FLAVOUR CHANGING YUKAWA COUPLING IN TWO HIGGS DOUBLET MODELS

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September 2015

Collaboration

- Work done with: G.C. Branco, M. Nebot and M.Rebelo (also L. Pedro, A. Carmona). **arXiv:1508.05101**, JHEP 1407 (2014) 078, Phys.Lett. B722 (2013) 76-82, JHEP 1110 (2011) 037 and Phys.Lett. B687 (2010) 194-200

Introduction

- Study the Higgs like particle properties: Yukawa Couplings (YC).
- YC diagonal in the SM. Beyond SM non diagonal in general.
- Study processes mediated by Flavour Changing Yukawa Coupling (FCYC).
- A natural scenario is Two Higgs Doublet Model (2HDM) type **III**.
- To avoid too large FCNC and/or too many parameters use the Minimal Flavour Violating (MFV) avenue in the most broad sense.
- There are 2HDM MODELS - enforced by symmetries- that realize the MFV idea.
- The so called BGL models (Branco, Grimus, Lavoura) that incorporate important enhancements in the BAU.
- Present the **Flavour Changing phenomenology of BGL 2HDM in the 125 GeV Higgs sector**.

2HDM I

- The Yukawa sector of the 2HDM

$$\begin{aligned} L_Y &= -\overline{Q}_L\left(\Gamma_1\Phi_1+\Gamma_2\Phi_2\right)d_R-\overline{Q}_L\left(\Delta_1\widetilde{\Phi}_1+\Delta_2\widetilde{\Phi}_2\right)u_R+.h.c. \\ &\quad +\overline{L}_L\left(\Pi_1\Phi_1+\Pi_2\Phi_2\right)l_R-\overline{L}_L\left(\Sigma_1\widetilde{\Phi}_1+\Sigma_2\widetilde{\Phi}_2\right)\nu_R+.h.c. \end{aligned}$$

- The Higgs basis
$\langle H_1\rangle^T = \left(\begin{array}{cc} 0 & v/\sqrt{2}\end{array}\right)$, $\langle H_2\rangle^T = \left(\begin{array}{cc} 0 & 0\end{array}\right)$, $v^2 = v_1^2+v_2^2$

$$\left(\begin{array}{c}\Phi_1\\ \Phi_2\end{array}\right)=\left(\begin{array}{cc}\frac{v_1}{v} & \frac{v_2}{v}\\ \frac{v_2}{v} & -\frac{v_1}{v}\end{array}\right)\left(\begin{array}{c}H_1\\ H_2\end{array}\right)$$

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

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

2HDM II

- $H^{\pm}$ 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:

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

$$
\begin{aligned}
M_d^0 &= \frac{1}{\sqrt{2}} \left(\Gamma_1 v_1 + \Gamma_2 v_2 \right) \\
N_d^0 &= \frac{1}{\sqrt{2}} \left(\Gamma_1 v_2 - \Gamma_2 v_1 \right)
\end{aligned}
$$

2HDM III

$$
\begin{aligned}
M_u^0 &= \frac{1}{\sqrt{2}}\left(\Delta_1 v_1 + \Delta_2 v_2\right) \\
N_u^0 &= \frac{1}{\sqrt{2}}\left(\Delta_1 v_1 - \Delta_2 v_1\right)
\end{aligned}
$$

$$
\begin{aligned}
M_l^0 &= \frac{1}{\sqrt{2}}\left(\Pi_1 v_1 + \Pi_2 v_2\right) \\
N_l^0 &= \frac{1}{\sqrt{2}}\left(\Pi_1 v_2 - \Pi_2 v_1\right)
\end{aligned}
$$

$$
\begin{aligned}
M_\nu^0 &= \frac{1}{\sqrt{2}}\left(\Sigma_1 v_1 + \Sigma_2 v_2\right) \\
N_\nu^0 &= \frac{1}{\sqrt{2}}\left(\Sigma_1 v_2 - \Sigma_2 v_1\right)
\end{aligned}
$$

2HDM IV

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

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

  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

$$
\begin{aligned}
N_d &= U_L^{d\dagger} N_d^0 U_R^d \\
N_u &= U_L^{u\dagger} N_u^0 U_R^u
\end{aligned}
$$

2HDM V

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

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

- Where the *CKM* matrix is $V = U_L^{u\dagger}U_L^d$. Instead in the leptonic sector there are N_l^0, N_ν^0 and the *PMNS* matrix $U^\dagger$.
- 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 etc also appear in the charged Higgs $H^\pm$ couplings.

2HDM and MFV I

- The idea of Minimal Flavour Violation (MFV) applied to 2HDM imply to choose for example M_d^0 and M_u^0 as the basic flavour structures and therefore assume that N_d^0 and N_u^0 satisfy the following expansion:

$$\begin{aligned} N_d^0 &= \left[\epsilon_0 I + \epsilon_1 H_d + \epsilon_2 H_u + \epsilon_3 H_u H_d + \epsilon_4 H_d H_u + \cdots\right] M_d^0 \\ N_u^0 &= \left[\epsilon_0' I + \epsilon_1' H_d + \epsilon_2' H_u + \epsilon_3' H_u H_d + \epsilon_4' H_d H_u + \cdots\right] M_u^0 \end{aligned}$$

  with $H_d = M_d^0 M_d^{0\dagger}$ and $H_u = M_u^0 M_u^{0\dagger}$

- But using for the down sector

$$H_d = M_d^0 M_d^{0\dagger} = U_L^d M_d^2 U_L^{d\dagger} = U_L^d \sum_{i=1}^{3} m_{d_i}^2 P_i U_L^{d\dagger} = \sum_{i=1}^{3} m_{d_i}^2 \mathbf{P}_i^{d_L}$$

$$\boxed{\mathbf{P}_i^{d_L} = U_L^d P_i U_L^{d\dagger}} \quad ; \quad (P_i)_{jk} = \delta_{ij}\delta_{ik}$$

it turns out that this expansion is equivalent to - or a particular case of-

$$\boxed{\begin{aligned} N_d^0 &= \left(a_0 I + a_{1j}\mathbf{P}_j^{d_L} + a_{2j}\mathbf{P}_j^{u_L} + a_{3ij}\mathbf{P}_i^{u_L}\mathbf{P}_j^{d_L} + a_{4ij}\mathbf{P}_i^{d_L}\mathbf{P}_j^{u_L} + \cdots\right) M_d^0 \\ N_u^0 &= \left(a'_0 I + a'_1\mathbf{P}_j^{d_L} + a'_{2j}\mathbf{P}_j^{u_L} + a'_{3ij}\mathbf{P}_i^{u_L}\mathbf{P}_j^{d_L} + a'_{4ij}\mathbf{P}_i^{d_L}\mathbf{P}_j^{u_L} + \cdots\right) M_u \end{aligned}}$$

- 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 FCYC.** For example one BGL model is enforced by the flavour symmetry

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

It correspond to the model defined by the MFV expansion -with $t_\beta = \tan\beta = \frac{v_2}{v_1}$

$$
\begin{aligned}
N_d^0 &= \left[t_\beta I - \left(t_\beta + t_\beta^{-1} \right) \mathbf{P}_3^{u_L} \right] M_d^0 \\
N_u^0 &= \left[t_\beta I - \left(t_\beta + t_\beta^{-1} \right) \mathbf{P}_3^{u_L} \right] M_u^0
\end{aligned}
$$

or to the model with the following Yukawa couplings

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

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

2HDM and MFV IV

- This model is called a **top type model** after $u_{R_3} = t_R$. The symmetry contains $t_R \to e^{i2\alpha} t_R$ and it has FCYC just in the down sector. In the quark mass basis we have

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

or equivalently

$$(N_d)_{ij} = \left[t_\beta \delta_{ij} - \left(t_\beta + t_\beta^{-1} \right) \overbrace{V_{3i}^* V_{3j}}^{\textbf{FCYC}} \right] m_{dj}$$
$$(N_u)_{ij} = \left[t_\beta \delta_{ij} - \left(t_\beta + t_\beta^{-1} \right) \delta_{ij} \delta_{i3} \right] m_{u_j}$$

The BGL models in the quark and lepton sectors I

- 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

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

  They have FCYC in the down sector N_d.

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

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

  They have FCYC in the up sector N_u.

The BGL models in the quark and lepton sectors II

- In the lepton sector we have **three neutrino type models** (ν_1, ν_2, ν_3) defined by the following symmetries and with the corresponding couplings

$$\begin{array}{rcl} L_{L_k} & \longrightarrow & e^{i\alpha} L_{L_k} \\ \nu_{R_k} & \longrightarrow & e^{i2\alpha} \nu_{R_k} \\ \Phi_2 & \longrightarrow & e^{i\alpha} \Phi_2 \end{array} \quad \left\{ \begin{array}{c} \left(N_l\right)_{ij} = \left[t_\beta \delta_{ij} - \left(t_\beta + t_\beta^{-1}\right) U_{ik} U_{jk}^* \right] m_{l_j} \\ \left(N_\nu\right)_{ij} = \left[t_\beta - \left(t_\beta + t_\beta^{-1}\right) \delta_{ik} \right] \delta_{ij} m_{\nu_j} \end{array} \right.$$

  With FCYC in the charged lepton sector.

- And **three charged lepton type models** $(l_1 = e, l_2 = \mu, l_3 = \tau)$

$$\begin{array}{rcl} L_{L_k} & \longrightarrow & e^{i\alpha} L_{L_k} \\ l_{R_k} & \longrightarrow & e^{i2\alpha} l_{R_k} \\ \Phi_2 & \longrightarrow & e^{i\alpha} \Phi_2 \end{array} \quad \left\{ \begin{array}{c} \left(N_l\right)_{ij} = \left[t_\beta - \left(t_\beta + t_\beta^{-1}\right) \delta_{ik} \right] \delta_{ij} m_{l_j} \\ \left(N_\nu\right)_{ij} = \left[t_\beta \delta_{ij} - \left(t_\beta + t_\beta^{-1}\right) U_{ki}^* U_{kj} \right] m_{\nu_j} \end{array} \right.$$

The BGL models in the quark and lepton sectors III

- A general BGL model is defined both in the quark and in the leptonic sector. There are 36 different models grouped by having FCYC either in the up or down sector and either in the charged lepton or the neutrino sectors.
- All BGL models are invariant under $\Phi_2 \to e^{i\alpha}\Phi_2$. Therefore the Higgs potential should be the CP conserving

$$
\begin{aligned}
V &= \mu_1 \Phi_1^\dagger \Phi_1 + \mu_2 \Phi_2^\dagger \Phi_2 - m_{12}\left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right) \\
&\quad + 2\lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + 2\lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) \\
&\quad + \lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2
\end{aligned}
$$

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

The BGL models in the quark and lepton sectors IV

- By expanding the neutral scalar components around their vacuum expectation values $\Phi_i^0 = \frac{1}{\sqrt{2}}\left(v_i + \rho_i + i\eta_i\right)$ we can connect the real mass neutral eigenstates with the neutral fields in the Higgs basis:

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}$$

$$\begin{pmatrix} H^0 \\ R^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}$$

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 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 FCYC in the down sector controlled by

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

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

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

The Yukawa Couplings in BGL models II

- In the neutrino type model ν_k we have FCYC in the charged lepton sector controlled by

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

- 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 Yukawa Couplings in BGL models III

- 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	$s_{\beta\alpha} - c_{\beta\alpha}\left[\left(1 - \lvert V_{ib}\rvert^2\right) t_\beta - \lvert V_{ib}\rvert^2\, t_\beta^{-1}\right]$

- For the diagonal coupling to the tau in models l_i or ν_i we have

MODEL	COUPLING to tau in units of $\left(\frac{m_\tau}{v}\right)$
e, μ	$\left(s_{\beta\alpha} - c_{\beta\alpha} t_\beta\right)$
τ	$\left(s_{\beta\alpha} + c_{\beta\alpha} t_\beta^{-1}\right)$
ν_i	$s_{\beta\alpha} - c_{\beta\alpha}\left[\left(1 - \lvert U_{\tau i}\rvert^2\right) t_\beta - \lvert U_{\tau i}\rvert^2\, t_\beta^{-1}\right]$

Results: introduction

- All FCYC effects are proportional to $c_{\beta\alpha}\left(t_\beta + t_\beta^{-1}\right)$
- We can have at tree level: $t \longrightarrow hu, hc$ with down type models.
- We can have at tree level: $h \longrightarrow \mu\overline{\tau}, e\overline{\tau}, e\overline{\mu}$ in neutrino type models
- We can have at tree level $h \longrightarrow d\overline{b}, s\overline{b}$ in up type model.
- In general we will have modified diagonal couplings in all models.
- But all these new couplings are controlled by the free parameters α and β and the well-known CKM V and PMNS U matrices.
- Of course before making prediction we have to impose the constraint on α and β
    - From non FCYC: Higgs couplings to $\gamma\gamma$, WW, ZZ, $b\overline{b}$, $\tau\overline{\tau}$, $t\overline{t}$. Note that both production and decay are modified according to previous tables.
    - From low-energy flavour physics: rather involved since H and A are also present together with h; requires specific study (additional parameters) [Botella, Branco, Carmona, Nebot, Pedro & Rebelo, JHEP(2014)]

Constraints from the Higgs sector I

- We impose the signal strengths μ_i^X in different decay channels X, where i labels the different combinations of production mechanism:

$$\mu_i^X = \frac{\sigma\left(pp \to h\right)^i}{\sigma\left(pp \to h\right)^i_{SM}} \frac{Br\left(h \to X\right)}{Br\left(h \to X\right)_{SM}}$$

- We use for $m_h = 125\,GeV$ and $\sqrt{s} = 8\,TeV$ and $\sigma\left(pp \to h\right)^i_{SM}$ in pb.

Prod chan i	ggF	VBF	Wh	Zh	$t\bar{t}h$	$b\bar{b}h$
$\sigma\left(pp \to h\right)^i_{SM}$	19.27	1.578	0.7046	0.4153	0.1293	0.2035

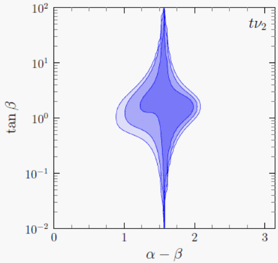
Decay chan X	$b\bar{b}$	WW^*	ZZ^*	$\tau\bar{\tau}$	$\gamma\gamma$	gg
$Br\left(h \to X\right)_{SM}$	0.578	0.216	0.0267	0.0637	0.0023	0.0856

and the data from ATLAS and CMS

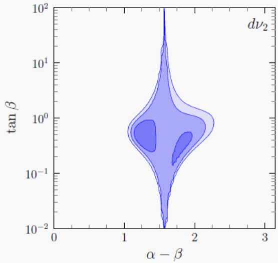
Constraints from the Higgs sector II

- We also impose constraints from CMS and ATLAS on $h \longrightarrow \mu\tau$ and $t \longrightarrow hq$
- The result for a few models are

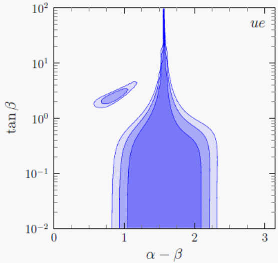
Constraints from the Higgs sector III

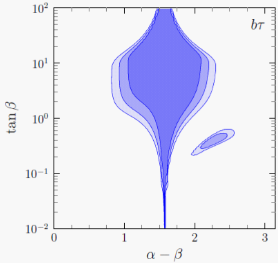


(a) Model $t\ \nu_2$



(b) Model $d\ \nu_1$





Rear top decays I

- In the down type models - d_k type model - there are tree level top decays like $t \longrightarrow uh, ch$

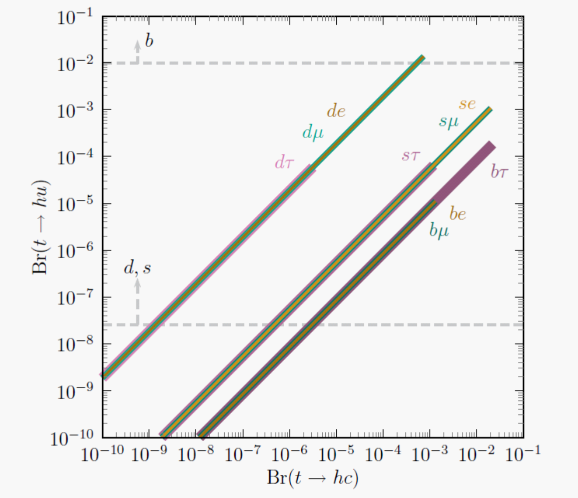
$$Br^{(d_k)}\left(t \rightarrow qh\right) = 0.131 \frac{\left|V_{tk} V_{qk}\right|^2}{\left|V_{tb}\right|^2} \left|c_{\beta\alpha}\left(t_\beta + t_\beta^{-1}\right)\right|^2$$

- CMS and ATLAS bound imply for models b and s: $\left|V_{tb} V_{cb}\right|^2 \sim \left|V_{ts} V_{cs}\right|^2 \sim \lambda^4$

$$\left|c_{\beta\alpha}\left(t_\beta + t_\beta^{-1}\right)\right| \lesssim 4.9$$

- For all models of the type down-charged lepton $\left(d_k, l_m\right)$ we have:

Rear top decays II



Rear top decays III

- Naive constraints from the Higgs tree level contributions to $D^0 - \overline{D}^0$ are included in the figures. But remember that in these models there are also contributions from H and A. In such a way that the total contribution is proportional to

$$\left(\frac{c^2_{\beta\alpha}}{m^2_h} + \frac{s^2_{\beta\alpha}}{m^2_H} - \frac{1}{m^2_A}\right)$$

Oblique corrections accommodates better with important cancellations. Therefore there are important "natural" cancellations invalidating to use the naive bounds coming from the tree level Higgs exchange contribution alone.

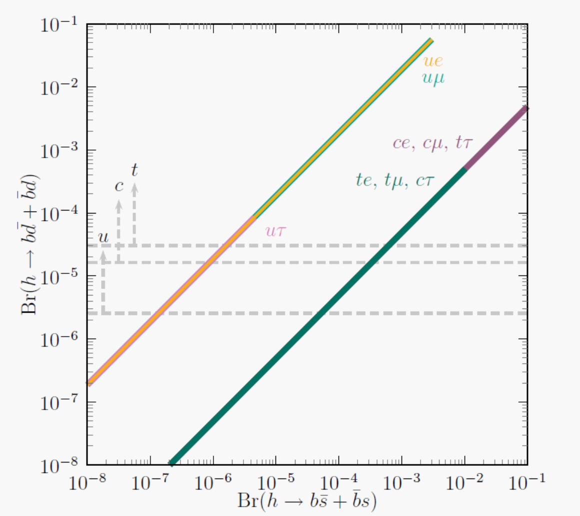
Flavour Changing Higgs decays to quarks I

- In up type models -u_k type models - there are tree level h decays like $h \longrightarrow s\overline{b}, b\overline{s}, d\overline{b}, b\overline{d}$, etc...

$$Br^{(u_k)}\left(h \longrightarrow q\overline{b} + b\overline{q}\right) = 0.578 \frac{\Gamma^{SM}(h)}{\Gamma(h)} \left|V_{kq}V_{kb}\right|^2 \left|c_{\beta\alpha}\left(t_\beta + t_\beta^{-1}\right)\right|^2$$

- For the c and t models: $\left|V_{cs}V_{cb}\right|^2 \sim \left|V_{ts}V_{tb}\right|^2 \sim \lambda^4$ the channel $h \longrightarrow sb$ can reach values for the branching ratio of order 10^{-1} for values of $\left|c_{\beta\alpha}\left(t_\beta + t_\beta^{-1}\right)\right| \sim 5 - 10$ in charged lepton models.
- For all models of the type up-charged lepton (d_k, l_m) we have:

Flavour Changing Higgs decays to quarks II



Flavour Changing Higgs decays to quarks III

- As before naive bounds from $K^0-\overline{K}^0$, $B_d^0-\overline{B}_d^0$ and $B_s^0-\overline{B}_s^0$ mixing are displayed in the figure. They correspond, in the u and c (t) models to $\left|c_{\beta\alpha}\left(t_\beta+t_\beta^{-1}\right)\right| \lesssim 0.43\ (0.60)$

Rare Higgs decays to leptons and correlation with rare decays to quarks I

- In neutrino type models - ν_k type models - we have the interesting processes $h \to \mu^\pm \tau^\mp, e^\pm \tau^\mp, e^\pm \mu^\mp$

$$Br^{(\nu_k)}\left(h \to \mu\tau\right) = 0.0637 \frac{\Gamma^{SM}\left(h\right)}{\Gamma\left(h\right)} \left|U_{\mu k} U_{\tau k}\right|^2 \left|c_{\beta\alpha}\left(t_\beta + t_\beta^{-1}\right)\right|^2$$

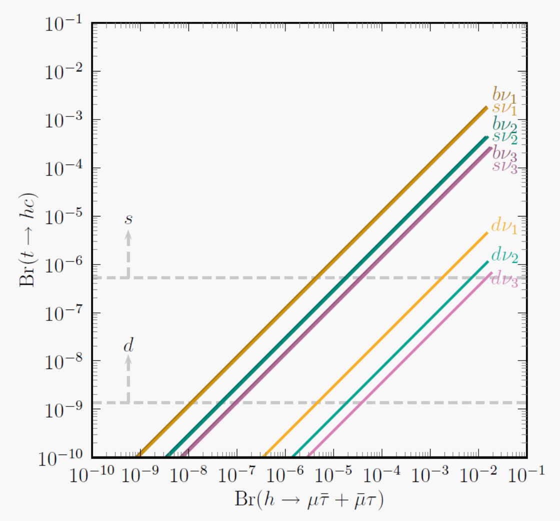
- For the ν_3 in order to get a $h \to \mu\tau$ branching ratio of order 10^{-2} - $Br\left(h \to \mu\tau\right) = \left(\begin{array}{cc} 0.84 & \begin{array}{c} +0.39 \\ -0.37 \end{array} \end{array}\right)\%$ - we need a value of $\left|c_{\beta\alpha}\left(t_\beta + t_\beta^{-1}\right)\right| \sim 1$

Rare Higgs decays to leptons and correlation with rare decays to quarks II

- If we consider model of type down-neutrino (d_k, ν_l) we will have correlations among $t \to hc$ and $h \to \mu\tau$ controlled by

$$Br^{(d_k)}(t \to qh) = 2.06 \left| \frac{V_{tk} V_{qk}}{V_{tb} U_{\mu l} U_{\tau l}} \right|^2 \frac{\Gamma^{SM}(h)}{\Gamma(h)} Br^{(\nu_k)}(h \to \mu\tau)$$

Rare Higgs decays to leptons and correlation with rare decays to quarks III

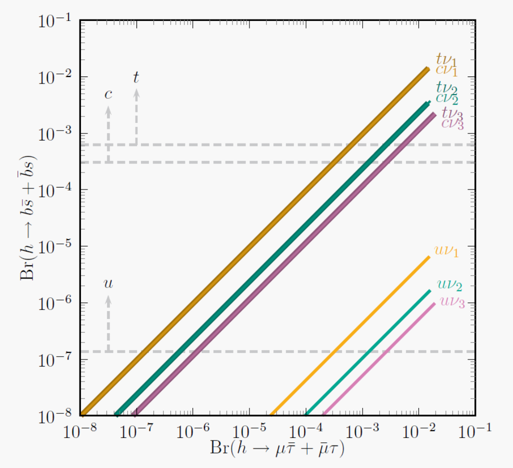


Rare Higgs decays to leptons and correlation with rare decays to quarks IV

note that the constraint on $h \to \mu\tau$ has reduced the range of variation of $Br^{(d_k)}(t \to ch)$ respect to charged lepton models.

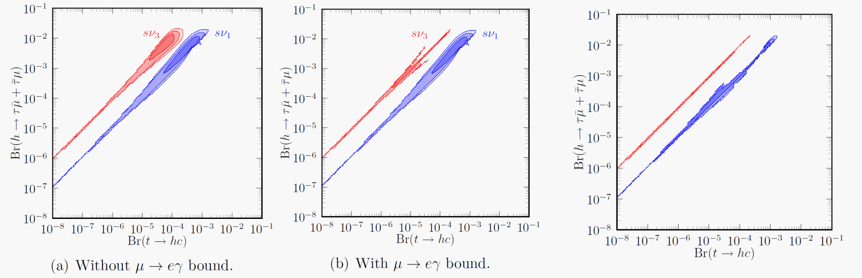
Rare Higgs decays to leptons and correlation with rare decays to quarks V

- In the case of (u_k, ν_l) models we get correlations among rare leptonic and hadronic Higgs decays



Incorporating low energy constraints

- $\mu \to e\gamma$ constrains very severely the coupling $h \to \mu e$ via the two-loop Barr-Zee diagrams. In BGL models $\mu \to e\gamma$ will translate into an important constraint on $c_{\beta\alpha}\left(t_\beta + t_\beta^{-1}\right)$. However not only the Higgs h can be exchanged but also H and A will enter with the known tendency to produce destructive interference between the different contribution - as in neutral meson mixing-.
- The results of our analysis are shown in the following figures:



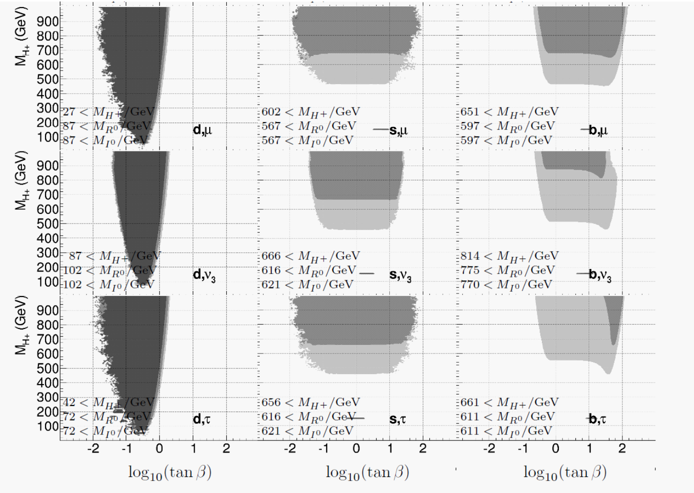
(a) Without $\mu \to e\gamma$ bound.

(b) With $\mu \to e\gamma$ bound.

Conclusions

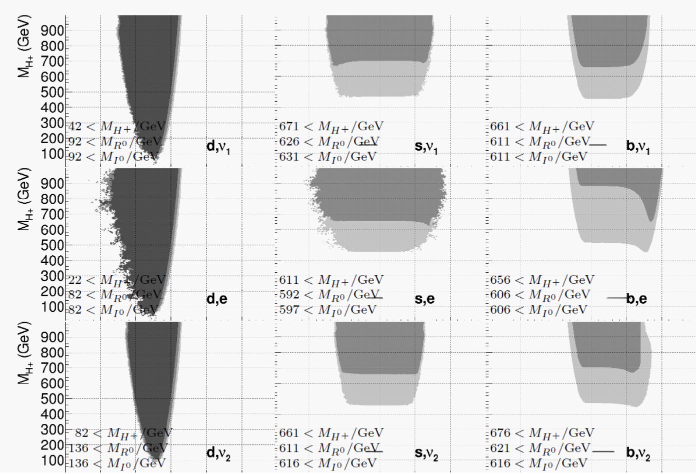
- We have analyzed 2HDM with tree level FCYC, controlled and suppressed by V_{CKM} and/or light quark masses (or U_{PMNS} in the leptonic sector).
- There are 36 different BGL models, enforced by different symmetries, and having either FCYC in the up or in the down sector (similar in the leptonic sector)
- Given a model, the free parameters in the Yukawa coupling are $\tan\beta$ and $\cos(\beta-\alpha)$.
- BGL 2HDM lead to New Physics effects interesting at LHC and /or at a Linear Collider: $t \to qh$, $h \to l\overline{\tau}$, $h \to q\overline{b}$
- We have used all the constraints related to Higgs production and its subsequent Higgs decay.
- Low energy flavour constraints have been considered, but important cancellations operate both in meson mixing and in $\mu \to e\gamma$ among others.

Back I

- 

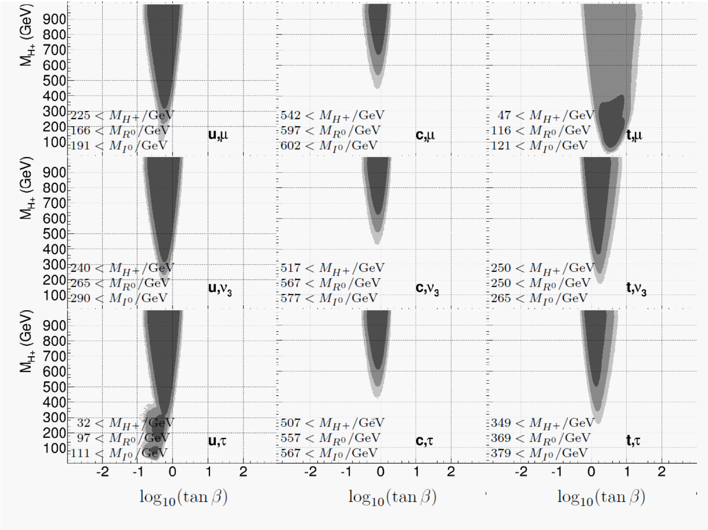
M_{H^+} (GeV)
900
800
700
600
500
400
300
200
100
$27 < M_{H^+}/\mathrm{GeV}$
$87 < M_{R^0}/\mathrm{GeV}$
$87 < M_{I^0}/\mathrm{GeV}$
d,μ
$602 < M_{H^+}/\mathrm{GeV}$
$567 < M_{R^0}/\mathrm{GeV}$
$567 < M_{I^0}/\mathrm{GeV}$
s,μ
$651 < M_{H^+}/\mathrm{GeV}$
$597 < M_{R^0}/\mathrm{GeV}$
$597 < M_{I^0}/\mathrm{GeV}$
b,μ
$87 < M_{H^+}/\mathrm{GeV}$
$102 < M_{R^0}/\mathrm{GeV}$
$102 < M_{I^0}/\mathrm{GeV}$
d,ν$_3$
$666 < M_{H^+}/\mathrm{GeV}$
$616 < M_{R^0}/\mathrm{GeV}$
$621 < M_{I^0}/\mathrm{GeV}$
s,ν$_3$
$814 < M_{H^+}/\mathrm{GeV}$
$775 < M_{R^0}/\mathrm{GeV}$
$770 < M_{I^0}/\mathrm{GeV}$
b,ν$_3$
$42 < M_{H^+}/\mathrm{GeV}$
$72 < M_{R^0}/\mathrm{GeV}$
$72 < M_{I^0}/\mathrm{GeV}$
d,τ
$656 < M_{H^+}/\mathrm{GeV}$
$616 < M_{R^0}/\mathrm{GeV}$
$621 < M_{I^0}/\mathrm{GeV}$
s,τ
$661 < M_{H^+}/\mathrm{GeV}$
$611 < M_{R^0}/\mathrm{GeV}$
$611 < M_{I^0}/\mathrm{GeV}$
b,τ
-2 -1 0 1 2
$\log_{10}(\tan\beta)$

Back II

- 

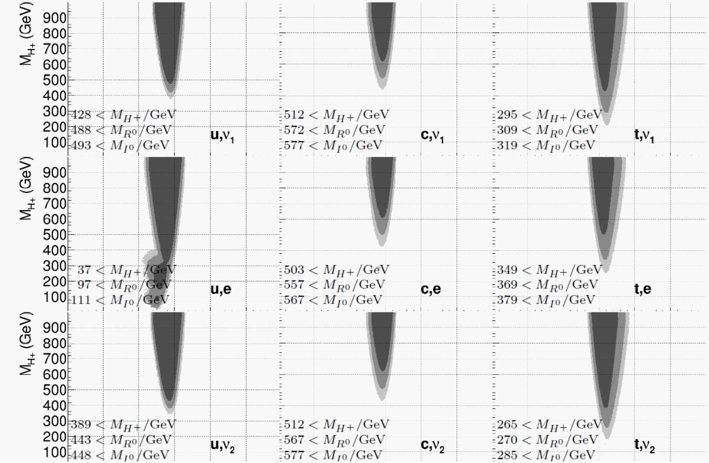
M_{H^+} (GeV)
900
800
700
600
500
400
300
200
100
$42 < M_{H^+}/\mathrm{GeV}$
$92 < M_{R^0}/\mathrm{GeV}$
$92 < M_{I^0}/\mathrm{GeV}$
d,ν_1
$671 < M_{H^+}/\mathrm{GeV}$
$626 < M_{R^0}/\mathrm{GeV}$
$631 < M_{I^0}/\mathrm{GeV}$
s,ν_1
$661 < M_{H^+}/\mathrm{GeV}$
$611 < M_{R^0}/\mathrm{GeV}$
$611 < M_{I^0}/\mathrm{GeV}$
b,ν_1
$22 < M_{H^+}/\mathrm{GeV}$
$82 < M_{R^0}/\mathrm{GeV}$
$82 < M_{I^0}/\mathrm{GeV}$
d,e
$611 < M_{H^+}/\mathrm{GeV}$
$592 < M_{R^0}/\mathrm{GeV}$
$597 < M_{I^0}/\mathrm{GeV}$
s,e
$656 < M_{H^+}/\mathrm{GeV}$
$606 < M_{R^0}/\mathrm{GeV}$
$606 < M_{I^0}/\mathrm{GeV}$
b,e
$82 < M_{H^+}/\mathrm{GeV}$
$136 < M_{R^0}/\mathrm{GeV}$
$136 < M_{I^0}/\mathrm{GeV}$
d,ν_2
$661 < M_{H^+}/\mathrm{GeV}$
$611 < M_{R^0}/\mathrm{GeV}$
$616 < M_{I^0}/\mathrm{GeV}$
s,ν_2
$676 < M_{H^+}/\mathrm{GeV}$
$621 < M_{R^0}/\mathrm{GeV}$
$616 < M_{I^0}/\mathrm{GeV}$
b,ν_2

Back III

- 

M_{H+} (GeV)
900
800
700
600
500
400
300
200
100
$225 < M_{H^+}/\mathrm{GeV}$
$166 < M_{R^0}/\mathrm{GeV}$
$191 < M_{I^0}/\mathrm{GeV}$
u,μ
$542 < M_{H^+}/\mathrm{GeV}$
$597 < M_{R^0}/\mathrm{GeV}$
$602 < M_{I^0}/\mathrm{GeV}$
c,μ
$47 < M_{H^+}/\mathrm{GeV}$
$116 < M_{R^0}/\mathrm{GeV}$
$121 < M_{I^0}/\mathrm{GeV}$
t,μ
$240 < M_{H^+}/\mathrm{GeV}$
$265 < M_{R^0}/\mathrm{GeV}$
$290 < M_{I^0}/\mathrm{GeV}$
u,ν_3
$517 < M_{H^+}/\mathrm{GeV}$
$567 < M_{R^0}/\mathrm{GeV}$
$577 < M_{I^0}/\mathrm{GeV}$
c,ν_3
$250 < M_{H^+}/\mathrm{GeV}$
$250 < M_{R^0}/\mathrm{GeV}$
$265 < M_{I^0}/\mathrm{GeV}$
t,ν_3
$32 < M_{H^+}/\mathrm{GeV}$
$97 < M_{R^0}/\mathrm{GeV}$
$111 < M_{I^0}/\mathrm{GeV}$
u,τ
$507 < M_{H^+}/\mathrm{GeV}$
$557 < M_{R^0}/\mathrm{GeV}$
$567 < M_{I^0}/\mathrm{GeV}$
c,τ
$349 < M_{H^+}/\mathrm{GeV}$
$369 < M_{R^0}/\mathrm{GeV}$
$379 < M_{I^0}/\mathrm{GeV}$
t,τ
-2 -1 0 1 2
$\log_{10}(\tan\beta)$

Back IV

- 

M_{H+} (GeV)
900
800
700
600
500
400
300
200
100
$428 < M_{H+}/\mathrm{GeV}$
$488 < M_{R^0}/\mathrm{GeV}$
$493 < M_{I^0}/\mathrm{GeV}$
u,ν_1
$512 < M_{H+}/\mathrm{GeV}$
$572 < M_{R^0}/\mathrm{GeV}$
$577 < M_{I^0}/\mathrm{GeV}$
c,ν_1
$295 < M_{H+}/\mathrm{GeV}$
$309 < M_{R^0}/\mathrm{GeV}$
$319 < M_{I^0}/\mathrm{GeV}$
t,ν_1
$37 < M_{H+}/\mathrm{GeV}$
$97 < M_{R^0}/\mathrm{GeV}$
$111 < M_{I^0}/\mathrm{GeV}$
u,e
$503 < M_{H+}/\mathrm{GeV}$
$557 < M_{R^0}/\mathrm{GeV}$
$567 < M_{I^0}/\mathrm{GeV}$
c,e
$349 < M_{H+}/\mathrm{GeV}$
$369 < M_{R^0}/\mathrm{GeV}$
$379 < M_{I^0}/\mathrm{GeV}$
t,e
$389 < M_{H+}/\mathrm{GeV}$
$443 < M_{R^0}/\mathrm{GeV}$
$448 < M_{I^0}/\mathrm{GeV}$
u,ν_2
$512 < M_{H+}/\mathrm{GeV}$
$567 < M_{R^0}/\mathrm{GeV}$
$577 < M_{I^0}/\mathrm{GeV}$
c,ν_2
$265 < M_{H+}/\mathrm{GeV}$
$270 < M_{R^0}/\mathrm{GeV}$
$285 < M_{I^0}/\mathrm{GeV}$
t,ν_2

The CP Violating contribution to the Baryon Asymmetry

- In the SM the *CP* violating contribution to the BAU at the electroweak phase transition is proportional to

$$\prod_{i>j,k>l}\left(m_{u_i}^2-m_{u_j}^2\right)\left(m_{d_k}^2-m_{d_l}^2\right)\mathrm{Im}\left(V_{ud}V_{cs}V_{us}^*V_{cd}^*\right)$$

$$\sim\quad m_t^4 m_c^2 m_b^4 m_s^2\,\mathrm{Im}\left(V_{ud}V_{cs}V_{us}^*V_{cd}^*\right)$$

- In the *d* (also in *s*) BGL type model the *CP* violating contribution to the BAU at the electroweak phase transition is proportional to

$$\left(t_\beta+t_\beta^{-1}\right)\left(m_b^2-m_s^2\right)\prod_{i>j}\left(m_{u_i}^2-m_{u_j}^2\right)\mathrm{Im}\left(V_{ud}V_{cs}V_{us}^*V_{cd}^*\right)$$

$$\sim\quad\left(t_\beta+t_\beta^{-1}\right)m_t^4 m_c^2 m_b^2\,\mathrm{Im}\left(V_{ud}V_{cs}V_{us}^*V_{cd}^*\right)$$

- If *E* is the relevant scale for baryogenesis at the electroweak phase transition one can get an **enhancement** of order

$$\left(t_\beta+t_\beta^{-1}\right)\frac{E^4}{m_b^2 m_s^2}\Bigg|_{E\sim 100\ GeV}\sim 10^{10}$$