Role of Heavy Scalars through higher-dimensional operators in Neutrino-mass and Z' phenomenology in an Anomaly-free U(1) extension

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Abstract

We consider an anomaly-free $U(1)$ extension of the Standard Model with three right-handed neutrinos (RHNs) and two complex scalars, wherein the charge assignments preclude all tree-level mass terms for the neutrinos. Considering this setup, in turn, to be only a low-energy effective theory, we introduce higher-dimensional terms *a la* Froggatt-Nielsen to naturally generate tiny neutrino masses. One of the RHNs turns out to be very light, thereby constituting the main decay mode for the Z' and hence relaxing the LHC dilepton resonance search constraints. The lightest RHN has a lifetime comparable to or bigger than the age of the Universe, and, hence, could account for a non-negligible fraction of the dark matter.

Motivation for an extra U(1)

- Theoretical motivation to introduce higher-dimensional operators through an extra $U(1)$: concept of generalized Frogatt-Nielsen set up.
- Traditional Z' phenomenology can be altered by initiation of new decay modes(eg. a pair of right-handed neutrinos(RHN), pair of new scalars etc.)
- It can potentially relax hitherto most constraining dilepton bound on the Z' mass.
- These higher-D operators can be utilized to produce small SM neutrino mass through a see-saw like mechanism, allowing for light RHN, such that they are accessible at colliders.
- If some of the RHNs are light, they can be viable dark matter.
- If two of the RHNs have similar masses, it can lead to resonant leptogenesis

The model

- The scalar lagrangian is given by:

$$\mathcal{L}_{\rm scalar} = (D^\mu H)^\dagger D_\mu H + \sum_A (\tilde{D}^\mu \chi_A)^\dagger \tilde{D}_\mu \chi_A - V(H^\dagger H, \{\chi_A^\dagger \chi_A\})$$

$$D_\mu = \partial_\mu - i g_s T^a G^a_\mu - i g_w \frac{\sigma^i}{2} W^i_\mu - i g_y \frac{Y}{2} B_\mu - i g_z \frac{z_{\mathcal{F}}}{2} X_\mu$$

- The heavy neutral gauge boson masses are given by

$$M_Z^2(M_{Z'}^2) = \frac{e^2 v_h^2 \cos^2 t}{\sin^2(2w)} + \frac{g_z^2}{4}\left(z_H^2 v_h^2 + \sum_A z_{\chi_A}^2 v_A^2\right)\sin^2 t \mp \frac{e g_z z_H v_h^2}{2\sin(2w)} \sin 2t$$

- The scalar part is constructed out of two complex scalars, with a $U(1)\times U(1)$ global symmetry with the potential:

$$V(\chi_1,\chi_2) = -\mu_1^2 \chi_1^\dagger \chi_1 - \mu_2^2 \chi_2^\dagger \chi_2 + \frac{\lambda_1}{2}(\chi_1^\dagger\chi_1)^2 + \frac{\lambda_2}{2}(\chi_2^\dagger\chi_2)^2 + \lambda_{12}(\chi_1^\dagger\chi_1)(\chi_2^\dagger\chi_2)\,.$$

$$\chi_{1,2} = \frac{1}{\sqrt{2}}(x_{1,2} + \xi_{1,2} + i\rho_{1,2})\ ,$$

where $\xi_{1,2}, \rho_{1,2}$ are real fields and $x_{1,2}$ are the two vevs.

- The massless pseudoscalar is given by

$$A = \rho_1 \sin\gamma_A - \rho_2 \cos\gamma_A\,, \qquad \tan\gamma_A = \frac{z_{\chi_2} x_2}{z_{\chi_1} x_1}$$

- The mixing angle and the masses of the two real scalars and are given by:

$$\tan(2\alpha_\chi) = \frac{2\lambda_{12} x_1 x_2}{\lambda_1 x_1^2 - \lambda_2 x_2^2}$$

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$$m_{1,2}^2 = \frac{1}{2}\left[\lambda_1 x_1^2 + \lambda_2 x_2^2 \pm |\lambda_1 x_1^2 - \lambda_2 x_2^2| \sec(2\alpha_\chi)\right]$$

- We stick to the most non-trivial rational values of z_i s: 4,4 and -5.

Anomaly	Expression
$[SU(3)_c]^2\, U(1)_z$	$2z_Q = z_u + z_d$
$[SU(2)]^2\, U(1)_z$	$3z_Q + z_L = 0$
$[U(1)_Y]^2\, U(1)_z$	$z_Q + 3z_L = 8z_u + 2z_d + 6z_e$
$U(1)_Y\, [U(1)_z]^2$	$z_Q^2 - z_L^2 = 2z_u^2 - z_d^2 - z_e^2$
$[U(1)_z]^3$	$6z_Q^3 + 2z_L^3 = 3z_u^3 + 3z_d^3 + z_e^3 + \sum_{i=1}^{3} z_i^3$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_z$
q_L	3	2	1/6	z_Q
u_R	3	1	2/3	$1+4z_Q$
d_R	3	1	$-1/3$	$-1-2z_Q$
ℓ_L	1	2	$-1/2$	$-3z_Q$
e_R	1	1	-1	$-1-6z_Q$
H	1	2	1/2	$1+3z_Q$
N_{1R}, N_{2R}	1	1	0	4
N_{3R}	1	1	0	-5
χ_1	1	1	0	z_{χ_1}
χ_2	1	1	0	z_{χ_2}

Neutrino mass and interactions

- The Lagrangian for neutrino masses is given by:

$$\mathcal{L}_{\nu\rm mass} = \mathcal{L}_{\rm Dirac} + \mathcal{L}_{\rm Wein.};$$

$$\mathcal{L}_{\rm Dirac} = \sum_{i=1}^{3}\sum_{\alpha=1}^{2} y_{i\alpha} \bar{L}_{iL} N_{\alpha R} \widetilde{H}\, \frac{\chi_1^{a_1}\chi_2^{a_2}}{\Lambda^{|a_1|+|a_2|}} + \sum_{i=1}^{3} \tilde{y}_i \bar{L}_{iL} N_{3R} \widetilde{H}\, \frac{\chi_1^{a_3}\chi_2^{a_4}}{\Lambda^{|a_3|+|a_4|}} + \text{H.c.};$$

$$\mathcal{L}_{\rm Wein.} = \sum_{i,j=1}^{3} w_{ij} \overline{L^c_{iL}} L_{jL} H H \frac{\chi_1^{b_1}\chi_2^{b_2}}{\Lambda^{|b_1|+|b_2|+1}} + \sum_{\alpha,\beta=1}^{2} s_{\alpha\beta} \overline{N^c_{\alpha R}} N_{\beta R} \frac{\chi_1^{b_3}\chi_2^{b_4}}{\Lambda^{|b_3|+|b_4|-1}} + \sum_{\alpha=1}^{2} s_{\alpha 3} \overline{N^c_{\alpha R}} N_{3R} \frac{\chi_1^{b_5}\chi_2^{b_6}}{\Lambda^{|b_5|+|b_6|-1}} + s_{33} \overline{N^c_{3R}} N_{3R} \frac{\chi_1^{b_7}\chi_2^{b_8}}{\Lambda^{|b_7|+|b_8|-1}} + \text{H.c.},$$

where the couplings $y_{i\alpha}, \tilde{y}_i, w_{ij}, s_{\alpha\beta}, s_{\alpha 3}$ and s_{33} are dimensionless and the exponents satisfy

$$z_{\chi_1} a_1 + z_{\chi_2} a_2 = -3 \qquad z_{\chi_1} a_3 + z_{\chi_2} a_4 = 6$$
$$z_{\chi_1} b_1 + z_{\chi_2} b_2 = -2 \qquad z_{\chi_1} b_3 + z_{\chi_2} b_4 = -8$$
$$z_{\chi_1} b_5 + z_{\chi_2} b_6 = 1 \qquad z_{\chi_1} b_7 + z_{\chi_2} b_8 = 10\,.$$

- Taking $z_{\chi_1} = -3/4$,$z_{\chi_2} = -4$ and restricting ourselves to operators of mass-dimension 12, we have

$$\mathcal{L}_{\nu\rm mass} \approx \mathcal{L}^{(5)} + \mathcal{L}^{(8)} + \mathcal{L}^{(12)} + \text{H.c.}$$

$$\mathcal{L}^{(5)} \equiv \sum_{\alpha,\beta=1}^{2} s_{\alpha\beta} \overline{N^c_{\alpha R}} N_{\beta R} \frac{x_2^2}{\Lambda},$$

$$\mathcal{L}^{(8)} \equiv \sum_{i=1}^{3}\sum_{\alpha=1}^{2} y_{i\alpha} \bar{L}_{iL} N_{\alpha R} \widetilde{H}\, \frac{x_1^4}{\Lambda^4} + \sum_{\alpha=1}^{2} s_{\alpha 3} \overline{N^c_{\alpha R}} N_{3R} \frac{x_1^4 x_2^*}{\Lambda^4},$$

$$\mathcal{L}^{(12)} \equiv \sum_{i=1}^{3} \tilde{y}_i \bar{L}_{iL} N_{3R} \widetilde{H}\, \frac{x_1^{*8}}{\Lambda^8}\ ,$$

- From the previous table we see that the charge assignment makes one of the RHN to become very light(can be a viable dark matter).
- The structure of the neutrino mass matrix looks like:

$$\mathcal{M}_\nu = \begin{pmatrix} 0_{3\times 3} & \mathcal{D} \\ D^T & M_N \end{pmatrix}$$

$$\mathcal{D} \approx v\xi^4 \begin{pmatrix} y_{13}\xi^4 & y_{11} & y_{12} \\ y_{23}\xi^4 & y_{21} & y_{22} \\ y_{33}\xi^4 & y_{31} & y_{32} \end{pmatrix} M_N \sim \frac{x^2}{\Lambda} \begin{pmatrix} 0 & s_{31}\xi^3 & s_{32}\xi^3 \\ s_{31}\xi^3 & a_1 & 0 \\ s_{32}\xi^3 & 0 & a_2 \end{pmatrix}.$$

- The 3×3 block diagonalised matrix is then given by:

$$M_{3\times 3} = -\mathcal{D} M_N^{-1} \mathcal{D}^T + \mathcal{O}(M_N^{-2}).$$

- The mass matrix is diagonalised by the PMNS matrix U

$$U^T M_{3\times 3} U = \widehat{M}\,, \qquad \widehat{M} \equiv \text{diag}(\nu_1, \nu_2, 0)$$

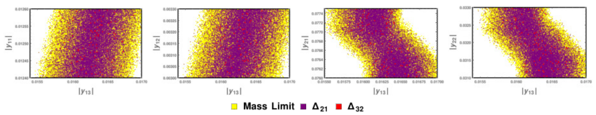

Figure 1: Correlation of Yukawa couplings in the Dirac sector for neutrino masses in normal hierarchy. Allowed points after diagonalization of neutrino mass matrix satisfying the bound on total mass of three neutrino species (in yellow), points with satisfying the bound on Δm^2_{32} (in purple) and allowed points after another bound of Δm^2_{12} (in red).

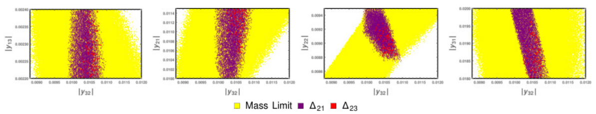

Figure 2: Correlation of Yukawa couplings in the Dirac sector for an inverted hierarchy of neutrino masses.

Z'phenomenology

- To leading order, the production cross-section is given by:

$$\sigma(pp \to Z' + X) \propto (z_Q^2 + z_u^2) F_u + (z_Q^2 + z_d^2) F_d\,.$$

$$F_u \equiv \int_{M^2_{Z'}/s}^{1} \frac{dx}{x}\left[f_u(x,Q^2) f_{\bar{u}}\left(\frac{M^2_{Z'}}{s\,x}, Q^2\right) + f_{\bar{u}}(x,Q^2) f\left(\frac{M^2_{Z'}}{s\,x}, Q^2\right)\right],$$

- Following three figures show branching ratios of relevant channels:

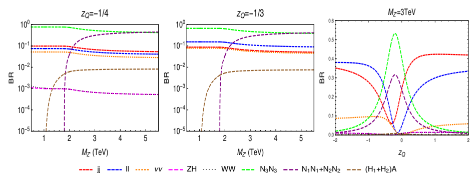

Figure 3: Branching ratios of various two-body decay modes of Z' as functions of its mass $M_{Z'}$ for (a) $z_Q = -1/4$ and (b) $z_Q = -1/3$. In (c), we show similar BRs as functions of z_Q for $M_{Z'} = 3$ TeV. For these plots, we choose $g_z = 0.15$. Here, j includes u, d, c, s, b and ℓ includes e, μ, τ.

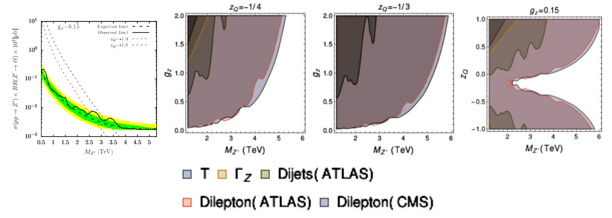

Figure 4: Comparison of the 95% CL upper bound on the observed and the expected $\sigma(pp \to Z') \times BR(Z' \to \ell\ell)$ obtained from the ATLAS dilepton resonance search data at the 13 TeV LHC with $L = 139\ \text{fb}^{-1}$ with the theoretical predictions of our model for $z_Q = -1/4$ and $-1/3$ choices. We use the reference value for the $U(1)_z$ gauge coupling $g_z = 0.15$. The green and yellow bands represent the 1σ and 2σ uncertainty regions of the expected values respectively.Exclusion regions in the $M_{Z'} - g_z$ plane for fixed (a) $z_Q = -1/4$ and (b) $z_Q = -1/3$ and in (c) in the $M_{Z'} - z_Q$ plane for fixed $g_z = 0.15$. We show exclusion regions using T-parameter, Z-width, and the latest dilepton and dijet data from the LHC.

DM?

- The mass of the lightest RHN is given by:

$$m(\Psi) \sim \left(s_{\alpha 3}\frac{x_1^4 x_2}{\Lambda^4}\right)^2 \frac{\Lambda}{x_2^2} \sim s_{\alpha 3}^2 \xi^7 x\,.$$

This gives a mass of few keVs for $s_{\alpha 3}$ of 0.05 and $N_{1,2}$ 1.2 TeV.

- The mixing between the lightest RHN and the three light neutrinos can be written as:

$$\Psi \approx \cos\theta_i N_3 + \sin\theta_i \nu_i\,, \qquad \nu' \approx -\sin\theta_i N_3 + \cos\theta_i \nu\,,$$

- This leads to the Z-mediated decay mode:

$$\Gamma_i = \Gamma(\Psi \to \nu_i \bar{\nu}_j \nu_j) \sim \frac{G_F^2 M_{N_3}^5}{192\pi^3} \sin^2\theta_i \left(1 - \frac{\delta_{ij}}{2}\right),$$

- This gives a lifetime barely $\tau_\psi > \tau_U$. We plan to investigate the relic density and the various contraints on it in a future project.

Conclusion

- We introduced Higher-Dimensional effective operators by extending the SM gauge group by an extra U(1).
- We utilised the power of higher-dimensional operators to arrive at the correct neutrino masses obeying all neutrino constraints and without resorting to ultra-small couplings.
- We showed that this kind of framework leads to a relaxed bound on Z' mass from the dilepton and dijet data.
- We can potentially solve two big shortcomings of SM: Dark Matter and Matter-Antimatter asymmetry.

Acknowledgements

DC and TM acknowledge partial support from the SERB, India under research grant CRG/2018/004889. DC also acknowledges the European Union's Horizon 2020 research and innovation program under Marie Skłodowska-Curie grant No 690575. KD acknowledges Council for Scientific and Industrial Research(CSIR), India for JRF fellowship with award letter no. 09/045(1654)/2019-EMR-1. SS thanks UGC for the DS Kothari postdoctoral fellowship grant with award letter No.F.4-2/2006 (BSR)/PH/17-18/0126.

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