2HDM with Soft CP-violation: EDM and Collider Tests

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- ◇ Based on papers: Phys. Rev. D **102**, 075029 (2020) (in collaboration with **Kingman Cheung**, **Adil Jueid**, and **Stefano Moretti**); and my another paper in preparation.

I. INTRODUCTION

- CP-violation: first discovered in 1964 ($K_L \to 2\pi$ decay), found in K-, B-, and D-meson sectors till now, successfully explained by Kobayashi-Maskawa mechanism (complex phase in CKM matrix if three or more generations of quarks exist).

- CP-violation beyond SM: a kind of new physics.

- Other tests in low- or high-energy experiments other than flavor: typically EDM (low energy) and collider (high energy) experiments.

  - EDM tests: electron, neutron, atoms and molecules (para- or diamagnetic), etc.

  - Collider tests: $t\bar{t}H$ or $\tau^+\tau^-H$ vertices, spin information can be found in the distribution of final states from t or τ decay, etc.

- A famous theoretical motivation for new CP-violation sources: connection between new CP-violation sources and baryogenesis in the Universe.
    - Baryon number violation;
    - P- and CP-violation;
    - Away from thermal equilibrium (first-order EW phase transition).
- SM itself cannot generate enough matter-antimatter asymmetry.
- Theoretically, CP-violation may appear in models with extended scalar sector. Here we choose a widely studied example, two-Higgs-doublet model (2HDM) with soft CP-violation to study its EDM and collider tests, and also briefly discuss the connection with matter-antimatter asymmetry in the Universe.

- EDM interaction $-\mathrm{i}(d_f/2)\bar{f}\sigma^{\mu\nu}\gamma^5 f F_{\mu\nu} \to d_f \vec{E}\cdot\vec{s}/s$: violates P- and CP-symmetries.

- Current EDM results: no nonzero evidence, and the upper limits [see Refs. ACME collaboration, nature **562**, 355 (2018) and nEDM collaboration, Phys. Rev. Lett. **124**, 081803 (2020) etc.] @ 90% C.L. are separately

$$|d_e| < 1.1\times 10^{-29}\ e\cdot\mathrm{cm} \qquad \text{and} \qquad |d_n| < 1.8\times 10^{-26}\ e\cdot\mathrm{cm}.$$

- Still far above SM predictions $d_e \sim 10^{-38}\ e\cdot\mathrm{cm}$ and $d_n \sim 10^{-32}\ e\cdot\mathrm{cm}$ at three- or four-loop level, but models in which EDMs can be generated at one- or two-loop level are already facing strict constraints.

- No extra CP-violation evidence at LHC, $|\arg(g_{h\tau\tau})| < 0.6$ @ 95% C.L. [CMS collaboration, Report No. **CMS-PAS-HIG-20-006**].

II. MODEL SET-UP

- 2HDM with soft CP-violation: mainly follow 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$\rightarrow$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: $\text{Im}\,(m_{12}^2) = v_1 v_2 \text{Im}(\lambda_5)$.

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

- 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); in this talk we discuss only the nearly mass-degenerate scenario due to time limit.

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

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

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

$c_{f,i} = R_{ij} c_{f,j}$ 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}	$-\text{i}t_\beta^{-1}$	0	s_β^{-1}	$\text{i}t_\beta^{-1}$	0	s_β^{-1}	$\text{i}t_\beta^{-1}$
II	0	s_β^{-1}	$-\text{i}t_\beta^{-1}$	c_β^{-1}	0	$-\text{i}t_\beta$	c_β^{-1}	0	$-\text{i}t_\beta$
III	0	s_β^{-1}	$-\text{i}t_\beta^{-1}$	0	s_β^{-1}	$\text{i}t_\beta^{-1}$	c_β^{-1}	0	$-\text{i}t_\beta$
IV	0	s_β^{-1}	$-\text{i}t_\beta^{-1}$	c_β^{-1}	0	$-\text{i}t_\beta$	0	s_β^{-1}	$\text{i}t_\beta^{-1}$

III. ELECTRIC DIPOLE MOMENTS (EDM): OVERVIEW

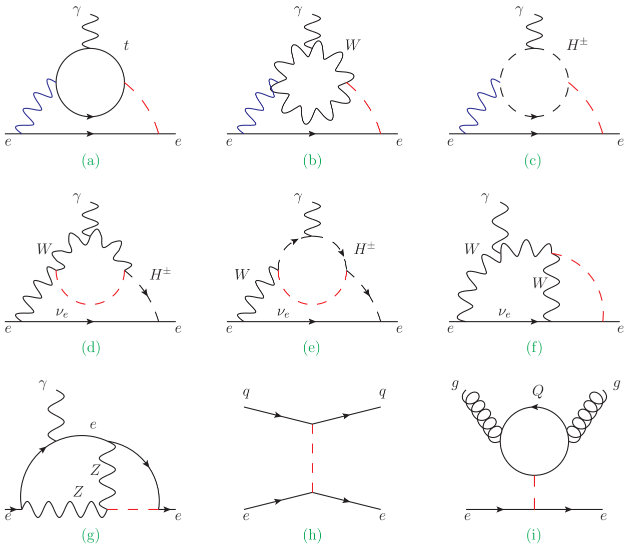
- **Electron**: measured through ThO [ACME collaboration, nature **562**, 355 (2018)], $d_e + kC$ where the second term comes from the electron-nucleon interaction $C\bar{N}N\bar{e}\mathrm{i}\gamma^5 e$.

- $k \approx 1.6 \times 10^{-21}$ TeV$^2 \cdot e \cdot$ cm in ThO, similar order for other materials.

- CP-violation vertices: $H_i\bar{e}e$, $H_i\bar{t}t$, $H_iW^{\pm}H^{\mp}$.

- d_e in this model is generated at two-loop level [for detailed calculations, see Refs. S. M. Barr and A. Zee, Phys. Rev. Lett. **65**, 21 (1990); R. G. Leigh, S. Paban, and R.-M. Xu, Nucl. Phys. B **352**, 45 (1991); T. Abe *et al.*, JHEP **01** (2014), 106; J. Brod, U. Haisch, and J. Zupan, JHEP **11** (2013), 180; etc.]

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



Colored lines: γ, Z, and H_i.

No.	CPV	Related Couplings
(a)	$H_i t\bar{t}$, $H_i e\bar{e}$	$\text{Im}(c_{e,i})\text{Re}(c_{t,i})$, $\text{Im}(c_{t,i})\text{Re}(c_{e,i})$
(b)	$H_i e\bar{e}$	$c_{V,i}\text{Im}(c_{e,i})$
(c)	$H_i e\bar{e}$	$c_{\pm,i}\text{Im}(c_{e,i})$
(d)	$H_i H^\pm W^\mp$	$c_{V,i}\text{Im}(c_{e,i})$
(e)	$H_i H^\pm W^\mp$	$c_{\pm,i}\text{Im}(c_{e,i})$
(f)	$H_i e\bar{e}$	$c_{V,i}\text{Im}(c_{e,i})$
(g)	$H_i e\bar{e}$	$c_{V,i}\text{Im}(c_{e,i})$
(h)	$H_i e\bar{e}$	$\text{Im}(c_{e,i})\text{Re}(c_{q,i})$
(i)	$H_i e\bar{e}$	$\text{Im}(c_{e,i})\text{Re}(c_{Q,i})$

- **Neutron**: light quark EDM, light quark CEDM, and Weinberg operator

$$\mathcal{L} \supset \sum_{q=u,d} \Big(C_q(\mu)\mathcal{O}_q(\mu) + \tilde{C}_q(\mu)\tilde{\mathcal{O}}_q(\mu) \Big) + C_g(\mu)\mathcal{O}_g(\mu),$$

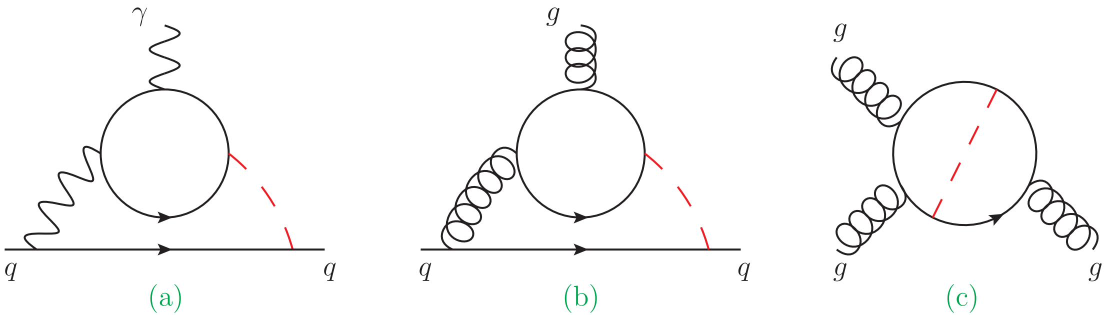
with

$$\begin{aligned} \mathcal{O}_q &= -\frac{\mathrm{i}}{2} e Q_q m_q \bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu}, \\ \tilde{\mathcal{O}}_q &= -\frac{\mathrm{i}}{2} g_s m_q \bar{q}\sigma^{\mu\nu} t^a \gamma_5 q G^a_{\mu\nu}, \\ \mathcal{O}_g &= -\frac{1}{3} g_s f^{abc} G^a_{\mu\rho} G^{b,\rho}_{\nu} \tilde{G}^{c,\mu\nu}; \end{aligned}$$

and

$$d_q(\mu)/e \equiv Q_q m_q(\mu) C_q(\mu), \quad \tilde{d}_q(\mu) \equiv m_q(\mu)\tilde{C}_q(\mu).$$

- Corresponding Feynman diagrams:



- RGE running from weak scale ($\mu_W \sim m_t$) to hadron scale ($\mu_H \sim 1$ GeV):

$$\begin{pmatrix} C_q(\mu_H) \\ \tilde{C}_q(\mu_H) \\ C_g(\mu_H) \end{pmatrix} = \begin{pmatrix} 0.42 & -0.38 & -0.07 \\ & 0.47 & 0.15 \\ & & 0.20 \end{pmatrix} \begin{pmatrix} C_q(\mu_W) \\ \tilde{C}_q(\mu_W) \\ C_g(\mu_W) \end{pmatrix} .$$

[J. Brod *et al.*, JHEP **11** (2013), 180; etc.]

- Final result of neutron EDM [J. Hisano *et al.*, Phys. Rev. D **85**, 114044 (2012)]

$$\frac{d_n}{e} = m_d(\mu_H)\left(0.27Q_dC_d(\mu_W) + 0.31\tilde{C}_d(\mu_W)\right) \\ +m_u(\mu_H)\left(-0.07Q_uC_u(\mu_W) + 0.16\tilde{C}_u(\mu_W)\right) + (9.6\ \mathrm{MeV})\, w(\mu_W).$$

- The theoretical uncertainty $\sim 50\%$, which can be reduced by current and future lattice results [N. Yamanaka *et al.* (JLQCD collaboration), Phys. Rev. D **98**, 054516 (2018); B. Yoon *et al.*, Pos **LATTICE2019** (2019), 243].

- Atoms' EDM are not important in the scenario we discuss here, thus we do not show much details about them in this talk.

IV. EDM CONSTRAINTS ON 2HDM: NUMERICAL ANALYSIS

- We divide all the four models into two groups: (I, IV) and (II, III). For eEDM, in each group, we have almost the same result in the two models.

A. eEDM in Type I & IV models

- No cancellation behavior in eEDM, in the case $m_{2,3} \simeq 500$ GeV, $m_\pm \simeq 600$ GeV, $\mu^2 \equiv \mathrm{Re}(m_{12}^2)/s_{2\beta}$ and $\alpha_1 \sim 0$,

$$d_e^{\mathrm{I,IV}} \simeq -6.7 \times 10^{-27} \left(s_{2\alpha_2}/t_\beta\right) \; e \cdot \mathrm{cm}.$$

- $\longrightarrow |s_{\alpha_2}/t_\beta| \lesssim 8.2 \times 10^{-4}$: extremely small CP-phase, far away from the sensitivity of colliders and the explanation to baryogenesis.

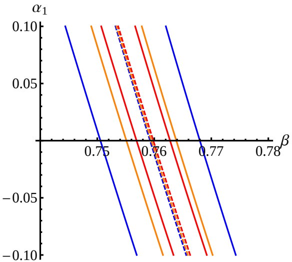
B. eEDM in Type II & III models

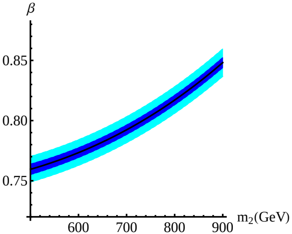
- Possible cancellation behavior between different contributions in eEDM [see Refs. S. Inoue *et al.*, Phys. Rev. D **89**, 115023 (2014); Y.-N. Mao and S.-H. Zhu, Phys. Rev. D **90**, 115024 (2014); L. Bian *et al.*, Phys. Rev. Lett. **115**, 021801 (2015); L. Bian and N. Chen, Phys. Rev. D **95**, 115029 (2017); etc.]

- Consider the scenario with close $m_{2,3}$, in the case $m_{2,3} \simeq 500$ GeV, $m_{\pm} \simeq 600$ GeV, $\mu^2 \equiv \mathrm{Re}(m_{12}^2)/s_{2\beta} = (450\ \mathrm{GeV})^2$, $\alpha_3 = 0.8$, and $\alpha_1 \sim 0$:

$$d_e^{\mathrm{II,III}} \simeq 3.4 \times 10^{-27} s_{2\alpha_2} \left(t_\beta - 0.904/t_\beta\right)\ e \cdot \mathrm{cm}.$$

- Note: latest constraint favors $m_{\pm} \gtrsim 800$ GeV hence we need heavier $H_{2,3}$ [M. Misiak *et al.*, JHEP **06** (2020), 175], but all main properties discussed in this talk are left unchanged, with only slightly numerical changing.





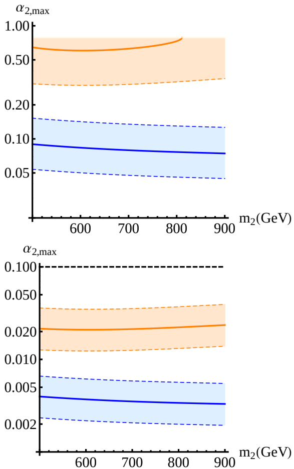
- A cancellation can appear around $t_\beta \simeq 0.95$ ($\beta \simeq 0.76$), and the region depends weakly on $\alpha_{1,2,3}$ and $m_{2,3,\pm}$.

- $\alpha_2 = (0.05, 0.1, 0.15)$, strict constraint on α_2 turns to strong correlation between β and α_1, similar behavior in Type II and III models.

- Large $|\alpha_2| \sim \mathcal{O}(0.1)$ allowed without t_β^{-1} suppression in CP-phases$\longrightarrow$possible collider effects and explanation to EW baryogenesis.

- Added: another cancellation region locates at $t_\beta \sim (10-20)$, but the CP-phase is strongly constrained by mercury EDM since in that region the $e-N$ interaction with small uncertainties contributes dominantly to $d_{\rm Hg}$.

C. nEDM: Current and Future Constraints



- No cancellation behavior in the same region for nEDM.
- Main contribution comes from $\tilde{d}_d$ and $d_n \propto s_{2\alpha_2}$ insensitive to $\alpha_{1,3}$, current limit: $|\alpha_2| \lesssim 0.1$ in Type II model, almost no limit in Type III model.
- Future test: nEDM to accuracy $10^{-27}\ e \cdot \text{cm}$, $|\alpha_2| \sim 0.1$ will be easily tested then, and null result will set $|\alpha_2| \lesssim 4 \times 10^{-3} (2 \times 10^{-2})$ in Type II (III) model$\longrightarrow$Type II model cannot explain baryogenesis if no evidence in future nEDM.
- The n2EDM experiment @ PSI: most powerful EDM test in the future several years, show evidence or set strict constraints on the scenarios even with cancellation in eEDM.

V. LHC PHENOMENOLOGY: $t\bar{t}H(125)$ ASSOCIATED PRODUCTION

- CPV in $t\bar{t}H_1$ coupling: $\mathcal{L} = -c_{t,1}\bar{t}_L t_R H_1 + \text{H.c.}$, with $c_{t,1} = c_{\alpha_2} s_{\beta+\alpha_1}/s_\beta - \mathrm{i} s_{\alpha_2}/t_\beta$.

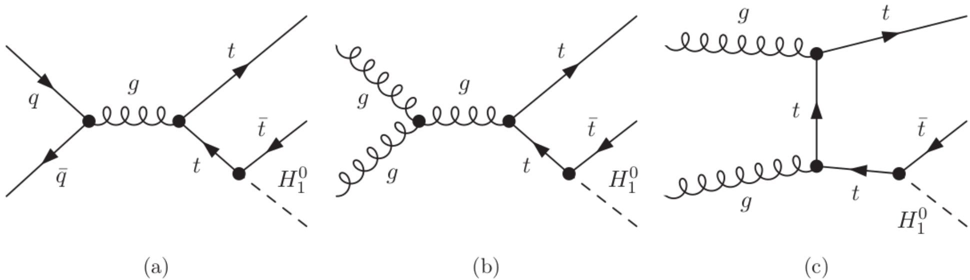
- EDM and LHC favored region: $\alpha_1 \sim 0$ and $t_\beta \sim 1$, thus $c_{t,1} \sim \mathrm{e}^{-\mathrm{i}\alpha_2}$ is mainly sensitive to mixing angle α_2, independent on α_3.

- Benchmark point: LHC data set the constraint on Type III model, $|\alpha_2| \lesssim 0.27$ in the case $m_2 \sim 500$ GeV, weaker than neutron EDM constraint on Type II model.

- We choose $\beta = 0.76$, $\alpha_1 = 0.02$, and $\alpha_2 = 0.27$ (Type III) as the benchmark point in the following collider study, corresponding to $c_{t,1} = 0.984 - 0.28\mathrm{i}$; the experimentally favored region depends weakly on heavy scalar sector.

Phenomenological Set-up:

- Process: $pp(gg, q\bar{q}) \to t\bar{t}(\to b\bar{b}\ell^+\ell^-\nu\bar{\nu})H(\to b\bar{b})$



- Event selection: two opposite leptons $\ell^+\ell^-$, ≥ 4 b-tagged jets.

- Cuts: $p_T^{e/\mu/j} > 30/27/30$ GeV, $\eta^{e/\mu/j} < 2.5/2.4/2.4$, jet radius $D = 0.4$, b-tagging efficiency $\epsilon_b = 0.8$, $|m_{b\bar{b}} - m_h| < 15$ GeV, and $p_T^{b\bar{b}} > 50$ GeV.

Cross sections:

- SM $t\bar{t}H(125)$ cross section (parton level) @ 13 TeV LHC

	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]
No cuts	$398.9^{+32.7\%}_{-22.9\%}$ (scale)$^{+1.91\%}_{-1.54\%}$ (PDF)	$470.6^{+5.8\%}_{-9.0\%}$ (scale)$^{+2.2\%}_{-2.1\%}$ (PDF)
$p_T^H > 50$ GeV	$325.2^{+32.8\%}_{-22.9\%}$ (scale)$^{+1.96\%}_{-1.56\%}$ (PDF)	$382.8^{+5.4\%}_{-8.8\%}$ (scale)$^{+2.3\%}_{-2.1\%}$ (PDF)
$p_T^H > 200$ GeV	$55.6^{+33.9\%}_{-23.5\%}$ (scale)$^{+2.44\%}_{-1.81\%}$ (PDF)	$69.8^{+8.3\%}_{-10.6\%}$ (scale)$^{+2.9\%}_{-2.6\%}$ (PDF)

- Gluon fusion contributes dominantly $\sim 70\%$.

- $\sigma_{\rm 2HDM}/\sigma_{\rm SM} \simeq [{\rm Re}(c_{t,1})]^2 + 0.4\,[{\rm Im}(c_{t,1})]^2$.

- Selecting $p_T^H > 50$ GeV will keep most signal events.

CP observables:

- We choose a lot of observables in this paper, mainly using the distributions carrying spin information of top and anti-top quarks.

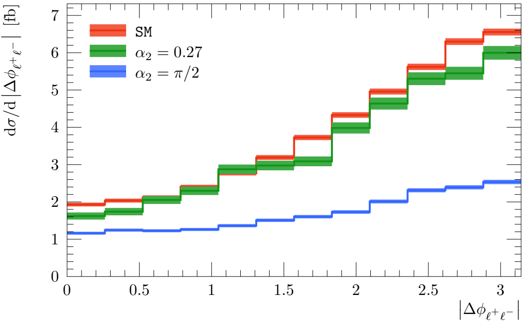
- Among those, we just take the most sensitive on in this talk as an example: $d\sigma/d|\Delta\phi|$ where $|\Delta\phi|$ is the azimuthal angle between two leptons. It carries the spin-correlation information between top and anti-top quarks.

- Define the asymmetry $\mathcal{A}$ (N_+ means the event number with $|\Delta\phi| > \pi/2$, N_- means the event number with $|\Delta\phi| < \pi/2$, $N = N_+ + N_-$, and $\sigma_{\mathcal{A}}$ is its uncertainty)

$$\mathcal{A} \equiv \frac{N_+ - N_-}{N_+ + N_-}, \quad \text{with} \quad \sigma_{\mathcal{A}}^2 = \frac{4N_+N_-}{N^3}.$$

Numerical result as an example:

- Distribution of the azimuthal angle between two leptons.



- ○ In a CP-violation case, the distribution (green) is a combination of the SM case (red) and pure pseudoscalar case (blue).
- ○ Distribution of pseudoscalar case is flatter than SM case.

- Result: $\chi^2 \equiv (\mathcal{A} - \mathcal{A}_{\rm SM})^2/\sigma_{\mathcal{A}}^2 = 5.81$ with 3 ab^{-1} luminosity at LHC, corresponding to the p-value 1.59×10^{-2} (about 2.4σ deviation).

VI. SUMMARY AND DISCUSSION

- In this talk, we take 2HDM with soft CP-violation as an example, to discuss the CPV effects confronting both EDM and LHC tests. Type I and IV models are set strict constraint by eEDM $\arg(c_{t\tau,1}) \lesssim 8.2 \times 10^{-4}$ thus we do not consider it further.

- For Type II and III models, there is a cancellation region in eEDM allowing large $\alpha_2 \sim \mathcal{O}(0.1)$. For Type II model, the limit is $|\alpha_2| \lesssim 0.1$ due to nEDM; and for Type III model, $|\alpha_2| \lesssim 0.27$ due to LHC data.

- $\alpha_2 \sim \mathcal{O}(0.1)$ will first appear in future nEDM test to the accuracy $10^{-27}\ e\cdot\text{cm}$, else we will set the limit $|\alpha_2| \lesssim 4\times 10^{-3}(2\times 10^{-2})$ in Type II (III) model: Type II model cannot be used to explain the baryon asymmetry if no evidence arises in nEDM.

- We also discuss the CP-violation in $t\bar{t}H(125)$ production with $|\alpha_2| \simeq 0.27$ as a complementary cross-check: expected p-value $\sim 1.59\times 10^{-2}$ ($\sim 2.4\sigma$ significance), a direct search for CP-violation but less sensitive than nEDM experiments.


The end,
thank you!
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