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Multi-Higgs models with softly broken large discrete symmetry groups

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PROGRAMA OPERACIONAL **POTENCIAL HUMANO**

INVESTIGADOR FCT

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V with Large Symmetries, $\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix}$

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

Softly Broken ... M_{ij}

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

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Method – as exemplified by Σ(36)

Exploring multi-Higgs models with softly broken large discrete symmetry groups #4

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The scalar potential of 3HDM invariant under $\Sigma(36)$ has the following form:

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

alignment A: $A_1=(\omega,1,1)$, $A_2=(1,\omega,1)$, $A_3=(1,1,\omega)$

alignment A': $A_1'=(\omega^2,1,1)$, $A_2'=(1,\omega^2,1)$, $A_3'=(1,1,\omega^2)$

alignment B: $B_1=(1,0,0)$, $B_2=(0,1,0)$, $B_3=(0,0,1)$

alignment C: $C_1=(1,1,1)$, $C_2=(1,\omega,\omega^2)$, $C_3=(1,\omega^2,\omega)$

$\omega \equiv e^{i\frac{2\pi}{3}}$

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Spectra (B) $\quad (1,0,0) \rightarrow \left\langle \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix} \right\rangle = v \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$

$$\left.\begin{aligned} m_{h_{SM}}^2 &= 2\lambda_1 v^2 = 2m^2, \\ m_{H^\pm}^2 &= \frac{1}{2}\lambda_2 v^2 \quad \text{(double degenerate)}, \\ m_h^2 &= \frac{1}{2}\lambda_3 v^2 \quad \text{(double degenerate)}, \\ m_H^2 &= 3m_h^2 = \frac{3}{2}\lambda_3 v^2 \quad \text{(double degenerate)}. \end{aligned}\right\} \text{Mass degeneracies}$$

No SCPV

"Automatic" h_{SM} alignment

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VEV Preserving M_{ij}:

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

Eigenvectors:

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

Parametrize

$$\mu_1 = m^2(1-\zeta^2), \quad \mu_2, \quad \mu_3, \quad \theta, \quad \xi\,.$$

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

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$\Sigma(36)$

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

The four non-SM-like neutral Higgs bosons have the following masses:

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

where the quantity $x \in [0, 1]$ is

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

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Decays

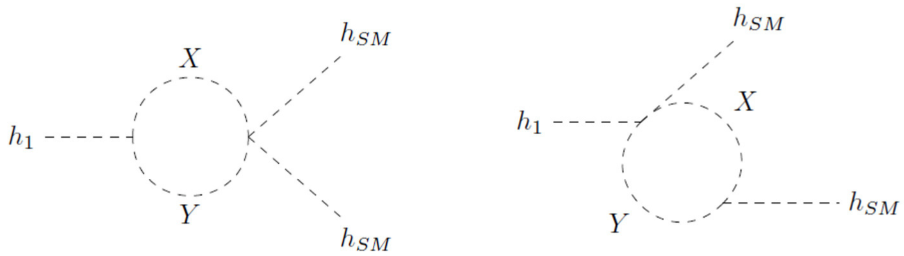

Figure 2: Scalar loop diagrams inducing $h_1 \to h_{SM} h_{SM}$ decays in the softly broken $\Sigma(36)$ 3HDM, where X, Y denote any scalar field.

Tree level forbidden ($\Sigma(36)$); loop level

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M‾d applied to A_4/S_4

Softly-broken A_4 or S_4 3HDMs with stable states #1

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Spectra (B)

$$m_{h_i}^2 = \frac{v^2}{4}\left(\Lambda_1 + \Lambda_2 + 2|\Lambda_3| - \sqrt{(\Lambda_1 - \Lambda_2)^2 + \Lambda_4^2}\right) \qquad \text{(double degenerate)}$$

$$m_{H_i}^2 = \frac{v^2}{4}\left(\Lambda_1 + \Lambda_2 + 2|\Lambda_3| + \sqrt{(\Lambda_1 - \Lambda_2)^2 + \Lambda_4^2}\right) \qquad \text{(double degenerate)}$$

$$m_{H_i^\pm}^2 = \frac{v^2}{2}|\Lambda_3| \qquad \text{(double degenerate).}$$

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Softly broken

$$
\begin{aligned}
m_{h_1}^2 &= \frac{v^2}{12}\left(\Gamma_{12}^+ - \Sigma\Gamma_3 - \sqrt{\left(\Gamma_{12}^-\right)^2 + \Delta^2\Gamma_3^2 + \Gamma_4^2 + |\Delta\Gamma_3|\, s}\right) \\
m_{h_2}^2 &= \frac{v^2}{12}\left(\Gamma_{12}^+ - \Sigma\Gamma_3 - \sqrt{\left(\Gamma_{12}^-\right)^2 + \Delta^2\Gamma_3^2 + \Gamma_4^2 - |\Delta\Gamma_3|\, s}\right) \\
m_{H_1}^2 &= \frac{v^2}{12}\left(\Gamma_{12}^+ - \Sigma\Gamma_3 + \sqrt{\left(\Gamma_{12}^-\right)^2 + \Delta^2\Gamma_3^2 + \Gamma_4^2 - |\Delta\Gamma_3|\, s}\right) \\
m_{H_2}^2 &= \frac{v^2}{12}\left(\Gamma_{12}^+ - \Sigma\Gamma_3 + \sqrt{\left(\Gamma_{12}^-\right)^2 + \Delta^2\Gamma_3^2 + \Gamma_4^2 + |\Delta\Gamma_3|\, s}\right),
\end{aligned}
$$

$$
\begin{cases}
\Gamma_1 &= 3\left(\Lambda_1 - \Lambda_3\right) \\
\Gamma_2 &= 3\left(\Lambda_2 - \Lambda_3\right) \\
\Gamma_3 &= 2\left(\Lambda_0 + \Lambda_3\right) \\
\Gamma_4 &= 3\Lambda_4 .
\end{cases},
$$

with s defined as

$$
s = 2\sqrt{\left(\Gamma_{12}^-\right)^2\left(1 - s_\xi^2 s_{2\theta}^2\right) + \Gamma_4^2\left(1 - c_\xi^2 s_{2\theta}^2\right) - \Gamma_{12}^-\Gamma_4 s_{2\xi} s_{2\theta}^2}\,.
$$

Regarding the charged pairs, we have

$$
\begin{aligned}
m_{H_1^\pm}^2 &= \frac{v^2}{6}\left(-3\Lambda_3 - \frac{\Gamma_3}{2}(\Sigma + \Delta)\right) \implies \Delta m_{H_1^\pm}^2 = -\frac{\sqrt{3}M_0}{6}\mu_2 \\
m_{H_2^\pm}^2 &= \frac{v^2}{6}\left(-3\Lambda_3 - \frac{\Gamma_3}{2}(\Sigma - \Delta)\right) \implies \Delta m_{H_2^\pm}^2 = -\frac{\sqrt{3}M_0}{6}\mu_3 .
\end{aligned}
$$

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Decays

$\rho = \begin{pmatrix} 1 & & \\ & -1 & \\ & & -1 \end{pmatrix}$, preserved by $(1,0,0)$ and by M_1.

Residual $\mathbb{Z}_2$ symmetry remains...

Lightest scalar h_1 is stable!

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Conclusions

- Method with soft-breaking terms that preserve VEV direction.
- Scalar Alignment.
- Masses and decays.
- In a special case, stable scalars Dark Matter candidates.

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