Controlled Flavour Changing Neutral Couplings in Two Higgs Doublet Models

João M. Alves[1]

[1]Instituto Superior Técnico,
Universidade de Lisboa

The Standard Model and Beyond, Corfu, 2018

Multi-Higgs Doublet Models
Definition

- Fermionic content: SM;
- Gauge symmetry: $G_{SM} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$;
- Scalar content: N scalars $\phi_a = (1, 2, \frac{1}{2})$.

- Why MHDMs?
  - Strong CP Problem;
  - Baryogenesis;
  - Dark Matter;
  - Hierarchy Problem*.

- Scalar Potential
  - $V(\phi) = \mu_{ab}(\phi_a^\dagger \phi_b) + \lambda_{ab,cd}(\phi_a^\dagger \phi_b)(\phi_c^\dagger \phi_d)$;
  - $\frac{1}{2}N^2(N^2+3) - 2$ new parameters.

- Yukawa sector
  - $-\mathcal{L}_{yuk} = (R_a + i\epsilon_q J_a)\left(\bar{q}_L N_{qa} q_R\right)/v + h.c.$;
  - $N_{qa} = \frac{1}{\sqrt{2}} v O_{ab} e^{i\epsilon_q \alpha_b} \left(U_{qL}^\dagger Y_b^q U_{qR}\right)$;
  - $36(N-1)$ new parameters.

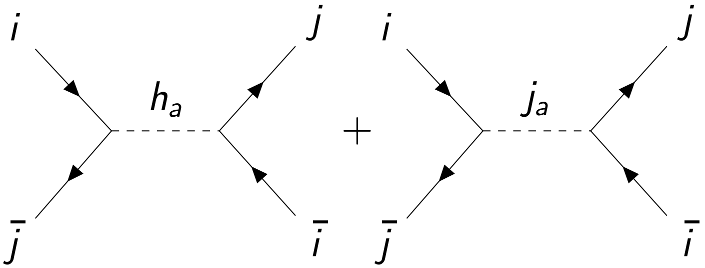


Figure: Tree-level diagrams contributing to meson-antimeson mixing in a MHDM

$$\left| f_1\left(\frac{m_P^2}{m_j^2}\right)\sum_a \frac{1-R_{a1}^2}{m_{h_a}^2}(\tau_a^+)^2 - f_2\left(\frac{m_P^2}{m_j^2}\right)\sum_a \frac{1}{m_{j_a}^2}(\tau_a^+)^2 + (\dots)\right| \leq \frac{24v^2\Delta m_P}{m_P f_P^2}$$

- Take decoupling limit, $m_h \ll m_{h_a}, m_{j_a}$

$$c_{\beta\alpha}^2 \left\{ g_1 \sum_b \left[|(N_{qb})_{ij}|^2 + |(N_{qb})_{ji}|^2 \right] - g_2 \sum_b \mathrm{Re}\left[(N_{qb})_{ij}(N_{qb})_{ji}\right] \right\} \le \frac{24 v^2 m_h^2 \Delta m_P}{m_P f_P^2}$$

- Assume Yukawa couplings of order one
  - Up sector restriced by $D - \bar{D}$;
  - Down sector restricted by $K - \bar{K}$.

$$c_{\beta\alpha}^2 (1.1 c_1^u - c_2^u) < 3 \times 10^{-9}, \qquad c_{\beta\alpha}^2 (1.2 c_1^d - c_2^d) < 8 \times 10^{-10}.$$

- 2HDM invariant under the Abelian Flavour Symmetry*

[Branco, Grimus and Lavoura, arXiv:9601383]

$$q_{L3} \to \Upsilon q_{L3}, \quad u_{R3} \to \Upsilon^2 u_{R3}, \quad \phi_2 \to \Upsilon \phi_2, \quad \Upsilon^2 \neq 1.$$

- Yukawa textures of BGL models*

$$\Gamma_1 = \begin{bmatrix} x & x & x \\ x & x & x \\ 0 & 0 & 0 \end{bmatrix}, \Gamma_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ x & x & x \end{bmatrix}, \Delta_1 = \begin{bmatrix} x & x & 0 \\ x & x & 0 \\ 0 & 0 & 0 \end{bmatrix}, \Delta_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & x \end{bmatrix}.$$

- WBI definition of BGL models*

$$\Gamma_1^\dagger \Gamma_2 = \Delta_1^\dagger \Delta_2 = \Gamma_1^\dagger \Delta_2 = \Gamma_2^\dagger \Delta_1 = \Delta_1 \Delta_2^\dagger = 0, \quad \Gamma_1 \neq 0, \quad \Gamma_2 \neq 0.$$

BGL Models

Review

- Non-diagonal couplings of BGL models*

$$(N_d)_{ij} = \left[t_\beta \delta_{ij} - (t_\beta + t_\beta^{-1}) V_{ti}^* V_{tj}\right] (m_d)_{jj},$$

$$N_u = \mathrm{diag}\left\{t_\beta m_u, t_\beta m_c, -t_\beta^{-1} m_t\right\}.$$

- Experimental Constraints*

$$|c_{\beta\alpha}(t_\beta + t_\beta^{-1})| < 3 .$$

- Baryon Asymmetry of the Universe*

$$\frac{BAU_{BGL}}{BAU_{SM}} = (t_\beta + t_\beta^{-1}) \frac{E^4}{m_t^4} \sim 1.$$

Left Models
Definition

- MHDM invariant under abelian symmetry

[Alves, Botella, Branco, Cornet-Gomez, Nebot and Silva, arXiv:1803.11199]

$$N_d^0 = L_d^0 D_d^0, \qquad N_u^0 = L_u^0 D_u^0.$$

- For 2HDM, $(L_d^0)_{ii}$ are determined by

$$(\Gamma_1)_{ij} \neq 0 \Rightarrow (L_d^0)_{ii} = t_\beta,$$
$$(\Gamma_2)_{ij} \neq 0 \Rightarrow (L_d^0)_{ii} = -t_\beta^{-1}.$$

- Each line of a mass matrix of a quark of a given charge can only receive contributions from one scalar;
- There are only five classes of left models in 2HDM.

- 2HDM invariant under the Abelian Flavour Symmetry

[Alves, Botella, Branco, Cornet-Gomez and Nebot, arXiv:1703.03796]

$$q_{L3} \to -q_{L3}, \quad \phi_2 \to -\phi_2.$$

- Yukawa textures of gBGL models

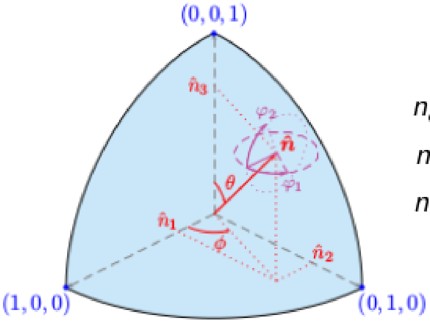
$$\Gamma_1 \sim \Delta_1 \sim \begin{bmatrix} x & x & x \\ x & x & x \\ 0 & 0 & 0 \end{bmatrix}, \quad \Gamma_2 \sim \Delta_2 \sim \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ x & x & x \end{bmatrix}.$$

- WBI definition of gBGL models

$$\Gamma_1^\dagger \Gamma_2 = \Delta_1^\dagger \Delta_2 = \Gamma_1^\dagger \Delta_2 = \Gamma_2^\dagger \Delta_1 = 0, \quad \Gamma_1 \neq 0, \quad \Gamma_2 \neq 0.$$

- Non-diagonal couplings of gBGL models

$$(N_d)_{ij} = \left[t_\beta \delta_{ij} - (t_\beta + t_\beta^{-1}) V_{mi}^* V_{nj} n_m^* n_n \right] (m_d)_{jj},$$
$$(N_u)_{ij} = \left[t_\beta \delta_{ij} - (t_\beta + t_\beta^{-1}) n_i^* n_j \right] (m_u)_{jj}.$$



$$n_d = (V_{ud}^*, V_{cd}^*, V_{td}^*), \quad n_u = (1, 0, 0)$$
$$n_s = (V_{us}^*, V_{cs}^*, V_{ts}^*), \quad n_c = (0, 1, 0)$$
$$n_b = (V_{ub}^*, V_{cb}^*, V_{tb}^*), \quad n_t = (0, 0, 1)$$

- Experimental Constraints

$$|c_{\beta\alpha}(t_\beta + t_\beta^{-1})| < 0.02,$$
$$|c_{\beta\alpha}(t_\beta + t_\beta^{-1})| < 3\ [\sim tBGL].$$

- Baryon Asymmetry of the Universe

$$\frac{BAU_{gBGL}}{BAU_{SM}} \sim 10^{16}(t_\beta + t_\beta^{-1})|n_2^* n_3| \sin\left[\arg\left(n_3^* n_2 V_{tb}^* V_{cb}\right)\right],$$
$$\frac{BAU_{\sim tBGL}}{BAU_{SM}} \sim 10^{16}(t_\beta + t_\beta^{-1})|V_{ts}| \mathrm{Im}\left[\delta_b + \delta_s^*\right] \sim 10^{12}.$$

- 2HDM invariant under the Abelian Flavour Symmetry

$$\phi_2 \to \Upsilon \phi_2, \quad q_{L3}^0 \to \Upsilon^{-1} q_{L3}^0, \quad d_R^0 \to \Upsilon^{-1} d_R^0$$

- Yukawa textures of gBGL models

$$\Delta_1 \sim \Gamma_2 \sim \begin{bmatrix} x & x & x \\ x & x & x \\ 0 & 0 & 0 \end{bmatrix}, \quad \Delta_2 \sim \Gamma_1 \sim \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ x & x & x \end{bmatrix}.$$

- WBI definition of jBGL models

$$\Gamma_1^\dagger \Gamma_2 = \Delta_1^\dagger \Delta_2 = \Gamma_1^\dagger \Delta_1 = \Gamma_2^\dagger \Delta_2 = 0, \quad \Gamma_1 \neq 0, \quad \Gamma_2 \neq 0.$$

- Non-diagonal couplings of jBGL models

$$(N_d)_{ij} = \left[-t_\beta^{-1} \delta_{ij} + (t_\beta + t_\beta^{-1}) V_{mi}^* V_{nj} n_m^* n_n \right] (m_d)_{jj},$$
$$(N_u)_{ij} = \left[t_\beta \delta_{ij} - (t_\beta + t_\beta^{-1}) n_i^* n_j \right] (m_u)_{jj}.$$

- Experimental Constraints

$$|c_{\beta\alpha}(t_\beta + t_\beta^{-1})| < 0.02$$

- Baryon Asymmetry of the Universe

$$\frac{BAU_{jBGL}}{BAU_{SM}} \sim 10^{16}(t_\beta + t_\beta^{-1})|n_2^* n_3| \sin\left[\arg\left(n_3^* n_2 V_{tb}^* V_{cb}\right)\right],$$

Right Models

Definition

- MHDM invariant under abelian symmetry

[Alves, Botella, Branco, Cornet-Gomez, Nebot and Silva, arXiv:1803.11199]

$$N_d^0 = D_d^0 R_d^0, \qquad N_u^0 = D_u^0 R_u^0$$

- For 2HDM, $(R_d^0)_{ii}$ are determined by

$$(\Gamma_1)_{ij} \neq 0 \Rightarrow (R_d^0)_{jj} = t_\beta$$
$$(\Gamma_2)_{ij} \neq 0 \Rightarrow (R_d^0)_{jj} = -t_\beta^{-1}$$

- Each column of a mass matrix of a quark of a given charge can only receive contributions from one scalar;
- There are only eight classes of right models in 2HDM.

- Type A(B)

$$\Gamma_1 \sim \begin{bmatrix} x & x & x \\ x & x & x \\ x & x & x \end{bmatrix}, \quad \Gamma_2 = 0, \quad \Delta_1 \sim \begin{bmatrix} x & x & 0 \\ x & x & 0 \\ x & x & 0 \end{bmatrix}, \quad \Delta_2 \sim \begin{bmatrix} 0 & 0 & x \\ 0 & 0 & x \\ 0 & 0 & x \end{bmatrix}.$$

- Type E(F)

$$\Gamma_1 \sim \Delta_1 \sim \begin{bmatrix} x & x & 0 \\ x & x & 0 \\ x & x & 0 \end{bmatrix}, \quad \Gamma_2 \sim \Delta_2 \sim \begin{bmatrix} 0 & 0 & x \\ 0 & 0 & x \\ 0 & 0 & x \end{bmatrix}.$$

- Experimental constraints

$$|c_{\beta\alpha}(t_\beta + t_\beta^{-1})| < 0.02$$

- Type C (D)

$$\Gamma_1 \sim \begin{bmatrix} x & x & 0 \\ x & x & 0 \\ x & x & 0 \end{bmatrix}, \quad \Gamma_2 \sim \begin{bmatrix} 0 & 0 & x \\ 0 & 0 & x \\ 0 & 0 & x \end{bmatrix}, \quad \Delta_1 \sim \begin{bmatrix} x & x & x \\ x & x & x \\ x & x & x \end{bmatrix}, \quad \Delta_2 = 0.$$

- Experimental constraints

$$|c_{\beta\alpha}(t_\beta + t_\beta^{-1})| < 0.03$$

	$(3,0)$	$(0,3)$	$(2,1)$	$(1,2)$
$(3,0)$	Type I	Type II	Type A	Type B
$(0,3)$	Type II	Type I	Type B	Type A
$(2,1)$	Type C	Type D	Type E	Type F
$(1,2)$	Type D	Type C	Type F	Type E

Table: WBI identification of Right Models.