Large Pseudoscalar Yukawa Couplings in the complex 3HDM

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arXiv:2407.19856

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Workshop on Multi-Higgs Models, September 2024

Introduction

We study the softly-broken $Z_2 \times Z_2$ - symmetric C3HDM.

We are interested in the, potentially CPV, $h_{125}ff$ couplings.

$$\mathcal{L}_{hff} = \frac{m_f}{v} h\, \bar{f}(c_f^e + i c_f^o \gamma_5) f$$

New sources of CPV are needed to address the baryon asymmetry problem.

[arXiv:2403.02425]

The possibility of maximal/mostly CPV hbb couplings was recently ruled out in the C2HDM.

The novel type-Z Yukawa couplings could ease the effect of constraints on $h_{125}bb$.

$$\begin{aligned} \Phi_1 &= \Phi_\tau, \\ \Phi_2 &= \Phi_b, \\ \Phi_3 &= \Phi_u \end{aligned}$$

The Scalar Potential

complex parameters

$$V = \mu_{11}(\Phi_1^\dagger\Phi_1) + \mu_{22}(\Phi_2^\dagger\Phi_2) + \mu_{33}(\Phi_3^\dagger\Phi_3) + \left(\mu_{12}(\Phi_1^\dagger\Phi_2) + \mu_{13}(\Phi_1^\dagger\Phi_3) + \mu_{23}(\Phi_2^\dagger\Phi_3) + h.c.\right)$$
$$+\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_3^\dagger\Phi_3)^2 + \lambda_4(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_5(\Phi_1^\dagger\Phi_1)(\Phi_3^\dagger\Phi_3)$$
$$+\lambda_6(\Phi_2^\dagger\Phi_2)(\Phi_3^\dagger\Phi_3) + \lambda_7(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \lambda_8(\Phi_1^\dagger\Phi_3)(\Phi_3^\dagger\Phi_1) + \lambda_9(\Phi_2^\dagger\Phi_3)(\Phi_3^\dagger\Phi_2)$$
$$+ \left(\lambda_{10}(\Phi_1^\dagger\Phi_2)^2 + \lambda_{11}(\Phi_1^\dagger\Phi_3)^2 + \lambda_{12}(\Phi_2^\dagger\Phi_3)^2 + h.c\right)$$

24 parameters

Parametrization

$$\lambda, \mu\ (v_i,\ m_i^2,\ R_{ij})$$

$$(G^0,\ z_2',\ z_3')^T = R_H\,(z_1,\ z_2,\ z_3)^T$$

$$(h_1,\ h_2,\ h_3,\ h_4,\ h_5)^T = R\,(x_1,\ x_2,\ x_3,\ z_2',\ z_3')^T$$

3 of the 5 neutral scalar masses become dependent parameters.

There are 22 free parameters in the scalar potential (20 after fixing the Higgs mass and the vev).

The Yukawa Sector

We consider h_{125} to be the lightest neutral scalar.

The $Z_2 \times Z_2$ symmetry ensures **NFC**.

The couplings of the neutral scalars are then:

$$h_{125} = h_1$$

$$Z_2 : \Phi_1 \to -\Phi 1,\ \ell_R \to -\ell_R$$
$$Z_2' : \Phi_2 \to -\Phi 2,\ d_R \to -d_R$$

$$c^e_{h_j f f} = \frac{v}{v_f} Q_{j+1,f}$$
$$c^o_{h_j f f} = \pm \frac{v}{v_f} Q_{j+1,3+f}$$

Q is the rotation matrix from the symmetry basis to the mass basis

Inverting the Higgs couplings

$$c_f^e = \frac{v}{v_f} Q_{2,f}$$
$$c_f^o = \pm \frac{v}{v_f} Q_{2,3+f}$$

$$\kappa_V = Q_{2i}\hat{v}_i = R_{1i}\hat{v}_i$$

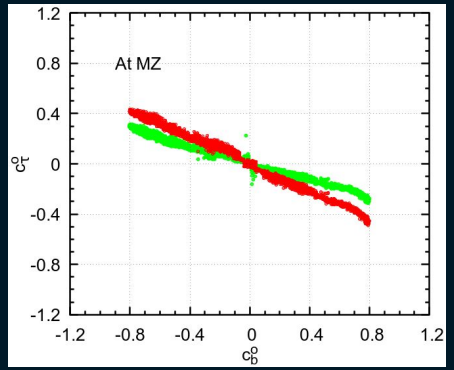
The seven Higgs couplings to fermions and gauge bosons are regulated by six parameters.

There is a constraint between these couplings:

$$\Delta_i = (c_i^e)^2 + (c_i^o)^2 - 1$$

$$\kappa_V \left(\Delta_1 c_{23}^o + \Delta_2 c_{31}^o + \Delta_3 c_{12}^o\right) = \Delta_1 \left(c_2^o c_3^e - c_3^o c_2^e\right) + \Delta_2 \left(c_3^o c_1^e - c_1^o c_3^e\right) + \Delta_3 \left(c_1^o c_2^e - c_2^o c_1^e\right)$$

$h_{125}tt$ near the SM value suggest an anti-correlation between the odd components c_τ^o / c_b^o



$$c_\tau^o \approx -\tan^2(\beta_1)\, c_b^o$$

scan points in **red**;
equation above in **green**.

Constraints

Theoretical:

1. Perturbative Yukawa Couplings;
2. Perturbative Unitarity;
3. Sufficient BFB conditions.

Phenomenological:

1. Higgs Signal Strengths;
2. Searches for nonstandard scalars, using HiggsTools;
3. STU parameters;
4. Flavor constraints: $b \to s\gamma$ and meson mass differences;
5. EDM.

Scanning strategies

- Random Scan;
- Importing from the real model (near alignment)

  +

  Enlarging the pseudoscalar component;
- Wrong Sign;

  [arXiv:2301.00231]

Random Scan

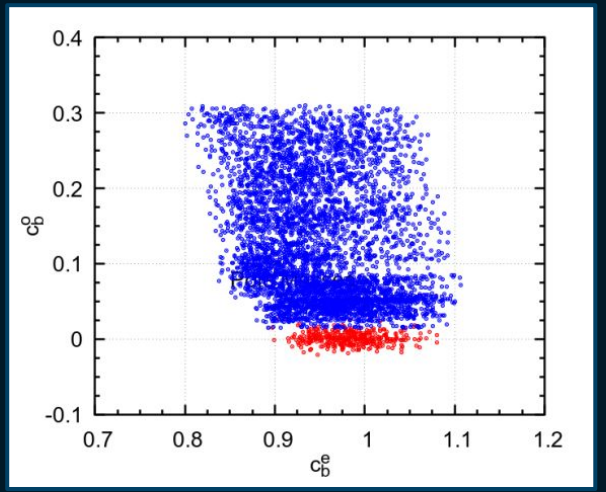
$$\theta,\ \varphi,\ \alpha_{12},\ \alpha_{13},\ \alpha_{14},\ \alpha_{15},\ \alpha_{23},\ \alpha_{24},\ \alpha_{25},\ \alpha_{34},\ \alpha_{35},\ \alpha_{45} \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right];$$

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

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

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

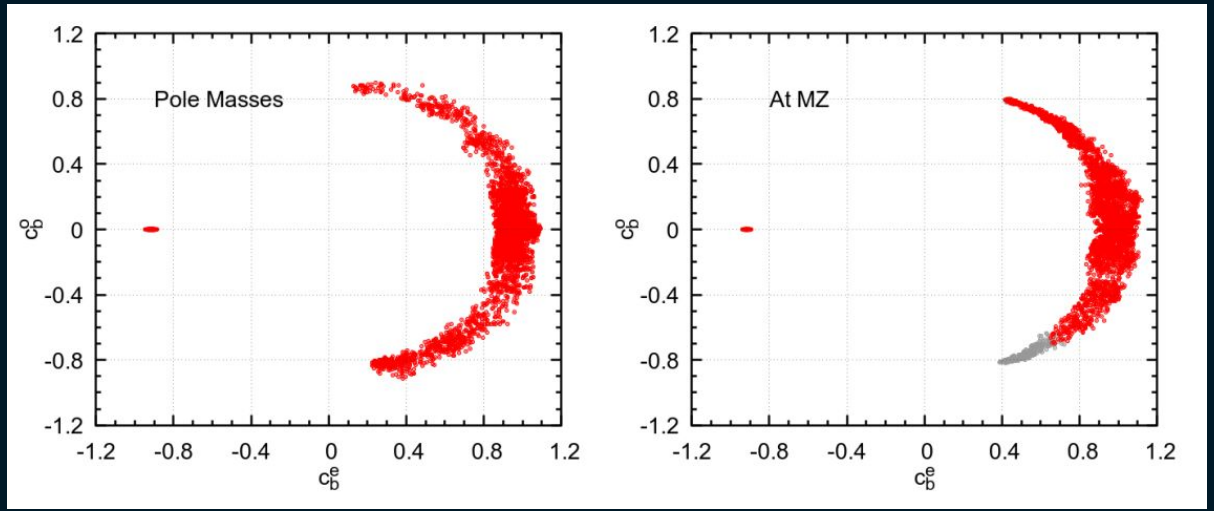
Enlarging the pseudoscalar component



Results

We revive the possibility of CPV $h_{125}bb$ couplings;

The anti-correlation between c_τ^o/c_b^o impacts our results.



Conclusions

We derived the parametrization of the softly-broken $Z_2 \times Z_2$ - symmetric C3HDM.

The freedom of the type-Z is still limited.

The possibility of mostly CPV hbb couplings is resuscitated in the C3HDM, with the maximal value around (0.4, 0.8).