Controlled Flavour Changing Neutral Couplings in Two Higgs Doublet Models

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Collaboration

- Work done with: J.M. Alves, G.C. Branco, F. Cornet-Gomez and M. Nebot (**arXiv:1703.03796)** and with M.Rebelo (**Eur.Phys.J. C76 (2016) no.3, 161, Phys.Lett. B722 (2013) 76-82, JHEP 1110 (2011) 037 and Phys.Lett. B687 (2010) 194-200)**, and with A. Carmona and L. Pedro **JHEP 1407 (2014) 078**,

Introduction

- Are the couplings of the Higgs to fermions like in the SM or do we have a more complex scalar sector?
- A natural scenario is Two Higgs Doublet Model (2HDM) where 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 a la Glashow-Weinberg leads to Natural Flavour Conservation (NFC) in the scalar sector.
- Beyond NFC there are 2HDM MODELS - enforced by symmetries- that give rise to FCNC controlled by V_{CKM} realizing the MFV idea.
- These are the so called 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.

2HDM I

- The Yukawa sector of the 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

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

2HDM II

- $G^{\pm}$ 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.

- The Lagrangian in the Higgs basis:

$$\begin{aligned} L_Y &= -\overline{Q}_L \frac{\sqrt{2}}{v} \left(M_d^0 H_1 + N_d^0 H_2 \right) d_R - \overline{Q}_L \frac{\sqrt{2}}{v} \left(M_u^0 \widetilde{H}_1 + N_u^0 \widetilde{H}_2 \right) u_R \\ &\quad + h.c \end{aligned}$$

$$\begin{aligned} M_d^0 &= \frac{v}{\sqrt{2}} \left(c_\beta \Gamma_1 + e^{i\theta} s_\beta \Gamma_2 \right) \\ N_d^0 &= \frac{v}{\sqrt{2}} \left(s_\beta \Gamma_1 - e^{i\theta} c_\beta \Gamma_2 \right) \end{aligned}$$

2HDM III

$$M_u^0 = \frac{v}{\sqrt{2}} \left(c_\beta \Delta_1 + e^{-i\theta} s_\beta \Delta_2 \right)$$
$$N_u^0 = \frac{v}{\sqrt{2}} \left(s_\beta \Delta_1 - e^{-i\theta} c_\beta \Delta_2 \right)$$

- The mass basis is obtained by bidiagonalizing M_d^0, M_u^0

$$U_L^{d\dagger} M_d^0 U_R^d = M_d = diag\,(m_d, m_s, m_b)$$
$$U_L^{u\dagger} M_u^0 U_R^u = M_u = diag\,(m_u, m_c, m_t)$$

  The components of H_1 $\left(H^0, G^0\right)$ are coupled in a flavour diagonal way.

- In the mass basis the neutral components of H_2 $\left(R^0, A\right)$ generate "**interesting**" (**dangerous**) FCNC proportional to the arbitrary matrices

$$N_d = U_L^{d\dagger} N_d^0 U_R^d$$
$$N_u = U_L^{u\dagger} N_u^0 U_R^u$$

2HDM IV

- The components of H_1 and H_2 in the quark mass basis interact with

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

- Where the *CKM* matrix is $V = U_L^{u\dagger}U_L^d$.
- It is remarkable - and trivial- that the couplings that appear with the new neutral Higgs R^0 and A- in general Flavour Changing- N_u, N_d also appear in the charged Higgs $H^\pm$ couplings.

- Remarkably enough it can be shown that **renormalizable models known long time ago and enforced by flavour symmetries** (Branco, Grimus, Lavoura) **realize the most simple MFV expansion with controlled FCNC.** For example one BGL model is enforced by the $U(1)$ flavour symmetry

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

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

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

The BGL models II

or to the model with the following Yukawa couplings

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

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

This model is called a **top type model** after $u_{R_3} = t_R$.

The BGL models III

- In the quark sector we have **three up type models** ($u_1 = u, u_2 = c, u_3 = t$) defined by the following symmetries and with the corresponding couplings

$$\begin{array}{c} Q_{L_k} \to e^{i\alpha} Q_{L_k} \\ u_{R_k} \to e^{i2\alpha} u_{R_k} \\ \Phi_2 \to e^{i\alpha} \Phi_2 \end{array} \left\{ \begin{array}{c} (N_d)_{ij} = \left[t_\beta \delta_{ij} - \left(t_\beta + t_\beta^{-1} \right) V_{ki}^* V_{kj} \right] m_{dj} \\ (N_u)_{ij} = \left[t_\beta - \left(t_\beta + t_\beta^{-1} \right) \delta_{ik} \right] \delta_{ij} m_{u_j} \end{array} \right.$$

They have FCNC in the down sector N_d.

- And **three down type models** ($d_1 = d, d_2 = s, d_3 = b$)

$$\begin{array}{c} Q_{L_k} \to e^{i\alpha} Q_{L_k} \\ d_{R_k} \to e^{i2\alpha} d_{R_k} \\ \Phi_2 \to e^{i\alpha} \Phi_2 \end{array} \left\{ \begin{array}{c} (N_d)_{ij} = \left[t_\beta - \left(t_\beta + t_\beta^{-1} \right) \delta_{ik} \right] \delta_{ij} m_{dj} \\ (N_u)_{ij} = \left[t_\beta \delta_{ij} - \left(t_\beta + t_\beta^{-1} \right) V_{ik} V_{jk}^* \right] m_{u_j} \end{array} \right.$$

They have FCNC in the up sector N_u.

The BGL models IV

- **BGL models have FCNC either in the up or in the down sector never in both**
- A general BGL model is defined both in the quark and in the leptonic sector. There are 6 different models grouped by having FCNC either in the up or down sector and 36 if we include the leptonic sector.
- All BGL models are invariant under $\Phi_2 \to e^{i\alpha}\Phi_2$. Therefore the Higgs potential should be the CP conserving

$$
\begin{aligned}
V \;=\;& \mu_{11}^2 \Phi_1^\dagger \Phi_1 + \mu_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}\left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right) \\
& + 2\lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + 2\lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) \\
& + \lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2
\end{aligned}
$$

where a soft breaking term has been introduced to avoid a Goldstone boson.

The BGL models V

- By expanding the neutral scalar components around their vacuum expectation values $\Phi_i^0 = \frac{e^{i\theta_i}}{\sqrt{2}}\left(v_i + \rho_i + i\eta_i\right)$ we can connect the neutral real mass eigenstates with the neutral fields in the Higgs basis:

$$\left(\begin{array}{c} H \\ h \end{array}\right) = \left(\begin{array}{cc} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{array}\right)\left(\begin{array}{c} \rho_1 \\ \rho_2 \end{array}\right)$$

$$\left(\begin{array}{c} H^0 \\ R^0 \end{array}\right) = \left(\begin{array}{cc} c_\beta & s_\beta \\ s_\beta & -c_\beta \end{array}\right)\left(\begin{array}{c} \rho_1 \\ \rho_2 \end{array}\right)$$

The relevant angle is $(\beta-\alpha)$: $c_{\beta\alpha} = \cos(\beta-\alpha)$, $s_{\beta\alpha} = \sin(\beta-\alpha)$

$$\left(\begin{array}{c} H^0 \\ R^0 \end{array}\right) = \left(\begin{array}{cc} c_{\beta\alpha} & s_{\beta\alpha} \\ -s_{\beta\alpha} & c_{\beta\alpha} \end{array}\right)\left(\begin{array}{c} H \\ h \end{array}\right)$$

The BGL models VI

- The Yukawa couplings of the 125 GeV scalar is for all type of fermions f

$$
\begin{aligned}
L_{h\bar{f}f} &= -\overline{f_L} Y^{(f)} f_R h + h.c \\
Y^{(f)} &= \frac{1}{v}\left[s_{\beta\alpha} M_f + c_{\beta\alpha} N_f\right]
\end{aligned}
$$

- In the k-up type model u_k we have FCNC in the down sector controlled by

$$
Y^{(d)}_{ij}\left[u_k\right] = -c_{\beta\alpha}\left(t_\beta + t_\beta^{-1}\right) V^*_{ki} V_{kj} \frac{m_{d_j}}{v} \quad ; \quad i \neq j
$$

- In the k-down type model d_k we have FCNC in the up sector controlled by

$$Y_{ij}^{(u)}\left[d_k\right] = -c_{\beta\alpha}\left(t_\beta + t_\beta^{-1}\right) V_{ik} V_{jk}^* \frac{m_{u_j}}{v} \quad ; \quad i \neq j$$

For the diagonal coupling to the top in model q_i we have

MODEL	COUPLING to top in units of $\left(\frac{m_t}{v}\right)$
u, c	$\left(s_{\beta\alpha} - c_{\beta\alpha} t_\beta\right)$
t	$\left(s_{\beta\alpha} + c_{\beta\alpha} t_\beta^{-1}\right)$
d_i	$s_{\beta\alpha} - c_{\beta\alpha}\left[\left(1 - \lvert V_{ti}\rvert^2\right) t_\beta - \lvert V_{ti}\rvert^2 t_\beta^{-1}\right]$

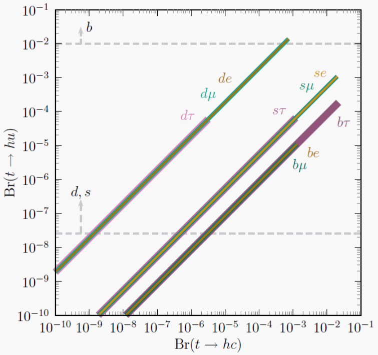
The BGL models VIII

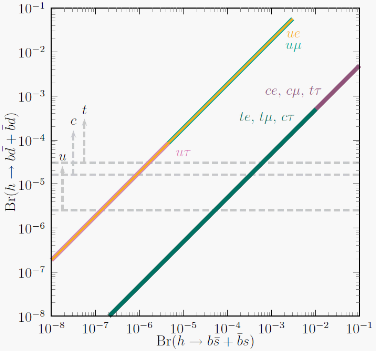
- For the diagonal coupling to the bottom in model q_i we have

MODEL	COUPLING to bottom in units of $\left(\frac{m_b}{v}\right)$
d, s	$\left(s_{\beta\alpha} - c_{\beta\alpha} t_\beta\right)$
b	$\left(s_{\beta\alpha} + c_{\beta\alpha} t_\beta^{-1}\right)$
u_i	$s_{\beta\alpha} - c_{\beta\alpha}\left[\left(1 - \lvert V_{ib}\rvert^2\right) t_\beta - \lvert V_{ib}\rvert^2\, t_\beta^{-1}\right]$

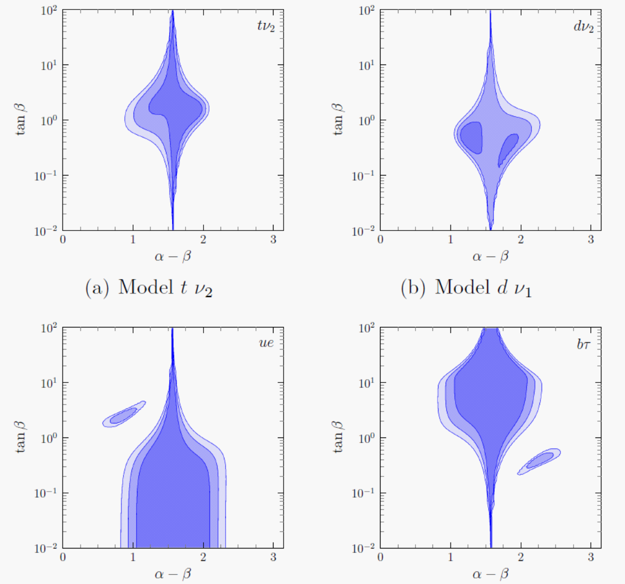
The BGL models IX

- Some results are given here:





The BGL models X



(a) Model $t\ \nu_2$

(b) Model $d\ \nu_1$

Generalizing BGL models: gBGL I

- 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:

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

- Now the Yukawa textures are:

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

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

Generalizing BGL models: gBGL II

Obviously they include both up-type and down-type BGL models. Note that the G-W NFC model is also implemented by this Z_2 symmetry. The difference is the way the left-handed fields transform under this symmetry: the principle leading to gBGL constraints the Yukawa couplings so that each line of Γ_i, Δ_j couples only to one Higgs doublet.

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

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

or if we call

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

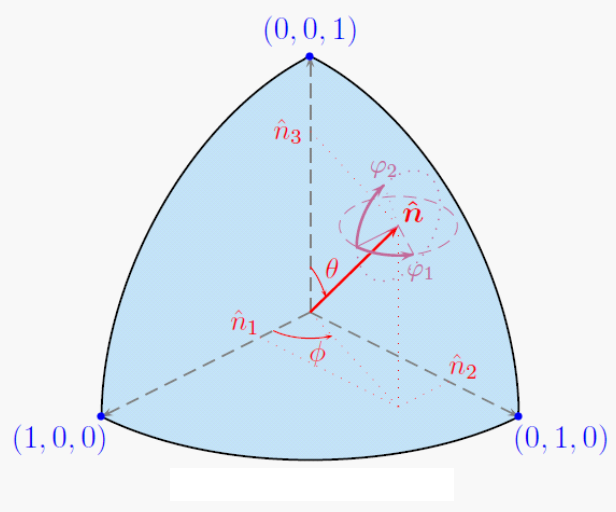
Generalizing BGL models: gBGL III

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

Generalizing BGL models: gBGL IV

- 

Generalizing BGL models: gBGL V

- This is the generalization of BGL models that correspond to the down models (d, s, b)

$$\left|\widehat{d}_d\right\rangle = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \quad ; \quad \left|\widehat{s}_d\right\rangle = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \quad ; \quad \left|\widehat{b}_d\right\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

or with the other parametrization

$$\left|\widehat{d}_u\right\rangle = \begin{pmatrix} V_{ud} \\ V_{cd} \\ V_{td} \end{pmatrix} \quad ; \quad \left|\widehat{s}_u\right\rangle = \begin{pmatrix} V_{us} \\ V_{cs} \\ V_{ts} \end{pmatrix} \quad ; \quad \left|\widehat{b}_u\right\rangle = \begin{pmatrix} V_{ub} \\ V_{cb} \\ V_{tb} \end{pmatrix}$$

Generalizing BGL models: gBGL VI

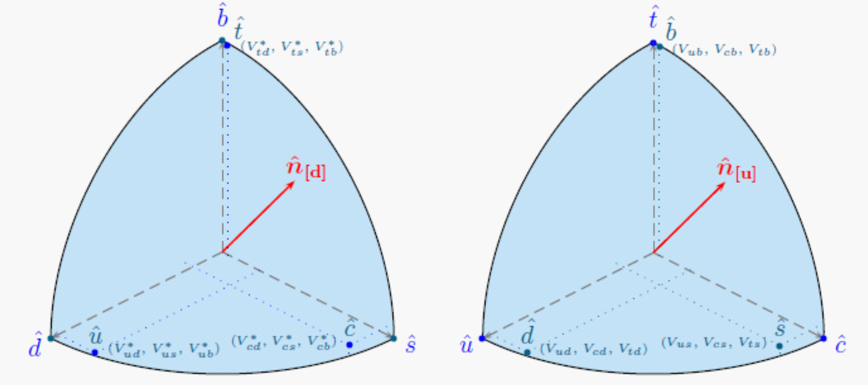
- and for the up models

$$|\widehat{u}_u\rangle = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \quad ; \quad |\widehat{c}_u\rangle = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \quad ; \quad |\widehat{t}_u\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

or

$$|\widehat{u}_d\rangle = \begin{pmatrix} V_{ud}^* \\ V_{us}^* \\ V_{ub}^* \end{pmatrix} \quad ; \quad |\widehat{c}_d\rangle = \begin{pmatrix} V_{cd}^* \\ V_{cs}^* \\ V_{cb}^* \end{pmatrix} \quad ; \quad |\widehat{t}_d\rangle = \begin{pmatrix} V_{td}^* \\ V_{ts}^* \\ V_{tb}^* \end{pmatrix}$$

where both parametrizations are represented in the following figure



(a) Down parametrisation. (b) Up parametrisation.

Generalizing BGL models: gBGL VIII

- The Higgs sector coincides with the Glashow-Weinberg NFC model. Both have the Z_2 symmetry

$$\begin{aligned} V &= \mu_{11}^2 \Phi_1^\dagger \Phi_1 + \mu_{22}^2 \Phi_2^\dagger \Phi_2 + \left[\lambda_5 \left(\Phi_1^\dagger \Phi_2 \right)^2 + h.c. \right] \\ &+ 2\lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) + 2\lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) \\ &+ \lambda_1 \left(\Phi_1^\dagger \Phi_1 \right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2 \right)^2 \end{aligned}$$

we do not need the softly breaking piece $\left(m_{12} \Phi_1^\dagger \Phi + h.c. \right)$, therefore there is no CP violation in the Higgs sector and the physical Higgs fields are defined as in the BGL case by H, h and the unmixed pseudoscalar A.

BGL: the intensity of FCNC I

- The Yukawa coupling to the $125 GeV$ 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 $i \longrightarrow j$ transition it is proportional to m_{q_i}/v
- In an $i \longrightarrow j$ transition it is proportional to $\left(|\widehat{n}_q\rangle \langle \widehat{n}_q|\right)_{ji}$ with maximal value $\left(1/\sqrt{2}\right)\left(1/\sqrt{2}\right) = 1/2$

BGL: the intensity of FCNC II

- To be compared with the most intense case of BGL u model in the $s \longrightarrow d$ 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 $t \longrightarrow hq$

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

- 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 the top and the bottom models I

- BGL top and bottom models are renormalizable 2HDM that verify the MFV principle in any of the different versions one can find in the literature.
- We will study the properties of gBGL that are **close to** the t and b BGL models in the sense that they give the **same contribution to meson mixing**. If the top and bottom models are

$$\left|\widehat{t}_u\right\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad ; \quad \left|\widehat{t}_d\right\rangle = \begin{pmatrix} V_{td}^* \\ V_{ts}^* \\ V_{tb}^* \end{pmatrix}$$

$$\left|\widehat{b}_u\right\rangle = \begin{pmatrix} V_{ub} \\ V_{cb} \\ V_{tb} \end{pmatrix} \quad ; \quad \left|\widehat{b}_d\right\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

we will study small departures from these models defined by $(\delta_d, \delta_s, \delta_b)$ and $(\delta_u, \delta_c, \delta_t)$

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

$$\left|\left(\widehat{b}+\widehat{\delta b}\right)_u\right\rangle = \begin{pmatrix} V_{ub}\,(1+\delta_u) \\ V_{cb}\,(1+\delta_c) \\ V_{tb}\,(1+\delta_t) \end{pmatrix}$$

$$\begin{aligned} M_{12}\left[K^0\right] &\propto \left(V_{td}^* V_{ts}\right)^2\left[1+2\left(\delta_d+\delta_s^*\right)\right] \\ M_{12}\left[B_d^0\right] &\propto \left(V_{td}^* V_{tb}\right)^2\left[1+2\left(\delta_d+\delta_b^*\right)\right] \\ M_{12}\left[B_s^0\right] &\propto \left(V_{ts}^* V_{tb}\right)^2\left[1+2\left(\delta_s+\delta_b^*\right)\right] \end{aligned}$$

Near the top and the bottom models III

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

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

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

$$\left|\left(\widehat{t} + \delta\widehat{t}\right)_u\right\rangle = V\left|\left(\widehat{t} + \delta\widehat{t}\right)_d\right\rangle \sim \begin{pmatrix} \mathcal{O}\left(\lambda^5\right) \\ \delta_b V_{cb} \\ 1 + \delta_b \end{pmatrix}$$

by

$$M_{12}\left[D^0\right] \propto \left(\delta_b V_{cb} \lambda^5\right)^2 \leq \lambda^{18}$$

and therefore not dangerous at all.

Near the top and the bottom models IV

- The down models near the bottom give the same contribution to meson mixing than the bottom model provided

$$\delta_u \sim \delta_c \sim \delta_t \leq \mathcal{O}\left(\lambda^2\right)$$

the relevant quantity to study the constraints from meson mixing in the down sector is

$$\begin{aligned}\left|\left(\widehat{b}+\delta\widehat{b}\right)_d\right\rangle &= V^\dagger \left|\left(\widehat{b}+\delta\widehat{b}\right)_u\right\rangle \\ &\sim \begin{pmatrix} V_{td}^* V_{tb}\left(\delta_t-\delta_c\right) + V_{ud}^* V_{ub}\left(\delta_u-\delta_c\right) \\ V_{ts}^* V_{tb}\left(\delta_t-\delta_c\right) \\ \left(1+\delta_t\right) \end{pmatrix}\end{aligned}$$

and the contribution to any meson mixing is smaller than any up BGL model

Near the top and the bottom models V

- **But we will see that there are important difference in other observables when we consider these near bottom and top models respect to the top and bottom BGL models**

Weak basis invariants and the 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:

$$\frac{1}{2}\det\left(i\left[M_u^0 M_u^{0\dagger}, M_d^0 M_d^{0\dagger}\right]\right) = -\frac{i}{6} Tr\left(\left[M_u^0 M_u^{0\dagger}, M_d^0 M_d^{0\dagger}\right]^3\right)$$

explicitly

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

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

Weak basis invariants and the BAU II

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

$$I_8(u_i) = \mathrm{Im}\, Tr\left[N_d^0 M_d^{0\dagger} M_d^0 M_d^{0\dagger} M_u^0 M_u^{0\dagger} M_d^0 M_d^{0\dagger}\right] \quad (u_i \text{ models})$$
$$I_8(d_i) = \mathrm{Im}\, Tr\left[N_u^0 M_u^{0\dagger} M_u^0 M_u^{0\dagger} M_d^0 M_d^{0\dagger} M_u^0 M_u^{0\dagger}\right] \quad (d_i \text{ models})$$

for top, bottom and down models

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

Weak basis invariants and the BAU III

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

$$
\begin{aligned}
I_4\left(\widehat{n}_d\right) &= \mathrm{Im}\ Tr\left[N_d^0 M_d^{0\dagger} M_u^0 M_u^{0\dagger}\right] \\
&= \frac{i}{2}\left(t_\beta + t_\beta^{-1}\right)\sum_{i,j,k}\left(m_{d_i}^2 - m_{d_j}^2\right) m_{u_k}^2 \left(\left|\widehat{n}_d\right\rangle\left\langle\widehat{n}_d\right|\right)_{ij} V_{ki} V_{kj}^* \\
&\sim \left(t_\beta + t_\beta^{-1}\right) m_t^2 m_b^2\, \mathrm{Im}\left[\left(\left|\widehat{n}_d\right\rangle\left\langle\widehat{n}_d\right|\right)_{32} V_{tb} V_{ts}^*\right]
\end{aligned}
$$

- 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 $E \sim 100 GeV$ 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

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

Weak basis invariants and the BAU IV

and we define the enhancement respect to the SM factor by

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

	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
$\frac{\eta}{\left(t_\beta + t_\beta^{-1}\right)}$	$10^{16}\,\lvert V_{ts}\rvert\, \text{Im}\,(\delta_b + \delta_s^*)$	$10^{16}\,\lvert V_{ts}\rvert\, \text{Im}\,(\delta_t^* - \delta_c^*)$
$\eta \precsim$	10^{12}	10^{13}

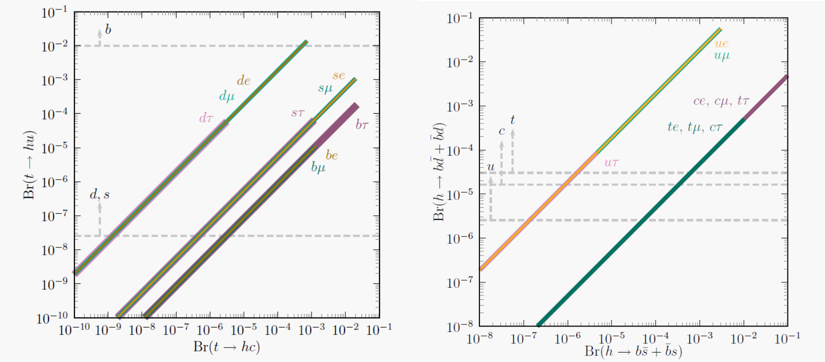
Where $10^{16} = \left(\lvert V_{ts}\rvert\, E^8\right) / \left(m_t^2 m_c^2 m_b^2 m_s^2 J\right)$.

- 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

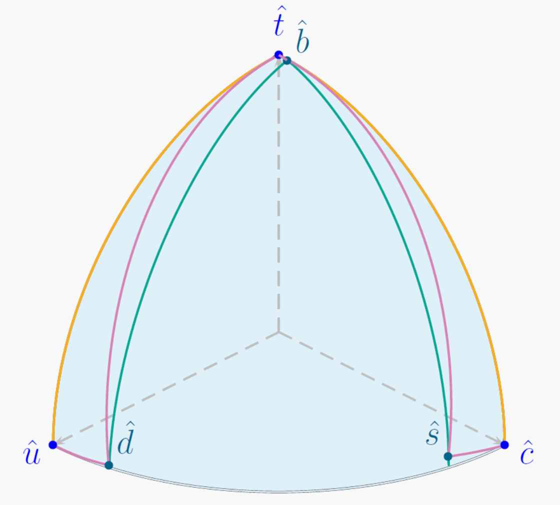
- The most relevant: the presence of FCNC at tree level, in the Higgs sector and at an important rate. As in BGL



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

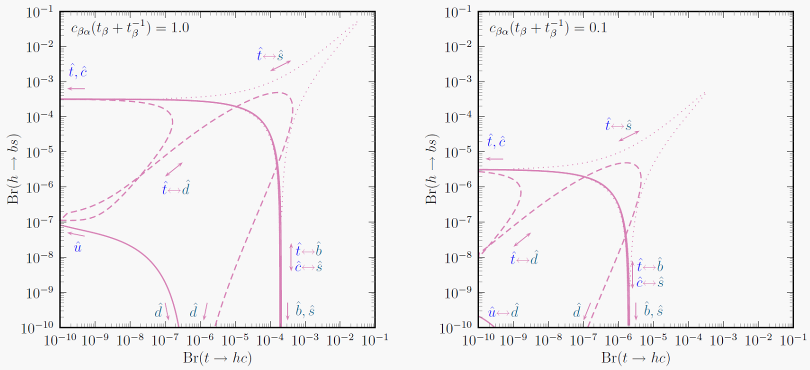
Other Phenomenological Implications II

- 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

- BGL can be generalized into a unique family of 2HDM arising from a flavour symmetry.
- These gBGL (not MFV, 4 new parameters) have tree level FCNC but in controlled manner.
- They have simoultaneously FCNC in the up and in the down sectors. Leading to New Physics effects interesting at LHC and /or at a Linear Collider: $t \to qh$, $h \to l\overline{\tau}$, $h \to q\overline{b}$
- They arise from the symmetry Z_2. The same that the one proposed by Glashow and Weinberg for NFC. The difference is in the way quark fields transform under Z_2.
- gBGL models contains BGL models. In the parameter space of gBGL there are regions were the Lagrangian acquires a larger symmetry Z_4 or $U(1)$, depending on the neutrino type (Majorana or Dirac).
- These models can produce enough CP violation to contribute to BAU