Role of Higher-Dimensional Operators in an Anomaly-free U(1) extension

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Plan of the talk

1. Motivation
2. The model
3. Neutrino interactions and masses
4. Z' phenomenology
5. Interesting Collider Signatures
6. Dark Matter?
7. Resonant Leptogenesis
8. Conclusion

Motivation for extra U(1)

- Frogatt-Nielsen(FN) setup ascribed higgs and quarks some extra charges corresponding to a discrete or continous symmetry.
- Higher-Dimensional terms could instead be written by inserting an appropriate number of "Flavon" scalar field $\mathcal{F}$.
- Here we consider a setup where the flavon charges correspond to an U(1), but restricted strictly to neutrino sector.
- Can help alter the traditional Z' phenomenology.
- The higher-D an be utilized to produce small SM neutrino mass.
- 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.

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

- Existence of mass terms of the fermions require

$$z_H = z_L - z_e = z_Q - z_d = z_u - z_Q \ . \tag{1}$$

- After simplification of all the constraints, the RHNs satisfy:

$$\sum_i z_i^3 = 3 \ . \tag{2}$$

- We stick to the most non-trivial rational values of z_i s: 4,4 and -5.
- The other fermion charges can be simplified to:

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_z$
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}

Table: The charge assignments for the fermions and scalars of the model.

- Proceeding with the choice $z_{\chi_1} = -3/4$ and $z_{\chi_2} = -4$ for the scalars, the neutrino mass terms can be written as:

$$
\begin{aligned}
\mathcal{L}_{\nu\mathrm{mass}} &\approx \mathcal{L}^{(5)} + \mathcal{L}^{(8)} + \mathcal{L}^{(12)} + \mathrm{H.c.} \\
\mathcal{L}^{(5)} &\equiv \sum_{\alpha,\beta=1}^{2} s_{\alpha\beta}\,\overline{N^c_{\alpha R}} N_{\beta R}\,\frac{x_2^2}{\Lambda}\,, \\
\mathcal{L}^{(8)} &\equiv \sum_{i=1}^{3}\sum_{\alpha=1}^{2} y_{i\alpha}\,\bar{L}_{iL}\,N_{\alpha R}\widetilde{H}\;\frac{x_1^4}{\Lambda^4} + \sum_{\alpha=1}^{2} s_{\alpha 3}\,\overline{N^c_{\alpha R}} N_{3R}\,\frac{x_1^4\,x_2^*}{\Lambda^4}\,, \\
\mathcal{L}^{(12)} &\equiv \sum_{i=1}^{3} \tilde{y}_i\,\bar{L}_{iL}\,N_{3R}\widetilde{H}\;\frac{x_1^{*8}}{\Lambda^8}\;,
\end{aligned}
\tag{3}
$$

- The structure of the neutrino mass matrix looks like:

$$\mathcal{M}_\nu = \begin{pmatrix} 0_{3\times 3} & \mathcal{D} \\ D^T & M_N \end{pmatrix} \tag{4}$$

$$\mathcal{D} \approx v\xi^4 \begin{pmatrix} y_{13}\xi^4 & y_{11} & y_{12} \\ y_{23}\xi^4 & y_{21} & y_{22} \\ y_{33}\xi^4 & y_{31} & y_{32} \end{pmatrix} M_N \sim \frac{x^2}{\Lambda} \begin{pmatrix} 0 & s_{31}\xi^3 & s_{32}\xi^3 \\ s_{31}\xi^3 & a_1 & 0 \\ s_{32}\xi^3 & 0 & a_2 \end{pmatrix}. \tag{5}$$

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

$$M_{3\times 3} = -\mathcal{D} M_N^{-1} \mathcal{D}^T + \mathcal{O}(M_N^{-2}). \tag{6}$$

- The matrix explicitely is:

$$M_{3\times 3} = \frac{-v^2\xi^6}{2\Lambda} \begin{pmatrix} M_{11} & M_{12} & M_{13} \\ M_{12} & M_{22} & M_{23} \\ M_{13} & M_{23} & M_{33} \end{pmatrix} . \tag{7}$$

- The mass matrix is diagonalised by the PMNS matrix U

$$U^T M_{3\times 3} U = \widehat{M} \ , \qquad \widehat{M} \equiv \mathrm{diag}(\nu_1, \nu_2, 0) \tag{8}$$

Normal Hierarchy

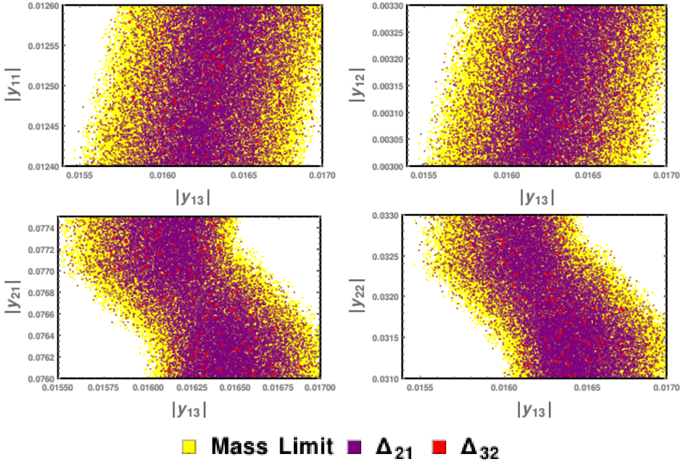


Figure: Correlation of Yukawa couplings in the Dirac sector for neutrino masses in normal hierarchy. Allowed points after diagonalization of neutrino mass matrix satisfying the bound on total mass of three neutrino species (in yellow), points with satisfying the bound on Δm_{32}^2 (in purple) and allowed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

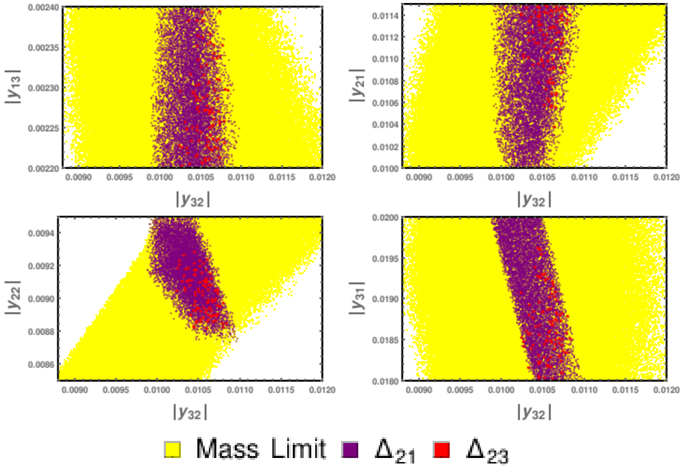
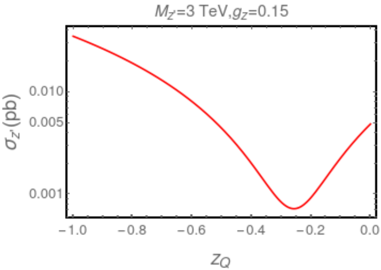
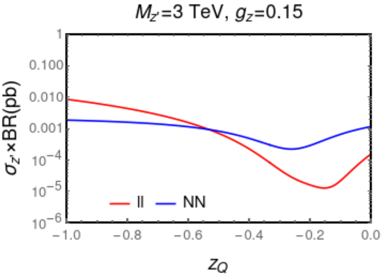


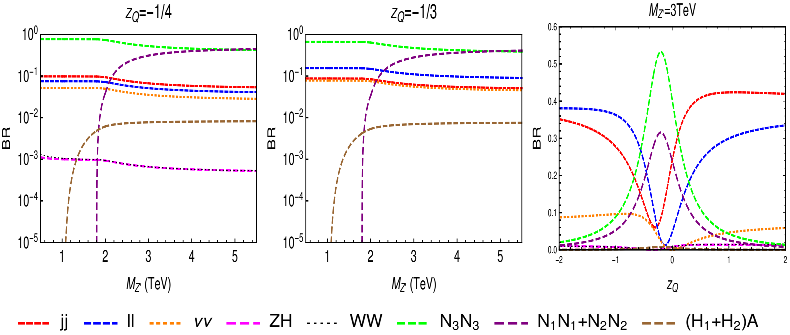
Figure: Correlation of Yukawa couplings in the Dirac sector for an inverted hierarchy of neutrino masses.

Z' phenomenology

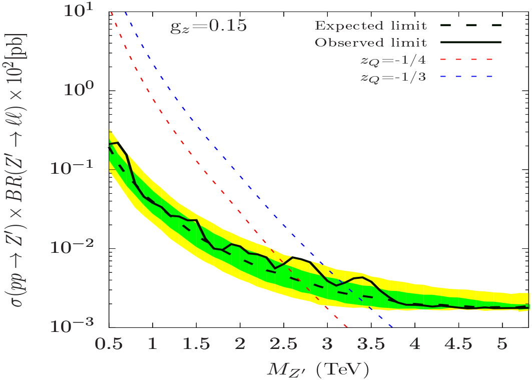
- g_z can be best investigated at colliders through direct production or by effecting precesion studies.

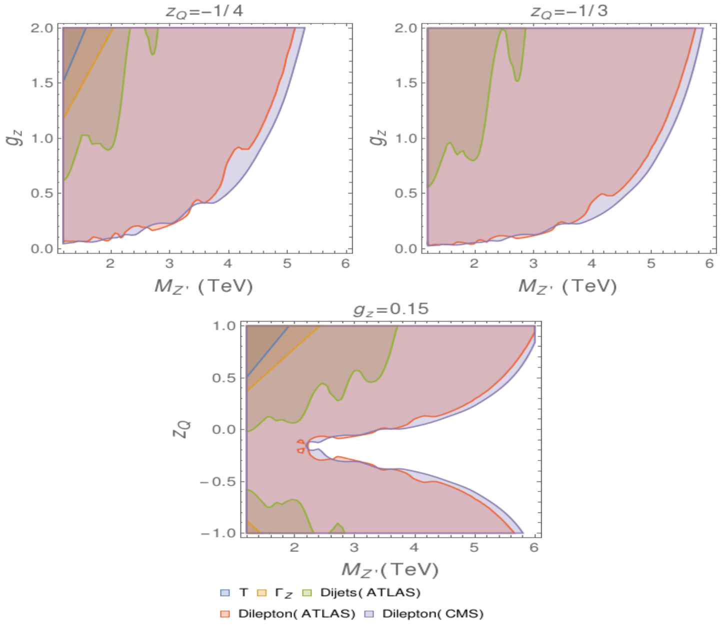





z_Q=−1/4
z_Q=−1/3
M_Z=3TeV
BR
M_Z (TeV)
z_Q
jj
ll
νν
ZH
WW
N_3N_3
$N_1N_1+N_2N_2$
$(H_1+H_2)A$

Exclusion Plots





z_Q=−1/4
z_Q=−1/3
g_z=0.15
g_z
z_Q
$M_{Z'}$ (TeV)
T
Γ_Z
Dijets(ATLAS)
Dilepton(ATLAS)
Dilepton(CMS)

- **Mono-lepton:** The mono-lepton signature can arise from the following decay

$$pp \to Z' \to N_1 N_1 + N_2 N_2 \left\{ \begin{array}{cc} \to & (W_h^\pm \ell^\mp)(Z_h \nu) \\ \to & (W_h^\pm \ell^\mp)(H_h \nu) \end{array} \right\} , \tag{9}$$

- **Di-lepton:** The di-lepton signature can arise from the following decay

$$pp \to Z' \to N_1 N_1 + N_2 N_2 \to (W_h^\pm \ell^\mp)(W_h^\pm \ell^\mp) \ . \tag{10}$$

- **Tri-lepton:** The tri-lepton signature can arise from the following decay

$$pp \to Z' \to N_1 N_1 + N_2 N_2 \left\{ \begin{array}{cc} \to & (W_\ell^\pm \ell^\mp)(W_h^\pm \ell^\mp) \\ \to & (W_h^\pm \ell^\mp)(Z_\ell \nu) \end{array} \right\} . \tag{11}$$

- If the light-heavy neutrino mixing angle is very small, the RHNs become long-lived which can lead to a unique displaced vertex (DV) signature.

A Dark-Matter Candidate?

- The mass of the lightest RHN is given by:

$$m(\Psi) \sim \left(s_{\alpha 3} \frac{x_1^4 x_2}{\Lambda^4} \right)^2 \frac{\Lambda}{x_2^2} \sim s_{\alpha 3}^2 \xi^7 x \ . \tag{12}$$

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

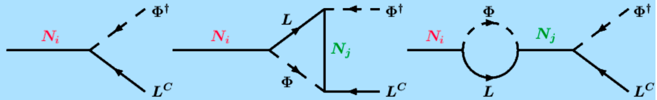
- The mixing between the lightest RHN and the three light neutrinos can be written as:

$$\Psi \approx \cos\theta_i N_3 + \sin\theta_i \nu_i \ , \qquad \nu' \approx - \sin\theta_i N_3 + \cos\theta_i \nu \ , \tag{13}$$

- This leads to the Z-mediated decay mode:

$$\Gamma_i = \Gamma(\Psi \to \nu_i \bar{\nu}_j \nu_j) \sim \frac{G_F^2 M_{N_3}^5}{192\pi^3} \sin^2\theta_i \left(1 - \frac{\delta_{ij}}{2}\right) \ , \tag{14}$$

- Lepton number and CP violation can occur through the out of equilibrium decay of a heavy RHN.



- The CP asymmetry is given by:

$$\epsilon^l_{N_k} = -\sum \frac{\Gamma(N_k \to L_l + H^+, \nu_l + H^0) - \Gamma(N_k \to L_l + H^-, \nu_l^c + H^{0^*})}{\Gamma(N_k \to L_l + H^+, \nu_l + H^0) + \Gamma(N_k \to L_l + H^-, \nu_l^c + H^{0^*})} \tag{15}$$

- For Resonant Leptogenesis

$$M_{Ni} - M_{Nj} \sim \frac{\Gamma_{N_{i,j}}}{2}, \quad \frac{\mathrm{Im}\left(Y_\nu^\dagger Y_\nu\right)^2_{ij}}{\left(Y_\nu^\dagger Y_\nu\right)_{ii}\left(Y_\nu^\dagger Y_\nu\right)_{jj}} \sim 1. \tag{16}$$

- The approximate expression for baryon to photon ratio can be written as:

$$\eta_B \sim \sum_{l,i} \frac{\epsilon_{il}}{200 * K_i} \tag{17}$$

- The approximate baryon asymmetry can be achieved:

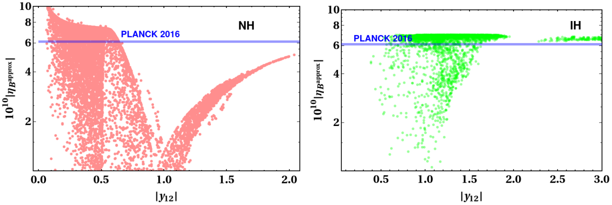
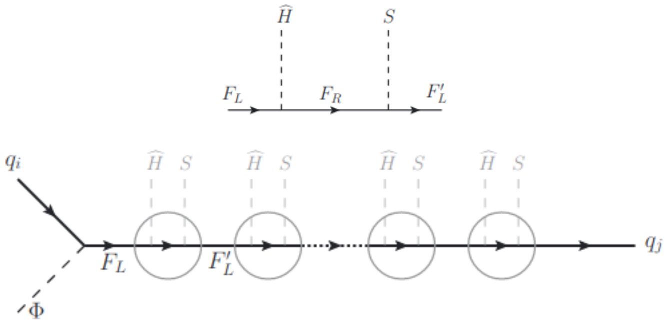


Figure: Baryon asymmetry as a function of Yukawa coupling (y_{12}) for NH (left panel) and IH (right panel). The violate line indicates the Planck bound reporting the baryon to photon ratio to be $\eta_B = (6 - 6.18) \times 10^{-10}$.

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.

Thank You!



$$\mathcal{L}_{\text{eff}}^{\text{Down}} = -\sum_{ij} \varepsilon^{b_i+a_j+R}\,\overline{Q}_i Y_{ij} \Phi D_j. \qquad Y_{ij} = g_{q_i \Phi F_1} g_{F_n S q_j} \prod_{k=1}^{n-1} g_{F_k S F_{k+1}}.$$

[3]

- The scalar lagrangian is given by:

$$\mathcal{L}_{\rm scalar} = (D^\mu H)^\dagger D_\mu H + \sum_A (\tilde{D}^\mu \chi_A)^\dagger \tilde{D}_\mu \chi_A - V(H^\dagger H, \{\chi_A^\dagger \chi_A\}) \tag{18}$$

- The mass matrix and the mixing angles are given by:

$$\mathcal{M}^2 = \frac{1}{4}\begin{bmatrix} g_y^2 v_h^2 & -g_y g_w v_h^2 & g_y g_z z_H v_h^2 \\ -g_y g_z v_h^2 & g_w^2 v_h^2 & -g_w g_z z_H v_h^2 \\ g_y g_z z_h v_h^2 & -g_w g_z z_H v_h^2 & g_z^2 (z_H^2 v_h^2 + \sum_A z_{\chi_A}^2 x_A^2) \end{bmatrix} \tag{19}$$

$$\cot(2t)\,\frac{4 z_H g_z e}{\sin(2w)} = \frac{g_z^2}{v_h^2}\left(\sum_A z_{\chi_A}^2 v_A^2 + z_H^2 v_h^2\right) - \frac{4e^2}{\sin^2(2w)} \tag{20}$$

- The heavy neutral gauge boson masses are given by

$$M_Z^2 (M_{Z'}^2) = \frac{e^2 v_h^2 \cos^2 t}{\sin^2(2w)} + \frac{g_z^2}{4}\left(z_H^2 v_h^2 + \sum_A z_{\chi_A}^2 v_A^2\right)\sin^2 t \mp \frac{e g_z z_H v_h^2}{2\sin(2w)}\sin 2t \tag{21}$$

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

$$V(\chi_1, \chi_2) = -\mu_1^2 \chi_1^\dagger \chi_1 - \mu_2^2 \chi_2^\dagger \chi_2 + \frac{\lambda_1}{2} (\chi_1^\dagger \chi_1)^2 + \frac{\lambda_2}{2} (\chi_2^\dagger \chi_2)^2 + \lambda_{12} (\chi_1^\dagger \chi_1)(\chi_2^\dagger \chi_2) . \quad (22)$$

$$\chi_{1,2} = \frac{1}{\sqrt{2}} (x_{1,2} + \xi_{1,2} + i\rho_{1,2}) \ , \quad (23)$$

  where $\xi_{1,2}, \rho_{1,2}$ are real fields and $x_{1,2}$ are the two vevs.
- For charges z_{χ_1} and z_{χ_2}, one combination is gauged which gives the longitudinal mode of $Z^{'}$.
- The massless pseudoscalar is given by

$$A = \rho_1 \sin\gamma_A - \rho_2 \cos\gamma_A \ , \qquad \tan\gamma_A = \frac{z_{\chi_2} x_2}{z_{\chi_1} x_1} \quad (24)$$

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

$$\tan(2\alpha_\chi) = \frac{2\lambda_{12} x_1 x_2}{\lambda_1 x_1^2 - \lambda_2 x_2^2} \quad (25)$$

$$m_{1,2}^2 = \frac{1}{2} \left[\lambda_1 x_1^2 + \lambda_2 x_2^2 \pm |\lambda_1 x_1^2 - \lambda_2 x_2^2| \sec(2\alpha_\chi) \right] \quad (26)$$

- The Lagrangian for neutrino masses is given by:

$$
\begin{aligned}
\mathcal{L}_{\nu\text{mass}} &= \mathcal{L}_{\text{Dirac}} + \mathcal{L}_{\text{Wein.}}; \\
\mathcal{L}_{\text{Dirac}} &= \sum_{i=1}^{3}\sum_{\alpha=1}^{2} y_{i\alpha}\bar{L}_{iL}N_{\alpha R}\widetilde{H}\,\frac{\chi_1^{a_1}\,\chi_2^{a_2}}{\Lambda^{|a_1|+|a_2|}} + \sum_{i=1}^{3}\tilde{y}_i\bar{L}_{iL}N_{3R}\widetilde{H}\,\frac{\chi_1^{a_3}\,\chi_2^{a_4}}{\Lambda^{|a_3|+|a_4|}} + \text{H.c.}; \\
\mathcal{L}_{\text{Wein.}} &= \sum_{i,j=1}^{3} w_{ij}\overline{L_{iL}^{c}}L_{jL}HH\,\frac{\chi_1^{b_1}\,\chi_2^{b_2}}{\Lambda^{|b_1|+|b_2|+1}} + \sum_{\alpha,\beta=1}^{2} s_{\alpha\beta}\overline{N_{\alpha R}^{c}}N_{\beta R}\,\frac{\chi_1^{b_3}\,\chi_2^{b_4}}{\Lambda^{|b_3|+|b_4|-1}} \\
&+ \sum_{\alpha=1}^{2} s_{\alpha 3}\overline{N_{\alpha R}^{c}}N_{3R}\,\frac{\chi_1^{b_5}\,\chi_2^{b_6}}{\Lambda^{|b_5|+|b_6|-1}} + s_{33}\overline{N_{3R}^{c}}N_{3R}\,\frac{\chi_1^{b_7}\,\chi_2^{b_8}}{\Lambda^{|b_7|+|b_8|-1}} + \text{H.c.},
\end{aligned}
\tag{27}
$$

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

$$
\begin{aligned}
z_{\chi_1}a_1 + z_{\chi_2}a_2 &= -3 & \qquad z_{\chi_1}a_3 + z_{\chi_2}a_4 &= 6 \\
z_{\chi_1}b_1 + z_{\chi_2}b_2 &= -2 & \qquad z_{\chi_1}b_3 + z_{\chi_2}b_4 &= -8 \\
z_{\chi_1}b_5 + z_{\chi_2}b_6 &= 1 & \qquad z_{\chi_1}b_7 + z_{\chi_2}b_8 &= 10\ .
\end{aligned}
\tag{28}
$$