Controlled Flavour Changing Neutral Couplings in Two Higgs Doublet Models

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Controlled flavour changing neutral couplings in 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)
  - Symmetries are needed to avoid or suppress FCNC.
- To avoid FCNC: postulate that quarks of a given charge receive contributions to their mass only from one Higgs doublet.
- A Z_2 symmetry (Glashow-Weinberg) leads to Natural Flavour Conservation (NFC) in the scalar sector.
- Minimal Flavour Violation (MFV) 2HDM
  - Enforced by symmetries $\Rightarrow$ FCNC controlled by V_{CKM}
  - BGL models (Branco, Grimus, Lavoura) that have FCNC in the up or in the down sector, but not in both.
- Here we will present a new family of models generalizing the BGL one and having FNCN both in the up and in the down scalar sectors.

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 $\langle \Phi_i \rangle^T = e^{i\theta_i} \begin{pmatrix} 0 & v_i/\sqrt{2} \end{pmatrix}$ we define the Higgs basis by $\langle H_1 \rangle^T = \begin{pmatrix} 0 & v/\sqrt{2} \end{pmatrix}, \langle H_2 \rangle^T = \begin{pmatrix} 0 & 0 \end{pmatrix}, v^2 = v_1^2 + v_2^2, c_\beta = v_1/v, s_\beta = v_2/v, t_\beta = v_2/v_1$

$$\begin{pmatrix} e^{-i\theta_1}\Phi_1 \\ e^{-i\theta_2}\Phi_2 \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ s_\beta & -c_\beta \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

then we have

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

- $G^{\pm}$ and G^0 longitudinal degrees of freedom of $W^{\pm}$ and Z^0.
- $H^{\pm}$ 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.

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

BGL

A BGL model is enforced by the $U(1)$ 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 -$(P_3)_{ij} = \delta_{i3}\delta_{j3}$-

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

or to the model with the following Yukawa couplings

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

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

Generalizing BGL models: gBGL

The generalized BGL models (gBGL) are implemented through a Z_2 symmetry, where u_R and d_R are even and only one of the scalars doublets and one of the left-handed quark doublets are odd:

$$\begin{array}{ccc} Q_{L_3} \to -Q_{L_3} & , & \\ d_R \to d_R & , & \Phi_1 \to \Phi_1 \\ u_R \to u_R & , & \Phi_2 \to -\Phi_2 \end{array}$$

Now the Yukawa textures are:

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

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

This time, in the quark sector, the model is fully defined , in the mass basis, by

$$\begin{aligned} N_d &= \left[t_\beta I - \left(t_\beta + t_\beta^{-1}\right) \left|\widehat{n}_d\right\rangle \left\langle\widehat{n}_d\right|\right] M_d \\ N_u &= \left[t_\beta I - \left(t_\beta + t_\beta^{-1}\right) V \left|\widehat{n}_d\right\rangle \left\langle\widehat{n}_d\right| V^\dagger\right] M_u \end{aligned}$$

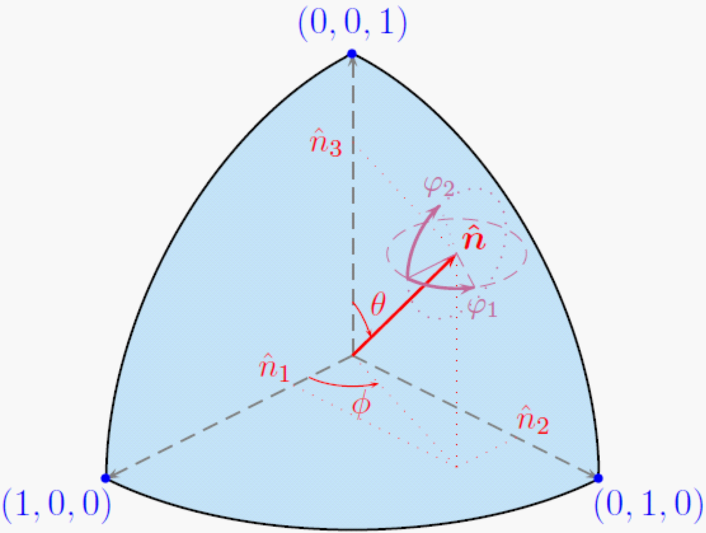
or if we call

$$\left|\widehat{n}_u\right\rangle = V \left|\widehat{n}_d\right\rangle$$

we also have

$$\begin{aligned} N_d &= \left[t_\beta I - \left(t_\beta + t_\beta^{-1}\right) V^\dagger \left|\widehat{n}_u\right\rangle \left\langle\widehat{n}_u\right| V\right] M_d \\ N_u &= \left[t_\beta I - \left(t_\beta + t_\beta^{-1}\right) \left|\widehat{n}_u\right\rangle \left\langle\widehat{n}_u\right|\right] M_u \end{aligned}$$

the free parameters are two angles to define the unitary vector $\left|\widehat{n}_u\right\rangle$ or $\left|\widehat{n}_d\right\rangle$ and two phases of the three complex component



(c) Generic parametrisation.

Intesity of FCNC I

- The Yukawa coupling to the $125GeV$ Higgs

$$
\begin{aligned}
Y^{(q)} &= \frac{1}{v}\left[s_{\beta\alpha} M_q + c_{\beta\alpha} N_q\right] \\
N_d &= \left[t_\beta I - \left(t_\beta + t_\beta^{-1}\right) |\widehat{n}_d\rangle \langle\widehat{n}_d|\right] M_d
\end{aligned}
$$

in general generate FCNC

$$
Y^{(q)} = \left[\left(s_{\beta\alpha} + c_{\beta\alpha}\right) I - c_{\beta\alpha}\left(t_\beta + t_\beta^{-1}\right) |\widehat{n}_q\rangle \langle\widehat{n}_q|\right] \frac{M_q}{v}
$$

  - All FCNC effects are proportional to $c_{\beta\alpha}\left(t_\beta + t_\beta^{-1}\right)$
  - In an $i \to j$ transition it is proportional to m_{q_i}/v
  - In an $i \to j$ transition it is proportional to $\left(|\widehat{n}_q\rangle \langle\widehat{n}_q|\right)_{ji}$ with maximal value $\left(1/\sqrt{2}\right)\left(1/\sqrt{2}\right) = 1/2$

Intesity of FCNC II

- To be compared with the most intense case of BGL u model in the $s \to d$ transition $\sim V_{ud}^* V_{us} \sim \lambda$

- From meson mixing we have the following naive constraints

	$D^0 - \overline{D}^0$	$K^0 - \overline{K}^0$	$B^0 - \overline{B}^0$	$B_s^0 - \overline{B}_s^0$
$\left\| c_{\beta\alpha} \left(t_\beta + t_\beta^{-1} \right) \right\| \leq$	0.02	0.04	0.003	0.007

and from rare top decays $t \to hq$

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

- There are many regions of the model parameter space where $\left| c_{\beta\alpha} \left(t_\beta + t_\beta^{-1} \right) \right|$ can get its maximum value of order one.

Near Top model

We will study the properties of gBGL that are **close to** the t BGL model in the sense that they give the **same contribution to meson mixing**

$$\left|\left(\widehat{t}+\widehat{\delta t}\right)_d\right\rangle = N\begin{pmatrix} V_{td}^*\left(1+\delta_d\right) \\ V_{ts}^*\left(1+\delta_s\right) \\ V_{tb}^*\left(1+\delta_b\right) \end{pmatrix}$$

The up models near the top give the same contribution to meson mixing than the top BGL model provided

$$\mathrm{Re}\left(\delta_{d,s,b}\right)\sim \mathrm{Im}\left(\delta_s\right)\leq \mathcal{O}\left(\lambda^2\right)\text{ , and Im }\left(\delta_{d,b}\right)\leq \mathcal{O}\left(\lambda^3\right)$$

and the contribution to $D^0-\overline{D}^0$ contribution is easily seen to be controlled from

$$V\left|\left(\widehat{t}+\widehat{\delta t}\right)_d\right\rangle \sim \begin{pmatrix} \mathcal{O}\left(\lambda^5\right) \\ \delta_b V_{cb} \\ 1+\delta_b \end{pmatrix} \Rightarrow M_{12}\left[D^0\right]\propto\left(\delta_b V_{cb}\lambda^5\right)^2\leq\lambda^{18}$$

BAU I

The contribution to the Baryon asymmetry of the Universe is proportional the a weak basis invariant with an imaginary piece.
In the SM it appears for the first time **at order 12th in Yukawa couplings** and is given by the Jarlskog (see also Bernabeu, Branco, Gronau) Invariant:

$$
\begin{aligned}
I_{12} &= \mathrm{Im} Tr\left[\left(M_u^0 M_u^{0\dagger}\right)\left(M_d^0 M_d^{0\dagger}\right)\left(M_u^0 M_u^{0\dagger}\right)^2\left(M_d^0 M_d^{0\dagger}\right)^2\right] \\
\sim \quad & m_t^4 m_c^2 m_b^4 m_s^2 J
\end{aligned}
$$

where $J \equiv \mathrm{Im}\left(V_{us} V_{cb} V_{ub}^* V_{cs}^*\right)$

BAU II

In the BGL models an imaginary part appears first **at order 8th in Yukawa couplings** and is given by

$$
\begin{aligned}
I_8\left(t\right) &\sim \left(t_\beta + t_\beta^{-1}\right) m_b^4 m_c^2 m_s^2 J \\
I_8\left(b\right) &\sim \left(t_\beta + t_\beta^{-1}\right) m_t^4 m_c^2 m_s^2 J \\
I_8\left(d\right) &\sim \left(t_\beta + t_\beta^{-1}\right) m_t^4 m_c^2 m_b^2 J
\end{aligned}
$$

BAU III

In the gBGL models an imaginary part appears first **at order 4th in Yukawa couplings** and is given by

$$I_4\left(\widehat{n}_d\right) \sim \left(t_\beta + t_\beta^{-1}\right) m_t^2 m_b^2 \mathrm{Im}\left[\left(\left|\widehat{n}_d\right\rangle \left\langle\widehat{n}_d\right|\right)_{32} V_{tb} V_{ts}^*\right]$$

A summary of enhancements in the CP violating weak basis invariant factors of the BAU respect to the SM one is given bellow where we use $E \sim 100GeV$ and $J \equiv \mathrm{Im}\left(V_{us}V_{cb}V_{ub}^*V_{cs}^*\right) \sim 3 \times 10^{-5}$. The contribution to the BAU should be proportional to

$$\frac{\mathrm{Im} I_n}{E^n}$$

and we define the enhancement respect to the SM factor by

$$\eta\left(\mathrm{model}\right) = \left(\frac{\mathrm{Im} I_n}{E^n}\right) / \left(\frac{\mathrm{Im} I_{12}}{E^{12}}\right)$$

BAU IV

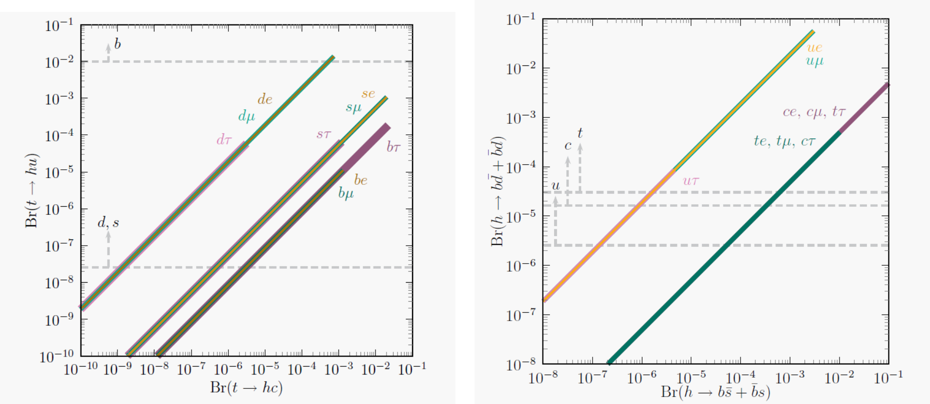
	top	bottom
$\frac{\eta}{\left(t_\beta+t_\beta^{-1}\right)}$	$\frac{E^4}{m_t^4}$	$\frac{E^4}{m_b^4}$
$\eta \sim$	1	10^5
	near top	near bottom
$\frac{\eta}{\left(t_\beta+t_\beta^{-1}\right)}$	$10^{16}\left\lvert V_{ts}\right\rvert \mathrm{Im}\left(\delta_b+\delta_s^*\right)$	$10^{16}\left\lvert V_{ts}\right\rvert \mathrm{Im}\left(\delta_t^*-\delta_c^*\right)$
$\eta \precsim$	10^{12}	10^{13}

Where $10^{16}=\left(\left|V_{ts}\right| E^8\right) / \left(m_t^2 m_c^2 m_b^2 m_s^2 J\right)$.
Note also that we have two BGL models d, s where

$$\eta_{d,s} \sim \frac{\left(t_\beta+t_\beta^{-1}\right) E^4}{m_b^2 m_s^2} \sim 10^{10}$$

Other Phenomenological Implications I

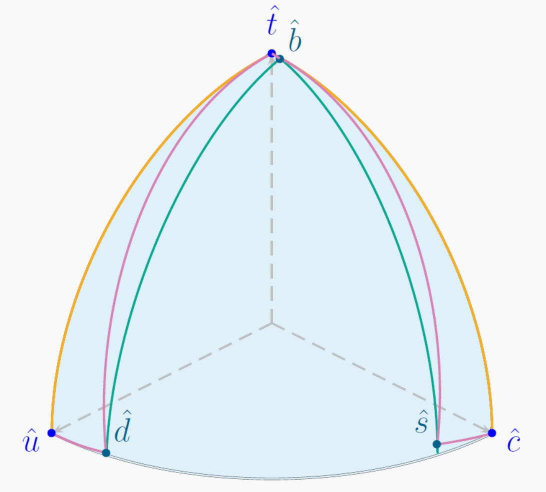
The most relevant: the presence of FCNC at tree level, in the Higgs sector and at an important rate. As in BGL



In gBGL models one has, in general, FCNC both in the up and in the down sectors simultaneously.

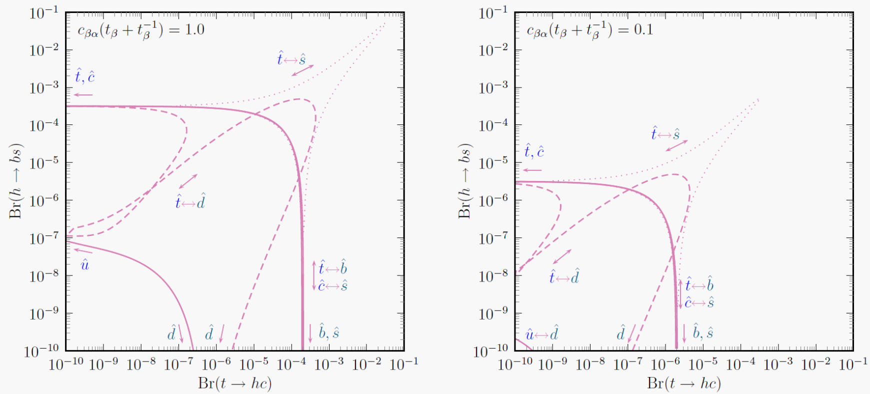
Other Phenomenological Implications II

With the trajectories in model space



Other Phenomenological Implications III

One can draw correlations of the down and the up sector



(a) $c_{\beta\alpha}(t_\beta + t_\beta^{-1}) = 1.$ (b) $c_{\beta\alpha}(t_\beta + t_\beta^{-1}) = 0.1.$

Conclusions I

Thanks!