Towards phenomenology of CP4 3HDM

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based on:
IPI, J. P. Silva, PRD 93, 095014 (2016)
A. Aranda, IPI, E. Jiménez, PRD 95, 055010 (2017)

A. Aranda, P. Ferreira, IPI, E. Jiménez, R. Pasechnik, E. Peinado, H. Serodio, work in progress

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Model-building with multiple Higgses

Within SM:

1. *CP*-violation does not follow from the gauge structure; just put to comply with experimental measurements;
2. the scalar sector is overstretched: gives mass to gauge bosons, up-quarks, and down-quarks $\to$ no explanation for flavor puzzle.

An attractive idea

the scalar sector can well be non-minimal, and it can provide a natural explanation to CPV and fermion puzzle.

$\Rightarrow$ intense model-building activity with non-minimal Higgs sectors, see e.g. the recent review [Ivanov, 1702.03776]

Model-building with multiple Higgses

Many Higgses → many interaction terms → huge number of free parameters.

Extra global symmetries are useful when building multi-Higgs models.

- Impose a large discrete symmetry group $G = A_4, \Delta(27), \ldots$: very few free parameters, nicely calculable, very predictive, and unphysical.
- Allow for soft breaking of G or introduce new fields → many more parameters, *ad hoc* assumptions, less predictive.
- Impose small symmetry groups: still many free parameters, compatible with experiment but not particularly predictive.

Ideal choice

a symmetry setting which assumes little, predicts much, and fits experiment in a non-trivial way.

CP4 3HDM

I will show a peculiar model based on three Higgs doublets (3HDM) which is attractive in several aspects.

- assumes very little: this is the minimal model realizing one particular symmetry;
- this symmetry is unusual: generalized *CP*-symmetry of order 4 (CP4). This is the first ever model based on CP4 without any accidental symmetry.
- It is tractable analytically and quite predictive.

In short, a good balance of minimality, predictive power, and theoretical flair.

Freedom of defining CP

in QFT, CP is not uniquely defined *a priori*.

- phase factors $\phi(\vec{r},t) \xrightarrow{CP} e^{i\alpha}\phi^*(-\vec{r},t)$ [Feinberg, Weinberg, 1959],
- with N scalar fields ϕ_i, the general CP transformation is

$$J: \quad \phi_i \xrightarrow{CP} X_{ij}\phi_j^*\,, \quad X \in U(N)\,.$$

  If $\mathcal{L}$ is invariant under such J with whaever fancy X, it is explicitly CP-conserving [Grimus, Rebelo, 1997; Branco, Lavoura, Silva, 1999].

- NB: The “standard” convention $\phi_i \xrightarrow{CP} \phi_i^*$ is basis-dependent!

Freedom of defining CP

$$J: \quad \phi_i \xrightarrow{CP} X_{ij}\phi_j^*\,, \quad X \in U(N)\,,$$

Applying J twice leads to family transformation $J^2 = XX^*$ which may be non-trivial. It may happen than only $J^k = \mathbb{I}$ ($k =$ power of 2).

CP-symmetry does not have to be of order 2

The usual CP = CP2, the first non-trivial is CP4, then CP8, CP16, etc.

Models with higher-order GCP were known in 2HDM [Ferreira, Haber, Maniatis, Nachtmann, Silva, 2011] but they always led to accidental symmetries including the usual CP.

The question

what is the minimal multi-Higgs-doublet model

realizing CP4 without accidental symmetries?

CP4 3HDM

The answer was given in [Ivanov, Keus, Vdovin, 2012].

Consider 3HDM with the following potential $V = V_0 + V_1$ (notation: $i \equiv \phi_i$):

$$V_0 = -m_{11}^2(1^\dagger 1) - m_{22}^2(2^\dagger 2 + 3^\dagger 3) + \lambda_1(1^\dagger 1)^2 + \lambda_2\left[(2^\dagger 2)^2 + (3^\dagger 3)^2\right]$$
$$+\lambda_3(1^\dagger 1)(2^\dagger 2 + 3^\dagger 3) + \lambda_3'(2^\dagger 2)(3^\dagger 3) + \lambda_4\left[(1^\dagger 2)(2^\dagger 1) + (1^\dagger 3)(3^\dagger 1)\right] + \lambda_4'(2^\dagger 3)(3^\dagger 2)\,,$$

with all parameters real, and

$$V_1 = \lambda_5(3^\dagger 1)(2^\dagger 1) + \frac{\lambda_6}{2}\left[(2^\dagger 1)^2 - (3^\dagger 1)^2\right] + \lambda_8(2^\dagger 3)^2 + \lambda_9(2^\dagger 3)\left[(2^\dagger 2) - (3^\dagger 3)\right] + h.c.$$

with real $\lambda_{5,6}$ and complex $\lambda_{8,9}$. It is invariant under CP4 $J:\ \phi_i \xrightarrow{CP} X_{ij}\phi_j^*$ with

$$X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & i \\ 0 & -i & 0 \end{pmatrix}, \quad J^2 = \mathrm{diag}(1, -1, -1)\,, \quad J^4 = \mathbb{I}\,.$$

Two versions of CP4 3HDM

Two versions of CP4 3HDM:

- DM CP4 3HDM: CP4 is only within scalar sector, ϕ_2, ϕ_3 decouple from fermions and don't get vevs $\to$ similar to the inert doublet model in 2HDM.

  Contains *CP*-half-odd scalars: $\Phi(\vec{x}, t) \xrightarrow{CP} i\Phi(-\vec{x}, t)$.
- flavored CP4 3HDM: CP4 is extended to the Yukawa sector and must be spontaneously broken $\to$ leads to particular patterns in the flavor sector.

Both versions are now under investigation.

Flavored CP4 3HDM

Extending CP4 to the Yukawa sector: must mix fermion families $\psi_i \to Y_{ij}\psi_j^{CP}$, where $\psi^{CP} = \gamma^0 C \bar{\psi}^T$.

$$-\mathcal{L}_Y = \bar{q}_L \Gamma_a d_R \phi_a + \bar{q}_L \Delta_a u_R \phi_a^* + h.c.$$

is invariant under CP4 with known X_{ab} if

$$(Y^L)^\dagger \Gamma_a Y^d X_{ab} = \Gamma_b^*\,, \quad (Y^L)^\dagger \Delta_a Y^u X_{ab}^* = \Delta_b^*\,.$$

We solved these equations = found Yukawa matrices Γ's and Δ's and mixing matrices Y^L, Y^d, Y^u, which satisfy all these conditions and do not lead to immediate problems with masses and mixing.

Very few possibilities arise: cases A, B1, B2, B3.

Flavored CP4 3HDM

For example, case B3:

$$\Gamma_1 = \begin{pmatrix} g_1 & 0 & 0 \\ 0 & g_1^* & 0 \\ 0 & 0 & g_3 \end{pmatrix}, \quad \Gamma_2 = \begin{pmatrix} 0 & 0 & g_{13} \\ 0 & 0 & g_{23} \\ g_{31} & g_{32} & 0 \end{pmatrix}, \quad \Gamma_3 = \begin{pmatrix} 0 & 0 & -g_{23}^* \\ 0 & 0 & g_{13}^* \\ g_{32}^* & -g_{31}^* & 0 \end{pmatrix}.$$

When multiplied by vevs (v_1, v_2, v_3), they produce fermion mass matrices

$$M_d = \frac{1}{\sqrt{2}} \sum \Gamma_a v_a\,, \quad M_u = \frac{1}{\sqrt{2}} \sum \Delta_a v_a^*\,.$$

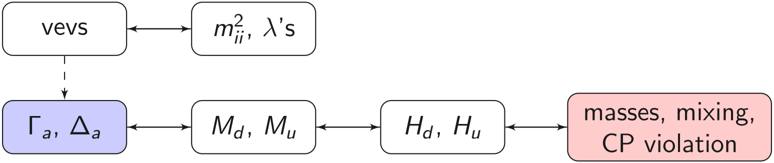
which need to reproduce the experimental values of masses, mixing, CPV.

NB: v_2, v_3 must be nonzero to avoid degenerate fermions!

Flavored CP4 3HDM

Enough free parameters to fit the fermion properties? YES!

[A. Aranda, P. Ferreira, IPI, E. Jiménez, R. Pasechnik, E. Peinado, H. Serodio, work in progress]

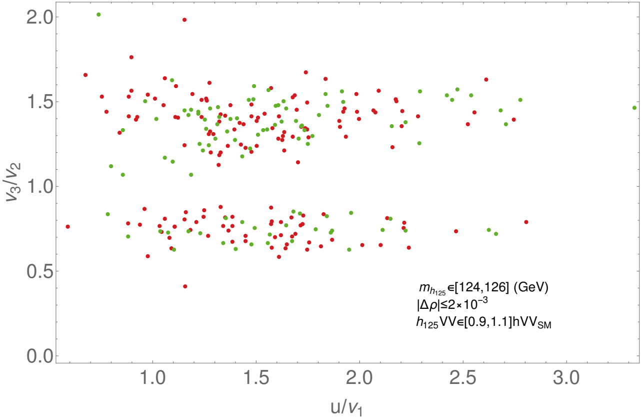


We developed a very efficient backward scan in the Yukawa sector:

- $H_{d,u} \equiv M_{d,u} M_{d,u}^\dagger$ compatible with masses and CKM is generated;
- M_d, M_u are reconstructed numerically from H_d, H_u ($+V_R$'s);
- with known vevs, Γ_a, Δ_a are reconstructed uniquely and analytically.

Flavored CP4 3HDM

Typical vevs: v_3/v_2 vs. $u/v_1 \equiv \sqrt{v_2^2 + v_3^2}/v_1$.



Red dots = wrong sign Yukawas, green dots = normal Yukawas.

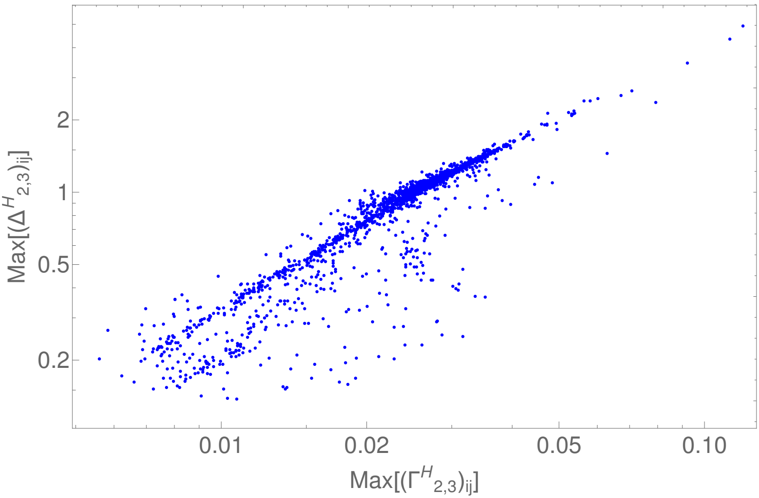
Tree-level FCNCs

- Γ_a and Δ_a do not possess built-in suppression of FCNCs.
- In the Higgs basis ($\langle \Phi_1^0 \rangle = v/\sqrt{2}$, $\langle \Phi_{2,3} \rangle = 0$):

$$\bar{d}_L D_d d_R (1 + h_1/v) + \bar{d}_L \Gamma_2^{(H)} d_R \Phi_2^0 + \bar{d}_L \Gamma_3^{(H)} d_R \Phi_3^0 \,,$$

where $\Gamma_{2,3}^{(H)}$ and $\Delta_{2,3}^{(H)}$ generically have large off-diagonal elements.

Tree-level FCNCs



Tree-level FCNCs

The only resort is a strong alignment in the scalar sector: $h_1 = h_{125}$.

$$\begin{aligned} V &= -m_{11}^2(1^\dagger 1) - m_{22}^2(2^\dagger 2 + 3^\dagger 3) + \lambda_1(1^\dagger 1)^2 + \lambda_2\left[(2^\dagger 2)^2 + (3^\dagger 3)^2\right] \\ &+\lambda_3(1^\dagger 1)(2^\dagger 2 + 3^\dagger 3) + \lambda_3'(2^\dagger 2)(3^\dagger 3) + \lambda_4\left[(1^\dagger 2)(2^\dagger 1) + (1^\dagger 3)(3^\dagger 1)\right] + \lambda_4'(2^\dagger 3)(3^\dagger 2)\,, \\ &+\lambda_5(3^\dagger 1)(2^\dagger 1) + \frac{\lambda_6}{2}\left[(2^\dagger 1)^2 - (3^\dagger 1)^2\right] + \lambda_8(2^\dagger 3)^2 + \lambda_9(2^\dagger 3)\left[(2^\dagger 2) - (3^\dagger 3)\right] + h.c. \end{aligned}$$

Exact alignment condition

$$m_{11}^2 = m_{22}^2$$

Potentially large FCNCs are still generated by other Higgses
$\Rightarrow$ they must be kept heavy to satisfy flavor constraints.

Conclusions

- CP4 3HDM is the minimal model implementing higher-order CP without accidental symmetries.
- If unbroken, CP4 leads to *CP*-half-odd scalars—something never seen before.
- CP4 can be extended to the Yukawa sector $\rightarrow$ very few cases possible, CP4 must be broken $\rightarrow$ very characteristic flavor sectors.
- The model is built on a single assumption and is, surprisingly, rather unique, predictive, and rich. It easily fits all fermion masses, mixing, CPV, and brings FCNCs of h_{125} under control.
- We are now working on it implementing the model in SARAH/SPheno and checking flavor and collider observables.