

Fermion masses and mixings in 3HDM with S_3 flavor symmetry

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- 3 fermion generations - 3 Higgs doublets
- S_3 group is a permutation group of a set of 3 elements
- The existing works focus on some specific situation of S_3 3HDM:
 - S_3 3HDM with extra Z_2 symmetry in lepton sector without scalar part considered. (J.Kubo, A. Mondragon, M. Mondragon, E Rodrigue)
 - Scalar potential part with CP conservation. (M. Gomez-Bock, M. Mondragon, A.Perez-Martinez)
- We investigate the Yukawa and the scalar sectors of a general S_3 -symmetric three-Higgs doublet model
 - Flavor sector:
 - Masses, mixing matrix
 - FCNC
 - Scalar sector:
 - Stability/Unitarity
 - EDM



Yukawa Coupling Lagrangian

Flavor section in S_3 3HDM:

$$Q_L^i = \begin{pmatrix} u^i \\ d^i \end{pmatrix}_L, \quad u_R^i, \quad d_R^i, \quad L_L^i = \begin{pmatrix} \nu^i \\ \ell^i \end{pmatrix}_L, \quad \ell_R^i, \quad \nu_R^i, \quad H_i$$

$$\begin{aligned} \mathcal{L}_{Y_d} = & -Y_1^d \bar{Q}_L^I H_3 d_R^I - Y_2^d \left(\bar{Q}_L^I \kappa_{IJ} H_1 d_R^J + \bar{Q}_L^I \eta_{IJ} H_2 d_R^J \right) \\ & - Y_3^d \bar{Q}_L^3 H_3 d_R^3 - Y_4^d \bar{Q}_L^3 H_I d_R^I - Y_5^d \bar{Q}_L^I H_I d_R^3 + h.c. \end{aligned}$$

$$\mathcal{L}_M = -M_1 \nu_R^{I,T} C \nu_R^I - M_3 \nu_R^{3,T} C \nu_R^3$$

$$\langle H_1 \rangle = \begin{pmatrix} 0 \\ \frac{v_1 e^{i\theta_1}}{\sqrt{2}} \end{pmatrix}, \quad \langle H_2 \rangle = \begin{pmatrix} 0 \\ \frac{v_2 e^{i\theta_2}}{\sqrt{2}} \end{pmatrix}, \quad \langle H_3 \rangle = \begin{pmatrix} 0 \\ \frac{v_3}{\sqrt{2}} \end{pmatrix}$$

With $\sqrt{v_1^2 + v_2^2 + v_3^2} = 246 \text{ GeV}$



Fermion Mass Matrices

$$M_{d,\ell} = \begin{pmatrix} \frac{Y_2^{d,\ell} v_2 e^{i\theta_2}}{\sqrt{2}} + \frac{Y_1^{d,\ell} v_3}{\sqrt{2}} & \frac{Y_2^{d,\ell} v_1 e^{i\theta_1}}{\sqrt{2}} & \frac{Y_5^{d,\ell} v_1 e^{i\theta_1}}{\sqrt{2}} \\ \frac{Y_2^{d,\ell} v_1 e^{i\theta_1}}{\sqrt{2}} & -\frac{Y_2^{d,\ell} v_2 e^{i\theta_2}}{\sqrt{2}} + \frac{Y_1^{d,\ell} v_3}{\sqrt{2}} & \frac{Y_5^{d,\ell} v_2 e^{i\theta_2}}{\sqrt{2}} \\ \frac{Y_4^{d,\ell} v_1 e^{i\theta_1}}{\sqrt{2}} & \frac{Y_4^{d,\ell} v_2 e^{i\theta_2}}{\sqrt{2}} & \frac{Y_3^{d,\ell} v_3}{\sqrt{2}} \end{pmatrix}$$

$$M_{u,\nu} = \begin{pmatrix} \frac{Y_2^{u,\nu} v_2 e^{-i\theta_2}}{\sqrt{2}} + \frac{Y_1^{u,\nu} v_3}{\sqrt{2}} & \frac{Y_2^{u,\nu} v_1 e^{-i\theta_1}}{\sqrt{2}} & \frac{Y_5^{u,\nu} v_1 e^{-i\theta_1}}{\sqrt{2}} \\ \frac{Y_2^{u,\nu} v_1 e^{-i\theta_1}}{\sqrt{2}} & -\frac{Y_2^{u,\nu} v_2 e^{-i\theta_2}}{\sqrt{2}} + \frac{Y_1^{u,\nu} v_3}{\sqrt{2}} & \frac{Y_5^{u,\nu} v_2 e^{-i\theta_2}}{\sqrt{2}} \\ \frac{Y_4^{u,\nu} v_1 e^{-i\theta_1}}{\sqrt{2}} & \frac{Y_4^{u,\nu} v_2 e^{-i\theta_2}}{\sqrt{2}} & \frac{Y_3^{u,\nu} v_3}{\sqrt{2}} \end{pmatrix}.$$

$$M_\nu^{\text{Majorana}} = M_\nu \tilde{M}^{-1} (M_\nu)^T$$

where $\tilde{M} = \text{diag}(M_1, M_1, M_3)$



Quark Mass Matrix Parametrization

$$U_{d(u,\ell)L}^\dagger M_{d(u,\ell)} U_{d(u,\ell)R} = \text{diag}(m_{d(u,e)}, m_{s(c,\mu)}, m_{b(t,\tau)})$$

$$M_d = \begin{pmatrix} \epsilon & xm_1 & xm_2 \\ xm_1 & -2m_1 + \epsilon & m_2 \\ xm'_2 & m'_2 & m_3 \end{pmatrix}$$

Where

$$\begin{aligned} \epsilon &= m_0 + m_1 & x &= \frac{v_1 e^{i\theta_1}}{v_2 e^{i\theta_2}} & m_1 &= \frac{Y_2^d v_2 e^{i\theta_2}}{\sqrt{2}} & m_2 &= \frac{Y_5^d v_1 e^{i\theta_1}}{\sqrt{2}} \\ m_3 &= \frac{Y_3^d v_3 e^{i\theta_3}}{\sqrt{2}} & m'_2 &= \frac{Y_4^d v_2 e^{i\theta_2}}{\sqrt{2}} & m_0 &= \frac{Y_1^d v_3 e^{i\theta_3}}{\sqrt{2}} \end{aligned}$$



Higgs Potential

Scalar Potential with S_3 symmetry:

$$\begin{aligned} V = & \mu_0^2(h_1^\dagger h_1 + h_2^\dagger h_2) + \mu_1^2(h_s^\dagger h_s) + \lambda_1(h_1^\dagger h_1 + h_2^\dagger h_2)^2 \\ & + \lambda_2(h_1^\dagger h_2 - h_2^\dagger h_1)^2 + \lambda_3[(h_1^\dagger h_1 - h_2^\dagger h_2)^2 + (h_1^\dagger h_2 + h_2^\dagger h_1)^2] \\ & + [\lambda_4 e^{ic_4} [(h_s^\dagger h_1)(h_1^\dagger h_2 + h_2^\dagger h_1) + (h_s^\dagger h_2)(h_1^\dagger h_1 - h_2^\dagger h_2)] + h.c.] \\ & + \lambda_5[(h_s^\dagger h_s)(h_1^\dagger h_1 + h_2^\dagger h_2)] + \lambda_6[(h_s^\dagger h_1)(h_1^\dagger h_s) + (h_s^\dagger h_2)(h_2^\dagger h_s)] \\ & + [\lambda_7 e^{ic_7} [(h_s^\dagger h_1)^2 + (h_s^\dagger h_2)^2] + h.c.] + \lambda_8(h_s^\dagger h_s)^2 \end{aligned}$$

The soft-breaking terms:

$$\begin{aligned} V'_2 = & \mu_2^2(h_1^\dagger h_1 - h_2^\dagger h_2) + \frac{1}{2}(\mu_3^2 e^{ib_3} h_1^\dagger h_2 + h.c.) + \frac{1}{2}(\mu_4^2 e^{ib_4} h_1^\dagger h_s + h.c.) \\ & + \frac{1}{2}(\mu_5^2 e^{ib_5} h_2^\dagger h_s + h.c.) \end{aligned}$$



Higgs Basis Transformation

Rotating into Higgs basis:

$$R_H = \begin{pmatrix} \frac{e^{-i\theta_1} v_1}{v} & \frac{e^{-i\theta_2} v_2}{v} & \frac{v_3}{v} \\ 0 & \frac{e^{-i\theta_2} v_3}{v_{23}} & -\frac{v_2}{v_{23}} \\ -\frac{e^{-i\theta_1} v_{23}}{v} & \frac{e^{-i\theta_2} v_{12}}{v v_{23}} & \frac{v_1 v_3}{v v_{23}} \end{pmatrix}$$

$$v_{23} = \sqrt{v_2^2 + v_3^2} \quad v_{12} = \sqrt{v_1^2 + v_2^2} \quad v = \sqrt{v_1^2 + v_2^2 + v_3^2}$$



Yukawa Coupling Matrices After All Transformations

$$U_k^L(ab)B_H(ij)X_j^k(bc)O(in)U_k^R(cd) = X_n^k(ad)$$

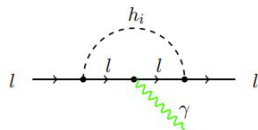
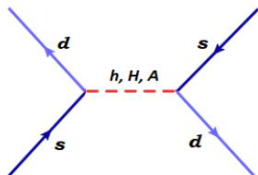
where $i, j, n = 1, \dots, 6$; $k = u, d, e$; $a, b, c, d = 1, 2, 3$

$$U_k^L(ab)R_H(ij)S_j^k(bc)P(in)U_k^R(cd) = S_n^k(ad)$$

where $i, j, n = 1, 2, 3$; $k = u, d, e$; $a, b, c, d = 1, 2, 3$



- FCNC and EDM Constraints



- Unitarity (Dipankar Das, Ujjal Kumar Dey)
- BFB, necessary conditions:

$$\lambda_1 > 0, \quad \lambda_1 - \lambda_2 > 0, \quad \lambda_1 + \lambda_3 > 0, \quad \lambda_8 > 0$$

For the best fitting point, BFB is further checked numerically.

Higgs Masses Result

Higgs	h_2	A_2	h_2^\pm
m(GeV)	7114.614	7124.454	7123.214
Higgs	h_3	A_3	h_3^\pm
m(GeV)	348487.001	348487.021	348487.105



Conclusion

- General S_3 3HDM with CPV, soft-breaking terms
- Global Fitting:
 - Fermions masses, CKM/PMNS matrix
 - FCNC constraints
 - EDM
 - BFB/Unitarity
- Lowest heavy Higgs masses found to be 7114.614 GeV
 - Still space for us to improve to get lighter mass result
- Future studies:
 - Fitting against both Normal/Inverse Hierarchy
 - Collider Phenomenology
 - Heavy Majorana Neutrino
 - Heavy Higgs

