Multi-Higgs Doublet Models and symmetries

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Multi-Higgs Doublet Models

Multi-Higgs Doublet Models: add more doublets.
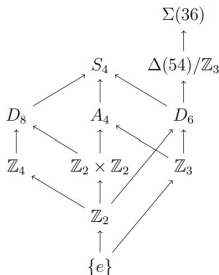
Well motivated Beyond Standard Model scenario:

- 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

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

$T_A \to T_{AU} = U_A T_A U_A^\dagger,$ ⟵ U_A, fermionic mixing

$m_{AU} = T_{AU}^\dagger m_{AU} T_{AU}.$ ⟵ Syms. of mass matrix (not of L)

UV Origin
e.g. Flavon VEVs

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

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MHDMs and FCNCs
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MHDMs with softly broken large discrete groups
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Summary
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FCNC in MHDM

In MHDM,

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

Higgs Basis

$$H_1 = \frac{1}{\sqrt{2}} \left(\begin{array}{c} \sqrt{2} G^+ \\ v + S_1^0 + iG^0 \end{array} \right), \ H_{k>1} = \frac{1}{\sqrt{2}} \left(\begin{array}{c} \sqrt{2} S_k^+ \\ S_k^0 + iP_k^0 \end{array} \right),$$

$$\mathcal{L}^Y = -\left(1 + \frac{S_1^0}{v} \right) \left(\bar{d}_L m_d d_R + \bar{u}_L m_u u_R + \bar{l}_L m_e e_R \right)$$

$$- \frac{1}{v} \sum_{k=2}^{N} \left(S_k^0 + iP_k^0 \right) \left(\bar{d}_L Y_k^d d_R + \bar{u}_L Y_k^u u_R + \bar{l}_L Y_k^e e_R \right) \ \text{FCNC}$$

$$- \frac{\sqrt{2}}{v} \sum_{k=2}^{N} S_k^+ \left(\bar{u}_L V Y_k^d d_R - \bar{u}_R Y_k^{u,\dagger} V d_L + \bar{\nu}_L Y_k^e e_R \right)$$

$$+ h.c.,$$

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Summary
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Yukawa alignment from residual symmetries

$$Y_k^A \stackrel{!}{=} T_A Y_k^A T_A^\dagger, \qquad \text{Alignment}$$

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

"Realistic Toy Model"

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

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

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

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

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

$\Sigma(36)$

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

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

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MHDMs and FCNCs
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MHDMs with softly broken large discrete groups
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Summary
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$\Sigma(36)$ masses

A, A'

$$m_{h_{SM}}^2 = 2\lambda_1 v^2 = 2m^2,$$

$$m_{H^\pm}^2 = \frac{1}{2}\lambda_2 v^2 \quad \text{(double degenerate)},$$

$$m_h^2 = \frac{1}{2}\lambda_3 v^2 \quad \text{(double degenerate)},$$

$$m_H^2 = 3m_h^2 = \frac{3}{2}\lambda_3 v^2 \quad \text{(double degenerate)}.$$

B, C

$$m_{h_{SM}}^2 = 2(\lambda_1 + \lambda_3) v^2 = 2m^2,$$

$$m_{H^\pm}^2 = \frac{1}{2}(\lambda_2 - 3\lambda_3) v^2 \quad \text{(double degenerate)},$$

$$m_h^2 = -\frac{1}{2}\lambda_3 v^2 \quad \text{(double degenerate)},$$

$$m_H^2 = 3m_h^2 = -\frac{3}{2}\lambda_3 v^2 \quad \text{(double degenerate)}.$$

NO SCPV

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MHDMs with softly broken large discrete groups
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Summary
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Alignment preserving soft breaking

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

Add

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

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

Reqint $\quad v|_{V \text{ extremum}} = \zeta \cdot v|_{V_0 \text{ extremum}}\,.$

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

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

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

Example $(1, 1, 1)$

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

$(1, 1, 1)$ $(0, 1, \cdot 1)$ $(2, \cdot 1, \cdot 1)$

ℓ_1 ϱ_2 ℓ_3

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

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

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Summary
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Universal results

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

$$\Delta m^2_{H^\pm_1} = \mu_2 = \frac{\Sigma + \delta}{2}, \quad \Delta m^2_{H^\pm_2} = \mu_3 = \frac{\Sigma - \delta}{2}.$$

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

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

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 SBP_s preserve ρ!

Dark Matter Candidates

Not a general feature!

$\Delta(54)$, $(1,3,0)$ Alignment

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

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.