Introduction
Brief review
Model
Anomalies
$\mathbb{Z}_4$
m_ν
Mass Spectrum
$0\nu4\beta$
Dark Matter Candidates
Leptogenesis
Conclusions

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

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

Overview

Introduction
Brief review
Model
Anomalies
$\mathbb{Z}_4$
m_ν
Mass Spectrum
$0\nu4\beta$
Dark Matter Candidates
Leptogenesis
Conclusions

1 Introduction
2 Brief review
3 Model
4 Anomalies
5 $\mathbb{Z}_4$
6 m_ν
7 Mass Spectrum
8 $0\nu4\beta$
9 Dark Matter Candidates
10 Leptogenesis
11 Conclusions

Introduction/Motivation

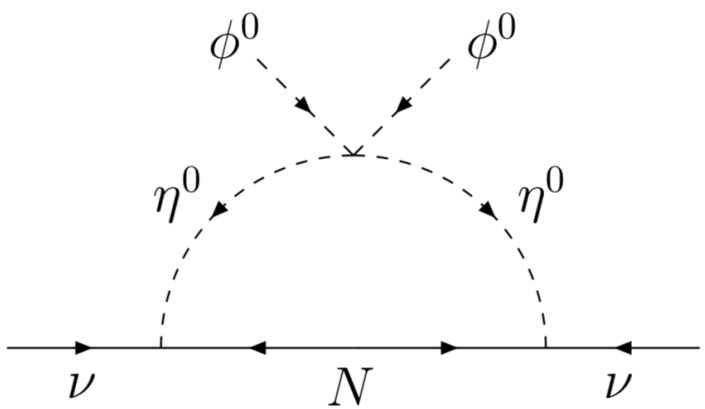
Introduction
Brief review
Model
Anomalies
$\mathbb{Z}_4$
m_ν
Mass Spectrum
$0\nu4\beta$
Dark Matter Candidates
Leptogenesis
Conclusions

- 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: $\frac{f_{ij}}{2\Lambda}\left(\nu_i\phi^0 - l_i\phi^+\right)\left(\nu_j\phi^0 - l_j\phi^+\right)$ + 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

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

Introduction

Brief review

Model

Anomalies

$\mathbb{Z}_4$

m_ν

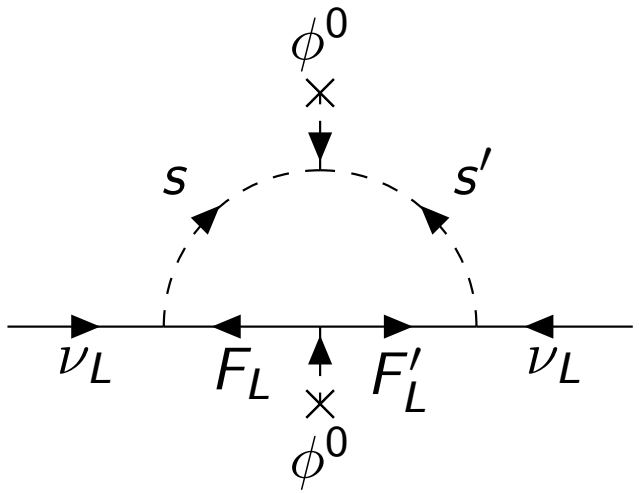
Mass Spectrum

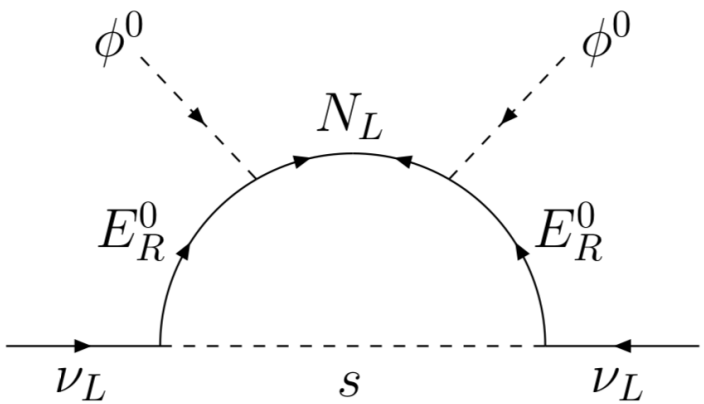
$0\nu4\beta$

Dark Matter Candidates

Leptogenesis

Conclusions



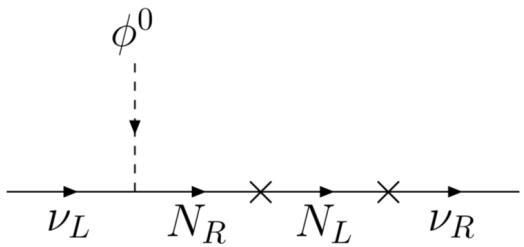


†

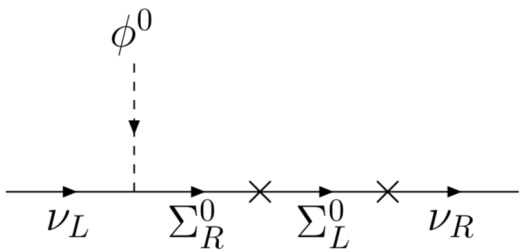
† Zee model (1980), Phys.Lett. 93B (1980) 389; Scot-Inverse-Seesaw Phys.Lett. B737 (2014) 280-282.

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 $\bar{\nu}_R \Sigma_L^0$ term.



‡ arXiv:1609.02538

Brief reveiw

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

Introduction

Brief review

Model

Anomalies

$\mathbb{Z}_4$

m_ν

Mass Spectrum

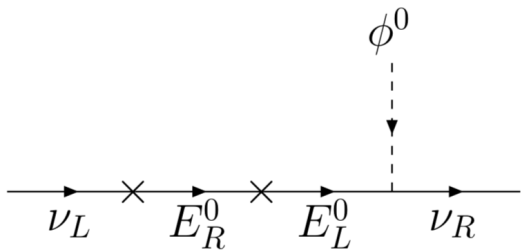
$0\nu4\beta$

Dark Matter Candidates

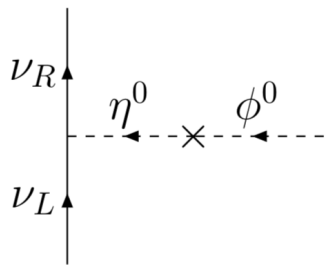
Leptogenesis

Conclusions

- 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

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

Introduction

Brief review

Model

Anomalies

$\mathbb{Z}_4$

m_ν

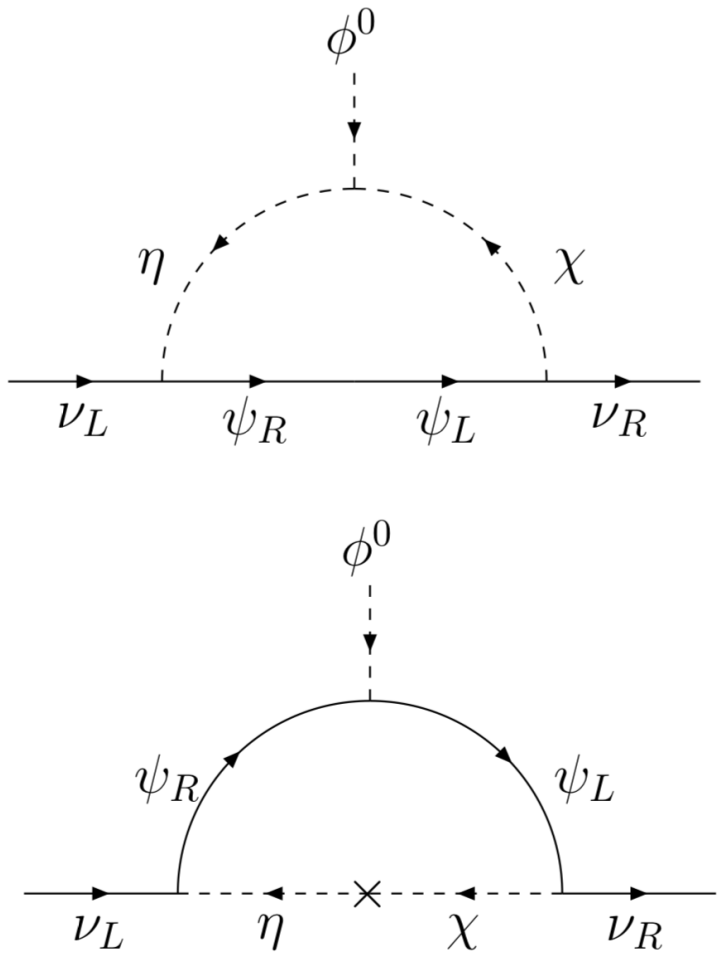
Mass Spectrum

$0\nu4\beta$

Dark Matter Candidates

Leptogenesis

Conclusions



Model particle content

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

Lagrangian

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

Leptogenesis

Conclusions

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

Potential

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

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

Radiative neutrino mass generation

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

Introduction

Brief review

Model

Anomalies

$\mathbb{Z}_4$

m_ν

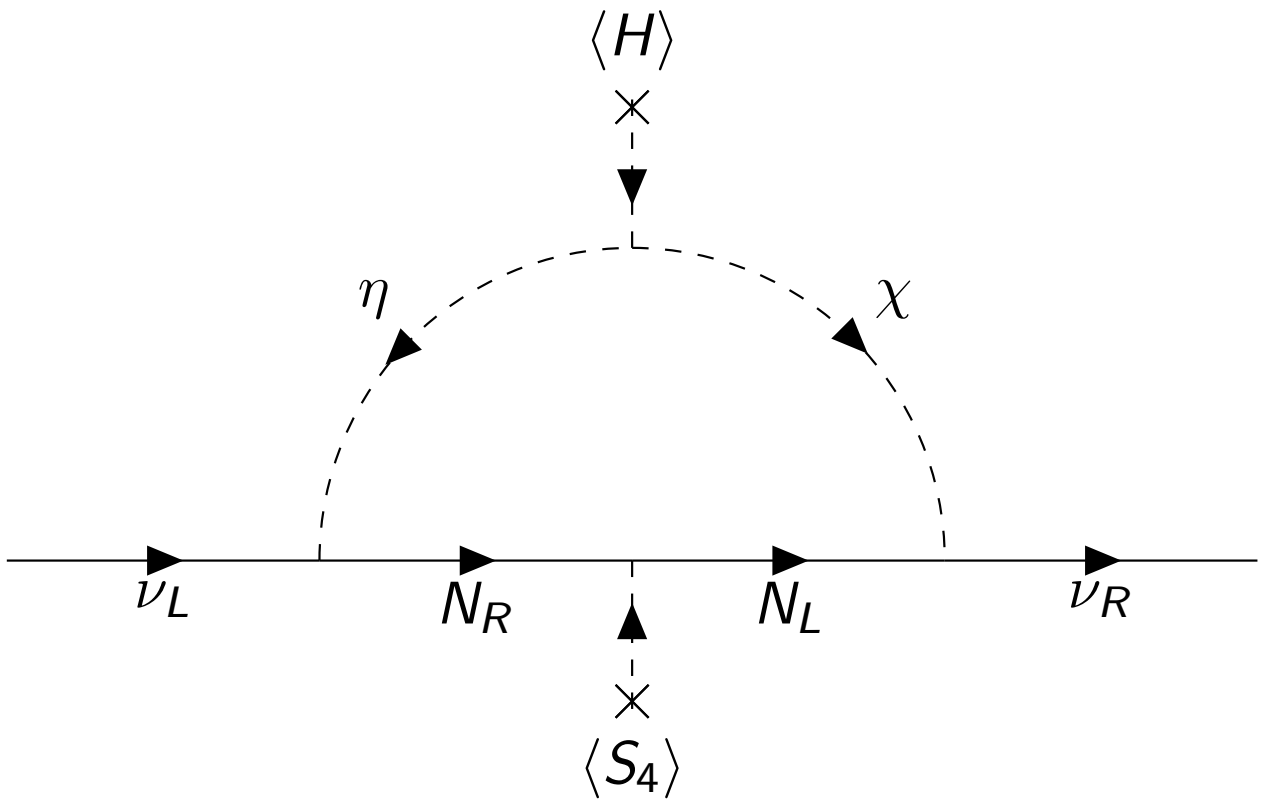
Mass Spectrum

$0\nu4\beta$

Dark Matter Candidates

Leptogenesis

Conclusions



Radiative neutrino mass generation

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Leptogenesis

Conclusions

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

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

Neutrinoless quadruple beta decay

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

Introduction

Brief review

Model

Anomalies

$\mathbb{Z}_4$

m_ν

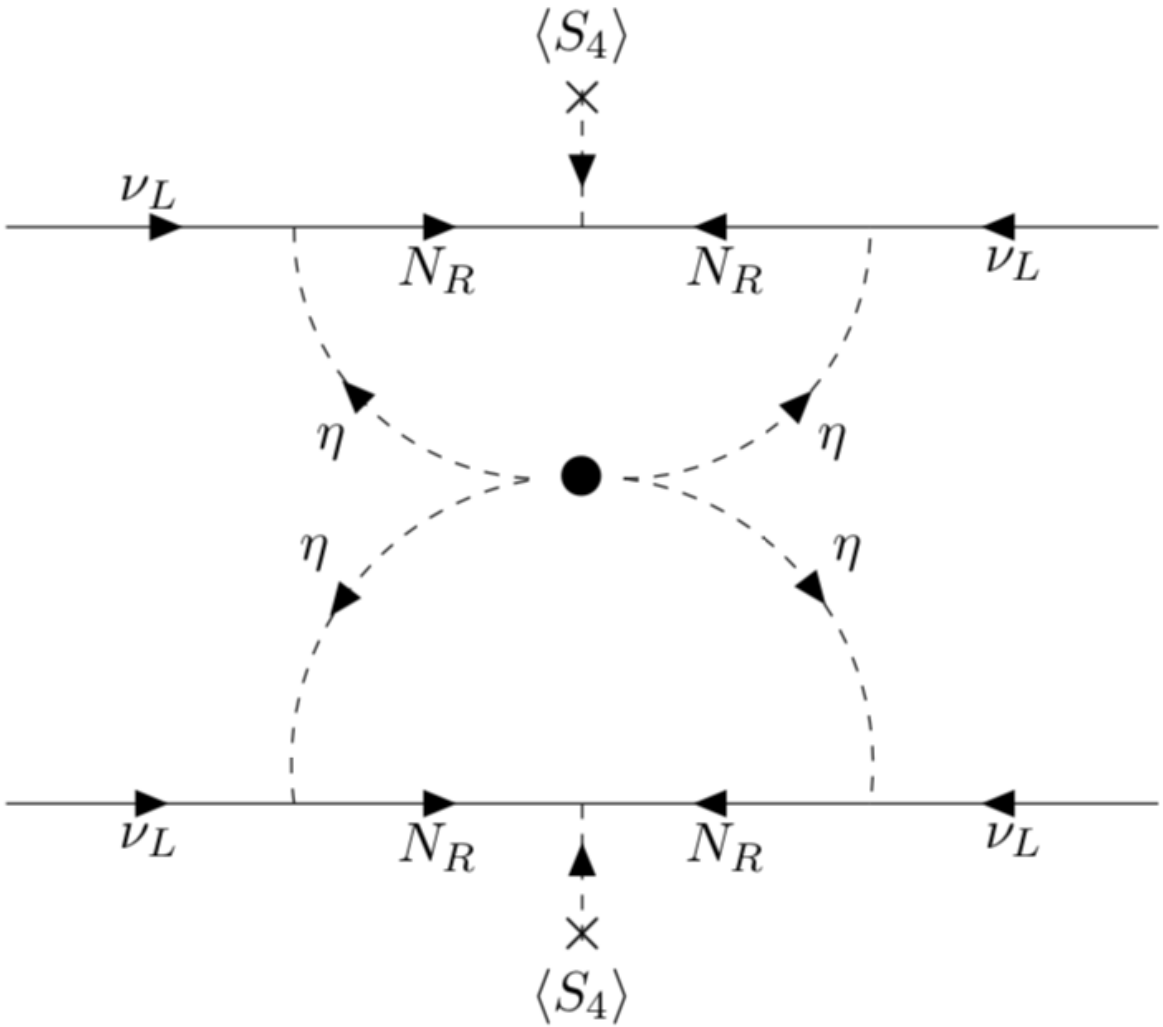
Mass Spectrum

$0\nu4\beta$

Dark Matter Candidates

Leptogenesis

Conclusions



Neutrinoless quadruple beta decay

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

Introduction

Brief review

Model

Anomalies

$\mathbb{Z}_4$

m_ν

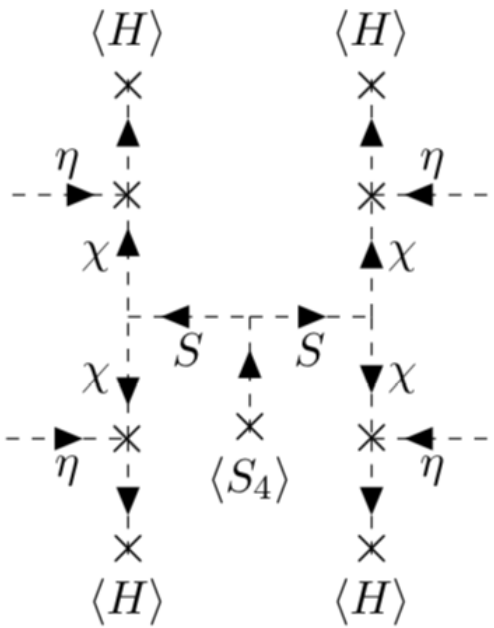
Mass Spectrum

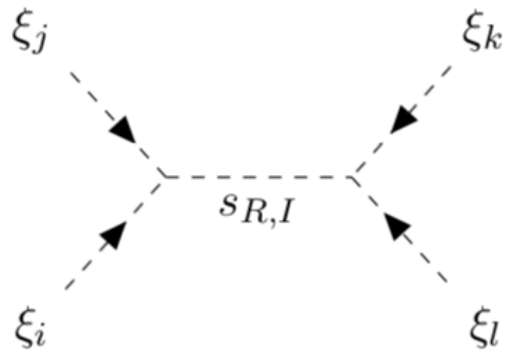
$0\nu4\beta$

Dark Matter Candidates

Leptogenesis

Conclusions





Neutrinoless quadruple beta decay

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

Leptogenesis

Conclusions

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

$$\mu^R_{ij}=\begin{pmatrix}s^2 & cs\\ cs & c^2\end{pmatrix}\left(\sqrt{2}\mu_S+\lambda_2\nu_4\right)$$

$$\mu^I_{ij}=\begin{pmatrix}s^2 & cs\\ cs & c^2\end{pmatrix}\imath\left(-\sqrt{2}\mu_S+\lambda_2\nu_4\right)$$

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

Neutrinoless quadruple beta decay

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

Leptogenesis

Conclusions

$$\frac{Q^{abcd}}{\Lambda^2} = \imath c_4 Y_L^{a\alpha} (v_s)_j \left[s_N^2 \frac{F(x_{l1}, y_{lj}, x_{j1})}{m_{N_1}} + c_N^2 \frac{F(x_{l2}, y_{lj}, x_{j2})}{m_{N_2}} \right]_{\alpha\beta} (M_s)_{jl} (v_s)_l Y_L^{\beta b} \times$$

$$Y_L^{c\gamma} (v_s)_i \left[s_N^2 \frac{F(x_{k1}, y_{ki}, x_{i1})}{m_{N_1}} + c_N^2 \frac{F(x_{k2}, y_{ki}, x_{i2})}{m_{N_2}} \right]_{\gamma\delta} (M_s)_{ik} (v_s)_k Y_L^{\delta d} \times$$

$$\frac{\left(m_{S_I}^2 - m_{S_R}^2\right)\left(2\mu_s^2 + \lambda_2^2 v_4^2\right) + \left(m_{S_I}^2 + m_{S_R}^2\right) 2\sqrt{2}\mu_S \lambda_2 v_4}{m_{S_I}^2 m_{S_R}^2},$$

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

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

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

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

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

Neutrinoless quadruple beta decay

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

Introduction

Brief review

Model

Anomalies

$\mathbb{Z}_4$

m_ν

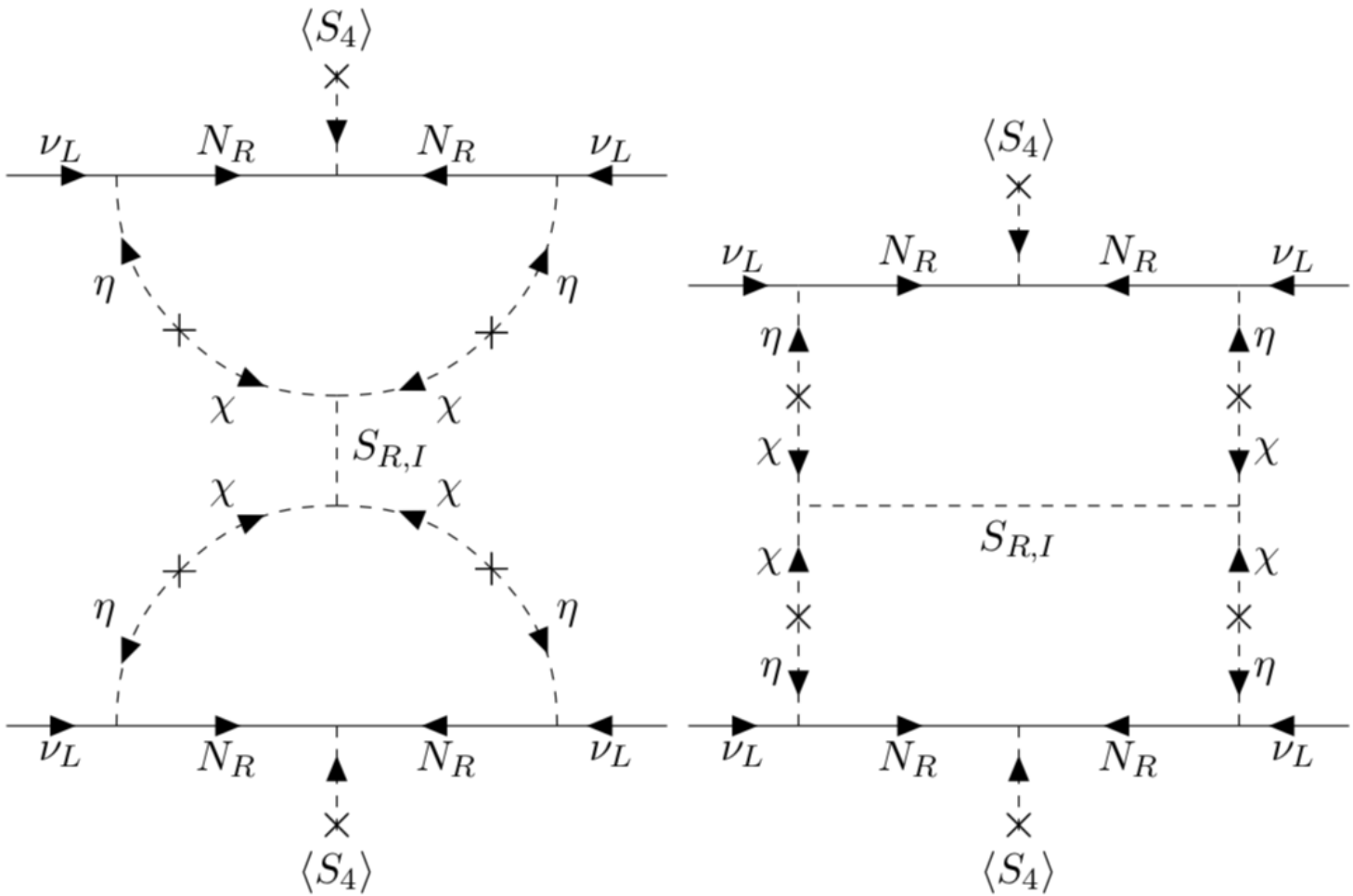
Mass Spectrum

$0\nu4\beta$

Dark Matter Candidates

Leptogenesis

Conclusions



Dark matter candidates

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

Leptogenesis

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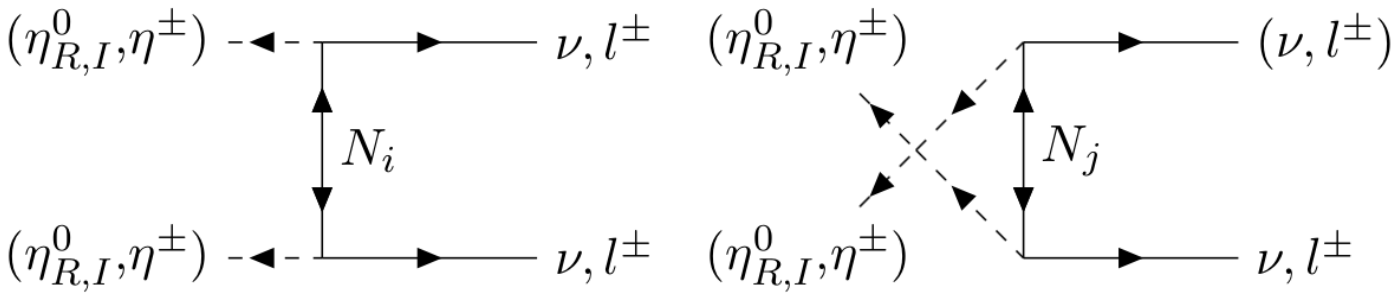
Mass Spectrum

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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]