Limiting FCNC in CP4 3HDM

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Zhao, Ivanov, Pasechnik, Zhang, JHEP 04 (2023) 116 arxiv: 2302.03094,

Multi-Higgs model

- NHDM is a framework for BSM
  - 2HDM
  - 3HDM
  - ....
- In 3HDM

  Scalar sector + Yukawa sector lead to too many parameters

- Imposing global symmetries to reduce the parameters

  such as CP4 symmetry

CP4 Transformation

What is CP4 Transformation ?

- In QFT, CP is not uniquely defined, with N scalar fields CP Transformation

$$\phi_i(\mathbf{r},t) \to (CP)\phi_i(\mathbf{r},t)\,(CP)^{-1} = X_{ij}\phi_j^*(-\mathbf{r},t), \quad X_{ij} \in U(N)\,.$$

- CP4 Transformation is an order-4 transformation
- A possible CP4 Transformation

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

- CP4 3HDM is the minimal NHDM which realizing CP4 Scalar + Yukawa

Scalar sector

CP4 3HDM scalar sector $V = V_0 + V_1$

$$
\begin{aligned}
V_0 &= -m_{11}^2(\phi_1^\dagger\phi_1) - m_{22}^2(\phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3) + \lambda_1(\phi_1^\dagger\phi_1)^2 \\
&\quad +\lambda_2\left[(\phi_2^\dagger\phi_2)^2 + (\phi_3^\dagger\phi_3)^2\right] \\
&+ \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3) + \lambda_3'(\phi_2^\dagger\phi_2)(\phi_3^\dagger\phi_3) \\
&+ \lambda_4\left[(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + (\phi_1^\dagger\phi_3)(\phi_3^\dagger\phi_1)\right] + \lambda_4'(\phi_2^\dagger\phi_3)(\phi_3^\dagger\phi_2),
\end{aligned}
$$

$$
V_1 = \lambda_5(\phi_3^\dagger\phi_1)(\phi_2^\dagger\phi_1) + \lambda_8(\phi_2^\dagger\phi_3)^2 + \lambda_9(\phi_2^\dagger\phi_3)(\phi_2^\dagger\phi_2 - \phi_3^\dagger\phi_3) + h.c.
$$

CP4 transformation could be extended to Yukawa Sector........

Ferreira et al, 1711.02042

CP4 Yukawa sector

CP4 3HDM Yukawa sector

$$\psi_i \to Y_{ij}\psi_j^{CP}, \quad \text{where} \quad \psi^{CP} = \gamma^0 C \bar{\psi}^T .$$

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

$$-\mathscr{L}_Y = \bar{Q}_L^0(\Gamma_1\phi_1 + \Gamma_2\phi_2 + \Gamma_3\phi_3)d_R^0 + \bar{Q}_L^0(\Delta_1\tilde{\phi}_1 + \Delta_2\tilde{\phi}_2 + \Delta_3\tilde{\phi}_3)u_R^0 + h.c.$$

- Mass matrices and coupling matrices could not be diagonalized simultaneously

FCNC need to be satisfied by experiment constraints

CP4 Yukawa sector

- Case A

$$\Gamma_1 = \begin{pmatrix} g_{11} & g_{12} & g_{13} \\ g_{12}^* & g_{11}^* & g_{13}^* \\ g_{31} & g_{31}^* & g_{33} \end{pmatrix}, \quad \Gamma_{2,3} = 0$$

- 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 Yukawa sector

A full Yukawa sector includes up sector and down sector

- Because up sector and down sector share the same left-hand doublet, they are not totally independent, only 8 possible cases

$$\begin{aligned}\text{(down, up):}\quad & (B_1, B_1)\,,\quad (B_1, B_3)\,,\quad (B_3, B_1)\,,\quad (B_3, B_3)\,,\\ & (A, B_2)\,,\quad (B_2, A)\,,\quad (B_2, B_2)\,,\quad (A, A)\,.\end{aligned}$$

- (A, A) is free from FCNC, But no CP-violating phase for CKM matrix

There are 7 physical cases

FCNC matrices

The goal of this work

- The typical magnitude of the FCNC
- Which case can satisfy all the constraints from neutral meson oscillations without any additional cancellation mechanism

FCNC matrices in Higgs basis

$$\bar{Q}_L^0(\Gamma_1\phi_1^0+\Gamma_2\phi_2^0+\Gamma_3\phi_3^0)d_R^0=\frac{\sqrt{2}}{v}\bar{Q}_L^0(H_1^0M_d^0+H_2^0N_{d2}^0+H_3^0N_{d3}^0)d_R^0,$$

- After rotating quark field, the off-diagnal elements of N_{d2}, N_{d3} will describe FCNC

$$N_{d2}=V_{dL}^\dagger N_{d2}^0V_{dR}\,,\quad N_{d3}=V_{dL}^\dagger N_{d3}^0V_{dR}$$

The inversion procedure

$$
\begin{tikzcd}
\Gamma_i,\, \Delta_i \arrow[r, "v_i"'] \arrow[dr] & M_d^0,\, M_u^0 \arrow[r, "\text{diag}"'] \arrow[l, bend right, "\text{inversion}"'] & m_q,\, V_{\text{CKM}} \arrow[d, "{V_{dL}, V_{dR}, V_{uL}, V_{uR}}"] \\
 & N_d^0,\, N_u^0 \arrow[r] & N_d,\, N_u
\end{tikzcd}
$$

In inversion procedure, we will express FCNC in terms of quark mass (inputs) and rotation matrices(scan randomly)

- For example Case B_1

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

Compare to usual procedure, inversion procedure is more efficient

Constraints

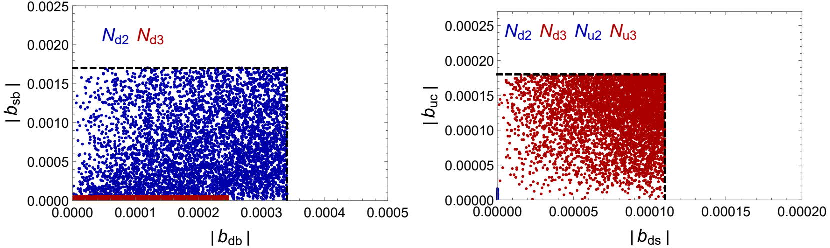
FCNC matrices N_{d2},N_{d3},N_{u3} and N_{u2} meet upper limits from neutral oscillations

	Meson	A	B
1 TeV scalar	$K^0 - \overline{K^0}$	$\lvert a_{ds}\rvert < 3.7 \times 10^{-4}$	$\lvert b_{ds}\rvert < 1.1 \times 10^{-4}$
	$B^0 - \overline{B^0}$	$\lvert a_{db}\rvert < 9.0 \times 10^{-4}$	$\lvert b_{db}\rvert < 3.4 \times 10^{-4}$
	$B_s^0 - \overline{B_s^0}$	$\lvert a_{sb}\rvert < 45 \times 10^{-4}$	$\lvert b_{sb}\rvert < 17 \times 10^{-4}$
	$D^0 - \overline{D^0}$	$\lvert a_{uc}\rvert < 5.0 \times 10^{-4}$	$\lvert b_{uc}\rvert < 1.8 \times 10^{-4}$

$$A = \frac{N_d + N_d^\dagger}{2v}, \quad iB = \frac{N_d - N_d^\dagger}{2v}.$$

Nebot, Silva arxiv:1507.07941

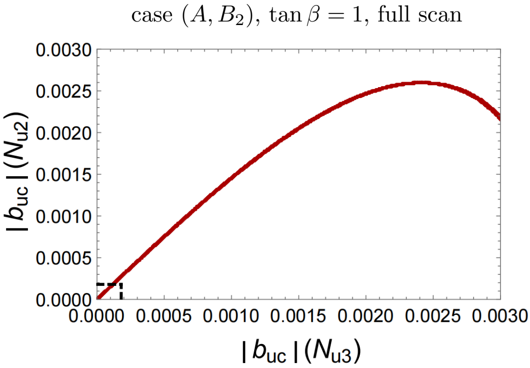
Case (B_1, B_1)



- We can get the viable points (pass all the above constraints) for Case (B_1, B_1)

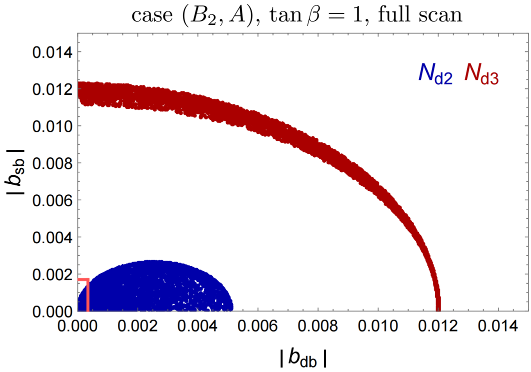
Case (A, B_2)

Case (A, B_2)



- In Case (A, B_2), the down-quark sector is free from FCNC .
- The only D-meson constraints can be satisfied

Case (B_2, A)
Other cases are ruled out, such as



- Case (B_2, A) have be ruled out, because of big FCNC from N_{d3}

Conclusions

- Our study lead to several follow-up studies
- Numerical results
  (1) Only (A, B_2) and (B_1, B_1) can pass all constraints without any additional cancellation mechanism
  (2) In the most of cases, N_{d3} and N_{u3} are more difficult to satisfy constraints than N_{d2} and N_{u2}.
  (3) Kaons and D-mesons are the strongest constraints

Thank You