On the viability of a light scalar spectrum for 331 models

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Abstract

In this work we study an effective version of the 3-3-1 model, in which the particle content is the same of the 2HDM. We show that the inherited structure from the $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ gauge group has a series of consequences, the most relevant one being the prediction of the masses of the neutral scalar to be of the order or lower than the mass of the charged scalar. Given current constraints from collider searches, B-physics, as well as theoretical constraints such as perturbativity of quartic couplings and stability of the scalar potential, we find that the new scalars cannot be lighter than 350 GeV.

3-3-1 model in a nutshell

Proposed by [1, 2] in the 90's, the 3-3-1 model provides an explanation for the number of families found in Nature. Also, the model can provide candidates to dark matter, explain neutrinos masses, the strong CP problem, among other issues. In a nutshell, one usually adds three scalar triplets (χ, ρ, η) and extent the fermionic doublets of the SM to triplets (or anti-triplets). New gauge bosons are generated also (W' and Z'). The gauge breaking pattern, triggered by the scalars, is given by

$$SU(3)_C \otimes SU(3)_L \otimes U(1)_X \xrightarrow{v_\chi} SU(3)_C \otimes SU(2)_L \otimes U(1)_X \xrightarrow{v_\eta, v_\rho} SU(3)_C \otimes U(1)$$

The masses of the new gauge bosons is proportional to v_χ. Since no new particles have been found at the LHC yet, the limits on the masses are already at a few TeV. In this scenario, it is natural to ask:

if the scale of v_χ is inaccessible at present and near-future colliders, could the 3-3-1 model still provide new particles at sub-TeV region?

We aim to answer this question in the context of the scalar sector of the model.

Scalar sector of 3-3-1 models and the 2HDM

Usually, the scalar sector of 3-3-1 models contain the triplets

$$\eta = \begin{pmatrix} \eta^0 \\ \eta^- \\ \eta^{-A} \end{pmatrix}, \quad \rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^{-B} \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi^A \\ \chi^B \\ \chi^0 \end{pmatrix},$$

where the charges under $U(1)_X$ are

$$X_\eta = -\frac{1}{2} - \frac{\beta_Q}{2\sqrt{3}}, \quad X_\rho = \frac{1}{2} - \frac{\beta_Q}{2\sqrt{3}}, \quad X_\chi = \frac{\beta_Q}{\sqrt{3}}.$$

As is well-known, to define a 3-3-1 model one must adopt a specific value for β_Q, which enters in the charge generator $Q = T_3 + \beta_Q T_8 + XI$. Only the neutral components will acquire vev's. Under the limit $v_\chi >> v_\rho, v_\eta$, and after the first gauge breaking, the scalar potential can be written as [3, 4]

$$\begin{aligned} V_{eff}(\Phi_\eta, \Phi_\rho) = {} & \mu_\rho^2 \Phi_\rho^\dagger \Phi_\rho + \mu_\eta^2 \Phi_\eta^\dagger \Phi_\eta + \lambda_1 (\Phi_\rho^\dagger \Phi_\rho)^2 + \lambda_2 (\Phi_\eta^\dagger \Phi_\eta)^2 \\ & + \lambda_{12} (\Phi_\rho^\dagger \Phi_\rho)(\Phi_\eta^\dagger \Phi_\eta) + \zeta_{12} (\Phi_\eta^T \varepsilon \Phi_\rho)^\dagger (\Phi_\eta^T \varepsilon \Phi_\rho) \\ & + \{\mu_{\eta\rho}^2 \Phi_\eta^T \varepsilon \Phi_\rho + \text{H.c.}\} \end{aligned}$$

where $\varepsilon = i\tau_2$ to comply with scalar products in the $SU(2)$ group and the doublets have hypercharge $Y = (-1/2, 1/2)$ respectively as below

$$\Phi_\eta = \begin{pmatrix} \eta^0 \\ -\eta^- \end{pmatrix}, \quad \Phi_\rho = \begin{pmatrix} \rho^+ \\ \rho^0 \end{pmatrix}.$$

At this point it is clear that we will have the same particle content of the 2HDM. We can compare the scalar potential in this case as well

$$\begin{aligned} V(\Phi_i) = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\Lambda_1}{2} \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\Lambda_2}{2} \left(\Phi_2^\dagger \Phi_2\right)^2 \\ & + \Lambda_3 \left(\Phi_1^\dagger \Phi_1\right) \left(\Phi_2^\dagger \Phi_2\right) + \Lambda_4 \left(\Phi_1^\dagger \Phi_2\right) \left(\Phi_2^\dagger \Phi_1\right) + \big[- m_{12}^2 \Phi_1^\dagger \Phi_2 \\ & + \frac{\mathbf{\Lambda_5}}{\mathbf{2}} \left(\Phi_1^\dagger \Phi_2\right)^2 + \mathbf{\Lambda_6} \left(\Phi_1^\dagger \Phi_1\right) \left(\Phi_1^\dagger \Phi_2\right) + \mathbf{\Lambda_7} \left(\Phi_2^\dagger \Phi_2\right) \left(\Phi_1^\dagger \Phi_2\right) + \text{H.c.}\big] \end{aligned}$$

The couplings Λ_5, Λ_6, and Λ_7 cannot be mapped in the $V_{eff}(\Phi_\eta, \Phi_\rho)$, implying in a more predictive pattern for scalar couplings, for instance. Regarding the Yukawa sector, we will obtain

$$\begin{aligned} -\mathcal{L}_{\text{Yuk}}^q &= y_{mi}^u \bar{q}_{mL} \phi_\eta u_{iR} + y_{3i}^u \bar{q}_{3L} \phi_\rho^* u_{iR} + y_{mi}^d \bar{q}_{mL} \phi_\rho d_{iR} + y_{3i}^d \bar{q}_{3L} \phi_\eta^* d_{iR} + h.c \\ -\mathcal{L}_{\text{Yuk}}^l &= y_{mn}^e \bar{L}_{mL} \phi_\eta^* e_{nR} + h.c \end{aligned}$$

None of the usual 2HDM types (types I, II, X, Y) can be mapped in the 3-3-1 model.

Phenomenological and theoretical constraints

Since we have a model with multiple scalars, one consider as theoretical constraints: stability of the scalar potential, perturbativity of its couplings as well as perturbative unitarity of the scattering matrix.

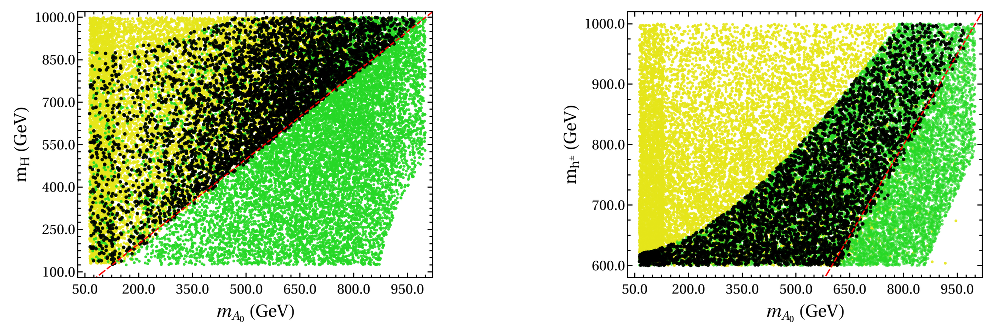

Fig. 1: Yellow points comply with the stabiltiy bound, green points with perturbativity and unitarity, while black points comply with all theoretical constraints. The dashed red line is for degenerate masses.

Given the new measurement of the W-mass by the CDF collaboration, we consider the impact from three choices for the S, T, U parameters (PDG, combination with CDF, only CDF)

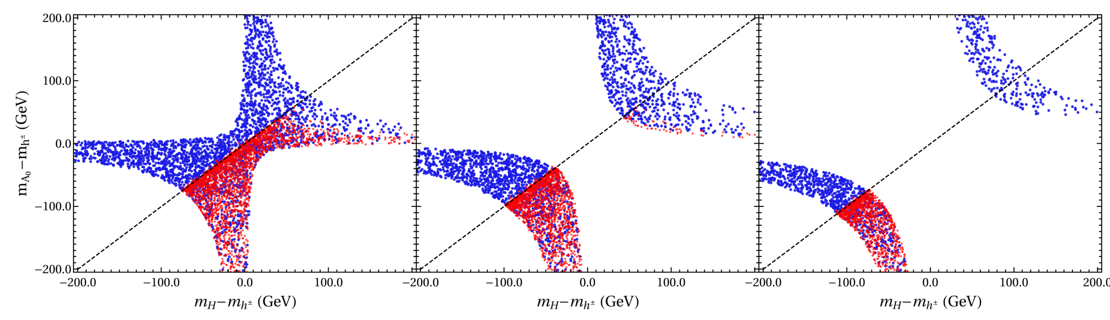

Fig. 2: Difference in mass among the neutral scalars H, A_0 and the charged scalar $h^\pm$ complying at 95% C.L. with three choice for the oblique parameters. Blue points are for 2HDM, while red are for 3-3-1 model.

Finally, the decay $B \to X_s\gamma$, gives a lower limit on $m_{h^\pm} > 600$ GeV, while collider constraints reduce the parameter space further. For $m_{h^\pm} = 600$ GeV

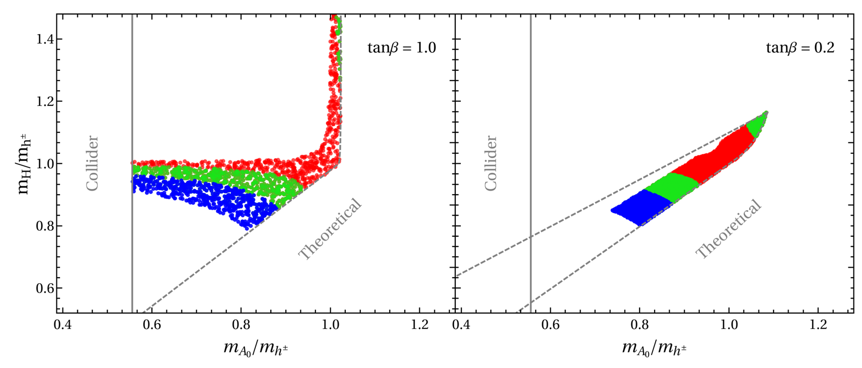

Fig. 3: Summary plot when all constraints are enforced. Outside the dashed lines, the region is excluded by theoretical bounds, while the left region from the gray line is excluded by collider bounds.

Conclusions

The 331 model, proposed in the 90's [1, 2], remains an appealing candidate for extending the Standard Model. A drawback is the introduction of a new scale (related to the first gauge symmetry breaking), whose upper limit is no bound, implying that most of the new particles introduced in the model will escape present and near-future colliders. However, even in this discouraging scenario, the model allows some of the extra scalars to be light, at the sub-TeV range, resembling a two-higgs doublet model (2HDM).

In this contribution we studied in detail this effective realization of the 331 model, focusing on its differences to a general 2HDM. We found that there is a lower and upper limit for the mass of the neutral scalars that strongly depends on the mass of the charged scalar. This is in clear contrast to the general 2HDM, in which a upper limit for the masses cannot be enforced. Moreover, the predicted mass range depends on the W-mass through the oblique parameters, opening the possibility to support (or not) the CDF result if new scalars are found and their masses determined.

References

[1] F. Pisano and V. Pleitez. *Phys. Rev. D* 46 (1992), pp. 410–417. arXiv: hep-ph/9206242.

[2] P. H. Frampton. *Phys. Rev. Lett.* 69 (1992), pp. 2889–2891.

[3] Hiroshi Okada et al. *Phys. Rev. D* 94.1 (2016), p. 015002. arXiv: 1604.01948 [hep-ph].

[4] Zhiyi Fan and Kei Yagyu. *JHEP* 06 (2022), p. 014. arXiv: 2201.11277 [hep-ph].

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