The flavour sector of 2HDM

(BGL 2HDM models confront charged Higgs data)

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Introduction

- Flavour in Two Higgs Doublet Model (2HDM) means suppress or control Flavour Changing Neutral Currents (FCNC)
- A natural scenario is using symmetries to avoid or suppress FCNC.
- 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 Minimal Flavour Violation (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.
- We will try to confront BGL models to charged Higgs data, in particular to some hints related to a light charged Higgs.
- We will use the framework of the so called generalized BGL models (gBGL).

2HDM I

- The quark 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 $\langle\Phi_i\rangle^T = e^{i\theta_i}\begin{pmatrix} 0 & v_i/\sqrt{2}\end{pmatrix}$ 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

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

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 (if we have CP invariant Higgs potential).
- H^0 and R^0 CP even scalars. H^0 has the SM Higgs couplings.

- 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

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

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

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

  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 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 IV

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

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

- The flavour is in M_u, M_d, N_u, N_d and the *CKM* matrix $V = U_L^{u\dagger}U_L^d$.
- **It is trivial that the couplings N_u, N_d that appear with the new neutral Higgs R^0 and A (in general non diagonal) also appear in the charged Higgs $H^\pm$ couplings.**
- **This last statement will be the key to analyze how the flavour structure of BGL models confront with the experimental data.**

The BGL models I

- Remarkably enough it was shown that **renormalizable models 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 $U\left(1\right)$ flavour symmetry

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

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

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

The BGL models II

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

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

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

The BGL models 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:

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

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

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 BGL models VI

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

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

Generalized 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:

$$Q_{L_3} \to -Q_{L_3} \; ; \; d_R \to d_R \; ; \; u_R \to u_R \; ; \; \Phi_2 \to -\Phi_2 \; ; \; \Phi_1 \to \Phi_1$$

- Now the Yukawa textures are:

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

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

Obviously they include both up-type and down-type BGL models.

Generalized BGL models: gBGL II

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

$$\begin{aligned}(N^u)_{ij} &= \left[t_\beta \delta_{ij} - \left(t_\beta + t_\beta^{-1}\right) \widehat{n}_{[u]i} \widehat{n}^*_{[u]j}\right] m_{u_j} \\ \left(N^d\right)_{ij} &= \left[t_\beta \delta_{ij} - \left(t_\beta + t_\beta^{-1}\right) \widehat{n}_{[d]i} \widehat{n}^*_{[d]j}\right] m_{d_j}\end{aligned}$$

where it can be chosen

$$\widehat{n}_{[u]i} = \left(\mathcal{U}_L^{u\dagger}\right)_{i3} \text{ and } \widehat{n}_{[d]i} = \left(\mathcal{U}_L^{d\dagger}\right)_{i3}$$

in such a way that

$$\widehat{n}_{[u]i} = V_{ij} \widehat{n}_{[d]i}$$

the new free parameters are two angles to define the unitary vector $\widehat{n}_{[u]}$ **or** $\widehat{n}_{[d]}$ and two phases of the three complex component

Generalized BGL models: gBGL III

- Note that N^u and N^d, in BGL models, inherit from the standard Yukawa couplings the masses and V. gBGL models additionally inherit also a unitary vector from $\mathcal{U}_L^{u\dagger}$, introducing four additional parameters.
- This is the generalization of BGL models that correspond to the down models (d, s, b)

$$\hat{d}_{[d]} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \quad ; \quad \hat{s}_{[d]} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \quad ; \quad \hat{b}_{[d]} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

or with the other parametrization

$$\hat{d}_{[u]} = \begin{pmatrix} V_{ud} \\ V_{cd} \\ V_{td} \end{pmatrix} \quad ; \quad \hat{s}_{[u]} = \begin{pmatrix} V_{us} \\ V_{cs} \\ V_{ts} \end{pmatrix} \quad ; \quad \hat{b}_{[u]} = \begin{pmatrix} V_{ub} \\ V_{cb} \\ V_{tb} \end{pmatrix}$$

Generalized BGL models: gBGL IV

- and for the up models

$$\hat{u}_{[u]} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \quad ; \quad \hat{c}_{[u]} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \quad ; \quad \hat{t}_{[u]} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

or

$$\hat{u}_{[d]} = \begin{pmatrix} V_{ud}^* \\ V_{us}^* \\ V_{ub}^* \end{pmatrix} \quad ; \quad \hat{c}_{[d]} = \begin{pmatrix} V_{cd}^* \\ V_{cs}^* \\ V_{cb}^* \end{pmatrix} \quad ; \quad \hat{t}_{[d]} = \begin{pmatrix} V_{td}^* \\ V_{ts}^* \\ V_{tb}^* \end{pmatrix}$$

Generalized BGL models: gBGL V

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

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

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.

The charged Higgs couplings I

- If we write

$$L = -\sum_{i,j} \overline{u_i} \left(Y_{ij}^{(u)} L + Y_{ij}^{(d)} R \right) d_j H^+ + h.c$$
$$-\sum_{i,j} \overline{\nu_i} \left(Y_{ij}^{(\nu)} L + Y_{ij}^{(l)} R \right) l_j H^+ + h.c.$$

- In general we have

$$Y^{(u)} = -\frac{\sqrt{2}}{v} N^{u\dagger} V \;\; ; \;\; Y^{(d)} = \frac{\sqrt{2}}{v} V N^d$$
$$Y^{(\nu)} = -\frac{\sqrt{2}}{v} N^{\nu\dagger} U_\nu^\dagger \;\; ; \;\; Y^{(l)} = \frac{\sqrt{2}}{v} U_\nu^\dagger N^l$$

where V is the CKM matrix and U the PMNS matrix.

The charged Higgs couplings II

- For our fits we need $\left(y_{q_i} = \sqrt{2} m_{q_i}/v\right)$, (**in gBGL**)

$$\begin{aligned}
\left(Y^{(u)}\right)_{u_i d_j} &= y_{u_i} F^{(u)}_{u_i d_j} \ ; \ \left(Y^{d}\right)_{u_i d_j} = y_{d_j} F^{(d)}_{u_i d_j} \\
F^{(u)}_{u_i d_j} &= -F^{(d)}_{u_i d_j} \equiv F^{(Q)}_{u_i d_j} \\
F^{(u)}_{u_i d_j} &= -t_\beta V_{u_i d_j} + \left(t_\beta + t_\beta^{-1}\right) \widehat{n}_{[u]i} \widehat{n}^*_{[d]j}
\end{aligned}$$

$$\begin{aligned}
\widehat{\Gamma}\left(H^+ \to u_i \overline{d}_j\right) &\equiv \left[\left|\left(Y^{(u)}\right)_{u_i d_j}\right|^2 + \left|\left(Y^{(d)}\right)_{u_i d_j}\right|^2\right] \\
&= \left(y^2_{u_i} + y^2_{d_i}\right) \left|F^{(Q)}_{u_i d_j}\right|^2
\end{aligned}$$

where we have introduced the reduced rate $\widehat{\Gamma}\left(H^+ \to u_i \overline{d}_j\right)$

The charged Higgs couplings III

- **In the BGL model q_k we have**

$$\left|F^{(Q)}_{u_i d_j}\right|^2 = \left|V_{u_i d_j}\right|^2 g^{(q_k)}_{u_i d_j}$$

with

$$g^{(q_k)}_{u_i d_j} = \begin{cases} t_\beta^{-2} \; ; \; u_i = q_k \text{ or } d_j = q_k \\ t_\beta^2 \; ; \text{ other cases} \end{cases}$$

- In the leptonic sector we get

$$\widehat{\Gamma}\left(H^+ \to \nu_i l_j^+\right) = \left[\left|\left(Y^{(\nu)}\right)_{\nu_i l_j}\right|^2 + \left|\left(Y^{(l)}\right)_{\nu_i l_j}\right|^2\right] = y_{l_j}^2 \left|F^{(L_k)}_{\nu_i l_j}\right|^2$$

The charged Higgs couplings IV

- **In the BGL $L_k = \nu_k, l_k$ model** we get

$$\left|F_{\nu_i l_j}^{(L_k)}\right|^2 = \left|U_{l_j \nu_i}^*\right|^2 g_{\nu_i l_j}^{(L_k)}$$

with

$$g_{\nu_i l_j}^{(L_k)} = \begin{cases} t_\beta^{-2} \; ; \nu_i = L_k \text{ or } l_j = L_k \\ t_\beta^2; \;\; \text{other cases} \end{cases}$$

Rates and branching ratios I

- The relevant hadronic rates for us are:

$$\Gamma\left(H^+ \to u_i \overline{d}_j\right) = \frac{3m_{H^+}}{16\pi}\left(1 + \frac{17\alpha_s\left(m_{H^+}\right)}{3\pi}\right)\widehat{\Gamma}\left(H^+ \to u_i \overline{d}_j\right)$$

and the leptonic one will be

$$\Gamma\left(H^+ \to \nu_i l_j^+\right) = \frac{m_{H^+}}{16\pi}\widehat{\Gamma}\left(H^+ \to \nu_i l_j^+\right)$$

the total hadronic and leptonic rates are

$$\begin{aligned} \Gamma\left(H^+ \to Q\right) &= \frac{3m_{H^+}}{16\pi}\left(1 + \frac{17\alpha_s\left(m_{H^+}\right)}{3\pi}\right)\widehat{\Gamma}\left(H^+ \to Q\right) \\ \widehat{\Gamma}\left(H^+ \to Q\right) &= \sum_{\substack{u_i = u,c \\ d_j = d,s,b}} \widehat{\Gamma}\left(H^+ \to u_i \overline{d}_j\right) \end{aligned}$$

Rates and branching ratios II

$$\Gamma\left(H^+ \to L\right) = \sum_{i,j=1}^{3} \Gamma\left(H^+ \to \nu_i l_j^+\right) = \frac{m_{H^+}}{16\pi}\widehat{\Gamma}\left(H^+ \to L\right)$$

$$\widehat{\Gamma}\left(H^+ \to L\right) = \sum_{i,j=1}^{3} \widehat{\Gamma}\left(H^+ \to \nu_i l_j^+\right)$$

- In BGL model (q, l), because

$$\widehat{\Gamma}_q\left(H^+ \to Q\right) = \sum_{\substack{u_i=u,c\\ d_j=d,s,b}} \left(y_{u_i}^2 + y_{d_i}^2\right)\left|V_{u_i d_j}\right|^2 g_{u_i d_j}^{(q)}$$

and

$$\widehat{\Gamma}_l\left(H^+ \to L\right) = \sum_{\substack{\nu_i=1,2,3\\ l_j=e,\mu,\tau}} \left(y_{l_j}^2\right)\left|U_{l_j\nu_i}\right|^2 g_{\nu_i l_j}^{(l)}$$

Rates and branching ratios III

and the $g_{u_i d_j}^{(q,l)}$ factors are either t_β^2 or t_β^{-2} we have

$$\begin{aligned}\Gamma_{(Q,L)}\left(H^+\right) &\sim \left(a_{(Q,L)} t_\beta^2 + b_{(Q,L)} t_\beta^{-2}\right) \times 10^{-4}\, GeV \\ a_{(Q,L)} &= 1.11 \times \widehat{A}_Q + 2.56 \times \widehat{A}_L \\ b_{(Q,L)} &= 1.11 \times \widehat{B}_Q + 2.56 \times \widehat{B}_L\end{aligned}$$

with

$$\begin{aligned}&\widehat{A}_{u,c,t} = \left(1.045, 6.7 \times 10^{-4}, 1.045\right);\ \widehat{B}_{u,c,t} = \left(6.7 \times 10^{-4}, 1.045, 0\right) \\ &\widehat{A}_{d,s,b} = \left(0.9942, 0.1016, 1.0058\right);\ \widehat{B}_{d,s,b} = \left(0.051, 0.95, 0.0387\right) \\ &\widehat{A}_{\nu_1,\nu_2,\nu_3} = \left(0.82, 0.63, 0.51\right);\ \widehat{B}_{\nu_1,\nu_2,\nu_3} = \left(0.16, 0.35, 0.47\right) \\ &\widehat{A}_{e,\mu,\tau} = \left(1, 1, 3 \times 10^{-3}\right);\ \widehat{B}_{e,\mu,\tau} = \left(0, 3 \times 10^{-3}, 1\right)\end{aligned}$$

Data on top going to b and charged Higgs I

- ATLAS [2302.11739] presented results on the search of a light charged Higgs boson in the $t \to H^+ b$ decay, with $H^+ \to c\bar{b}$. The largest excess in data is $m_{H^+} = 130$ GeV with a local significance of 3σ. The best fit is

$$Br\left(t \to H^+ b\right) Br\left(H^+ \to c\bar{b}\right) = (1.6 \pm 0.6) \times 10^{-3}$$

If we write

$$\begin{aligned} B_{tb} &= \frac{\Gamma_q\left(t \to H^+ b\right)}{\Gamma\left(t \to W^+ b\right)} = 0.22 \times \widehat{\Gamma}\left(H^+ \to t\bar{b}\right) \\ &= 0.22 \times \left(y_t^2 + y_b^2\right)\left|F_{tb}^{(q)}\right|^2 \end{aligned}$$

In BGL models

Data on top going to b and charged Higgs II

$$\left|F_{tb}^{(q)}\right|^2 = |V_{tb}|^2\, g_{tb}^{(q)}$$

$$B_{tb} = 0.198 g_{tb}^{(q)}$$

with

$$g_{tb}^{(q)} = \begin{cases} t_\beta^2 & ; q = u, c, s, d \\ t_\beta^{-2} & ; q = t, b \end{cases}$$

We also have in BGL

$$\begin{aligned} \Gamma_q\left(H^+ \to c\bar{b}\right) &= \frac{3 m_{H^+}}{16\pi}\left(1 + \frac{17\alpha_s\left(m_{H^+}\right)}{3\pi}\right)\widehat{\Gamma}\left(H^+ \to c\bar{b}\right) \\ &= \frac{3 m_{H^+}}{16\pi}\left(1 + \frac{17\alpha_s\left(m_{H^+}\right)}{3\pi}\right)\left(y_c^2 + y_b^2\right)|V_{cb}|^2\, g_{cb}^{(q)} \end{aligned}$$

and we get

$$\Gamma_q \left(H^+ \to c\overline{b}\right) = 4.33 \times 10^{-6} g_{cb}^{(q)} GeV$$

$$g_{cb}^{(q)} = \begin{cases} t_\beta^2 & ; q = u, t, s, d \\ t_\beta^{-2} & ; q = c, b \end{cases}$$

Our initial constraint can be written as

$$\frac{B_{tb}}{1 + B_{tb}} \frac{\Gamma_q \left(H^+ \to c\overline{b}\right)}{\Gamma_{(q,l)} \left(H^+\right)} = (1.6 \pm 0.6) \times 10^{-3}$$

and we arrive to

$$\frac{0.198 g_{tb}^{(q)}}{1 + 0.198 g_{tb}^{(q)}} \frac{4.33 g_{cb}^{(q)}}{\left(a_{(Q,L)} t_\beta^2 + b_{(Q,L)} t_\beta^{-2}\right)} = 0.16 \pm 0.06$$

Data on top going to b and charged Higgs IV

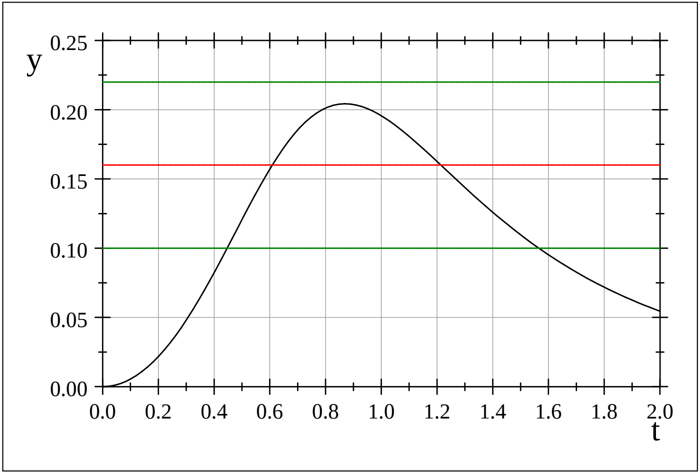
- The results of the fit are

t_β values	b	s	d
τ	$1.06\pm^{0.16}_{0.11}$	$0.97\pm^{0.05}_{0.08}$	$0.96\pm^{0.07}_{0.16}$
μ	$1.03\pm^{0.09}_{0.05}$	$0.94\pm^{0.11}_{0.12}$	$0.90\pm^{0.18}_{0.19}$
e	$1.03\pm^{0.08}_{0.05}$	$0.94\pm^{0.11}_{0.11}$	$0.90\pm^{0.18}_{0.19}$
ν_1	$1.04\pm^{0.09}_{0.06}$	$0.94\pm^{0.09}_{0.11}$	$0.92\pm^{0.14}_{0.15}$
ν_2	$1.04\pm^{0.11}_{0.07}$	$0.95\pm^{0.08}_{0.10}$	$0.93\pm^{0.12}_{0.12}$
ν_3	$1.05\pm^{0.11}_{0.08}$	$0.95\pm^{0.08}_{0.09}$	$0.94\pm^{0.10}_{0.12}$

t_β values	t	c	u
τ	$1.95\pm^{0.67}_{0.61}; 0.87\pm^{0.36}_{0.19}$	$7.06\pm^{1.06}_{0.70}; 0.90\pm^{0.18}_{0.21}$	$0.96\pm^{0.07}_{0.09}$
μ	$1.12\pm^{0.33}_{0.20}; 0.138\pm^{0.015}_{0.018}$	$1.15\pm^{0.31}_{0.34}; 0.51\pm^{0.23}_{0.13}$	$0.90\pm^{0.18}_{0.21}$
e	$1.12\pm^{0.33}_{0.20}$	$1.15\pm^{0.31}_{0.33}; 0.51\pm^{0.22}_{0.13}$	$0.90\pm^{0.18}_{0.21}$
ν_1	$1.16\pm^{0.38}_{0.26}; 0.45\pm^{0.10}_{0.08}$	$1.21\pm^{0.35}; 0.61\pm_{0.17}$	$0.91\pm^{0.15}_{0.15}$
ν_2	$1.12\pm^{0.55}; 0.60\pm_{0.12}$	$1.32\pm^{0.39}; 0.71\pm_{0.19}$	$0.93\pm^{0.11}_{0.13}$
ν_3	$1.22\pm^{0.45}; 0.60\pm_{0.12}$	$1.43\pm^{0.41}; 0.76\pm_{0.21}$	$0.94\pm^{0.10}_{0.12}$

All the models could fit the data.

Some of them even with two solutions



Bounds in leptonic modes I

- ATLAS [arXiv:1807.07915] and CMS [arXiv:1903.04560] published bounds corresponding to

$$Br\left(t \to H^+ b\right) Br\left(H^+ \to \tau^+ \nu\right) \leq 1.5 \times 10^{-3}$$

- Because there is signal in $H^+ \to c\bar{b}$ and not in $H^+ \to \tau^+ \nu$

$$\frac{\Gamma\left(H^+ \to c\bar{b}\right)}{\Gamma\left(H^+ \to \tau^+ \nu\right)} = 3\left(1 + \frac{17}{3}\alpha_S\right)\frac{\widehat{\Gamma}\left(H^+ \to c\bar{b}\right)}{\widehat{\Gamma}\left(H^+ \to \tau^+ \nu\right)} \geq 0.7$$

$$\frac{\widehat{\Gamma}\left(H^+ \to c\bar{b}\right)}{\widehat{\Gamma}\left(H^+ \to \tau^+ \nu\right)} = \left(\frac{m_b}{m_\tau}\right)^2 \left[1 + \left(\frac{m_c}{m_b}\right)^2\right] \left|V_{cb}\right|^2 F_{(q,l)}\left(t_\beta\right)$$

$$F_{(q,l)}\left(t_\beta\right) = \frac{g_{cb}^{(q)}}{\sum_{i=1}^{3} \left|U_{\tau i}\right|^2 g_{\nu_i \tau}^{(l)}}$$

Bounds in leptonic modes II

meaning

$$F_{(q,l)}\left(t_\beta\right) \geq 41.3\ ;\ F_{(q,l)}\left(t_\beta\right) = \frac{g_{cb}^{(q)}}{\sum_{i=1}^{3}\left|U_{\tau i}\right|^2 g_{\nu_i\tau}^{(l)}}$$

- Models $(u/t, e/\mu)$ and $(d/s, e/\mu)$ and $(c/b, \tau)$ has $F_{(q,l)}\left(t_\beta\right) = 1$. **These 10 models would be excluded.**
- **All neutrino models (18) are excluded** because the maximum of $F_{(q,l)}\left(t_\beta\right)$ is smaller than 41.3
- **The models** $(u/t, \tau)$ **and** $(d/s, \tau)$ **has** $F_{(q,l)}\left(t_\beta\right) = t_\beta^4$ **and are valid with** $t_\beta \geq 2.54$.
- **The models** $(c/b, e/\mu)$ **has** $F_{(q,l)}\left(t_\beta\right) = t_\beta^{-4}$ **and are valid with** $t_\beta \leq 0.39$.
- **The models** $(t, \tau), (c, e)$ **and** (c, μ) **are compatible with the fit to the potential signal.**

Bounds in hadronic modes I

- CMS [arXiv:2005.08900] presented bounds that can be translated, for our 130 GEV charged Higgs, into Bernal et al. [2307.11813]

$$B_r\left(t \to H^+ b\right) B_r\left(H^+ \to c\bar{b} + c\bar{s} + c\bar{d}\right) \leq 2.7 \times 10^{-3}$$

and therefore

$$\rho\left[1 + \frac{\Gamma\left(H^+ \to c\bar{s} + c\bar{d}\right)}{\Gamma\left(H^+ \to c\bar{b}\right)}\right] \leq 2.7 \times 10^{-3}$$

$$\rho = B_r\left(t \to H^+ b\right) B_r\left(H^+ \to c\bar{b}\right) = (1.6 \pm 0.6) \times 10^{-3}$$

So

$$\frac{\Gamma\left(H^+ \to c\bar{s} + c\bar{d}\right)}{\Gamma\left(H^+ \to c\bar{b}\right)} \leq \frac{2.7 \times 10^{-3}}{\rho} - 1 \leq 1.7$$

Bounds in hadronic modes II

- Therefore

$$\Phi_q = \frac{\Gamma_q\left(H^+ \to c\bar{b}\right)}{\Gamma_q\left(H^+ \to c\bar{s}\right) + \Gamma_q\left(H^+ \to c\bar{d}\right)} \geq 0.59$$

And in BGL's we have

$$\Phi_q = \left(\frac{m_b}{m_c}\right)^2 \frac{\left(1+\left(\frac{m_c}{m_b}\right)^2\right)}{\left(1+\left(\frac{m_s}{m_c}\right)^2\right)} \left|\frac{V_{cb}}{V_{cs}}\right|^2 \frac{g_{cb}^{(q)}}{g_{cs}^{(q)} + \frac{\left(1+\left(\frac{m_d}{m_c}\right)^2\right)}{\left(1+\left(\frac{m_s}{m_c}\right)^2\right)} \left|\frac{V_{cd}}{V_{cs}}\right|^2 g_{cd}^{(q)}}$$

- The additional constraint is

$$\Phi_q = \frac{4.09\times 10^{-2} g_{cb}^{(q)}}{g_{cs}^{(q)} + 5.30\times 10^{-2} g_{cd}^{(q)}} \geq 0.59$$

Bounds in hadronic modes III

- Note that when $g_{cb}^{(q)} = g_{cs}^{(q)} = g_{cd}^{(q)}$ we get $\Phi_q = 3.88 \times 10^{-2}$ that is excluded.

models u, c and t should **be excluded**

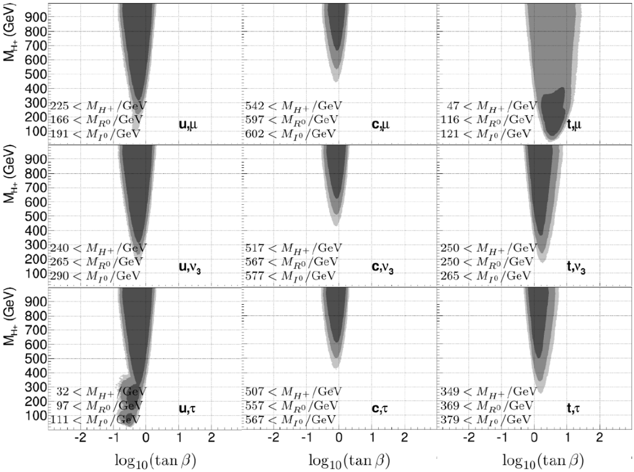
model d **is excluded**

model s **is allowed with** $t_\beta \geq 2.80$

model b **is allowed with** $t_\beta \leq 0.51$

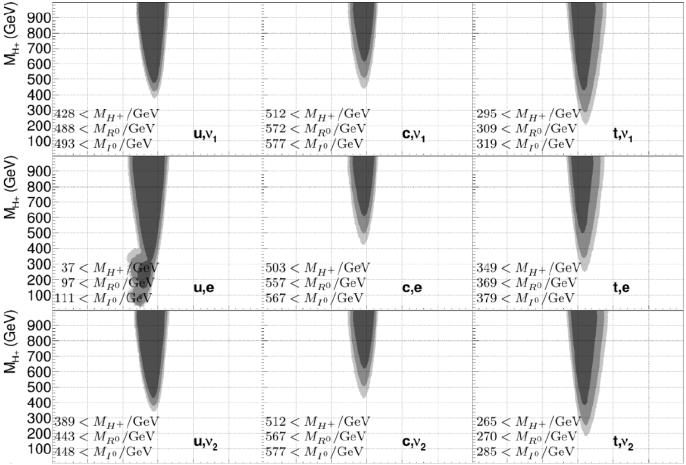
- But, the allowed t_β region of the s and b models are not compatible with the fits to the signal.

- In JHEP07(2014)078 we presented

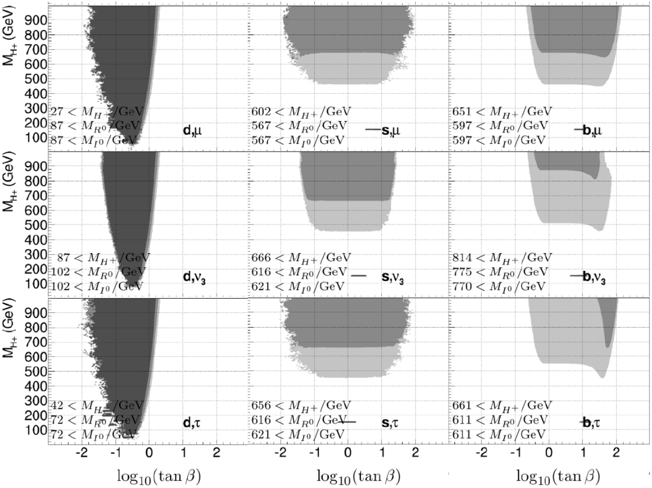


General constraints II

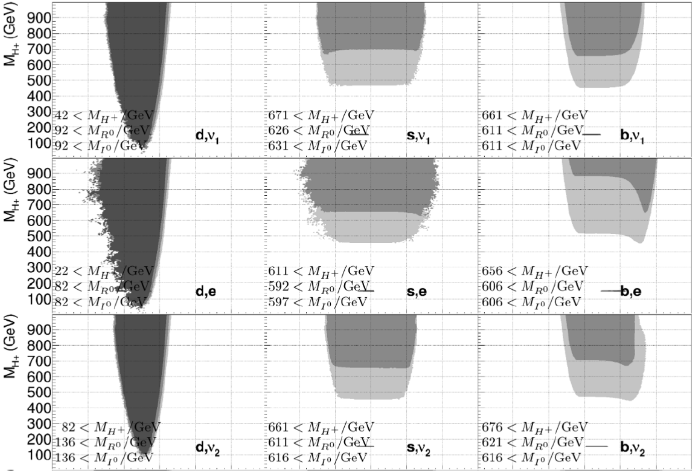
- the regions allowed for the 36 (Q, L) models



- Where all kinds of flavour constraints -tree and loop induced- were included



- And also oblique parameters



General constraints V

- **There is not any special region that reinforces some of the previous findings.** For example, If we look at models (t, τ), (c, e) and (c, μ) none of them matches a charged Higgs of 130 GeV.

Conclusions I

- We have confronted BGL models to the 3σ signal of a H^+ of 130 GeV, produced in $t \longrightarrow H^+ b \longrightarrow (c\bar{b})\, b$
- Even if all BGL models can fit the data, once we include other leptonic H^+ bounds from ATLAS and CMS only the models (t, τ), (c, e) and (c, μ) survive.
- When including other hadronic H^+ bounds from CMS only s and b models could survive but with wrong t_β values.
- The $m_{H^+} = 130\ GeV$ regions allowed in our 2014 analysis - including tree and loop flavour constraints, and electroweak- do not match any of the previously mention more favoured regions.
- We are working on the gBGL models confronting this charged Higgs hint.