2HDM with Soft CP-violation: Future LHC Search

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- Based on our paper [Phys. Rev. D **102** (2020), 075029, arXiv: 2003.04178], in collaboration with Kingman Cheung, Adil Jueid, and Stefano Moretti.

I. INTRODUCTION AND MOTIVATION

- CP-violation has been discovered in the meson sector.

- Besides this, there may also other effects: for example, electric dipole moments (EDM, low energy) or collider effects (LHC etc., high energy).

- CP-violation is also a necessary condition to explain the baryon asymmetry in the Universe: quantitatively not enough in the SM, that's why we need new physics.

- Two-Higgs-Doublet Model (2HDM) is a widely studied new physics model which can induce new CP-violation sources, and here we choose it as an example to study its observable CP-violation effects: sensitive to future EDM tests, and future LHC measurements will also provide complementary cross checks to the EDM tests.

II. THE MODEL AND CONSTRAINTS

We consider the 2HDM with soft Z_2-symmetry to avoid terrible FCNC

- Mainly following the conventions in [A. Arhrib *et al.*, JHEP **04** (2011), 089; etc].

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

- Potential with a soft broken Z_2-symmetry ($\phi_1 \to \phi_1$, $\phi_2 \to -\phi_2$):

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

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

- 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.

- 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: (b) 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: $\alpha_{1,2} \to 0$.

- Mixing angle α_2 is the key parameter which measures the CP-violation effects in the 125 GeV Higgs boson (denoted as H_1 here, whose properties are SM-like).

- 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 $H_{2,3}$; in this talk we only discuss the phenomenology for nearly mass-degenerate scenario for simplify.

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 $\tilde{\phi}_i \equiv \mathrm{i}\sigma_2 \phi_i^*$.
- 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)

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

Useful interactions:

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

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

$c_{f,i} = R_{ij} c_{f,j}$ 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}	$\mathrm{i}t_\beta^{-1}$

Constraints from low- and high-energy experiments:

- Electron EDM sets very strict constraints, but in Type II and III models, a cancellation between different contributions to EDM leads to the result that large $|\alpha_2| \sim \mathcal{O}(0.1)$ is still allowed [see Refs. S. Inoue *et al.*, Phys. Rev. D **89**, 115023 (2014); Y.-N. Mao and S.-H. Zhu, Phys. Rev. D **90**, 115024 (2014); L. Bian *et al.*, Phys. Rev. Lett. **115**, 021801 (2015); L. Bian and N. Chen, Phys. Rev. D **95**, 115029 (2017); etc.]

- Type II model: $|\alpha_2| \lesssim 0.1$ due to neutron EDM test.

- Type III model: $|\alpha_2| \lesssim 0.3$ due to global fit for Higgs signal strengths.

- $m_{2,3} \gtrsim 700$ GeV is favored and β depends weakly on heavy scalars mass in cancellation scenario, thus for $m_{2,3} \sim 700$ GeV, $\beta \simeq 0.79$; small α_1 is favored and α_3 is free in a very large region $\sim (0.3 - 1.1)$ for the nearly mass-degenerate scenario.

III. BENCHMARK POINTS

We choose the benchmark points based on the following reasons:

- Fix $m_2 = 700$ GeV satisfying the constraints on charged Higgs $m_{\pm} > 800$ GeV [M. Misiak *et al.*, JHEP **06** (2020), 175], and thus $\beta = 0.79$;

- For the key parameter α_2, take its largest allowed number (0.1 for Type II and 0.3 for Type III) for both models to obtain largest CP-violation effects.

- We choose $\alpha_1 = 0.02$ at its best-fit point and $\alpha_3 = 0.8$ as a central value, and choose $\mu^2 \equiv \mathrm{Re}\,(m_{12}^2)\,/s_{2\beta} = (450\ \mathrm{GeV})^2$ near its largest value due to vacuum stability: CP-violation effects are not sensitive to the values of these parameters;

- Last, calculate m_3 from other parameters.

Summary on the benchmark points and derived couplings:

TABLE I: Benchmark Points for Two-Higgs-doublet Models with Soft CP-violation.

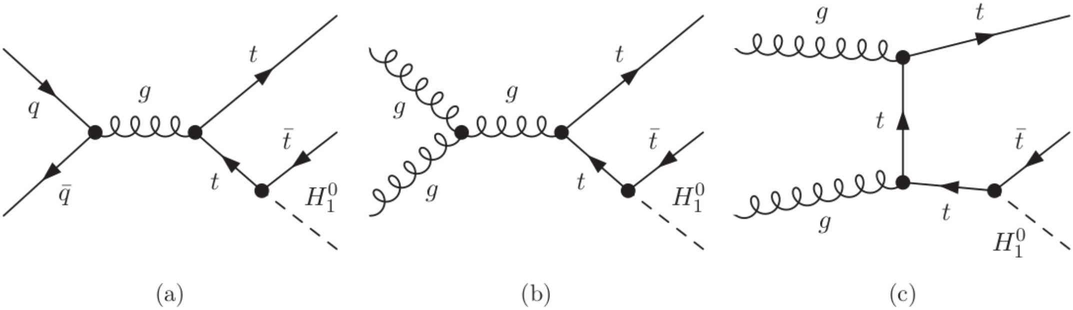
	m_1	m_2	m_3	$m_\pm$	β	α_1	α_2	α_3	$\mu^2 \equiv \mathrm{Re}(m_{12}^2)/s_{2\beta}$
Type II (BP1)	125 GeV	700 GeV	699 GeV	800 GeV	0.79	0.02	0.1	0.8	(450 GeV)^2
Type III (BP2)	125 GeV	700 GeV	696 GeV	800 GeV	0.79	0.02	0.3	0.8	(450 GeV)^2

TABLE II: Couplings derived from the benchmark points in Table I.

	$c_{t,1}$	$c_{t,2}$	$c_{t,3}$	$c_{V,1}$	$c_{V,2}$	$c_{V,3}$
Type II (BP1)	1.01 – 0.099i	0.603 – 0.707i	−0.767 – 0.687i	0.995	−0.086	−0.055
Type III (BP2)	0.974 – 0.293i	0.460 – 0.679i	−0.906 – 0.659i	0.955	−0.226	−0.192

IV. PHENOMENOLOGICAL STUDIES

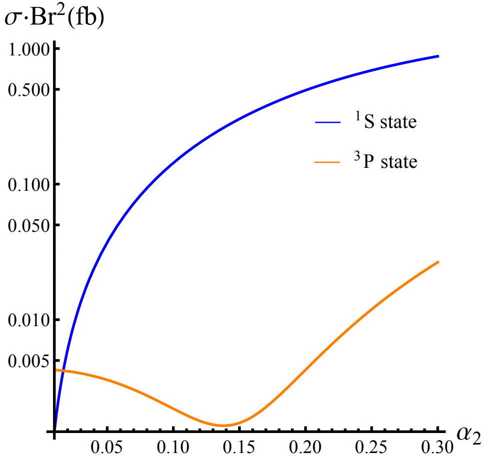
Two examples: (A) Final state distribution for $pp \to t\bar{t}H_1 \to \ell^+\ell^-\nu\bar{\nu} + 4b$



- $t\bar{t}H_1$ cross section can reach about 383 fb at $\sqrt{s} = 13$ TeV LHC with $p_T^H > 50$ GeV.

- A lot of CP-observables, and the best one is to study the azimuthal angle $\Delta\phi$ between the two leptons from top quarks: its asymmetry $\mathcal{A} \equiv \frac{N(\Delta\phi>\pi/2)-N(\Delta\phi<\pi/2)}{N(\Delta\phi>\pi/2)+N(\Delta\phi<\pi/2)}$ is sensitive to the CP-structure in $t\bar{t}H_1$ coupling which is helpful to prob CP-violation.

(B) VBF channel: $pp(VV) \to H_{2,3} \to t\bar{t}(^1S) \to b\bar{b}\ell^+\ell^-\nu\bar{\nu}u$ (in preparation)



- The VBF vertex $H_{2,3}VV$ must be CP-even at tree level, while the decay vertex $t\bar{t}H_{2,3}$ must contain CP-odd component to form the ^1S state, which can be measured through final state distribution.
- The discovery of ^1S state $t\bar{t}$ pair from VBF $H_{2,3}$ resonance will be the signature of CP-violation.
- No interference with SM background due to CP analysis: behave as a perfect peak structure.
- Interference between $H_{2,3}$ is important: peak cross section almost $\propto [c_{V,2}\text{Im}(c_{t,2}) + c_{V,3}\text{Im}(c_{t,3})]^2 \sim s_{\alpha_2}^2$, and ^3P state almost disappears since $c_{V,2}\text{Re}(c_{t,2}) + c_{V,3}\text{Re}(c_{t,3}) \ll 1$.
- Cross sections for ^1S and ^3P states are shown in the upper plot, for the largest allowed $\alpha_2 = 0.3$, $\sigma_{VV\to H_{2,3}\to t\bar{t}(^1S)} \times \text{Br}^2_{t\to b\ell\nu}$ can reach about 0.8 fb for $m_{2,3} \sim 700$ GeV.

V. SUMMARY

- We chose the widely studied 2HDM with soft CP-violation to analyze its high- and low-energy constraints, and showed that a large CP-violation mixing angle $\alpha_2 \simeq 0.1(0.3)$ is still allowed for Type II(III) model.

- We chose two processes to study the CP-violation effects at LHC: asymmetry of lepton azimuthal angle for $pp \to t\bar{t}H_1 \to \ell^+\ell^-\nu\bar{\nu} + 4b$, and the ^1S $t\bar{t}$ state from VBF $H_{2,3}$ resonance as the probe of CP-violation (in preparation).

- For the VBF process, ^3P state is negligible and ^1S state will not interfere with SM background, $\sigma_{^1S} \times \mathrm{Br}^2_{t\to b\ell\nu}$ can reach about 0.8 fb for the largest allowed CP-violation angle $\alpha_2 = 0.3$, and the spin-correlation can be probed through final state distribution.


The end,
thank you!
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