2HDM with CP-violation Facing EDM and Collider Tests

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1 Introduction

- CP-violation was first discovered in 1964 through $K_L \to 2\pi$ decay, and is already confirmed in $K-$, $D-$, and $B-$meson sectors now [Particle Data Group, PRD 110, 030001 (2024)].

- CP-violation beyond the K(obayashi)-M(askawa) mechanism: a typical type of new physics, and also one of the necessary conditions to understand the baryon asymmetry in the Universe.

- CP-violation beyond the K-M mechanism may arise in different ways:

  - Theoretically, the extended scalar sector is an attractive solution to generate new CP-violation, since it may lead to the mixing between scalars and pseudo-scalars;

  - Experimentally, we may probe it indirectly or directly:

    - Indirect tests: we just probe CP-violation itself but we cannot immediately find its origin, measurements on the **E**lectric **D**ipole **M**oments are typical indirect tests;

    - Direct tests: when we probe the CP-violation, we know its exact origin (on the other hand, the CP-violated interactions) at the same time, collider measurements are typical direct tests.

- As an extended scalar sector model which is not so complex, **2**-**H**iggs-**D**oublet-**M**odel was widely studied in the past decades, which becomes a good candidate as an example, to study further and uncover the potentially correlation between EDM and collider tests.

- Overall, if there really exists new CP-violation in the scalar sector in 2HDM, the first signature must arise in EDM tests, while the collider tests can provide a complementary cross-check.

2 Model Set-up

- We begin from the 2HDM with a soft broken Z_2-symmetry to avoid large F(lavor)-C(hanging)-N(eutal)-C(urrent), the scalar potential is then

$$
\begin{aligned}
V(\phi_1,\phi_2) &= -\frac{1}{2}\left[m_1^2\phi_1^\dagger\phi_1 + m_2^2\phi_2^\dagger\phi_2 + \left(m_{12}^2\phi_1^\dagger\phi_2 + \text{H.c.}\right)\right] + \left[\frac{\lambda_5}{2}\left(\phi_1^\dagger\phi_2\right)^2 + \text{H.c.}\right] \\
&+\frac{1}{2}\left[\lambda_1\left(\phi_1^\dagger\phi_1\right)^2 + \lambda_2\left(\phi_2^\dagger\phi_2\right)^2\right] + \lambda_3\left(\phi_1^\dagger\phi_1\right)\left(\phi_2^\dagger\phi_2\right) + \lambda_4\left(\phi_1^\dagger\phi_2\right)\left(\phi_2^\dagger\phi_1\right),
\end{aligned}
$$

the nonzero m_{12}^2 softly breaks Z_2-symmetry.

  - Scalar doublets: $\phi_1 \equiv (\varphi_1^+, (v_1+\eta_1+\mathrm{i}\chi_1)/\sqrt{2})^T$, $\phi_2 \equiv (\varphi_2^+, (v_2+\eta_2+\mathrm{i}\chi_2)/\sqrt{2})^T$;
  - Here $m_{1,2}^2$ and $\lambda_{1,2,3,4}$ must be real, while m_{12}^2 and λ_5 can be complex→CP-violation;
  - The vacuum expected value (VEV) for the scalar fields: $\langle\phi_1\rangle \equiv (0,v_1)^T/\sqrt{2}$, $\langle\phi_2\rangle \equiv (0,v_2)^T/\sqrt{2}$, and we denote $t_\beta \equiv |v_2/v_1|$;

- m_{12}^2, λ_5, and v_2/v_1 can all be complex, but we can always perform a rotation to keep at least one of them real, thus we choose v_2/v_1 real, which leads to the relation: $\mathrm{Im}\left(m_{12}^2\right) = v_1 v_2 \mathrm{Im}(\lambda_5)$.
- Diagonalization: (a) Charged Sector

$$G^{\pm} = c_\beta \varphi_1^{\pm} + s_\beta \varphi_2^{\pm}, \quad H^{\pm} = -s_\beta \varphi_1^{\pm} + c_\beta \varphi_2^{\pm};$$

(b) Neutral Sector

$$G^0 = c_\beta \chi_1 + s_\beta \chi_2, \quad A = -s_\beta \chi_1 + c_\beta \chi_2,$$

and for the CP-conserving case, A is a CP-odd mass eigenstate; while for CP-violation case, $(H_1, H_2, H_3)^T = R(\eta_1, \eta_2, A)^T$, with

$$R = \begin{pmatrix} 1 & & \\ & c_{\alpha_3} & s_{\alpha_3} \\ & -s_{\alpha_3} & c_{\alpha_3} \end{pmatrix} \begin{pmatrix} c_{\alpha_2} & & s_{\alpha_2} \\ & 1 & \\ -s_{\alpha_2} & & c_{\alpha_2} \end{pmatrix} \begin{pmatrix} c_{\beta+\alpha_1} & s_{\beta+\alpha_1} & \\ -s_{\beta+\alpha_1} & c_{\beta+\alpha_1} & \\ & & 1 \end{pmatrix};$$

SM limit: $\alpha_{1,2} \to 0$.

- Parameter Set (8): $[m_1, m_2, m_\pm, \beta, \alpha_1, \alpha_2, \alpha_3, \mathrm{Re}(m_{12}^2)]$;
- Mass relation:

$$m_3^2 = \frac{c_{\alpha_1+2\beta}(m_1^2 - m_2^2 s_{\alpha_3}^2)/c_{\alpha_3}^2 - m_2^2 s_{\alpha_1+2\beta} t_{\alpha_3}}{c_{\alpha_1+2\beta} s_{\alpha_2} - s_{\alpha_1+2\beta} t_{\alpha_3}}.$$

- Four Yukawa types:
  - A fermion bilinear couples to only one scalar doublet under given Z_2-number, and we assume up-type quarks $\bar{u}_i u_i$ always couple to ϕ_2;
  - The Z_2-number for different fields

Z_2 Number	ϕ_1	ϕ_2	Q_L	u_R	d_R	L_L	ℓ_R	Z, γ, W
Type I	+	−	+	−	−	+	−	+
Type II	+	−	+	−	+	+	+	+
Type III	+	−	+	−	−	+	+	+
Type IV	+	−	+	−	+	+	−	+

Coupling	$\bar{u}_i u_i$	$\bar{d}_i d_i$	$\bar{\ell}_i \ell_i$
Type I	ϕ_2	ϕ_2	ϕ_2
Type II	ϕ_2	ϕ_1	ϕ_1
Type III	ϕ_2	ϕ_2	ϕ_1
Type IV	ϕ_2	ϕ_1	ϕ_2

3 EDM Analysis

- Experimental limits overview:
  - We mainly care about the EDMs of electron (experimentally obtained from paramagnetic atoms, molecules, or ions), neutron, diamagnetic atoms, etc;
  - Electron: current limits from ThO [ACME collaboration, nature 562, 355 (2018)] and HfF^+ [T. S. Roussy *et. al.*, Science 381, 46 (2023)] @ 90% C.L.

$$|d_e| < \begin{cases} 1.1 \times 10^{-29}\ e \cdot \mathrm{cm}, & (\mathrm{ThO}); \\ 4.1 \times 10^{-30}\ e \cdot \mathrm{cm}, & (\mathrm{HfF}^+). \end{cases}$$

  - Neutron: $|d_n| < 1.8 \times 10^{-26}\ e \cdot \mathrm{cm}$ @ 90% C.L. (nEDM experiment @ PSI) [nEDM collaboration, PRL 124, 081803 (2020)]; Mercury (Hg): $|d_{\mathrm{Hg}}| < 7.4 \times 10^{-30}\ e \cdot \mathrm{cm}$ @ 95% C.L. [B. Graner *et. al.*, PRL 116, 161601 (2016)].
  - Still far above the SM predictions, but effective to limit or probe new physics.

- Method overview:

$$\text{NP} \xrightarrow{\text{CPV}} \left\{ \begin{array}{l} \text{eEDM} \xrightarrow{\text{RGE}} \text{eEDM} \\ \left.\begin{array}{ccc} \text{e-q int.} & & \text{e-q int.} \\ & \xrightarrow{\text{RGE}} & \\ \text{e-g int.} & & \text{e-g int.} \\ \color{red}{\mu_{\text{high}}} & & \color{red}{\mu_{\text{low}}} \end{array}\right\} \xrightarrow{\text{Matching}} \text{e-N int.} \end{array} \right\} \xrightarrow{\text{NR}} \color{blue}{\begin{array}{c}\text{EDMs in paramagnetic} \\ \text{atoms, ions or molecules}\end{array}}$$

$$\text{NP} \xrightarrow{\text{CPV}} \left\{ \begin{array}{lcl} \text{qEDM} & & \text{qEDM} \\ \text{qCEDM} & & \text{qCEDM} \\ \text{Weinberg } \mathcal{O}\ (GG\tilde{G}) & \xrightarrow{\text{RGE}} & \text{Weinberg } \mathcal{O}\ (GG\tilde{G}) \\ \ldots & & \ldots \\ \color{red}{\mu_{\text{high}}} & & \color{red}{\mu_{\text{low}}} \end{array} \right\} \xrightarrow[\cdots]{\substack{\text{QCDSR} \\ \text{Lattice}}} \color{blue}{\text{nEDM}}$$

$$\text{NP} \xrightarrow{\text{CPV}} \left\{ \begin{array}{l} \cdots \longrightarrow \text{nEDM, pEDM, e-N int., etc.} \\ \left.\begin{array}{ccc} \text{q-q int.} & & \text{q-q int.} \\ \text{q-g int.} & & \text{q-g int.} \\ & \xrightarrow{\text{RGE}} & \\ \text{qCEDM} & & \text{qCEDM} \\ \ldots & & \ldots \\ \color{red}{\mu_{\text{high}}} & & \color{red}{\mu_{\text{low}}} \end{array}\right\} \xrightarrow{\text{Matching}} \underset{(\pi-\text{N})}{\text{N-N}}\ \text{int.} \end{array} \right\} \xrightarrow{\text{NR}} \color{blue}{\begin{array}{c}\text{EDMs in diamagnetic} \\ \text{atoms or molecules}\end{array}}$$

- Current limits and future tests: electron
  - For Type I and IV models: no cancellation behavior$\longrightarrow$very strict constraint $|\alpha_2| \lesssim \mathcal{O}(10^{-3})$;
  - For Type II and III models: cancellation behavior thus $|\alpha_2| \sim \mathcal{O}(0.1)$ is still allowed for $t_\beta \sim 1$, whose exact location depends weakly on the mass scale of the heavy scalar sector;
    [PRD 102, 075029 (2020), with Kingman Cheung, Adil Jueid, and Stefano Moretti.]
  - Consistent with the results in earlier literatures [S. Inoue *et.al.*, PRD 89, 115023 (2014); Y.-N. Mao *et.al.*, PRD 90, 115024 (2014); L. Bian *et.al.*, PRL 115, 021801 (2015); D. Fontes *et.al.*, JHEP 06, 060 (2015); etc.]
  - Another cancellation region $t_\beta \sim \mathcal{O}(10)$, see also [S. Inoue *et.al.*, PRD 89, 115023 (2014); W. Altmannshofer *et.al.*, PRD 102, 115042 (2020); etc.]
  - For the large t_β case above, large $|\alpha_2|$ is disfavored, due to the limit from Hg EDM
    [Preliminary, Y.-N. Mao, in preparation.]

- Currently using merely electron EDM results, we cannot set useful limit on $|\alpha_2|$ and hence the CP-angle, since we mainly choose the cancellation region; the result from HfF^+ is similar with that from ThO;
- For future tests, when both HfF^+ and ThO experiments are reaching better accuracy, we have the chance to set limit directly on $|\alpha_2|$: the physical reason is that the contributions from $e-N$ interaction are different: $d_e^i = d_e + k_i C$ where C is the coefficient of $\bar{e}\left(\mathrm{i}\gamma^5\right)e\bar{N}N$ term

$$k_{\mathrm{ThO}} \approx 1.8\times10^{-21}\ \mathrm{TeV}^2\cdot e\cdot\mathrm{cm}, \qquad k_{\mathrm{HfF}} \approx 1.1\times10^{-21}\ \mathrm{TeV}^2\cdot e\cdot\mathrm{cm}.$$

  [L. V. Skripnikov, JCP 145, 214310 (2016), and also private discussions.]
- Such a different will lead us directly to the limit on $|\alpha_2|$: if both EDMs' measurements reach the accuracy $\sim 10^{-31}\ e\cdot\mathrm{cm}$ and still no nonzero signal appears, we will have $|\alpha_2| \lesssim 0.02$ [Preliminary, Y.-N. Mao, in preparation.]

- Current limits and future tests: neutron

- Following the benchmarks above: we choose Type II and III models and $t_\beta \sim 1$ cancellation region;
- It sets limit on $|\alpha_2|$: $|\alpha_2^{\rm II}| \lesssim 0.1$, and $|\alpha_2^{\rm III}| \lesssim 0.6$ (LHC Higgs data will set further limit $|\alpha_2^{\rm III}| \lesssim 0.3$)
- Future limit: if the accuracy for d_n reach $10^{-27}\, e\cdot$cm, we will have $|\alpha_2^{\rm II}| \lesssim 4\times 10^{-3}$, and $|\alpha_2^{\rm III}| \lesssim 2\times 10^{-2}$, else a nonzero d_n must arise

  [PRD 102, 075029 (2020), with Kingman Cheung, Adil Jueid, and Stefano Moretti.]

- The role of diamagnetic atoms: mercury (Hg) as an example
  - We just now mentioned that we gave up another cancellation region $t_\beta \sim \mathcal{O}(10)$, due to Hg EDM.
  - For the Hg EDM, we have two main types of contributions:

    (a) CP-violated $N - N$ interaction, with large relative uncertainty;

    (b) CP-violated $e - N$ interaction, with its relative uncertainty $\sim (20\% - 30\%)$.
  - In the $t_\beta \sim 1$ region, two contributions are comparable and the result is consistent with zero within $(1-2)\sigma$, such large theoretical uncertainty made it difficult to set further limit;

- In the $t_\beta \sim \mathcal{O}(10)$ region, $e - N$ interaction contributes dominantly, which has small theoretical uncertainty and can further set $|\alpha_2| \lesssim \mathcal{O}(10^{-3})$.
  [Preliminary, Y.-N. Mao, in preparation.]

- EDM Summary
  - Currently we still have parameter region ($t_\beta \sim 1$) with $|\alpha_2| \sim \mathcal{O}(0.1)$, which may lead to some significance at future colliders;
  - Future measurements for eEDM can set further limit due to different $e-N$ interactions in different materials (mainly ThO and HfF^+, which are easier to get better accuracy);
  - Future measurements for nEDM can also set further limit with an order's improvement.

4 Collider Analysis

- 5 scalars in total: H_1 (125 GeV, light); $H_{2,3,\pm}$ ($\gtrsim$ 700 GeV, heavy).
- For H_1: we choose $t\bar{t}H_1$ associated production at LHC, until 3 ab^{-1} luminosity
  - We checked a lot of observables, and the best one is the distribution of the azimuthal angle between leptons from $t\bar{t}$: we name it as $\Delta\phi_{\ell^+\ell^-}$;
  - For the largest allowed $|\alpha_2| \simeq 0.3$, the final significance can reach about 2.4σ (in the paper we used $|\alpha_2| = 0.27$, the result is similar);
  - It is not quite significant, since the distributions are close between SM and CP-violation case.
- For $H_{2,3}$: we tried but LHC significance is quite small
  - We choose CLIC with $\sqrt{s} = 3$ TeV and 5 ab^{-1} luminosity ($\sqrt{s} = 1.5$ TeV and 2.5 ab^{-1} luminosity case shows also quite small significance);

- We choose the process $W^+W^- \to H_{2/3} \to t(\to b\ell^+\nu)\bar{t}(\to b\ell^-\nu)$;
- The VBF vertex can be used to confirm the CP-even component in H, and we can use the final $\Delta\phi_{\ell^+\ell^-}$ distribution to probe the CP-odd component in H;
- In 2HDM, the discovery for CP-violation at $3(5)\sigma$ level corresponds to $|\alpha_2| \gtrsim 0.12(0.18)$; [2304.04390, with Kingman Cheung, Stefano Moretti, and Rui Zhang.]
- Our latest update considered the beam polarisation with $P_+ = 0$ and $P_- = -0.8(+0.8)$ for 80%(20%) luminosity, but the final result is similar to that in the case without beam polarisation.

- For $H_\pm$: choose $e^+e^-/\mu^+\mu^- \to b\bar{b}H^+(\to W^+H_1)\ell^-\nu, b\bar{b}H^-(\to W^-H_1)\ell^+\nu$, for the CP-asymmetry
  - Quite small results at LHC and CLIC with $\sqrt{s} = 1.5$ TeV;
  - We try to find the CP-asymmetry through the interference between signal and background:

$$\mathcal{M}_\pm = \mathcal{M}_b + \mathcal{M}_s \mathrm{e}^{\pm \mathrm{i}\delta_W} \mathrm{e}^{\mathrm{i}\delta_S} \longrightarrow \mathcal{A} = \frac{|\mathcal{M}_+|^2 - |\mathcal{M}_-|^2}{|\mathcal{M}_+|^2 + |\mathcal{M}_-|^2} \propto \sin\delta_W \sin\delta_S$$

- δ_W: CP-violation (weak) phase in $H^{\pm}W^{\mp}H_1$-vertex, $\sim \pi/2$.
- δ_S: Strong phase crossing charged Higgs threshold: $\frac{\mathrm{i}}{p^2 - m_{\pm}^2 - \mathrm{i}m_{\pm}\Gamma_{\pm}}$.

  [Preliminary, with Qianxi Li and Kechen Wang, in preparation.]

5 Summary

- In 2HDM with soft Z_2-symmetry, CP-violation can arise due to mixing between scalars and the pseudo-scalar, α_2 is a key parameter measuring the CP-violation;
- CP-violation can appear in $H_i f\bar{f}$ couplings or $H^{\pm}W^{\mp}H_i$ couplings;
- We analyze the EDMs in 2HDM for different materials:
  - Currently large $\alpha_2 \sim \mathcal{O}(0.1)$ still allowed, with $t_\beta \sim 1$;
  - The large t_β does not allow large $\alpha_2 \sim \mathcal{O}(0.1)$ due to Hg EDM;
  - Future limits on α_2 from both eEDM and nEDM measurements.
- We have performed the collider analysis for CP-violation in neutral Higgs sector, at LHC and CLIC, while the work for charged Higgs is still in preparation;
- If CP-violation exists in 2HDM, the first signal must be EDM.


The end,
thank you!
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