Flavour Conservation in 2HDM

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X CPAN Days

Salamanca, October 29th, 2018

Introduction and Motivation

- PRD 98, 035046 (1803.08521) 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 ansätz)
    - 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

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

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

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

- $G^{\pm}$ 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.

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

$$M_d \propto c_\beta\Gamma_1 + s_\beta\Gamma_2 \quad N_d \propto -s_\beta\Gamma_1 + c_\beta\Gamma_2 \tag{1}$$

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

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

that is, their elements commute

$$\begin{aligned} \left[\Gamma_\alpha \Gamma_\beta^\dagger, \Gamma_\gamma \Gamma_\delta^\dagger\right] &= 0 \qquad & \left[\Gamma_\alpha^\dagger \Gamma_\beta, \Gamma_\gamma^\dagger \Gamma_\delta\right] &= 0 \\ \left[\Delta_\alpha \Delta_\beta^\dagger, \Delta_\gamma \Delta_\delta^\dagger\right] &= 0 \qquad & \left[\Delta_\alpha^\dagger \Delta_\beta, \Delta_\gamma^\dagger \Delta_\delta\right] &= 0 \end{aligned} \tag{3}$$

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:

$$\mathcal{D}\left[\Gamma_\alpha\Gamma_\beta^\dagger, \Gamma_\gamma\Gamma_\delta^\dagger\right] = 0 \qquad \mathcal{D}\left[\Gamma_\alpha^\dagger\Gamma_\beta, \Gamma_\gamma^\dagger\Gamma_\delta\right] = 0$$
$$\mathcal{D}\left[\Delta_\alpha\Delta_\beta^\dagger, \Delta_\gamma\Delta_\delta^\dagger\right] = 0 \qquad \mathcal{D}\left[\Delta_\alpha^\dagger\Delta_\beta, \Delta_\gamma^\dagger\Delta_\delta\right] = 0 \quad \text{with} \tag{4}$$

$$\mathcal{D}\Gamma_\alpha = a_d\Gamma_\alpha + \sum_{\rho=1}^{n=2} T^d_{\alpha,\rho}\Gamma_\rho + \sum_{\rho=1}^{n=2}\left(-2\Delta_\rho\Delta_\alpha^\dagger\Gamma_\rho + \Gamma_\alpha\Gamma_\rho^\dagger\Gamma_\rho + \frac{1}{2}\Delta_\rho\Delta_\rho^\dagger\Gamma_\alpha + \frac{1}{2}\Gamma_\rho\Gamma_\rho^\dagger\Gamma_\alpha\right) \tag{5}$$

$$\mathcal{D}\Delta_\alpha = a_u\Delta_\alpha + \sum_{\rho=1}^{n=2} T^u_{\alpha,\rho}\Delta_\rho + \sum_{\rho=1}^{n=2}\left(-2\Gamma_\rho\Gamma_\alpha^\dagger\Delta_\rho + \Delta_\alpha\Delta_\rho^\dagger\Delta_\rho + \frac{1}{2}\Gamma_\rho\Gamma_\rho^\dagger\Delta_\alpha + \frac{1}{2}\Delta_\rho\Delta_\rho^\dagger\Delta_\alpha\right) \tag{6}$$

RGE II

with $\mathcal{D} \equiv 16\pi^2 \frac{d}{dln\mu}$ and $T^u_{\alpha,\rho} \equiv 3tr(\Delta_\alpha\Delta^\dagger_\rho + \Gamma^\dagger_\alpha\Gamma_\rho) + tr(\Pi^\dagger_\alpha\Pi_\rho) = {T^d_{\alpha,\rho}}^*$
Asking the product of matrices to commute (2) we get equations such as

$$
\begin{aligned}
0 = \sum_{q=1}^{3}\sum_{h=1}^{2} V^*_{qa}V_{qb}\Big\{ & |y^{\rm u}_{h,q}|^2 \left(|y^{\rm d}_{i,a}|^2|y^{\rm d}_{k,b}|^2 - |y^{\rm d}_{i,b}|^2|y^{\rm d}_{k,a}|^2\right) \\
& - 2\left(y^{\rm u}_{h,q}y^{\rm u*}_{i,q}y^{\rm d}_{h,b}y^{\rm d*}_{i,b} + y^{\rm u}_{i,q}y^{\rm u*}_{h,q}y^{\rm d}_{i,a}y^{\rm d*}_{h,a}\right)\left(|y^{\rm d}_{k,b}|^2 - |y^{\rm d}_{k,a}|^2\right) \\
& + 2\left(y^{\rm u}_{h,q}y^{\rm u*}_{k,q}y^{\rm d}_{h,b}y^{\rm d*}_{k,b} + y^{\rm u}_{k,q}y^{\rm u*}_{h,q}y^{\rm d}_{k,a}y^{\rm d*}_{h,a}\right)\left(|y^{\rm d}_{i,b}|^2 - |y^{\rm d}_{i,a}|^2\right)\Big\}.
\end{aligned} \tag{7}
$$

that only contain parameters of CKM and

$$
\begin{aligned}
Y_{[{\rm d}]i} = \text{diag}(y^{\rm d}_{i,j}), \quad & \{y^{\rm d}_{1,1}, y^{\rm d}_{1,2}, y^{\rm d}_{1,3}\} = \{m_d, m_s, m_b\}, \\
& \{y^{\rm d}_{2,1}, y^{\rm d}_{2,2}, y^{\rm d}_{2,3}\} = \{n_d, n_s, n_b\}, \\
Y_{[{\rm u}]i} = \text{diag}(y^{\rm u}_{i,j}), \quad & \{y^{\rm u}_{1,1}, y^{\rm u}_{1,2}, y^{\rm u}_{1,3}\} = \{m_u, m_c, m_t\}, \\
& \{y^{\rm u}_{2,1}, y^{\rm u}_{2,2}, y^{\rm u}_{2,3}\} = \{n_u, n_c, n_t\}.
\end{aligned} \tag{8}
$$

Known solutions

- Recover known result (Ferreira, Lavoura & Silva, **1001.2561**)
  - Applying the stability conditions and asking the matrices to be proportional
$$N_q = \alpha_q M_q \tag{9}$$
  - 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:
$$N_l = cot\beta \left(\frac{-tan\beta + \xi_l}{cot\beta + \xi_l} \right) M_l \tag{10}$$

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,

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

- 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

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

- 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

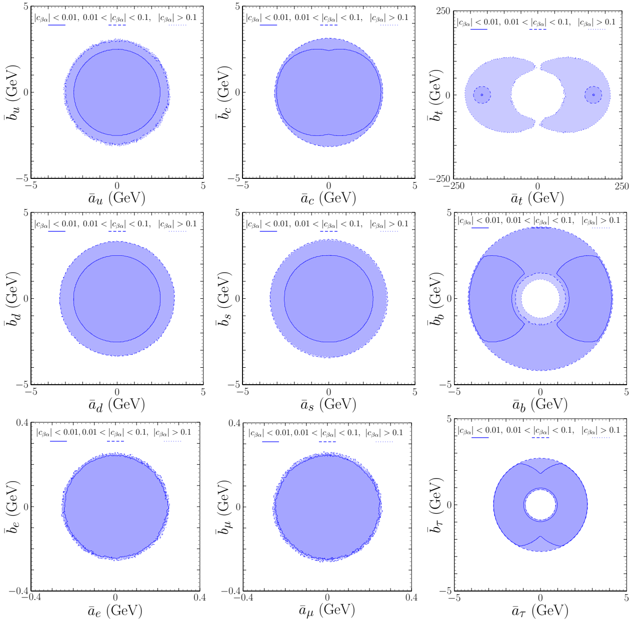
Pheno

- 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:

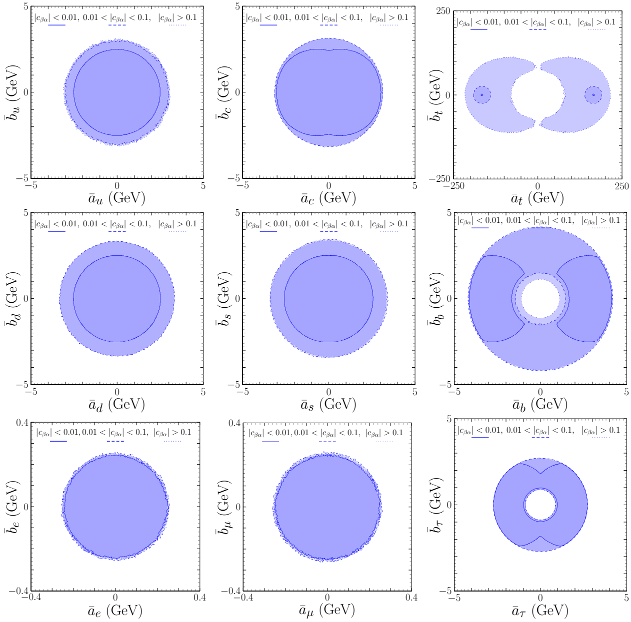
$$\frac{|n_f|}{v} \leq \mathcal{O}(1) \tag{13}$$

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

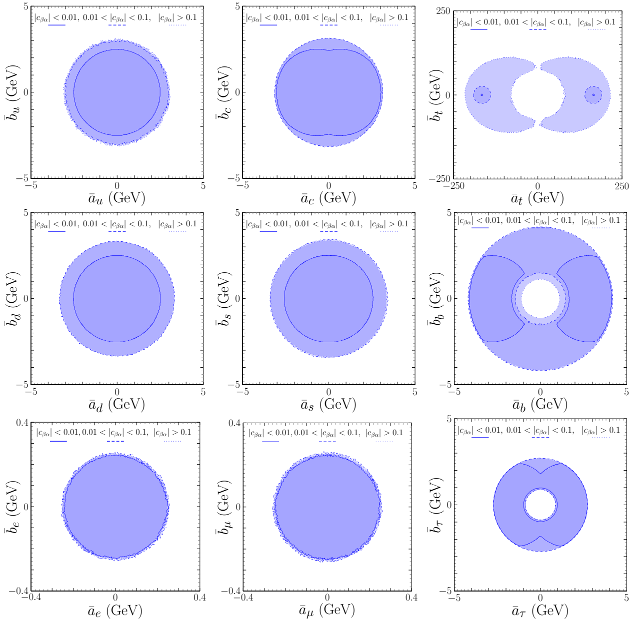
$$\bar{a}_f \equiv s_{\beta\alpha} m_f + c_{\beta\alpha} \mathrm{Re}(n_f), \quad \bar{b}_f \equiv c_{\beta\alpha} \mathrm{Im}(n_f) \tag{14}$$



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.



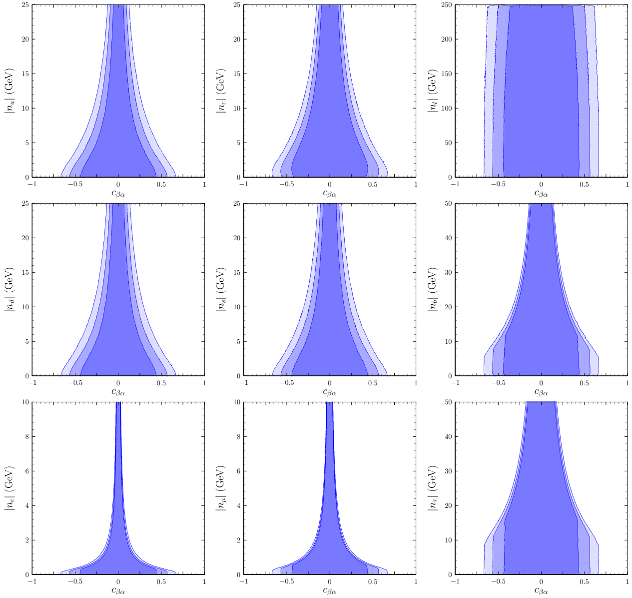
For the top quark two separate regions due to independent sign changes in $\bar{a}_t$ and $\bar{b}_t$. For$c_{\beta\alpha} < 0.01$ regions around m_t



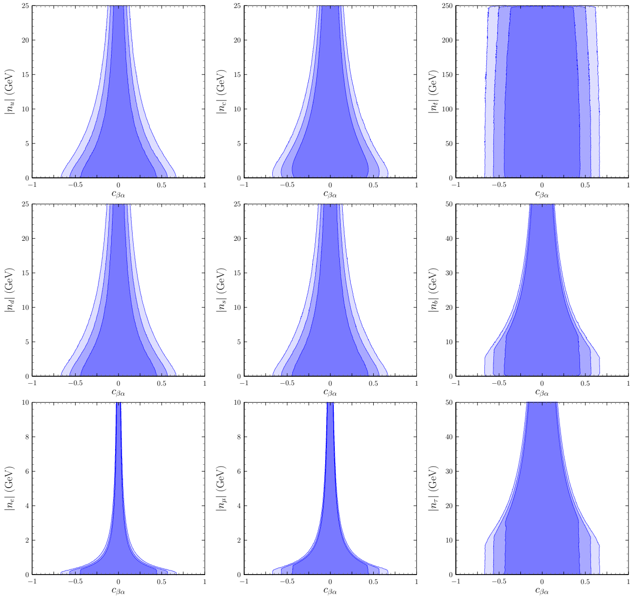
For b and τ the regions for not too small mixing are ring shaped (radii related to masses). For small mixings perturvativity requirements limits departure from $(\pm m_f, 0)$

Thanks!

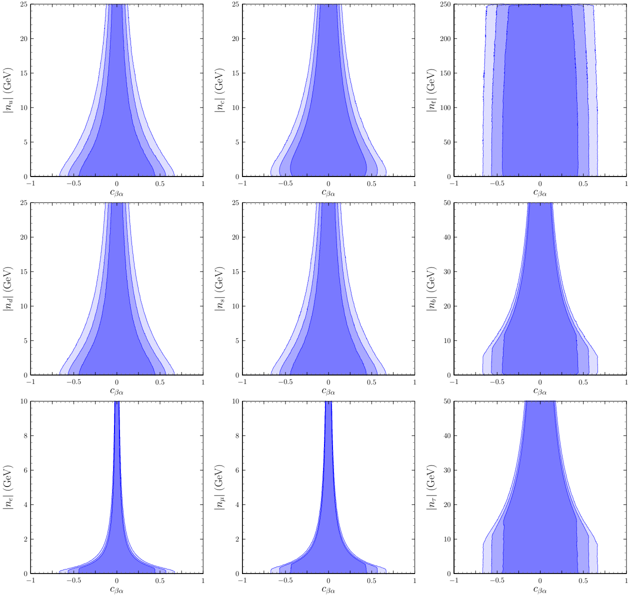
Backup



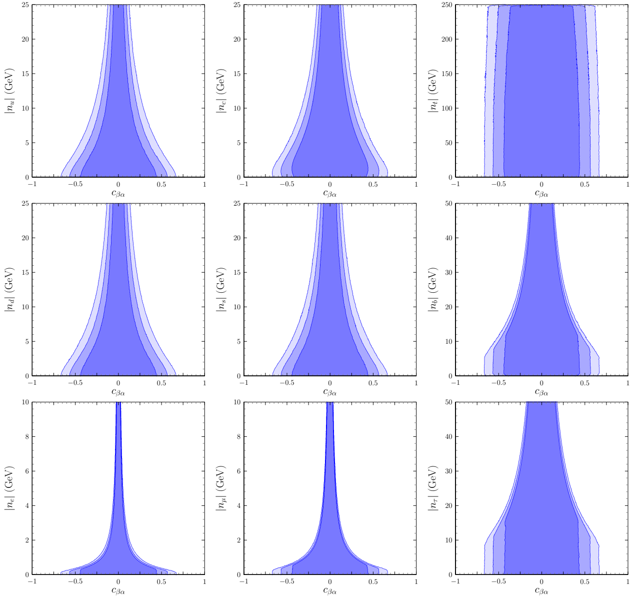
As expected, for $|c_{\beta\alpha}| \to 0$, the constraints on n_f disappear.



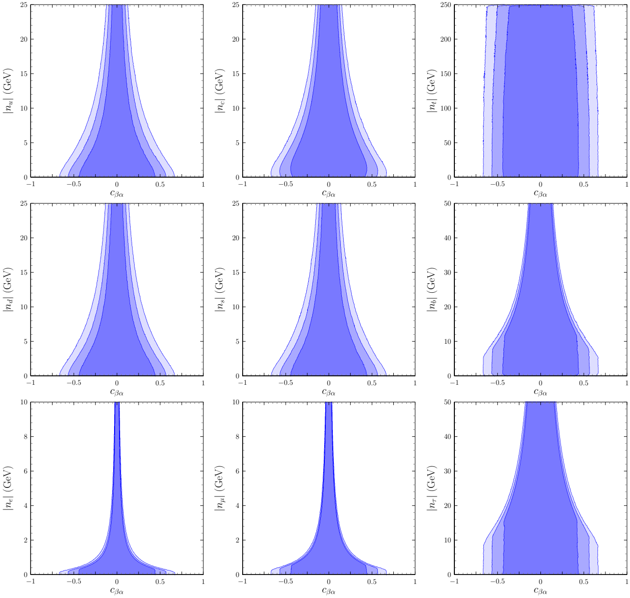
For u, c, d, and s, the allowed regions are almost identical, as one could anticipate from their irrelevant role, within the SM, in the available production $\times$ decay Higgs signal strengths. The corresponding n_f's appear to be effectively limited by the contributions to the Higgs width.



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



The n_b and n_τ 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_μ, the allowed regions are much more constrained, owing to the bounds set by dedicated $pp \to h \to e^+e^-, \mu^+\mu^-$ analyses