Radiative Dirac neutrino masses with $\mathbb{Z}_4$ symmetry from $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

Oleg Popov
Seoul National University of Science and Technology
opopo001@ucr.edu

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In collaboration with Prof. Dr. Sin Kyu Kang and Arnab Dasgupta

Overview

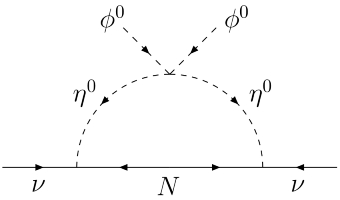
Introduction/Motivation

- Generate naturaly small neutrino masses
- Naturealy accomodate DM (Dirac, Majorana, or bosonic)
- Connect the existance of DM to $m_\nu \neq 0$ neutrino masses (Scotogenicness)
- $0\nu4\beta$ as leading order of $0\nu2n\beta$ processes

Brief reveiw

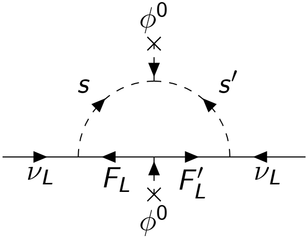
d-5 Weinberg operator: $\frac{f_{ij}}{2\Lambda}\left(\nu_i\phi^0 - l_i\phi^+\right)\left(\nu_j\phi^0 - l_j\phi^+\right) + \text{h.c.}$.* $\rightarrow$ Majorana neutrino masses

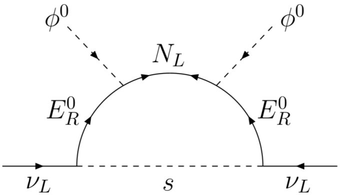
- See-saw-1, Add SM singlet fermion, $m_\nu = -\frac{m_D^2}{M_N}$
- See-saw-2, add SM triplet scalar, $m_\nu = -\frac{f\mu v}{M^2}$
- See-saw-3, add SM triplet fermion, $m_\nu = -\frac{m_D^2}{M_\Sigma}$



*Phys. Rev. Lett. 43(1979), 1566;Phys. Rev. Lett. 81 (1998) 1171

Brief reveiw





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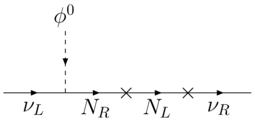
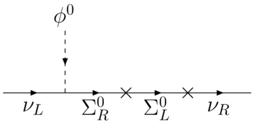
† Zee model (1980), Phys.Lett. 93B (1980) 389; Scot-Inverse-Seesaw Phys.Lett. B737 (2014) 280-282.

Brief 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 $\bar{\nu}_R \Sigma^0_L$ term.

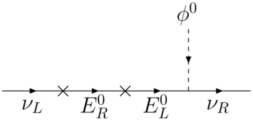


‡

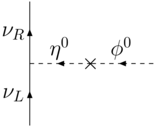
[‡] arXiv:1609.02538

Brief reveiw

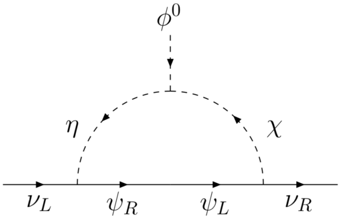
- Insert a Dirac fermion doublet (E^0, E^-) which transforms as ν_R under $\mathcal{S}$, then break $\mathcal{S}$ softly by the dimension-three $(\bar{E}^0\nu_L + E^+e^-)$ term.

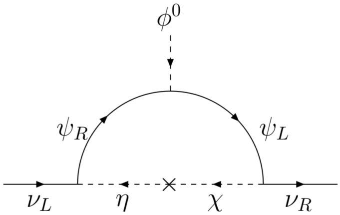


- Insert a scalar doublet (η^+, η^0) which transforms as ν_R under $\mathcal{S}$, then break $\mathcal{S}$ softly by the dimension-two $(\eta^-\phi^+ + \bar{\eta}^0\phi^0)$ term.



Brief reveiw





Model particle content

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$	Flavor
Q	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$\frac{1}{3}$	3
u^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	$-\frac{1}{3}$	3
d^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	$-\frac{1}{3}$	3
L	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-1	3
e^c	$\mathbf{1}$	$\mathbf{1}$	1	1	3
ν^c	$\mathbf{1}$	$\mathbf{1}$	0	5	3
N	$\mathbf{1}$	$\mathbf{1}$	0	-6	3
N^c	$\mathbf{1}$	$\mathbf{1}$	0	2	3
Ψ_1	$\mathbf{1}$	$\mathbf{1}$	0	13	3
Ψ_2	$\mathbf{1}$	$\mathbf{1}$	0	-14	2×3
Ψ_3	$\mathbf{1}$	$\mathbf{1}$	0	15	3
H	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	0	1
η	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	-1	1
χ	$\mathbf{1}$	$\mathbf{1}$	0	1	1
S	$\mathbf{1}$	$\mathbf{1}$	0	2	1
S_4	$\mathbf{1}$	$\mathbf{1}$	0	4	1

Lagrangian

$$\begin{aligned}\mathcal{L}_{\text{Yuk}} = \mathcal{L}_{\text{Yuk}}^{\text{SM}} &- \bar{N}_{aR} Y_L^{ab} L_{bi} \eta_j \epsilon^{ij} - \bar{\nu}_{aR} Y_R^{ab} N_{bL} \chi \\ &- \bar{N}_{aR} Y_{ND}^{ab} N_{bL} S_4 - N_{aR} Y_{NM}^{ab} N_{bR} S_4 \\ &- \Psi_{1aL} Y_{12}^{ab} \Psi_{2bL} \chi - \Psi_{2aL} Y_{23}^{ab} \Psi_{3bL} \chi^* \\ &- \Psi_{1aL} Y_{13}^{ab} \Psi_{3bL} \frac{(S_4^*)^7}{\Lambda^6} - \Psi_{2aL} Y_{22}^{ab} \Psi_{2bL} \frac{S_4^7}{\Lambda^6} + \text{H.c.}\end{aligned}$$

Potential

$$
\begin{aligned}
V\left(H,\eta,\chi,S,S_4\right) = &- m_H^2 H^\dagger H + \frac{1}{2}\lambda_H \left(H^\dagger H\right)^2 + m_\eta^2 \eta^\dagger \eta + \frac{1}{2}\lambda_\eta \left(\eta^\dagger \eta\right)^2 \\
&+ m_\chi^2 \chi^* \chi + \frac{1}{2}\lambda_\chi \left(\chi^*\chi\right)^2 + m_S^2 S^* S + \frac{1}{2}\lambda_S \left(S^* S\right)^2 \\
&- m_{S_4}^2 S_4^* S_4 + \frac{1}{2}\lambda_{S_4}\left(S_4^* S_4\right)^2 + \lambda_{H\eta}\left(H^\dagger H\right)\left(\eta^\dagger\eta\right) \\
&+ \lambda'_{H\eta}\left(H^\dagger \eta\right)\left(\eta^\dagger H\right) + \lambda_{H\chi}\left(H^\dagger H\right)\left(\chi^*\chi\right) \\
&+ \lambda_{HS}\left(H^\dagger H\right)\left(S^* S\right) + \lambda_{HS_4}\left(H^\dagger H\right)\left(S_4^* S_4\right) \\
&+ \lambda_{\eta\chi}\left(\eta^\dagger\eta\right)\left(\chi^*\chi\right) + \lambda_{\eta S}\left(\eta^\dagger\eta\right)\left(S^* S\right) \\
&+ \lambda_{\eta S_4}\left(\eta^\dagger\eta\right)\left(S_4^* S_4\right) + \lambda_{\chi S}\left(\chi^*\chi\right)\left(S^* S\right) + \lambda_{\chi S_4}\left(\chi^*\chi\right)\left(S_4^* S_4\right) \\
&+ \lambda_{SS_4}\left(S^* S\right)\left(S_4^* S_4\right) + \Big[\mu_H\left(H^\dagger\eta\right)\chi + \mu_S \chi^2 S^* + \mu_{S_4} S^2 S_4^* \\
&+ \lambda_1\left(H^\dagger\eta\right)\chi^* S + \lambda_2 \chi^2 S S_4^* + \text{H.c.}\Big]
\end{aligned}
$$

Triangle Anomalies

$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$	$SU3_C^2 U1_Y$	$SU3_L^2\ U1_Y$	$U1_Y^3$	$U1_Y\ U1_{B-L}^2$	$SU3_C^2\ U1_{B-L}$	$U1_{B-L}\ SU3_L^2$	$U1_Y^2\ U1_{B-L}$	$U1_{B-L}^3$	$SU3_C^3$
$Q \sim \mathbf{3} \otimes \mathbf{2} \otimes \frac{1}{6} \otimes \frac{1}{3}$	$\frac{1}{6}$	$\frac{1}{4}$	$\frac{1}{36}$	$\frac{1}{9}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{18}$	$\frac{2}{9}$	1
${u_R}^c \sim \bar{\mathbf{3}} \otimes \mathbf{1} \otimes -\frac{2}{3} \otimes -\frac{1}{3}$	$-\frac{1}{3}$	0	$-\frac{8}{9}$	$-\frac{2}{9}$	$-\frac{1}{6}$	0	$-\frac{4}{9}$	$-\frac{1}{9}$	$-\frac{1}{2}$
${d_R}^C \sim \bar{\mathbf{3}} \otimes \mathbf{1} \otimes \frac{1}{3} \otimes -\frac{1}{3}$	$\frac{1}{6}$	0	$\frac{1}{9}$	$\frac{1}{9}$	$-\frac{1}{6}$	0	$-\frac{1}{9}$	$-\frac{1}{9}$	$-\frac{1}{2}$
$L \sim \mathbf{1} \otimes \mathbf{2} \otimes -\frac{1}{2} \otimes -1$	0	$-\frac{1}{4}$	$-\frac{1}{4}$	-1	0	$-\frac{1}{2}$	$-\frac{1}{2}$	-2	0
${e_R}^C \sim \mathbf{1} \otimes \mathbf{1} \otimes 1 \otimes 1$	0	0	1	1	0	0	1	1	0
${\nu_R}^C \sim \mathbf{1} \otimes \mathbf{1} \otimes 0 \otimes 5$	0	0	0	0	0	0	0	125	0
$N_L \sim \mathbf{1} \otimes \mathbf{1} \otimes 0 \otimes -6$	0	0	0	0	0	0	0	-216	0
${N_R}^C \sim \mathbf{1} \otimes \mathbf{1} \otimes 0 \otimes 2$	0	0	0	0	0	0	0	8	0
$\Psi_{1L} \sim \mathbf{1} \otimes \mathbf{1} \otimes 0 \otimes 13$	0	0	0	0	0	0	0	2197	0
$\Psi_{2L} \sim \mathbf{1} \otimes \mathbf{1} \otimes 0 \otimes -14$	0	0	0	0	0	0	0	-2744	0
$\Psi_{2L} \sim \mathbf{1} \otimes \mathbf{1} \otimes 0 \otimes -14$	0	0	0	0	0	0	0	-2744	0
$\Psi_{3L} \sim \mathbf{1} \otimes \mathbf{1} \otimes 0 \otimes 15$	0	0	0	0	0	0	0	3375	0
Total:	0	0	0	0	0	0	0	0	0

§

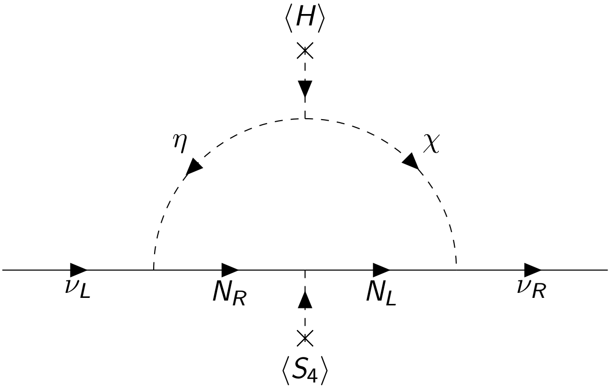
$$\sum Q_{B-L}\Big|_{\text{Grav.}} = 3\left(2 \times \frac{1}{3} - \frac{1}{3} - \frac{1}{3}\right) - 2 \times 1 + 1 + 5 - 6 + 2 + 13 - 2 \times 14 + 15 = 0$$

§Generated using Susyno:Renato M. Fonseca, Calculating the renormalisation group equations of a SUSY model with Susyno, Computer Physics Communications 183 (2012) 2298

Residual symmetries

$\mathbb{Z}_4$	Fields
$\mathbb{1}$	$H,\ S_4$
w^*	$\nu^a,\ e^a,\ \Psi^{a*}_{1L},\ \Psi^a_{3R},\ \eta^0,\ \eta^+,\ \chi^*$
w^2	$N^a_{L,R},\ \Psi^a_{i2L},\ S$
Global $U(1)_{(B-L)}$	Fields
$\frac{1}{3}$	$u^a,\ d^a$

Radiative neutrino mass generation



Radiative neutrino mass generation

$$
\begin{aligned}
m_\nu^{ab} = \frac{s_N c_N s_{\eta\chi} c_{\eta\chi}}{16\pi^2} Y_L^{ac} \Bigg\{ m_{N_1} \left[F\left(\frac{m^2_{\xi_1}}{m^2_{N_1}}\right) - F\left(\frac{m^2_{\xi_2}}{m^2_{N_1}}\right)\right] \\
+ m_{N_2} \left[F\left(\frac{m^2_{\xi_2}}{m^2_{N_2}}\right) - F\left(\frac{m^2_{\xi_1}}{m^2_{N_2}}\right)\right] \Bigg\}_{cd} Y_R^{db}
\end{aligned}
$$

$$
F(x) = \frac{x}{1-x} \ln x
$$

Fermion Masses

$$\mathcal{L}_N = (\bar{N}_L^c, \bar{N}_R) \begin{pmatrix} 0 & Y_{ND} v_4 \\ Y_{ND} v_4 & Y_{NM}^\dagger v_4 \end{pmatrix} \begin{pmatrix} N_L \\ N_R^c \end{pmatrix} + \text{H.c.}$$

$$m_{N_{1,2}} = \frac{v_4}{2} \left(|Y_{NM}| \pm \sqrt{|Y_{NM}|^2 + 4\,|Y_{ND}|^2} \right),$$

$$\begin{pmatrix} N_1 \\ N_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} N_L \\ N_R^c \end{pmatrix},$$

$$\tan(2\theta_N) = -2\frac{|Y_{ND}|}{|Y_{NM}|}.$$

Fermion Masses

Ψ_i get their masses in one of two ways:

- Effectively: $m_{\Psi_{1,3}}^{ab} = Y_{13}^{ab}\frac{\langle S_8\rangle^7}{\Lambda^6}$ and $m_{\Psi_{22}}^{\alpha\beta} = Y_{22}^{\alpha\beta}\frac{\langle S_8\rangle^7}{\Lambda^6}$ with $a, b = 1-3$ and $\alpha, \beta = 1-6$, respectively.
- Add scalar $U(1)_{B-L} \sim 28 \to \Psi_{1L}^a Y_{13}^{ab} \Psi_{3L}^b S_{28}^*$ and $\Psi_{2L}^a Y_{22}^{ab} \Psi_{2L}^b S_{28}$. Potential $m = 0$ Goldstone mode $\to$ more scalars.

Scalar Masses

$$\left.\frac{\partial V(s_i)}{\partial v_i}\right|_{v_i\in\{v,v_4\}} = 0 \rightarrow$$

$$\lambda_H v^2 + \lambda_{HS_4} v_4^2 - 2m_H^2 = 0,$$

$$\lambda_{S_4} v_4^2 + \lambda_{HS_4} v^2 - 2m_{S_4}^2 = 0.$$

3 sectors: $(\mathbb{1}, w, w^2 \sim \mathbb{Z}_4)$

$\mathbb{1} \sim \mathbb{Z}_4$ scalar sector

$$\left(Re[H^0], Re[S_4]\right) \to \begin{pmatrix} \lambda_H v^2 & \lambda_{HS_4} v v_4 \\ \lambda_{HS_4} v v_4 & \lambda_{S_4} v_4^2 \end{pmatrix}$$

$$m_{1,2}^2 = \frac{\left(\lambda_H v^2 + \lambda_{S_4} v_4^2\right) \pm \sqrt{\left(\lambda_H v^2 - \lambda_{S_4} v_4^2\right)^2 + 4\lambda_{HS_4}^2 v^2 v_4^2}}{2}$$

$$\tan\left(2\theta_{H^0 S_4}\right) = \frac{2\lambda_{HS_4} v v_4}{\lambda_H v^2 - \lambda_{S_4} v_4^2},$$

$$\text{with } \begin{pmatrix} s_h \\ s_H \end{pmatrix} = \begin{pmatrix} \cos\theta_{H^0 S_4} & \sin\theta_{H^0 S_4} \\ -\sin\theta_{H^0 S_4} & \cos\theta_{H^0 S_4} \end{pmatrix} \begin{pmatrix} Re[H^0] \\ Re[S_4] \end{pmatrix}.$$

$Im[H^0]$, $Im[S_4]$, and $H^\pm$ correspond to would-be Nambu-Goldstone bosons

$m_{\eta^\pm}^2 = m_\eta^2 + \lambda_{H\eta} v^2/2 + \lambda_{\eta S_4} v_4^2/2.$

$w, w^* \sim \mathbb{Z}_4$ scalar sector

$$Re/Im[(\eta,\chi)] \to \begin{pmatrix} m_\eta^2 + (\lambda_{H\eta}+\lambda_{H\eta 2})\,\frac{v^2}{2} + \lambda_{\eta S_4}\,\frac{v_4^2}{2} & \pm\mu_H\,\frac{v}{\sqrt{2}} \\ \pm\mu_H\,\frac{v}{\sqrt{2}} & m_\chi^2 + \lambda_{H\chi}\,\frac{v^2}{2} + \lambda_{\chi S_4}\,\frac{v_4^2}{2} \end{pmatrix}$$

$$m_{1,2}^2 = \frac{1}{2}\left[m_\eta^2 + m_\chi^2 + (\lambda_{H\eta}+\lambda_{H\eta 2}+\lambda_{H\chi})\,\frac{v^2}{2} + \left(\lambda_{\eta S_4}+\lambda_{\chi S_4}\right)\frac{v_4^2}{2}\right]$$
$$\pm\frac{1}{2}\sqrt{\left[m_\eta^2 - m_\chi^2 + (\lambda_{H\eta}+\lambda_{H\eta 2}-\lambda_{H\chi})\,\frac{v^2}{2} + \left(\lambda_{\eta S_4}-\lambda_{\chi S_4}\right)\frac{v_4^2}{2}\right]^2 + 4\mu_H^2\,\frac{v^2}{2}}$$

$w, w^* \sim \mathbb{Z}_4$ scalar sector

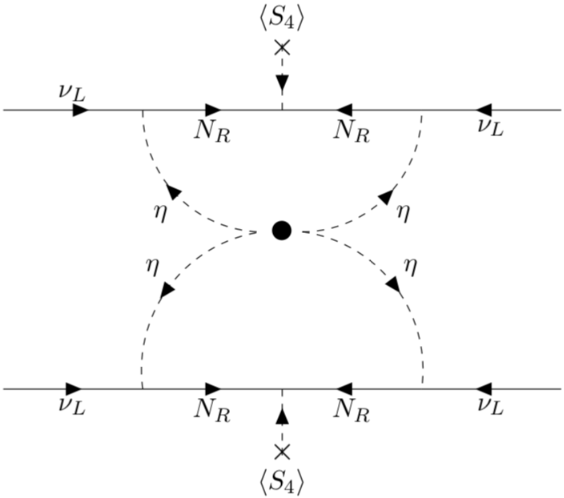
$$\tan\left(2\theta_{\eta\chi R/I}\right) = \frac{\pm 2\mu_H \frac{v}{\sqrt{2}}}{m_\eta^2 - m_\chi^2 + \left(\lambda_{H\eta} + \lambda_{H\eta 2} - \lambda_{H\chi}\right)\frac{v^2}{2} + \left(\lambda_{\eta S_4} - \lambda_{\chi S_4}\right)\frac{v_4^2}{2}},$$

$$\text{with } \begin{pmatrix} \xi_1 \\ \xi_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\eta\chi} & \sin\theta_{\eta\chi} \\ -\sin\theta_{\eta\chi} & \cos\theta_{\eta\chi} \end{pmatrix} \begin{pmatrix} \eta^0 \\ \chi \end{pmatrix}.$$

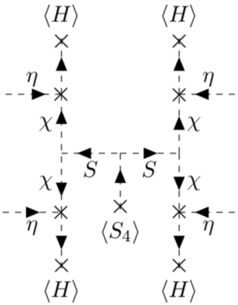
$w^2 \sim \mathbb{Z}_4$ scalar sector

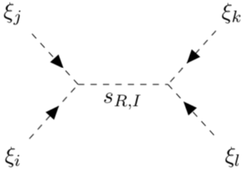
$$m^2_{\mathrm{Re}[S]} = m_S^2 + \lambda_{HS}\frac{v^2}{2} + \lambda_{SS_4}\frac{v_4^2}{2} + \sqrt{2}\mu_{S_4}v_4,$$
$$m^2_{\mathrm{Im}[S]} = m_S^2 + \lambda_{HS}\frac{v^2}{2} + \lambda_{SS_4}\frac{v_4^2}{2} - \sqrt{2}\mu_{S_4}v_4.$$

Neutrinoless quadruple beta decay



Neutrinoless quadruple beta decay





Neutrinoless quadruple beta decay

$$\left(\frac{\mu^R_{ij}\mu^R_{kl}}{m^2_{s_R}} + \frac{\mu^I_{ij}\mu^I_{kl}}{m^2_{s_I}}\right)\xi_i\xi_j\xi_k\xi_l + \text{H.c.}$$

$$\mu^R_{ij} = \begin{pmatrix} s^2 & cs \\ cs & c^2 \end{pmatrix}\left(\sqrt{2}\mu_S + \lambda_2 v_4\right)$$

$$\mu^I_{ij} = \begin{pmatrix} s^2 & cs \\ cs & c^2 \end{pmatrix}\imath\left(-\sqrt{2}\mu_S + \lambda_2 v_4\right)$$

$$\frac{Q^{abcd}}{\Lambda^2}\left(\nu_a\nu_b\right)\left(\nu_c\nu_d\right)$$

Neutrinoless quadruple beta decay

$$\frac{Q^{abcd}}{\Lambda^2} = \imath c_4 Y_L^{a\alpha} \left(v_s\right)_j \left[s_N^2 \frac{F(x_{l1}, y_{lj}, x_{j1})}{m_{N_1}} + c_N^2 \frac{F(x_{l2}, y_{lj}, x_{j2})}{m_{N_2}} \right]_{\alpha\beta} \left(M_s\right)_{jl} \left(v_s\right)_l Y_L^{\beta b} \times$$
$$Y_L^{c\gamma} \left(v_s\right)_i \left[s_N^2 \frac{F(x_{k1}, y_{ki}, x_{i1})}{m_{N_1}} + c_N^2 \frac{F(x_{k2}, y_{ki}, x_{i2})}{m_{N_2}} \right]_{\gamma\delta} \left(M_s\right)_{ik} \left(v_s\right)_k Y_L^{\delta d} \times$$
$$\frac{\left(m_{S_I}^2 - m_{S_R}^2\right)\left(2\mu_s^2 + \lambda_2^2 v_4^2\right) + \left(m_{S_I}^2 + m_{S_R}^2\right) 2\sqrt{2}\mu_S \lambda_2 v_4}{m_{S_I}^2 m_{S_R}^2},$$

$$v_S = \begin{pmatrix} \cos\left(\theta_{\eta\chi}\right) \\ -\sin\left(\theta_{\eta\chi}\right) \end{pmatrix},$$

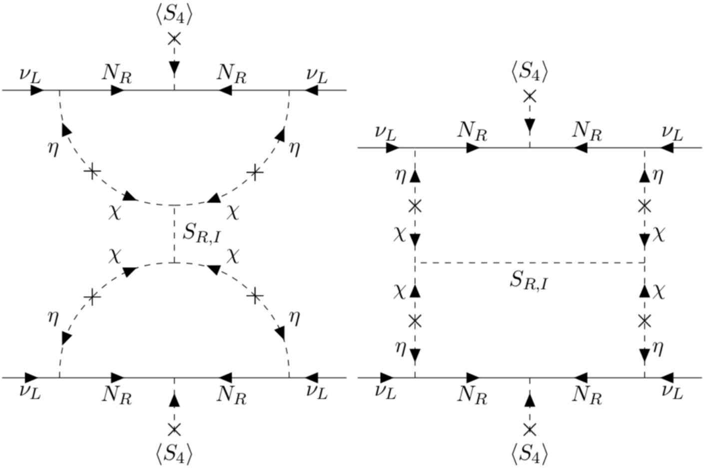
$$M_S = \begin{pmatrix} \sin^2\left(\theta_{\eta\chi}\right) & \sin\left(\theta_{\eta\chi}\right)\cos\left(\theta_{\eta\chi}\right) \\ \cos\left(\theta_{\eta\chi}\right)\sin\left(\theta_{\eta\chi}\right) & \cos^2\left(\theta_{\eta\chi}\right) \end{pmatrix}$$

$$F(x,y,z) = \frac{\ln x}{(1-z)(1-x)} - \frac{\ln y}{(1-z)(1-y)}$$

$$x_{ij} = \frac{m_i^2}{m_{N_j}^2}, \quad y_{ij} = \frac{m_i^2}{m_j^2},$$

$$c_4 = \begin{cases} 4! & i=j=k=l \mid i,j,k,l \in \{1,2\} \\ 3! & i=j=k\neq l \vee i=j=l\neq k \vee i=k=l\neq j \vee i\neq j=k=l \mid i,j,k,l\in\{1,2\} \\ 4 & (i=j \wedge k=l) \vee (i=k \wedge j=l) \vee (i=l \wedge j=k) \mid i,j,k,l \in\{1,2\} \end{cases}.$$

Neutrinoless quadruple beta decay



Neutrinoless quadruple beta decay

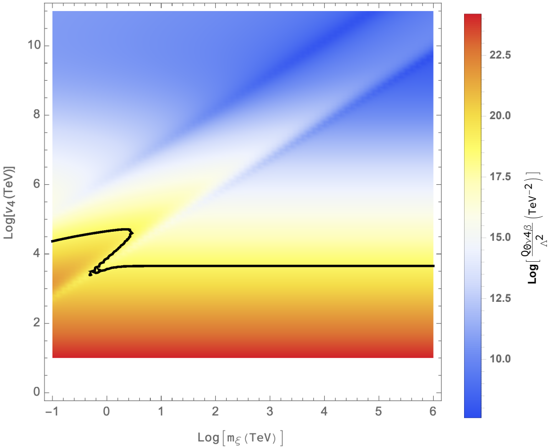
$$\tau_{1/2}^{0\nu4\beta} > 3.2 \times 10^{21} years$$

$$\tau_{1/2}^{-1} = \Gamma_{0\nu4\beta} = G_{0\nu4\beta} \left|A_{0\nu4\beta}\right|^2 = G_{0\nu4\beta} \left(\frac{G_F^4}{q^4}\frac{Q_{0\nu4\beta}}{\Lambda^2}\right)^2$$

$$= Q^{11} \left(\frac{G_F^4}{q^4}\frac{Q_{0\nu4\beta}}{\Lambda^2}\right)^2 q^{18}$$

$$\frac{Q_{0\nu4\beta}}{\Lambda^2} \leq \left(\tau_{1/2} Q^{11} q^{10} G_F^8\right)^{-1/2} = 7.8 \times 10^{18} \mathrm{TeV}^{-2}$$

Neutrinoless quadruple beta decay



$\frac{Q_{0\nu4\beta}}{\Lambda^2}$ *vs.* m_ξ and v_4 for $\mu_S = 10^9\,\mathrm{TeV}$, $\frac{m_{\xi_2}}{m_{\xi_1}} - 1 = 10^{-2}$, $\frac{Y_D}{Y_M} = 10^{-3}$, $Y_{M,L} \sim O(1)$, $\theta_\xi = \pi/4$, and $m_{S_{R(I)}} = 0.8(2)\mathrm{TeV}$. Solid curve corresponds to current half-life constraint on $\frac{Q_{0\nu4\beta}}{\Lambda^2}$ from NEMO-3 and KURF

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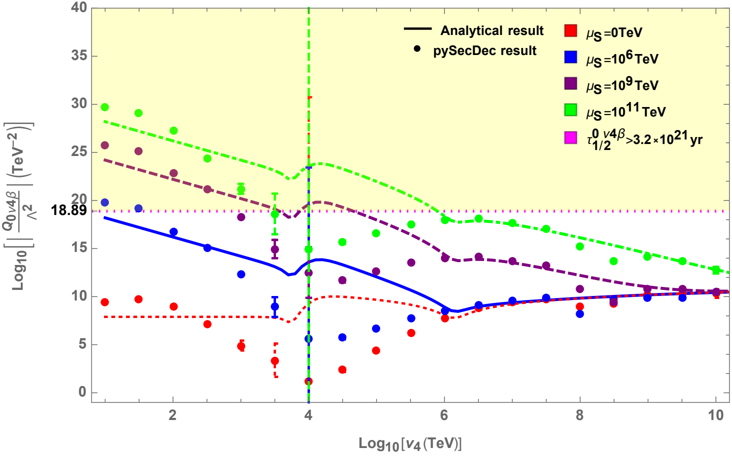
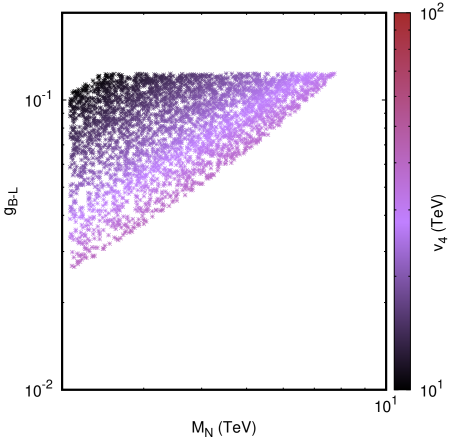


Comparison of numerically obtained result from `pySecDec` (solid circles) with analytically derived formula (curves) for different values of v_4, and μ_S for $m_\xi = 1$ TeV, $\frac{m_{\xi_2}}{m_{\xi_1}} - 1 = 10^{-2}$, $\frac{Y_D}{Y_M} = 10^{-3}$, $Y_{M,L} \sim O(1)$, $\lambda_2 \sim O(1)$, $\theta_\xi = \pi/4$, and $m_{S_{R(I)}} = 0.8(2)$ TeV.

Dark matter candidates

- Majorana type: N_i
- Dirac type: $\Psi_{1,3}$
- Real scalar: $s_{R,I}$

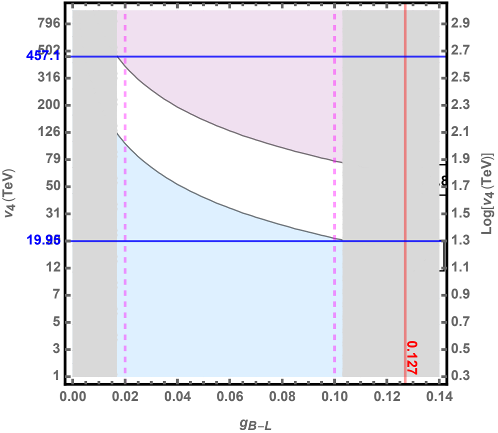
N as DM



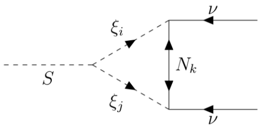
Scatter plot of the $U(1)_{B-L}$ gauge coupling g_{B-L} versus the DM mass $|m_N|$ for $\frac{Y_D}{Y_M} \ll 1$ and $10\ \mathrm{TeV} v_4 100\ \mathrm{TeV}$

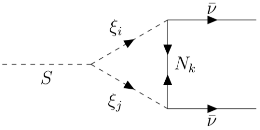
$$m_N \approx -v_4 \frac{Y_D^2}{Y_M} = 2.2 \sim 7.8\mathrm{TeV}$$

N as DM


796
502
457.1
316
200
126
79
50
31
19.95
12
7
5
3
1
2.9
2.7
2.5
2.3
2.1
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0.127
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
v_4(TeV)
Log[v_4(TeV)]
g_{B-L}

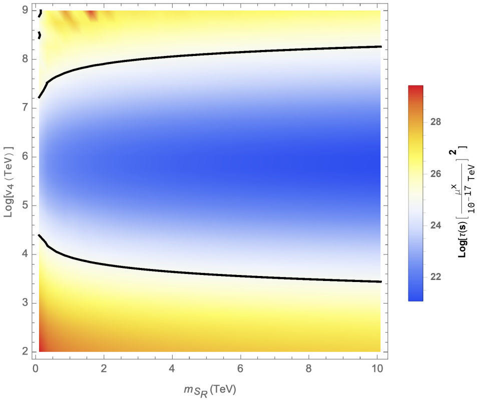
S as DM





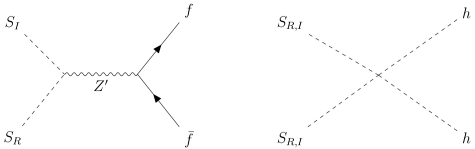
$$
\begin{aligned}
\Gamma(S \to \nu\nu) &= \frac{\sum |A|^2}{16\pi m_S} \\
&= \frac{m_S}{16\pi}\left[\left|\sum_{ijk}\mu^x_{ij} C_0(0,0,m_S^2,m_j,m_k,m_i)A_L\right|^2 + \left|\sum_{ijk}\mu^x_{ij} C_0(0,0,m_S^2,m_j,m_k,m_i)A_R\right|^2\right] \\
A_L &= (s_N, c_N)^2_k Y_L m_{N_k} Y_L \begin{pmatrix} c_\xi^2 & -s_\xi c_\xi \\ -s_\xi c_\xi & s_\xi^2 \end{pmatrix} \\
A_R &= (c_N, -s_N)^2_k Y_R^* m_{N_k} Y_R^* \begin{pmatrix} s_\xi^2 & s_\xi c_\xi \\ s_\xi c_\xi & c_\xi^2 \end{pmatrix}
\end{aligned}
$$

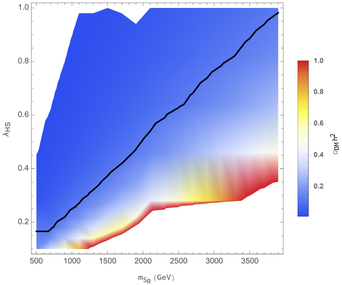
S as DM



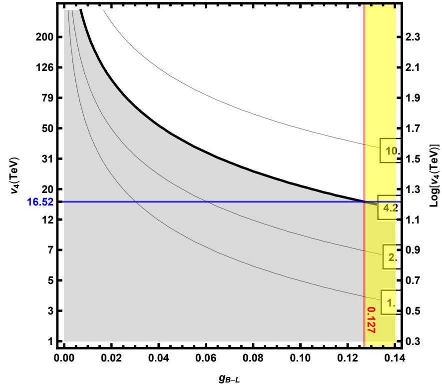
$S_{R,I}$ lifetime *vs.* v_4, m_S, and μ^x for $\frac{m_{\xi_1}}{m_{\xi_2}} - 1 = 10^{-2}$ and $Y_{M,L} \sim O(1)$, $Y_R \sim 10^{-4}$, $\theta_\xi = \pi/4$, and $Y_D = 10^{-2}$. The solid line indicates the lower limit on $\tau_s > 10^{25}$s

S as DM


S_I
f
Z'
S_R
$\bar{f}$
$S_{R,I}$
h
$S_{R,I}$
h


1.0
0.8
0.6
0.4
0.2
λ_{HS}
500
1000
1500
2000
2500
3000
3500
m_{S_R} (GeV)
1.0
0.8
0.6
0.4
0.2
$\Omega_{DM}\,h^2$

Constraints



Unitarity and collider constraints, $g_{B-L} < 0.127$ and $M'_Z > 4.2$TeV are imposed. Contours represent M'_Z in TeV units

Constraints

Radiative Dirac neutrino masses via $\mathbb{Z}_4$ from 3211

Introduction

Brief review

Model

Anomalies

$\mathbb{Z}_4$

m_ν

Mass Spectrum

$0\nu4\beta$

Dark Matter Candidates

Conclusions

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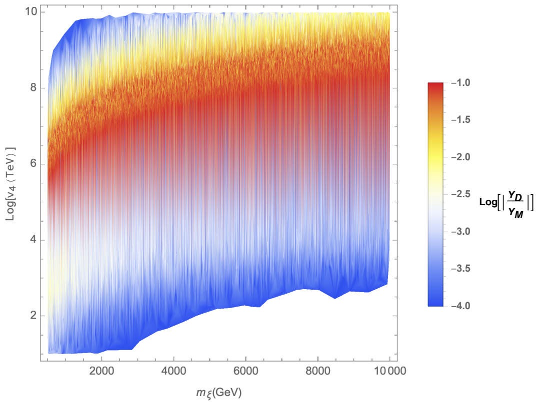

Correlation between v_4 and $\frac{Y_D}{Y_M}$ for $\frac{m_{\xi_1}}{m_{\xi_2}} - 1 = 10^{-2}$, $Y_{M,L} \sim O(1)$, $Y_R \sim 10^{-4}$ and $\theta_\xi = \pi/4$

Conclusions

- $\mathbb{G}_{SM} \times U(1)_{B-L}$ extension
- Radiative Dicar neutrino masses
- multiple Dirac or Majorana DM candidates
- One symmetry responsible for DM stability and Diracness of the neutrinos
- $0\nu4\beta$ dominant $0\nu2n\beta$ process

Thank you!

Inetractions¶

#	Operator	Dim.	Self conj.?	Repeated fields	Symmetry and number of parameters
1	H[C] H[R]	2	True	–	{1, 1}
2	η[C] η[R]	2	True	–	{1, 1}
3	χ[C] χ[R]	2	True	–	{1, 1}
4	S[C] S[R]	2	True	–	{1, 1}
5	S_4[C] S_4[R]	2	True	–	{1, 1}
6	H[C] η[R] χ[R]	3	False	–	{1, 1}
7	χ[C] χ[C] S[R]	3	False	χ[C]	{S, 1, 1}
8	S[C] S[C] S_4[R]	3	False	S[C]	{S, 1, 1}
9	u[C] Q[R] H[R]	4	False	–	{9, 1}
10	d[C] Q[R] H[C]	4	False	–	{9, 1}
11	e[R] L[C] H[R]	4	False	–	{9, 1}
12	L[R] N_R[C] η[R]	4	False	–	{9, 1}
13	ν_R[R] N_L[C] χ[C]	4	False	–	{9, 1}
14	N_L[R] N_R[C] S_4[R]	4	False	–	{9, 1}
15	N_R[R] N_R[R] S_4[R]	4	False	N_R[R]	{S, 6, 1}
16	Ψ_{1L}[C] Ψ_{2L}[C] χ[C]	4	False	–	{9, 1}
17	Ψ_{2L}[R] Ψ_{3L}[R] χ[C]	4	False	–	{9, 1}
18	H[C] H[C] H[R] H[R]	4	True	{H[C], H[R]}	{{S, S}, 1, 1}
19	H[C] H[R] η[C] η[R]	4	True	–	{1, 2}
20	H[C] H[R] χ[C] χ[R]	4	True	–	{1, 1}
21	H[C] H[R] S[C] S[R]	4	True	–	{1, 1}
22	H[C] H[R] S_4[C] S_4[R]	4	True	–	{1, 1}
23	H[C] η[R] χ[C] S[R]	4	False	–	{1, 1}
24	η[C] η[C] η[R] η[R]	4	True	{η[C], η[R]}	{{S, S}, 1, 1}
25	η[C] η[R] χ[C] χ[R]	4	True	–	{1, 1}
26	η[C] η[R] S[C] S[R]	4	True	–	{1, 1}
27	η[C] η[R] S_4[C] S_4[R]	4	True	–	{1, 1}
28	χ[C] χ[C] χ[R] χ[R]	4	True	{χ[C], χ[R]}	{{S, S}, 1, 1}
29	χ[C] χ[C] S[C] S_4[R]	4	False	χ[C]	{S, 1, 1}
30	χ[C] χ[R] S[C] S[R]	4	True	–	{1, 1}
31	χ[C] χ[R] S_4[C] S_4[R]	4	True	–	{1, 1}
32	S[C] S[C] S[R] S[R]	4	True	{S[C], S[R]}	{{S, S}, 1, 1}
33	S[C] S[R] S_4[C] S_4[R]	4	True	–	{1, 1}
34	S_4[C] S_4[C] S_4[R] S_4[R]	4	True	{S_4[C], S_4[R]}	{{S, S}, 1, 1}

§Generated using Renato M. Fonseca, "The Sym2Int program: going from symmetries to interactions, arXiv:1703.05221 [hep-ph]

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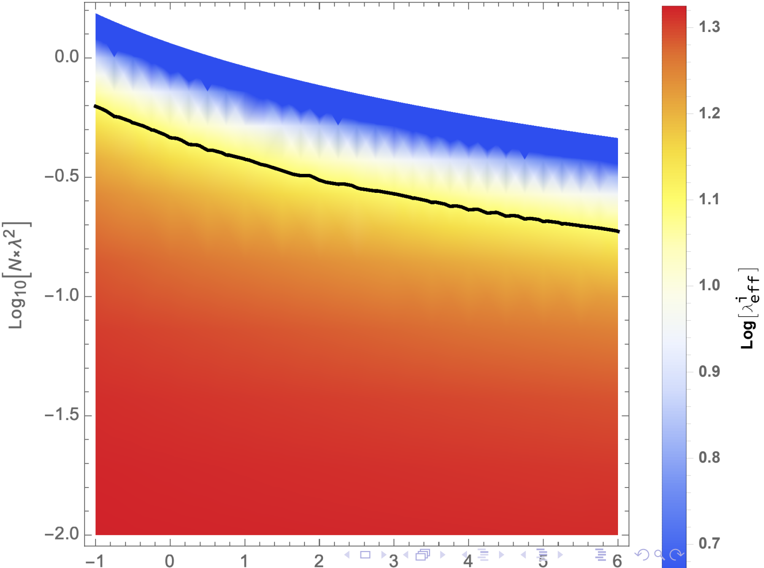
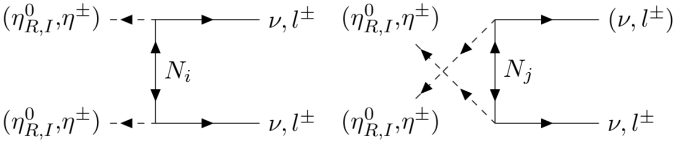
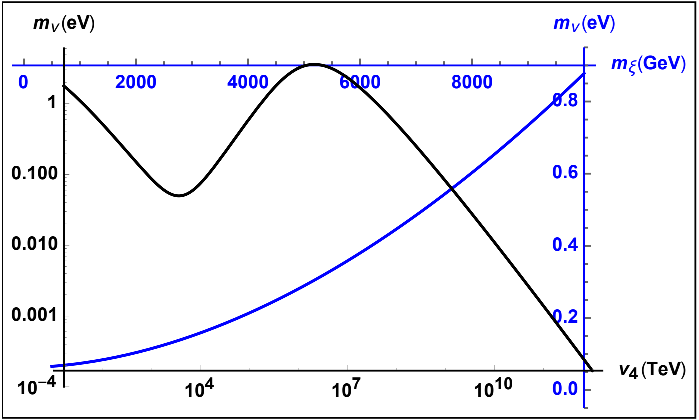


Leptogenesis



Constraints



Constraints

Radiative Dirac neutrino masses via $\mathbb{Z}_4$ from 3211

Out[100]=