Two-Higgs Doublet Model

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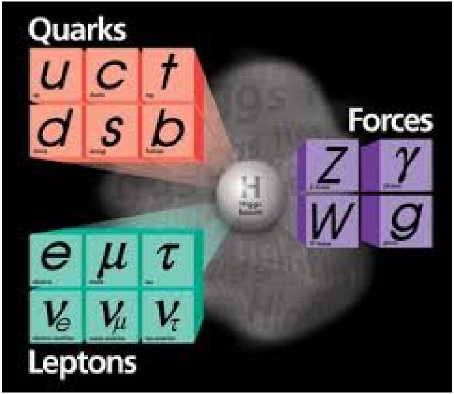
Standard Model



- It has $SU(3)_C \times SU(2)_L \times U(1)_Y$ structure

SM Potential

- The Higgs Lagrangian :

$$\mathcal{L}_{Higgs} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$$

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$$

$$D_\mu \Phi = \left(\partial_\mu - \frac{i\sigma^a}{2} g_1 W_\mu^a - \frac{iY}{2} g_2 B_\mu \right) \Phi$$

with: $\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix}$

$\langle 0|\Phi|0\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$

- By choosing $-\mu^2 < 0$ we break the electro-weak: $SU(2)_L \times U(1)_Y$

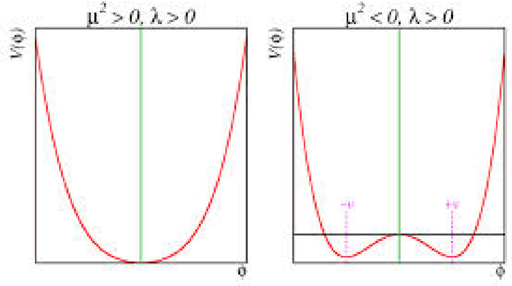


Figure : Plots of $V(\Phi)$ as a function of $|\Phi|$

- In 2HDM we add a doublet:

$$\mathcal{L}_\phi = \sum_{i=1,2} (D_\mu \phi_i)^\dagger (D^\mu \phi_i) - V(\phi_1, \phi_2)$$

- We write a potential that is Lorentz invariant, $SU(2)$ invariant and renormalizable:
- The potential is composed of the mass terms and the quartic terms

$$V = V_2 + V_4$$

$$V_2 = m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - (m_{12}^2 \phi_1^\dagger \phi_2 + h.c)$$

$$V_4 = \frac{\lambda_1}{2}(\phi_1^\dagger \phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger \phi_2)^2 + \lambda_3(\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4(\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1)$$

$$+ \left[\frac{\lambda_5}{2}(\phi_1^\dagger \phi_2)^2 + \lambda_6(\phi_1^\dagger \phi_1)(\phi_1^\dagger \phi_2) + \lambda_7(\phi_2^\dagger \phi_2)(\phi_1^\dagger \phi_2)\right]$$

With:

$$\Phi_a = \frac{1}{\sqrt{2}} \begin{pmatrix} \Phi_a^+ \\ (v_a + \rho_a + i\eta_a) \end{pmatrix}, a = 1, 2$$

set $\lambda_6, \lambda_7, m_{12}^2 = 0$

- Minimising the potential:

$$\frac{\partial V}{\partial \Phi_1^+}(\Phi_1 = \langle\Phi_1\rangle, \Phi_2 = \langle\Phi_2\rangle) = 0$$

$$\frac{\partial V}{\partial \Phi_2^+}(\Phi_1 = \langle\Phi_1\rangle, \Phi_2 = \langle\Phi_2\rangle) = 0$$

with:

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix}$$

$$\langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

- We get:

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

$$m_{22}^2 = m_{12}^2 \frac{v_1}{v_2} - \frac{\lambda_1}{2} v_1^2 - (\lambda_3 + \lambda_4 + \lambda_5) \frac{v_1^2}{2} \quad (2)$$

- Substituting (1) and (2) to the scalar potential with Φ_a and rewritting Φ_1 and Φ_2

$$\Phi_1 = \begin{pmatrix} G^+ \cos\beta + H^+ \sin\beta \\ \frac{1}{\sqrt{2}}(v\cos\beta + h\sin\alpha - H\cos\alpha + i(G^0\cos\beta + A\sin\beta)) \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} G^+ \sin\beta - H^+ \cos\beta \\ \frac{1}{\sqrt{2}}(v\sin\beta - h\cos\alpha - H\sin\alpha + i(G^0\sin\beta - A\cos\beta)) \end{pmatrix}$$

- There 8 degree's of freedom 3 Goldstone's get eaten to give mass to $W^{\pm}$ and Z^0 gauge bosons
- The remaining 5 are the physical scalar fields,the charged Higgs ($H^{\pm}$) two neutral scalars h and H where h is lighter than and H is heavier and neutral pseudoscalar
- Important Parameters
  - We use α to diagonalize the mass-squared matrices of the scalars
  - β to diagonalize the mass-squared matrices of the charged scalars and of the pseudoscalars and the ratio of the two vev's $\tan\beta = \frac{v_2}{v_1}$

- In 2HDM we have Flavour Changing Neutral Currents, this is due to the fact that it is not easy to diagonalize the mass matrix in the Yukawa sector
- Mass matrix of the down-quark becomes:

$$\mathcal{M}_{ij}^{d} = (y_{ij}^{d_1}\frac{v_1}{\sqrt{2}} + y_{ij}^{d_2}\frac{v_2}{\sqrt{2}})$$

- Diagonalizing the mass matrix of the Yukawa couplings, however does not diagonalize the orthogonal linear combination of the Yukawa couplings
- When this linear combination is not diagonalized in the mass basis there exists flavour changing couplings in the pseudoscalar such a vertex: $A\bar{s}d$ at tree level

- Linear combination of Yukawa coupling is :

$$y_{ij}^{d_1} \cos\beta + y_{ij}^{d_2} \sin\beta$$

- Orthogonal linear Yukawa couplings:

$$y_{\imath\jmath}^{d_1} \sin\beta + y_{ij}^{d_2} \cos\beta$$

- Similarly for the up-type quark and lepton sector
- These processses are known as Flavour-Changing Neutral Currents (FCNC)

- Imposing Z_2 symmetry

Model	$u_R^\imath$	$d_R^\imath$	$e_R^\imath$
Type 1	Φ_2	Φ_2	Φ_2
Type 2	Φ_2	Φ_1	Φ_1
Leptonic-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

Table: Models which lead to natural flavour conservation. The superscript $\imath$ is a generation index. By convention, the $u_R^\imath$ aways couple to Φ_2

- Type 1 Lagrangian Yukawa sector

$$\mathcal{L} = g_1^d[\bar{d}_q \Phi_1 d_R + \bar{d}_R \Phi_1^\dagger d_q] + g_2^u[\bar{u}_q \tilde{\Phi}_2 u_R + \bar{u}_R \tilde{\Phi_2}^\dagger u_q]$$

- Type 2 Lagrangian Yukawa sector

$$\mathcal{L} = g_1^d[\bar{d}_q \Phi_1 d_R + \bar{d}_R \Phi_1^\dagger d_q] + g_2^u[\bar{u}_q \tilde{\Phi}_2 u_R + \bar{u}_R \tilde{\Phi_2}^\dagger u_q]$$

where: $\Phi\tilde{(x)} = -i[\Phi_i^\dagger(x)\tau_2]^T \qquad i = 1, 2$

- In conclusion I have talked about the scalar potential in the standard model
- The scalar potential in the 2HDM
- the four types of 2HDM