Symmetry Constrained Two Higgs Doublet Models

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Symmetry Constrained Two Higgs Doublet Models

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Introduction and Motivation

- Higgs-fermions couplings SM-like or expanded complex scalar sector
- A natural scenario is Two Higgs Doublet Model (2HDM)
- 2HDM where Abelian symmetries have been introduced
  - Drastic reduction of free parameters
  - Stability under RGE
- Classification of all the models
- Brief phenomenological analysis of the most salient features of each class

General 2HDM

$$L_Y = -\overline{Q}_L \left(\Gamma_1 \Phi_1 + \Gamma_2 \Phi_2\right) d_R - \overline{Q}_L \left(\Delta_1 \widetilde{\Phi}_1 + \Delta_2 \widetilde{\Phi}_2\right) u_R + .h.c.$$

With the vev's given by $\langle \Phi_i \rangle^T = e^{i\theta_i} \left(\begin{array}{cc} 0 & v_i/\sqrt{2} \end{array} \right)$ we define the Higgs basis by $\langle H_1 \rangle^T = \left(\begin{array}{cc} 0 & v/\sqrt{2} \end{array} \right), \langle H_2 \rangle^T = \left(\begin{array}{cc} 0 & 0 \end{array} \right), v^2 = v_1^2 + v_2^2, c_\beta = v_1/v, s_\beta = v_2/v, t_\beta = v_2/v_1$

$$\left(\begin{array}{c} e^{-i\theta_1} \Phi_1 \\ e^{-i\theta_2} \Phi_2 \end{array} \right) = \left(\begin{array}{cc} c_\beta & s_\beta \\ s_\beta & -c_\beta \end{array} \right) \left(\begin{array}{c} H_1 \\ H_2 \end{array} \right)$$

then we have

$$H_1 = \left(\begin{array}{c} G^+ \\ \left(v + H^0 + iG^0\right)/\sqrt{2} \end{array} \right) \quad ; \quad H_2 = \left(\begin{array}{c} H^+ \\ \left(R^0 + iA\right)/\sqrt{2} \end{array} \right)$$

- $H^{\pm}$ new charged Higgs bosons.
- A new CP odd scalar (we will have CP invariant Higgs potential).
- H^0 and R^0 CP even scalars. If they do not mix, H^0 the SM Higgs.

$$
\begin{aligned}
\mathcal{L}_Y = & -\frac{\sqrt{2}H^+}{v}\bar{u}\left(VN_d\gamma_R - N_u^\dagger\, V\gamma_L\right)d + h.c. \\
& -\frac{H^0}{v}\left(\bar{u}M_u u + \bar{d}M_d\; d\right) - \\
& -\frac{R^0}{v}\left[\bar{u}(N_u\gamma_R + N_u^\dagger\gamma_L)u + \bar{d}(N_d\gamma_R + N_d^\dagger\gamma_L)\; d\right] \\
& +i\frac{A}{v}\left[\bar{u}(N_u\gamma_R - N_u^\dagger\gamma_L)u - \bar{d}(N_d\gamma_R - N_d^\dagger\gamma_L)\; d\right]
\end{aligned}
$$

Background: BGL (Branco, Grimus and Lavoura)

A BGL model is enforced by the $U\left(1\right)$ flavour symmetry (top type model)

$$Q_{L_3} \to e^{i\alpha} Q_{L_3} \quad ; \quad u_{R_3} \to e^{i2\alpha} u_{R_3} \quad ; \quad \Phi_2 \to e^{i\alpha} \Phi_2$$

In the quark mass basis it correspond to the model defined by the MFV expansion -$\left(P_3\right)_{ij} = \delta_{i3}\delta_{j3}$-

$$N_d = U_L^{d\dagger} N_d^0 U_R^d = \left[t_\beta I - \left(t_\beta + t_\beta^{-1}\right) V^\dagger P_3 V\right] M_d$$
$$N_u = U_L^{u\dagger} N_u^0 U_R^u = \left[t_\beta I - \left(t_\beta + t_\beta^{-1}\right) P_3\right] M_u$$

or to the model with the following Yukawa couplings

$$\Gamma_1 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix} \quad ; \quad \Gamma_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}$$

$$\Delta_1 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad ; \quad \Delta_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

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In the quark mass basis it correspond to the model defined by the MFV expansion -$(P_3)_{ij} = \delta_{i3}\delta_{j3}$-

$$N_d = U_L^{d\dagger} N_d^0 U_R^d = \left[t_\beta I - \left(t_\beta + t_\beta^{-1} \right) V^\dagger P_3 V \right] M_d$$

$$\boxed{N_u = U_L^{u\dagger} N_u^0 U_R^u = \left[t_\beta I - \left(t_\beta + t_\beta^{-1} \right) P_3 \right] M_u}$$

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$$\Delta_1 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad ; \quad \Delta_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

Definition

- Abelian symmetry transformations

$$\Phi_1 \mapsto \Phi_1,\ \Phi_2 \mapsto e^{i\theta}\Phi_2,\ Q^0_{Lj} \mapsto e^{i\alpha_j\theta}Q^0_{Lj},$$
$$d^0_{Rj} \mapsto e^{i\beta_j\theta}d^0_{Rj},\ u^0_{Rj} \mapsto e^{i\gamma_j\theta}u^0_{Rj}$$

- Classification$\rightarrow$ 1012.2874 (P. M. Ferreira and J. P. Silva)
- As in BGL $N_u = [t_\beta P_1 + t_\beta P_2 + t_\beta^{-1} P_3] M_u$
  - Left Conditions $N_d^0 = L_d^0\, M_d^0\,, \quad N_u^0 = L_u^0\, M_u^0\,,$ with $L_q^0 = l_1^{[q]} P_1 + l_2^{[q]} P_2 + l_3^{[q]} P_3$
  - Right Conditions $N_d^0 = M_d^0\, R_d^0\,, \quad N_u^0 = M_u^0\, R_u^0\,,$ with $R_q^0 = r_1^{[q]} P_1 + r_2^{[q]} P_2 + r_3^{[q]} P_3$

$$P_1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},\quad P_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix},\quad P_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Left Models

Model \ Properties	Sym.	Tree FCNC	Parameters
G-W	$\mathbb{Z}_2$	$(N_u)_{ij} \propto \delta_{ij} m_{u_j}$ $(N_d)_{ij} \propto \delta_{ij} m_{d_j}$	t_β, m_{q_k}
uBGL (t)	$\mathbb{Z}_{n\geq 4}$	$(N_u)_{ij} = \delta_{ij}(t_\beta - (t_\beta + t_\beta^{-1})\delta_{j3}) m_{u_j}$ $(N_d)_{ij} = (t_\beta \delta_{ij} - (t_\beta + t_\beta^{-1}) V_{ti}^* V_{tj}) m_{d_j}$	V, t_β, m_{q_k}
dBGL (b)	$\mathbb{Z}_{n\geq 4}$	$(N_u)_{ij} = (t_\beta \delta_{ij} - (t_\beta + t_\beta^{-1}) V_{ib} V_{jb}^*) m_{u_j}$ $(N_d)_{ij} = \delta_{ij}(t_\beta - (t_\beta + t_\beta^{-1})\delta_{j3}) m_{d_j}$	V, t_β, m_{q_k}
gBGL	$\mathbb{Z}_2$	$(N_u)_{ij} = (t_\beta \delta_{ij} - (t_\beta + t_\beta^{-1}) \hat{n}_{[u]i}^* \hat{n}_{[u]j}) m_{u_j}$ $(N_d)_{ij} = (t_\beta \delta_{ij} - (t_\beta + t_\beta^{-1}) \hat{n}_{[d]i}^* \hat{n}_{[d]j}) m_{d_j}$	V, t_β, m_{q_k} $\hat{n}_{[q]}$(+4)
jBGL	$\mathbb{Z}_{n\geq 2}$	$(N_u)_{ij} = (t_\beta \delta_{ij} - (t_\beta + t_\beta^{-1}) \hat{n}_{[u]i}^* \hat{n}_{[u]j}) m_{u_j}$ $(N_d)_{ij} = (-t_\beta^{-1} \delta_{ij} + (t_\beta + t_\beta^{-1}) \hat{n}_{[d]i}^* \hat{n}_{[d]j}) m_{d_j}$	V, t_β, m_{q_k} $\hat{n}_{[q]}$(+4)

Right Models

Model \ Properties	Sym.	Tree FCNC	Parameters
G-W	$\mathbb{Z}_2$	$(N_u)_{ij} \propto m_{u_i}\delta_{ij}$ $(N_d)_{ij} \propto m_{d_i}\delta_{ij}$	t_β, m_{q_k}
Type A	$\mathbb{Z}_{n\geq 2}$	$(N_u)_{ij} = m_{u_i}(t_\beta\delta_{ij} - (t_\beta + t_\beta^{-1})\hat{r}^*_{[\mathrm{u}]i}\hat{r}_{[\mathrm{u}]j})$ $(N_d)_{ij} = m_{d_i}t_\beta\delta_{ij}$	t_β, m_{q_k} $\hat{r}_{[\mathrm{u}]}(+4)$
Type B	$\mathbb{Z}_{n\geq 2}$	$(N_u)_{ij} = m_{u_i}(-t_\beta^{-1}\delta_{ij} + (t_\beta + t_\beta^{-1})\hat{r}^*_{[\mathrm{u}]i}\hat{r}_{[\mathrm{u}]j})$ $(N_d)_{ij} = m_{d_i}t_\beta\delta_{ij}$	t_β, m_{q_k} $\hat{r}_{[\mathrm{u}]}(+4)$
Type C	$\mathbb{Z}_{n\geq 2}$	$(N_u)_{ij} = m_{u_i}t_\beta\delta_{ij}$ $(N_d)_{ij} = m_{d_i}(t_\beta\delta_{ij} - (t_\beta + t_\beta^{-1})\hat{r}^*_{[\mathrm{d}]i}\hat{r}_{[\mathrm{d}]j})$	t_β, m_{q_k} $\hat{r}_{[\mathrm{d}]}(+4)$
Type D	$\mathbb{Z}_{n\geq 2}$	$(N_u)_{ij} = m_{u_i}t_\beta\delta_{ij}$ $(N_d)_{ij} = m_{d_i}(-t_\beta^{-1}\delta_{ij} + (t_\beta + t_\beta^{-1})\hat{r}^*_{[\mathrm{d}]i}\hat{r}_{[\mathrm{d}]j})$	t_β, m_{q_k} $\hat{r}_{[\mathrm{d}]}(+4)$
Type E	$\mathbb{Z}_{n\geq 2}$	$(N_u)_{ij} = m_{u_i}(t_\beta\delta_{ij} - (t_\beta + t_\beta^{-1})\hat{r}^*_{[\mathrm{u}]i}\hat{r}_{[\mathrm{u}]j})$ $(N_d)_{ij} = m_{d_i}(t_\beta\delta_{ij} - (t_\beta + t_\beta^{-1})\hat{r}^*_{[\mathrm{d}]i}\hat{r}_{[\mathrm{d}]j})$	t_β, m_{q_k} $\hat{r}_{[\mathrm{u}]}, \hat{r}_{[\mathrm{d}]}(+8)$
Type F	$\mathbb{Z}_{n\geq 2}$	$(N_u)_{ij} = m_{u_i}(-t_\beta^{-1}\delta_{ij} + (t_\beta + t_\beta^{-1})\hat{r}^*_{[\mathrm{u}]i}\hat{r}_{[\mathrm{u}]j})$ $(N_d)_{ij} = m_{d_i}(t_\beta\delta_{ij} - (t_\beta + t_\beta^{-1})\hat{r}^*_{[\mathrm{d}]i}\hat{r}_{[\mathrm{d}]j})$	t_β, m_{q_k} $\hat{r}_{[\mathrm{u}]}, \hat{r}_{[\mathrm{d}]}(+8)$

Pheno

If CP is conserved, the CP-odd neutral A, doesn't mix with the CP-even and the relevant angle is $(\beta - \alpha)$: $c_{\beta\alpha} = \cos(\beta - \alpha)$, $s_{\beta\alpha} = \sin(\beta - \alpha)$

$$\begin{pmatrix} H^0 \\ R^0 \end{pmatrix} = \begin{pmatrix} c_{\beta\alpha} & s_{\beta\alpha} \\ -s_{\beta\alpha} & c_{\beta\alpha} \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

The flavor changing Yukawa

$$-\mathcal{L}_{h\bar{q}_i q_j} = -h\bar{q}_i Y_{ij} q_j$$

and

$$Y_{ij} \supset c_{\beta-\alpha}(t_\beta + t_\beta^{-1})^{-1} \hat{n}^*_{[q]i} \hat{n}_{[q]j} \frac{m_{q_j}}{v}$$

- All FCNC effects are proportional to $c_{\beta\alpha}\left(t_\beta + t_\beta^{-1}\right) <= 1$
- In an $i \to j$ transition it is proportional to m_{q_i}/v
  - e.g. Transition $u \to c$ no factor m_t
- Taking into account Max$|\hat{n}^*_{[q]i}\hat{n}_{[q]j}| = 1/2$
- From meson mixing, we can get an universal bound, all the models are safe over the entire parameter space provided we take:

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

- In general Y_{ij} presents an extremely m_{q_i}/v suppression except for the top. Taking into account ATLAS and CMS experimental bounds for Br$(t \to hq)$ we get

$$\left|c_{\beta\alpha}\left(t_\beta + t_\beta^{-1}\right)\right| \leq 0.4$$

Thanks!