

# Higgs couplings in a class of Two Higgs Doublet models with controlled flavour changing interactions

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## 1 Introduction - 2HDM

## 2 BGL models

## 3 Analysis

## 4 Conclusions

Based on work done in collaboration with:

G.C. Branco, M.N. Rebelo, (Lisbon) & F.J. Botella (Valencia)

in progress, [arXiv:1507.soon](#)

# Two Higgs Doublet Models (I)

- Instead of a single doublet  $\Phi$   as in the SM,  
two doublets  $\Phi_1$  &  $\Phi_2$
- Full lagrangian

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

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

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

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

- Yukawa couplings  $\mathcal{L}_Y$

# Two Higgs Doublet Models (II)

- Spontaneous symmetry breaking

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

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

- 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  $\langle H_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$  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  $\mathcal{L}_Y$

# Yukawa couplings (I)

## ■ Yukawa couplings in 2HDM

$$\begin{aligned}\mathcal{L}_Y = & -\overline{Q}_L^0(\Delta_1\tilde{\Phi}_1 + \Delta_2\tilde{\Phi}_2)u_R^0 - \overline{Q}_L^0(\Gamma_1\Phi_1 + \Gamma_2\Phi_2)d_R^0 \\ & - \overline{L}_L^0(\Sigma_1\tilde{\Phi}_1 + \Sigma_2\tilde{\Phi}_2)\nu_R^0 - \overline{L}_L^0(\Pi_1\Phi_1 + \Pi_2\Phi_2)\ell_R^0 + \text{h.c.}\end{aligned}$$

## ■ Quark Yukawa couplings + Mass terms

$$\begin{aligned}\mathcal{L}_Y \supset & -\overline{u}_L^0\frac{1}{v}\left(\overline{M}_u^0(v + N^0) + \overline{N}_u^0R^0 + i\overline{N}_u^0A\right)u_R^0 \\ & - \overline{d}_L^0\frac{1}{v}\left(\overline{M}_d^0(v + N^0) + \overline{N}_d^0R^0 + i\overline{N}_d^0A\right)d_R^0 \\ & - \frac{\sqrt{2}}{v}\left(\overline{u}_L^0\overline{N}_d^0d_R^0 - \overline{u}_R^0\overline{N}_u^{0\dagger}d_L^0\right)H^+ + \text{h.c.}\end{aligned}$$

where  $\overline{M}_u^0 = \frac{1}{\sqrt{2}}(v_1\Delta_1 + v_2e^{i\theta}\Delta_2)$ ,  $\overline{M}_d^0 = \frac{1}{\sqrt{2}}(v_1\Gamma_1 + v_2e^{i\theta}\Gamma_2)$

and  $\overline{N}_u^0 = \frac{1}{\sqrt{2}}(v_2\Delta_1 - v_1e^{i\theta}\Delta_2)$ ,  $\overline{N}_d^0 = \frac{1}{\sqrt{2}}(v_2\Gamma_1 - v_1e^{i\theta}\Gamma_2)$

# Fermion Masses

## ■ Pictorially

$$\textcolor{red}{M} = v_1 \text{ (Higgs 1)} + v_2 e^{i\theta} \text{ (Higgs 2)} = v \text{ (Higgs 3)}, \quad \textcolor{red}{N} = v_2 \text{ (Higgs 1)} - v_1 e^{i\theta} \text{ (Higgs 2)} = v \text{ (Higgs 3)}$$

## ■ The “drama”:

$$U_{uL}^\dagger \textcolor{red}{M}_u^0 U_{uR} = M_u \equiv \text{diag} (m_u, m_c, m_t)$$

$$U_{dL}^\dagger \textcolor{red}{M}_d^0 U_{dR} = M_d \equiv \text{diag} (m_d, m_s, m_b)$$

is fine, but

$$U_{uL}^\dagger \textcolor{red}{N}_u^0 U_{uR} \equiv \textcolor{red}{N}_u = ?$$

$$U_{dL}^\dagger \textcolor{red}{N}_d^0 U_{dR} \equiv \textcolor{red}{N}_d = ?$$

gives **flavour changing couplings** with  $R^0$  and  $A$ ,  
the “non-SM” neutral scalars!

# Yukawa couplings (II)

- $\mathcal{L}_Y$  in terms of physical quark fields

$$\begin{aligned}
 \mathcal{L}_Y \supset & -\frac{1}{v} \mathbf{N}^0 (\bar{u} M_u u + \bar{d} M_d d) \\
 & - \frac{1}{v} \mathbf{R}^0 \left[ \bar{u} (\mathbf{N}_u \gamma_R + \mathbf{N}_u^\dagger \gamma_L) u + \bar{d} (\mathbf{N}_d \gamma_R + \mathbf{N}_d^\dagger \gamma_L) d \right] \\
 & + \frac{i}{v} \mathbf{A} \left[ \bar{u} (\mathbf{N}_u \gamma_R - \mathbf{N}_u^\dagger \gamma_L) u - \bar{d} (\mathbf{N}_d \gamma_R - \mathbf{N}_d^\dagger \gamma_L) d \right] \\
 & - \frac{\sqrt{2}}{v} \mathbf{H}^+ \bar{u} (\mathbf{V} \mathbf{N}_d \gamma_R - \mathbf{N}_u^\dagger \mathbf{V} \gamma_L) d + \text{h.c.}
 \end{aligned}$$

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

# FCNC (I)

## Ways out

- Discrete symmetries & Natural Flavour Conservation  
[Glashow & Weinberg, PRD 15 (1977), ...]
  - Type I:  $\Phi_2$  couples to  $u_R, d_R, e_R$
  - Type II:  $\Phi_2$  couples to  $u_R$ ,  $\Phi_1$  couples to  $d_R, e_R$
  - Lepton specific:  $\Phi_2$  couples to  $u_R, d_R$ ,  $\Phi_1$  couples to  $e_R$
  - Flipped:  $\Phi_2$  couples to  $u_R, e_R$ ,  $\Phi_1$  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

[Joshi *et al.*, 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

## ■ Symmetry

$$Q_{Lj}^0 \mapsto e^{i\tau} Q_{Lj}^0, \quad u_{Rj}^0 \mapsto e^{i2\tau} u_{Rj}^0, \quad \Phi_2 \mapsto e^{i\tau} \Phi_2$$

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

- Reminder:  $\mathcal{L}_Y \supset -\overline{Q_L^0}(\Delta_1 \tilde{\Phi}_1 + \Delta_2 \tilde{\Phi}_2)u_R^0 - \overline{Q_L^0}(\Gamma_1 \Phi_1 + \Gamma_2 \Phi_2)d_R^0$
- Consider for example  $j = 3$ ; this imposes

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

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

# Up Yukawas – Example up $j = 3$

- Up Yukawas:

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

- Reminder:

$$M_u^0 = \frac{1}{\sqrt{2}}(v_1 \Delta_1 + v_2 e^{i\theta} \Delta_2), \quad N_u^0 = \frac{1}{\sqrt{2}}(v_2 \Delta_1 - v_1 e^{i\theta} \Delta_2)$$

- For the Up Yukawas,  $M_u^0$  and  $N_u^0$  are simultaneously diagonalised  $\Rightarrow$  **NO FCNC**
- The  $U_{uL}$  rotation is block diagonal,  $U_{uL} = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 1 \end{pmatrix}$

# Down Yukawas – Example up $j = 3$

- Down Yukawas:

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

- Reminder:

$$M_d^0 = \frac{1}{\sqrt{2}}(v_1 \Gamma_1 + v_2 e^{i\theta} \Gamma_2), \quad N_d^0 = \frac{1}{\sqrt{2}}(v_2 \Gamma_1 - v_1 e^{i\theta} \Gamma_2)$$

- For the Down Yukawas

$$U_{dL}^\dagger M_d^0 U_{dR} = M_d, \quad U_{dL}^\dagger N_d^0 U_{dR} = ?$$

# The BGL magic (I) – Example up $j = 3$

## ■ Rewrite

$$N_d^0 = \frac{1}{\sqrt{2}} (v_2 \Gamma_1 - v_1 e^{i\theta} \Gamma_2) =$$

$$\frac{v_2}{v_1} \underbrace{\frac{1}{\sqrt{2}} (v_1 \Gamma_1 + v_2 e^{i\theta} \Gamma_2)}_{M_d^0} - \frac{v_2}{\sqrt{2}} \left( \frac{v_1}{v_2} + \frac{v_2}{v_1} \right) e^{i\theta} \Gamma_2$$

$$U_{dL}^\dagger N_d^0 U_{dR} = \frac{v_2}{v_1} M_d - \frac{v_2}{\sqrt{2}} \left( \frac{v_2}{v_1} + \frac{v_1}{v_2} \right) U_{dL}^\dagger e^{i\theta} \Gamma_2 U_{dR}$$

- Problem with  $U_{dL}^\dagger e^{i\theta} \Gamma_2 U_{dR}$
- The solution: if  $\Gamma_2 \propto P M_d^0$  with  $P$  some fixed matrix,

$$U_{dL}^\dagger \Gamma_2 U_{dR} \propto U_{dL}^\dagger P M_d^0 U_{dR} = U_{dL}^\dagger P U_{dL} M_d$$

# The BGL magic (II) – Example up $j = 3$

- Which  $P$ ?

$$P = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \Rightarrow \frac{v_2}{\sqrt{2}} e^{i\theta} \Gamma_2 = P M_d^0$$

- The final touch: as  $U_{uL} = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 1 \end{pmatrix}$ ,

$$V = U_{uL}^\dagger U_{dL} \Rightarrow [U_{dL}]_{3i} = V_{3i}$$

and

$$[U_{dL}^\dagger P U_{dL}]_{ij} = V_{3i}^* V_{3j}$$

- Finally

$$[N_d]_{ij} = [U_{dL}^\dagger N_d^0 U_{dR}]_{ij} = t_\beta [M_d]_{ij} - \left( t_\beta + t_\beta^{-1} \right) V_{3i}^* V_{3j} [M_d]_{jj}$$

# Neutral couplings in BGL models – Example up $j = 3$

## ■ Up sector

$$N_u = -t_\beta^{-1} \text{diag}(0, 0, m_t) + t_\beta \text{diag}(m_u, m_c, 0)$$

## ■ Down sector

$$N_d = t_\beta \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix} - \left( t_\beta + t_\beta^{-1} \right) \begin{pmatrix} m_d |V_{td}|^2 & m_s V_{td}^* V_{ts} & m_b V_{td}^* V_{tb} \\ m_d V_{ts}^* V_{td} & m_s |V_{ts}|^2 & m_b V_{ts}^* V_{tb} \\ m_d V_{tb}^* V_{td} & m_s V_{tb}^* V_{ts} & m_b |V_{tb}|^2 \end{pmatrix}$$

It all comes from the symmetry

# More BGL models (I)

- We have seen an example with

$$Q_{Lj}^0 \mapsto e^{i\tau} Q_{Lj}^0, \quad u_{Rj}^0 \mapsto e^{i2\tau} u_{Rj}^0, \quad \Phi_2 \mapsto e^{i\tau} \Phi_2$$

and  $j = 3$ , leading to FCNC in the **DOWN** sector,

controlled by  $V_{ti}V_{tk}^*$

- but we can as well choose  $j = 1$  or  $j = 2$ ,  
then leading to FCNC in the **DOWN** sector  
controlled by  $V_{ui}V_{uk}^*$  or  $V_{ci}V_{ck}^*$
- ...or start with this symmetry

$$Q_{Lj}^0 \mapsto e^{i\tau} Q_{Lj}^0, \quad d_{Rj}^0 \mapsto e^{i2\tau} d_{Rj}^0, \quad \Phi_2 \mapsto e^{i\tau} \Phi_2$$

which would lead to FCNC in the **UP** sector, controlled by  $V_{ij}V_{kj}^*$

- Models: for the moment 3 up quark + 3 down quark

# More BGL models (II)

## ■ Models

■ Quark sector 3 up quark + 3 down quark

■ Lepton sector 3  $\ell$  + 3  $\nu$  (Dirac neutrinos)

[N.B. for Majorana  $\nu$ 's, only half, no  $\nu$ -FCNC]

■ Need [all](#) for Renormalization Group Evolution, e.g.

$$\begin{aligned}
 \mathcal{D}\Gamma_k &= a_\Gamma \Gamma_k + \\
 &+ \sum_{l=1}^2 \left[ 3\text{Tr}(\Gamma_k \Gamma_l^\dagger + \Delta_k^\dagger \Delta_l) + \text{Tr}(\Pi_k \Pi_l^\dagger + \Sigma_k^\dagger \Sigma_l) \right] \Gamma_l + \\
 &+ \sum_{l=1}^2 \left( -2\Delta_l \Delta_k^\dagger \Gamma_l + \Gamma_k \Gamma_l^\dagger \Gamma_l + \frac{1}{2}\Delta_l \Delta_l^\dagger \Gamma_k + \frac{1}{2}\Gamma_l \Gamma_l^\dagger \Gamma_k \right) ,
 \end{aligned}$$

# BGL models - The zoo

- In the previous example, “model  $t$ ”,
  - flavour changing couplings of down quarks with  $R^0$  and  $A$ ,
  - flavour conserving couplings of up quarks with  $R^0$  and  $A$ ,
- 3 choices of symmetry with down fields,  
3 choices of symmetry with up fields  
→ 6 different quark models
- In the lepton sector: 6 different choices for neutrinos and charged leptons, overall, 36 models  
[Botella, Branco, Nebot & Rebelo, JHEP(2011) 1102.0520]
- 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),

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

with h “the Higgs”

- From

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

- to

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

# Higgs in BGL models

Most salient features

- Flavour changing couplings of the Higgs with up or with down quarks  $\Rightarrow h \rightarrow bs, bd, t \rightarrow hc, hu$
- Flavour changing couplings of the Higgs with neutrinos or with charged leptons,  $h \rightarrow \mu\tau$
- Modified flavour conserving (diagonal) couplings
- Only **two** new parameters involved,  $\tan\beta$  and  $\alpha - \beta$   
 $\Rightarrow$  correlated predictions, magic combination  $c_{\alpha\beta}(t_\beta + t_\beta^{-1})$

# Constraints

Before addressing rare decays, constraints on  $\tan\beta$  and  $\alpha - \beta$

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

Notice that both **decay** and **production** are modified!

- From low-energy flavour physics: more involved since H and A do participate together with h, requires specific study (additional parameters)

[Botella, Branco, ..., JHEP(2014) 1401.6147]

# Higgs signals (I)

Signal strengths of the form

$$\mu_i^X = \frac{[\sigma(pp \rightarrow h)]_i}{[\sigma(pp \rightarrow h)_{\text{SM}}]_i} \frac{\text{Br}(h \rightarrow X)}{\text{Br}(h \rightarrow X)_{\text{SM}}}$$

- $i$  for the different combinations of production mechanisms
- $X$  for the decay channels

# Higgs signals (II) – SM production & decays

| Prod. ch. $i$                                   | ggF   | VBF   | $Wh$   | $Zh$   | $t\bar{t}h$ | $b\bar{b}h$ |
|-------------------------------------------------|-------|-------|--------|--------|-------------|-------------|
| $[\sigma(pp \rightarrow h)_{\text{SM}}]_i$ (pb) | 19.27 | 1.578 | 0.7046 | 0.4153 | 0.1293      | 0.2035      |

**Table:** Production cross sections,  $m_h = 125$  GeV,  $\sqrt{s} = 8$  TeV.

| Decay channel $X$                          | $b\bar{b}$ | $WW^*$ | $ZZ^*$ | $\tau\bar{\tau}$ | $\gamma\gamma$ | $gg$   |
|--------------------------------------------|------------|--------|--------|------------------|----------------|--------|
| $[\text{Br}(h \rightarrow X)]_{\text{SM}}$ | 0.578      | 0.216  | 0.0267 | 0.0637           | 0.0023         | 0.0856 |

**Table:** Decay BRs,  $m_h = 125$  GeV (width  $\Gamma_h = 4.03$  MeV).

# Higgs signals (III) – LHC results

- $h \rightarrow \gamma\gamma$ ,

$$\mu_{ggF}^{\gamma\gamma} = 1.12^{+0.37}_{-0.32}, \quad \mu_{VBF}^{\gamma\gamma} = 1.58^{+0.77}_{-0.68}, \quad \mu_{VH}^{\gamma\gamma} = -0.16^{+1.16}_{-0.79},$$

$$\mu_{ggF}^{\gamma\gamma} = 1.32^{+0.41}_{-0.33}, \quad \mu_{VBF}^{\gamma\gamma} = 0.78^{+0.80}_{-0.64}.$$

- $h \rightarrow ZZ$ ,

$$\mu_{0/1\text{jet}}^{ZZ} = 0.858^{+0.321}_{-0.258}, \quad \mu_{2\text{jet}}^{ZZ} = 1.235^{+0.852}_{-0.583},$$

in 0/1 jet, ggF:VBF  $\sim$  20:1; in 2 jets, ggF:VBF:VH  $\sim$  4:2:1 .

- $h \rightarrow WW$ ,

$$\mu_{0/1\text{jet}}^{WW} = 0.74^{+0.22}_{-0.20}, \quad \mu_{VBF+VH}^{WW} = 0.60^{+0.54}_{-0.46},$$

0/1 jet ggF dominated.

# Higgs signals (IV) – LHC results

- $h \rightarrow \tau\bar{\tau}$ ,

$$\mu_{0\text{jet}}^{\tau\tau} = 0.34 \pm 1.09, \quad \mu_{1\text{jet}}^{\tau\tau} = 1.07 \pm 0.46, \quad \mu_{2\text{jet-VBF}}^{\tau\tau} = 0.94 \pm 0.41,$$

0 and 1 jet ggF dominated, for 2 jet-VBF tag, ggF  $\sim$  VBF.

- $h \rightarrow b\bar{b}$ ,

$$\mu_{\text{VH}}^{bb} = 1.0 \pm 0.5, \quad \mu_{\text{VH}}^{bb} = 0.65^{+0.43}_{-0.40}.$$

# BGL vs. Higgs signals – Modified couplings

| u,c                                        | t                                               | Down model $d_i$                                                                          |
|--------------------------------------------|-------------------------------------------------|-------------------------------------------------------------------------------------------|
| $s_{\alpha\beta} - c_{\alpha\beta}t_\beta$ | $s_{\alpha\beta} + c_{\alpha\beta}t_\beta^{-1}$ | $s_{\alpha\beta} - c_{\alpha\beta}[(1 -  V_{td_i} ^2)t_\beta -  V_{td_i} ^2t_\beta^{-1}]$ |

Table:  $h\bar{t}t$  coupling ( $m_t/v \times$ ).

| d,s                                        | b                                               | Up model $u_i$                                                                            |
|--------------------------------------------|-------------------------------------------------|-------------------------------------------------------------------------------------------|
| $s_{\alpha\beta} - c_{\alpha\beta}t_\beta$ | $s_{\alpha\beta} + c_{\alpha\beta}t_\beta^{-1}$ | $s_{\alpha\beta} - c_{\alpha\beta}[(1 -  V_{u_ib} ^2)t_\beta -  V_{u_ib} ^2t_\beta^{-1}]$ |

Table:  $h\bar{b}b$  coupling ( $m_b/v \times$ ).

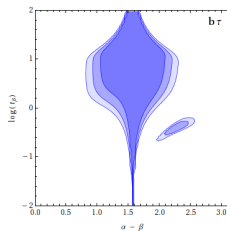
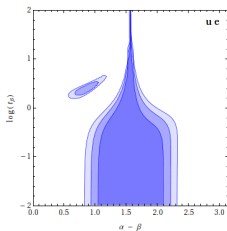
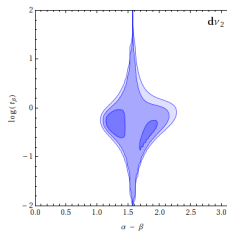
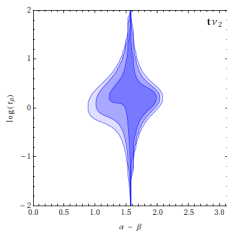
| e, $\mu$                                   | $\tau$                                          | Neutrino model $\nu_i$                                                                        |
|--------------------------------------------|-------------------------------------------------|-----------------------------------------------------------------------------------------------|
| $s_{\alpha\beta} - c_{\alpha\beta}t_\beta$ | $s_{\alpha\beta} + c_{\alpha\beta}t_\beta^{-1}$ | $s_{\alpha\beta} - c_{\alpha\beta}[(1 -  V_{\tau i} ^2)t_\beta -  V_{\tau i} ^2t_\beta^{-1}]$ |

Table:  $h\bar{\tau}\tau$  coupling ( $m_\tau/v \times$ )

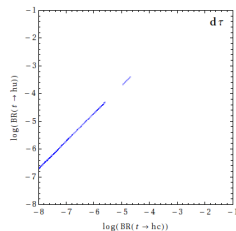
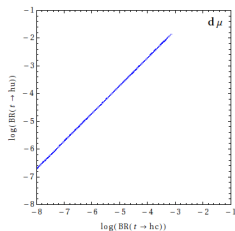
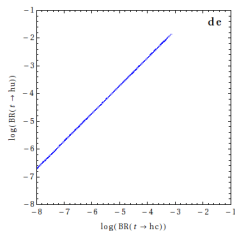
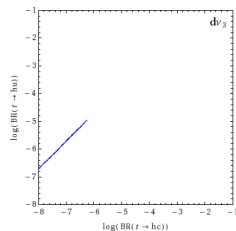
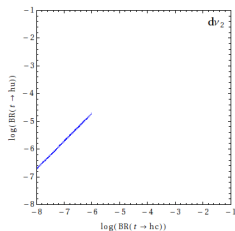
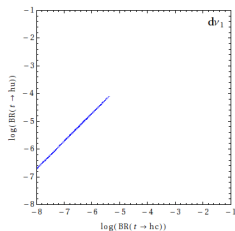
Don't forget  $hVV \mapsto s_{\alpha\beta}hVV$



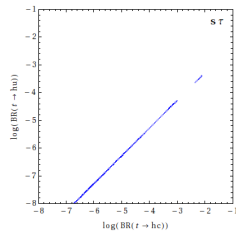
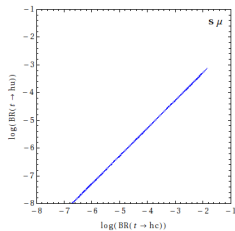
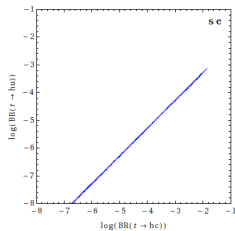
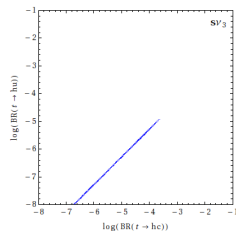
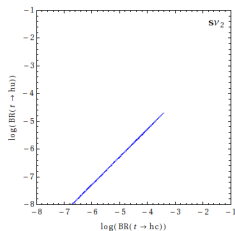
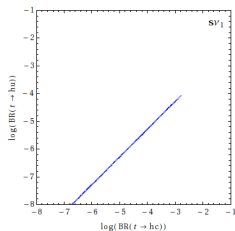
# $\log_{10} \tan \beta$ vs. $\alpha - \beta$ , examples



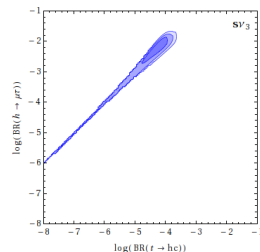
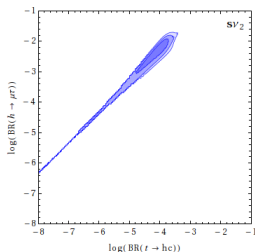
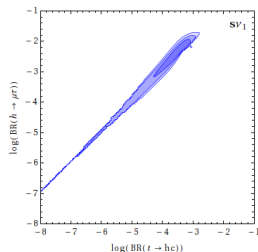
# $\log[\text{Br}(t \rightarrow hu)]$ vs. $\log[\text{Br}(t \rightarrow hc)]$ in $d$ models



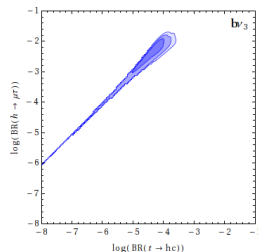
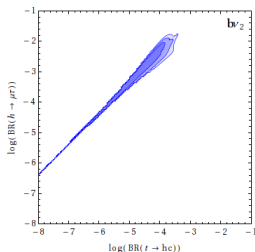
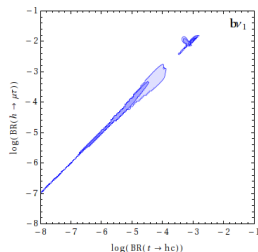
# $\log[\text{Br}(t \rightarrow hu)]$ vs. $\log[\text{Br}(t \rightarrow hc)]$ in $s$ models



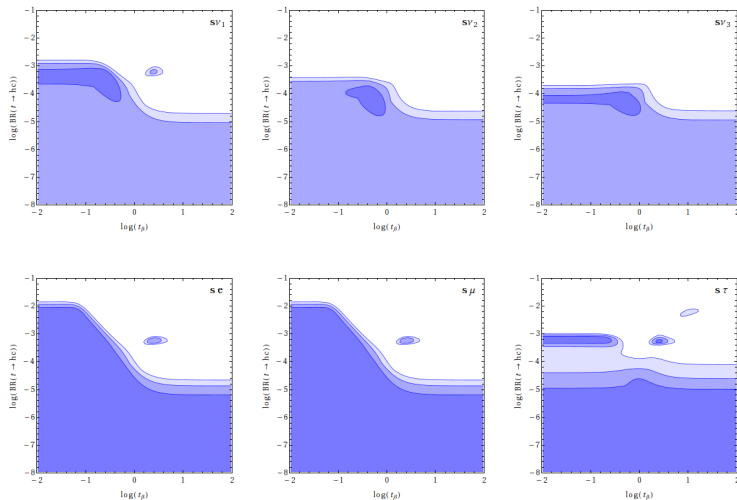
# $\log[\text{Br}(h \rightarrow \mu\tau)]$ vs. $\log[\text{Br}(t \rightarrow hc)]$ in $s\nu_i$ models



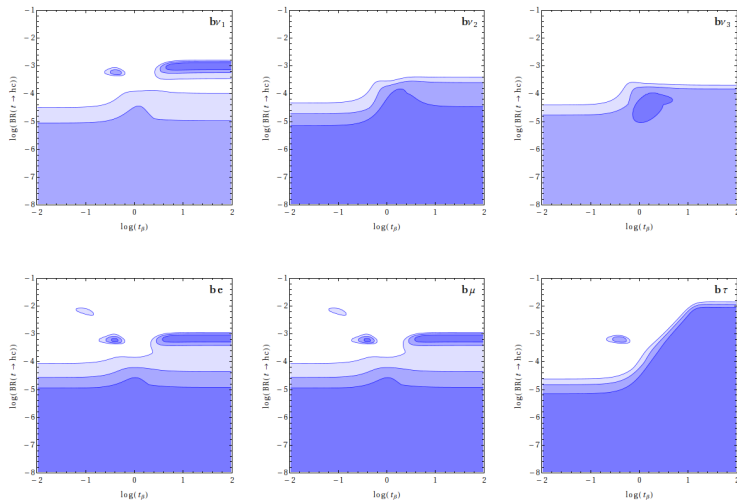
$\log[\text{Br}(h \rightarrow \mu\tau)]$  vs.  $\log[\text{Br}(t \rightarrow hc)]$  in  $b\nu_i$  models



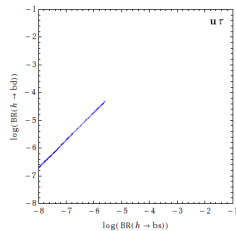
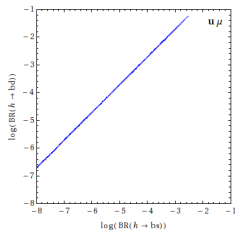
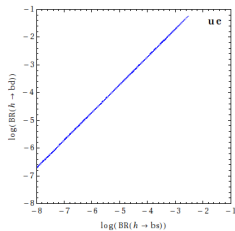
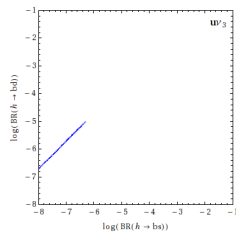
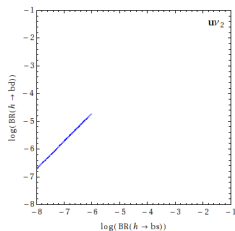
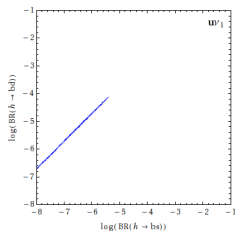
# $\log[\text{Br}(t \rightarrow hc)]$ vs. $\log t_\beta$ in $s$ models



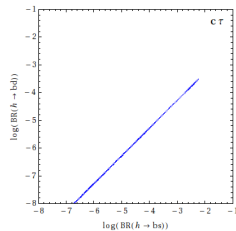
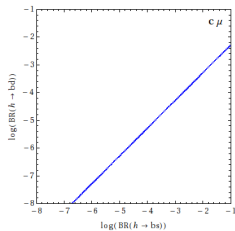
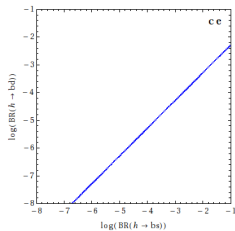
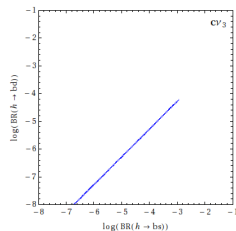
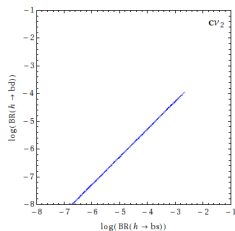
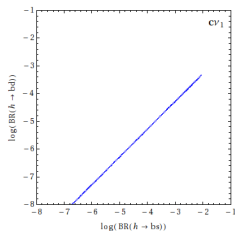
# $\log[\text{Br}(t \rightarrow hc)]$ vs. $\log t_\beta$ in $b$ models



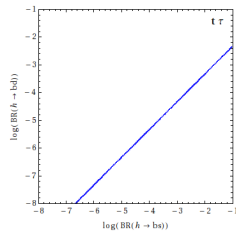
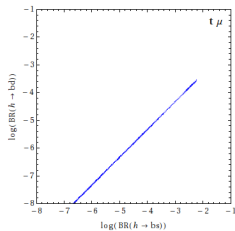
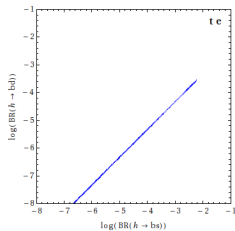
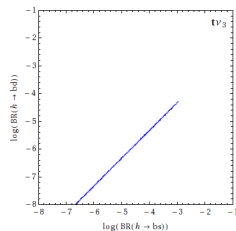
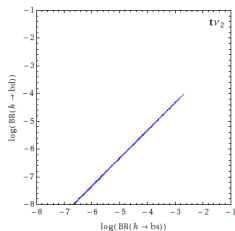
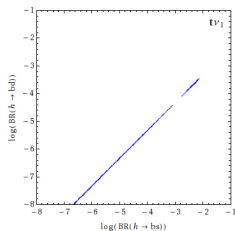
# $\log[\text{Br}(h \rightarrow bd)]$ vs. $\log[\text{Br}(h \rightarrow bs)]$ in $u$ models



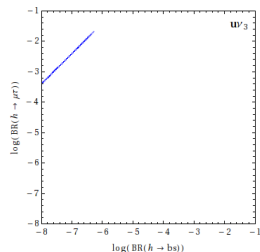
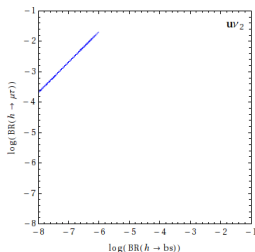
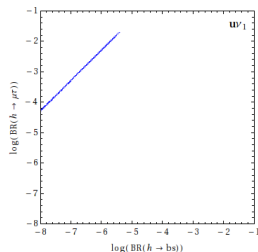
# $\log[\text{Br}(h \rightarrow bd)]$ vs. $\log[\text{Br}(h \rightarrow bs)]$ in $c$ models



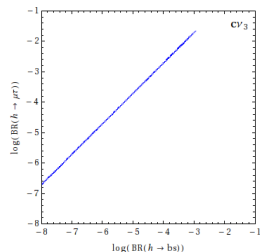
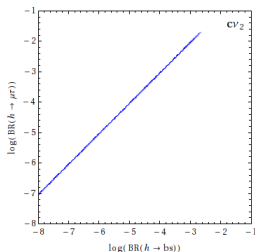
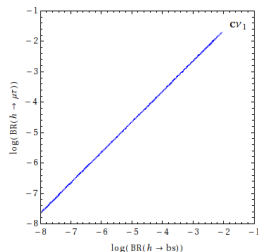
# $\log[\text{Br}(h \rightarrow bd)]$ vs. $\log[\text{Br}(h \rightarrow bs)]$ in $t$ models



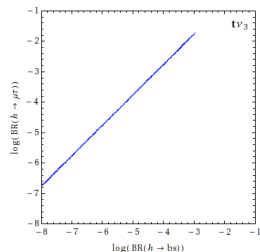
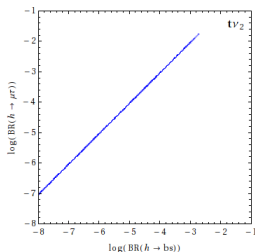
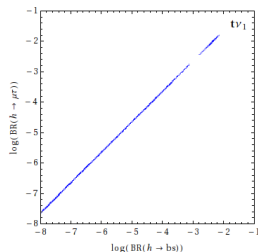
# $\log[\text{Br}(h \rightarrow \mu\tau)]$ vs. $\log[\text{Br}(h \rightarrow bs)]$ in $u\nu_i$ models



# $\log[\text{Br}(h \rightarrow \mu\tau)]$ vs. $\log[\text{Br}(h \rightarrow bs)]$ in $c\nu_i$ models



# $\log[\text{Br}(h \rightarrow \mu\tau)]$ vs. $\log[\text{Br}(h \rightarrow bs)]$ in $t\nu_i$ 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.
- $t \rightarrow hu$  &  $t \rightarrow hc$  branching ratios can saturate current bounds
- Different correlated patterns,  $\text{Br}(t \rightarrow hc) > \text{Br}(t \rightarrow hu)$  in  $s, b$  models but  $\text{Br}(t \rightarrow hc) < \text{Br}(t \rightarrow hu)$  in  $d$  models
- $h \rightarrow bs$  &  $h \rightarrow bd$  branching ratios within reach of ILC sensitivity
- $h \rightarrow \mu\tau$  branching ratios can be at the level of the “CMS hint”
- Correlations between flavour changing processes in the quark and lepton sectors
- Word of caution (1): in some models low-energy constraints from meson mixings may reduce the expectations
- Word of caution (2): 2-loop Barr-Zee contributions in  $\mu \rightarrow e\gamma$  require detailed analysis

Thank you for your attention!