FLAVOUR CHANGING YUKAWA COUPLING IN TWO HIGGS DOUBLET MODELS

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Introduction

- Work done with: G.C. Branco, M. Nebot and M.Rebelo **arXiv:1508.05101**, Phys.Lett. B722 (2013) 76-82, JHEP 1110 (2011) 037 and Phys.Lett. B687 (2010) 194-200. And also (with L. Pedro, A. Carmona) JHEP 1407 (2014) 078
- Study the Higgs like particle properties: Yukawa Couplings including 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: The so called BGL models (Branco, Grimus, Lavoura)
- 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 $\langle H_1 \rangle^T = \begin{pmatrix} 0 & v/\sqrt{2} \end{pmatrix}$, $\langle H_2 \rangle^T = \begin{pmatrix} 0 & 0 \end{pmatrix}$, $v^2 = v_1^2 + v_2^2$, $\tan\beta \equiv t_\beta = v_2/v_1$

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \frac{v_1}{v} & \frac{v_2}{v} \\ \frac{v_2}{v} & -\frac{v_1}{v} \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

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

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

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

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

2HDM III

- Where V is the CKM matrix. D_u and D_d the diagonal mass matrices. N_u and N_d are in general the "dangerous" Flavour Changing couplings that appear with R^0 and A.
- Instead in the leptonic sector there are $D_l, D_\nu, N_l^0, N_\nu^0$ 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 : N_u, N_d etc also appear in the charged Higgs $H^\pm$ couplings.

The BGL models in the quark and lepton sectors I

- The BGL models (after Branco, Grimus and Lavoura) are 2HDM with Flavour Symmetries in such a way that they implement the "general" idea of Minimal Flavour Violation (MFV) in a renormalizable model. In general the symmetry has to be implemented both in the quark and lepton sectors. The different types of symmetries we can impose give rise to different models
- 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

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

They have FCYC in the down sector N_d.

The BGL models in the quark and lepton sectors II

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

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

They have FCYC in the up sector N_u.

- 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

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

With FCYC in the charged lepton sector.

The BGL models in the quark and lepton sectors III

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

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

- 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 $\Phi_2 \to e^{i\tau}\Phi_2$. 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 V

- 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 in BGL models I

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

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

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

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

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

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

- 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	$s_{\beta\alpha} - c_{\beta\alpha}\left[\left(1 - \left\|V_{ti}\right\|^2\right) t_\beta - \left\|V_{ti}\right\|^2 t_\beta^{-1}\right]$

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

A first summary

- All FCYC effects are proportional to $c_{\beta\alpha}\left(t_\beta + t_\beta^{-1}\right)$
- We can have at tree level: $t \to hu, hc$ with down type models.
- We can have at tree level: $h \to \mu\overline{\tau}, e\overline{\tau}, e\overline{\mu}$ in neutrino type models
- We can have at tree level $h \to d\overline{b}, s\overline{b}$ 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, $b\bar{b}$, $\tau\bar{\tau}$, $t\bar{t}$. 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

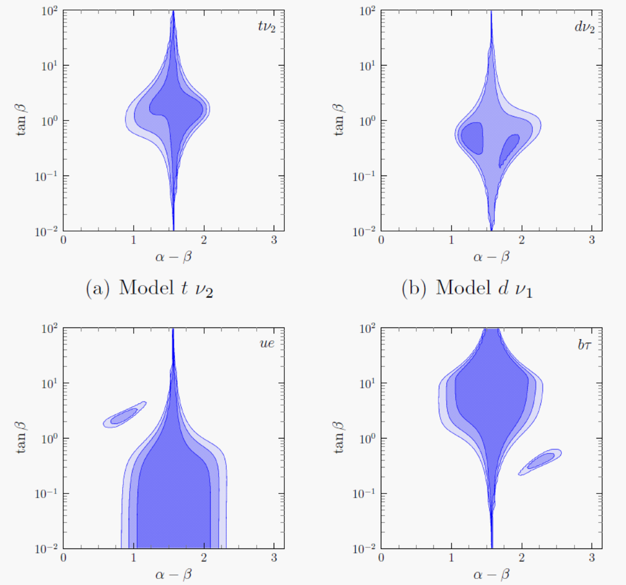
Decay chan X	$b\bar{b}$	WW^*	ZZ^*	$\tau\bar{\tau}$	$\gamma\gamma$	gg
$Br\left(h \to X\right)_{SM}$	0.578	0.216	0.0267	0.0637	0.0023	0.0856

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



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

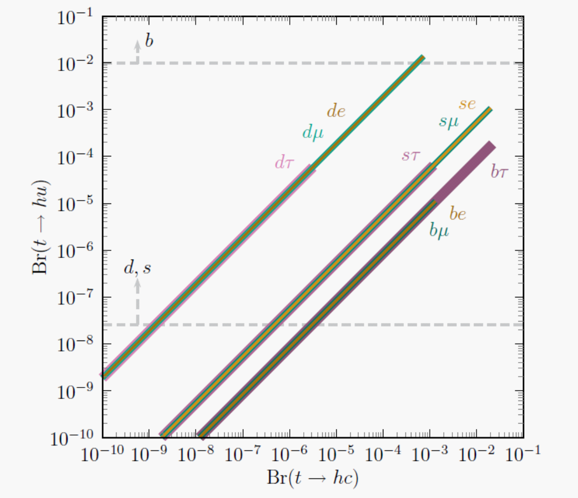
$$Br^{(d_k)}(t \to qh) = 0.131 \frac{|V_{tk} V_{qk}|^2}{|V_{tb}|^2} \left| c_{\beta\alpha} \left(t_\beta + t_\beta^{-1} \right) \right|^2$$

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

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

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

Rare top decays II



Rare 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. It turns out that neglecting low quark masses in each meson - i.e. $m_d\,/\,m_s$ in $K^0 - \overline{K}^0$ - the total contribution is proportional to

$$\left(\frac{c_{\beta\alpha}^2}{m_h^2} + \frac{s_{\beta\alpha}^2}{m_H^2} - \frac{1}{m_A^2}\right)$$

Oblique corrections accommodates better with important cancellations. Therefore these models present important "characteristic" cancellations invalidating the direct use of the naive bounds coming from the tree level Higgs exchange contribution alone.

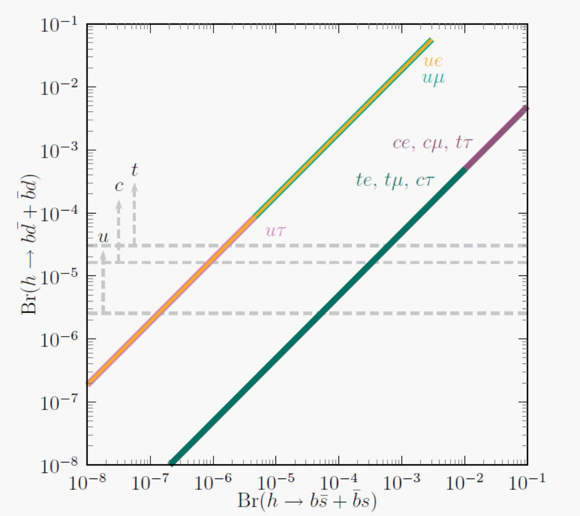
Flavour Changing Higgs decays to quarks I

- 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 $h \to \mu^{\pm}\tau^{\mp}, e^{\pm}\tau^{\mp}, e^{\pm}\mu^{\mp}$

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

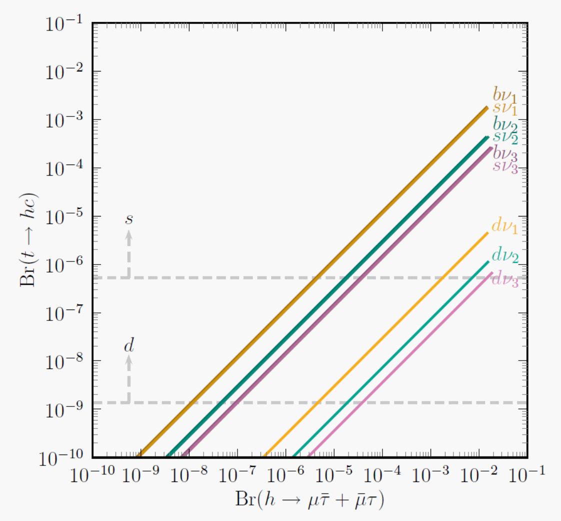
- For the ν_3 in order to get a $h \to \mu\tau$ branching ratio of order 10^{-2} - $Br(h \to \mu\tau) = \left(\begin{array}{cc} 0.84 & \begin{array}{c} +0.39 \\ -0.37 \end{array} \end{array}\right)\%$ - we need a value of $\left|c_{\beta\alpha}\left(t_\beta + t_\beta^{-1}\right)\right| \sim 1$

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

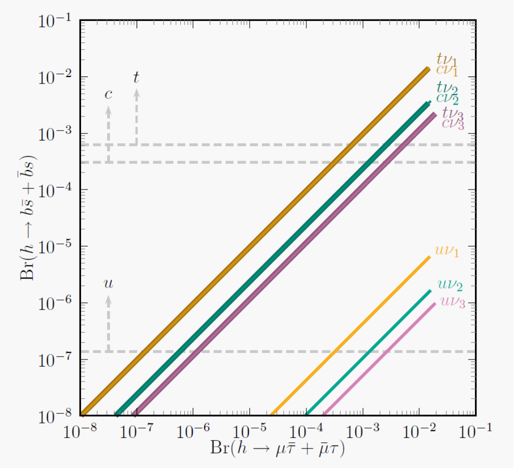


Rare Higgs decays to leptons and correlation with rare decays to quarks IV

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.

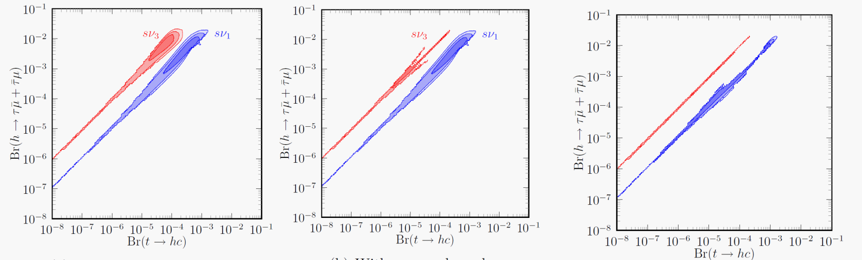
Rare Higgs decays to leptons and correlation with rare decays to quarks V

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



Incorporating leptonic constraint

- $\mu \to e\gamma$ 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 discussed, but important cancellations operate both in meson mixing and in $\mu \to e\gamma$ among others.

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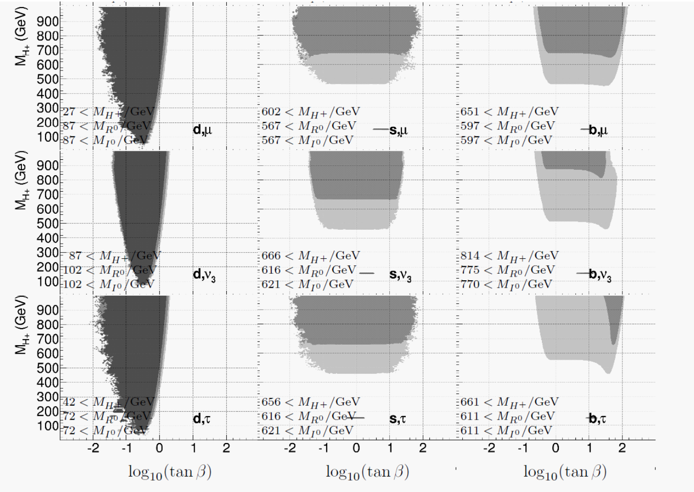
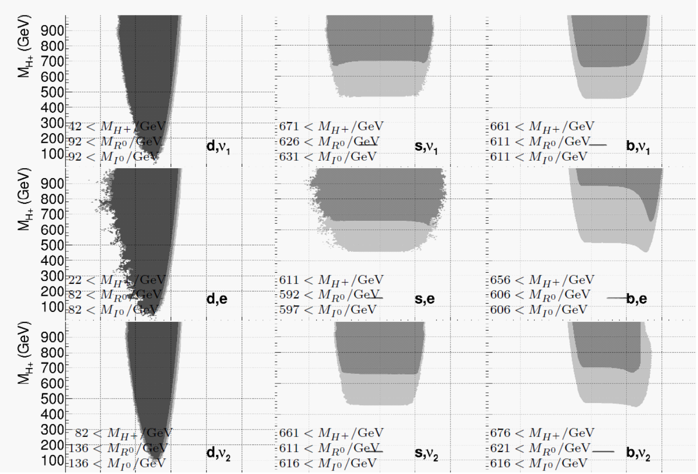
- 

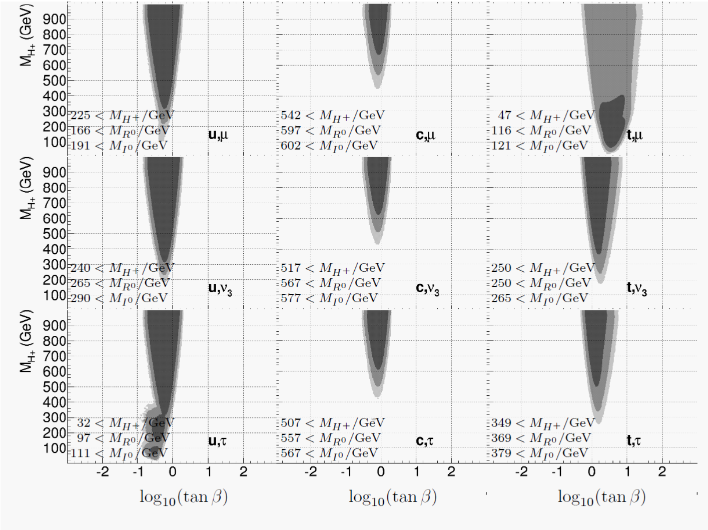
M_{H^+} (GeV)
900
800
700
600
500
400
300
200
100
$27 < M_{H^+}/\text{GeV}$
$87 < M_{R^0}/\text{GeV}$
$87 < M_{I^0}/\text{GeV}$
d,μ
$602 < M_{H^+}/\text{GeV}$
$567 < M_{R^0}/\text{GeV}$
$567 < M_{I^0}/\text{GeV}$
s,μ
$651 < M_{H^+}/\text{GeV}$
$597 < M_{R^0}/\text{GeV}$
$597 < M_{I^0}/\text{GeV}$
b,μ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

Back II

- 

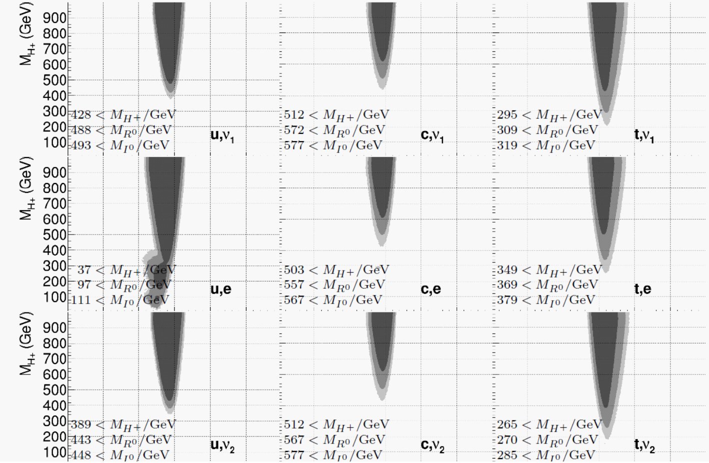
M_{H^+} (GeV)
900
800
700
600
500
400
300
200
100
$42 < M_{H^+}/\text{GeV}$
$92 < M_{R^0}/\text{GeV}$
$92 < M_{I^0}/\text{GeV}$
d,ν_1
$671 < M_{H^+}/\text{GeV}$
$626 < M_{R^0}/\text{GeV}$
$631 < M_{I^0}/\text{GeV}$
s,ν_1
$661 < M_{H^+}/\text{GeV}$
$611 < M_{R^0}/\text{GeV}$
$611 < M_{I^0}/\text{GeV}$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

Back III

- 

M_{H^+} (GeV)
900
800
700
600
500
400
300
200
100
225 < M_{H^+}/GeV
166 < M_{R^0}/GeV
191 < M_{I^0}/GeV
u,μ
542 < M_{H^+}/GeV
597 < M_{R^0}/GeV
602 < M_{I^0}/GeV
c,μ
47 < M_{H^+}/GeV
116 < M_{R^0}/GeV
121 < M_{I^0}/GeV
t,μ
240 < M_{H^+}/GeV
265 < M_{R^0}/GeV
290 < M_{I^0}/GeV
u,ν_3
517 < M_{H^+}/GeV
567 < M_{R^0}/GeV
577 < M_{I^0}/GeV
c,ν_3
250 < M_{H^+}/GeV
250 < M_{R^0}/GeV
265 < M_{I^0}/GeV
t,ν_3
32 < M_{H^+}/GeV
97 < M_{R^0}/GeV
111 < M_{I^0}/GeV
u,τ
507 < M_{H^+}/GeV
557 < M_{R^0}/GeV
567 < M_{I^0}/GeV
c,τ
349 < M_{H^+}/GeV
369 < M_{R^0}/GeV
379 < M_{I^0}/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
$428 < M_{H^+}/\text{GeV}$
$488 < M_{R^0}/\text{GeV}$
$493 < M_{I^0}/\text{GeV}$
u,ν1
$512 < M_{H^+}/\text{GeV}$
$572 < M_{R^0}/\text{GeV}$
$577 < M_{I^0}/\text{GeV}$
c,ν1
$295 < M_{H^+}/\text{GeV}$
$309 < M_{R^0}/\text{GeV}$
$319 < M_{I^0}/\text{GeV}$
t,ν1
$37 < M_{H^+}/\text{GeV}$
$97 < M_{R^0}/\text{GeV}$
$111 < M_{I^0}/\text{GeV}$
u,e
$503 < M_{H^+}/\text{GeV}$
$557 < M_{R^0}/\text{GeV}$
$567 < M_{I^0}/\text{GeV}$
c,e
$349 < M_{H^+}/\text{GeV}$
$369 < M_{R^0}/\text{GeV}$
$379 < M_{I^0}/\text{GeV}$
t,e
$389 < M_{H^+}/\text{GeV}$
$443 < M_{R^0}/\text{GeV}$
$448 < M_{I^0}/\text{GeV}$
u,ν2
$512 < M_{H^+}/\text{GeV}$
$567 < M_{R^0}/\text{GeV}$
$577 < M_{I^0}/\text{GeV}$
c,ν2
$265 < M_{H^+}/\text{GeV}$
$270 < M_{R^0}/\text{GeV}$
$285 < M_{I^0}/\text{GeV}$
t,ν2

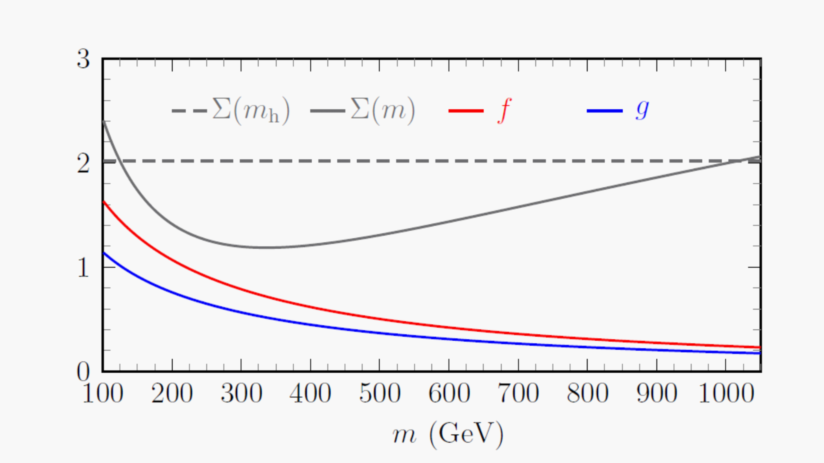
Back V

- $$B_r\left(\mu \to e\gamma\right)_{2l} = \frac{3}{8}\left(\frac{\alpha}{\pi}\right)^3 \left(t_\beta + t_\beta^{-1}\right)^2 \left|U_{ej}U_{\mu j}^*\right|^2 |A|^2$$

$$A = c_{\beta\alpha}s_{\beta\alpha}\left[\Sigma\left(m_h\right) - \Sigma\left(m_H\right)\right] + \frac{8K_t}{3}\left[c_{\beta\alpha}^2 f\left(z_h\right) + s_{\beta\alpha}^2 f\left(z_H\right) - g\left(z_A\right)\right]$$

where $z_X = m_t^2 / m_X^2$

Back VI



$\Sigma(m_h)$
$\Sigma(m)$
f
g
3
2
1
0
100
200
300
400
500
600
700
800
900
1000
m (GeV)

Back VII

- With

$$\left(t_\beta + t_\beta^{-1}\right) = \frac{1}{c_\beta s_\beta}$$

$$\frac{c_{\beta-\alpha} s_{\beta-\alpha}}{c_\beta s_\beta} = \frac{v^2}{2m_A^2}\left[s_{2\alpha}\left(\lambda_2 t_\beta - \lambda_1 t_\beta^{-1}\right) + 2\lambda_{34} c_{2\alpha}\right]$$

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