Physics Beyond the Standard Model

Extended Higgs sector: Two-Higgs-Doublet Models II

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The 2HDM Higgs potential

We take CP-conserving and soft Z_2-breaking potential: $\lambda_6 = \lambda_7 = 0$, m_{12}^2 and λ_5 are real.

$$
\begin{aligned}
V_{2HDM}(\Phi_1, \Phi_1^\dagger, \Phi_2, \Phi_2^\dagger) = & \; m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \{\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\} \\
& + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\
& + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{1}{2}\lambda_5 \{(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2\}
\end{aligned}
$$

Theoretical constraints: $\lambda_1 > 0, \lambda_2 > 0, \lambda_3 + \lambda_4 + \lambda_5 + 2\sqrt{\lambda_1 \lambda_2} > 0$

Conditions for potential extrema:

$$m_{11}^2 = m_{12}^2 \frac{v_2}{v_1} - \frac{\lambda_1}{2} v_1^2 - \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5) v_2^2$$

$$m_{22}^2 = m_{12}^2 \frac{v_1}{v_2} - \frac{\lambda_2}{2} v_2^2 - \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5) v_1^2$$

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Mass eigenstates

Rewrite Φ_1 and Φ_2 in real and complex fields

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \phi_1^0 + i\chi_1) \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \phi_2^0 + i\chi_2) \end{pmatrix}$$

Express the potential in $\binom{\phi_1^+}{\phi_2^+}$, $\binom{\phi_1^0}{\phi_2^0}$, $\binom{\chi_1}{\chi_2}$

$\mathcal{M}^2_{\phi^\pm}, \mathcal{M}^2_{\phi^0}, \mathcal{M}^2_{\chi}$

Intruduce two unitary matrices $R^\alpha = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix}$, $R^\beta = \begin{pmatrix} -s_\beta & c_\beta \\ c_\beta & s_\beta \end{pmatrix}$

$$\mathcal{M}^2_{\phi^\pm} = \begin{pmatrix} m_{12}^2 \frac{v_2}{v_1} - \frac{1}{2}(\lambda_4 + \lambda_5) v_2^2 & -m_{12}^2 + \frac{1}{2}(\lambda_4 + \lambda_5) v_1 v_2 \\ -m_{12}^2 + \frac{1}{2}(\lambda_4 + \lambda_5) v_1 v_2 & m_{12}^2 \frac{v_1}{v_2} - \frac{1}{2}(\lambda_4 + \lambda_5) v_1^2 \end{pmatrix}$$

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Mass eigenstate A

$$\mathcal{M}_\chi^2 = \frac{1}{2}\begin{pmatrix} m_{12}^2\frac{v_2}{v_1} + \lambda_1 v_1^2 & -m_{12}^2 + \lambda_{345} v_1 v_2 \\ -m_{12}^2 + \lambda_{345} v_1 v_2 & m_{12}^2\frac{v_1}{v_2} + \lambda_2 v_2^2 \end{pmatrix}$$

Mass eigenstates h and H

$$\mathcal{M}^2_{\phi^0} = \frac{1}{2}\begin{pmatrix} m_{12}^2 \frac{v_2}{v_1} - \lambda_5 v_2^2 & -m_{12}^2 + \lambda_5 v_1 v_2 \\ -m_{12}^2 + \lambda_5 v_1 v_2 & m_{12}^2 \frac{v_1}{v_2} - \lambda_5 v_1^2 \end{pmatrix}$$

Potential in mass eigenstates:

$$V_{\text{2HDM}} = m_{H^\pm}^2 H^+ H^- + \frac{1}{2} m_A^2 A^2 + \frac{1}{2} m_H^2 H^2 + \frac{1}{2} m_h^2 h^2 + \text{cubic, quartic terms}$$

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Higgs Basis: Φ_v, $\Phi_\perp$

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \phi_1^0 + i\chi_1) \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \phi_2^0 + i\chi_2) \end{pmatrix}$$

$$\Rightarrow \begin{pmatrix} H^+ \\ G^+ \end{pmatrix} = R^\beta \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}, \quad \begin{pmatrix} A \\ G^0 \end{pmatrix} = R^\beta \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}, \quad \begin{pmatrix} H \\ h \end{pmatrix} = R^\alpha \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}$$

$$R^\beta \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$$

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The Kinetic terms: $\mathcal{L}_{\text{kin.}}$

$\mathcal{L}_{\text{kin.}} = \sum_i (D^\mu \Phi_i)^\dagger D_\mu \Phi_i$

Gauge boson masses (EWSB)

Higgs -gauge boson Interaction and the Sum Rule $\sum_i g^2_{s_i VV} = (g_{h_{SM} VV})^2$

The Yukawa terms: the general form

$$-\mathcal{L}_{\text{Yuk.}} = \bar{Q}_i^0(\Sigma_{ij}^d\Phi_v + \Delta_{ij}^d\Phi_\perp)d_{Rj}^0 + \bar{Q}_i^0(\Sigma_{ij}^u\Phi_v^c + \Delta_{ij}^u\Phi_\perp^c)u_{Rj}^0 + \bar{L}_i^0(\Sigma_{ij}^l\Phi_v + \Delta_{ij}^l\Phi_\perp)e_{Rj}^0 + \text{H.c}$$

$$-\mathcal{L}_{\text{Yuk.}} \ni \bar{f}_i f_j S_1 \frac{m_f}{v}\delta_{ij} + \bar{f}_i f_j \frac{S_2}{\sqrt{2}}\bar{\Delta}_{ij}^f + i\bar{f}_i\gamma^5 f_j \frac{A}{\sqrt{2}}\bar{\Delta}_{ij}^f\text{: arbitrary } \bar{\Delta} \Rightarrow \text{FCNC}$$