$\mu \to e\gamma$ and $\mu \to ee\bar{e}$ in a model of electroweak-scale right-handed neutrinos

刘继元

南开大学

Based on J.-P. Bu, Y. Liao, J.-Y. Liu, arXiv: 0802.3241 [hep-ph]

Outline

Outline

Neutrino Mass - Beyond SM

- There is no neutrino mass in SM.
  No right-handed neutrinos exist in SM.
- Experimental fact from neutrino oscillation:
  1. Solar Neutrino Experiment:
     SNO, Homestake, SAGE, GNO, Kamiokande and Super-K, Borexino, $\cdots$
  2. Atmospheric Neutrino Experiment:
     Super-K, $\cdots$
  3. Accelerator and reactor neutrino experiment:
     CHOOZ, Double-CHOOZ, LSND, K2K, Neutrino Factory $\cdots$

Seesaw Mechanism

How is a tiny mass possible?

- Consider mass matrix of ν_L and ν_R:

$$-\frac{1}{2}\left(\overline{\nu_L}, \overline{\nu_R^C}\right)\begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix}\begin{pmatrix} \nu_L^C \\ \nu_R \end{pmatrix} + \text{h.c.}$$

- Eigenvalues for $m_R \gg m_D$:

$$\sim m_R \text{ (huge) and } \sim -\frac{m_D^2}{m_R} \text{ (tiny)}$$

Seesaw Mechanism

- Standard seesaw

For example, $\frac{m_D^2}{m_R} \sim$ eV and $m_D \sim \mathrm{GeV}$ desired $\Rightarrow m_R \sim 10^{18}\mathrm{eV}$

A huge scale whose phys is inaccessible at colliders!

- TeV seesaw

Desired both $\frac{m_D^2}{m_R} \sim$ eV and $m_R \sim \mathrm{TeV}$

by fine-tuning or other mechanisms.

Lepton Flavor Violation (LFV)

- μ decay modes

$\mathrm{BR}(\mu \to e\gamma) < 1.2 \times 10^{-11}$ MEGA Colla., 1999

hopefully to $10^{-13} \sim 10^{-14}$ in near future MEG Colla.

$\mathrm{BR}(\mu \to ee\bar{e}) < 1.0 \times 10^{-12}$ SINDRUM Colla., 1988

- τ decay modes

Impressive bounds on LFV τ decays start to appear at Belle and BaBar, but not comparable to μ decays in foreseeable future.

Outline

Motivation

- Rich phenomenology accessible if $m_R \sim \Lambda_{\rm EW}$
- Associate m_R with SM non-singlets' vev, and m_D with SM singlet vev
- RH neutrinos also active $\Rightarrow$ Rich lepton flavor structure

Fields

- Same gauge group as in SM. Matter fields extended by mirror fermions:

$$\text{ordinary}: F_L = \begin{pmatrix} n_L \\ f_L \end{pmatrix} (\mathbf{2}, Y=-1),\ \ f_R\ (\mathbf{1}, -2);$$

$$\text{mirror}: F_R^M = \begin{pmatrix} n_R^M \\ f_R^M \end{pmatrix} (\mathbf{2}, -1),\ \ f_L^M\ (\mathbf{1}, -2)$$

- Besides SM scalar doublet Φ, new scalars are

$$\phi\ (\mathbf{1}, 0),\ \chi\ (\mathbf{3}, 2),$$

plus ξ $(\mathbf{3}, 0)$ for preserving custodial sym. Chanowitz-Golden, 1985

- VEV's

$$\langle\Phi\rangle = \frac{v_2}{\sqrt{2}}\begin{pmatrix} 0 \\ 1 \end{pmatrix},\ \langle\phi\rangle = v_1,\ \langle\chi\rangle = v_3\begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix},$$

$v_{2,3} \sim \Lambda_{\mathrm{EW}};\ \ v_1$ required to be tiny

- Yukawa couplings

$$\begin{aligned} -\mathscr{L}_\Phi &= y\overline{F_L}\Phi f_R + y_M\overline{F_R^M}\Phi f_L^M + \mathrm{h.c.}, \\ -\mathscr{L}_\phi &= x_F\overline{F_L}F_R^M\phi + x_f\overline{f_R}f_L^M\phi + \mathrm{h.c.}, \\ -\mathscr{L}_\chi &= \frac{1}{2}z_M\overline{(F_R^M)^C}(i\tau^2)\chi F_R^M + \mathrm{h.c.} \end{aligned}$$

Lepton Masses

- Charged lepton masses

$$-\mathscr{L}_{\rm m}^{f} = \left(\overline{f_L}, \overline{f_L^M}\right) m_f \begin{pmatrix} f_R \\ f_R^M \end{pmatrix} + \text{h.c.},$$

$$m_f = \begin{pmatrix} \frac{v_2}{\sqrt{2}} y & v_1 x_F \\ v_1 x_f^\dagger & \frac{v_2}{\sqrt{2}} y_M^\dagger \end{pmatrix}, \quad X_L^\dagger m_f X_R = \text{diag}(m_\alpha)$$

- Neutrino masses

$$-\mathscr{L}_{\rm m}^{n} = \frac{1}{2} \left(\overline{n_L}, \overline{(n_R^M)^C}\right) m_n \begin{pmatrix} n_L^C \\ n_R^M \end{pmatrix} + \text{h.c.},$$

$$m_n = \begin{pmatrix} 0 & v_1 x_F \\ v_1 x_F^T & v_3 z_M \end{pmatrix}, \quad Y^T m_n Y = \text{diag}(m_i)$$

Mixing in leptonic gauge interactions

$$\mathscr{L}_g = g_2\left(j_W^{+\mu}W_\mu^+ + j_W^{-\mu}W_\mu^- + J_Z^\mu Z_\mu\right) + eJ_{\rm em}^\mu A_\mu,$$

$$\sqrt{2}j_W^{+\mu} = \bar{\nu}\gamma^\mu\left(V_L P_L + V_R P_R\right)\ell,$$

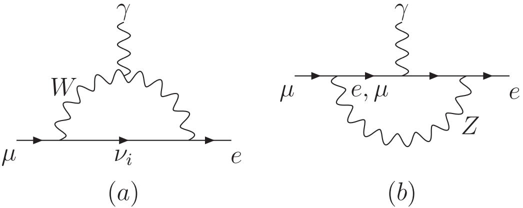
$$c_W J_Z^\mu = \frac{1}{2}\bar{\nu}\gamma^\mu\left(V_L V_L^\dagger P_L + V_R V_R^\dagger P_R\right)\nu - \frac{1}{2}\bar{\ell}\gamma^\mu\left(V_L^\dagger V_L P_L + V_R^\dagger V_R P_R\right)\ell + s_W^2\bar{\ell}\gamma^\mu\ell,$$

$$J_{\rm em}^\mu = -\bar{\ell}\gamma^\mu\ell$$

Nonunitarity of V_L (V_R) induces FCNC in both neutral and charged sectors. This causes interesting phenomena in $\mu \to e\gamma$.

Outline

$\mu \to e\gamma$



$$\mathscr{A}_W = \frac{e}{(4\pi)^2}\sqrt{2}G_F q^\beta \varepsilon^{\alpha *} \times \bar{u}_e i\sigma_{\alpha\beta}\left[m_\mu(V_1P_R+V_2P_L)\mathscr{F}(r_i)+m_i(V_3P_L+V_4P_R)\mathscr{G}(r_i)\right]u_\mu,$$

$$\mathscr{A}_Z = \frac{e}{(4\pi)^2}\sqrt{2}G_F q^\beta \varepsilon^{\alpha *} \times \bar{u}_e i\sigma_{\alpha\beta} m_\mu \frac{2}{3}\left[-2(1+s_W^2)V_1P_R+(3-2s_W^2)V_2P_L\right]u_\mu$$

- $r_i = m_i^2 / m_W^2$
- Matrices appear in the forms:

$$V_1 = (V_L^\dagger)_{ei}(V_L)_{i\mu}, \qquad V_2 = (V_R^\dagger)_{ei}(V_R)_{i\mu},$$
$$V_3 = (V_R^\dagger)_{ei}(V_L)_{i\mu}, \qquad V_4 = (V_L^\dagger)_{ei}(V_R)_{i\mu}.$$

- Loop functions:

$$\mathscr{F}(r) = \frac{1}{6(1-r)^4}\left(10 - 43r + 78r^2 - 49r^3 + 4r^4 + 18r^3 \ln r\right),$$
$$\mathscr{G}(r) = \frac{1}{(1-r)^3}\left(-4 + 15r - 12r^2 + r^3 + 6r^2 \ln r\right).$$

- Summation over neutrino index i understood in both amplitudes.

Parameters

- Too many free parameters - further approximations required

  1. Light neutrinos treated safely as massless.
  2. Heavy neutrinos considered almost degenerate, m_h.

- Free parameters: m_h and 6 complex combinations:

$$V_1^l = \sum_{i=1}^{3} (V_L^\dagger)_{ei} (V_L)_{i\mu}, \qquad V_2^l = \sum_{i=1}^{3} (V_R^\dagger)_{ei} (V_R)_{i\mu},$$

$$V_1^h = \sum_{i=4}^{6} (V_L^\dagger)_{ei} (V_L)_{i\mu}, \qquad V_2^h = \sum_{i=4}^{6} (V_R^\dagger)_{ei} (V_R)_{i\mu},$$

$$V_3^h = \sum_{i=4}^{6} (V_R^\dagger)_{ei} (V_L)_{i\mu}, \qquad V_4^h = \sum_{i=4}^{6} (V_L^\dagger)_{ei} (V_R)_{i\mu}$$

Final result

- $(r_h = m_h^2/m_W^2)$

$$
\begin{aligned}
\mathrm{BR}(\mu \to e\gamma) &= \frac{3\alpha}{8\pi}\left(|h_L|^2 + |h_R|^2\right), \\
h_L &= \frac{5}{3}V_2^l + V_2^h \mathscr{F}(r_h) + \frac{m_W}{m_\mu} V_3^h \sqrt{r_h}\,\mathscr{G}(r_h) + \frac{2}{3}(3 - 2s_W^2)(V_2^l + V_2^h), \\
h_R &= \frac{5}{3}V_1^l + V_1^h \mathscr{F}(r_h) + \frac{m_W}{m_\mu} V_4^h \sqrt{r_h}\,\mathscr{G}(r_h) - \frac{4}{3}(1 + s_W^2)(V_1^l + V_1^h).
\end{aligned}
$$

$\mu \longrightarrow ee\bar{e}$

- Via tree level FCNC. 2 diagrams.

$$
\begin{aligned}
\mathrm{BR}(\mu \to ee\bar{e}) &= \frac{1}{2}|V_1^l + V_1^h|^2 \left[(1-2s_W^2)^2 + 2s_W^4\right] \\
&+ \frac{1}{4}|V_2^l + V_2^h|^2 \left[(1-2s_W^2)^2 + 8s_W^4\right].
\end{aligned}
$$

Outline

Generally Estimation

- For all 6 $V_j^{l,h}$ of similar magnitude and $m_h \sim m_W$

$$\frac{\mathrm{BR}(\mu \to e\gamma)}{\mathrm{BR}(\mu \to ee\bar{e})} \sim \frac{\alpha}{\pi} \sim 2 \times 10^{-3}$$

- Better quantitative feel can only be obtained after further simplifications.
- To demonstrate relevance of our results, we consider some scenarios by sampling randomly $V_j^{l,h}$ in certain ranges.

Scenario A

- $Y = \begin{pmatrix} y_{ul} & y_{ur} \\ y_{dl} & y_{dr} \end{pmatrix} \quad y_{..}:\ 3\times 3$
- Suppose y_{ur} is real.

  $\Rightarrow y_{ur} = y_{dl} = 0_3,\ y_{dr} = 1_3,\ y_{ul}^\dagger = y_{ul}^{-1}$ so that all but $V_1^l,\ V_2^h$ vanish.
- Re and Im parts of $V_1^l,\ V_2^h$ are sampled between -2×10^{-6} and $+2\times 10^{-6}$. $m_h = 50,\ 100,\ 200, \ldots,\ 10^3$ GeV.

  $\Rightarrow$ For $\mathrm{BR}(\mu \to ee\bar{e}) < 10^{-12}$, we have $\mathrm{BR}(\mu \to e\gamma) \sim 10^{-14}$
  - at the edge of MEG precision.

Scenario B

- $V_3^h = V_4^h = 0$ while Re and Im parts of $V_{1,2}^l$, $V_{1,2}^h$ run within $[-1,1] \times 10^{-6}$. m_h as in Scenario A.

  $\Rightarrow$ Slightly larger $\mathrm{BR}(\mu \to e\gamma)$.

Scenario C

- Only contribution of light neutrinos important:

  Re and Im parts of $V^l_{1,2}$ within $[-1.5, 1.5] \times 10^{-6}$ while $V^h_{1,2,3,4} = 0$. $\Rightarrow$ Most points drop in the region with $\mathrm{BR}(\mu \to e\gamma) \lesssim \mathrm{a\ few}\ \times 10^{-14}$ for $\mathrm{BR}(\mu \to ee\bar{e}) < 10^{-12}$.

- But better analysis is possible:

$$\mathrm{BR}(\mu \to e\gamma) \approx 10^{-4} \left[0.0064 |V^l_1|^2 + 102 |V^l_2|^2 \right],$$

destructive interf between W&Z graphs

$$\mathrm{BR}(\mu \to ee\bar{e}) \approx 0.20 |V^l_1|^2 + 0.18 |V^l_2|^2.$$

- If no Z graph, 0.0064 $\to$ 25: $\mu \to e\gamma$ sets stringent bound on $|V_1^l|^2$ - unitarity violation in light sector Antusch et al, 2006
- When FCNC appears in charged sector, no useful bound on $|V_1^l|^2$ retains.
  But a stringent one comes from $\mu \to ee\bar{e}$: $|V_1^l|^2 < 5 \times 10^{-12}$
- The largest numbers for both that one can expect are

$$\mathrm{BR}(\mu \to e\gamma) \lesssim 5.7 \times 10^{-13}, \quad \mathrm{BR}(\mu \to ee\bar{e}) \lesssim 10^{-12}$$

In particular, not possible for both to reach $\sim 10^{-12}$.

Scenario D

- How important is the mixed effect between LH and RH CC currents involving light charged leptons and heavy neutrinos?

  Difficult to get an exact handle of $V_j^{h,l}$ since heavy charged lepton masses set in via $X_{L,R}$.

- $V_1^{l,h}$, $V_2^{l,h}$ within $[-1,1]\times 10^{-6}$; $V_{3,4}^{h}$ within $[-1,1]\times 10^{-9}$. $m_h = 50,\ 100,\ 150,\cdots,\ 500$ GeV.

  $\Rightarrow \mathrm{BR}(\mu \to e\gamma)$ can reach 10^{-13} without breaking $\mathrm{BR}(\mu \to ee\bar{e})$.

Figures

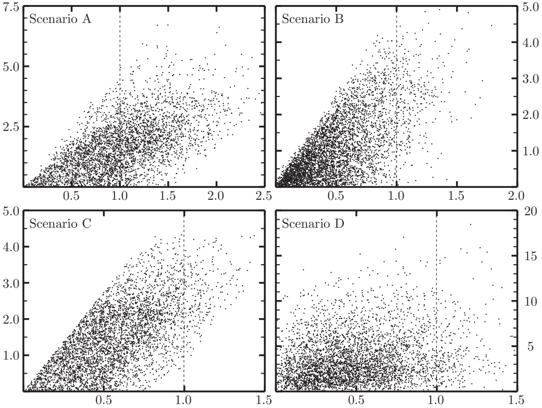


Figure: Sampled points for $\mathrm{BR}(\mu \to ee\bar{e})$ (horizontal, in units of 10^{-12}) and $\mathrm{BR}(\mu \to e\gamma)$ (vertical, in units of 10^{-14}) for the four scenarios described in the text. The dashed vertical line shows the current upper bound on $\mathrm{BR}(\mu \to ee\bar{e})$.

Outline

Summary

- Observation of LFV charged lepton decays

  $\Rightarrow$ non-trivial new phys associated with origin of neutrino mass

- In a model of heavy neutrinos at $\Lambda_{\rm EW}$, $\mu \to e\gamma$ can reach or be within MEG precision without breaking $\mathrm{BR}(\mu \to ee\bar{e})$.

  But it is generally impossible to reach $\sim 10^{-12}$ for both.

- In a special scenario where light neutrinos are only important, $\mu \to e\gamma$ cannot set a useful bound on unitarity violation in the light lepton sector, but $\mu \to ee\bar{e}$ can.

  The best one can expect is:

  $\mathrm{BR}(\mu \to e\gamma) \lesssim 5.7 \times 10^{-13}, \quad \mathrm{BR}(\mu \to ee\bar{e}) \lesssim 10^{-12}$

The End

谢谢!