Testing CP-violation in the Scalar Sector at Lepton Colliders

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- Mainly based on an old paper [G. Li, Y.-N. Mao, C. Zhang, and S.-H. Zhu, Phys. Rev. D **95** (2017), 035015][arXiv][Inspire], together with some related but unpublished results.

I. INTRODUCTION

- CP-violation has already been discovered in (K-, B-, and D-) meson sectors, and the measured CP-violation effects can be explained well by the complex phase in CKM-matrix [Particle Data Group, PTEP **2020** (2020), 083C01].
- It is still an important topic in particle physics because:
    - Discrete symmetry is a basic topic in particle physics sduty;
    - It is also a possible path to new physics;
    - It is one of the necessary conditions to understand the matter-antimatter asymmetry in the Universe [A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5** (1967), 32; JETP Lett. **5** (1967), 24]; etc.

- People have already measured CP-violation in meson sectors, but there are also other possible ways to test CP-violation effects, such as:
  - Indirect search: electric dipole moments (probe the existence of CP-violation but cannot lead us directly to the CP-violation vertices);
  - Direct search: collider measurements (directly lead us to the CP-violated interactions); etc.
- Collider search: in previous works people mainly focus on CP-violation in Yukawa sector using final state distributions (e.g., $H \to \tau^+\tau^-$).
- In this talk, we focus on searching CP-violation in scalar sector at lepton colliders.

II. THE METHOD

- General case: if at least two scalars are discovered, the CP-properties analysis

$$\text{Vertices at tree level}: \qquad \underset{+}{H_i\, ZZ} \qquad \underset{+}{H_j\, ZZ} \qquad \begin{array}{cc} H_i & H_j\; Z \\ +? & -? \\ -? & +? \end{array}$$

- Minimal case: effective interaction

$$\mathcal{L} \supset \frac{m_Z^2}{v} Z_\mu Z^\mu \left(c_1 H_1 + c_2 H_2\right) + \frac{c_{12} m_Z}{v} Z_\mu \left(H_1 \partial^\mu H_2 - H_2 \partial^\mu H_1\right).$$

- If all the three vertices are measured nonzero (all $c_{1,2,12} \neq 0$): evidence of CP-violation.

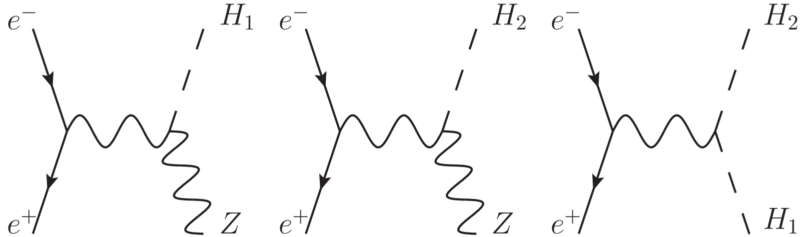
- Set a quantity $K \equiv c_1 c_2 c_{12}$ and $K \neq 0$ is a sufficient (but not necessary) condition of the existence of CP-violation.

Denote H_1 as the 125 GeV Higgs boson, H_1VV couplings have already been measured.

- At hadron colliders, $H_2 \to ZZ/ZH_1$ cascade decay channels will be the evidence of nonzero c_2 and c_{12} thus CP-violation can be confirmed.

- However, at hadron colliders we cannot extract c_2 and c_{12} (and hence K) in a model-independent way, since the inclusive cross section cannot be measured.

- At lepton colliders, inclusive corss sections $e^+e^- \to ZH_1, ZH_2, H_1H_2$ can all be measured, thus we can extract K in a model-independent way.



- Simple observables: inclusive cross sections are enough

$$\sigma_{ZH_2} = \frac{\pi\alpha^2 s c_2^2}{96\left(s-m_Z^2\right)^2}\cdot\frac{1-4s_W^2+8s_W^4}{s_W^4 c_4^W}\cdot\left[f^3\left(\frac{m_2^2}{s},\frac{m_Z^2}{s}\right)+\frac{12m_Z^2}{s}f\left(\frac{m_2^2}{s},\frac{m_Z^2}{s}\right)\right];$$
$$\sigma_{H_1H_2} = \frac{\pi\alpha^2 s c_{12}^2}{96\left(s-m_Z^2\right)^2}\cdot\frac{1-4s_W^2+8s_W^4}{s_W^4 c_4^W}\cdot f^3\left(\frac{m_1^2}{s},\frac{m_2^2}{s}\right).$$

- The function

$$f(x,y)\equiv\sqrt{1+x^2+y^2-2x-2y-2xy}.$$

- The cross sections are sensitive to the couplings c_2, c_{12} but do not depend on other details of the model: good observables to test CP-violation model-independently.

How to measure the inclusive cross sections: recoil mass method

- At a lepton collider, all components of the 4-momentum $(E, \vec{p})$ can be reconstructed since $\sqrt{s} = (p_+ + p_-)^2$ is fixed.

- Consider a process $e^+e^- \to A(\to f_1 + f_2) + B$, fermions $f_{1,2}$ should be fully reconstructed, thus it is easy to derive that if we define

$$m_{\text{rec}} \equiv \sqrt{s + m_{f_1 f_2}^2 - 2\sqrt{s}(E_{f_1} + E_{f_2})}$$

  (The invariant mass $m_{f_1 f_2}^2 \equiv (E_{f_1} + E_{f_2})^2 - |\vec{p}_{f_1} + \vec{p}_{f_2}|^2$ is also m_A^2.)

- Its distribution must behave as a peak around m_B even if B is unreconstructed: meaning that we can measure the inclusive cross sections without reconstructing B [CEPC Study Group, arXiv: 1811.10545 (CEPC CDR)].

An example: light H_2 scenario

- Processes: $e^+e^- \to ZH_1, ZH_2, H_1H_2$ at CEPC with $\sqrt{s} = 250$ GeV.

- σ_{ZH_1} (and hence c_1) is expected to be measured to the accuracy $\mathcal{O}(10^{-3})$ at CEPC with 5 ab^{-1} luminosity, and thus we need only to focus on ZH_2, H_1H_2 associated production cross sections.

- $e^+e^- \to Z(\to \mu^+\mu^-)H_2/H_1(\to b\bar{b})H_2$ can be used to measure the inclusive σ_{ZH_2/H_1H_2} without reconstructing H_2.

- In the further simulation study, we choose a benchmark point $m_2 = 40$ GeV.

A. ZH_2 Production at CEPC

- We used WHIZARD-2.3.1 with $\sqrt{s} = 250$ GeV and expected luminosity 5 ab^{-1}.

- For $e^+e^- \to Z(\to \mu^+\mu^-)H_2$, main backgrounds are
  $e^+e^- \to \mu^+\mu^- X$ (with $X = \ell^+\ell^-, \tau^+\tau^-, \nu\bar{\nu}, q\bar{q}, b\bar{b}, \gamma\gamma$)

- Selection cuts: $|\cos\theta_\mu| < 0.8$, $p_T(\mu^+\mu^-) > 35$ GeV, $|m_{\mu^+\mu^-} - m_Z| < 10$ GeV, 30 GeV $<$ $m_{\text{rec}} < 60$ GeV, after which we have the signal and background cross sections

$$\sigma_{\text{sig}} = 7.348 c_2^2 \text{ fb}; \qquad \sigma_{\text{bkg}} = 5.916 \text{ fb}.$$

- Dominant background $\sigma_{\mu^+\mu^-\gamma\gamma} = 4.659$ fb.

"p_T-balance" cut

- Ref: [H. Li, PhD Thesis (2009)].

- Motivation: to further reduce the backgrounds with photons, but without breaking the inclusiveness much: still "quasi-model-independent".

- Method: tag the most energetic photon with a transverse momentum $p_T(\gamma)$, and define $p_{T,\mathrm{bal}} \equiv p_T(\gamma) - p_T(\mu^+\mu^-)$.

- Based on its distribution, if we add another cut $p_{T,\mathrm{bal}} > 20$ GeV, the background will be reduced to $\sigma_{\mathrm{bkg}} = 1.468$ fb.

- $\mathrm{Br}_{H_i \to n\gamma}$ is expected to be small in most models, thus tagging a photon breaks the inclusiveness only a little bit.

B. H_1H_2 Production at CEPC

- For $e^+e^- \to H_1(\to b\bar{b})H_2$, main backgrounds are
  $e^+e^- \to ZH_1(\to b\bar{b}), b\bar{b}X$ (with $X = \ell^+\ell^-, \tau^+\tau^-, \nu\bar{\nu}, q\bar{q}, b\bar{b}, \gamma\gamma, g\gamma, gg$)

- Selection cuts: 70 GeV $< p_T(b\bar{b}) <$ 100 GeV, 30 GeV $< p_T^{\text{sub}}(b) <$ 70 GeV $< p_T^{\text{lead}}(b) <$ 110 GeV, $|m_{b\bar{b}} - m_1| <$ 25 GeV, 20 GeV $< m_{\text{rec}} <$ 70 GeV, after which we have the signal and background cross sections

$$\sigma_{\text{sig}} = 12.5\kappa c_{12}^2 \text{ fb}; \qquad \sigma_{\text{bkg}} = (20.54 + 0.577\kappa) \text{ fb}.$$

($\kappa \equiv \text{Br}_{H_1\to b\bar{b}}/\text{Br}^{\text{SM}}_{H_1\to b\bar{b}} \simeq 1$ which can also be measured.)

- Main background $\sigma_{b\bar{b}gg} = 13.2$ fb cannot be reduced through "p_T-balance" method.

- Background $b\bar{b}g\gamma + b\bar{b}\gamma\gamma$ can be reduced by "p_T-balance" cut, after which $\sigma_{\rm bkg} = (16.66 + 0.577\kappa)$ fb: not very efficient.

- Assuming $\kappa = 1$, we summarize the sensitivities on c_2 and c_{12}, before and after "p_T-balance" cut, at $\sqrt{s} = 250$ GeV CEPC with 5 ab^{-1} luminosity.

c_2	Inclusive	Quasi-inclusive (add "p_T balance")	Exclusive ($h_2 \to b\bar{b}$)
3σ Discovery	> 0.118	> 0.083	$> 0.033/\sqrt{\mathrm{Br}_{h_2\to b\bar{b}}}$
5σ Discovery	> 0.152	> 0.107	$> 0.042/\sqrt{\mathrm{Br}_{h_2\to b\bar{b}}}$
c_{12}	Inclusive	Quasi-inclusive (add "p_T balance")	Exclusive ($h_2 \to b\bar{b}$)
3σ Discovery	> 0.125	> 0.119	$> 0.064/\sqrt{\mathrm{Br}_{h_2\to b\bar{b}}}$
5σ Discovery	> 0.161	> 0.153	$> 0.083/\sqrt{\mathrm{Br}_{h_2\to b\bar{b}}}$

Further discussion on c_{12} (unpublished)

- For other m_2: the sensitivities on c_2 or c_{12} depends weakly on m_2 when $m_2 \lesssim 70$ GeV.

- When 70 GeV $< m_2 <$ 110 GeV, its mass becomes close to Z boson, and large $e^+e^- \to ZZ/ZH_1$ background pollution will reduce the sensitivity on both c_2 and c_{12}; and when $m_2 \gtrsim 110$ GeV, $\sqrt{s}$ of CEPC is not large enough and we need larger lepton colliders for our method.

- Another channel $H_1 \to Z^* H_2$ is also possible to measure c_{12}, but its sensitivity depends strongly on m_2: $\mathrm{Br}_{H_1 \to Z^* H_2}$ decreases quickly when m_2 increases.

- When $m_2 \lesssim 70$ GeV, the channel $H_1 \to Z^* H_2$ is expected to have better sensitivity than $e^+e^- \to ZH_2$ without breaking the inclusiveness: because $H_1 \to \mu^+\mu^-\gamma\gamma$ is an extremely rare decay channel, but $e^+e^- \to \mu^+\mu^-\gamma\gamma$ is a large QED process.

III. SUMMARY

- We propose a model-independent method to test CP-violation effects in the scalar sector through measuring the inclusive cross sections $e^+e^- \to ZH_1, ZH_2, H_1H_2$, if another scalar is discovered.

- At CEPC with 5 ab^{-1} luminosity, the couplings at $\mathcal{O}(10^{-1})$ level can be discovered, corresponding to $K \equiv c_1c_2c_{12} \gtrsim \mathcal{O}(10^{-2})$, depending weakly on m_2 if $m_2 \lesssim 70$ GeV.

- $H_1 \to Z^*H_2$ process is expected to have better sensitivity on c_{12} than H_1H_2 associated production, but depends strongly on m_2 (unpublished).

- Limitation: $K \neq 0$ is only a sufficient but not necessary condition of CP-violation, meaning that sometimes $K = 0$ holds in a model with CP-violation (e.g., SM with a complex scalar singlet extension).


The end,
thank you!
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