

# Flavour Conservation in 2HDM

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# Introduction and Motivation

- PRD 98, 035046 (1803.08521) with Francisco J. Botella and Miguel Nebot
- Avoid or suppress FCNC
  - ▶ Natural Flavour Conservation. Each right-handed fermion couples only to one doublet.
    - ★ A  $Z_2$  symmetry (Glashow-Weinberg) leads to Natural Flavour Conservation (NFC) in the scalar sector.
    - ★ Some implementations via extra  $U(1)$
  - ▶ Suppression rather than forbiddance
    - ★ Given by masses (Cheng-Sher ansatz)
    - ★ BGL models, suppression by CKM
    - ★ Aligned 2HDM, proportional yukawa matrices
- Explore different scenarios with general flavour conservation (gFC)
  - ▶ Yukawa matrices diagonalizable at the same time
  - ▶ Study stability under RGE
  - ▶ Lepton sector

## General 2HDM

$$L_Y = -\bar{Q}_L (\Gamma_1 \Phi_1 + \Gamma_2 \Phi_2) d_R - \bar{Q}_L (\Delta_1 \tilde{\Phi}_1 + \Delta_2 \tilde{\Phi}_2) u_R + .h.c.$$

With the vev's given by  $\langle \Phi_i \rangle^T = e^{i\theta_i} (0 \quad v_i/\sqrt{2})$  we define the Higgs basis by  $\langle H_1 \rangle^T = (0 \quad v/\sqrt{2})$ ,  $\langle H_2 \rangle^T = (0 \quad 0)$ ,  $v^2 = v_1^2 + v_2^2$ ,  $c_\beta = v_1/v$ ,  $s_\beta = v_2/v$ ,  $t_\beta = v_2/v_1$

$$\begin{pmatrix} e^{-i\theta_1} \Phi_1 \\ e^{-i\theta_2} \Phi_2 \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ s_\beta & -c_\beta \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

then we have

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

- $G^\pm$  and  $G^0$  longitudinal degrees of freedom of  $W^\pm$  and  $Z^0$ .
- $H^\pm$  new charged Higgs bosons.
- A new  $CP$  odd scalar (we will have  $CP$  invariant Higgs potential).
- $H^0$  and  $R^0$   $CP$  even scalars. If they do not mix,  $H^0$  the SM Higgs.

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

$$M_d \propto c_\beta \Gamma_1 + s_\beta \Gamma_2 \quad N_d \propto -s_\beta \Gamma_1 + c_\beta \Gamma_2 \quad (1)$$

## General Flavour Conservation

We want  $N_f$  and  $M_f$  to be diagonalizable at the same time.  
Each of the following sets must be abelian

$$\{\Gamma_\alpha \Gamma_\beta^\dagger\}, \quad \{\Gamma_\alpha^\dagger \Gamma_\beta\}, \quad \{\Delta_\alpha \Delta_\beta^\dagger\}, \quad \{\Delta_\alpha^\dagger \Delta_\beta\} \quad (2)$$

that is, their elements commute

$$\begin{aligned} [\Gamma_\alpha \Gamma_\beta^\dagger, \Gamma_\gamma \Gamma_\delta^\dagger] &= 0 & [\Gamma_\alpha^\dagger \Gamma_\beta, \Gamma_\gamma^\dagger \Gamma_\delta] &= 0 \\ [\Delta_\alpha \Delta_\beta^\dagger, \Delta_\gamma \Delta_\delta^\dagger] &= 0 & [\Delta_\alpha^\dagger \Delta_\beta, \Delta_\gamma^\dagger \Delta_\delta] &= 0 \end{aligned} \quad (3)$$

This is independent of the spontaneous symmetry breaking vacuum i.e. any linear combination of the yukawa matrices, in particular,  $\{M_q^0, N_q^0\}$  is bidiagonalizable.

# RGE I

To study the cases stable under RGE:

$$\begin{aligned} \mathcal{D} \left[ \Gamma_\alpha \Gamma_\beta^\dagger, \Gamma_\gamma \Gamma_\delta^\dagger \right] &= 0 & \mathcal{D} \left[ \Gamma_\alpha^\dagger \Gamma_\beta, \Gamma_\gamma^\dagger \Gamma_\delta \right] &= 0 \\ \mathcal{D} \left[ \Delta_\alpha \Delta_\beta^\dagger, \Delta_\gamma \Delta_\delta^\dagger \right] &= 0 & \mathcal{D} \left[ \Delta_\alpha^\dagger \Delta_\beta, \Delta_\gamma^\dagger \Delta_\delta \right] &= 0 \quad \text{with} \end{aligned} \quad (4)$$

$$\begin{aligned} \mathcal{D}\Gamma_\alpha &= a_d \Gamma_\alpha + \sum_{\rho=1}^{n=2} T_{\alpha,\rho}^d \Gamma_\rho + \\ &\sum_{\rho=1}^{n=2} \left( -2\Delta_\rho \Delta_\alpha^\dagger \Gamma_\rho + \Gamma_\alpha \Gamma_\rho^\dagger \Gamma_\rho + \frac{1}{2} \Delta_\rho \Delta_\rho^\dagger \Gamma_\alpha + \frac{1}{2} \Gamma_\rho \Gamma_\rho^\dagger \Gamma_\alpha \right) \end{aligned} \quad (5)$$

$$\begin{aligned} \mathcal{D}\Delta_\alpha &= a_u \Delta_\alpha + \sum_{\rho=1}^{n=2} T_{\alpha,\rho}^u \Delta_\rho + \\ &\sum_{\rho=1}^{n=2} \left( -2\Gamma_\rho \Gamma_\alpha^\dagger \Delta_\rho + \Delta_\alpha \Delta_\rho^\dagger \Delta_\rho + \frac{1}{2} \Gamma_\rho \Gamma_\rho^\dagger \Delta_\alpha + \frac{1}{2} \Delta_\rho \Delta_\rho^\dagger \Delta_\alpha \right) \end{aligned} \quad (6)$$

## RGE II

with  $\mathcal{D} \equiv 16\pi^2 \frac{d}{d\ln\mu}$  and  $T_{\alpha,\rho}^u \equiv 3\text{tr}(\Delta_\alpha \Delta_\rho^\dagger + \Gamma_\alpha^\dagger \Gamma_\rho) + \text{tr}(\Pi_\alpha^\dagger \Pi_\rho) = T_{\alpha,\rho}^{d*}$   
 Asking the product of matrices to commute (2) we get equations such as

$$0 = \sum_{q=1}^3 \sum_{h=1}^2 V_{qa}^* V_{qb} \left\{ |y_{h,q}^u|^2 \left( |y_{i,a}^d|^2 |y_{k,b}^d|^2 - |y_{i,b}^d|^2 |y_{k,a}^d|^2 \right) \right. \quad (7)$$

$$- 2 \left( y_{h,q}^u y_{i,q}^{u*} y_{h,b}^d y_{i,b}^{d*} + y_{i,q}^u y_{h,q}^{u*} y_{i,a}^d y_{h,a}^{d*} \right) \left( |y_{k,b}^d|^2 - |y_{k,a}^d|^2 \right)$$

$$\left. + 2 \left( y_{h,q}^u y_{k,q}^{u*} y_{h,b}^d y_{k,b}^{d*} + y_{k,q}^u y_{h,q}^{u*} y_{k,a}^d y_{h,a}^{d*} \right) \left( |y_{i,b}^d|^2 - |y_{i,a}^d|^2 \right) \right\}.$$

that only contain parameters of CKM and

$$Y_{[d]i} = \text{diag}(y_{i,j}^d), \quad \{y_{1,1}^d, y_{1,2}^d, y_{1,3}^d\} = \{m_d, m_s, m_b\},$$

$$\{y_{2,1}^d, y_{2,2}^d, y_{2,3}^d\} = \{n_d, n_s, n_b\},$$

$$Y_{[u]i} = \text{diag}(y_{i,j}^u), \quad \{y_{1,1}^u, y_{1,2}^u, y_{1,3}^u\} = \{m_u, m_c, m_t\},$$

$$\{y_{2,1}^u, y_{2,2}^u, y_{2,3}^u\} = \{n_u, n_c, n_t\}. \quad (8)$$

## Known solutions

- Recover known result (Ferreira, Lavoura & Silva, **1001.2561**)
  - ▶ Applying the stability conditions and asking the matrices to be proportional

$$N_q = \alpha_q M_q \quad (9)$$

- ▶ We get the Type I, Type II and Inert 2HDM solutions.
- It was known that FA was stable on lepton sector
  - ▶ Due to the absence of right-handed neutrinos and Yukawa couplings involving them, general flavor alignment is one-loop stable in the lepton sector.
  - ▶ It is possible to analyze Type I and X or Type II and Y together (by pairs) with the more general leptonic structure:

$$N_l = \cot\beta \left( \frac{-\tan\beta + \xi_l}{\cot\beta + \xi_l} \right) M_l \quad (10)$$



# Stable gFC in the Lepton Sector

- We show that gFC is stable in the lepton sector, that means it is not necessary to have  $N_l \propto M_l$  but asking them to be diagonalizable at the same time is sufficient. That is, in the mass basis,

$$N_l = \text{diag}(n_e, n_\mu, n_\tau) \quad (11)$$

- That means that 2HDM Type I and Type II with a gFC leptonic sector -  $N_l$  **diagonal and arbitrary**- are "1-loop stable under RGE"

# Stable gFC with Cabibbo-like mixing

Keeping only the largest mixing of CKM matrix

$$V_{\theta_c} = \begin{pmatrix} \cos\theta_c & \sin\theta_c & 0 \\ -\sin\theta_c & \cos\theta_c & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (12)$$

- Third generation decoupled.
- Three classes of gFC scenarios
  - ▶ Type I for the two first generations
    - ★  $N_d = \text{diag}(\alpha m_d, \alpha m_s, n_b)$ ,  $N_u = \text{diag}(\alpha^* m_u, \alpha^* m_c, n_t)$
  - ▶ Type II for the two first generations
    - ★  $N_d = \text{diag}(e^{i\varphi_d} m_s, e^{i\varphi_d} m_d, n_b)$ ,  $N_u = \text{diag}(e^{i\varphi_u} m_c, e^{i\varphi_u} m_u, n_t)$
    - ★ Note that  $N$  and  $M$  are not even proportional in the first two generations

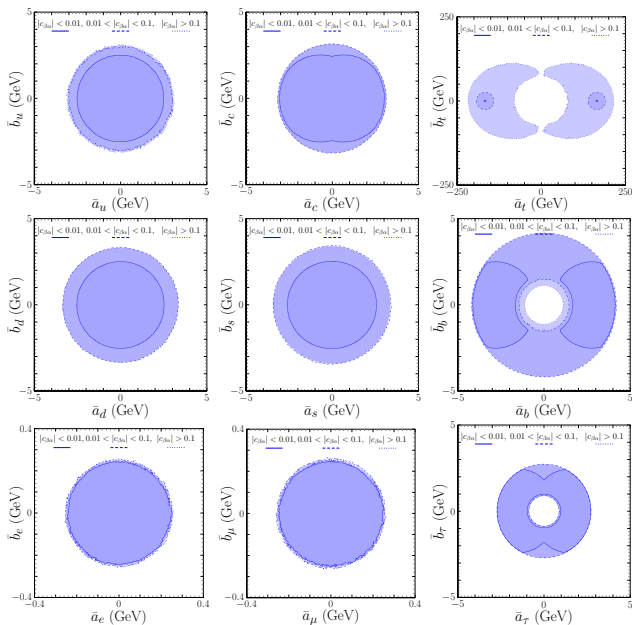
# Pheno

- For simplicity we consider the CP-conserving case
- Among the observable of interest, we choose:
  - ▶ Observables probing the couplings of the 125 GeV Higgs-like scalar (production and decay)
    - ★ Full Run-I + some Run-II ( $b\bar{b}$ ,  $\tau\bar{\tau}$ )
- Perturbativity of the Yukawa couplings:

$$\frac{|n_f|}{v} \leq \mathcal{O}(1) \quad (13)$$

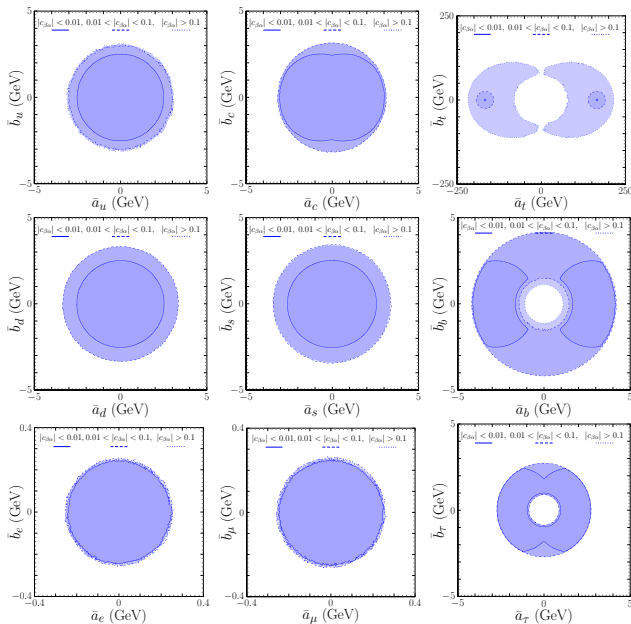
- We can study the slowed regions in term of the scalar and pseudoscalar couplings

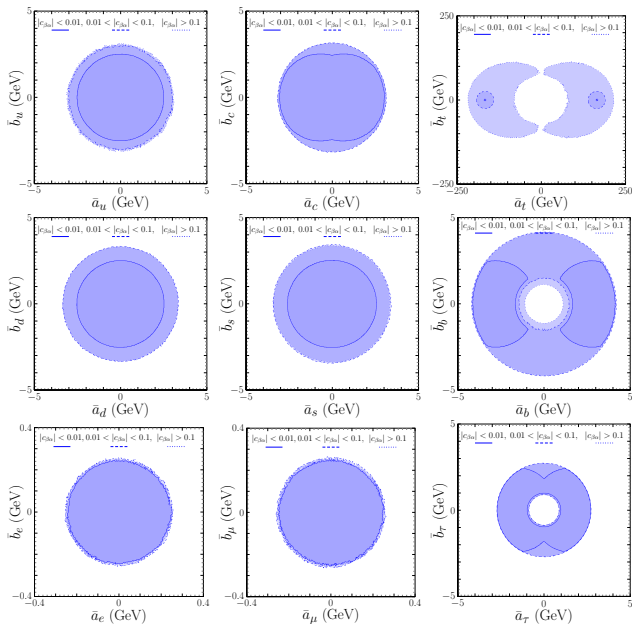
$$\bar{a}_f \equiv s_{\beta\alpha} m_f + c_{\beta\alpha} \text{Re}(n_f), \quad \bar{b}_f \equiv c_{\beta\alpha} \text{Im}(n_f) \quad (14)$$



First and second generations, no dependence on  $\arg(n_f)$  since only decays with rates proportional to  $|\bar{a}_f|^2 + |\bar{b}_f|^2$ , are relevant. For quarks, the allowed region for  $|c_{\beta\alpha}| < 0.01$  is smaller due to the perturbativity.

For the top quark two separate regions due to independent sign changes in  $\bar{a}_t$  and  $\bar{b}_t$ . For  $c_{\beta\alpha} < 0.01$  regions around  $m_t$





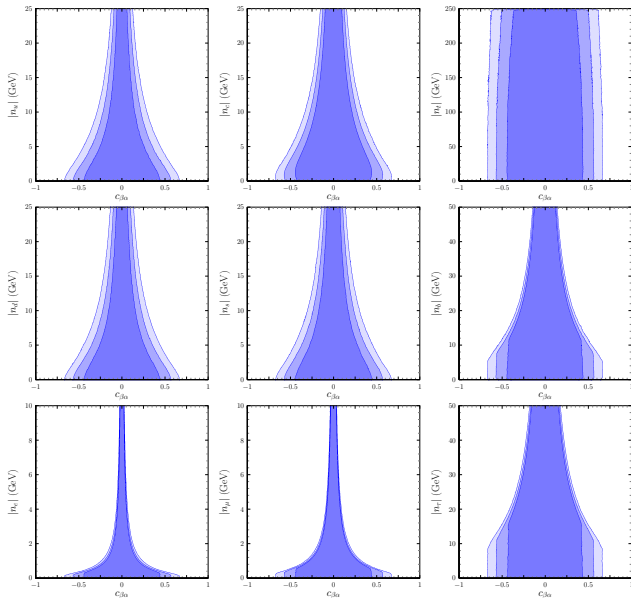
For  $b$  and  $\tau$  the regions for not too small mixing are ring shaped (radii related to masses). For small mixings perturbativity requirements limits departure from  $(\pm m_f, 0)$

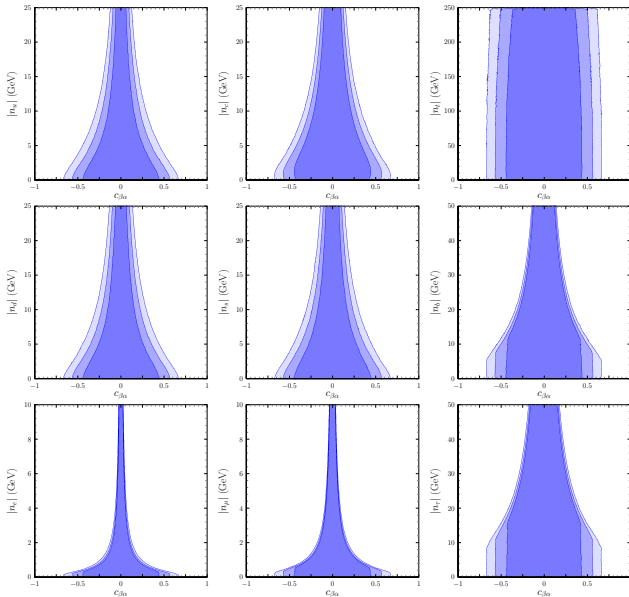
# Thanks!

# Backup



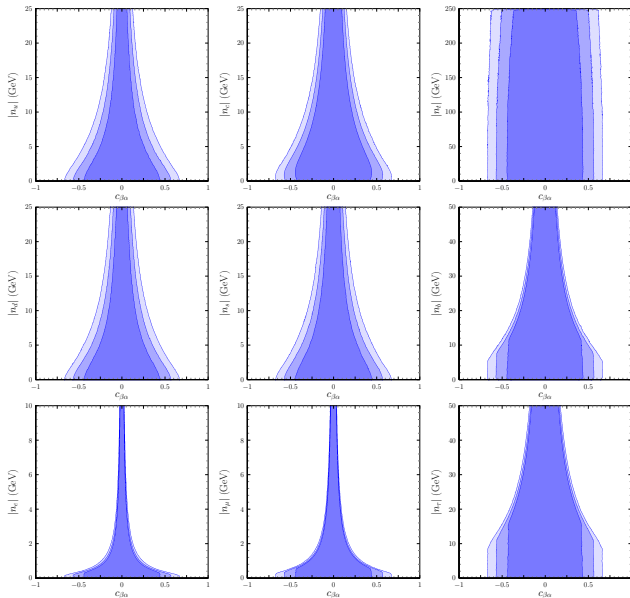
As expected, for  $|c_{\beta\alpha}| \rightarrow 0$ , the constraints on  $n_f$  disappear.

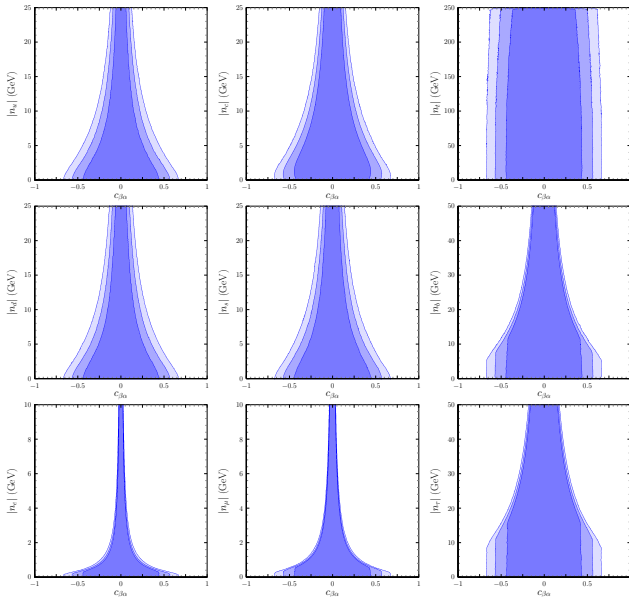




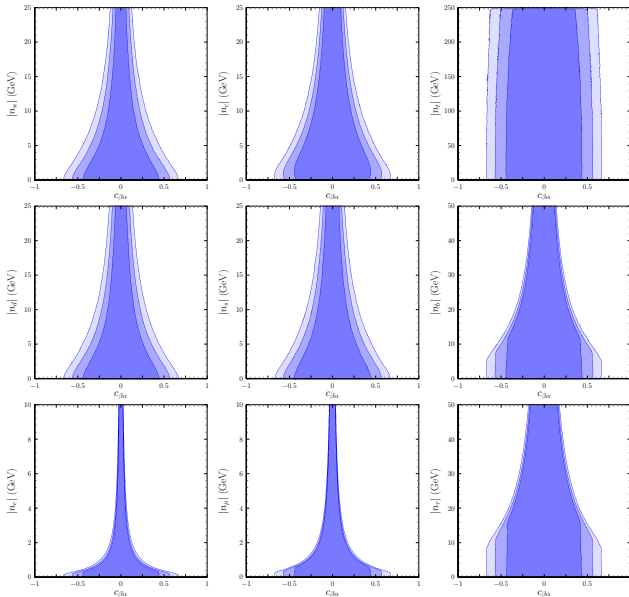
For  $u$ ,  $c$ ,  $d$ , and  $s$ , the allowed regions are almost identical, as one could anticipate from their irrelevant role, within the SM, in the available production  $\times$  decay Higgs signal strengths. The corresponding  $n_f$ 's appear to be effectively limited by the contributions to the Higgs width.

Surprisingly, the allowed size of  $|n_t|$  appears to be independent of  $C_{\beta\alpha}$





The  $n_b$  and  $n_\tau$  cases are also similar, with allowed regions differing from the  $u$ ,  $c$ ,  $d$ , and  $s$  cases for  $|n_q|$ 's below 10–15 GeV and not small  $c_{\beta\alpha}$ .



For  $n_e$  and  $n_\mu$ , the allowed regions are much more constrained, owing to the bounds set by dedicated  $pp \rightarrow h \rightarrow e^+e^-, \mu^+\mu^-$  analyses