3HDM with a CP symmetry of order 4: a phenomenological update

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Higgs 2023

Beijing, November 30th, 2023

Based on: Zhao, Ivanov, Pasechnik, Zhang, JHEP 04 (2023) 116 = arXiv:2302.03094
Liu, Ivanov, Gonçalves, work in progress, and earlier papers.

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N-Higgs-doublet models

Higgses can come in generations → NHDMs [T.D.Lee 1973, Weinberg 1976, . . .]

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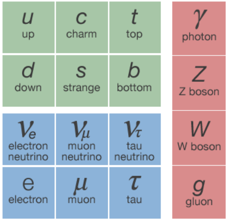

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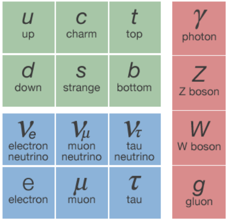
Multi-Higgs-doublet models



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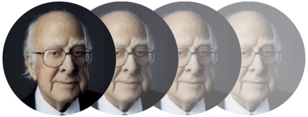

3HDM vs 2HDM

2HDMs explored in thousands of papers [Branco et al, 1106.0034].

What new can 3HDMs bring? [Ivanov, 1702.03776]

- More options for model-building (scalar and fermion) ⇒ richer pheno!
  - new options for *CP* violation [Branco, Gerard, Grimus, 1984];
  - an exotic *CP* symmetry of order 4 [Ivanov, Silva, 2015];
  - combining features of 2HDM: NFC + CPV [Weinberg, 1976; Branco, 1979], scalar DM + CPV [Grzadkowski et al, 2009].
  - astroparticle consequences: various dark sectors [Cordero et al, 2017]; new options for baryon asymmetry [Davoudiasl, Lewis, Sullivan, 2019]; multi-step phase transitions.

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  - astroparticle consequences: various dark sectors [Cordero et al, 2017]; new options for baryon asymmetry [Davoudiasl, Lewis, Sullivan, 2019]; multi-step phase transitions.
- Many symmetry options tested starting from late 1970's [many classic papers].

Symmetries = the single most powerful novelty of the 3HDMs.

CP4 3HDM

A dilemma in symmetry-based multi-Higgs model building:

- Large symmetry groups $\to$ very few free parameters, nicely calculable, very predictive, but conflicts experiment.
- Small symmetry groups $\to$ many free parameters, compatible with experiment but not quite predictive.

I will show a peculiar model based on three Higgs doublets (3HDM) which

- assumes very little: the minimal model realizing a particular symmetry;
- this symmetry is unusual: *CP*-symmetry of order 4 (CP4);
- remarkable connections between the scalar and Yukawa sectors $\to$ predictions.

A good balance between minimality, predictive power, and theoretical appeal.

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A hidden gem: CP4 3HDM

CP4 = CP symmetry of order 4 = you need to apply it four times to get the identity.

Higher order 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].

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- With N scalar fields ϕ_i, the general CP transformation is $\phi_i \xrightarrow{CP} X_{ij}\phi_j^*$, $X \in U(N)$.
- If $\mathcal{L}$ is invariant under CP with any X, it is explicitly CP-conserving [Grimus, Rebelo, 1997; Branco, Lavoura, Silva, 1999].

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- If $\mathcal{L}$ is invariant under CP with any X, it is explicitly CP-conserving [Grimus, Rebelo, 1997; Branco, Lavoura, Silva, 1999].
- Squaring general $CP \to$ a family transformation:

$$\phi_i \xrightarrow{CP} X_{ij}\phi_j^* \xrightarrow{CP} X_{ij}(X_{jk}^*\phi_k) = (XX^*)_{ik}\phi_k\,.$$

It can happen that $(CP)^2 = XX^* \neq \mathbb{I}$ but $(CP)^k = \mathbb{I}$ for $k > 2$.

CP-symmetry can be of a higher order $k > 2$.

The usual CP is of order 2. The exotic CP with $k = 4$ is denoted CP4.

CP4 3HDM

What is the minimal NHDM realizing CP4 without accidental symmetries?

The answer was given in Ivanov, Silva, 1512.09276.

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

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

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 $\phi_i \xrightarrow{CP} X_{ij}\phi_j^*$ with

$$X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & i \\ 0 & -i & 0 \end{pmatrix} \quad \Rightarrow \quad XX^* = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}.$$

Different versions of CP4 3HDM

- A *CP*-conserving model based on CP4 can be distinguished from a *CP*-conserving model based on the usual CP [Haber et al, 1808.08629].
- DM CP4 3HDM: unbroken CP4 with scalar DM candidates, similar to the inert doublet model in 2HDM. We assume that ϕ_2, ϕ_3 don't get vevs $\to$ scalar DM candidates with very peculiar properties [Ivanov, Silva, 2015; Ivanov, Laletin, 2018]:

  neutral scalars are neither CP even nor CP odd but are "CP-half-odd".

  Scalar DM stabilized by a CP-symmetry!

- flavored CP4 3HDM: CP4 is extended to the Yukawa sector and must be spontaneously broken $\to$ patterns in the flavor sector [Aranda et al, 1608.08922; Ferreira et al, 1711.02042]

The flavored CP4 3HDM

CP4-symmetric quark sector

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

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

is invariant under CP4 if

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

Only X_{ab} is known. Γ_a, Δ_a, Y^L, Y^{d_R}, Y^{u_R} are to be found.

Solved in Ferreira et al, 1711.02042 $\to$ only four options for Γ_a and for Δ_a exist.

CP4-symmetric quark sector

case A: $\Gamma_1 \simeq$ arbitrary real matrix, $\Gamma_{2,3} = 0$.

case B_1

$$\Gamma_1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ g_{31} & g_{31}^* & g_{33} \end{pmatrix}, \quad \Gamma_2 = \begin{pmatrix} g_{11} & g_{12} & g_{13} \\ g_{21} & g_{22} & g_{23} \\ 0 & 0 & 0 \end{pmatrix}, \quad \Gamma_3 = \begin{pmatrix} -g_{22}^* & -g_{21}^* & -g_{23}^* \\ g_{12}^* & g_{11}^* & g_{13}^* \\ 0 & 0 & 0 \end{pmatrix}.$$

case B_2

$$\Gamma_1 = \begin{pmatrix} 0 & 0 & g_{13} \\ 0 & 0 & g_{13}^* \\ 0 & 0 & g_{33} \end{pmatrix}, \quad \Gamma_2 = \begin{pmatrix} g_{11} & g_{12} & 0 \\ g_{21} & g_{22} & 0 \\ g_{31} & g_{32} & 0 \end{pmatrix}, \quad \Gamma_3 = \begin{pmatrix} g_{22}^* & -g_{21}^* & 0 \\ g_{12}^* & -g_{11}^* & 0 \\ g_{32}^* & -g_{31}^* & 0 \end{pmatrix}.$$

case B_3

$$\Gamma_1 = \begin{pmatrix} g_{11} & g_{12} & 0 \\ -g_{12}^* & g_{11}^* & 0 \\ 0 & 0 & g_{33} \end{pmatrix}, \quad \Gamma_2 = \begin{pmatrix} 0 & 0 & g_{13} \\ 0 & 0 & g_{23} \\ g_{31} & g_{32} & 0 \end{pmatrix}, \quad \Gamma_3 = \begin{pmatrix} 0 & 0 & -g_{23}^* \\ 0 & 0 & g_{13}^* \\ g_{32}^* & -g_{31}^* & 0 \end{pmatrix}.$$

CP4-symmetric quark sector

When combining up and down quarks, need to match α_L: 8 combinations.

$$(A^{down}, A^{up})\,, \quad (A^{down}, B_2^{up})\,, \quad (B_2^{down}, A^{up})\,, \quad (B_2^{down}, B_2^{up})\,,$$
$$(B_1^{down}, B_1^{up})\,, \quad (B_1^{down}, B_3^{up})\,, \quad (B_3^{down}, B_1^{up})\,, \quad (B_3^{down}, B_3^{up})\,.$$

- case (A, A) implies a real CKM $\to$ disregarded.
- cases B_1, B_2, B_3: quark mass matrices

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

all v_i must be nonzero to avoid mass-degenerate quarks.

FCNC in CP4 3HDM

- Tree-level flavor-changing neutral couplings (FCNC) are a generic feature of multi-Higgs models.
- Unsuppressed FCNCs conflict meson oscillation parameters $\to$ need to be eliminated or suppressed (recent review: Sher, 2207.06771).

What's the status of FCNCs in the CP4 3HDM?

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What's the status of FCNCs in the CP4 3HDM?

- CP4 leads to remarkably tight connections between the Yukawa and scalar sectors
  $\to$ no built-in suppression of FCNC.
- Avoiding FCNC from h_{125} via the scalar alignment condition: $m_{11}^2 = m_{22}^2$.
- But then the additional neutral Higgses may exhibit significant FCNCs.

Must be explored in a full scan of the parameter space.

FCNC in CP4 3HDM

- In Ferreira et al, 1711.02042, we reported the first pheno scan of the parameter space (theory constraints, EWPT, fermion masses and mixing, meson oscillation parameters) $\rightarrow$ many benchmark points found.
- Ruled out in Ivanov, Obodenko, 2104.11440 based on the LHC Run 2 charged Higgs searches.
- Need to repeat the scan — but do it in a smart way.

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- Need to repeat the scan — but do it in a smart way.
- The usual scanning procedure

$$\text{random seed point in } \Gamma_i,\, \Delta_i \quad \Rightarrow \quad \text{fit } m_q,\, \text{CKM}$$

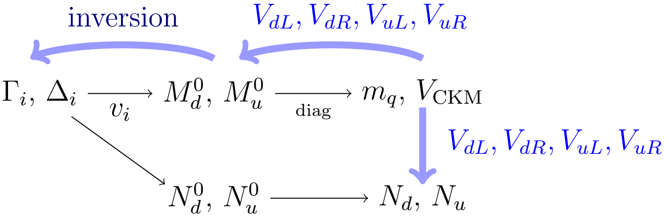
  is very time consuming: many trial points are thrown away.
- A more efficient scanning procedure is needed:

$$\text{start with } m_q,\, \text{CKM} \quad \Rightarrow \quad \text{reconstruct } \Gamma_i,\, \Delta_i$$

  If this inversion is feasible, every trial point will give a viable model.

Scanning CP4 3HDM Yukawa sector: inversion

In Zhao et al, 2302.03094 = JHEP 04 (2023) 116, we constructed an inversion procedure.



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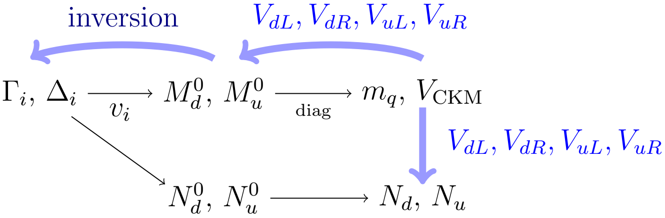

We expressed the FCNC matrices N_d, N_u via physical quark observables and quark rotation parameters.

FCNC in CP4 3HDM

Let's gain some intuition with a toy model:

$$V_{dL}, V_{dR}, V_{uL}, V_{uR} \sim \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix} = \begin{pmatrix} c_\theta e^{i\alpha} & s_\theta e^{i\zeta} & 0 \\ -s_\theta e^{-i\zeta} & c_\theta e^{-i\alpha} & 0 \\ 0 & 0 & e^{i\gamma} \end{pmatrix} .$$

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Then, in the case B_1, we get

$$N_{d2} = \begin{pmatrix} m_d \cot\beta & 0 & 0 \\ 0 & m_s \cot\beta & 0 \\ 0 & 0 & -m_b \tan\beta \end{pmatrix},$$

$$N_{d3} = \frac{1}{s_\beta} \begin{pmatrix} -m_s c_{2\theta} & -m_s s_{2\theta} e^{-i(\alpha-\zeta)} & 0 \\ -m_d s_{2\theta} e^{i(\alpha-\zeta)} & m_d c_{2\theta} & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

CP4 feature: $\Phi_3 d\bar{d} \propto m_s$, not m_d; $\Phi_3 d\bar{s} \propto m_s$, not $\sqrt{m_d m_s}$.

FCNC in CP4 3HDM

Before doing a full pheno scan, the dimensionless off-diagonal elements of N_d's and N_u's can be constrained by K, B, B_s and D-meson oscillation parameters.

- What is the typical FCNC magnitude in each Yukawa sector?
- How small the FCNCs can in principle become? What controls their smallness?
- Can some CP4 3HDM Yukawa sectors be already excluded?

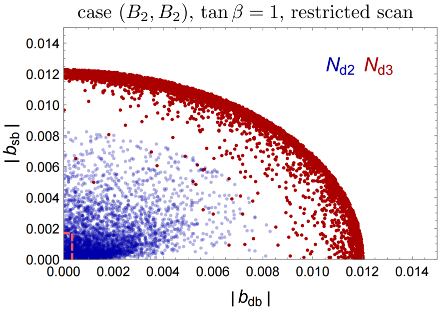
In Zhao et al, 2302.03094, we explored these questions with our inversion procedure.

Results of the numerical study 2302.03094

Out of 8 possible CP4 Yukawa sectors, only two are viable: (A, B_2) and (B_1, B_1).

The other scenarios fail! For example, (B_2, B_2) is excluded by B_s vs. B.

Here, FCNCs from N_{d3} are far outside the box even for a 1 TeV scalar!



The full pheno scan should only be based on (A, B_2) and (B_1, B_1).

Conclusions

- CP4 3HDM is the minimal model implementing a CP symmetry of order 4 (CP4) without accidental symmetries.
- CP4 can be extended to the Yukawa sector $\to$ very characteristic flavor sector.
- Out of 8 possible CP4 invariant Yukawa sectors, only two scenarios — (A, B_2) and (B_1, B_1) — lead to viable models!
- Detailed pheno study (scalar + mesons obs. + leptons) is underway.

Tired of the 2HDM and singlets? Try CP4 3HDM

- based on a single symmetry assumption,
- quite predictive with rich phenomenology,
- analytical insights guide numerical exploration.