CP-symmetry of order 4: model-building and phenomenology

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based on:
I. P. Ivanov, J. P. Silva, PRD 93, 095014 (2016)
A. Aranda, I. P. Ivanov, E. Jiménez, PRD95, 055010 (2017)
work in progress

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Model-building with multiple Higgses

1. Within SM, *CP*-violation does not follow from the gauge structure of the model. It is put by hand as a numerical fact needed to comply with experiment.
2. Within SM, the scalar sector is overstretched: gives mass to gauge bosons, up-quarks, and down-quarks. $\rightarrow$ no explanation to fermion sector puzzles (quark masses/mixing, neutrinos, etc.).

An attractive idea

the scalar sector can 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. 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 well tractable analytically and quite predictive.

In short, a good balance of minimality, predictiveness, and peculiarity.

Freedom of defining CP

In QFT, discrete transformations such as CP are not uniquely defined *a priori* e.g. [Feinberg, Weinberg, 1959]. If a multi-Higgs-doublet model is invariant under a generalized *CP* transformation (GCP)

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

with any X, then it is *CP*-conserving, and J plays the role of "the CP symmetry" e.g. [Branco, Lavoura, Silva, 1999]. The "standard" convention $\phi_i \xrightarrow{CP} \phi_i^*$ is basis-dependent.

Applying J twice leads to family transformation $J^2 = XX^* \neq \mathbb{I}$
$\to$ *CP*-symmetry does not have to be of order 2.

Examples of higher-order CP were known in 2HDM [Ferreira, Haber, Maniatis, Nachtmann, Silva, 2011] but so far they always led to accidental symmetries including usual CP.

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CP4 3HDM

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 order-4 CP:

$$J:\ \phi_i \xrightarrow{CP} X_{ij}\phi_j^*\,, \quad X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & i \\ 0 & -i & 0 \end{pmatrix}.$$

Its square, $J^2 = XX^* = \mathrm{diag}(1, -1, -1)$ and $J^4 = \mathbb{I}$.
This model has no other symmetries [Ivanov, Keus, Vdovin, 2012].

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.
- 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.

DM CP4 3HDM

CP4-conserving minimum: $v_i = (v,\, 0,\, 0)$.

Physical scalars: h_{SM}, degenerate $H^{\pm}_{2,3}$, and two pairs of degenerate neutrals: the heavier H and A and the ligher h and a, with masses

$$M^2,\, m^2 = -m_{22}^2 + \frac{v^2}{2}\left(\lambda_3 + \lambda_4 \pm \sqrt{\lambda_5^2 + \lambda_6^2}\right)\,.$$

These real neutrals are not CP-eigenstates:

$$H \xrightarrow{CP} A, \quad A \xrightarrow{CP} -H\,, \quad h \xrightarrow{CP} -a, \quad a \xrightarrow{CP} h\,.$$

They can be combined into neutral complex CP-eigenstate fields

$$\Phi = \frac{1}{\sqrt{2}}(H - iA)\,, \quad \varphi = \frac{1}{\sqrt{2}}(h + ia)\,, \quad \Phi \xrightarrow{CP} i\Phi\,, \quad \varphi \xrightarrow{CP} i\varphi\,.$$

Conserved quantum number: not CP-parity but CP-charge q defined mod 4.

DM CP4 3HDM

$$\Phi(t,\vec{x}) \xrightarrow{CP} i\Phi(t,-\vec{x})\,, \quad \varphi(t,\vec{x}) \xrightarrow{CP} i\varphi(t,-\vec{x})\,.$$

The absence of conjugation is highly peculiar. It comes from the enhanced freedom of basis change transformations $U(N) \to O(2N)$, which becomes available for multiple mass-degenerate zero-charge fields [Aranda, Ivanov, Jimenez, 2017].

Notice that $\varphi^*|0\rangle$ is not the antiparticle of $\varphi|0\rangle$ but is a different one-particle state with the same mass $\to$ an example of spectrum doubling beyond Kramers degeneracy mentioned e.g. in [Weinberg, vol. 1, app. 2C].

NB: we never redefine the CP-symmetry itself. It is the same CP4 as in the starting lagrangian. We just applied the allowed basis change.

DM CP4 3HDM

Some properties of the two DM candidates: h, a (in terms of real fields) or φ, φ^* (in terms of complex fields):

- their mass degeneracy follows from discrete rather continuous symmetry,
- they cannot coannihilate into Z-boson; they need to pick up a heavier scalar for that:

$$\mathcal{L} \supset \frac{\bar{g}}{2} Z_\mu \left(H \overleftrightarrow{\partial} a + h \overleftrightarrow{\partial} A \right) \quad \text{or} \quad i\frac{\bar{g}}{2} Z_\mu \left(\varphi \overleftrightarrow{\partial} \Phi - \varphi^* \overleftrightarrow{\partial} \Phi^* \right) .$$

- they can rescatter not only as $ha \to ha$ or $hh \leftrightarrow aa$ but also $aa \leftrightarrow ha \leftrightarrow hh$, or $\varphi\varphi \to \varphi^*\varphi^*$.
- They can scatter on SM fields without changing type: h+SM $\not\to$ a+SM.

We are now implementing this model in micrOMEGAs.

Flavored CP4 3HDM

Can the CP-half-odd scalars have CP-conserving Yukawa interactions?
Yes, provided the CP mixes the fermion families.

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

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

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.

Flavored CP4 3HDM

case A: $\Gamma_1 =$ arbitrary real, $\Gamma_2, \Gamma_3 = 0$

- resembles other 3HDMs with two inert doublets [Machado, Pleitez, 2012; Keus, King, Moretti, Sokolowska, 2014];
- vevs (v_1, v_2, v_3) spontaneously break CP4 $\to$ the model is *CP*-violating;
- nevertheless tree-level V_{CKM} is real, tree-level FCNCs are absent, but they can arise via loops with extra scalars. Is it sufficient to produce enough CPV in the RGE-improved V_{CKM}?

Flavored CP4 3HDM

Cases B1, B2, B3 with non-trivial Γ's and Δ's. For example, in case B3:

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

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.

Flavored CP4 3HDM

We have developed efficient codes for parameter scans in scalar and Yukawa sector which start with random scan and, with $\sim 50\%$ efficiency, find good parameter space points (models which are fully compatible with all quark masses, mixing, and CPV).

The next steps (work in progress):

- checking couplings and FCNCs of the SM-like Higgs,
- implementing the model in SARAH+SPheno and checking all flavor observables,
- checking collider bounds on extra Higgses.

We will soon have concrete examples of this very minimalistic model passing all experimental constraints and leading to specific predictions.

Conclusions

- CP4 3HDM is the minimal model realizing the idea of higher-order generalized CP, without producing extra accidental symmetries.
- It leads to *CP*-half-odd scalars — something never seen before.
- On the pheno side, it produces, in different regimes, models with two DM candidates with particular properties, or models which address the flavor puzzle via spontaneous breaking of CP4. We are now exploring both.
- The model assumes very little, but surprisingly enough leads to rich and predictive phenomenology.