Two-Higgs-Doublet Model with Soft CP-violation Confronting EDM and Collider Tests

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Based on our new paper [arXiv: 2003.04178] (PRD accepted) in collaboration with Kingman Cheung, Adil Jueid, and Stefano Moreti.

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, typically EDM (low energy) and collider (high energy) experiments.

- Another theoretical motivation: connection between new CP-violation sources and matter-antimatter asymmetry in the Universe.

- CP-violation may appear in models with extended scalar sector, and in this paper/talk, we choose the widely studied example, two-Higgs-doublet model (2HDM) with soft CP-violation, discussing the current and future EDM and collider tests.

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

- Current EDM results: no nonzero evidence, and the upper limits [see Refs. ACME collaboration, nature **562**, 355 (2018) (electron) and nEDM collaboration, Phys. Rev. Lett. **124**, 081803 (2020) (neutron)] @ 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 in one- or two-loop level is 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:

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

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

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

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

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

	$\bar{u}_i u_i$	$\bar{d}_i d_i$	$\bar{\ell}_i \ell_i$
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. ELECTRIC DIPOLE MOMENTS (EDM): OVERVIEW

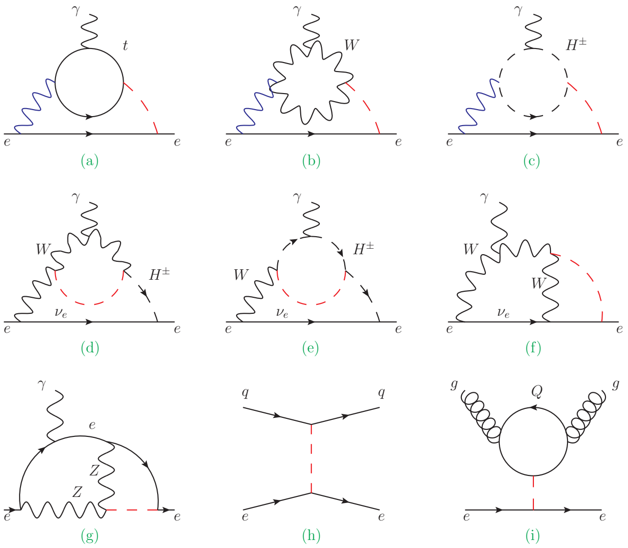
- **Electron**: measured through ThO [ACME collaboration, nature **562**, 355 (2018)], $d_e + kC$ where the second term comes from the electron-nucleon interaction $C\bar{N}N\bar{e}\mathrm{i}\gamma^5 e$.

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

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

- 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. **B352**, 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:



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

Colored lines: γ, Z, and H_i.

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

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

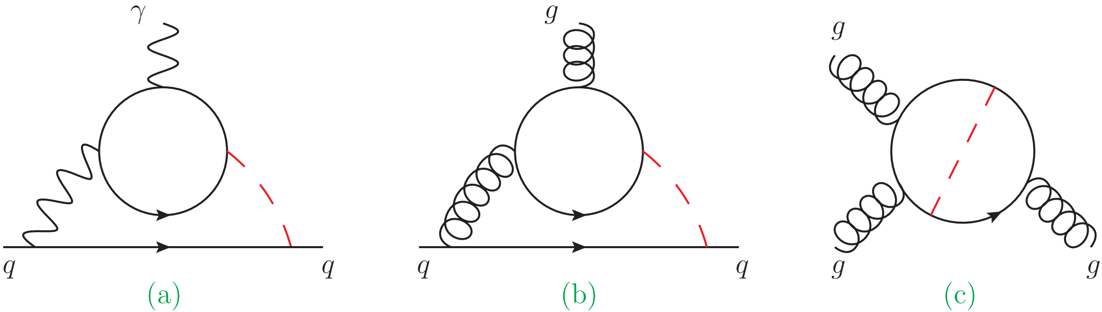
with

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

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. **D85**, 114044 (2012)]

$$\begin{aligned}\frac{d_n}{e} &= m_d(\mu_H)\left(0.27 Q_d C_d(\mu_W) + 0.31 \tilde{C}_d(\mu_W)\right) \\ &\quad + m_u(\mu_H)\left(-0.07 Q_u C_u(\mu_W) + 0.16 \tilde{C}_u(\mu_W)\right) + (9.6\ \mathrm{MeV})\, w(\mu_W).\end{aligned}$$

- The theoretical uncertainty $\sim 50\%$, which can be reduced by current and future lattice results [N. Yamanaka *et al.* (JLQCD collaboration), Phys. Rev. **D98**, 054516 (2018); B. Yoon *et al.*, Pos **LATTICE2019** (2019), 243].

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

IV. EDM CONSTRAINTS ON 2HDM: NUMERICAL ANALYSIS

- **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 $\alpha_1 \sim 0$,

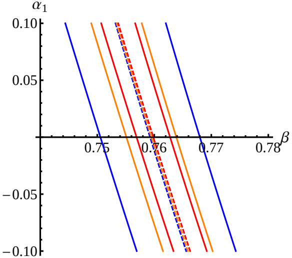
$$d_e^{\mathrm{I,IV}} \simeq -6.7 \times 10^{-27} \left(s_{2\alpha_2}/t_\beta\right) \; e \cdot \mathrm{cm}.$$

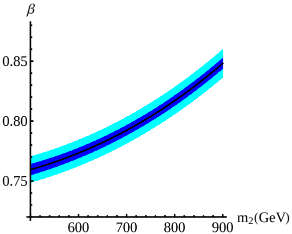
- $\longrightarrow$ $|s_{\alpha_2}/t_\beta| \lesssim 8.2 \times 10^{-4}$: extremely small CP-phase away from the sensitivity of colliders and the explanation to baryogenesis.

- **Type II & III models**: possible cancellation behavior between different contributions in eEDM [see Refs. S. Inoue, M. J. Ramsey-Musolf, and Y. Zhang, Phys. Rev. **D89**, 115023 (2014); Y.-N. Mao and S.-H. Zhu, Phys. Rev. **D90**, 115024 (2014); L. Bian, T. Liu, and J. Shu, Phys. Rev. Lett. **115**, 021801 (2015); L. Bian and N. Chen, Phys. Rev. **D95**, 115029 (2017); etc.]

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

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

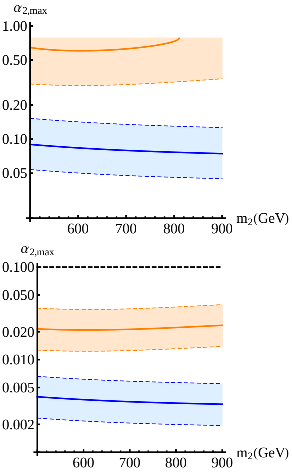




- A cancellation can appear around $t_\beta \simeq 0.95$ ($\beta \simeq 0.76$), and the region depends weakly on $\alpha_{1,2,3}$ and $m_{2,3,\pm}$.

- $\alpha_2 = (0.05, 0.1, 0.15)$, 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.



- 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.

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

- CPV in $t\bar{t}H_1$ coupling: $\mathcal{L} = -c_{t,1}\bar{t}_L t_R H_1 + \mathrm{H.c.}$, 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.

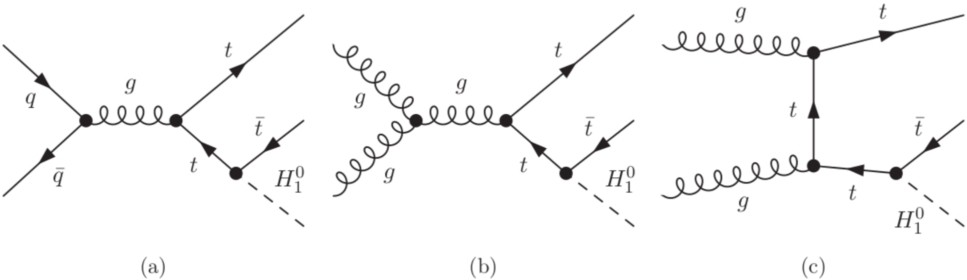
- Benchmark point: LHC data set the constraint on Type III model, $|\alpha_2| \lesssim 0.27$ in the case $m_2 \sim 500$ GeV, weaker than neutron EDM constraint on Type II model.

- 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 $c_{t,1} = 0.984 - 0.28\mathrm{i}$.

- It is not sensitive to the heavy scalar sector.

Phenomenological Set-up:

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



(a) (b) (c)

- 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

	σ_{LO} [fb]	σ_{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 $\sim 70\%$.

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

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

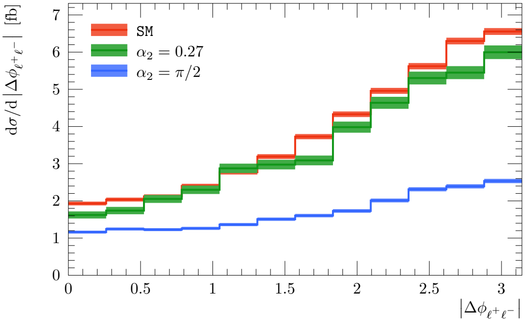
CP observables:

- 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)

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



- 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. CONCLUSIONS AND DISCUSSION

- In this paper/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 $\arg(c_{t\tau,1}) \lesssim 8.2 \times 10^{-4} \longrightarrow$ to small that we do not consider its collider phenomenology.

- 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 $10^{-27}\ e \cdot \mathrm{cm}$, else we will set the limit $|\alpha_2| \lesssim 4 \times 10^{-3} (2 \times 10^{-2})$ in Type II (III) model.

- We discuss the CPV effects in $t\bar{t}H(125)$ production, using the benchmark point $\beta = 0.76$, $\alpha_1 = 0.02$, and $\alpha_2 = 0.27$ in Type III model.

- The effects appear in some observables, among which the azimuthal angle $\Delta\phi$ between two leptons from $t(\bar{t})$ decay is the most sensitive one.

- The χ^2 can reach 5.81 corresponding to a p-value 1.59×10^{-2}.

- It is less sensitive than future nEDM experiments, but can provide a complementary cross-check of the EDM results.

- In future projects, we will discuss the phenomenology of the heavy scalar sector ($H_{2,3,\pm}$), in which the interference effects between signal and SM background become important.


The end,
thank you!
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