Two-Higgs-Doublet Model with Soft CP-violation Confronting EDM and Other Constraints

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I. INTRODUCTION

- CP-violation had already been discovered in K-, D-, and B-meson systems [M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. **D98**, 030001 (2018)].

- All discovered CP-violation effects in meson systems are consistent with the explanation by Kobayashi-Maskawa mechanism [M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973)].

- However, it is still worthy to study further origins of CP-violation, not only because it is a possible kind of new physics (NP), it is also a condition to explain the matter-antimatter asymmetry in the Universe.

- CP-violation may also appear elsewhere, for example, behave as the electric dipole moments (EDM) of particles, or some observable at current or future colliders.

- Theoretically, new CP-violation may appear in the extended scalar sector, such as in the Two-Higgs-doublet model (2HDM) which was widely studied [G. C. Branco *et al.*, Phys. Rep. **516**, 1 (2012)].

- Any Model with new CP-violation must face EDM constraints [ACME Collaboration, Nature **562**, 355 (2018); C. A. Baker *et al.*, Phys. Rev. Lett. **97**, 131801 (2006)]

$$|d_e| < 1.1 \times 10^{-29}\ e \cdot \mathrm{cm}\ (90\%\ \mathrm{C.L.}), \quad |d_n| < \begin{cases} 3.0 \times 10^{-26}\ e \cdot \mathrm{cm}\ (90\%\ \mathrm{C.L.}), \\ 3.6 \times 10^{-26}\ e \cdot \mathrm{cm}\ (95\%\ \mathrm{C.L.}). \end{cases}$$

- In this talk, we choose the 2HDM with soft CP-violation as an example, discussing its EDM constraints and the corresponding cancelation mechanism; we don't discuss the collider tests here due to the limited time and unfinished research.

II. THE MODEL

- For the 2HDM with soft CP-violation, we follow the convention: [A. Arhrib *et al.*, JHEP **04** (2011), 089; A. W. E. Kaffas *et al.*, Nucl. Phys. **B775**, 45 (2007)]

$$\mathcal{L} = |D\phi_1|^2 + |D\phi_2|^2 - V(\phi_1, \phi_2)$$

- The potential contain a Z_2 symmetry which is softly broken

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

- Nonzero m_{12}^2 will break the Z_2 symmetry softly.

- Fields definition: $\phi_1 \equiv (\varphi_1^+, (v_1 + \eta_1 + \mathrm{i}\chi_1)/\sqrt{2})^T$, $\phi_2 \equiv (\varphi_2^+, (v_2 + \eta_2 + \mathrm{i}\chi_2)/\sqrt{2})^T$.

- 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.

- A relation: $\mathrm{Im}\,(m_{12}^2) = v_1 v_2 \mathrm{Im}(\lambda_5)$.

- Diagonalization: (a) Charged Sector

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

- Diagonalization: (a) Neutral Sector

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

- For the CP-conserving case, A is a CP-odd mass eigenstate.

- 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): $(M_1, M_2, M_\pm, \beta, \alpha_1, \alpha_2, \alpha_3, \mathrm{Re}(m_{12}^2))$.

- Relation:

$$M_3^2 = \frac{c_{(\alpha_1+2\beta)}(M_1^2 - M_2^2 s_{\alpha_3}^2)/c_{\alpha_3}^2 - M_2^2 s_{(\alpha_1+2\beta)} t_{\alpha_3}}{c_{(\alpha_1+2\beta)} s_{\alpha_2} - s_{(\alpha_1+2\beta)} t_{\alpha_3}}$$

  or equivalently

$$t_{\alpha_3} = \frac{(m_3^2 - m_2^2) \pm \sqrt{(m_3^2 - m_2^2)^2 s_{(2\beta+\alpha_1)}^2 - 4(m_3^2 - m_1^2)(m_2^2 - m_1^2) s_{\alpha_2}^2 c_{(2\beta+\alpha_1)}^2}}{2(m_2^2 - m_1^2) s_{\alpha_2} c_{(2\beta+\alpha_1)}}.$$

- Useful for different scenarios: mass-splitting scenario or nearly mass-degenerate scenario for the two heavy scalars (denote H_1 as the SM-like scalar thus $M_1 = 125$ GeV).

Yukawa Couplings

- Three types of interaction: $\bar{Q}_L \phi_i d_R$, $\bar{Q}_L \tilde{\phi}_i u_R$, $\bar{L}_L \phi_i \ell_R$, with $\tilde{\phi}_i \equiv i\sigma_2 \phi_i^*$.
- The Z_2 symmetry is helpful to avoid the FCNC problem, and with this symmetry, each kind of the above bilinear can couple only to one scalar doublet.
- Four different types (I, II, III, IV)

	$\bar{u}_i u_i$	$\bar{d}_i d_i$	$\bar{\ell}_i \ell_i$
Type I	ϕ_2	ϕ_2	ϕ_2
Type II	ϕ_2	ϕ_1	ϕ_1
Type III (lepton-specific)	ϕ_2	ϕ_2	ϕ_1
Type IV (flipped)	ϕ_2	ϕ_1	ϕ_2

Interaction: $\mathcal{L} \supset \sum c_{V,i} H_i (2m_W^2/v W^+ W^- + m_Z^2/v ZZ) - \sum (m_f/v)(c_{f,i} H_i \bar{f}_L f_R + \text{H.c.})$

$c_{V,1}$	$c_{V,2}$	$c_{V,3}$
$c_{\alpha_1} c_{\alpha_2}$	$-c_{\alpha_3} s_{\alpha_1} - c_{\alpha_1} s_{\alpha_2} s_{\alpha_3}$	$-c_{\alpha_1} c_{\alpha_3} s_{\alpha_2} + s_{\alpha_1} s_{\alpha_3}$

$c_{f,i} = R_{ij} c_{f,j}$ where $j = \eta_1, \eta_2, A$

Type	c_{u,η_1}	c_{u,η_2}	$c_{u,A}$	c_{d,η_1}	c_{d,η_2}	$c_{d,A}$	c_{ℓ,η_1}	c_{ℓ,η_2}	$c_{\ell,A}$
I	0	s_β^{-1}	$-\mathrm{i}t_\beta^{-1}$	0	s_β^{-1}	$\mathrm{i}t_\beta^{-1}$	0	s_β^{-1}	$\mathrm{i}t_\beta^{-1}$
II	0	s_β^{-1}	$-\mathrm{i}t_\beta^{-1}$	c_β^{-1}	0	$-\mathrm{i}t_\beta$	c_β^{-1}	0	$-\mathrm{i}t_\beta$
III	0	s_β^{-1}	$-\mathrm{i}t_\beta^{-1}$	0	s_β^{-1}	$\mathrm{i}t_\beta^{-1}$	c_β^{-1}	0	$-\mathrm{i}t_\beta$
IV	0	s_β^{-1}	$-\mathrm{i}t_\beta^{-1}$	c_β^{-1}	0	$-\mathrm{i}t_\beta$	0	s_β^{-1}	$\mathrm{i}t_\beta^{-1}$

III. EDM CONSTRAINTS AND CANCELATION MECHANISM

- The electron and neutron EDM are usually useful to set constraints on models with new CP-violation sources, such as the effective interaction $\mathcal{L} \supset -\frac{\mathrm{i}}{2} d_f \bar{f} \sigma^{\mu\nu} \gamma^5 f F_{\mu\nu}$.
- Electron-nucleon interaction can also contribute an "effective" EDM in atom or molecule measurements, such as the effective interaction $\mathcal{L} \supset C \bar{N} N \bar{e} \mathrm{i} \gamma^5 e$, and the modification $\delta d_e = kC$ with $k \approx 1.6 \times 10^{-21}\ \mathrm{TeV}^2 \cdot e \cdot \mathrm{cm}$ for ACME experiment. [C. Cesarotti *et al.*, JHEP **05** (2019), 059.]
- Usually, the electron EDM measurement can set stricter constraint than neutron; however, some models allow some cancelation mechanism that the electron EDM measurement itself can provide only a correlation behavior between different parameters, thus the neutron EDM is also important [see e.g., Y.-N. Mao, Phys. Rev. **D90**, 115024 (2014); Phys. Rev. **D94**, 055008 (2016); L. Bian *et al.*, Phys. Rev. Lett. **115**, 021801 (2015); L. Bian and N. Chen, Phys. Rev. **D95**, 115029 (2017); etc.].

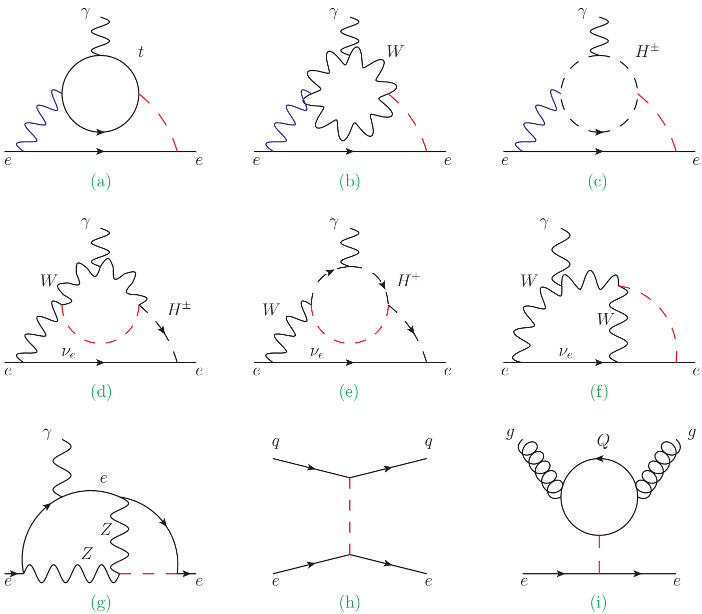
- The scalar or vector interactions are not affected by the Yukawa type.

- We divide the four Yukawa types into two groups: (I, IV) and (II, III).

- Reason: in each group, the two models share the same electron-scalar and top-scalar interactions, which means the dominant behavior for the two models in a same group must be the the same.

- $b \to s\gamma$ decay set $m_\pm \gtrsim 570$ GeV for Type II and IV models, while for Type I and III models, $H^\pm$ can be lighter in large t_β limit [Belle Collaboration, **1608.02344**; M. Misiak and M. Steinhauser, Eur. Phys. J. **C77**, 201 (2017).].

Two-loop diagrams and $e - N$ interaction:



- Typical Feynman diagrams.
- Barr-Zee type, non Barr-Zee type, $e - N$ interaction.
- Blue lines denote γ and Z, red lines denote neutral scalars.
- Refs: [S. M. Barr and A. Zee, PRL**65**, 21 (1990); T. Abe *et al.*, JHEP **04** (2016), 106; N-P**B352**, 45 (1991); etc.]

A. Type I & IV Models

- In these two models, cancelation mechanism cannot affect.

- In most region $t_\beta \sim \mathcal{O}(1-10)$, $|d_e^{\text{eff}}| \simeq -(1-4) \times 10^{-26} s_{\alpha_2}/t_\beta$ depending on α_1 and $m_{2,3}$ $\rightarrow$no cancelation happens as mentioned above.

- $|\alpha_2| \lesssim 10^{-3} t_\beta$ thus the CP-phase in $H_1 t\bar{t}$ coupling $< 10^{-3}$; $|\alpha_2| \to 0$ also leads to mass degeneration between m_2 and m_3 $\rightarrow$very small CP-violation effects.

- No further constraint through neutron EDM measurement.

- Very difficult for further tests.

B. Type II & III Models

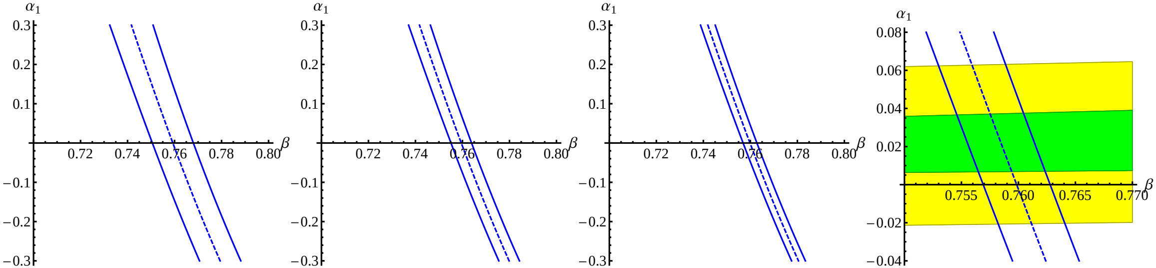
- Cancelation between different contributions can occur in this scenario.
- Two different scenarios: (a) nearly mass degeneration with $s_{2\alpha_3} \sim \mathcal{O}(1)$ and $|m_3 - m_2|/v \ll 1$; (b) mass splitting scenario with large $m_{2,3}$ splitting but $|s_{2\alpha_3}| \ll 1$.
- Recall the relation above:

$$M_3^2 = \frac{c_{(\alpha_1+2\beta)}(M_1^2 - M_2^2 s_{\alpha_3}^2)/c_{\alpha_3}^2 - M_2^2 s_{(\alpha_1+2\beta)} t_{\alpha_3}}{c_{(\alpha_1+2\beta)} s_{\alpha_2} - s_{(\alpha_1+2\beta)} t_{\alpha_3}}$$

or equivalently

$$t_{\alpha_3} = \frac{(m_3^2 - m_2^2) \pm \sqrt{(m_3^2 - m_2^2)^2 s_{(2\beta+\alpha_1)}^2 - 4\,(m_3^2 - m_1^2)\,(m_2^2 - m_1^2)\, s_{\alpha_2}^2 c_{(2\beta+\alpha_1)}^2}}{2\,(m_2^2 - m_1^2)\, s_{\alpha_2} c_{(2\beta+\alpha_1)}}.$$

(a) The nearly mass degenerate scenario, example, $m_{2,3} \simeq 500$ GeV



- Insensitive to α_3, and cancelation appear around $\beta \sim 0.76$.
- The β location when cancelation appear is insensitive to α_2 $(0.05, 0.1, 0.15)$ L→R.
- The last figure combine also the Higgs signal strength global fit.

Neutron EDM:

- From the last page, we see that the electron EDM itself cannot set an upper limit of CP-violation phase because when a cancelation appear, it is not sensitive to the exact number of α_2, thus α_2 itself is not directly constrained.

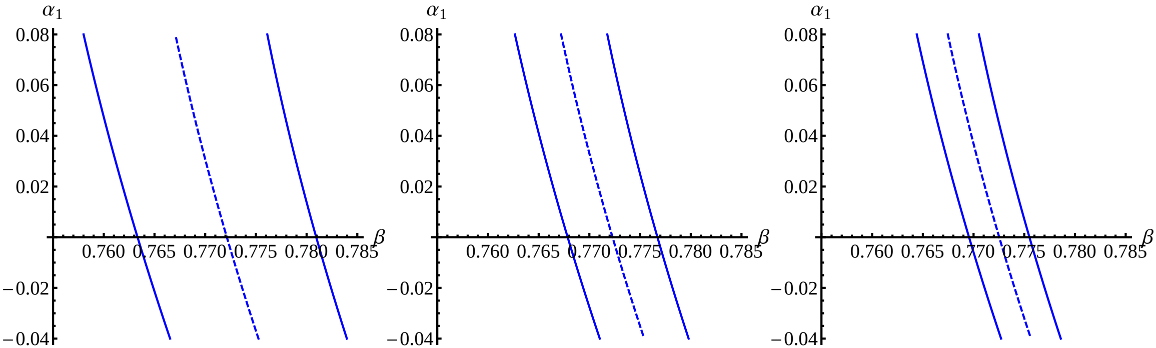
- However, cancelation for neutron EDM usually do not appear at the same time.

- We do not show the calculation of neutron in details here, when cancelation appear in the electron EDM, the neutron EDM is almost $\propto s_{\alpha_2}$, with an uncertainty o $\sim 50\%$.

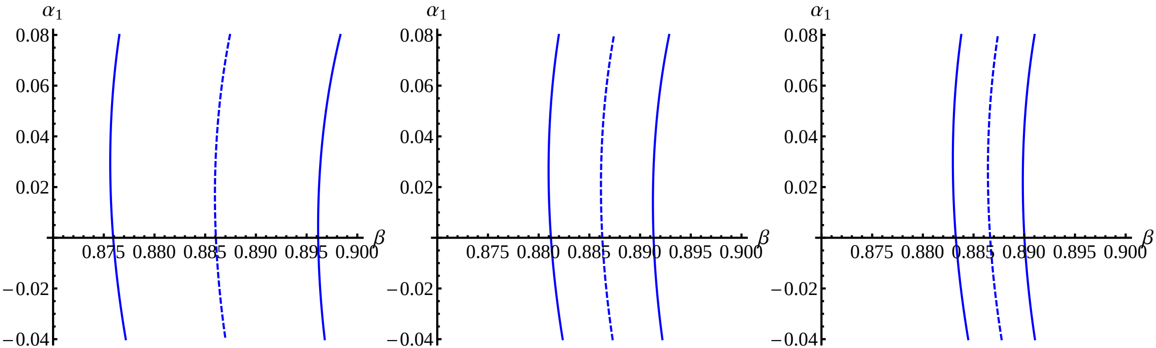
- Using its central value, we can set the upper limit $|\alpha_2| \lesssim 0.15$, this result is stricter than that obtained from Higgs global fit.

(b)The mass splitting scenario:

$\alpha_3 \sim \pi/2$



$\alpha_3 \sim 0$



- Choose $m_2 = 500$ GeV and $m_3 = 650$ GeV.
- Similar cancelation behavior as the nearly mass degenerate scenario.
- Value of β changed due to the different behavior of $\alpha_3(\sim 0$ or $\pi/2)$.
- Neutron EDM constraint: similar to the nearly mass degenerate scenario $|\alpha_2| \lesssim 0.14$.
- In this scenario, $H_3 \to ZH_2$ decay is open and thus it can be used as a collider test: its coupling is $\mathcal{O}(1)$ which brings significant branching ratio.

IV. SUMMARY AND DISCUSSION

- In this talk (and the corresponding unfinished paper), we discuss the CP-violation in extended Higgs sector, and take the soft CP-violation 2HDM as an example.

- Electron EDM set strict constraint on all types of models, for Type I and IV, the CP-violation Higgs-fermion phase are set as $< 10^{-3}$; while for Type II and III, it set a strong correlation between parameters.

- When cancelation happens, neutron EDM becomes important, because it can set the limit directly on $|\alpha_2| < 0.15$; this limit is stricter than that from Higgs global fit, but the Higgs-fermion CP-phase is still allowed at $\mathcal{O}(0.1)$.

- We do not discuss the collider test in this talk in details, because the time is limited and this part have not been finally finished.


The end,
thank you!
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