Constraining CP4 3HDM with meson oscillations

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HPNP 2023, Osaka, Japan

June 9th, 2023

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

and work in progress

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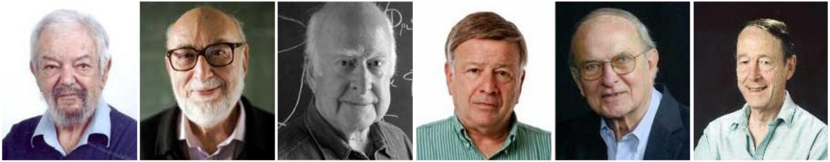
1. Model building with exotic CP
2. Flavored CP4 3HDM
3. CP4 3HDM: smart scan
4. Conclusions

Brout-Englert-Higgs-Guralnik-Hagen-Kibble mechanism

HPNP: Higgs as a probe of New Physics

Maybe Higgs is not alone → extended scalar sectors



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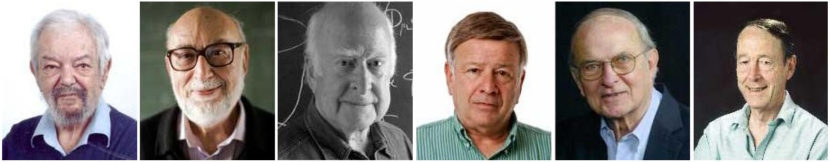

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Multi-Higgs model building

Many new fields → many interaction terms → 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 → 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: generalized *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 flair.

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CP4 3HDM

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

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

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

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

Higher order CP

Squaring the CP transformation:

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

The transformation $(CP)^2 = XX^*$ does not have to be identity!

It may happen than $(CP)^k = \mathbb{I}$ for $k > 2$.

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

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

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

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

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.

Remarks on CP4

- *CP*-conserving 3HDMs based on CP4 and the usual CP can be distinguished, at least in principle [Haber, Ogreid, Osland, Rebelo, 1808.08629].
- The presence of CP4 can be detected in a basis-independent way [Ivanov, Nishi, Silva, Trautner, 1810.13396].
- If the minimum conserves CP4 $\to$ scalar DM stabilized by CP4 $\to$ peculiar DM properties and evolution [Ivanov, Silva, 2016; Ivanov, Laletin, 2018].
- CP4 can be extended to the Yukawa sector $\to$ flavored CP4 3HDM. But then it must be spontaneously broken $\to$ patterns in the flavor sector [Ferreira et al, 1711.02042].

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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 → only four options 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 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 vevs $v_1 v_2$ 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 $\to$ 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 $\to$ 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 $\to$ 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 $\to$ 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.

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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 $\rightarrow$ 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.
- Get a feeling of the FCNC before undertaking the full scan.

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Scanning CP4 3HDM Yukawa sector: the usual way

Down quarks ($\mathcal{H}_i^0$ = neutral scalars in the Higgs basis):

$$\begin{aligned}\bar{d}_L^0(\Gamma_1\phi_1^0 + \Gamma_2\phi_2^0 + \Gamma_3\phi_3^0)d_R^0 &= \frac{\sqrt{2}}{v}\bar{d}_L^0(\mathcal{H}_1^0 M_d^0 + \mathcal{H}_2^0 N_{d2}^0 + \mathcal{H}_3^0 N_{d3}^0)d_R^0 \\ &= \frac{\sqrt{2}}{v}\bar{d}_L(\mathcal{H}_1^0 D_d + \mathcal{H}_2^0 N_{d2} + \mathcal{H}_3^0 N_{d3})d_R\end{aligned}$$

where 0 in d_R^0, N_{d2}^0 etc. means "before the quark fields rotation".

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&= \frac{\sqrt{2}}{v}\bar{d}_L(\mathcal{H}_1^0 D_d + \mathcal{H}_2^0 N_{d2} + \mathcal{H}_3^0 N_{d3})d_R
\end{aligned}$$

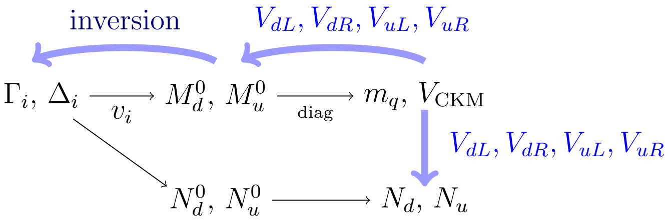
where 0 in d_R^0, N_{d2}^0 etc. means "before the quark fields rotation".

The usual scanning procedure:

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

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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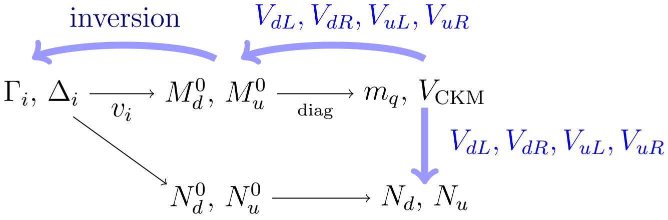

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The goal is to express FCNC matrices N_d, N_u via physical quark observables and quark rotation parameters.

FCNC in CP4 3HDM

- In Zhao, Ivanov, Pasechnik, Zhang, 2302.03094, we found expressions for N_d's and N_u's for all Yukawa sectors of the CP4 3HDM (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?

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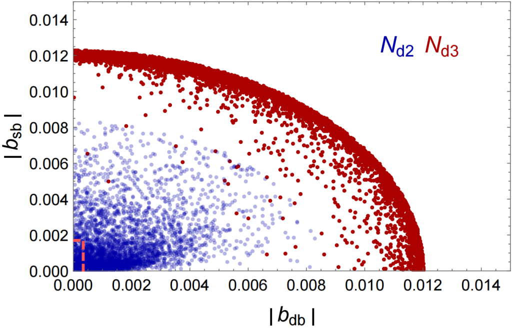
Results the numerical study 2302.03094

- 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):

case (B_2, B_2), $\tan\beta = 1$, restricted scan



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

Work in progress

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- 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!
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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.