New constraints on the 3-3-1 model with right-handed neutrinos

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Outline

1. The Model
   - Gauge group
   - Matter Content
   - Lagrangian
2. The Model with $\mathbb{Z}_2$ symmetry
3. The Model with soft $\mathbb{Z}_2$ breaking terms
   - $\mu_4^2 \chi^\dagger \eta$ term
   - $\frac{f}{\sqrt{2}} \epsilon_{ijk} \eta_i \rho_j \chi_k$ term
4. Summary and Conclusions

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4. Summary and Conclusions

Gauge Group

$$
\begin{array}{rc}
\text{3-3-1}: & \mathrm{SU}(3)_L \otimes \mathrm{U}(1)_N \\
 & \downarrow \langle \chi \rangle \\
\text{SM}: & \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \\
 & \downarrow \langle \rho \rangle \,, \langle \eta \rangle \\
 & \mathrm{U}(1)_Q
\end{array}
$$

Why 3-3-1?

- Dark matter;
- Neutrino masses;
- Chiral anomaly free.

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Matter Content

Scalar triplets

$$\eta = \begin{pmatrix} \eta_1^0 \\ \eta_2^- \\ \eta_3^0 \end{pmatrix}, \quad \rho = \begin{pmatrix} \rho_1^+ \\ \rho_2^0 \\ \rho_3^+ \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi_1^0 \\ \chi_2^- \\ \chi_3^0 \end{pmatrix}$$

Left-handed fermions

$$f_{aL} = \begin{pmatrix} \nu_a \\ e_a \\ N_a^c \end{pmatrix}_L, \quad Q_L = \begin{pmatrix} u_1 \\ d_1 \\ u_4 \end{pmatrix}_L, \quad Q_{bL} = \begin{pmatrix} d_b \\ u_b \\ d_{b+2} \end{pmatrix}_L,$$

where $a = 1, 2, 3$ and $b = 2, 3$.

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Matter content

Right-handed fermions

$e_{aR}, \quad u_{sR}, \quad d_{tR}$ are singlets with respect to $SU(3)_L$

where $s = 1, \ldots, 4$ and $t = 1, \ldots, 5$.

Outline

Yukawa Lagrangian

$\mathcal{L}_{\text{Yuk}}$

$$\mathcal{L}_{\text{Yuk}} = \mathcal{L}^{\rho}_{\text{Yuk}} + \mathcal{L}^{\eta}_{\text{Yuk}} + \mathcal{L}^{\chi}_{\text{Yuk}} \quad ,$$

$$\mathcal{L}^{\rho}_{\text{Yuk}} = \alpha_t \bar{Q}_L d_{tR}\rho + \alpha_{bs}\bar{Q}_{bL} u_{sR}\rho^* + Y_{aa'}\varepsilon_{ijk}\left(\bar{f}_{aL}\right)_i \left(f_{a'L}\right)^c_j \left(\rho^*\right)_k + Y'_{aa'}\bar{f}_{aL} e_{a'R}\rho + \text{H.c.},$$

where $a, a', i, j, k = 1, 2, 3$; $b = 2, 3$; $s = 1, ..., 5$; $t = 1, ..., 4$.

Yukawa Lagrangian

$\mathcal{L}_{\rm Yuk}$

$$\mathcal{L}_{\rm Yuk} = \mathcal{L}^{\rho}_{\rm Yuk} + \mathcal{L}^{\eta}_{\rm Yuk} + \mathcal{L}^{\chi}_{\rm Yuk} \quad ,$$

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where $a, a', i, j, k = 1, 2, 3;\ b = 2, 3;\ s = 1, ..., 5;\ t = 1, ..., 4.$

Yukawa Lagrangian

$$\mathcal{L}^{\eta}_{\text{Yuk}} = \beta_s \bar{Q}_L u_{sR} \eta + \beta_{bt} \bar{Q}_{bL} d_{tR} \eta^* + \text{H.c.},$$

$$\mathcal{L}^{\chi}_{\text{Yuk}} = \gamma_s \bar{Q}_L u_{sR} \chi + \gamma_{bt} \bar{Q}_{bL} d_{tR} \chi^* + \text{H.c.}$$

where $b = 2, 3$; $s = 1, ..., 5$; $t = 1, ..., 4$.

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Spontaneous Symmetry breaking

Minimally general vacuum structure

$$\langle\eta\rangle = \frac{1}{\sqrt{2}}\left(\begin{array}{c} v_{\eta_1} \\ 0 \\ 0 \end{array}\right), \quad \langle\rho\rangle = \frac{1}{\sqrt{2}}\left(\begin{array}{c} 0 \\ v_{\rho_2} \\ 0 \end{array}\right), \quad \langle\chi\rangle = \frac{1}{\sqrt{2}}\left(\begin{array}{c} 0 \\ 0 \\ v_{\chi_3} \end{array}\right)$$

- $\langle\chi\rangle$: mass to the exotic quarks: d_4,d_5 and u_4;
- $\langle\rho\rangle$: mass to e, μ, τ; d_1, u_2, u_3 quarks; 2 neutrinos;
- $\langle\eta\rangle$: mass to u_1, d_2, d_3 quarks.

Scalar Potential

$$V(\eta,\rho,\chi) = V_{\mathbb{Z}_2}(\eta,\rho,\chi) + V_{\not{\mathbb{Z}}_2}(\eta,\rho,\chi);$$

$$\begin{aligned}
V_{\mathbb{Z}_2}(\eta,\rho,\chi) \quad = \quad & -\mu_1^2\eta^\dagger\eta - \mu_2^2\rho^\dagger\rho - \mu_3^2\chi^\dagger\chi \\
& +\lambda_1\left(\eta^\dagger\eta\right)^2 + \lambda_2\left(\rho^\dagger\rho\right)^2 + \lambda_3\left(\chi^\dagger\chi\right)^2 \\
& +\lambda_4\left(\chi^\dagger\chi\right)\left(\eta^\dagger\eta\right) + \lambda_5\left(\chi^\dagger\chi\right)\left(\rho^\dagger\rho\right) \\
& +\lambda_6\left(\eta^\dagger\eta\right)\left(\rho^\dagger\rho\right) + \lambda_7\left(\chi^\dagger\eta\right)\left(\eta^\dagger\chi\right) \\
& +\lambda_8\left(\chi^\dagger\rho\right)\left(\rho^\dagger\chi\right) + \lambda_9\left(\eta^\dagger\rho\right)\left(\rho^\dagger\eta\right) \\
& +[\lambda_{10}\left(\chi^\dagger\eta\right)^2 + \mathrm{H.c.}];
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Scalar Potential

$$\begin{aligned} V_{\not{\mathbb{Z}}_2}(\eta,\rho,\chi) &= -\mu_4^2\chi^\dagger\eta + \lambda_{11}\left(\chi^\dagger\eta\right)\left(\eta^\dagger\eta\right) \\ &+\lambda_{12}\left(\chi^\dagger\eta\right)\left(\chi^\dagger\chi\right) + \lambda_{13}\left(\chi^\dagger\eta\right)\left(\rho^\dagger\rho\right) \\ &+\lambda_{14}\left(\chi^\dagger\rho\right)\left(\rho^\dagger\eta\right) + \frac{f}{\sqrt{2}}\epsilon_{ijk}\eta_i\rho_j\chi_k + \mathrm{H.c.} \end{aligned}$$

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The Model with $\mathbb{Z}_2$ symmetry

Transformation

$\mathbb{Z}_2$: $\chi \rightarrow -\chi$, $u_{4R} \rightarrow -u_{4R}$, $d_{(4,5)R} \rightarrow -d_{(4,5)R}$

Most studied 3-3-1 scenario.

Consequences of $\mathbb{Z}_2$

- It brings simplicity to the model;
- Possibility of DM through the χ transformation;
- It alleviates FCNC processes, since the u_{4R} and $d_{(4,5)R}$ quarks only interact with one of the triplets, χ.

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The Model with $\mathbb{Z}_2$ symmetry

U(1) symmetries

	Q_L	Q_{iL}	$(u_{aR},\ u_{4R})$	$\left(d_{aR}, d_{(4,5)R}\right)$	f_{aL}	e_{aR}	η	ρ	χ
$U(1)_N$	1/3	0	2/3	-1/3	-1/3	-1	-1/3	2/3	-1/3
$U(1)_B$	1/3	1/3	1/3	1/3	0	0	0	0	0
$U(1)_{\mathrm{PQ}}$	1	-1	0	0	-1/2	-3/2	1	1	1

Constraining the 3 VEVs case

NG boson

$$J = \frac{1}{N_J}\left(\frac{v_{\eta_1} v_{\chi_3}}{v_{\rho_2}} \mathrm{Im}\,\rho_2^0 + v_{\chi_3} \mathrm{Im}\,\eta_1^0 + v_{\eta_1} \mathrm{Im}\,\chi_3^0\right)$$

g_{eeJ} coupling

- This coupling implies an energy loss channel through the process $\gamma + e^- \to e^- + J$;
- Evolution of red-giant stars: $|g_{e\bar{e}J}| \lesssim g_{\max} = 10^{-13}$;
- Our model: $g_{e\bar{e}J} = \frac{\sqrt{2} m_e v_{\eta_1} v_{\chi_3}}{N_J v_{\rho_2}^2}$ because $\mathcal{L}^{\rho}_{\mathrm{Yuk}} \supset Y'_{aa'} \bar{f}_{aL} e_{a'R} \rho + \mathrm{H.c.}$.

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Constraining the 3 VEVs case

Together with $M_{W^\pm}^2 = \frac{g_L^2}{4}\left(v_{\eta_1}^2 + v_{\rho_2}^2\right) = \frac{g_L^2}{4} v_{\mathrm{SM}}^2$, one finds

$v_{\chi_3} = v_{\chi_3}\left(v_{\rho_2}\right)$

$$v_{\chi_3} \leq v_{\chi\mathrm{max}}(v_{\rho_2}) \equiv v_{\rho_2}\left[2g_{\mathrm{max}}^{-2} m_e^2/v_{\rho_2}^2 - 1/\left(1 - v_{\rho_2}^2/v_{\mathrm{SM}}^2\right)\right]^{-1/2}.$$

$$v_{\chi\mathrm{max}}\left(v_{\rho_2} \to v_{\mathrm{SM}}^-\right) \simeq 11.5\ \mathrm{keV}.$$

which contradicts $\langle\chi\rangle > \langle\rho\rangle, \langle\eta\rangle$, which is assumed at the SSB.
BAD!

4 and 5 VEVs cases

- 2 NG bosons: J_I and J_R;
- $Z \to J_R J_I$, therefore these scenarios are **ruled out!**

Making the $\mathbb{Z}_2$-symmetric model safe

- Add terms which break explicitly the additional U(1) symmetries;
- We explore two soft terms from the $\mathbb{Z}_2$-breaking potential: $\mu_4^2 \chi^\dagger \eta$ and $\frac{f}{\sqrt{2}} \epsilon_{ijk} \eta_i \rho_j \chi_k$.

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$\mu_4^2\,\chi^\dagger\eta$

- 1 NG boson with imaginary components;
- The case $(v_{\eta_1},\, v_{\rho_2},\, v_{\chi_3})$ is ruled out, because the NG boson has the same form as the earlier case;
- 4 VEVs: $v_{\chi_3} \lesssim 355\ \mathrm{GeV}$.
- 5 VEVs: $v_{\chi_3} \lesssim 355\ \mathrm{GeV}$ if $v_{\rho_2} \simeq v_{\mathrm{SM}}$.

We have used as constraints the $W^\pm$, Z masses, the g_{eeJ} coupling and the positivity of the VEVs.

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$\frac{f}{\sqrt{2}}\epsilon_{ijk}\eta_i\rho_j\chi_k$

There appear no physical NG bosons, therefore the model is safe regarding the appearance of massless scalars.

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Summary and conclusions

- This approach had not yet been considered in 3-3-1 models;
- Physical NG bosons play an important role at constraining parameters
  - Can interact with matter;
  - Example: $\gamma + e^- \to e^- + J \Longrightarrow g_{eeJ}$ coupling.
- $\mathbb{Z}_2$-symmetric potential
  - 3 VEVs: bad! $v_{\chi_3} \lesssim 11.5$ keV.
  - 4 and 5 VEVs: bad! $Z \to J_I + J_R$ allowed.
- Softly broken $\mathbb{Z}_2$
  - $\mu_4^2 \chi^\dagger \eta$: $v_{\chi_3} \lesssim 355$ GeV for 4 VEVs. The 5 VEVs case has more freedom;
  - $\frac{f}{\sqrt{2}} \epsilon_{ijk} \eta_i \rho_j \chi_k$: NO massless scalars!

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