Non-standard interactions in radiative seesaw mechanism of neutrino mass

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Neutrino masses

Neutrino masses

- In the standard model, neutrinos are massless.

Origin of the small neutrino masses

- 1. Add right handed Dirac neutrino ($\Rightarrow Y_\nu \overline{\ell_L} \phi \nu_R$)
- 2. Seesaw mechanism ($\Rightarrow$ Majorana neutrino)

$$m_\nu \sim \frac{m^2}{M_R}$$

- 3. Radiative mass generation ($\Rightarrow$ Extension of scalar sector)

$$m_\nu \sim \frac{\lambda}{(4\pi^2)^n} \frac{m_\ell^2}{M_S}$$

Radiative neutrino mass model

Radiative neutrino mass model

- Coupling constant $\sim \mathcal{O}(1)$
- Muon g-2
  $\Rightarrow$ Can be large value (for such a large coupling constant)
- NSI(non-standard interaction) effects
  $\Rightarrow$ Can be large value (for inverted hierarchy)

[Ohlsson et al, Phys.Lett,B115(1982)]

Neutrino mass is generated via three loop diagram

$\Rightarrow$ [Krauss et al, Phys.Rev,D67(2003)]

- We search the inverted hierarchy masses in this model.
- We estimate the NSI effects and muon g-2 expreriment.

KNT model

Standard model with one $SU(2)_L$ doublet scalar

$$\Phi : (\mathbf{1}, \mathbf{2}, \frac{1}{2}),$$

New added particles

Two $SU(2)_L$ singlet scalar fields

$$S_1^+ : (\mathbf{1}, \mathbf{1}, 1), \quad S_2^+ : (\mathbf{1}, \mathbf{1}, 1).$$

Three right handed neutrinos [Ahriche and Nasri, JCAP, 1307(2013)]

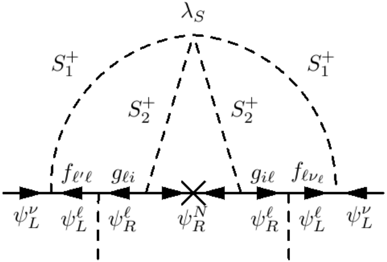
$$\psi_R^{N_1} : (\mathbf{1}, \mathbf{1}, 0), \quad \psi_R^{N_2} : (\mathbf{1}, \mathbf{1}, 0), \quad \psi_R^{N_3} : (\mathbf{1}, \mathbf{1}, 0).$$

Impose Z_2 discrete symmetry

$$Z_2 : \{S_2, \psi_R^N\} \to \{-S_2, -\psi_R^N\},$$

neutrino mass

Neutrino mass [Cheung and Seto, Phys.Rev,D69(2004)]



Yukawa coupling

$$\begin{cases} f_{\ell\ell'} & \text{anti symmetric} \\ g_{i\ell'} & (i = 1, 2, 3) \end{cases}$$

$$(m_\nu)_{\alpha\beta} = \frac{4\lambda_s}{(4\pi^2)^3 m_{S_2}} f_{\alpha\rho} m_{\ell_\rho} g_{\rho j} F_j g_{j\sigma} m_{\ell_\sigma} f_{\sigma\beta} \quad (F_j : \text{loop function})$$

Yukawa coupling constants f

In this model, antisymmetric coupling constants $f_{\ell\ell'}$ for the inverted neutrino mass hierarchy have the following relations [Babu and Macesanu, Phys.Rev,D67(2003)]
$(m_{\nu_3} = 0 \ll m_{\nu_1} < m_{\nu_2})$

$$\alpha = \frac{f_{e\tau}}{f_{\mu\tau}} = -\frac{s_{23}c_{13}}{s_{13}} e^{-i\delta}, \quad \beta = \frac{f_{e\mu}}{f_{\mu\tau}} = -\frac{c_{13}c_{23}}{s_{13}} e^{-i\delta},$$

This coupling constants have one free parameter using the value of neutrino oscilation experiments [Fogli, Phys.Rev,D86(2012)]

$$\begin{aligned}
\Delta m^2_{\rm sun} &= \Delta m^2_{21} = 7.54^{+0.64}_{-0.55} \times 10^{-5}\mathrm{eV}^2 \\
\Delta m^2_{\rm atm} &= \Delta m^2_{31} = +2.42^{+0.19}_{-0.25} \times 10^{-3}\mathrm{eV}^2 \\
\sin^2\theta_{12} &= 0.307^{+0.052}_{-0.048} \\
\sin^2\theta_{23} &= 0.392^{+0.271}_{-0.057} \\
\sin^2\theta_{13} &= 0.0244^{+0.0071}_{-0.0073}
\end{aligned}$$

In the following we assume that $\delta = 0$

Neutrino masss

1. To realize the inverted neutrino mass hierarchy, we assume some conditions

$$f_{a\rho} m_{\ell_\rho} g_{\rho j} F_j g_{j\sigma} m_{\ell_\sigma} f_{\sigma b} = f_{\mu\tau}^2 \begin{pmatrix} 0 & \alpha G_2 & \beta G_3 \\ -\alpha G_1 & 0 & G_3 \\ -\beta G_1 & -G_2 & 0 \end{pmatrix} \begin{pmatrix} 0 & -\alpha G_1 & -\beta G_1 \\ \alpha G_2 & 0 & -G_2 \\ \beta G_3 & G_3 & 0 \end{pmatrix}$$

2. We also assume that

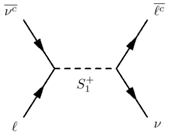
$$G_1^2 = G_2^2 = G_3^2 = G^2 \leq \mathcal{O}(0.01)\ \text{GeV}^2$$

3. The degenerate masses are

$$m_{\nu_1} = m_{\nu_2} = \frac{4}{(4\pi^2)^3} \frac{f_{\mu\tau}^2}{\sin^2\theta_{13}} \frac{\lambda_S G^2}{m_{S_1}}$$

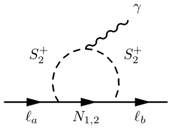
Lepton Flavor Violation

Lepton interactions with the exchange of singlet scalars S_1 and S_2



- $\ell_\alpha \to \ell_b \overline{\nu}\nu$ (Lepton universality)

$$\begin{aligned} |f_{e\mu}|^2 &< 0.015(m_{S_1}/\mathrm{TeV})^2 \\ \left||f_{\mu\tau}|^2 - |f_{e\tau}|^2\right| &< 0.05(m_{S_1}/\mathrm{TeV})^2 \\ \left||f_{e\tau}|^2 - |f_{e\mu}|^2\right| &< 0.06(m_{S_1}/\mathrm{TeV})^2 \\ \left||f_{\mu\tau}|^2 - |f_{e\mu}|^2\right| &< 0.06(m_{S_1}/\mathrm{TeV})^2 \end{aligned}$$

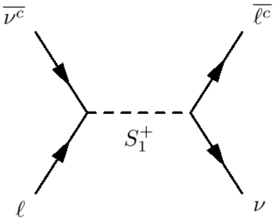


- $\ell_\alpha^- \to \ell_\beta^- \gamma$ (Rare lepton decays: one-loop)

$$\begin{aligned} & B(\mu \to e\gamma) \\ &= \frac{\alpha v^4}{384\pi}\left(\frac{|f_{\mu\tau}f_{e\tau}|^2}{m_{S_1}^4} + \frac{36}{m_{S_2}^4}\left|\sum_{i=1}^{3} g_{i\mu}g_{ie}F_2\left(\frac{m_{N_i}^2}{m_{S_2}^2}\right)\right|^2\right) \\ &< \quad 5.7\times 10^{-13} \quad [Adametal, MEGcollaboration(2013 \end{aligned}$$

Non-Standard Interaction(NSI)

Lepton interaction with the exchange of singlet scalar S_1^+



Since the effective Lagrangian is expressed as

$$\mathcal{L}_{NSI} = 4\frac{G_F}{\sqrt{2}}\epsilon_{\alpha\beta}^{\rho\sigma}(\overline{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\overline{\ell}_\rho\gamma^\mu P_{L,R}\ell_\sigma)$$

NSI parameters are defined by

$$\epsilon_{\alpha\beta}^{\rho\sigma} = \frac{f_{\sigma\beta}f_{\rho\alpha}^*}{\sqrt{2}G_F m_{S_1}^2} \cong 0.06 f_{\alpha\beta}f_{\rho\sigma}^*\left(\frac{m_{S_1}}{\mathrm{TeV}}\right)^{-2}$$

NSI parameters

1. The relevant NSI parameter in matter($e, u, d \Rightarrow \rho = \sigma = e$)

$$\epsilon^{m}_{\alpha\beta} = \epsilon^{ee}_{\alpha\beta} = \frac{f_{e\beta} f^{*}_{e\alpha}}{\sqrt{2} G_F m^2_{S_1}} \quad \Rightarrow \quad \epsilon^{m}_{\mu\tau}, \epsilon^{m}_{\mu\mu}, \epsilon^{m}_{\tau\tau}.$$

   where $\alpha, \beta \neq e$ from the antisymmetric property of f

2. The relevant NSI parameter for source ($\mu \to e\overline{\nu}_\beta \nu_\alpha \Rightarrow \sigma = \mu, \rho = e$)

$$\epsilon^{s}_{\alpha\beta} = \epsilon^{e\mu}_{\alpha\beta} = \frac{f_{\mu\beta} f^{*}_{e\alpha}}{\sqrt{2} G_F m^2_{S_1}} \quad \Rightarrow \quad \epsilon^{s}_{\mu\tau}, \epsilon^{s}_{\tau e}.$$

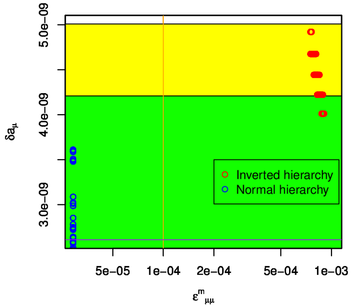
   for the main channels $\epsilon^{s}_{\mu\tau}(\nu_\mu \to \nu_\tau)ch, \epsilon^{s}_{e\tau}(\nu_e \to \nu_\tau)ch.$

3. We obtain a relation

$$\epsilon^{m}_{\mu\tau} = -\epsilon^{s*}_{\tau e}$$

NSI and muon g-2

Non standard interaction and muon g-2



Muon g-2 $(0.21 \times 10^{-9} < \delta a_\mu < 5.01 \times 10^{-9})$ [Hagiwara et al, J.Phys.G 38 (2011)]

$$\delta a_\mu = \frac{m_\mu^2}{16\pi^2}\left(\frac{|f_{e\mu}|^2 + |f_{\mu\tau}|^2}{6 m_{S_1}^2} + \sum_{i=1}^{3} \frac{|g_{\mu i}|^2}{m_{S_2}^2} F_2\left(\frac{m_{N_i}^2}{m_{S_2}^2}\right)\right)$$

Summary and Discussion

We found a parameter space realizing the inverted neutrino mass hierarchy of three loop radiative mass model under some assumptions.

- Large value of the NSI parameters and the value of muon g-2 are obtained in the inverted hierarchy
  $\Rightarrow \epsilon^{m}_{\mu\mu} < 9.0 \times 10^{-4}$
- Large value of the NSI parameters are not obtained in normal hierarchy
  $\Rightarrow \epsilon^{m}_{\mu\mu} < 1.0 \times 10^{-4}$

Discusstion

- We will observe the NSI effects of the inverted hierarchy at the Neutrino Factory.