CP4 miracle: Yukawa sector from CP4

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based on:

P. Ferreira, IPI, E. Jiménez, R. Pasechnik, H. Serôdio, arXiv:1711.02042

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PROGRAMA OPERACIONAL POTENCIAL HUMANO

QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL

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4. Conclusions

3HDM with CP4

Model-building with multiple Higgses

Model-building with non-minimal Higgs sectors in search for explanation of SM's loose ends (CPV, flavor puzzle, DM, etc), see e.g. [Ivanov, 1702.03776].

Many Higgses → many interaction terms → lots of free parameters.

Extra global symmetries could help but they lead to a dilemma:

- Large discrete symmetry group → very few free parameters, nicely calculable, very predictive, and unphysical.
- Small symmetry groups → many free parameters, compatible with experiment but not quite predictive.

Ideally balanced choice

a symmetry setting which assumes little, fits experiment, and predicts much.

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 $\phi(\vec{x}, t) \xrightarrow{CP} e^{i\alpha}\phi^*(-\vec{x}, t)$ [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 whatever 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 and does not grasp all possible cases!

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.

Within 2HDM: higher-order GCP always lead to accidental symmetries including the usual CP [Ferreira, Haber, Maniatis, Nachtmann, Silva, 2011].

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; Ivanov, Silva, 2016].

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:

- unbroken CP4 = similar to the inert doublet model in 2HDM: CP4 is only within scalar sector, ϕ_2, ϕ_3 decouple from fermions and don't get vevs → scalar DM candidates with peculiar properties (CP-half-odd scalars) [Ivanov, Silva, 2016]:

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

- flavored CP4 3HDM: CP4 is extended to the Yukawa sector and must be spontaneously broken → patterns in the flavor sector. [Aranda, Ivanov, Jimenez, 2017]

Quark sector with CP4

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

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

Matrix Y can be always broght to

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

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

CP4-symmetric quark sector

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.

Consider only down-sector first. We found only four possibilities: A, B_1, B_2, B_3.

- case A: $\alpha_L = 0$, $\alpha_{dR} = 0 \to \Gamma_1 \simeq$ is an arbitrary real matrix, $\Gamma_{2,3} = 0$.
- case B_1: $\alpha_L = \pi/2$, $\alpha_{dR} = 0$.
- case B_2: $\alpha_L = 0$, $\alpha_{dR} = \pi/2$.
- case B_3: $\alpha_L = \pi/2$, $\alpha_{dR} = \pi/2$.

CP4-symmetric quark sector

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, with CPV arising only in the scalar sector.
- 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, v_3 must be nonzero to avoid mass-degenerate quarks.
- v_2, v_3 cannot be very small: they produces quark mass splitting.

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.

The simplest way to avoid tree-level FCNCs for h_{125} is to impose the exact alignment in the scalar sector: $h_{125} = \mathrm{Re}\Phi_1^0/\sqrt{2}$.

Scalar alignment

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

but the scalar alignment condition is simple:

$$m_{11}^2 = m_{22}^2\,.$$

In fact, any NHDM potential of the form

$$V = -m^2 \sum_i \phi_i^\dagger \phi_i + \text{any quartic potential}$$

automatically incorporates scalar alignment.

Still, large FCNCs may be generated by other Higgses!

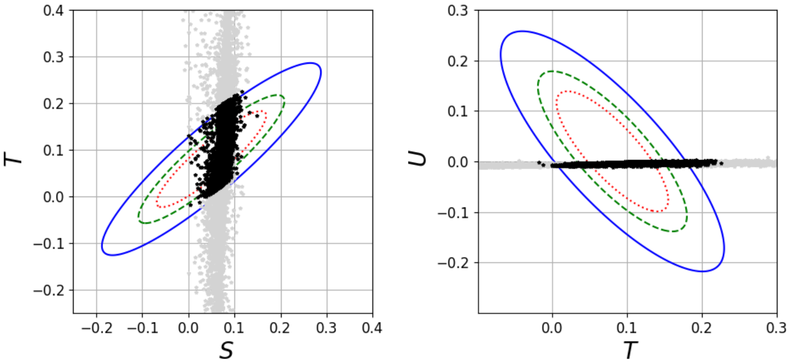
Numerical scan

Numerical scan procedure

Procedure:

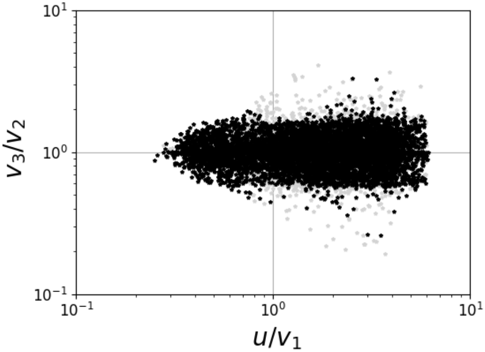
1. Scalar sector scan:
   - stick to the scalar alignment, take h_{125} to be the lightest scalar, vary 9 free parameters: v_3/v_2, u/v_1, and 7 λ's;
   - insure boundedness from below and perturbativity (all $|\lambda| < 5$);
   - insure S, T, U parameters are within 3σ of expt.
2. Yukawa sector scan
   - fit all quark masses, mixing, and CPV phase (easy);
   - add K and B oscillation parameters $|\epsilon_K|$, Δm_K, Δm_{B_d}, Δm_{B_s} via expressions from [Buras et al, 2013].

Scan: EPWT

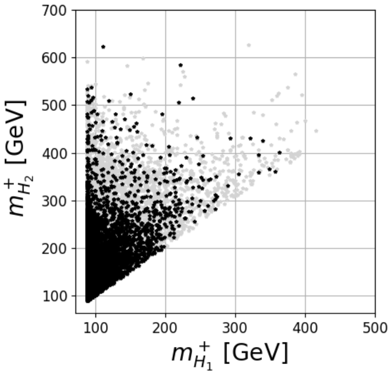

0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
T
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
S
0.3
0.2
0.1
0.0
−0.1
−0.2
U
0.0
0.1
0.2
0.3
T

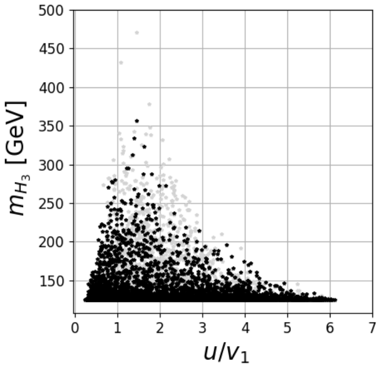
Scan: vev ratios

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



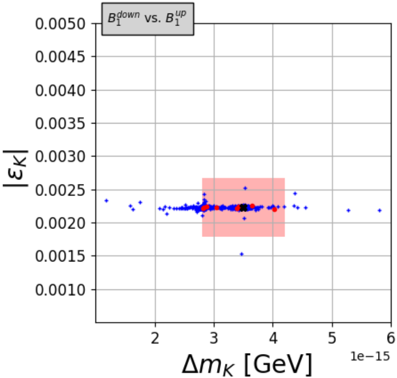
Scan: extra Higgses

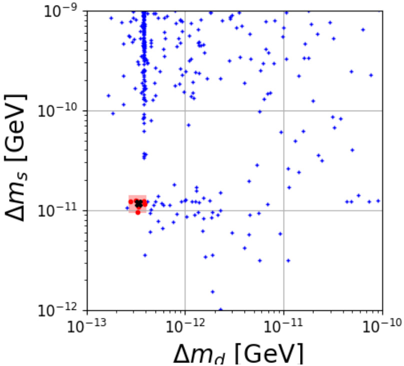




Scan: flavor observables

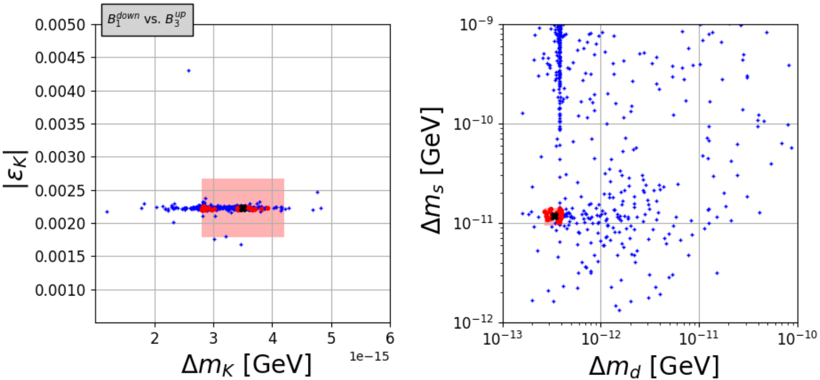
case (B_1^{down}, B_1^{up})





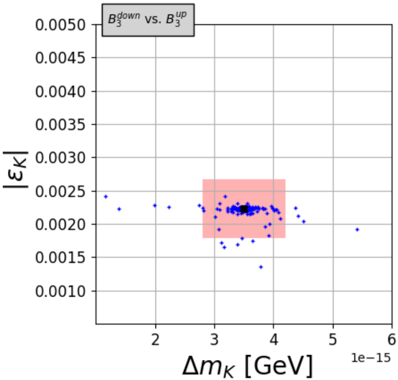
Scan: flavor observables

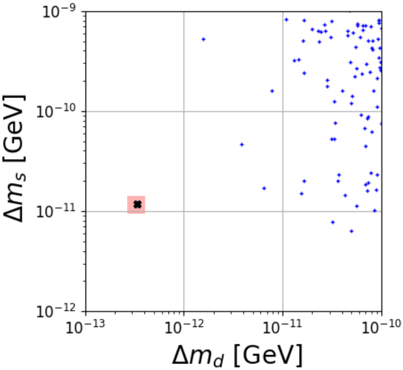
case (B_1^{down}, B_3^{up})



Scan: flavor observables

case (B_3^{down}, B_3^{up})





Overall results

- Four cases produced good points:

$$(A, B_2)\,, \quad (B_2, B_2)\,, \quad (B_1, B_1)\,, \quad (B_1, B_3)\,.$$

- Typical points have light Higgses (< 150 GeV); a few points have moderately heavy Higgses.
- Higgs spectrum in a benchmark point for (B_1, B_3):

$$\begin{array}{rllll} (v_1, v_2, v_3)\ [\text{GeV}]: & (142.8\,, & 66.1\,, & 74.6) & \\ \text{neutral Higgses [GeV]}: & 220.4\,, & 304.4\,, & 318.9\,, & 352.2 \\ \text{charged Higgses [GeV]}: & 209.3\,, & 242.1\,. & & \end{array}$$

Conclusions: what's done

- CP4 3HDM is the minimal model implementing higher-order CP without accidental symmetries.
- (spontaneously broken) CP4 can be extended to the Yukawa sector $\rightarrow$ very characteristic flavor sectors.
- It easily accommodates all fermion masses, mixing, CPV, and brings FCNCs of h_{125} under control.

Framework for conservative multi-Higgs model building

- based on a single symmetry assumption,
- quite predictive with rich phenomenology,
- tractable analytically.

Conclusions: yet to do

Phenomenology:

- collider signatures of extra Higgses
- other B-physics observables
- any chance to relax tensions in $b \to s\ell\ell$ or LFU violation via CP4?
- CP4-based neutrino sector

Theory:

- Can CP4 arise as a residual symmetry from a larger symmetry at high scale?
- Minimal models with CP8, CP16, etc

CP4 neutrinos

CP4-symmetric neutrino mass models proposed in [Ivanov, 1712.xxxxx]

- similar to Ma's scotogenic model [Ma, 2006] but with CP4 instead of $\mathbb{Z}_2$;
- despite having more Higgses, it is more constrained that Ma's model
- via a hybrid seesaw-scotogenic mechanism, it naturally predicts two mass scales m_{sol}, m_{atm}.