Snowmass2021 - Letter of Interest

Probing the Higgs CP nature via $e^+e^- \to ZH$ at the Circular Electron Positron Collider

Thematic Areas: (check all that apply □/■)

■ (EF01) EW Physics: Higgs Boson properties and couplings
■ (EF02) EW Physics: Higgs Boson as a portal to new physics
□ (EF03) EW Physics: Heavy flavor and top quark physics
□ (EF04) EW Precision Physics and constraining new physics
□ (EF05) QCD and strong interactions: Precision QCD
□ (EF06) QCD and strong interactions: Hadronic structure and forward QCD
□ (EF07) QCD and strong interactions: Heavy Ions
□ (EF08) BSM: Model specific explorations
□ (EF09) BSM: More general explorations
□ (EF10) BSM: Dark Matter at colliders
□ (Other) *[Please specify frontier/topical group]*

Contact Information:
Name (Institution) [email]: Institute of High Energy Physics, Beijing
shaqiyu@ihep.ac.cn, fangyq@ihep.ac.cn, amohammed@ihep.ac.cn,li.gang@ihep.ac.cn
Collaboration (optional):

Authors: Qiyu SHA, Yaquan FANG, Abdualazem FADOL, Gang LI

Abstract: Electron Positron Collider is an ideal machine to study the Higgs CP considering it has a clean background with respect to LHC. The production of $e^+e^- \to H(\to b\bar{b})Z(\to l^+l^-)$ will provide a unique process to investigate the angular asymmetries between Z and its decay products. Typically, an e^+e^- collider such as CEPC can produce approximately 36,000 events with the center of colliding energy at 240 GeV and integrated luminosity of 5.6 ab^{-1} which is much higher than the statistics from $H \to Z(\to l^+l^-)Z^\star(\to l^+l^-)$ at LHC. A maximum likelihood and optimal variable method will be implemented to optimize the analysis. Finally, an expected limit excluding the BSM hypothesis will be set and further discussions on the results will be addressed.

While the Higgs boson was discovered in 2012 and its spin is well established,[1] the CP nature still needs more experimental information. The reason is that Higgs CP property is still not yet solidly determined due to the limited experimental precision. On one hand, the present experimental results are sufficient to discriminate between distinct hypotheses in Higgs boson spin analysis. But on the other hand, the determination of the CP properties is in general much more difficult, since in principle the observed state could consist of any admixture of CP-even and CP-odd components.

The CP properties of the Higgs boson can be measured with the process of $e^+e^- \to H(\to b\bar{b})Z(\to l^+l^-)$ at CEPC or other e^+e^- colliders. The distributions of asymmetric angles between Z and decayed leptons in the process have been shown to be promising in probing BSM scenario. Monte Carlo (MC) simulated samples based on the CEPC baseline detector geometry will be generated to perform the study. The BSM model parametrized in term of the $SU(3) \times SU(2)_L \times U(1)_Y$ 6-dim effective Lagrangian is used to study the non-standard CP-odd couplings.[2] Those couplings under the introduced BSM model can generate asymmetries at the percent level, while having negligible impact on the di-lepton invariant mass spectrum in the process.

The differential cross section for $e^+e^- \to HZ(\to l^+l^-)$ at 240 GeV can be expressed as[2]

$$\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2 d\phi} = \frac{1}{m_H^2} N_\sigma(q^2) J(q^2, \theta_1, \theta_2, \phi)$$

The $N_\sigma(q^2)$is the normalisation factor and it can be written in terms of the dimensionless parameters r and s as:

$$N_\sigma(q^2) = \frac{1}{2^(10)(2\pi)^3} \frac{1}{\sqrt{r}\gamma Z} \frac{\sqrt{\lambda(1, s, r)}}{s^2}$$

The constant dimensionless parameters given by the following:

$$s = \frac{q_{th}^2}{m_H^2} \approx 2.98$$

$$r = \frac{m_Z^2}{m_H^2} \approx 0.53$$

$$\gamma Z = \frac{\Gamma_Z}{m_H} \approx 2.98$$

$J(q^2, \theta_1, \theta_2, \phi)$ depends on nine J_i functions expressed by:

$$\begin{aligned} J(q^2, \theta_1, \theta_2, \phi) = & J_1(1 + \cos^2\theta_1 \cos^2\theta_2 + \cos^2\theta_1 + \cos^2\theta_2) \\ & + J_2 \sin^2\theta_1 \sin^2\theta_2 + J_3 \cos^2\theta_1 \cos^2\theta_2 \\ & + (J_4 \sin^2\theta_1 \sin^2\theta_2 + J_5 \sin 2\theta_1 \sin 2\theta_2) \sin\phi \\ & + (J_6 \sin\theta_1 \sin\theta_2 + J_7 \sin 2\theta_1 \sin 2\theta_2) \cos\phi \\ & + J_8 \sin^2\theta_1 \sin^2\theta_2 \sin 2\phi + J_9 \sin^2\theta_1 \sin^2\theta_2 \cos 2\phi \end{aligned}$$

The optimal variable method[3] and maximum likelihood fit are going to be used to probe the Higgs CP nature. Firstly, the above formulas will be used to generate signal sample with full differential distribution. Secondly, we will then analyze the samples to reach an optimal signal/background level. The selected events are then used to extract non-CP-even contribution by a multi-dimensional maximum likelihood fit, where the full Standard Model backgrounds are going to be taken into account.

The sensitivity that the CEPC can reach will be investigated with sophisticated statistical approach. Intensive tests on various CP-mixture assumptions will further be performed to fully estimate the CEPC potential. Although the expected precision of the measurement can be provided, it is very sensitive to the position resolution of the tracker of the detector. Nevertheless, this study will offer a very important references for the detector design and optimization at next step.

References

[1] A. Collaboration, "A particle consistent with the higgs boson observed with the atlas detector at the large hadron collider," *Science*, vol. 338, no. 6114, pp. 1576–1582, 2012.

[2] M. Beneke, D. Boito, and Y.-M. Wang, "Anomalous higgs couplings in angular asymmetries of $h \to zl^+l^-$ and $e^+e^- \to hz$," *Journal of High Energy Physics*, vol. 2014, no. 11, p. 28, 2014.

[3] M. Davier, L. Duflot, F. Le Diberder, and A. Rougé, "The optimal method for the measurement of tau polarization," *Physics Letters B*, vol. 306, no. 3, pp. 411 – 417, 1993.

Additional Authors: