Radiative seesaw in minimal 3-3-1 model

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The Standard Model is the best theory of describing the nature of particle physics, which is in excellent agreement with almost of all current experiments.

Problems

- neutrino mass hierarchy
- 3 generations
- Dark matter
- …

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neutrino mass hierarchy
3 generations
Dark matter
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Neutrino mass hierarchy

→ radiative seesaw mechanism

3 generations

→ 3-3-1 model

Neutrino mass hierarchy

→ radiative seesaw mechanism

3 generations

→ 3-3-1 model

→ Radiative seesaw in 3-3-1 model

Neutrino hierarchy

Quark sector

$$m_u = 2.3 \times 10^{-3}\ GeV,\ m_c = 1.3\ GeV,\ m_t = 173\ GeV$$
$$m_d = 4.8 \times 10^{-3}\ GeV,\ m_s = 9.5 \times 10^{-2}\ GeV,\ m_b = 4.2\ GeV$$

Lepton sector

$$m_e = 5.1 \times 10^{-4}\ GeV,\ m_\mu = 0.11\ GeV,\ m_\tau = 1.8\ GeV$$

$$m_\nu \sim 10^{-11}\ GeV$$

Neutrino masses are very light

Seesaw mechanism

Dimension 5 Operator

$$\frac{f}{\Lambda} h h \nu_L \nu_L$$

$$m_\nu \sim \mathcal{O}(0.1) eV \Rightarrow \frac{f}{\Lambda} \sim \mathcal{O}(10^{-14}) GeV^{-1}$$

$$f \sim \mathcal{O}(1) \qquad \Lambda \sim \mathcal{O}(10^{14}) \mathbf{GeV}$$

Radiative seesaw mechanism

$$m_\nu = \frac{1}{(16\pi^2)^n} \frac{f v^2}{\sqrt{2}\Lambda}$$

Neutrino masses are suppressed by loop factor

$$\begin{aligned}\frac{f}{\Lambda} &\sim (16\pi^2)^n \times \mathcal{O}(10^{-14}) GeV^{-1} \\ &\sim \mathcal{O}(10^{2n-14}) GeV^{-1}\end{aligned}$$

Particle contents

	Lepton Fields	Scalar Fields			
	$L_L = (\nu_L, e_L, e_R^c)$	S	η	ρ	χ
$SU(3)_L$	3	6	3	3	3
$U(1)_X$	0	0	0	1	-1

$$\mathcal{L}_Y = y_{\ell_1} \sum_{i,j,k=1-3} \bar{L}_{Li}(L_L)^c_j \eta^*_k \epsilon^{ijk} + y_{\ell_2} \mathrm{Tr}[\bar{L}_L S (L_L)^c] + \text{h.c.}$$

Anomaly

$$Q = diag(0, -1, 1) + X$$

$$L_L^a = \begin{bmatrix} \nu_L^a \\ e_L^a \\ e_R^{c\ a} \end{bmatrix} \sim (1, 3, 0)$$

$$Q_L^i = \begin{bmatrix} u_L^i \\ d_L^i \\ J_L^i \end{bmatrix} \sim (3, 3, 2/3)$$

$$u_R^i \sim (3, 1, 2/3) \quad J_R^i \sim (3, 1, 5/3)$$

$$d_R^i \sim (3, 1, -1/3)$$

$$Q_L^j = \begin{bmatrix} d_L^j \\ u_L^j \\ J_L^j \end{bmatrix} \sim (3, 3^*, -1/3)$$

$$u_R^j \sim (3, 1, 2/3) \quad J_R^j \sim (3, 1, -4/3)$$

$$d_R^j \sim (3, 1, -1/3)$$

$$a = 1, 2, 3$$

$$i = 1, \ j = 2, 3$$

→ All gauge anomalies cancel

Why sextet?

$$\sum_{i,j,k=1-3} y^{ij}_{\ell_1} \bar{L}_{Li} (L_L)^c_j \eta^*_k \epsilon^{ijk}$$

Mass eigenvalues are 0, -M, M

Why sextet?

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$$\bar{L}_{Li}(L_L)^c_j \sim (1, 3+6^*, 0)$$

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$$\Rightarrow \quad y_{\ell_2} \mathrm{Tr}[\bar{L}_L S (L_L)^c]$$

Why sextet?

$$\sum_{i,j,k=1-3} y_{\ell_1}^{ij} \bar{L}_{Li}(L_L)^c_j \eta^*_k \epsilon^{ijk}$$

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Vacuum Expectation Values

$$\langle S \rangle = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{v_S}{\sqrt{2}} \\ 0 & \frac{v_S}{\sqrt{2}} & 0 \end{bmatrix}, \quad \langle \eta \rangle = \begin{bmatrix} \frac{v_\eta}{\sqrt{2}} \\ 0 \\ 0 \end{bmatrix}, \quad \langle \rho \rangle = \begin{bmatrix} 0 \\ \frac{v_\rho}{\sqrt{2}} \\ 0 \end{bmatrix}, \quad \langle \chi \rangle = \begin{bmatrix} 0 \\ 0 \\ \frac{v_\chi}{\sqrt{2}} \end{bmatrix},$$

$$v_\chi >> v = \sqrt{v_S^2 + v_\eta^2 + v_\rho^2}$$

Symmetry breakings

$$SU(3)_c \times SU(3)_L \times U(1)_X$$

$$\Downarrow \quad \langle \chi \rangle$$

$$SU(3)_c \times SU(2)_L \times U(1)_Y \;+\; W'^{\pm},\ Z',\ U^{\pm\pm}$$

$$\Downarrow \quad \langle \rho \rangle,\ \langle \eta \rangle,\ \langle S \rangle$$

$$SU(3)_c \times U(1)_{em} \;+\; W'^{\pm},\ Z',\ U^{\pm\pm}$$

$$+\; W^{\pm},\ Z$$

Bounds

ϱ parameter Pisano, Pleitez 1992

$$\frac{M_Z^2}{M_W^2} = \frac{1+4t^2}{1+3t^2} \qquad t = \frac{g_X}{g_{SU(3)_L}}$$

$$t^2 = \frac{s_W^2}{1-4s_W^2} \quad \Rightarrow \quad \rho = 1$$

Bounds

$M_{W'} > 230 GeV$ $\mu \to e \nu_e \bar{\nu}_\mu$ Ng 1994

$M_{Z'} > 2.2 TeV$

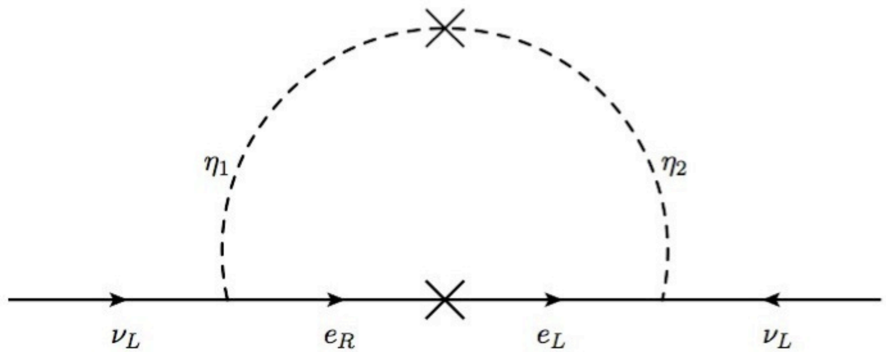
$v_\chi > 3.6 TeV$

LHC

Coutinho, Guimares, Nepomuceno 2013

Neutrino oscillation
LFV(μ->eγ,…)
Muon g-2

Neutrino oscillation

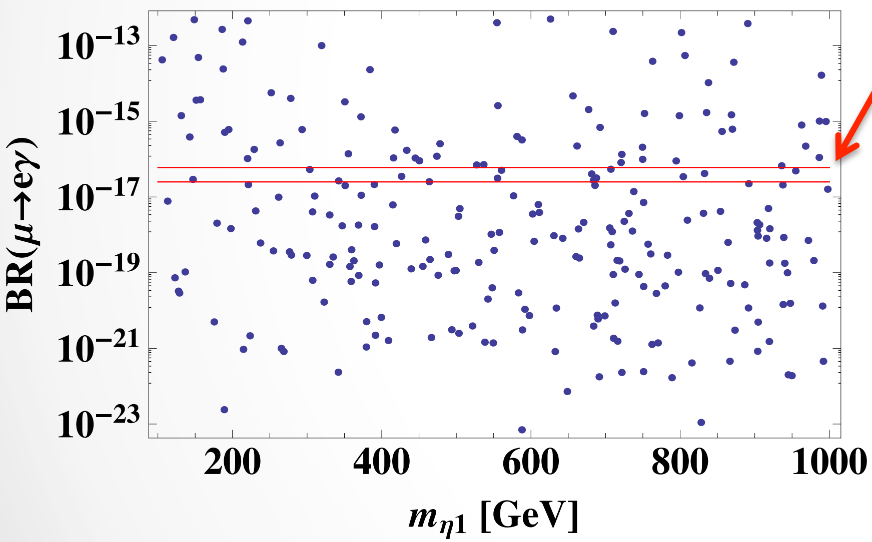


$$-(\mathcal{M}_\nu^{\rm th})_{ab} \approx \frac{\left[y_{\ell_1}\left(m_\ell^\dagger + m_\ell^*\right)y_{\ell_1}^T\right]_{ab}}{(4\pi)^2}\left[\frac{\delta m^{+2}_{\eta_1\eta_2}}{m^2_{\eta_1^+} - m^2_{\eta_2^+}}\right]\ln\left[\frac{m^2_{\eta_1^+}}{m^2_{\eta_2^+}}\right] - \frac{\left[y_{\ell_2}\left(m_\ell^\dagger + m_\ell^*\right)y_{\ell_2}^T\right]_{ab}}{(4\pi)^2}\left[\frac{\delta m^{+2}_{h_1\eta_2}}{m^2_{h_1^+} - m^2_{h_2^+}}\right]\ln\left[\frac{m^2_{h_1^+}}{m^2_{h_2^+}}\right]$$

$$- \frac{\left(y_{\ell_1} m_\ell^* y_{\ell_2}^T + y_{\ell_2} m_\ell^\dagger y_{\ell_1}^T\right)_{ab}}{2(4\pi)^2}\left[\frac{\delta m^{+2}_{\eta_2 h_1}}{m^2_{\eta_2^+} - m^2_{h_1^+}}\right]\ln\left[\frac{m^2_{\eta_2^+}}{m^2_{h_1^+}}\right] - \frac{\left(y_{\ell_2} m_\ell^* y_{\ell_1}^T + y_{\ell_1} m_\ell^\dagger y_{\ell_2}^T\right)_{ab}}{2(4\pi)^2}\left[\frac{\delta m^{+2}_{\eta_1 h_2}}{m^2_{\eta_1^+} - m^2_{h_2^+}}\right]\ln\left[\frac{m^2_{\eta_1^+}}{m^2_{h_2^+}}\right].$$

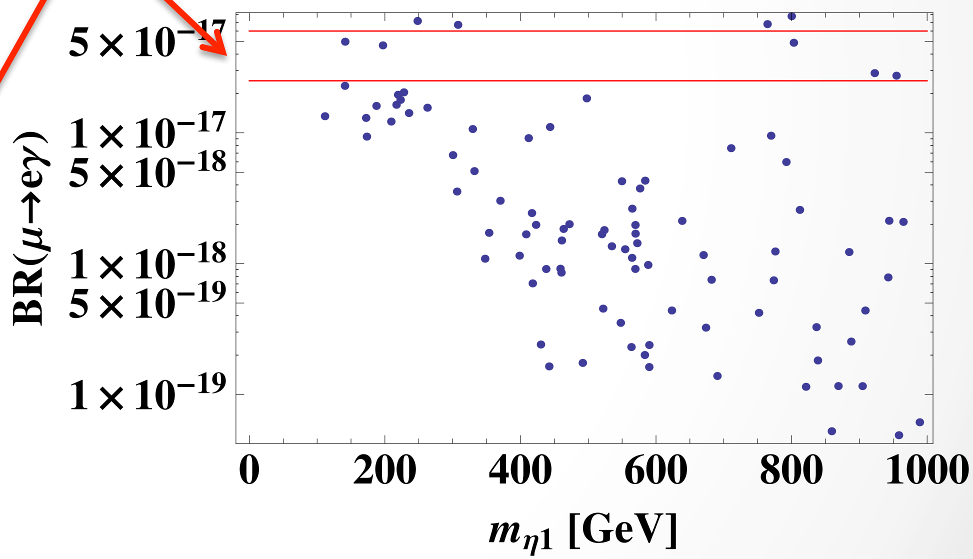
μ -> eγ

NH



Mu2e

IH



Radiative seesaw in 3-3-1 model

neutrino mass hierarchy
3 generations

Buckup

3-3-1 model

gauge group

$$SU(3)_c \times SU(3)_L \times U(1)_X$$

$$\Rightarrow \quad SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\Rightarrow \quad SU(3)_c \times U(1)_{em}$$

$$Q = T_3 - \sqrt{3}T_8 + X$$

$$T_3 = \frac{1}{2}diag(1,-1,0) \qquad T_8 = \frac{1}{2\sqrt{3}}diag(1,1,-2)$$

Parameter regions

NH

$$1\ \text{GeV} \le (v_\eta, v_\sigma) \le 100\ \text{GeV},\ 0.1\ \text{GeV}^2 \le (\delta m^{+2}_{\eta_1 h_1}, \delta m^{+2}_{\eta_2 h_1}) \le 10\ \text{GeV}^2,$$
$$100\ \text{GeV} \le m_{\eta^+_{1,2}} \le 1000\ \text{GeV}, \quad -1 \le (s_{eL(R)ij}, c_{eL(R)ij}) \le 1,$$

IH

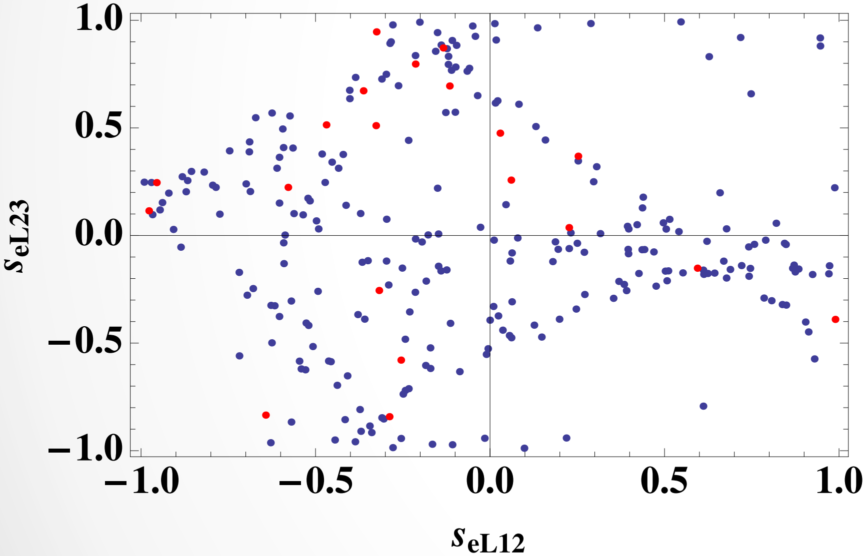
$$33\ \text{GeV} \le v_\eta \le 37\ \text{GeV},\ 44\ \text{GeV} \le v_\sigma \le 48\ \text{GeV},\ 0.1\ \text{GeV}^2 \le (\delta m^{+2}_{\eta_1 h_1}, \delta m^{+2}_{\eta_2 h_1}) \le 1\ \text{GeV}^2,$$
$$100\ \text{GeV} \le m_{\eta^+_{1,2}} \le 1000\ \text{GeV}, \quad -1 \le s_{eL12} \le 0,\ 0 \le s_{eL23} \le 0.5,\ -1 \le s_{eL13} \le -0.7,$$
$$-0.4 \le s_{eR12} \le -0.1,\ 0 \le s_{eR23} \le 0.2,\ 0.4 \le s_{eR13} \le 0.7,$$

Our parameter

$$(\bar{e}_L)_a(m_\ell)_{ab}(e_R)_b \equiv (\bar{e}_L)_a\left[\frac{(y_{\ell_1})v_\eta}{\sqrt{2}}+\frac{(y_{\ell_2})v_\sigma}{\sqrt{2}}\right]_{ab}(e_R)_b = (\bar{e}_L)_a(V^\dagger_{eL})_{ai}(m^{diag}_\ell)_i(V_{eR})_{ib}(e_R)_b$$

$$V_{eL(R)} \equiv \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{eL(R)23} & s_{eL(R)23} \\ 0 & -s_{eL(R)23} & c_{eL(R)23} \end{bmatrix}\begin{bmatrix} c_{eL(R)13} & 0 & s_{eL(R)13} \\ 0 & 1 & 0 \\ -s_{eL(R)13} & 0 & c^{eL(R)}_{13} \end{bmatrix}\begin{bmatrix} c_{eL(R)12} & s_{eL(R)12} & 0 \\ -s_{eL(R)12} & c_{eL(R)12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

NH



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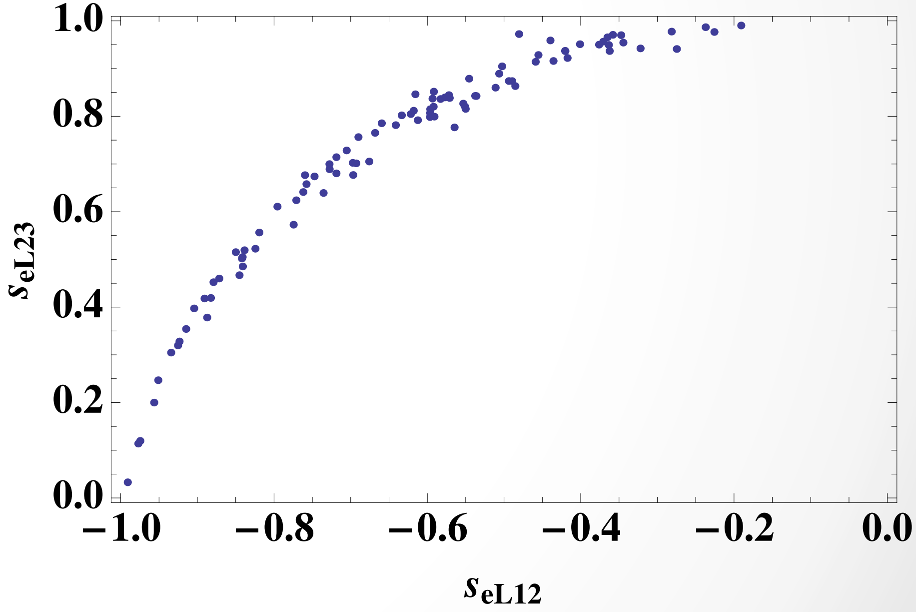
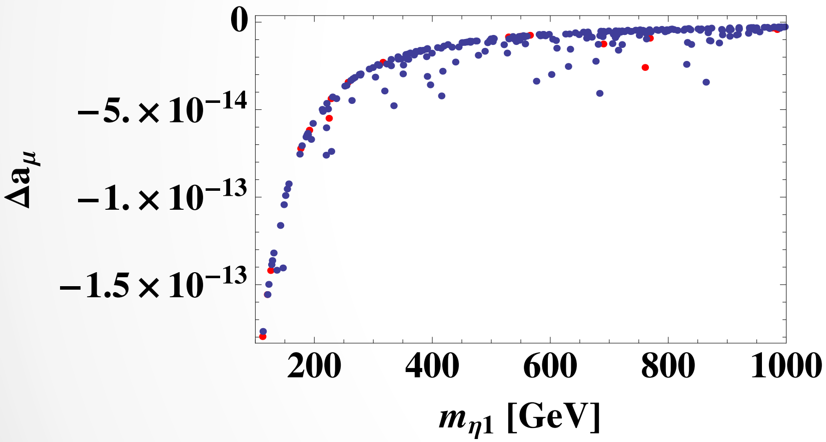


The red points do not satisfy the LFV constraints

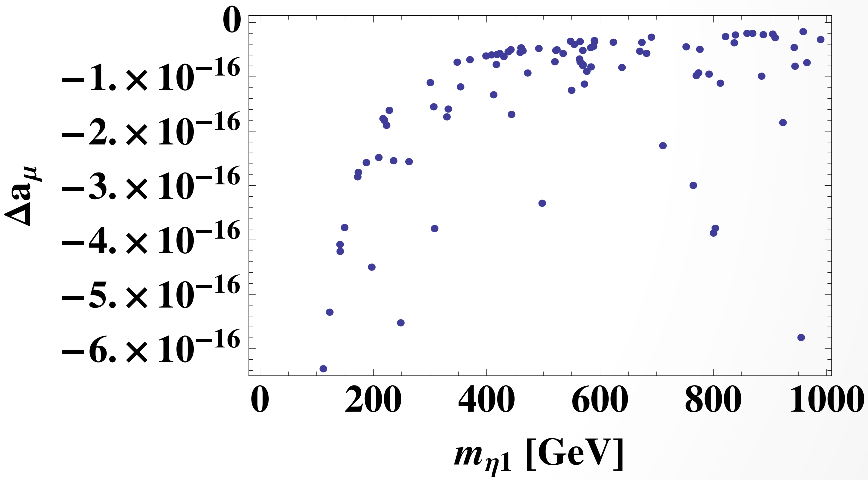
Muon g-2

NH



0
$-5.\times10^{-14}$
$-1.\times10^{-13}$
-1.5×10^{-13}
Δa_μ
200
400
600
800
1000
$m_{\eta1}$ [GeV]

IH



0
$-1.\times10^{-16}$
$-2.\times10^{-16}$
$-3.\times10^{-16}$
$-4.\times10^{-16}$
$-5.\times10^{-16}$
$-6.\times10^{-16}$
Δa_μ
0
200
400
600
800
1000
$m_{\eta1}$ [GeV]