Constraining CP4 3HDM with meson oscillations

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Based on: D. Zhao, I.P.I., R. Pasechnik, P. Zhang, JHEP 04 (2023) 116

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Multi-Higgs model building

New scalar fields $\rightarrow$ many interaction terms $\rightarrow$ lots of free parameters + often intractable analytically.

Imposing global symmetries: a way to proceed, e.g. Ishimori et al, 1003.3552.

Why imposing global symmetries?

- fewer parameters, often tractable analytically $\rightarrow$ anchor structures in the vast parameter space of the general model;
- robust way of achieving desired pheno features;
- but, of course, one needs to draw the map

$$\text{symmetry groups} \quad \Leftrightarrow \quad \text{phenomenology}$$

within each class of multi-Higgs models.

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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.

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

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Higher order CP

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

- with N scalar fields ϕ_i, the general CP transformation is

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

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

- 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 $k > 2$.

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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

$$X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & i \\ 0 & -i & 0 \end{pmatrix}, \quad XX^* = \mathrm{diag}(1, -1, -1)\,.$$

CP4 3HDM

A group-theoretic peculiarity: the symmetry group generated by

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

is the abelian group $\mathbb{Z}_4$ but it unavoidably mixes Higgs families.

There is no basis change which makes X diagonal.

This feature leads to important phenomenological consequences.

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 with known X_{ab} if

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

Matrices Y's can be brought to the form:

$$Y = \begin{pmatrix} 0 & e^{i\alpha} & 0 \\ e^{-i\alpha} & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

with α_L, α_{dR}, α_{uR} being free parameters.

Solved in Ferreira et al, 1711.02042 $\to$ only four options exist.

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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 real CKM $\to$ disregarded.
- cases B_1, B_2, B_3: quark mass matrices

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

$v_1 v_2$ AND v_3 must be nonzero to avoid mass-degenerate quarks.

FCNCs in multi-Higgs models

- Tree-level flavor-changing neutral couplings (FCNC) are a generic feature of multi-Higgs models.
- Unsuppressed FCNCs conflict meson oscillation parameters → need to be eliminated or suppressed (recent review: Sher, 2207.06771).
- 2HDM with natural flavor conservation (2HDM Type I, Type II, etc) as a way to eliminate tree-level FCNC altogether.
- Sufficiently small FCNCs (+ LFV) are welcome → extra handles on non-minimal Higgs sectors.
- BGL models (Branco, Grimus, Lavoura, 1996 + many more): in the 2HDMs with certain symmetries, FCNCs are governed by a product of the CKM matrix elements → naturally suppressed.

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FCNC in CP4 3HDM

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

- CP4 leads to remarkably tight connections between the Yukawa and scalar sectors $\rightarrow$ 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.

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- In Ferreira et al, 1711.02042, we reported the first pheno scan of the parameter space (theory constraints, EWPT, fermion masses and mixing, K, B, B_s oscillation parameters) $\to$ many viable parameter space points found.
- But almost all had light charged Higgses, $m_{H^\pm_{2,3}} < m_t$ leading to

$$t \to H^+ d_i\,, \quad H^+ \to \bar{d}_i u_j\,,$$

with a variety of $H^+ d_i u_j$ coupling patterns.
- In Ivanov, Obodenko, 2104.11440 we checked these points against
  - the total $\Gamma_t = 1.42^{+0.19}_{-0.15}$ GeV [PDG],
  - $Br(t \to H^+ b) \times Br(H^+ \to c\bar{b}) < 0.5\%$ based on [CMS, 2018],
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Exploring CP4 3HDM in a smart way

FCNC in CP4 3HDM

Lessons from 1711.02042 + 2104.11440:

- FCNC in the up-quark sector (such as D-meson oscillations) must also be checked $\to$ impact on the charged Higgs patterns.
- 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.

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The two goals

The two key goals of 2302.03094 = JHEP 04 (2023) 116:

- Learn how to perform an efficient parameter space scan!
- Check if some Yukawa scenarios can be ruled out right away, even before the full pheno scan.

Scanning CP4 3HDM Yukawa sector: the usual way

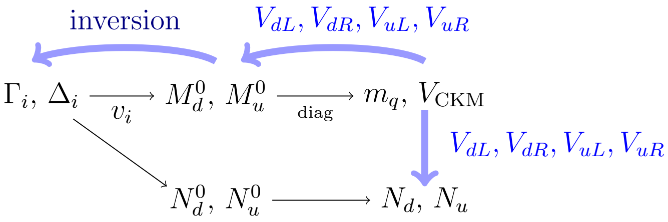
The usual scanning procedure:

$$\begin{array}{ccccc}
\Gamma_i,\, \Delta_i & \xrightarrow[v_i]{} & M_d^0,\, M_u^0 & \xrightarrow[\text{diag}]{} & m_q,\, V_{\text{CKM}} \\
 & \searrow & & & \\
 & & N_d^0,\, N_u^0 & \longrightarrow & N_d,\, N_u
\end{array}$$

where the superscript 0 means "before the quark fields rotation".

Scanning CP4 3HDM Yukawa sector: inversion

Inversion:



- From m_q, CKM to M_d^0, M_u^0: specific quark rotation matrices needed.
- From M_d^0, M_u^0 to Γ_i, Δ_i: a bonus feature of the CP4 3HDM.

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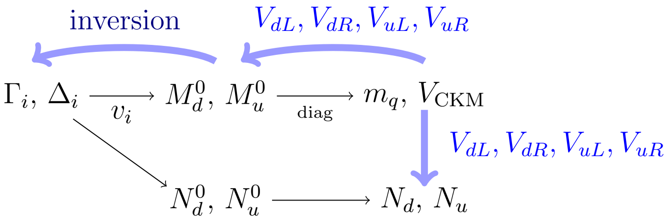

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The goal is to express FCNC matrices N_d, N_u via physical quark observables and quark rotation parameters.

FCNC in CP4 3HDM

- In 2302.03094, we found expressions for N_d's, N_u's for all CP4 3HDM Yukawa sectors (trivial for A, non-trivial for B_1, B_2, B_3).
- Remarkably, N_{d2} and N_{u2} are similar to the BGL-like models and offer some control over FCNCs. For example, in case B_1 we get:

$$(N_{d2})_{ij} = \cot\beta\, m_{d_j}\delta_{ij} - \frac{m_{d_j}}{c_\beta s_\beta}(V_{dL,3i})^* V_{dL,3j}\,.$$

- However N_{d3} and N_{u3} show completely different patterns.

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

Numerical scan:

- Select specific Yukawa sector of the CP4 3HDM, such as (B_1^{down}, B_1^{up}).
- Starting from m_q and CKM, scan over matrices V_{dL}, V_{dR}, V_{uR}, which lead M_d^0 and M_u^0 of the correct texture.
- Compute N_d's and N_u's. Then, following Nebot, Silva, 1507.07941 write

$$\frac{1}{v}\bar{d}_{Li}\,(N_d)_{ij} d_{Rj} + h.c = \bar{d}_i\left(A_{ij} + iB_{ij}\gamma^5\right) d_j\,,$$

  where $A = (N_d + N_d^\dagger)/(2v)$, $iB = (N_d - N_d^\dagger)/(2v)$.
- The dimensionless off-diagonal elements of A_{ij} and B_{ij} can be constrained by K, B, B_s and D-meson oscillation parameters. For example, K oscillations constrain the FCNCs of a generic 1 TeV scalar as

$$|a_{ds}| < 3.7\times 10^{-4}\,, \quad |b_{ds}| < 1.1\times 10^{-4}\,.$$

  For smaller scalar masses, the constraints are tighter.
- Check how different CP4 Yukawa scenarios compare with these constraints.

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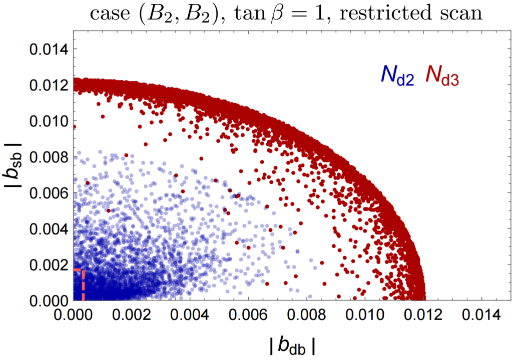
Some clarifications.

- This is not yet a full pheno scan. Such a scan requires a combined study of the vast Yukawa + scalar sectors, and it cannot be blind.
- This is a step towards understanding how to do a clever CP4 3HDM scan.
    - 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?

Results of the numerical study 2302.03094

- Out of 8 possible CP4 invariant sectors, only two scenarios have chances to yield viable models: (A, B_2) and (B_1, B_1).
- Other scenarios fail! For example, B_s vs. B for (B_2, B_2):



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

Work in progress

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- A full scan (scalar + Yukawa) of the CP4 3HDM based on these two Yukawa scenarios: (A, B_2) and (B_1, B_1). We hope to find benchmark models compatible with all the collider constraints.
- Investigating CP4 invariant lepton sectors.
  - $\mathcal{H}_3^0 e\bar{e}$ and $\mathcal{H}_3^0 e\bar{\mu}$ couplings are $\propto m_\mu$, instead of m_e!
  - This is a key feature of the CP4 symmetry.
  - Perhaps, the recent CMS hint at $H \to e\mu$ with $m_H = 146$ GeV 2305.18106 can be accommodated within this scenario.
  - If so, then a comparable $H \to ee$ is expected!
- Consequences of CP4 for the neutrino mass models.

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  - This is a key feature of the CP4 symmetry.
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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!

Tired of 2HDMs? Try CP4 3HDM

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