TÉCNICO LISBOA

Possible large pseudoscalar Yukawa couplings in the complex 3HDM

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Motivation

- We investigate the curious possibility that h125 couples to the top quark mostly as a scalar, while it couples to the bottom quark mostly as a pseudoscalar.

- This possibility was allowed by 2017 data for the so-called C2HDM; a two Higgs doublet model with a single source of explicit CP violation. It was shown recently that this possibility almost disappears when using the full experimental data of 2024 (see Duarte Fontes talk)

- Here we discuss a three Higgs doublet with explicit CP violation (C3HDM), and show that the curious CP-even/CP-odd tt/bb possibility is partly resuscitated, prompting further experimental exploration of this prospect.

Collaborators: J. P. Silva, R. Boto, L. Lourenço, 2407.19856 [JHEP in print.]

The scalar potential

- The scalar potential obeying the $Z_2 \times Z_2$ symmetry is

$$V = V_2 + V_4 = \mu_{ij}(\Phi_i^\dagger \Phi_j) + z_{ijkl}(\Phi_i^\dagger \Phi_j)(\Phi_k^\dagger \Phi_l) \ ,$$

- where

$$\begin{aligned} V_2 =& \mu_{11}(\Phi_1^\dagger \Phi_1) + \mu_{22}(\Phi_2^\dagger \Phi_2) + \mu_{33}(\Phi_3^\dagger \Phi_3) \\ & + \left(\mu_{12}(\Phi_1^\dagger \Phi_2) + \mu_{13}(\Phi_1^\dagger \Phi_3) + \mu_{23}(\Phi_2^\dagger \Phi_3) + h.c.\right) \ , \end{aligned}$$

$$\begin{aligned} V_4 =& V_{RI} + V_{Z_2\times Z_2} \ , \\ V_{RI} =& \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_3^\dagger\Phi_3)^2 + \lambda_4(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\ & + \lambda_5(\Phi_1^\dagger\Phi_1)(\Phi_3^\dagger\Phi_3) + \lambda_6(\Phi_2^\dagger\Phi_2)(\Phi_3^\dagger\Phi_3) + \lambda_7(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + \lambda_8(\Phi_1^\dagger\Phi_3)(\Phi_3^\dagger\Phi_1) + \lambda_9(\Phi_2^\dagger\Phi_3)(\Phi_3^\dagger\Phi_2) \ , \end{aligned}$$

$$V_{Z_2\times Z_2} = \lambda_{10}(\Phi_1^\dagger\Phi_2)^2 + \lambda_{11}(\Phi_1^\dagger\Phi_3)^2 + \lambda_{12}(\Phi_2^\dagger\Phi_3)^2 + h.c. \ ,$$

The scalar potential

- The soft terms μ_{11}, μ_{22}, μ_{33} are real
- The complex μ_{12}, μ_{13}, μ_{23} parameters break the $Z_2 \times Z_2$ symmetry softly.
- The quartic parameters λ_{10}, λ_{11}, λ_{12} can in general be complex, while all other quartic parameters are real
- The potential piece V_{RI} is invariant under the independent rephasings of each scalar
- The piece $V_{Z_2 \times Z_2}$ is invariant under $Z_2 \times Z_2$ but not under general independent rephasings of each scalar.

Parameterization in terms of physical quantities

- We define

$$\Phi_i = \begin{bmatrix} w_i^+ \\ (v_i + x_i + i\ z_i)/\sqrt{2} \end{bmatrix}, \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} = v \begin{pmatrix} c_{\beta_2} c_{\beta_1} \\ c_{\beta_2} s_{\beta_1} \\ s_{\beta_2} \end{pmatrix}.$$

- Higgs Basis (HB)

$$\begin{bmatrix} x \\ z' \end{bmatrix} = \begin{bmatrix} \mathbb{1} & 0 \\ 0 & R_H \end{bmatrix} \begin{bmatrix} x \\ z \end{bmatrix}, w^{+\prime} = R_H w^+, R_H \equiv \begin{bmatrix} c_{\beta_2} c_{\beta_1} & c_{\beta_2} s_{\beta_1} & s_{\beta_2} \\ -s_{\beta_1} & c_{\beta_1} & 0 \\ -s_{\beta_2} c_{\beta_1} & -s_{\beta_2} s_{\beta_1} & c_{\beta_2} \end{bmatrix}.$$

- Rotation from HB to Mass Eigenstates

$$M_{ch}^{2\prime} = W^\dagger \begin{bmatrix} m^2_{H_1^\pm} & 0 \\ 0 & m^2_{H_2^\pm} \end{bmatrix} W, M_n^{2\prime} = R^T \begin{bmatrix} m^2_{h_1} & 0 & 0 & 0 & 0 \\ 0 & m^2_{h_2} & 0 & 0 & 0 \\ 0 & 0 & m^2_{h_3} & 0 & 0 \\ 0 & 0 & 0 & m^2_{h_4} & 0 \\ 0 & 0 & 0 & 0 & m^2_{h_5} \end{bmatrix} R$$

Independent parameters

- The unitary matrix W is parameterized by two angles, θ and φ
- The orthogonal 5×5 matrix R is parameterized by ten angles,

$$\alpha_{12},\ \alpha_{13},\ \alpha_{14},\ \alpha_{15},\ \alpha_{23},\ \alpha_{24},\ \alpha_{25},\ \alpha_{34},\ \alpha_{35},\ \alpha_{45}$$

- Using the minimization eqs and the rotations W and R we can solve for all the quartic parameters and for the imaginary part of the soft terms.
- However one can not take all the masses as independent, there are three relations to be satisfied (one in the C2HDM), giving $m_{h_3}, m_{h_4}, m_{h_5}$
- Our fixed inputs are $v = 246\,\text{GeV}$ and $m_{h_1} = 125\,\text{GeV}$
- The remaining 20 independent parameters are

$$\theta,\ \varphi,\ \alpha_{12},\ \alpha_{13},\ \alpha_{14},\ \alpha_{15},\ \alpha_{23},\ \alpha_{24},\ \alpha_{25},\ \alpha_{34},\ \alpha_{35},\ \alpha_{45},\ \beta_1,\ \beta_2$$

$$m_{h_2},\ m_{H_1^\pm},\ m_{H_2^\pm},\ \text{Re}(m_{12}^2), \text{Re}(m_{13}^2), \text{Re}(m_{23}^2)$$

Type-Z Yukawa couplings

- To avoid the stringent constraints from flavour experiments one normally imposes Natural Flavour Conservation (NFC)
- In the 2HDM there are four ways to implement NFC
- In contrast, in 3HDM there is the new possibility that each right-handed fermion species (up-type quark, down-type quark, and charged lepton) couples to a distinct scalar. This is the so-called type-Z model.

fermion type	type-I	type-II	type-X	type-Y	type-Z
up quarks (u)	Φ_3	Φ_3	Φ_3	Φ_3	Φ_3
down quarks (d)	Φ_3	Φ_2	Φ_3	Φ_2	Φ_2
charged leptons (ℓ)	Φ_3	Φ_2	Φ_2	Φ_3	Φ_1

Type-Z Yukawa couplings

- The simplest symmetry groups that can enforce the type-Z couplings in the 3HDM are Z_3 and $Z_2 \times Z_2$

- Here, we focus on the model with a $Z_2 \times Z_2$ symmetry, with the following action on scalars, right-handed down-type quarks (d_R), and right-handed charged-leptons (ℓ_R):

$$
\begin{aligned}
Z_2 &: \Phi_1 \to -\Phi_1 \,, \quad \ell_R \to -\ell_R \,, \\
Z_2' &: \Phi_2 \to -\Phi_2 \,, \quad d_R \to -d_R \,,
\end{aligned}
$$

  (with all other SM fields invariant under the transformation) leading to the type-Z couplings

- In this work, we study the type-Z 3HDM with a softly-broken $Z_2 \times Z_2$ symmetry, allowing for complex parameters in the potential; we dub this the complex 3HDM (C3HDM).

The Yukawa Lagrangian

- The Yukawa Lagrangian has then terms of the form

$$\mathcal{L}_{\text{Yukawa}} = \mathcal{L}_{ff} + \mathcal{L}_{\Phi ff} ,$$

- where $\mathcal{L}_{ff}$ are the fermion mass terms,

$$-\mathcal{L}_{ff} = \overline{d}_L D_d d_R + \overline{u}_L D_u u_R + \overline{\ell}_L D_\ell \ell_R + h.c. = \overline{d} D_d d + \overline{u} D_u u + \overline{\ell} D_\ell \ell ,$$

- and $\mathcal{L}_{\Phi ff}$ contains the scalar-fermion interactions

$$-\mathcal{L}_{\Phi ff} = (\overline{p}_L \; \overline{n}_L)\Gamma \begin{pmatrix} \varphi_d^+ \\ (x_d + i z_d)/\sqrt{2} \end{pmatrix} n_R + (\overline{p}_L \; \overline{n}_L)\Delta \begin{pmatrix} (x_u - i z_u)/\sqrt{2} \\ -\varphi_u^- \end{pmatrix} p_R$$
$$+ (\overline{\nu}_L \; \overline{\ell}_L) Y \begin{pmatrix} \varphi_\ell^+ \\ (x_\ell + i z_\ell)/\sqrt{2} \end{pmatrix} \ell_R + h.c.$$

- The interactions of fermion eigenstates with the unrotated neutral scalars ξ'_i are,

$$-\mathcal{L}_{\xi' ff} = \frac{m_{\ell i}}{v_\ell} \overline{\ell}_i (x_\ell + i\gamma_5 z_\ell) \ell_i + \frac{m_{di}}{v_d} \overline{d}_i (x_d + i\gamma_5 z_d) d_i + \frac{m_{ui}}{v_u} \overline{u}_i (x_u - i\gamma_5 z_u) u_i$$

Higgs Couplings to Fermions

- Now we have to rotate to the scalar mass eigenstates. We define

$$\xi' \equiv (x_\ell, x_d, x_u, z_\ell, z_d, z_u)^T \,, \quad \xi = Q\xi'$$

- The rotation matrix Q is obtained from R_H and R. We therefore have,

$$x_i = Q^T_{ij}\,\xi_j = Q_{ji}\,\xi_j \quad , z_i = Q^T_{3+i,j}\,\xi_j = Q_{j,3+i}\,\xi_j \;,$$

where $\xi_1 = G^0$ is the pseudo-Goldstone boson absorbed by the Z boson, and $i \in \{1,\ldots,3\}$, while $j \in \{1,\ldots,6\}$.

- Therefore

$$-\mathcal{L}_{\xi f f} = \sum_{f,j} \frac{m_f}{v}\overline{f}\frac{v}{v_f}\left(Q_{jf} \pm i\gamma_5 Q_{j,N+f}\right) f\,\xi_j = \sum_{f,j}\frac{m_f}{v}\overline{f}\left(c^e_{\xi_j f f} + i\gamma_5 c^o_{\xi_j f f}\right) f\,\xi_j \;,$$

where we defined (+ for leptons and down quarks, − for up quarks)

$$c^e_{\xi_j f f} + i\gamma_5 c^o_{\xi_j f f} = \frac{v}{v_f}\left(Q_{jf} \pm i\gamma_5 Q_{j,N+f}\right)$$

Constraints

We have implemented all the known constraints:

- Bounded from Below (BFB)
- Perturbativity of Yukawa couplings
- Perturbative Unitarity
- S,T, U oblique parameters
- Stringent limits on EDM of the electron
- Signal strengths from LHC on the h_{125}
- Constraints from flavour like $b \to s\gamma$
- `HiggsSignals` and `HiggsBounds` from `HiggsTools`

How do we scan: random scan

- Our fixed inputs are $v = 246$ GeV and $m_{h1} = 125$ GeV
- We then would take random values in the ranges:

$$\theta,\ \varphi,\ \alpha_{12},\ \alpha_{13},\ \alpha_{14},\ \alpha_{15},\ \alpha_{23},\ \alpha_{24},\ \alpha_{25},\ \alpha_{34},\ \alpha_{35},\ \alpha_{45}\ \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right];$$

$$\tan\beta_1,\ \tan\beta_2\ \in [0.3, 10]\,;$$

$$m_{h_2},\ \in [125, 1000]\ \text{GeV},\ m_{H_1^\pm},\ m_{H_2^\pm}\ \in [100, 1000]\ \text{GeV};$$

$$\text{Re}(m_{12}^2), \text{Re}(m_{13}^2), \text{Re}(m_{23}^2) \in \left[\pm 10^{-1}, \pm 10^{7}\right]\ \text{GeV}^2$$

- These 20 free parameters (other than v and m_{h_1}) fully determine the point in parameter space
- However, as in the real 3HDM case, this random scan has a very low probability of success. In fact even worse than in the real case; lower than 1 point per 10^{13} sampled points

How do we scan: importing from the real 3HDM

- The C3HDM has a real limit corresponding to,

$$\alpha_{12} = \alpha_1, \quad \alpha_{13} = \alpha_2, \quad \alpha_{23} = \alpha_3, \quad \alpha_{45} = -\gamma_1, \quad \theta = -\gamma_2$$
$$\varphi = \alpha_{14} = \alpha_{15} = \alpha_{24} = \alpha_{25} = \alpha_{34} = \alpha_{35} = 0\,,$$

  where α_1, α_2, α_3, γ_1, γ_2 are the variables defined in the real 3HDM, and β_1, β_2 retain their meaning in both cases.

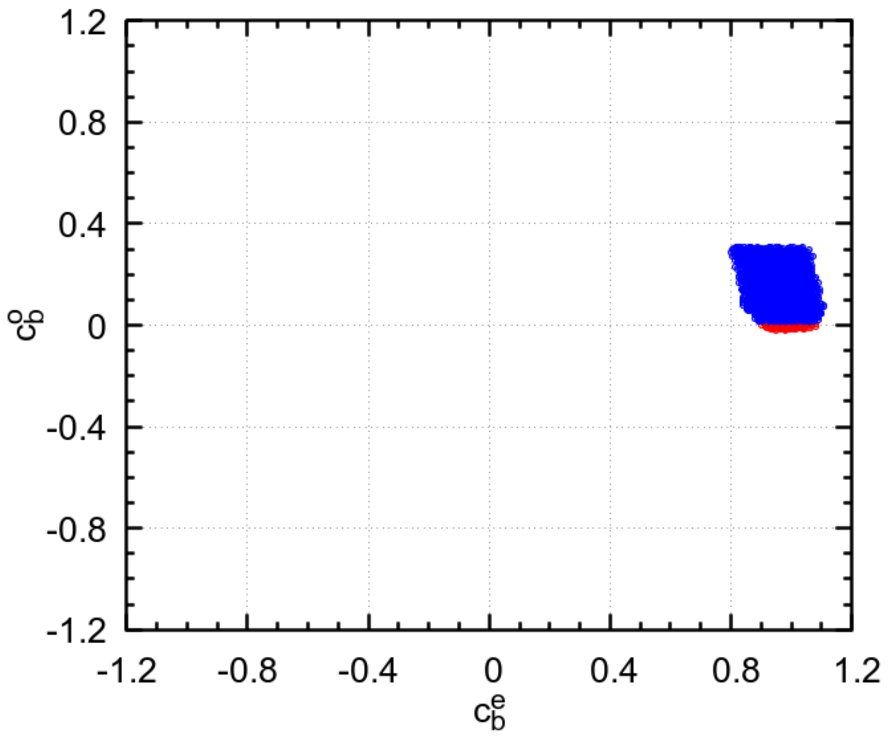
- So we produced sets of points in the real 3HDM, and then we imported them into the C3HDM

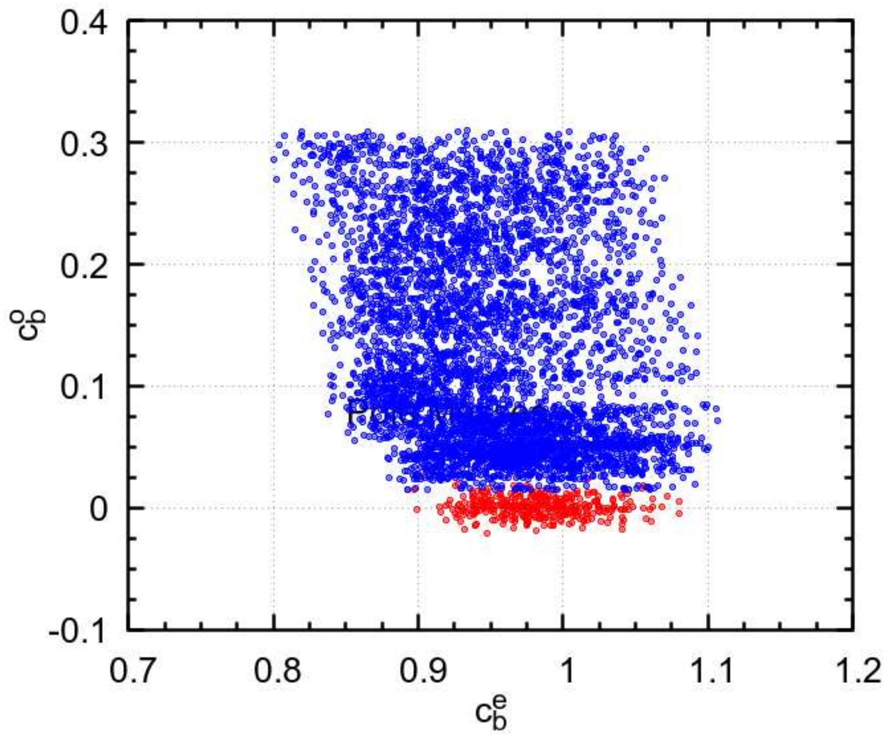
- The next step is to scan around these points. This was done within the ranges

$$\alpha_{14}, \alpha_{15} \in [-0.01, 0.01];$$
$$\varphi,\ \alpha_{24}, \alpha_{25},\ \alpha_{34},\ \alpha_{35} \in [-0.1, 0.1].$$

  These ranges were chosen to be close to the real case.

Enlarging the pseudoscalar component





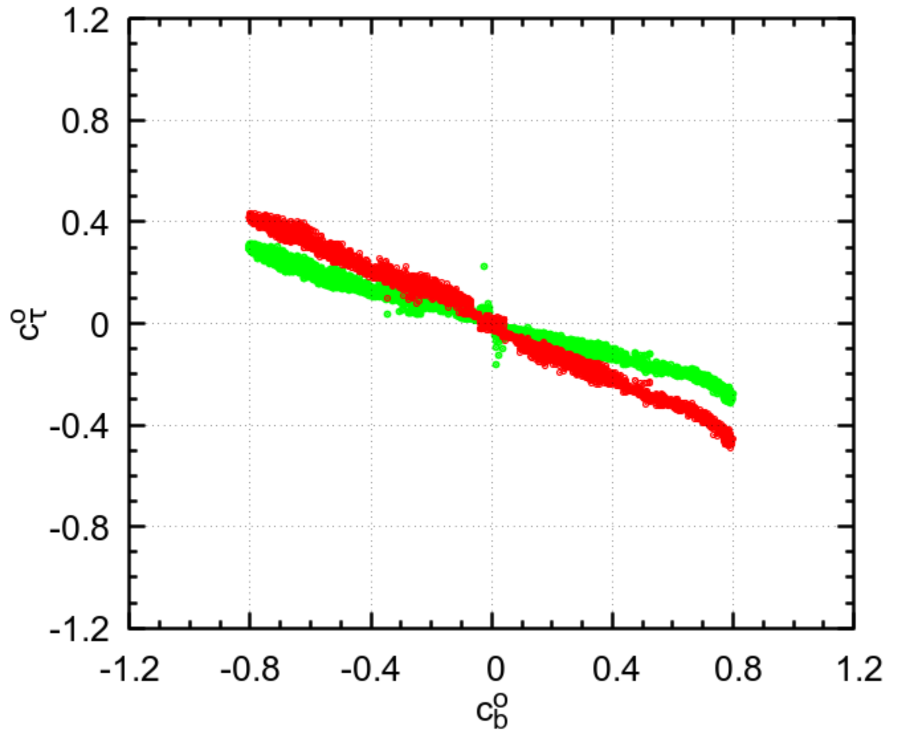
- In the left panel we show the whole range after a certain # of iterations
- In the right panel we show a closeup. The blue points were obtained from the red points by enlarging the pseudoscalar component

(Anti)-Correlation between c_τ^o and c_b^0

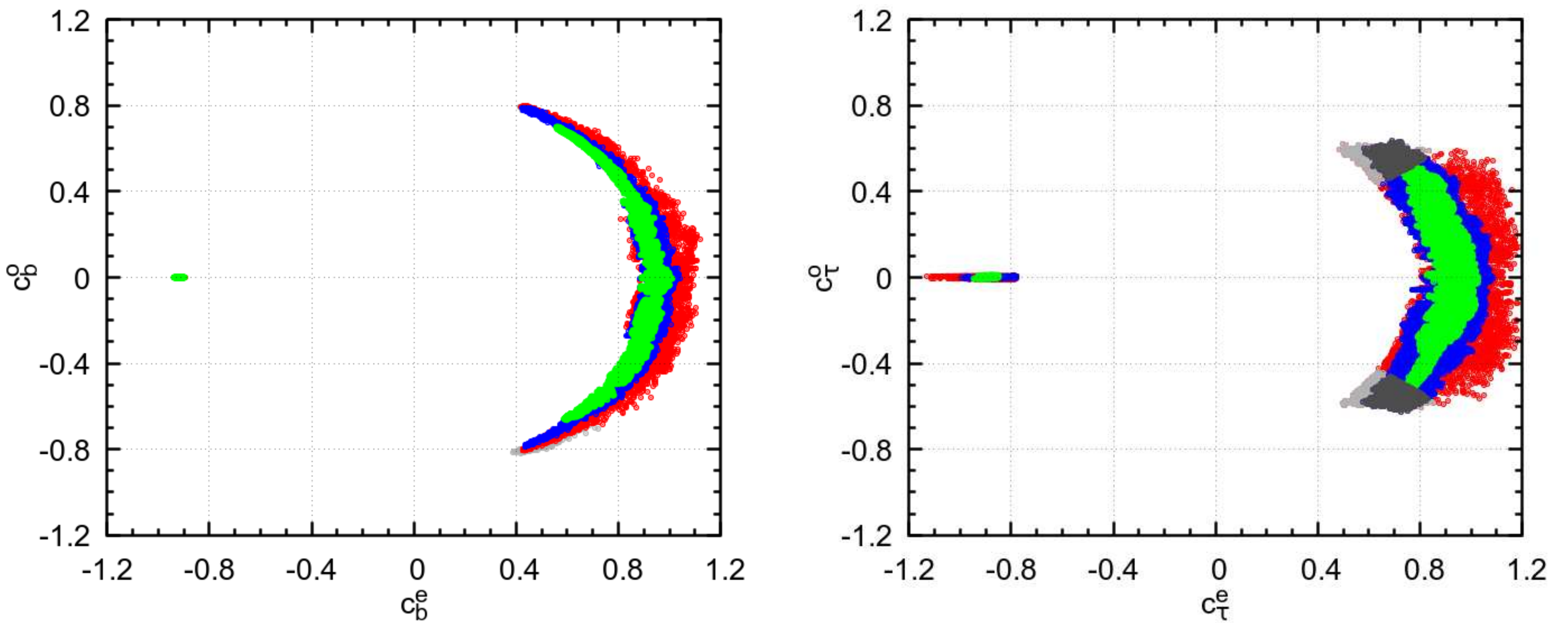
- As in type-Z one couples one Higgs doublet to each type of fermions, one would think that limits in one type would not affect the others
- This is important because in the C2HDM the experimental limits of the pseudoscalar component of the τ obtained in the decay $h_{125} \to \tau\bar{\tau}$ by CMS and ATLAS had an impact on large pseudoscalar components for the b-quark
- However we found that there is one relation among all the coefficients $c_f^{o,e}$. In the limit that the odd component of the top quark vanishes (a very good approximation) we have

$$\frac{c_\tau^0}{c_b^0} \simeq -\tan^2\beta_1$$

- In red our points, in green those satisfying the previous equation



Large pseudoscalar component of the b-quark and τ lepton



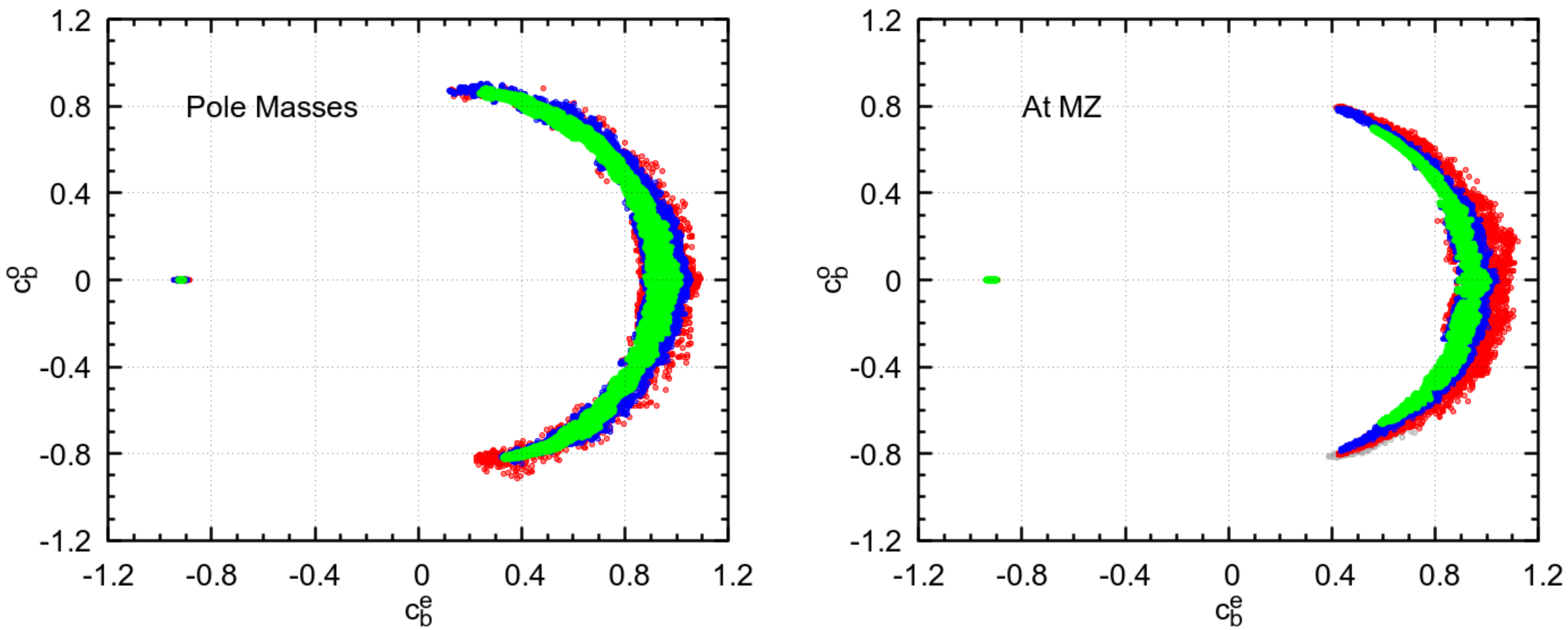
- Left panel c^o_b vs c^e_b and right panel c^o_τ vs c^e_τ
- In red we consider only the uncorrelated constraints on the signal strengths μ_{ij}. In blue we consider `HiggsSignals` at 3σ and in green `HiggsSignals` at 2σ
- The constraints on $h_{125} \to \tau\bar{\tau}$ only affect the τ lepton. For the b-quark a large pseudoscalar component is obtained, although not maximal.

Conclusions

- We have developed a parameterization for the C3HDM and implemented a code to study the model
- All known constraints were implemented
- Contrary to initial expectations although each doublet couples to a different type of fermion, there is still some correlation between the τ lepton and the b-quark
- However, the previous correlation does not preclude large pseudo scalar components for the couplings of the b-quark, although not maximal
- Therefore these results prompt further experimental exploration

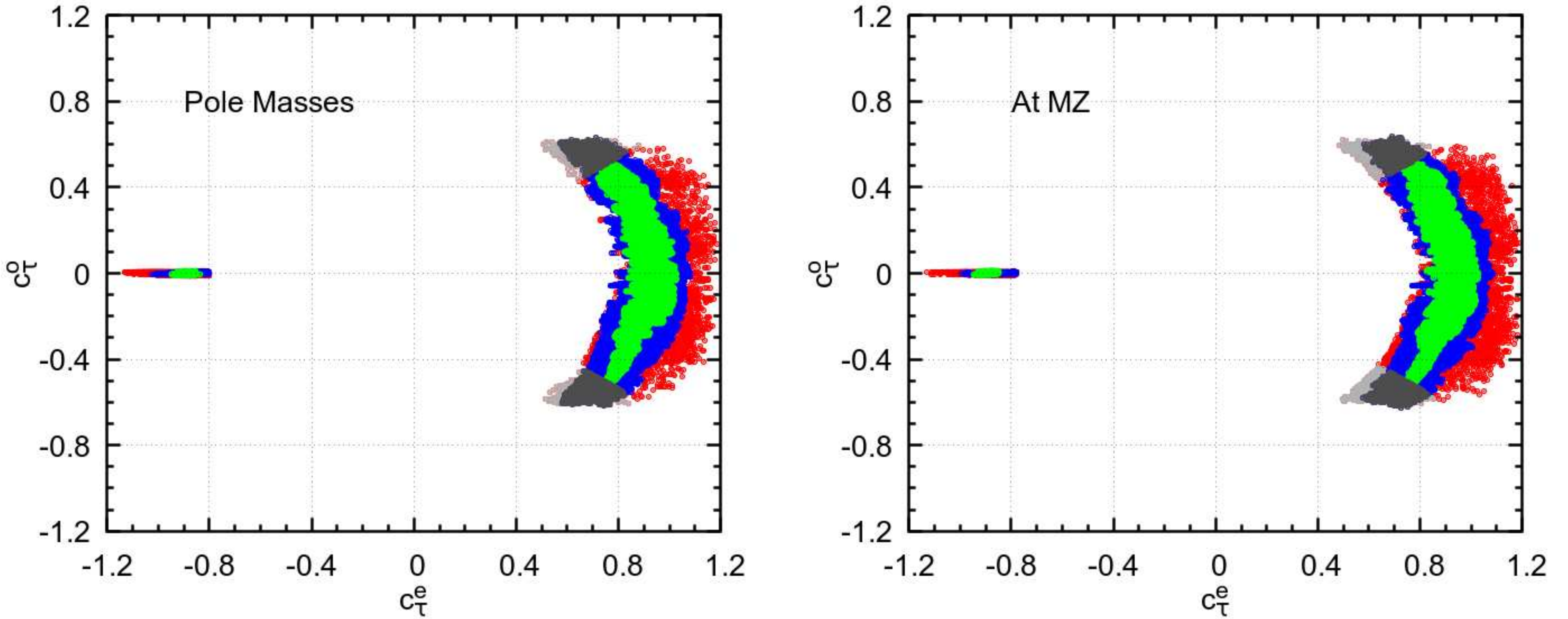
BACKUP SLIDES

Large pseudoscalar component of the b-quark: c_b^o versus c_b^e



- Left we take the pole masses and right we have masses at the M_Z scale
- In red we consider only the uncorrelated constraints on the signal strengths μ_{ij}. In blue we consider `HiggsSignals` at 3σ and in green `HiggsSignals` at 2σ
- The constraints on $h_{125} \to \tau\bar{\tau}$ do not affect the ranges
- Pole and At M_Z refer to the choice of constants in the eEDM (see 2403.02425)

Large pseudoscalar component of the τ: c_τ^o versus c_τ^e



- Left pole masses, right masses at M_Z
- Color code as before
- The constraints on $h_{125} \to \tau\bar{\tau}$ are important and are included as the gray regions.