Two Higgs Doublet Models with controlled Flavour Changing Neutral Couplings

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Based on work done in collaboration with:
J.M. Alves, G.C. Branco (Lisbon), F.J. Botella & F. Cornet-Gómez (Valencia)

Eur. Phys. J. C77 (2017) 9, 585, arXiv:1703.03796

and previous work, with M. Rebelo, L. Pedro & A. Carmona

Eur. Phys. J. C76 (2016) 3, 161, arXiv:1508.05101

JHEP 1407 (2014) 078 , arXiv:1401.6147

see also G. Branco's talk

2HDM (I) – reminder

- Instead of a single doublet Φ ( ), 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 $V(\Phi) = \lambda\big(v^2 - \Phi^\dagger\Phi\big)^2$

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

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

2HDM (II) – reminder

- 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

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

2HDM (III) – reminder

- 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

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

- G^0, $G^\pm$: 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.

... and now, the Yukawa couplings $\mathscr{L}_\mathrm{Y}$

Yukawa couplings (I)

- Yukawa couplings in 2HDM

$$\mathscr{L}_{\mathrm{Y}} = -\bar{Q}_L^0\big(\Delta_1\tilde{\Phi}_1 + \Delta_2\tilde{\Phi}_2\big)u_R^0 - \bar{Q}_L^0\big(\Gamma_1\Phi_1 + \Gamma_2\Phi_2\big)d_R^0 \\ - \bar{L}_L^0\big(\Sigma_1\tilde{\Phi}_1 + \Sigma_2\tilde{\Phi}_2\big)\nu_R^0 - \bar{L}_L^0\big(\Pi_1\Phi_1 + \Pi_2\Phi_2\big)\ell_R^0 + \text{h.c.}$$

- Quark Yukawa couplings + Mass terms

$$\mathscr{L}_{\mathrm{Y}} \supset -\bar{u}_L^0\frac{1}{v}\big(M_u^0(v+\mathrm{N}^0) + N_u^0\mathrm{R}^0 + iN_u^0 A\big)u_R^0 \\ - \bar{d}_L^0\frac{1}{v}\big(M_d^0(v+\mathrm{N}^0) + N_d^0\mathrm{R}^0 + iN_d^0 A\big)d_R^0 \\ - \frac{\sqrt{2}}{v}\big(\bar{u}_L^0 N_d^0 d_R^0 - \bar{u}_R^0 N_u^{0\dagger} d_L^0\big)H^+ + \text{H.C.}$$

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

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

Fermion Masses and Flavour Changing Couplings

- Pictorially

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

- Diagonalisation of mass matrices:

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

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

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

Yukawa couplings (II)

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

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

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

FCNC (I)

Ways out

- Discrete symmetries & Natural Flavour Conservation
  [Paschos, 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!

BGL models (I)

- Symmetry

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

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

- Reminder:

$$\mathscr{L}_Y \supset -\bar{Q}^0_L\big(\Delta_1\tilde{\Phi}_1 + \Delta_2\tilde{\Phi}_2\big)u^0_R - \bar{Q}^0_L\big(\Gamma_1\Phi_1 + \Gamma_2\Phi_2\big)d^0_R$$

Consider for example $j = 3$:

$$\Delta_1 \mapsto \Delta_1' = \begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & e^{-i\tau}\end{pmatrix}\ \Delta_1\ \begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & e^{i2\tau}\end{pmatrix}$$

$$\Rightarrow \arg\Delta_1' - \arg\Delta_1 = \begin{pmatrix}0 & 0 & +2\tau\\ 0 & 0 & +2\tau\\ -\tau & -\tau & +\tau\end{pmatrix}$$

BGL models (II)

while

$$\Delta_2 \mapsto \Delta_2' = e^{-i\tau}\begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & e^{-i\tau}\end{pmatrix}\ \Delta_2\ \begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & e^{i2\tau}\end{pmatrix}$$

$$\Rightarrow \arg\Delta_2' - \arg\Delta_2 = \begin{pmatrix}-\tau & -\tau & +\tau\\ -\tau & -\tau & +\tau\\ -2\tau & -2\tau & 0\end{pmatrix}$$

The symmetry requires

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

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

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:

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

- 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:

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

- 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

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

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

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

- 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?

$$P_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \Rightarrow \frac{v_2}{\sqrt{2}} e^{i\theta} \Gamma_2 = P_3 \, M_d^0$$

- The final touch: since $U_{uL} = \left(\begin{smallmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 1 \end{smallmatrix}\right)$,

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

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

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

- 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

BGL models - The zoo

- We have seen an example with

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

  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

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

  which would lead to FCNC in the UP sector, controlled by $V_{ij}V^*_{kj}$
- Models: (3 up quark + 3 down quark) $\times$ leptons (6 or 3)

Higgs in BGL models

Most salient features

- Include mixing in the scalar sector
- Flavour changing couplings of the Higgs with up or with down quarks, e.g. $\mathrm{h} \to bs, bd$, $t \to \mathrm{h}c, \mathrm{h}u$
- Flavour changing couplings of the Higgs with neutrinos or with charged leptons, e.g. $\mathrm{h} \to \mu\tau$
- Modified flavour conserving (diagonal) couplings
- Only two new parameters involved, $\tan\beta$ and $\beta - \alpha$
  $\Rightarrow$ correlated predictions, magic combination $c_{\beta\alpha}(t_\beta + t_\beta^{-1})$

gBGL Models

Going from BGL to gBGL models

- In BGL models, FCNC controlled *but only in one sector*
- Can we generalise this flavour control to *both* sectors?
- Yes, a symmetry which is both “up-BGL” and “down-BGL”

$$Q_{L3} \mapsto -Q_{L3},\ d_R \mapsto d_R,\ u_R \mapsto u_R,\ \Phi_1 \mapsto \Phi_1,\ \Phi_2 \mapsto -\Phi_2$$

- *Each fermion doublet couples to one and only one Higgs doublet*

gBGL

- Yukawa matrices
  - Down:

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

  - Up:

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

- Projection $P_3 = \mathrm{diag}(0,0,1)$

$$P_3\Gamma_1 = 0, \quad (\mathbf{1} - P_3)\Gamma_2 = 0,$$
$$P_3\Delta_1 = 0, \quad (\mathbf{1} - P_3)\Delta_2 = 0.$$

gBGL

- Yukawa matrices
  - Down:

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

  - Up:

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

- Weak basis independent conditions

$$\Gamma_2^\dagger \Gamma_1 = 0, \quad \Gamma_2^\dagger \Delta_1 = 0,$$
$$\Delta_2^\dagger \Delta_1 = 0, \quad \Delta_2^\dagger \Gamma_1 = 0.$$

Back to N's

- Simple relations

$$N_d^0 = \left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1}) P_3 \right] M_d^0,$$
$$N_u^0 = \left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1}) P_3 \right] M_u^0$$

Back to N's

- Simple relations

$$U_{dL}^{\dagger}N_d^0U_{dR}=\left[t_\beta\mathbf{1}-(t_\beta+t_\beta^{-1})U_{dL}^{\dagger}P_3U_{dL}\right]U_{dL}^{\dagger}M_d^0U_{dR},$$
$$U_{uL}^{\dagger}N_u^0U_{uR}=\left[t_\beta\mathbf{1}-(t_\beta+t_\beta^{-1})U_{uL}^{\dagger}P_3U_{uL}\right]U_{uL}^{\dagger}M_u^0U_{uR}$$

Back to N's

- Simple relations

$$N_d = \left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1}) U_{dL}^\dagger P_3 U_{dL}\right] M_d,$$

$$N_u = \left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1}) U_{uL}^\dagger P_3 U_{uL}\right] M_u$$

Back to N's

- Simple relations

$$N_d = \left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1}) U_{dL}^\dagger P_3 U_{dL}\right] M_d,$$
$$N_u = \left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1}) U_{uL}^\dagger P_3 U_{uL}\right] M_u$$

- Parameterisation $[U^\dagger P_3 U]_{ij} = U_{3i}^* U_{3j}$

Unitary vectors $\quad U_{3i} \to \hat{n}_i$

Back to N's

- Simple relations

$$N_d = \left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1}) U_{dL}^\dagger P_3 U_{dL}\right] M_d,$$
$$N_u = \left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1}) U_{uL}^\dagger P_3 U_{uL}\right] M_u$$

- Parameterisation $[U^\dagger P_3 U]_{ij} = U_{3i}^* U_{3j}$

Unitary vectors $\quad U_{3i} \to \hat{n}_i$

$$\hat{n}_{[\mathrm{d}]i} = [U_{dL}]_{3i},\ \hat{n}_{[\mathrm{u}]i} = [U_{uL}]_{3i}$$

Back to N's

- Simple relations

$$N_d = \left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1}) U_{dL}^\dagger P_3 U_{dL}\right] M_d,$$
$$N_u = \left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1}) U_{uL}^\dagger P_3 U_{uL}\right] M_u$$

- Parameterisation $[U^\dagger P_3 U]_{ij} = U_{3i}^* U_{3j}$

Unitary vectors $\quad U_{3i} \to \hat{n}_i$

$$\hat{n}_{[\mathrm{d}]i} = [U_{dL}]_{3i},\ \hat{n}_{[\mathrm{u}]i} = [U_{uL}]_{3i}, \quad \hat{n}_{[\mathrm{u}]i} V_{ij} = [U_{uL} U_{uL}^\dagger]_{3k} [U_{dL}]_{kj}$$

Back to N's

- Simple relations

$$N_d = \left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1}) U_{dL}^\dagger P_3 U_{dL}\right] M_d,$$
$$N_u = \left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1}) U_{uL}^\dagger P_3 U_{uL}\right] M_u$$

- Parameterisation $[U^\dagger P_3 U]_{ij} = U_{3i}^* U_{3j}$

Unitary vectors $\quad U_{3i} \to \hat{n}_i$

$$\hat{n}_{[\mathrm{d}]i} = [U_{dL}]_{3i},\ \hat{n}_{[\mathrm{u}]i} = [U_{uL}]_{3i}, \quad \hat{n}_{[\mathrm{u}]i} V_{ij} = [U_{dL}]_{3j}$$

Back to N's

- Simple relations

$$N_d = \left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1}) U_{dL}^\dagger P_3 U_{dL}\right] M_d,$$
$$N_u = \left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1}) U_{uL}^\dagger P_3 U_{uL}\right] M_u$$

- Parameterisation $[U^\dagger P_3 U]_{ij} = U_{3i}^* U_{3j}$

$$\text{Unitary vectors} \quad U_{3i} \to \hat{n}_i$$

$$\hat{n}_{[\mathrm{d}]i} = [U_{dL}]_{3i},\ \hat{n}_{[\mathrm{u}]i} = [U_{uL}]_{3i}, \quad \hat{n}_{[\mathrm{u}]i} V_{ij} = \hat{n}_{[\mathrm{d}]j}$$

N's with controlled FCNC

- In the mass basis

$$[N_d]_{ij} = t_\beta m_{d_j}\delta_{ij} - (t_\beta + t_\beta^{-1})\hat{n}^*_{[\mathrm{d}]i}\hat{n}_{[\mathrm{d}]j} m_{d_j}\,,$$
$$[N_u]_{ij} = t_\beta m_{u_j}\delta_{ij} - (t_\beta + t_\beta^{-1})\hat{n}^*_{[\mathrm{u}]i}\hat{n}_{[\mathrm{u}]j} m_{u_j}\,,$$
$$\hat{n}_{[\mathrm{u}]i}V_{ij} = \hat{n}_{[\mathrm{d}]j},\;\; \hat{n}_{[\mathrm{u}]i} = V^*_{ij}\hat{n}_{[\mathrm{d}]j}$$

- Down parameterisation

$$[N_d]_{ij} = t_\beta m_{d_j}\delta_{ij} - (t_\beta + t_\beta^{-1})\hat{n}^*_{[\mathrm{u}]a}\hat{n}_{[\mathrm{u}]b} V^*_{ai}V_{bj} m_{d_j}\,,$$
$$[N_u]_{ij} = t_\beta m_{u_j}\delta_{ij} - (t_\beta + t_\beta^{-1})\hat{n}^*_{[\mathrm{u}]i}\hat{n}_{[\mathrm{u}]j} m_{u_j}\,,$$

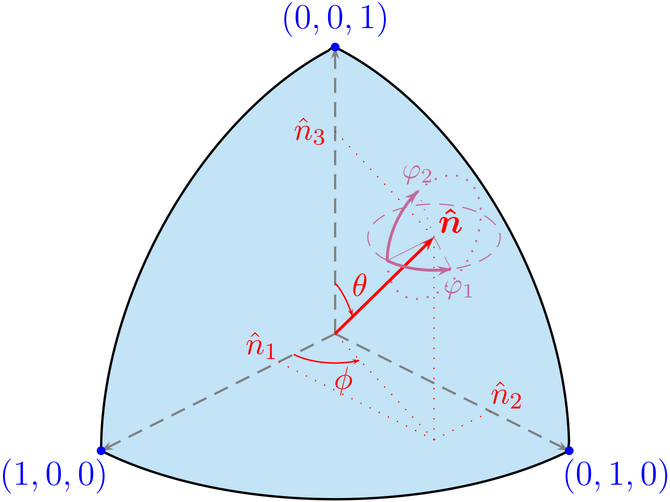
- Up parameterisation

$$[N_d]_{ij} = t_\beta m_{d_j}\delta_{ij} - (t_\beta + t_\beta^{-1})\hat{n}^*_{[\mathrm{d}]i}\hat{n}_{[\mathrm{d}]j} m_{d_j}\,,$$
$$[N_u]_{ij} = t_\beta m_{u_j}\delta_{ij} - (t_\beta + t_\beta^{-1})\hat{n}^*_{[\mathrm{d}]a}\hat{n}_{[\mathrm{d}]b} V_{ia}V^*_{jb} m_{u_j}\,.$$

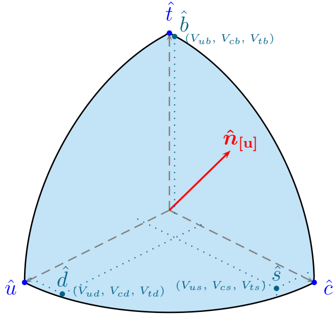
- BGL models recovered easily

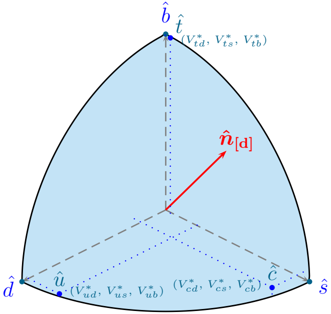
Just 4 new parameters

gBGL parameterisations



gBGL parameterisations



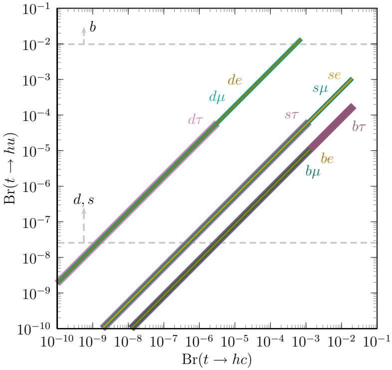


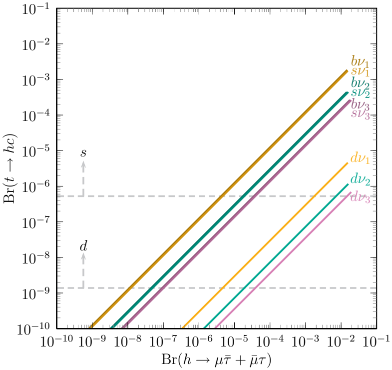
Phenomenology

Most interesting aspects

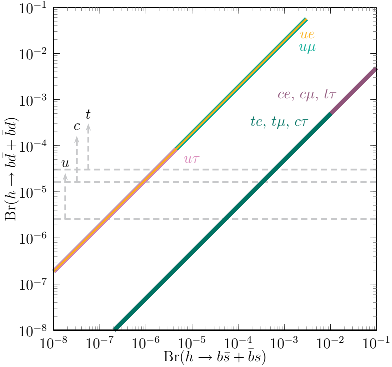
- Same observables as in BGL models
- ...but richer array of possibilities
- + improved contributions to the Baryon Asymmetry

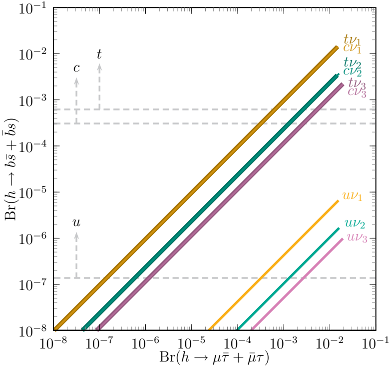
Example, BGL models – $t \to hq$ & $h \to \mu\tau$



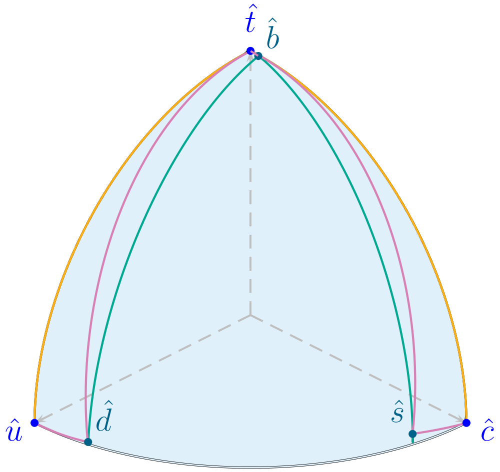


Example, BGL models – h $\to bq$ & h $\to \mu\tau$

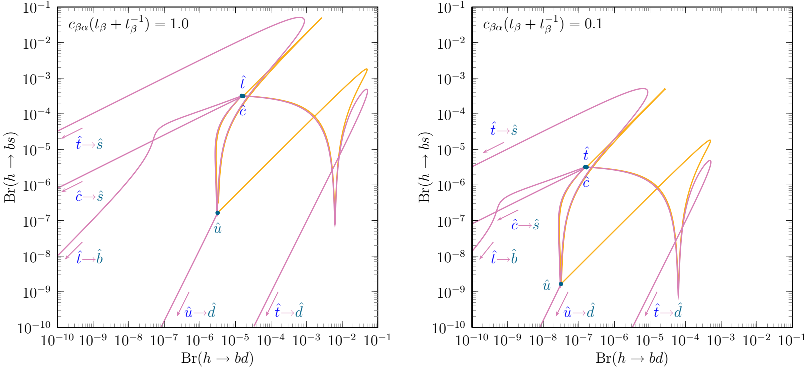




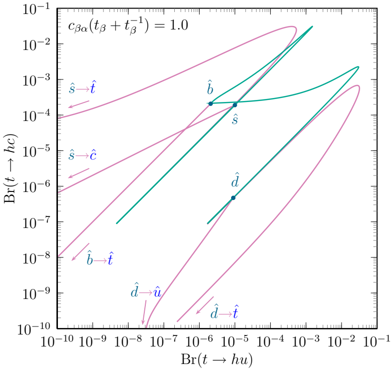
Example, gBGL "trajectories" between BGL models

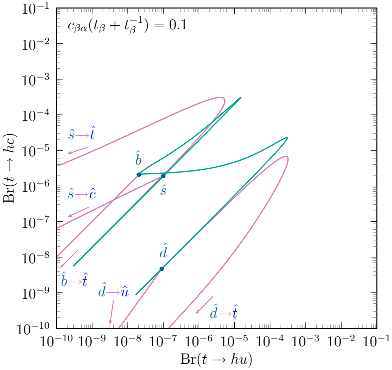


Example, gBGL models – h $\longrightarrow$ bq

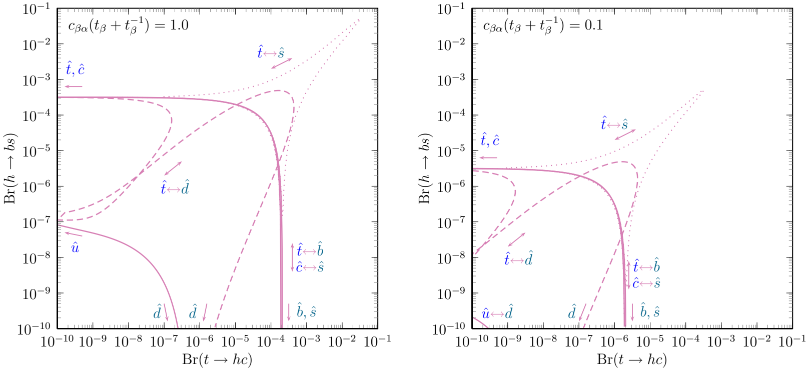


Example, gBGL models – $t \to hq$





Example, gBGL models – h $\to bq$ & $t \to$ hq

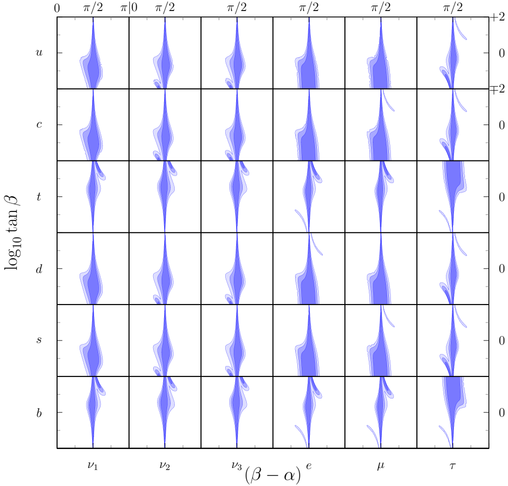


Summary & Conclusions

- Class of models with reduced parametric freedom,
  - BGL models: $\tan\beta$ & scalar mixing
  - gBGL models: + 4 parameters $\hat{n}_{[\mathrm{q}]}$
- Flavour diagonal Higgs data constrains FCNC
- Rich correlated patterns for $t \to \mathrm{h}q$ & $\mathrm{h} \to bq$, $\mathrm{h} \to \mu\tau$
  up vs. down, quarks vs. leptons!
- Can saturate current bounds for the LHC and the ILC
- FCNC are *controlled*

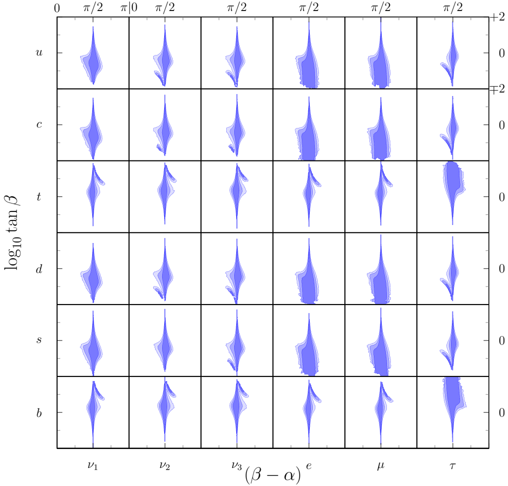
Thank you for your attention!

Example: BGL models



Only Higgs signals

Example: BGL models



+ Scalar potential (Positivity, Perturbative unit., ...) + oblique EW