CP-violation in the Scalar Sector and CEPC Tests

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G. Li, Y.-N. Mao, C. Zhang, S.-H. Zhu, Phys. Rev. D 95, 035015 (2017);

Y.-N. Mao, arXiv: 1703.10123;

Y.-N. Mao *et. al.*, in preparation.

Introduction

- CP-violation was first discovered in $K_L \to 2\pi$ decay in 1964;
- CPV effects have already been discovered in K- and B-sector;
- Kobayashi-Maskawa mechanism is successful to explain all known CPV effects;
- The 125 GeV Higgs boson is favored as a 0^+ state assuming no CPV;
- It seems that we don't need to study CPV beyond SM?

Motivation

- CPV is one of the conditions to generate matter-antimatter asymmetry;
- CPV in the SM is not enough thus extra CPV is required;
- Besides this, extra CPV itself is a type of new physics predicted by many models;
- Extra CPV can usually appear in models with extended scalar sector;
- 125 GeV Higgs boson data still allow a CP-mixing state (with large 0^- component);
- Thus it is still necessary and attractive to study CPV in the scalar sector.

How can we search for CPV beyond SM?

- Indirect Processes:

  A. $e/n/$atoms EDM— $-\mathrm{i}(d_f/2)\bar{f}\sigma_{\mu\nu}\gamma^5 f F^{\mu\nu}$;

  B. Modifications in meson mixing and/or decay parameters;

  C. Anomalous ZZZ vertex *et. al.* B. Grzadkowski *et al.*, JHEP 1411 (2014) 084;

- Direct Processes:

  D. $ht\bar{t}/h\tau^+\tau^-$ vertices— $\bar{f}(a+\mathrm{i}b\gamma^5)fh$;

  E. $h \to ZZ^* \to 4\ell$— $avhZ^\mu Z_\mu + bhZ^{\mu\nu}\tilde{Z}_{\mu\nu}/v$;

  F. h_1ZZ, h_2ZZ, h_1h_2Z, $h_1h_2h_2Z$ vertices— This talk.

CPV in the scalar sector at CEPC

Method I. Through $h_1 ZZ$, $h_2 ZZ$, $h_1 h_2 Z$ vertices

Denote h_1 the 125 GeV Higgs, assuming another light scalar h_2 is discovered

$$\mathcal{L} \supset (c_1 h_1 + c_2 h_2) \frac{g^2 v}{4c_W^2} Z^\mu Z_\mu + \frac{c_{12} g}{2c_W} Z_\mu \left(h_1 \partial^\mu h_2 - h_2 \partial^\mu h_1\right).$$

CP properties analysis (for tree level vertices):

$$\begin{array}{ccccc} h_1\, ZZ & \qquad & h_2\, ZZ & \qquad & h_1\, h_2\, Z \\ + & & + & & +?\ -? \\ & & & & -?\ +? \end{array}$$

All $c_{1,2,12} \neq 0 \longrightarrow$CP-violation

- Define $K \equiv c_1 c_2 c_{12}$ as a quantity to measure CPV;

- $K \neq 0$ is a sufficient (but not necessary) condition of CPV;

- We should measure $c_{1,2,12}$ respectively at CEPC;
  (In 2HDM, a similar quantity $K \equiv c_1 c_2 c_3 = c_i c_j c_{ij}$ was already used to measure CPV in scalar sector. See A. Mendez and A. Pomaral, Phys. Lett. B 272, 313 (1991); J. F. Gunion and H. E. Haber, Phys. Rev. D 72, 095002 (2005).)

Measurements of $c_{1,2,12}$ at CEPC

- Assuming h_1 couplings are SM-like (which means $c_1 \sim 1$);
- c_1 can be accurately measured to $\mathcal{O}(10^{-3})$ through $e^+e^- \to Z^* \to Zh_1$;

  The CEPC-SPPC Study Group, `http://cepc.ihep.ac.cn/preCDR/volume.html`
- Similarly, c_2 can be measured through the processes $e^+e^- \to Z^* \to Zh_2$;
- c_{12} can be measured through the processes $e^+e^- \to Z^* \to h_1h_2$;
- Recoil-mass technique is useful in this measurement (see next page);

  S. Kuhlman *et. al.* (The NLC ZDR Design Group and NLC Physics Working Group Collaborations), arXiv: hep-ex/9605011.

Recoil Mass Technique

- For a visible particle, all the 4-momentum components can be reconstructed at CEPC;
- For $e^+e^- \to Z(\mu^+\mu^-)h_2$, define $m_{\rm rec} \equiv \sqrt{s + m^2_{\mu^+\mu^-} - 2\sqrt{s}(E_{\mu^+} + E_{\mu^-})}$;
- A peak will appear around the mass of h_2;
- We can ignore the decay final states of h_2 and measure c_2 inclusively;
- If we choose a specific decay channel of h_2, the results would be model-dependent;
- Similarly, the same technique can be used in the process $e^+e^- \to Z^* \to h_1(b\bar{b})h_2$.

Simulation and Results

- Assuming another scalar h_2 is light (away from Z peak, $m_2 \lesssim 70$ GeV);
- For detailed simulation, we took $m_2 = 40$ GeV;
- For such a light scalar, the strictest constraints come from LEP experiments:

  (a) $c_2 < 0.18$ LEP Higgs Working Group, Phys. Lett. B565 61, (2003);

  (b) $c_{12} < 0.54$ LEP Higgs Working Group, Eur. Phys. J. C47, 547 (2003);

  both at 95% C.L. $h_1 \to Z^* h_2$ set weaker constraint; $h_1 \to 2h_2$ depends on models.

A. $e^+e^- \to Z^* \to Zh_2$

- Sig: $e^+e^- \to Z(\mu^+\mu^-)h_2$, Bkg: $e^+e^- \to \mu^+\mu^- X$ (X =anything);

- Basic cuts (cuts in the second line are used to avoid infrared and collinear divergences):

$$|\cos\theta_\mu| < 0.98, \quad m_{\mu^+\mu^-} > 15 \text{ GeV}, \quad m_{\text{rec}} > 15 \text{ GeV}$$

$$|\cos\theta_{e,\gamma}| < 0.995, \quad E_\gamma > 0.1 \text{ GeV}, \quad \Delta R_{ij} > 0.4;$$

- Selection cuts:

$$|\cos\theta_\mu| < 0.8, \quad |m_{\mu^+\mu^-} - m_Z| < 10 \text{ GeV},$$

$$p_{T,\mu^+\mu^-} > 35 \text{ GeV}, \quad 30 \text{ GeV} < m_{\text{rec}} < 60 \text{ GeV};$$

"p_T balance" Cut

- During inclusive measurements, background $X = n\gamma$ is large, especially for light h_2;

- However, $\mathrm{Br}_{h_2 \to n\gamma}$ is usually assumed small;

- We can reduce the backgrounds with photons by tagging a most energetic photon; (H. Li, `https://hal.inria.fr/file/index/docid/430432/filename/Li.pdf`; H. Li, arXiv: 1007.2999.)

- Define $p_{T,\mathrm{bal}} \equiv p_{T,\mu^+\mu^-} - p_{T,\gamma}$ where $p_{T,\gamma}$ is the transverse momentum of the most energetic photon tagged, add another cut $p_{T,\mathrm{bal}} > 20$ GeV;

- This method breaks the inclusiveness a little bit.

Results on c_2 at CEPC with 5 ab^{-1}

	Inclusive	Quasi-inclusive (add "p_T balance")	Exclusive ($h_2 \to b\bar{b}$)
3σ disc. bound	0.118	0.083	$0.033/\sqrt{\mathrm{Br}_{h_2\to b\bar{b}}}$
5σ disc. bound	0.152	0.107	$0.042/\sqrt{\mathrm{Br}_{h_2\to b\bar{b}}}$

- Inclusive measurement is model-independent; quasi-inclusive measurement is nearly model-independent (depend on $\mathrm{Br}_{h_2\to n\gamma}$ which is small);
- "p_T balance" cut is efficient to reduce backgrounds with photons since it is dominant;
- Exclusive measurement is more powerful to discover the process, but it is model-dependent, thus through the exclusive process we cannot obtain exact c_2.

B. $e^+e^- \to Z^* \to h_1 h_2$

- Sig: $e^+e^- \to h_1(b\bar{b})h_2$, Bkg: $e^+e^- \to b\bar{b}X$ (X =anything);
- Basic cuts (cuts in the second line are used to avoid infrared and collinear divergences):

$$m_{b\bar{b}} > 15 \text{ GeV}, \quad m_{\text{rec}} > 15 \text{ GeV}$$

$$|\cos\theta_{e,\gamma}| < 0.995, \quad E_\gamma > 0.1 \text{ GeV}, \quad E_g > 1 \text{ GeV}, \quad \Delta R_{ij} > 0.4;$$

- Selection cuts:

$$70 \text{ GeV} < p_{T,b\bar{b}} < 100 \text{ GeV}, \quad 70 \text{ GeV} < p_{T,b} < 110 \text{ GeV}, \quad 30 \text{ GeV} < p_{T,b}^{\text{sub}} < 70 \text{ GeV},$$

$$|m_{b\bar{b}} - m_Z| < 25 \text{ GeV}, \quad 20 \text{ GeV} < m_{\text{rec}} < 70 \text{ GeV};$$

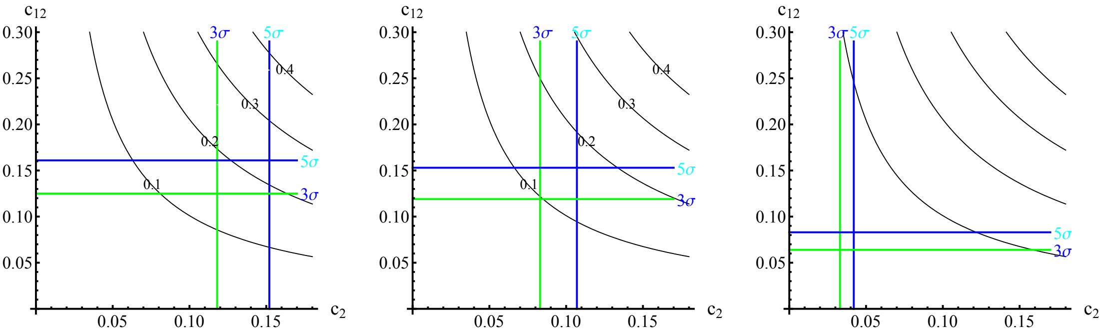
- $p_{T,\text{bal}} > 20$ GeV can also be added to reduce backgrounds with photons.

Results on c_{12} at CEPC with 5 $\mathbf{ab}^{-1}$

	Inclusive	Quasi-inclusive (add "p_T balance")	Exclusive ($h_2 \to b\bar{b}$)
3σ disc. bound	0.125	0.119	$0.064/\sqrt{\mathrm{Br}_{h_2\to b\bar{b}}}$
5σ disc. bound	0.161	0.153	$0.083/\sqrt{\mathrm{Br}_{h_2\to b\bar{b}}}$

- Assuming $\mathrm{Br}_{h_1\to b\bar{b}} = \mathrm{Br}_{h_1\to b\bar{b},\mathrm{SM}}$ in the table;
- "p_T balance" cut is not so efficient because the dominant background is $b\bar{b}gg$;
- Exclusive measurement is more powerful to discover a nonzero c_{12}, but cannot obtain its exact number—just like that in c_2 measurement.

A Benchmark Model: CPV2HDM



- From left to right: inclusive→quasi-inclusive→exclusive ($\mathrm{Br}_{h_2\to b\bar{b}}=1$);
- Extra constraint on $c_{12}(=c_3)$ from heavy Higgs data: about $(0.3-0.4)$;
- The distribution for different (c_2, c_{12}) and the corresponding K.

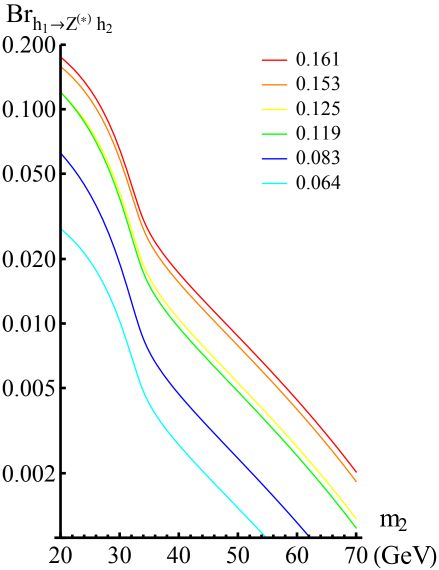
Some Discussions on Method I

- For both processes, the discovery bounds are not sensitive to the mass of h_2 when m_2 increases from 34 GeV (threshold for $h_1 \to Zh_2$ decay) to about 70 GeV;

- For larger m_2, Z peak will provide large backgrounds, this region need more analysis;

- For small m_2, $h_1 \to Z^{(*)}h_2$ is another process to measure c_{12};

- We have not finished the simulation for $h_1 \to Z^{(*)}h_2$, however, we can estimate the sensitivity to $\mathrm{Br}_{h_1 \to Z^{(*)}h_2}$ can reach about $\mathcal{O}(10^{-3})$ according to The CEPC-SPPC Study Group, `http://cepc.ihep.ac.cn/preCDR/volume.html`; Z. Liu, L.-T. Wang, and H. Zhang, Chin. Phys. C41, 063102 (2017).



- Numbers of c_{12} are chosen as the bounds in the table above;

- For the low m_2 region (when $h_1 \to Zh_2$ opens), this process must have a better sensitivity on c_{12} comparing with associated production;

- For heavier h_2, $\mathrm{Br}_{h_1 \to Z^* h_2}$ decreases quickly when m_2 increases, we need more detailed simulations.

Method II. Through $Zh_1h_2h_2$ Vertex

- CP properties analysis:

$$\begin{array}{cccc} Z & h_1 & h_2 & h_2 \\ & + & +? & -? \\ & & -? & +? \end{array}$$

- $\mathcal{L} \sim \kappa h_2^2 Z_\mu \partial^\mu h_1/f$;

- Through $h_1 \to Z^{(*)} h_2 h_2$ process CP-violation can be confirmed;

- This work is also unfinished, I need more collaborators.

A Benchmark Model: SLH with SCPV

- A variation of the simplest little Higgs model;
- An adding term $\epsilon(\Phi_1^\dagger\Phi_2)^2 + \text{H.c.}$ may lead to a nonzero VEV of the pseudoscalar field thus CP-violation occurs (both scalars become CP-mixing states);
- The $Zh_1h_2h_2$ interaction: $\mathcal{L} \supset (s_\theta/f)(t_\beta - 1/t_\beta)Z_\mu h_2^2\partial^\mu h_1$;
- For a light scalar $h_2(\lesssim 10\ \text{GeV})$, $\text{Br}_{h_1\to Zh_2h_2}$ can reach $\mathcal{O}(10^{-5})$;
- I still don't know whether it can be tested at CEPC since I proposed this idea just several days ago, I cannot finish it before this talk;
- Later we will finish a paper to discuss why we cannot use $h_1 \to Zh_2$ decay.

Conclusions, discussions, and Appendices (about CDR)

- We proposed two methods to test CP-violation in the scalar sector at CEPC;
- The first method is to search for tree level h_1ZZ, h_2ZZ, and h_1h_2Z vertices together, if all these three vertices exist, we can confirm CP-violation in the scalar sector;
- We simulated $e^+e^- \to Z^* \to Zh_2, h_1h_2$ associated production processes to show that this method is feasible at CEPC;
- This method can be used for the light scalar below Z peak;
- It is a sufficient but not necessary condition for CP-violation in the scalar sector;

- With this method, we can inclusively extract the exact number of each coupling, however, if we just want to discover these processes, exclusive search is more powerful;

- For the h_1h_2Z coupling, the rare decay process $h_1 \to Zh_2$ process should also be helpful and it may be more efficient for light h_2 (however this work is unfinished);

- Another method is to use the vertex $Zh_1h_2h_2$ (hence we need only one process $h_1 \to Z^{(*)}h_2h_2$ to confirm CP-violation in the scalar sector);

- It is possible to have $\mathrm{Br}_{h_1\to Zh_2h_2} \sim \mathcal{O}(10^{-4} - 10^{-5})$, we don't know the sensitivity of this process at CEPC, maybe I need more collaborators;

- About this topic in the CDR: since the first method $e^+e^- \to Zh_2, h_1h_2$ is completely finished, it can be included in the CDR;

- $h_1 \to Zh_2$ is in preparation, I don't know when can we finish it, if it can be finished soon, this part can also be included in CDR;

- This topic is strongly correlated to new scalars hidden below the EW scale, thus it may be combined with the searching of new physics at this scale, CP-violation can be one of the motivations but not the only motication;

- I cannot ensure whether the second method $(h_1 \to Z^{(*)}h_2h_2)$ is feasible at CEPC and whether we can finish it soon, if both are yes, this can also be included in the CDR.

The end, thank you! maoyn@inep.ac.cn