Multi-Higgs Doublet Models and symmetries

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Multi-Higgs Doublet Models

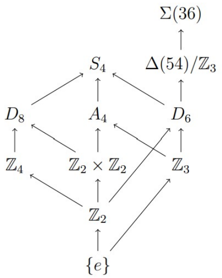
Multi-Higgs Doublet Models: add more doublets.

Well motivated Beyond Standard Model scenario:

- Baryogenesis
- Dark Matter candidates
- Spontaneous CP violation (SCPV)

Multi-Higgs and symmetries

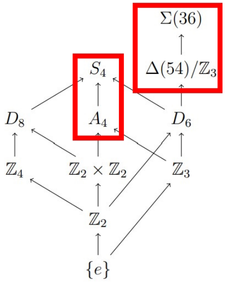
2HDM: Nishi (2006), Ivanov (2006, 2007)
3HDM list of realizable discrete symmetries: Ivanov, Vdovin
`https://arxiv.org/abs/1210.6553`



Recognizing symmetries in 3HDM in basis-independent way: IdMV, Ivanov
`https://arxiv.org/abs/1903.11110`

Multi-Higgs and symmetries

Realizable symmetries with triplet irreps



Recognizing symmetries in 3HDM in basis-independent way: IdMV, Ivanov

`https://arxiv.org/abs/1903.11110`

My talk today

FCNC-free multi-Higgs-doublet models from broken family symmetries: IdMV, Talbert
https://arxiv.org/abs/1908.10979

Exploring multi-Higgs models with softly broken large discrete symmetry groups: IdMV, Ivanov, Levy
https://arxiv.org/abs/2107.08227
Softly-broken A_4 or S_4 3HDMs with stable states: IdMV, Ivo
https://arxiv.org/abs/2202.00681

Residual symmetries

$$A \to T_A A, \quad \text{with} \quad A \in \{u_L, u_R, d_L, d_R, l_L, e_R\},$$
$$T_A = \text{diag}\left(e^{i\alpha_A}, e^{i\beta_A}, e^{i\gamma_A}\right).$$

Diagonal

$$T_A \to T_{AU} = U_A T_A U_A^\dagger, \quad \longleftarrow$$

U_A, fermionic mixing

$$m_{AU} = T_{AU}^\dagger m_{AU} T_{AU}. \quad \longleftarrow$$

Syms. of mass matrix (not of $\mathcal{L}$)

UV Origin

e.g. Flavon VEVs

$$T_A \langle\phi\rangle_A = \langle\phi\rangle_A$$

FCNC in MHDM

In MHDMs

$$\mathcal{L}^Y = -\sum_{k=1}^{N}\Big\{\bar{Q}'_L\left(Y_k^{d,\prime}\,H'_k\,d'_R + Y_k^{u,\prime}\,\tilde{H}'_k\,u'_R\right) + \bar{L}'_L\,Y_k^{e,\prime}\,H'_k\,e'_R + h.c.\Big\}\,.$$

Higgs Basis

$$H_1 = \frac{1}{\sqrt{2}}\begin{pmatrix}\sqrt{2}\,G^+\\ v + S_1^0 + iG^0\end{pmatrix}\,,\quad H_{k>1} = \frac{1}{\sqrt{2}}\begin{pmatrix}\sqrt{2}\,S_k^+\\ S_k^0 + iP_k^0\end{pmatrix}\,,$$

$$\begin{aligned}\mathcal{L}^Y = &-\left(1+\frac{S_1^0}{v}\right)\left(\bar{d}_L m_d d_R + \bar{u}_L m_u u_R + \bar{l}_L m_e e_R\right)\\ &-\frac{1}{v}\sum_{k=2}^{N}\left(S_k^0 + iP_k^0\right)\left(\bar{d}_L Y_k^d d_R + \bar{u}_L Y_k^u u_R + \bar{l}_L Y_k^e e_R\right) \quad \text{FCNC}\\ &-\frac{\sqrt{2}}{v}\sum_{k=2}^{N} S_k^+\left(\bar{u}_L V Y_k^d d_R - \bar{u}_R Y_k^{u,\dagger} V d_L + \bar{\nu}_L Y_k^e e_R\right)\\ &+ h.c.\,,\end{aligned}$$

Yukawa alignment from residual symmetries

$$Y_k^A \overset{!}{=} T_A Y_k^A T_A^\dagger ,$$

Alignment

$$\begin{pmatrix} Y_{11} & e^{i(\alpha_l-\beta_l)}\,Y_{12} & e^{i(\alpha_l-\gamma_l)}\,Y_{13} \\ e^{i(\beta_l-\alpha_l)}\,Y_{21} & Y_{22} & e^{i(\beta_l-\gamma_l)}\,Y_{23} \\ e^{i(\gamma_l-\alpha_l)}\,Y_{31} & e^{i(\gamma_l-\beta_l)}\,Y_{32} & Y_{33} \end{pmatrix} \overset{!}{=} \begin{pmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{pmatrix}$$

"Realistic Toy Model"

A_4 with $\langle \phi_l \rangle \propto \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$

$$\frac{H_1'}{\Lambda}\left(y_e^1[\bar{L}_L\phi_l]e_R + y_\mu^1[\bar{L}_L\phi_l]'\mu_R + y_\tau^1[\bar{L}_L\phi_l]''\tau_R\right) +$$
$$\frac{H_2'}{\Lambda}\left(y_e^2[\bar{L}_L\phi_l]e_R + y_\mu^2[\bar{L}_L\phi_l]'\mu_R + y_\tau^2[\bar{L}_L\phi_l]''\tau_R\right) .$$

$$Y_1^{e,\prime} = \frac{v_l}{\Lambda}\begin{pmatrix} y_e^1 & 0 & 0 \\ 0 & y_\mu^1 & 0 \\ 0 & 0 & y_\tau^1 \end{pmatrix} ,\quad Y_2^{e,\prime} = \frac{v_l}{\Lambda}\begin{pmatrix} y_e^2 & 0 & 0 \\ 0 & y_\mu^2 & 0 \\ 0 & 0 & y_\tau^2 \end{pmatrix} .$$

Soft breaking terms

A_4, S_4, $\Delta(54)$, $\Sigma(36)$

$$V_0 = -m^2(\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3) + V_4\,,$$

Soft terms

$$V_{\text{soft}} = m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2 + m_{33}^2\phi_3^\dagger\phi_3 + \left(m_{12}^2\,\phi_1^\dagger\phi_2 + m_{23}^2\,\phi_2^\dagger\phi_3 + m_{31}^2\,\phi_3^\dagger\phi_1 + h.c.\right)$$

Σ(36)

$$
\begin{aligned}
V_0 \;=\; & -m^2 \left[\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3\right] + \lambda_1 \left[\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3\right]^2 \\
& -\lambda_2 \left[|\phi_1^\dagger\phi_2|^2 + |\phi_2^\dagger\phi_3|^2 + |\phi_3^\dagger\phi_1|^2 - (\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) - (\phi_2^\dagger\phi_2)(\phi_3^\dagger\phi_3) - (\phi_3^\dagger\phi_3)(\phi_1^\dagger\phi_1)\right] \\
& +\lambda_3 \left(|\phi_1^\dagger\phi_2 - \phi_2^\dagger\phi_3|^2 + |\phi_2^\dagger\phi_3 - \phi_3^\dagger\phi_1|^2 + |\phi_3^\dagger\phi_1 - \phi_1^\dagger\phi_2|^2\right) .
\end{aligned}
$$

$$
\begin{array}{rlll}
\text{alignment } A: & A_1 = (\omega, 1, 1)\,, & A_2 = (1, \omega, 1), & A_3 = (1, 1, \omega) \\
\text{alignment } A': & A'_1 = (\omega^2, 1, 1)\,, & A'_2 = (1, \omega^2, 1), & A'_3 = (1, 1, \omega^2) \\
\text{alignment } B: & B_1 = (1, 0, 0)\,, & B_2 = (0, 1, 0), & B_3 = (0, 0, 1) \\
\text{alignment } C: & C_1 = (1, 1, 1)\,, & C_2 = (1, \omega, \omega^2)\,, & C_3 = (1, \omega^2, \omega)
\end{array}
$$

$\Sigma(36)$ masses

A, A'

$$
\begin{aligned}
m^2_{h_{SM}} &= 2\lambda_1 v^2 = 2m^2\,, \\
m^2_{H^\pm} &= \frac{1}{2}\lambda_2 v^2 \quad \text{(double degenerate)}\,, \\
m^2_{h} &= \frac{1}{2}\lambda_3 v^2 \quad \text{(double degenerate)}\,, \\
m^2_{H} &= 3m^2_h = \frac{3}{2}\lambda_3 v^2 \quad \text{(double degenerate)}\,.
\end{aligned}
$$

B, C

$$
\begin{aligned}
m^2_{h_{SM}} &= 2(\lambda_1 + \lambda_3) v^2 = 2m^2\,, \\
m^2_{H^\pm} &= \frac{1}{2}(\lambda_2 - 3\lambda_3) v^2 \quad \text{(double degenerate)}\,, \\
m^2_{h} &= -\frac{1}{2}\lambda_3 v^2 \quad \text{(double degenerate)}\,, \\
m^2_{H} &= 3m^2_h = -\frac{3}{2}\lambda_3 v^2 \quad \text{(double degenerate)}\,.
\end{aligned}
$$

NO SCPV

Alignment preserving soft breaking

$$\frac{\partial V_0}{\partial \phi_i^*} = -m^2 \phi_i + \frac{\partial V_4}{\partial \phi_i^*} = 0\,.$$

Add

$$V_{\text{soft}} = \phi_i^\dagger M_{ij} \phi_j\,, \quad M_{ij} = \begin{pmatrix} m_{11}^2 & m_{12}^2 & (m_{31}^2)^* \\ (m_{12}^2)^* & m_{22}^2 & m_{23}^2 \\ m_{31}^2 & (m_{23}^2)^* & m_{33}^2 \end{pmatrix}\,,$$

$$\frac{\partial V}{\partial \phi_i^*} = M_{ij}\phi_j - m^2 \phi_i + \frac{\partial V_4}{\partial \phi_i^*} = 0\,.$$

Require $v|_{V \text{ extremum}} = \zeta \cdot v|_{V_0 \text{ extremum}}.$

$$\left.\frac{\partial V_4}{\partial \phi_i^*}\right|_{V_0 \text{ extremum}} = m^2 \phi_i|_{V_0 \text{ extremum}}\,.$$

$$\left.\frac{\partial V_4}{\partial \phi_i^*}\right|_{V \text{ extremum}} = \zeta^2 \cdot m^2 \phi_i|_{V \text{ extremum}}\,.$$

$$M_{ij}\phi_j = (1-\zeta^2) m^2 \phi_i\,.$$ Eigenvector of M

Example $(1,1,1)$

$$M_{ij} = \mu_1\, n_{1i} n_{1j}^* + \mu_2\, n_{2i} n_{2j}^* + \mu_3\, n_{3i} n_{3j}^* \,.$$

(1, 1, 1) (0, 1, -1) (2, -1, -1)

e_1 e_2 e_3

$$\vec{n}_i = \mathcal{U}_{ij} \vec{e}_j \,, \quad i,j = 2,3, \quad \text{where} \quad \mathcal{U} = \begin{pmatrix} \cos\theta & e^{i\xi}\sin\theta \\ -e^{-i\xi}\sin\theta & \cos\theta \end{pmatrix} .$$

$$\Sigma = \mu_2 + \mu_3 \,, \quad \delta = \mu_2 - \mu_3 \,, \quad \theta, \quad \xi \,.$$

Universal results

Universal Correlations (A, A', B, C)

$$\Delta m^2_{H_1^\pm} = \mu_2 = \frac{\Sigma + \delta}{2}, \quad \Delta m^2_{H_2^\pm} = \mu_3 = \frac{\Sigma - \delta}{2}.$$

$$\begin{aligned}
m^2_{h_1} &= \frac{1}{2}\left(2|\lambda_3|v^2 + \Sigma - \sqrt{(\lambda_3 v^2)^2 + \delta^2 + 2x|\lambda_3||\delta|v^2}\right),\\
m^2_{h_2} &= \frac{1}{2}\left(2|\lambda_3|v^2 + \Sigma - \sqrt{(\lambda_3 v^2)^2 + \delta^2 - 2x|\lambda_3||\delta|v^2}\right),\\
m^2_{H_1} &= \frac{1}{2}\left(2|\lambda_3|v^2 + \Sigma + \sqrt{(\lambda_3 v^2)^2 + \delta^2 - 2x|\lambda_3||\delta|v^2}\right),\\
m^2_{H_2} &= \frac{1}{2}\left(2|\lambda_3|v^2 + \Sigma + \sqrt{(\lambda_3 v^2)^2 + \delta^2 + 2x|\lambda_3||\delta|v^2}\right),
\end{aligned}$$

$$x = \sqrt{1 - (\sin 2\theta \sin\xi)^2}.$$

All non-SM Higgses decay
(some decays suppressed...
displaced vertices?)

A_4, S_4: Dark Matter candidates

A_4, S_4, $(1,0,0)$ Alignment

$$\rho = \begin{pmatrix} 1 & & \\ & -1 & \\ & & -1 \end{pmatrix},$$

The AP SBPs preserve ρ!

Dark Matter Candidates

Not a general feature!

$\Delta(54)$, $(1,0,0)$ Alignment

$$\rho_{23} = \begin{pmatrix} 1 & & \\ & & 1 \\ & 1 & \end{pmatrix},$$ but $M_{22} \neq M_{33}$

Conclusions

- Multi-Higgs with symmetries are well motivated.
- Symmetries control flavour changing processes.
- Softly broken symmetries - interesting phenomenology.
- Multi-Higgs with softly broken A_4, S_4 - Dark Matter.