Effect of non-standard interactions for radiative neutrino mass model

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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)]

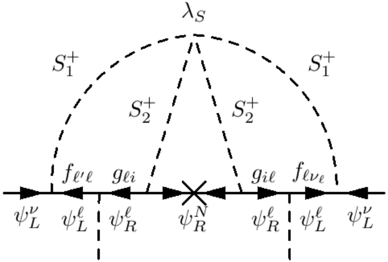
$$\psi_R^{N_1} : (\mathbf{1}, \mathbf{1}, 0), \quad \psi_R^{N_2} : (\mathbf{1}, \mathbf{1}, 0), \quad \psi_R^{N_3} : (\mathbf{1}, \mathbf{1}, 0).$$

Impose Z_2 discrete symmetry

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

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)]

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

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

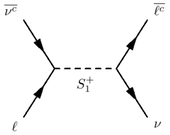
$$\begin{aligned} G^2 &= G_1^2 = (m_e g_{e1} + m_\tau g_{\tau 1}/\alpha) F_1 = (m_e g_{e1} - m_\mu g_{\mu 1}/\beta) F_1 \\ G^2 &= G_2^2 = (m_\mu g_{\mu 2} + \beta m_\tau g_{\tau 2}/\alpha) F_2 = (m_\mu g_{\mu 2} + \beta m_e g_{e2}) F_2 \\ G^2 &= G_3^2 = (\alpha m_\mu g_{\mu 3} + m_\tau g_{\tau 3}) F_3 = (-\alpha m_e g_{e3} + m_\tau g_{\tau 3}) F_3 \end{aligned}$$

3. The degenerate masses are

$$m_{\nu_1} = m_{\nu_2} = \frac{4}{(4\pi^2)^3} \frac{f_{\mu\tau}^2}{\sin^2\theta_{13}} \frac{\lambda_S G^2}{m_{S_2}}$$

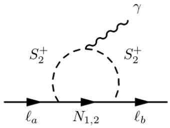
Lepton Flavor Violation

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)

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

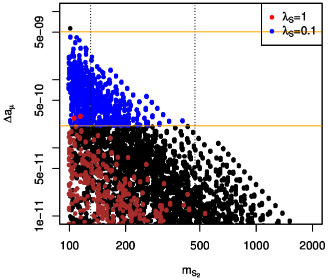
Neutrino masss

1. Since the neutrino mass matrix doesn't depend on the value coupling constants g_{ei}, we can put
$$g_{e1} \sim g_{e2} \sim g_{e3} \sim 0.$$
Then, the other coupling constants $g\ell i$
$$\begin{aligned} g_{\mu 3} \sim g_{\tau 2} &\sim 0 \\ g_{\tau 1} &= -(\alpha m_\mu g_{\mu 1})/(\beta m_\tau), \\ g_{\tau 3} &= \pm(F_2 m_\mu g_{\mu 2})/(F_3 m_\tau), \\ g_{\mu 2} &= \pm(F_1 g_{\mu 1})/(\beta F_2), \end{aligned}$$
2. From the constraints of lepton universality, the maximum value of $f_{\mu\tau}$ is determined by
$$f_{\mu\tau}^2 = \left(\frac{m_{S_1}^2}{\mathrm{GeV}^2}\right)\left(\frac{1.5\times 10^8}{\alpha^2}\right).$$
3. The degenerate masses are
$$m_{\nu_1} = m_{\nu_2} = \frac{4}{(4\pi^2)^3}\frac{f_{\mu\tau}^2}{\sin^2\theta_{13}}\frac{\lambda_S G^2(n_i,s)}{m_{S_2}}, \qquad \left(n_i = \frac{m_{N_i}}{m_{S_2}}, s = \frac{m_{S_1}}{m_{S_2}}\right).$$

Nuon g-2

Non standard interaction and muon g-2

The input parameters are $n_i, s, g_{\mu 1}$.
Masses of the DM



One of $m_{R_i} < 130\ \mathrm{GeV}(\lambda_S = 1.0)$

One of $m_{R_i} < 470\ \mathrm{GeV}(\lambda_S = 0.1)$

because

One of $m_{R_i} < m_{S_2}$,

where we assume

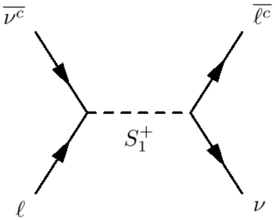
$m_{S_1}, m_{S_2} > 100\ \mathrm{GeV}$.

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

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

Non-Standard Interaction(NSI)

Lepton interaction with the exchange of singlet scalar S_1^+



Since the effective Lagrangian is expressed as

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

NSI parameters are defined by

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

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 ($\mu \to e\overline{\nu}_\beta \nu_\alpha \Rightarrow \sigma = \mu, \rho = e$)

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

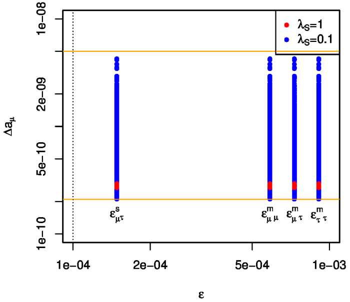
   for the main channels $\epsilon^s_{\mu\tau}(\nu_\mu \to \nu_\tau)ch, \epsilon^s_{e\tau}(\nu_e \to \nu_\tau)ch.$

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



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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
  $\Rightarrow \epsilon^m_{\tau\tau} < 9.0 \times 10^{-4}$
- 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.