Flavour Changing Top Decays $t \to hq$ in a class of Two-Higgs Doublet Models

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G.C. Branco, M.N. Rebelo, (Lisbon) & F.J. Botella (Valencia)
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Two Higgs Doublet Models (I)

- Instead of a single doublet Φ ( ) as in the SM,

  two doublets Φ_1 & Φ_2

- Full lagrangian

$$\mathscr{L} = \mathscr{L}_{\text{kin+gauge}} - V(\Phi_1, \Phi_2) + \mathscr{L}_{\text{Y}}$$

[T.D.Lee, PRD 8 (1973),. . . , Branco et al. Phys.Rep. 516 (2013)]

- In $\mathscr{L}_{\text{kin+gauge}}$, $(D_\mu \Phi)(D^\mu \Phi)^\dagger \to \sum_i (D_\mu \Phi_i)(D^\mu \Phi_i)^\dagger$
- Scalar potential, instead of $V(\Phi) = \lambda\left(v^2 - \Phi^\dagger\Phi\right)^2$

$$V(\Phi_1,\Phi_2) = \mu_{11}^2\, \Phi_1^\dagger\Phi_1 + \mu_{22}^2\, \Phi_2^\dagger\Phi_2 + \left(\mu_{12}^2\Phi_1^\dagger\Phi_2 + \text{H.C.}\right)$$
$$+\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \lambda_4\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right)$$
$$+\left(\lambda_5\left(\Phi_1^\dagger\Phi_2\right)^2 + \text{H.C.}\right) + \left[\left(\lambda_6\left(\Phi_1^\dagger\Phi_1\right) + \lambda_7\left(\Phi_2^\dagger\Phi_2\right)\right)\left(\Phi_1^\dagger\Phi_2\right) + \text{H.C.}\right]$$

- Yukawa couplings $\mathscr{L}_{\text{Y}}$

Two Higgs Doublet Models (II)

- Spontaneous symmetry breaking

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1\, e^{i\alpha_1}\end{pmatrix}, \quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2\, e^{i\alpha_2}\end{pmatrix}$$

$$\sqrt{v_1^2 + v_2^2} = v \simeq 246\,\mathrm{GeV}, \quad \frac{v_2}{v_1} \equiv \tan\beta$$

- Expansion around the minimum of $V(\Phi_1, \Phi_2)$

$$\Phi_j = e^{i\alpha_j}\begin{pmatrix} \varphi_j^+ \\ (v_j + \rho_j + i\eta_j)/\sqrt{2}\end{pmatrix}, \quad j = 1, 2$$

- Rotate to the "Higgs" basis with

$$U \equiv \frac{1}{\sqrt{v_1^2+v_2^2}}\begin{pmatrix} v_1 e^{-i\alpha_1} & v_2 e^{-i\alpha_2} \\ v_2 e^{-i\alpha_1} & -v_1 e^{-i\alpha_2}\end{pmatrix} = \begin{pmatrix} e^{-i\alpha_1}\cos\beta & e^{-i\alpha_2}\sin\beta \\ e^{-i\alpha_1}\sin\beta & -e^{-i\alpha_2}\cos\beta\end{pmatrix}$$

Two Higgs Doublet Models (III)

- Doublets: $\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = U \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$ with $\langle H_1 \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$ and $\langle H_2 \rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$
- Components

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

- G^0, $G^\pm$: pseudo-Goldstone bosons (longitudinal Z & $W^\pm$)
- IF the fields in the Higgs basis where the physical (mass eigenstates) scalars . . .
  - N^0, “SM Higgs”
  - additional R^0 scalar & A pseudoscalar,
  - additional $H^\pm$ charged scalar.

for the moment, focus on the Yukawa couplings $\mathscr{L}_{\mathrm{Y}}$

Yukawa couplings (I)

- Yukawa couplings in 2HDM

$$\mathscr{L}_{\rm Y} = -\overline{Q_L^0}\left(\Delta_1\tilde{\Phi}_1 + \Delta_2\tilde{\Phi}_2\right)u_R^0 - \overline{Q_L^0}\left(\Gamma_1\Phi_1 + \Gamma_2\Phi_2\right)d_R^0 \\ - \overline{L_L^0}\left(\Sigma_1\tilde{\Phi}_1 + \Sigma_2\tilde{\Phi}_2\right)\nu_R^0 - \overline{L_L^0}\left(\Pi_1\Phi_1 + \Pi_2\Phi_2\right)\ell_R^0 + \text{h.c.}$$

- Quark Yukawa couplings + Mass terms

$$\mathscr{L}_{\rm Y} \supset -\overline{u_L^0}\frac{1}{v}\left(M_u^0(v+N^0) + N_u^0 R^0 + iN_u^0 A\right)u_R^0 \\ - \overline{d_L^0}\frac{1}{v}\left(M_d^0(v+N^0) + N_d^0 R^0 + iN_d^0 A\right)d_R^0 \\ - \frac{\sqrt{2}}{v}\left(\overline{u_L^0}N_d^0 d_R^0 - \overline{u_R^0}N_u^{0\dagger} d_L^0\right)H^+ + \text{h.c.}$$

where $M_u^0 = \frac{1}{\sqrt{2}}\left(v_1\Delta_1 + v_2 e^{i\theta}\Delta_2\right)$, $M_d^0 = \frac{1}{\sqrt{2}}\left(v_1\Gamma_1 + v_2 e^{i\theta}\Gamma_2\right)$

and $N_u^0 = \frac{1}{\sqrt{2}}\left(v_2\Delta_1 - v_1 e^{i\theta}\Delta_2\right)$, $N_d^0 = \frac{1}{\sqrt{2}}\left(v_2\Gamma_1 - v_1 e^{i\theta}\Gamma_2\right)$

Fermion Masses

- Pictorially

$M = v_1$  $+ v_2 e^{i\theta}$  $= v$ , $N = v_2$  $- v_1 e^{i\theta}$  $= v$ 

- The "drama":

$$U_{uL}^{\dagger}\, M_u^0\, U_{uR} = M_u \equiv \text{diag}\,(m_u, m_c, m_t)$$
$$U_{dL}^{\dagger}\, M_d^0\, U_{dR} = M_d \equiv \text{diag}\,(m_d, m_s, m_b)$$

is fine, but

$$U_{uL}^{\dagger}\, N_u^0\, U_{uR} \equiv N_u = ?$$
$$U_{dL}^{\dagger}\, N_d^0\, U_{dR} \equiv N_d = ?$$

gives flavour changing couplings with R^0 and A,
the "non-SM" neutral scalars!

Yukawa couplings (II)

- $\mathscr{L}_{\mathrm{Y}}$ in terms of physical fields

$$\begin{aligned}\mathscr{L}_{\mathrm{Y}} \supset -\frac{1}{v}N^0\left(\bar{u}M_u u + \bar{d}M_d d\right) \\ -\frac{1}{v}R^0\left[\bar{u}\left(N_u\gamma_R + N_u^\dagger\gamma_L\right)u + \bar{d}\left(N_d\gamma_R + N_d^\dagger\gamma_L\right)d\right] \\ +\frac{i}{v}A\left[\bar{u}\left(N_u\gamma_R - N_u^\dagger\gamma_L\right)u - \bar{d}\left(N_d\gamma_R - N_d^\dagger\gamma_L\right)d\right] \\ -\frac{\sqrt{2}}{v}H^+\bar{u}\left(VN_d\gamma_R - N_u^\dagger V\gamma_L\right)d + \text{h.c.}\end{aligned}$$

- Mixing matrix (CKM), $V = U_{uL}^\dagger U_{dL}$

FCNC (I)

Ways out

- Discrete symmetries & Natural Flavour Conservation
  [Glashow & Weinberg, PRD 15 (1977), ...]
  - Type I: Φ_2 couples to u_R, d_R, e_R
  - Type II: Φ_2 couples to u_R, Φ_1 couples to d_R, e_R
  - Lepton specific: Φ_2 couples to u_R, d_R, Φ_1 couples to e_R
  - Flipped: Φ_2 couples to u_R, e_R, Φ_1 couples to d_R
- Aligned 2HDM: $\Delta_2 \propto \Delta_1$, $\Gamma_2 \propto \Gamma_1$
  [Pich & Tuzón, PRD 80 (2009), ...]
  - *Effective* alignment
    [Serôdio, PLB 700 (2011), Medeiros-Varzielas, PLB 701 (2011)]

FCNC (II)

Alternative:

- suppression factors in FCNC

[Joshipura & Rindani, PLB 260 (1991)]
[Antaramian, Hall & Rasin, PRL 69 (1992)]
[Hall & Weinberg, PRD 48 (1993)]
...

- naturally suppressed – i.e. "controlled" – FCNC

[Lavoura, Int.J.Mod.Phys. A9 (1994)]
[Branco, Grimus & Lavoura (BGL), PLB 380 (1996)]
[Botella, Branco & Rebelo, PLB 687 (2010)]
[Botella, Branco, Nebot & Rebelo, JHEP 1110 (2011)]
...
[Bhattacharyya, Das & Kundu, PRD 89 (2014)]

  - The general idea: symmetry imposes small FCNC
  - In the BGL case:

FCNC proportional to fermion masses & mixings!

Enter BGL models - The setup

- Symmetry

$$Q^0_{Lj} \mapsto e^{i\tau}\, Q^0_{Lj}\ , \qquad d^0_{Rj} \mapsto e^{i2\tau} d^0_{Rj}\ , \qquad \Phi_2 \mapsto e^{i\tau}\Phi_2$$

with $\tau \neq 0, \pi$ and j is 1 or 2 or 3 (at will)

- Reminder: $\mathscr{L}_Y \supset -\overline{Q^0_L}\big(\Delta_1\tilde{\Phi}_1 + \Delta_2\tilde{\Phi}_2\big)u^0_R - \overline{Q^0_L}\big(\Gamma_1\Phi_1 + \Gamma_2\Phi_2\big)d^0_R$
- Consider for example $j = 3$ – model "b" –, this imposes

$$\text{Up Yukawas:}\qquad \Delta_1 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix},\quad \Delta_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}$$

$$\text{Down Yukawas:}\qquad \Gamma_1 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix},\quad \Gamma_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

BGL models - The result

In this example,

Diagonal N_d:

$$N_d = \begin{pmatrix} m_d t_\beta & 0 & 0 \\ 0 & m_s t_\beta & 0 \\ 0 & 0 & -m_b t_\beta^{-1} \end{pmatrix}$$

Non-diagonal N_u:

$$N_u = \begin{pmatrix} 0 & -m_c(t_\beta + t_\beta^{-1})V_{cb}V_{ub}^* & -m_t(t_\beta + t_\beta^{-1})V_{tb}V_{ub}^* \\ -m_u(t_\beta + t_\beta^{-1})V_{ub}V_{cb}^* & 0 & -m_t(t_\beta + t_\beta^{-1})V_{tb}V_{cb}^* \\ -m_u(t_\beta + t_\beta^{-1})V_{ub}V_{tb}^* & -m_c(t_\beta + t_\beta^{-1})V_{cb}V_{tb}^* & 0 \end{pmatrix} +$$

$$\begin{pmatrix} m_u\left[(1-|V_{ub}|^2)t_\beta - |V_{ub}|^2 t_\beta^{-1}\right] & 0 & 0 \\ 0 & m_c\left[(1-|V_{cb}|^2)t_\beta - |V_{cb}|^2 t_\beta^{-1}\right] & 0 \\ 0 & 0 & m_t\left[(1-|V_{tb}|^2)t_\beta - |V_{tb}|^2 t_\beta^{-1}\right] \end{pmatrix}$$

BGL models - The zoo

- In the previous example, "model b",
  - flavour changing couplings of up quarks with R^0 and A,
  - flavour conserving couplings of down quarks with R^0 and A,
- 3 choices of symmetry with down fields,
  3 choices of symmetry with up fields
  $\to$ 6 different quark models
- In the lepton sector: 6 different choices for neutrinos and charged leptons, overall, 36 models
  [Botella, Branco, Carmona, Nebot, Pedro & Rebelo, JHEP(2014)]
- What about flavour changing couplings of the Higgs?
  The answer: N^0 and R^0 are NOT the physical scalars

- Neutral mass eigenstates, one mixing only (no CP),

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

with h "the Higgs".

- From

$$\mathscr{L}_{\bar{q}qN} \supset -N^0 \frac{1}{v} \left[\bar{u} M_u u + \bar{d} M_d d\right] - R^0 \frac{1}{v} \left[\bar{u} \left(N_u \gamma_R + N_u^\dagger \gamma_L\right) u + \bar{d} \left(N_d \gamma_R + N_d^\dagger \gamma_L\right) d\right]$$

- to

$$\begin{aligned}\mathscr{L}_{\bar{q}qN} \supset & -\frac{h}{v}\bar{u}\left((s_{\alpha\beta}M_u - c_{\alpha\beta}N_u)\gamma_R + (s_{\alpha\beta}M_u - c_{\alpha\beta}N_u^\dagger)\gamma_L\right) u \\ & -\frac{h}{v}\bar{d}\left((s_{\alpha\beta}M_d - c_{\alpha\beta}N_d)\gamma_R + (s_{\alpha\beta}M_d - c_{\alpha\beta}N_d^\dagger)\gamma_L\right) d \\ & +\frac{\mathrm{H}}{v}\bar{u}\left((c_{\alpha\beta}M_u + s_{\alpha\beta}N_u)\gamma_R + (c_{\alpha\beta}M_u + s_{\alpha\beta}N_u^\dagger)\gamma_L\right) u \\ & +\frac{\mathrm{H}}{v}\bar{d}\left((c_{\alpha\beta}M_d + s_{\alpha\beta}N_d)\gamma_R + (c_{\alpha\beta}M_d + s_{\alpha\beta}N_d^\dagger)\gamma_L\right) d\end{aligned}$$

Higgs in BGL models

Most salient features

- Flavour changing couplings of the Higgs with up or with down quarks[1]
- (Flavour changing couplings of the Higgs with neutrinos or with charged leptons)
- Modified flavour conserving (diagonal) couplings
- Only two new parameters involved, $\tan\beta$ and $\alpha - \beta$
  $\Rightarrow$ correlated predictions, magic combination $c_{\alpha\beta}(t_\beta + t_\beta^{-1})$
- To address $t \to hq$ decays, down quark models (like the previous example)

[1] Each model is defined by a quark and a lepton label, e.g. model $b\mu$ has flavour changing neutral couplings with up quarks and with neutrinos.

Constraints

Before addressing $t \to hq$ decays, constraints on $\tan\beta$ and $\alpha - \beta$

- From Higgs diagonal couplings: $\gamma\gamma$, WW, ZZ, $b\bar{b}$, $\tau\bar{\tau}$

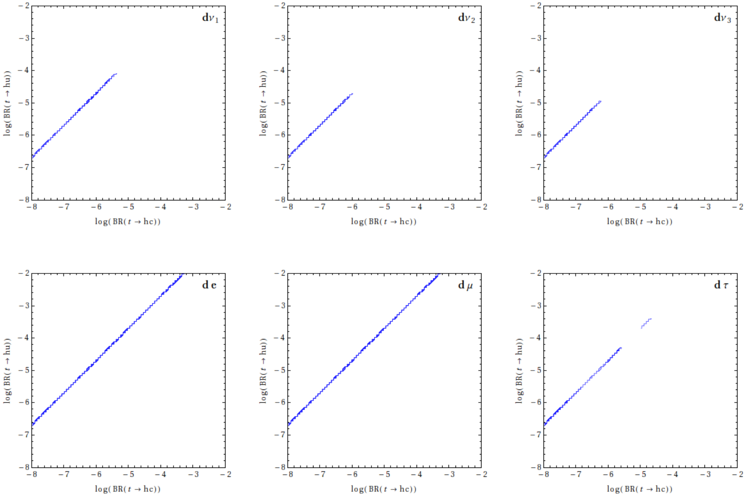
  N.B. Notice that both decay and production are modified!

- From low-energy flavour physics: rather involved since H and A are typically involved together with h, requires specific study (additional parameters)

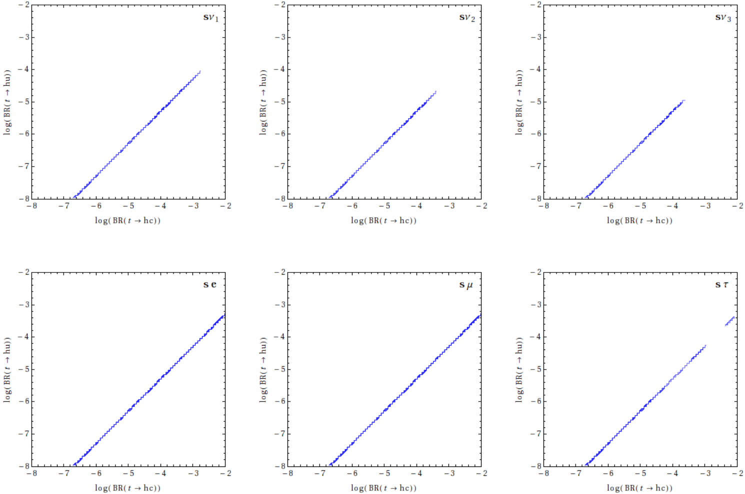
  [Botella, Branco, Carmona, Nebot, Pedro & Rebelo, JHEP(2014)]

- Br($h \to \mu\tau$) in ν_i models
- ... and now the results (plots)

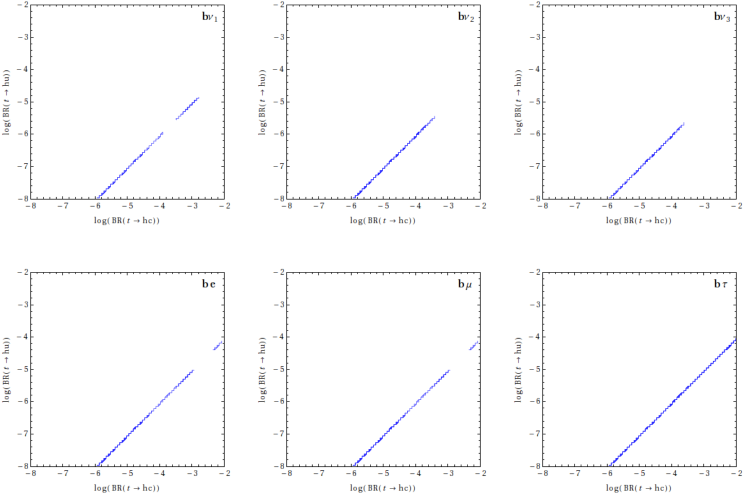
$\log[\mathrm{Br}(t \to hu)]$ vs. $\log[\mathrm{Br}(t \to hc)]$ in d models



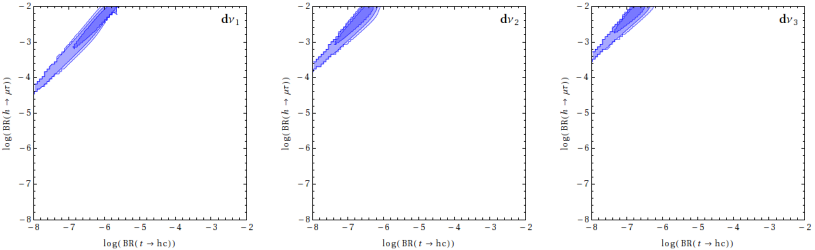
$\log[\mathrm{Br}(t \to hu)]$ vs. $\log[\mathrm{Br}(t \to hc)]$ in s models



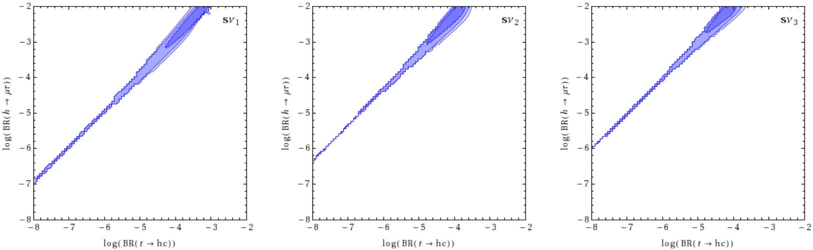
$\log[\mathrm{Br}(t \to hu)]$ vs. $\log[\mathrm{Br}(t \to hc)]$ in b models



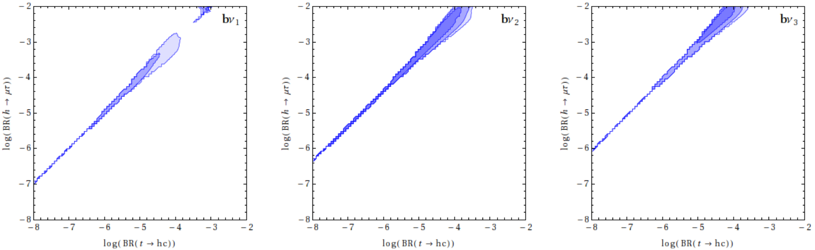
$\log[\mathrm{Br}(h \to \mu\tau)]$ vs. $\log[\mathrm{Br}(t \to hc)]$ in $d\nu_i$ models



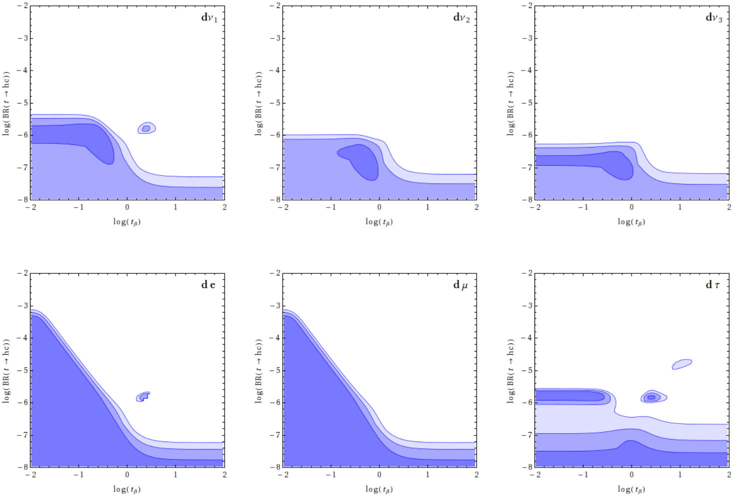
$\log[\mathrm{Br}(h \to \mu\tau)]$ vs. $\log[\mathrm{Br}(t \to hc)]$ in $s\nu_i$ models



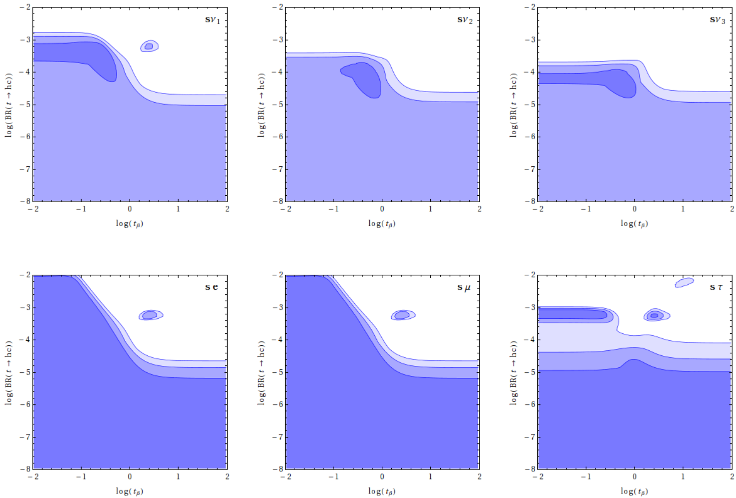
$\log[\mathrm{Br}(h \to \mu\tau)]$ vs. $\log[\mathrm{Br}(t \to hc)]$ in $b\nu_i$ models



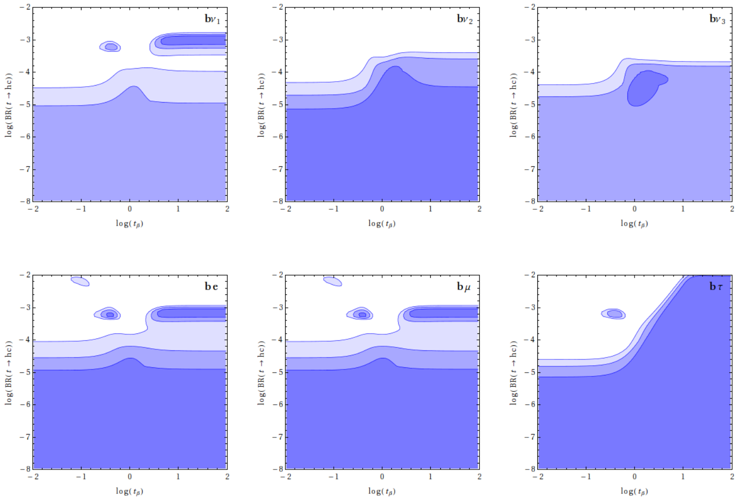
$\log[\mathrm{Br}(t \to hc)]$ vs. $\log t_\beta$ in d models



$\log[\mathrm{Br}(t \to hc)]$ vs. $\log t_\beta$ in s models



$\log[\mathrm{Br}(t \to hc)]$ vs. $\log t_\beta$ in b models



Summary & Conclusions

- Class of models with reduced parametric freedom: $\tan\beta$ & $\alpha - \beta$:
  $\Rightarrow$ predictivity & correlations,
  $\Rightarrow$ importance of flavour diagonal Higgs data to constrain flavour changing couplings.
- $t \to hu$ & $t \to hc$ branching ratios can saturate current bounds
- Different correlated patterns, $\mathrm{Br}(t \to hc) > \mathrm{Br}(t \to hu)$ in s, b models but $\mathrm{Br}(t \to hc) < \mathrm{Br}(t \to hu)$ in d models
- Additional correlations with Higgs flavour changing leptonic decays (indirect constraint!)
- Word of caution: in some models low-energy constraints from meson mixings (D^0–$\bar{D}^0$) may reduce the expectations for $t \to hq$

Thank you for your attention!