Extending trinity to the Scalar Sector

João M. Alves[1]

[1]Centro de Física Teórica de Partículas (CFTP),
Departamento de Física, Instituto Superior Técnico (IST)

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Extending trinity to the scalar sector through discrete flavoured symmetries

João M. Alves[1,a], Francisco J. Botella[2,b], Gustavo C. Branco[1,c], Miguel Nebot[1,d]

[1] Departamento de Física and Centro de Física Teórica de Partículas (CFTP), Instituto Superior Técnico (IST), U. de Lisboa (UL), Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal
[2] Departament de Fìsica Teòrica and Instituto de Física Corpuscular (IFIC), Universitat de València-CSIC, 46100 Valencia, Spain

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Outline

Introduction

- MHDMs arise naturally in a variety of BSM physics;
- General MHDM has tree-level scalar-mediated FCNC:

  $\Longrightarrow$ Glashow and Weinberg killed them with NFC;

- MHDMs can play a role in solving flavour physics:

  $\Longrightarrow$ NFC is too extreme of a scenario;

- **MHDMs need a safe framework to perform flavour physics.**

The Trinity Principle

- Remembering NFC of Glashow and Weinberg:
  $\Longrightarrow$ *"The mass matrix of a quark with a given charge may only receive contributions from one scalar."*
- We extend the idea above by proposing the TP:
  $\Longrightarrow$ *"Each row of the mass matrix of a quark with a given charge may only receive contributions from one scalar, and vice-versa."*
- Three massive generations require 3HDM.
- **To test this idea, we look at the minimal models (quarks only).**

The Models

Definition and Symmetries I

- Clearly that 3HDMs are the minimal implementations of the TP;

- TP is blind to the columns of each mass matrix:

  $\Longrightarrow$ All right-handed fermions are flavour singlets in a minimal model;

  $\Longrightarrow$ Each row is either completely null or has no zeros.

- Since scalar labels have no meaning, there are only three possibilities:

  $\Longrightarrow$ All scalars contribute to the same line in each mass matrix;

  $\Longrightarrow$ Only one scalar contributes to the same line in each mass matrix;

  $\Longrightarrow$ No scalar contributes to the same line in each mass matrix.

- **First two options work, last one is not supported by a symmetry.**

- The first option is implemented with two flavoured $\mathbb{Z}_2$:

$$\begin{aligned} \mathbb{Z}_2 : \qquad & \phi_1 \rightarrow -\phi_1, \quad q^0_{L1} \rightarrow -q^0_{L1}, \\ \mathbb{Z}'_2 : \qquad & \phi_2 \rightarrow -\phi_2, \quad q^0_{L2} \rightarrow -q^0_{L2}. \end{aligned}$$

- Gives rise to Yukawa couplings for the down (Γ_a) and up (Δ_a) quarks:

$$\Gamma_1 = \begin{pmatrix} x & x & x \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \Gamma_2 = \begin{pmatrix} 0 & 0 & 0 \\ x & x & x \\ 0 & 0 & 0 \end{pmatrix}, \quad \Gamma_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ x & x & x \end{pmatrix},$$

$$\Delta_1 = \begin{pmatrix} x & x & x \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \Delta_2 = \begin{pmatrix} 0 & 0 & 0 \\ x & x & x \\ 0 & 0 & 0 \end{pmatrix}, \quad \Delta_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ x & x & x \end{pmatrix}.$$

- This time, the model is protected by a flavoured-$\mathbb{Z}_3$:

$$\begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\end{pmatrix} \to \begin{pmatrix}1 & & \\ & \Upsilon & \\ & & \Upsilon^{-1}\end{pmatrix}\begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\end{pmatrix}, \quad q_L^0 \to \begin{pmatrix}1 & & \\ & \Upsilon & \\ & & \Upsilon^{-1}\end{pmatrix} q_L^0.$$

- Symmetry above produces the following Yukawa couplings:

$$\Gamma_1 = \begin{pmatrix}x & x & x\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}, \quad \Gamma_2 = \begin{pmatrix}0 & 0 & 0\\ x & x & x\\ 0 & 0 & 0\end{pmatrix}, \quad \Gamma_3 = \begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ x & x & x\end{pmatrix},$$

$$\Delta_1 = \begin{pmatrix}x & x & x\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}, \quad \Delta_2 = \begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ x & x & x\end{pmatrix}, \quad \Delta_3 = \begin{pmatrix}0 & 0 & 0\\ x & x & x\\ 0 & 0 & 0\end{pmatrix}.$$

The Models

Flavour Changing Neutral Couplings I

- For the $\mathbb{Z}_2 \times \mathbb{Z}_2'$ model, all FCNCs are controlled by:

$$N_d = \left(v_2/v_1 P_1^{dL} - v_1/v_2 P_2^{dL}\right) D_d, \quad N_d' = \left(1 - v^2/v_3^2 P_3^{dL}\right) D_d,$$
$$N_u = \left(v_2/v_1 P_1^{uL} - v_1/v_2 P_2^{uL}\right) D_u, \quad N_u' = \left(1 - v^2/v_3^2 P_3^{uL}\right) D_u.$$

- Notice the mass matrices D_d and the projection operators P_i^{qL}:

$$P_i^{qL} = U_{qL}^\dagger P_i U_{qL}.$$

- For the Z_3 model, we have:

$$N_d = \left(v_2/v_1 P_1^{dL} - v_1/v_2 P_2^{dL}\right) D_d, \quad N_d' = \left(1 - v^2/v_3^2 P_3^{dL}\right) D_d,$$
$$N_u = \left(v_2/v_1 P_1^{uL} - v_1/v_2 P_3^{uL}\right) D_u, \quad N_u' = \left(1 - v^2/v_3^2 P_2^{uL}\right) D_u.$$

Flavour Changing Neutral Couplings II

- With just quarks, most stringent constraints come from meson mixing:

$$\left| \sum_{a=0}^{4} \frac{(Y_a^{q\dagger})^2_{ji}}{m^2_{h_a}} \right| < \frac{12 m_j^2 \Delta m_P}{5 m_P^3 f_P^2}.$$

- For generality, we considered the meson $P^0 = q_i \bar{q}_j$;
- The couplings Y_a^q envolve N_q, N_q' and the scalar mixing matrix O.

- Through some inequalities, we obtain for the D-mesons:

$$\left(\frac{2v^2}{v_1^2} + \frac{2v^2}{v_2^2} + \frac{v^2}{v_3^2} - \frac{3v^2}{v'^2} \right) \sum_{a=0}^{4} \frac{1 - O_{a0}^2}{m^2_{h_a}/m^2_{h_0}} < 2 \times 10^{-4}.$$

- This bound is sufficient for ensuring validity, but not necessary.

- **These models require a cancellation of the order of 10^{-2}.**

The Models
Scalar Potentials

- The most general potentials invariant under these symmetries are:

$$V_{\mathbb{Z}_2\times\mathbb{Z}_2'}(\phi) \supset \sigma_{12}\left(\phi_1^\dagger\phi_2\right)^2 + \sigma_{23}\left(\phi_2^\dagger\phi_3\right)^2 + \sigma_{31}\left(\phi_3^\dagger\phi_1\right)^2 + h.c.,$$

$$V_{\mathbb{Z}_3}(\phi) \supset \sigma_1\left(\phi_1^\dagger\phi_2\right)\left(\phi_1^\dagger\phi_3\right) + \sigma_2\left(\phi_2^\dagger\phi_3\right)\left(\phi_2^\dagger\phi_1\right) + \sigma_3\left(\phi_3^\dagger\phi_1\right)\left(\phi_3^\dagger\phi_2\right) + h.c..$$

- The missing terms play no role in the generation of CPV.

- After SSB, in the $\mathbb{Z}_3$ model we have:

$$\cos(\alpha_1 - 2\alpha_2 + \alpha_3) = \frac{\sigma_1\sigma_3 v_1 v_3}{2\sigma_2^2 v_2^2} - \frac{\sigma_1 v_1}{2\sigma_3 v_3} - \frac{\sigma_3 v_3}{2\sigma_1 v_1},$$

$$\cos(\alpha_1 + \alpha_2 - 2\alpha_3) = \frac{\sigma_1\sigma_2 v_1 v_2}{2\sigma_3^2 v_3^2} - \frac{\sigma_1 v_1}{2\sigma_2 v_2} - \frac{\sigma_2 v_2}{2\sigma_1 v_1}.$$

- **Both scalar potentials can generate spontaneous CPV.**

- Both flavour sectors are entirely defined by the unitary matrix U_{qL}:

$$N_d' = \left[1 - v^2/v_3^2 \left(U_{dL}^\dagger P_3 U_{dL}\right)\right] D_d.$$

- In principle, will have six new flavour parameters in each model.

- If Lagrangian is CP invariant, mass matrices are given by:

$$\Gamma_1 = \begin{pmatrix} x & x & x \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \Rightarrow M_d = \begin{pmatrix} e^{i\alpha_1} & & \\ & e^{i\alpha_2} & \\ & & e^{i\alpha_3} \end{pmatrix} \hat{M}_d.$$

- Since $\hat{M}_d$ is real, the matrices which diagonalize it are:

$$U_{dL} = \begin{pmatrix} e^{i\alpha_1} & & \\ & e^{i\alpha_2} & \\ & & e^{i\alpha_3} \end{pmatrix} O_{dL}.$$

- As the up and down sectors receive opposite phases, we get the CKM:

$$V_{\mathbb{Z}_3} = e^{i(\alpha_2+\alpha_3)} O_{uL}^T \,\mathrm{diag}\left\{e^{i(2\alpha_1-\alpha_2-\alpha_3)}, 1, 1\right\} O_{dL},$$
$$V_{\mathbb{Z}_2\times\mathbb{Z}_2'} = O_{uL}^T \,\mathrm{diag}\left\{e^{2i\alpha_1}, e^{2i\alpha_2}, e^{2i\alpha_3}\right\} O_{dL}.$$

- **From 1808.00493, we check that a complex CKM is generated;**
- **From 2105.14054, we see that we may relate δ_{CKM} with δ_{PMNS}.**

Conclusions

- We have probed two distinct models which implement the TP:

  $\Longrightarrow$ Both have naturally suppressed FCNC;

  $\Longrightarrow$ Both have potentials that can generate spontaneous CPV;

  $\Longrightarrow$ Both can produce a complex CKM matrix out of the vacuum phases.

- **Implementing the TP generates naturally suppressed FCNC;**
- **Nevertheless, it still leaves room for perfoming flavour physics.**