Radiative Neutrino Mass via Fermion Kinetic Mixing in the $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_D$ Model

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NDM2018, 29.06.2018

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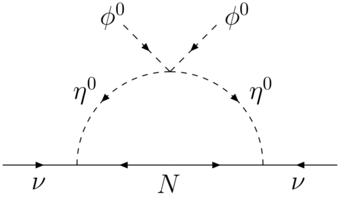
Overview

Introduction/Motivation

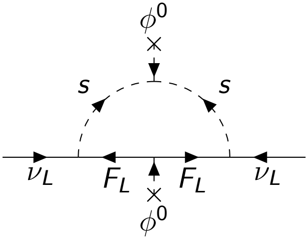
- Generate neutrino masses
- Naturealy accomodate DM
- Connect the existance of DM to non-zero neutrino masses

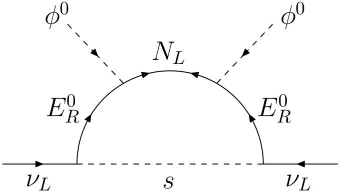
Breef reveiw

- See-saw-1, Add SM singlet fermion, $m_\nu = -\frac{m_D^2}{M_N}$
- See-saw-2, add SM triplet scalar, $m_\nu = -\frac{f \mu v}{M^2}$
- See-saw-3, add SM triplet fermion



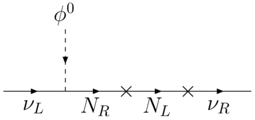
Breef reveiw



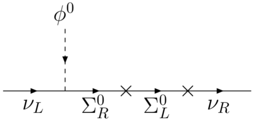


Breef reveiw

- Insert a Dirac fermion singlet N which does not transform under $\mathcal{S}$, then break $\mathcal{S}$ softly by the dimension-three $\bar{\nu}_R N_L$ term.

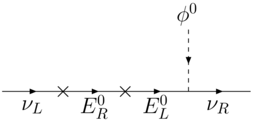


- Insert a Dirac fermion triplet $(\Sigma^+, \Sigma^0, \Sigma^-)$ which does not transform under $\mathcal{S}$, then break $\mathcal{S}$ and $SU(2)_L \times U(1)$ together spontaneously to obtain the dimension-three $\bar{\nu}_R \Sigma_L^0$ term.

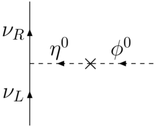


Breef reveiw

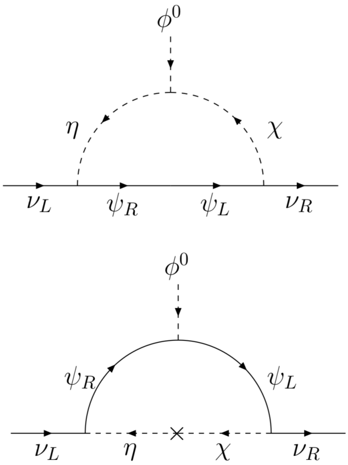
- Insert a Dirac fermion doublet (E^0, E^-) which transforms as ν_R under $\mathcal{S}$, then break $\mathcal{S}$ softly by the dimension-three $(\bar{E}^0\nu_L + E^+e^-)$ term.



- Insert a scalar doublet (η^+, η^0) which transforms as ν_R under $\mathcal{S}$, then break $\mathcal{S}$ softly by the dimension-two $(\eta^-\phi^+ + \bar{\eta}^0\phi^0)$ term.



Breef reveiw



Model particle content

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_D$	Flavors	copies
$Q \sim (u, d)^T$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	0	3	1
u^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	0	3	1
d^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	0	3	1
$L \sim (\nu, e)^T$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	0	3	1
e^c	$\mathbf{1}$	$\mathbf{1}$	1	0	3	1
$H \sim \left(H^+, H_0\right)^T$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	0	1	1
A_L	$\mathbf{1}$	$\mathbf{1}$	0	3	3	1
C_L	$\mathbf{1}$	$\mathbf{1}$	0	1	3	5
N_L	$\mathbf{1}$	$\mathbf{1}$	0	-4	3	1
N_R^c	$\mathbf{1}$	$\mathbf{1}$	0	4	3	1
F_{2L}	$\mathbf{1}$	$\mathbf{1}$	0	-2	3	4
Ψ_L	$\mathbf{1}$	$\mathbf{1}$	0	$\frac{5}{2}$	3	1
Ψ_R^c	$\mathbf{1}$	$\mathbf{1}$	0	$-\frac{5}{2}$	3	1
$\eta_L \sim \left(\eta^0, \eta^{-1}\right)^T$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	3	1	1
η_D	$\mathbf{1}$	$\mathbf{1}$	0	-1	1	1
ϕ	$\mathbf{1}$	$\mathbf{1}$	0	2	1	1
s_7	$\mathbf{1}$	$\mathbf{1}$	0	$\frac{7}{2}$	1	1
s_{11}	$\mathbf{1}$	$\mathbf{1}$	0	$-\frac{11}{2}$	1	1

Lagrangian

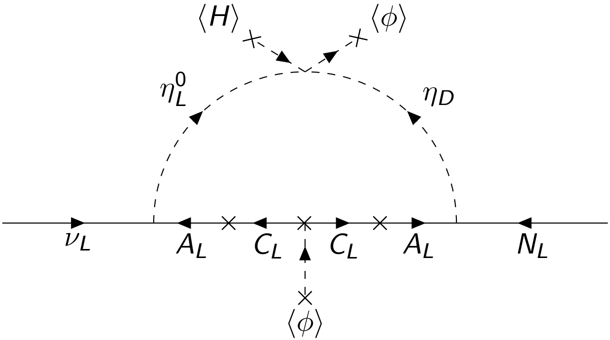
$$
\begin{aligned}
-\mathscr{L}^{SM}_{Yuk} &= \bar{u}_{Ra} Y_u^{ab} Q_{Lbi} H_j \epsilon^{ij} + \bar{d}_{Ra} Y_d^{ab} Q_{Lbi} H^{\dagger i} + \bar{L}^i_a Y_e^{ab} e_{Rb} H_i + \text{h.c.} \\
-\mathscr{L}^{New}_{m_F} &= \bar{\Psi}_{La} m_\Psi^{ab} \Psi_{Rb} + \bar{N}_{La} m_N^{ab} N_{Rb} + \text{h.c.} \\
-\mathscr{L}^{New}_{Yuk} &= L_{ai} Y_L^{ab} A_{Lb} \eta_L^{\dagger i} + \Psi_{La} Y_A^{ab} A_{Lb} s_{11} + \Psi_{La} Y_C^{ab\alpha} C_{Lb\alpha} s_7^* \\
&+ A_{La} Y_N^{ab} N_{Lb} \eta_D^* + C_{La\alpha} Y_{cc}^{ab\alpha\beta} C_{Lb\beta} \phi^* + A_{La} Y_{AF}^{ab\alpha} F_{2Lb\alpha} \eta_D \\
&+ C_{La\alpha} Y_{CF}^{ab\alpha\beta} F_{2Lb\beta} \eta_D^* + \bar{F}_{2La\alpha} Y_{NF}^{ab\alpha} N_{Rb} \phi + \text{h.c.} \\
V_0 &= \sum_{\substack{H,\phi,\eta_L,\eta_D,\\ s_{11},s_7 \in x}} \left((-1)^{q_x} m_x^2 |x|^2 + \frac{\lambda_x}{2} |x|^4 \right) + \sum_{\substack{H,\phi,\eta_L,\eta_D,s_{11},\\ s_7 \in \{x<y\}}} \lambda_{xy} |x|^2 |y|^2 \\
V_3 &= \mu_D \eta_D^2 \phi + \mu_3 \phi s_{11} s_7 + \text{h.c.} \\
V_4 &= \lambda_{H\eta\phi} H_i \eta_{Lj} \eta_D \phi^* \epsilon^{ij} + \lambda_{s\eta} \eta_D^2 s_7^* s_{11}^* + \text{h.c.}
\end{aligned}
$$

Triangle Anomalies

$$\sum_i Q_{Di} = 1 \times (3) + 5 \times (1) + 4 \times (-2) + 1 \times (-4) + 1 \times (4) + 1 \times \left(\frac{5}{2}\right) + 1 \times \left(-\frac{5}{2}\right) = 0$$

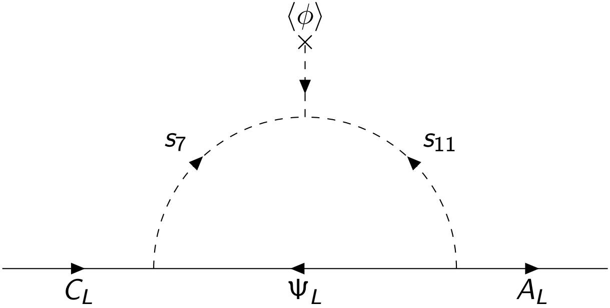
$$\sum_i Q_{Di}^3 = 1 \times (3)^3 + 5 \times (1)^3 + 4 \times (-2)^3 + 1 \times (-4)^3 + 1 \times (4)^3 + 1 \times \left(\frac{5}{2}\right)^3 + 1 \times \left(-\frac{5}{2}\right)^3 = 0$$

Radiative neutrino mass generation



$$m_\nu = \frac{1}{16\pi^2} Y_N m_{F_2} Y_L \frac{\epsilon}{1-\epsilon^2} F(m_{s_i}, m_{F_2}, \theta_{\eta_L,\eta_D})$$

Radiative Kinetic Mixing of Fermions



Radiative Kinetic Mixing of Fermions

$$\epsilon = \frac{1}{16\pi^2} Y_A^* \gamma(m_{s_i}, m_\Psi, \theta_{s_7,s_{11}}) Y_C e^{-i2\Delta}$$

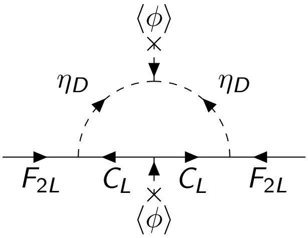
$$\begin{pmatrix} A_L \\ C_L \end{pmatrix} = U(\pi/4, \Delta)^\dagger R_{rescale}^{-1} U(\alpha)^\dagger \begin{pmatrix} F_{1L} \\ F_{2L} \end{pmatrix} =$$

$$\begin{pmatrix} 1 & -\frac{\epsilon}{\sqrt{1-\epsilon^2}} \\ 0 & \frac{\epsilon}{\sqrt{1-\epsilon^2}} \end{pmatrix} \begin{pmatrix} F_{1L} \\ F_{2L} \end{pmatrix}$$

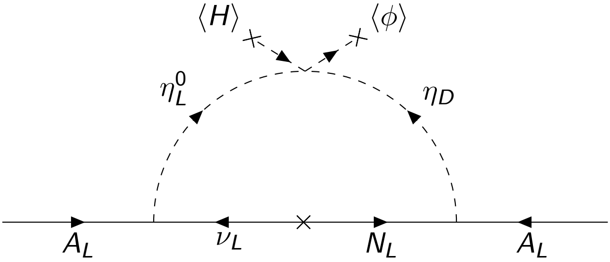
$$\tan(2\alpha) = \frac{-\sqrt{1-\epsilon^2}}{\epsilon}$$

Hiden Sector Fermion Masses

- $m_{A_D}^2 = \frac{g_d^2}{2}(2\nu_\phi)^2$
- 5×5 C_L mass matrix generated by $C_{La\alpha} Y_{cc}^{ab\alpha\beta} C_{Lb\beta} \phi^*$
- $$\begin{pmatrix} 0 & m_\nu & 0 & 0 \\ m_\nu & 0 & m_N & 0 \\ 0 & m_N & 0 & Y_{NF} v_\phi \\ 0 & 0 & Y_{NF} v_\phi & 0 \end{pmatrix}$$ in the $(\nu_L, N_L, N_R^c, F_{2Li})$ bases.



Mass of A dark fermion



Scalar Masses

- $m_{H\phi R} = \begin{pmatrix} \lambda_H \nu^2 & \lambda_{H\phi}\nu\nu_\phi \\ \lambda_{H\phi}\nu\nu_\phi & \lambda_\phi \nu_\phi^2 \end{pmatrix}$
- $m_{\eta LD[R/I]} =$
$$\begin{pmatrix} m_{\eta L}^2 + \frac{\lambda_{HL}\nu^2}{2} + \frac{\lambda_{\phi L}\nu_\phi^2}{2} & \mp\frac{\lambda_{H\eta\phi}\nu\nu_\phi}{2} \\ \mp\frac{\lambda_{H\eta\phi}\nu\nu_\phi}{2} & m_{\eta D}^2 + \frac{\lambda_{HD}\nu^2}{2} + \frac{\lambda_{\phi D}\nu_\phi^2}{2} \pm \sqrt{2}\mu_D\nu_\phi \end{pmatrix}$$
- $m_{s[R/I]} =$
$$\begin{pmatrix} m_{s7}^2 + \lambda_{H7}\nu^2 + \lambda_{\phi 7}\nu_\phi^2 & \pm\frac{\mu_3\nu_\phi}{\sqrt{2}} \\ \pm\frac{\mu_3\nu_\phi}{\sqrt{2}} & m_{s11}^2 + \lambda_{H11}\nu^2 + \lambda_{\phi 11}\nu_\phi^2 \end{pmatrix}$$

Dark matter candidates

- 2 dark separeted sectors
- Q_D odd charged particles: A, C, η_L, η_D (equivalent to canonical Scotogenic case)
- Particles with frational Q_D charges: Ψ, s_7, s_{11} (Needed for kinetic mixing), like dark sector within dark sector

Conclusions

- generate naturaly small neutrino masses
- naturally accomodate multilayer DM

Thank you!