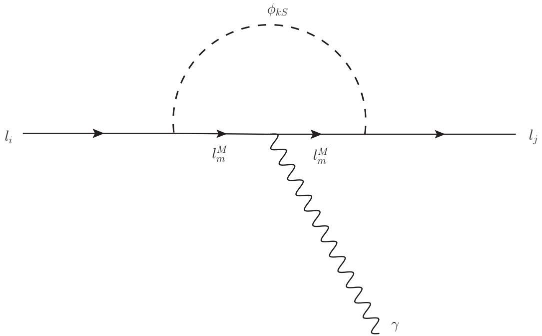

Figure 1: One-loop induced Feynman diagram for $l_i \to l_j\gamma$ in EW-scale ν_R model

- The work makes full use of the results on mixings developed above.
- Many possibilities which depend on the relative sizes of the Yukawa couplings g_{0S} and g_{iS} to the Higgs singlets. One example shown in the plot here.

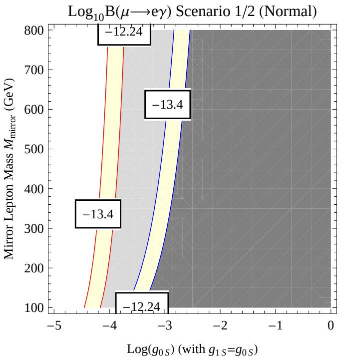

Figure : $g_{0S} = g'_{0S} = g_{1S} = g'_{1S}$.

-13.4 $\to \mathrm{Log}_{10}$BR(MEG-projected); -12.24 $\to \mathrm{Log}_{10}$BR(MEG-limit).

scenario 1: $U^M_{\mathrm{PMNS}} = U'_{\mathrm{PMNS}} = U'^M_{\mathrm{PMNS}} = U^\dagger_{CW}$

scenario 2: $U^M_{\mathrm{PMNS}} = U'_{\mathrm{PMNS}} = U'^M_{\mathrm{PMNS}} = U_{\mathrm{PMNS}}$

Charged-lepton mass

[6] P.Q. Hung, 2007

Charged-lepton mass

• Charged leptons can couple to singlet Higgs field which give rise to a mass mixing between charged SM and mirror leptons. However, the mixing is very small so its contribution to the charged-lepton mass matrix can be negligible [6].

[6] P.Q. Hung, 2007

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• The Yukawa couplings (with Higgs doublet)

$$\begin{aligned} L_{Y_l} &= g_l \, \bar{l}_L \;\; \Phi_2 \;\; e_R + h.c. \\ &= \underline{3} \otimes \underline{1} \otimes \underline{3} \end{aligned} \tag{15}$$

[6] P.Q. Hung, 2007

Charged lepton mass

The charged-lepton mass matrix is

$$\mathcal{M}_l = g_l \frac{v_2}{\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{16}$$

which gives rise to

$$U_{lL} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{17}$$

This is not satisfactory because it causes degenerate charged leptons. We will modify this later.

Numerical Analysis

- For the masses of the singlet scalars ϕ_{kS}
  $m_{\phi_{0S}} : m_{\phi_{1S}} : m_{\phi_{2S}} : m_{\phi_{3S}} = M_S : 2M_S : 3M_S : 4M_S$ with $M_S = 10$ MeV.
- For the masses of the mirror lepton l_m^M
  $m_{l_m^M} = M_{\mathrm{mirror}} + \delta_m$ with $\delta_1 = 0$, $\delta_2 = 10$ GeV, $\delta_3 = 20$ GeV and $100\ GeV \leq M_{\mathrm{mirror}} \leq 800 GeV$
- Scenario 1 $U^M_{\mathrm{PMNS}} = U'_{\mathrm{PMNS}} = U'^M_{\mathrm{PMNS}} = U^\dagger_{CW}$
- Scenario 2 $U^M_{\mathrm{PMNS}} = U'_{\mathrm{PMNS}} = U'^M_{\mathrm{PMNS}} = U_{\mathrm{PMNS}}$

ρ parameter

$$\rho \equiv \frac{M_W^2}{M_Z^2 cos^2\theta_W} = 1$$

$$\rho = \frac{\sum_i [T(T+1) - T_3^2]_i v_i^2 c_{T,Y}}{2\sum_i T_{3i}^2 v_i^2}$$

- If only the Higgs triplet is present to break SM, $\rho = 1/2$.
- Experimentally, $\rho = 1$ to a good precision.

Possible signature of EW ν_R model

The fact

1. ν_R interacts with the W and Z (part of a doublet)
2. Both ν_R and e_R^M interact with ν_L and e_L through the singlet scalar field ϕ_S

Since $m_{\phi_S} \sim O(10^5\ eV)$, it's possible

$$\begin{aligned} \nu_R &\rightarrow \nu_L + \phi_S \\ e_R^M &\rightarrow e_L + \phi_S \end{aligned}$$

If $m_{\nu_R} \lesssim m_{e_R^M}$:

$$\begin{aligned} e_M^R \rightarrow \quad & \nu_R + e_L + \bar{\nu}_L \\ & \nu_R \rightarrow \nu_L + \phi_S \end{aligned}$$

Possible signature of EW ν_R model

The heaviest ν_R could be pair produced

$$
\begin{aligned}
q + \bar{q} &\rightarrow Z \rightarrow \nu_R + \nu_R \\
\nu_R &\rightarrow e_R^M + W^*(W) \\
e_R^M &\rightarrow e_L + \phi_S
\end{aligned}
$$

at a 'displaced' vertex.
If ν_R is Majorana

$$e_R^{M,-} + W^+ + e_R^{M,-} + W^+ \rightarrow e_L + e_L + W^+ + W^+ + 2\phi_S$$

same-sign dilepton event which is distinctively different from the Dirac case!