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Probing Higgs CP properties at the CEPC in the $e^+e^- \rightarrow ZH \rightarrow l^+l^-H$ using optimal variables

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ECFA MEETING ON E+E- TO ZH ANGULAR MEASUREMENTS

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Probing Higgs CP properties at the CEPC in the $e^+e^- \rightarrow ZH \rightarrow l^+l^-H$ using optimal variables

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Abstract In the Circular Electron Positron Collider (CEPC), a measurement of the Higgs CP mixing through $e^+e^- \rightarrow ZH \rightarrow l^+l^-(e^+e^-/\mu^+\mu^-)H(\rightarrow bb/\bar{c}\bar{c}/gg)$ process is presented, with $5.6 \text{ ab}^{-1} e^+e^-$ collision data at the center-of-mass energy of 240 GeV. In this study, the CP -violating parameter c_{ZY} is constrained between the region of -0.30 and 0.27 and c_{ZZ} between -0.06 and 0.06 at 68% confidence level. This study demonstrates the great potential of probing Higgs CP properties at the CEPC.

1 Introduction

The historic discovery of Higgs boson with a mass around 125 GeV in 2012 by the ATLAS and CMS collaborations at the Large Hadron Collider (LHC) [1,2] completed the Standard Model (SM). This particle provides a new portal to search for new physics beyond the SM (BSM). The Higgs boson is predicted to be a scalar particle ($J^P = 0^{++}$) under the SM of particle physics. As a result, any observation of charge-parity violation (CPV) in Higgs would be a sign of physics BSM and could account for the explanation of the observed baryon asymmetry of the universe.

At present, the Higgs boson CP -mixing measurements are performed at hadron colliders. The hypothesis of spin-1 or spin-2 Higgs has been excluded by ATLAS and CMS at 99% confidence level (CL) with $\sqrt{s} = 7$ and 8 TeV, 25 fb^{-1} data [3]. Studies of the CP properties of the Higgs boson interactions with gauge bosons have been performed by the ATLAS [4–6] and CMS [7–9] experiments, and the results show no deviations from the SM predictions. ATLAS and CMS also finished analyses of $H\tilde{t}\tilde{t}$ coupling, which provides an alternative and independent avenue for CP testing in the Higgs sector because it is particularly sensitive to deviations from the SM coupling [10,11]. Their results show exclusion of the pure CP -odd structure of the top quark Yukawa ($t\tilde{t}H$) coupling at 3.9σ (3.2σ) and the fractional contribution of the CP -odd component is measured to be $f_{CP}^{H\tilde{t}\tilde{t}} = 0.00 \pm 0.33$.

However, small anomalous contributions were not excluded. At the HL-LHC [12], the CP -odd VVH couplings are introduced and the expected results constrain the CP -odd parameters c_{ZY} between -0.22 and 0.22 and the c_{ZZ} between -0.33 and 0.33 at the 68% confidence level.

In terms of probing the CP -odd Higgs couplings, a lepton collider operating as a Higgs factory has great advantages, as it is free of the QCD background and has tunable and precisely defined initial energies. Several future lepton colliders, including the International Linear Collider (ILC) [13], the e^+e^- Future Circular Collider (FCC-ee) [14], the Compact Linear Collider (CLIC) [15], and the Circular Electron-Positron Collider (CEPC) [16], have been proposed with the capability of precise measurement of Higgs boson parameters. There are plenty of approaches to the Higgs CP measurements at the future lepton colliders by using different probes, like the VH process, the $t\tilde{t}H$ process, the VBF

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Introduction

Properties of Higgs in Standard Model: $m_H = 125.10\text{GeV}$, $J^{PC} = 0^{++}$

Related experiments in LHC:

- The hypothesis of spin-1 or spin-2 Higgs has been excluded by the ATLAS and CMS at >99% CL in $\sqrt{s} = 7\&8\text{ TeV}$, 25 fb^{-1} data. [Eur. Phys. J. C75 \(2015\) 476](#)
- The results of the study on the CP properties of the Higgs boson interactions with gauge bosons by the ATLAS and CMS show no deviations from the SM predictions.

However, small violation of CP symmetry in those interactions cannot be excluded within the experimental precision of current measurements.

Higgs-gauge vector boson interaction lacks precise measurement in all inclusive Higgs production mode.

Our purpose in doing this analysis is to **squeezing the allowed range of CP-violating parameters.**

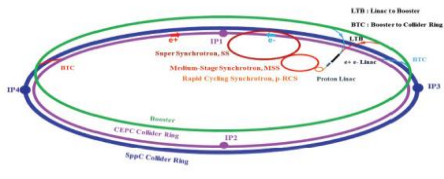
- We need new facilities to achieve more precise measurement.

Any observation of CP violation in Higgs would be New Physics!

Introduction

Future e^+e^- collider experiment as Higgs factory :

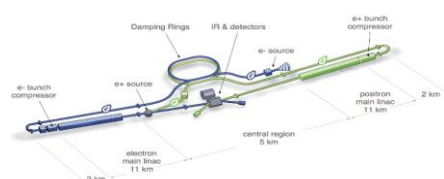
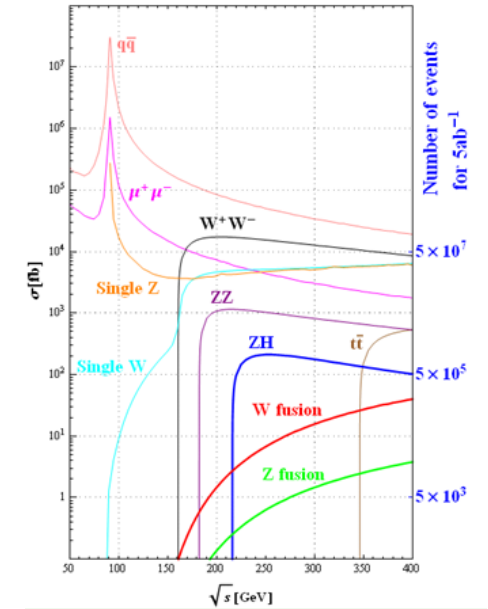
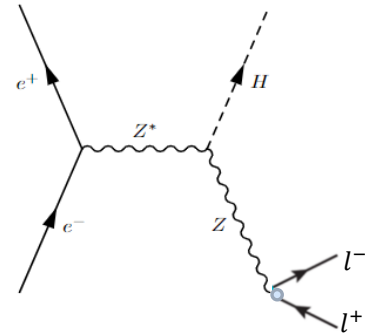
- At a center of mass energy of $\sqrt{s} \sim 240 \text{ GeV}$ which maximizes the Higgs boson production cross section through $e^+e^- \rightarrow ZH$ process.
- Cleaner environment and more events produced than (HL)-LHC.
- More precise Higgs-gauge boson coupling study.



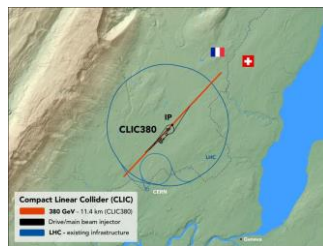
CEPC, 5.6 ab^{-1} @ 240 GeV



FCC-ee, 5 ab^{-1} @240 GeV



ILC, 2 ab^{-1} @250 GeV



CLIC, 380 GeV for Higgs & top

Theory framework

Consider a 6-dimension EFT model: $\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda^2} \sum_{k=1}^{59} \alpha_k \mathcal{O}_k (\mathcal{L}_{BSM})$

$$\mathcal{L}_{eff} \supset c_{ZZ}^{(1)} H Z_\mu Z^\mu + c_{ZZ}^{(2)} H Z_{\mu\nu} Z^{\mu\nu} + c_{Z\tilde{Z}} H Z_{\mu\nu} \tilde{Z}^{\mu\nu} + c_{AZ} H Z_{\mu\nu} A^{\mu\nu} + c_{A\tilde{Z}}^{HZ_{\mu\nu}} \tilde{A}^{\mu\nu} \\ + H Z_\mu \bar{\ell} \gamma^\mu (c_V + c_A \gamma_5) \ell + Z_\mu \bar{\ell} \gamma^\mu (g_V - g_A \gamma_5) \ell - g_{em} Q_\ell A_\mu \bar{\ell} \gamma^\mu \ell$$

Where: $c_{ZZ}^{(1)} = m_Z^2 (\sqrt{2} G_F)^{1/2} (1 + \hat{\alpha}_{ZZ}^{(1)})$, $c_{ZZ}^{(2)} \& = (\sqrt{2} G_F)^{1/2} \hat{\alpha}_{ZZ}$, $c_{Z\tilde{Z}} \& = (\sqrt{2} G_F)^{1/2} \hat{\alpha}_{Z\tilde{Z}}$,
 $c_{AZ} = (\sqrt{2} G_F)^{1/2} \hat{\alpha}_{AZ}$, $c_{A\tilde{Z}} = (\sqrt{2} G_F)^{1/2} \hat{\alpha}_{A\tilde{Z}}$.

- In this base, the experimental observables G_F, m_Z, α_{em} could be presented:

$$m_Z = m_{Z0} (1 + \delta_Z), \quad G_F = G_{F0} (1 + \delta_{GF}), \quad \alpha_{em} = \alpha_{em0} (1 + \delta_A)$$

$$\text{where: } \delta_Z = \hat{\alpha}_{ZZ} + \frac{1}{4} \hat{\alpha}_{\Phi D}, \quad \delta_{GF} = -\hat{\alpha}_{4l} + 2\hat{\alpha}_{\Phi l}^{(3)}, \quad \delta_A = 2\hat{\alpha}_{AA}.$$

$$m_{Z0} = 91.1876$$

$$G_{F0} = 1.166367e-5$$

$$\alpha_{em0} = 1/127.940$$

The $H \rightarrow Zll$ matrix element:

$$\mathcal{M}_{HZ\ell\ell}^\mu = \frac{1}{m_H} \bar{u}(p_3, s_3) \left[\gamma^\mu (H_{1,V} + H_{1,A}\gamma_5) + \frac{q^\mu \not{p}}{m_H^2} (H_{2,V} + H_{2,A}\gamma_5) + \frac{\epsilon^{\mu\nu\sigma\rho} p_\nu q_\sigma}{m_H^2} \gamma_\rho (H_{3,V} + H_{3,A}\gamma_5) \right] v(p_4, s_4)$$

- Where $\epsilon_{0123} = +1$ and $q = p_3 + p_4$.

And the parameters in the function are following:

$$H_{1,V} = \frac{2m_H(\sqrt{2}G_F)^{1/2} r}{r-s} g_V \left(1 + \hat{\alpha}_1^{\text{eff}} - \frac{\kappa}{r} \hat{\alpha}_{ZZ} - \frac{\kappa}{2r} \frac{Q_\ell g_{em}(r-s)}{sg_V} \hat{\alpha}_{AZ} \right)$$

$$H_{1,A} = \frac{2m_H(\sqrt{2}G_F)^{1/2} r}{r-s} g_A \left(1 + \hat{\alpha}_2^{\text{eff}} - \frac{\kappa}{r} \hat{\alpha}_{ZZ} \right),$$

$$H_{2,V} = -\frac{2m_H(\sqrt{2}G_F)^{1/2}}{r-s} g_V \left[2\hat{\alpha}_{ZZ} + \frac{Q_\ell g_{em}(r-s)}{sg_V} \hat{\alpha}_{AZ} \right]$$

$$H_{2,A} = \frac{4m_H(\sqrt{2}G_F)^{1/2}}{r-s} g_A \hat{\alpha}_{ZZ}$$

$$H_{3,V} = -\frac{2m_H(\sqrt{2}G_F)^{1/2}}{r-s} g_V \left[2\hat{\alpha}_{Z\bar{Z}} + \frac{Q_\ell g_{em}(r-s)}{sg_V} \hat{\alpha}_{A\bar{Z}} \right]$$

$$H_{3,A} = \frac{4m_H(\sqrt{2}G_F)^{1/2}}{r-s} g_A \hat{\alpha}_{ZZ}$$

$$\hat{\alpha}_1^{\text{eff}} \equiv \hat{\alpha}_{ZZ}^{(1)} - \frac{m_H(\sqrt{2}G_F)^{1/2}(r-s)}{2\sqrt{r}} \frac{\hat{\alpha}_{\Phi l}^V}{g_V}$$

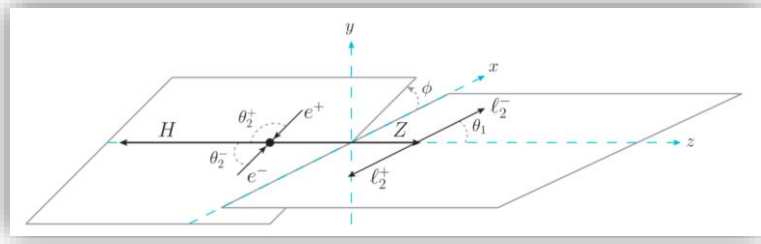
$$\hat{\alpha}_2^{\text{eff}} \equiv \hat{\alpha}_{ZZ}^{(1)} + \frac{m_H(\sqrt{2}G_F)^{1/2}(r-s)}{2\sqrt{r}} \frac{\hat{\alpha}_{\Phi l}^A}{g_A}$$

 : SM term
Others : EFT contribution

Differential cross section for $e^+e^- \rightarrow ZH \rightarrow llH$:

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

$$\mathcal{N}_\sigma(q^2) = \frac{1}{2^{10}(2\pi)^3} \cdot \frac{1}{\sqrt{r}\gamma_Z} \cdot \frac{\sqrt{\lambda(1,s,r)}}{s^2}$$



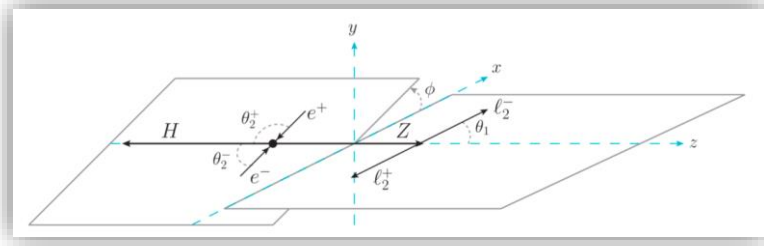
$$\begin{aligned} \mathcal{J}(q^2, \theta_1, \theta_2, \phi) = & J_1(1 + \cos^2 \theta_1 \cos^2 \theta_2 + \cos^2 \theta_1 + \cos^2 \theta_2) \\ & + J_2 \sin^2 \theta_1 \sin^2 \theta_2 + J_3 \cos \theta_1 \cos \theta_2 \\ & + (J_4 \sin \theta_1 \sin \theta_2 + J_5 \sin 2\theta_1 \sin 2\theta_2) \sin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

Variables for studying distribution: θ_1, θ_2, ϕ

Differential cross section for $e^+e^- \rightarrow ZH \rightarrow llH$:

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

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

Variables for studying distribution: θ_1, θ_2, ϕ

Assumption for simplification:

- $\hat{\alpha}_{AZ}$ and $\hat{\alpha}_{Z\bar{Z}}$ contribute to cp-odd. (useful parameters)
- Others are set to 0, so $H_{2,V/A} = 0$.

$$J_1 = 2rs(g_A^2 + g_V^2)(|H_{1,V}|^2 + |H_{1,A}|^2),$$

$$J_2 = \kappa(g_A^2 + g_V^2)[\kappa(|H_{1,V}|^2 + |H_{1,A}|^2) + \lambda \text{Re}(H_{1,V}H_{2,V}^* + H_{1,A}H_{2,A}^*)],$$

$$J_3 = 32rs g_A g_V \text{Re}(H_{1,V}H_{1,A}^*),$$

$$J_4 = 4\kappa\sqrt{rs}\lambda g_A g_V \text{Re}(H_{1,V}H_{3,A}^* + H_{1,A}H_{3,V}^*),$$

$$J_5 = \frac{1}{2}\kappa\sqrt{rs}\lambda(g_A^2 + g_V^2) \text{Re}(H_{1,V}H_{3,V}^* + H_{1,A}H_{3,A}^*),$$

$$J_6 = 4\sqrt{rs}g_A g_V [4\kappa \text{Re}(H_{1,V}H_{1,A}^*) + \lambda \text{Re}(H_{1,V}H_{2,A}^* + H_{1,A}H_{2,V}^*)],$$

$$J_7 = \frac{1}{2}\sqrt{rs}(g_A^2 + g_V^2) [2\kappa(|H_{1,V}|^2 + |H_{1,A}|^2) + \lambda \text{Re}(H_{1,V}H_{2,V}^* + H_{1,A}H_{2,A}^*)],$$

$$J_8 = 2rs\sqrt{\lambda}(g_A^2 + g_V^2) \text{Re}(H_{1,V}H_{3,V}^* + H_{1,A}H_{3,A}^*),$$

$$J_9 = 2rs(g_A^2 + g_V^2)(|H_{1,V}|^2 + |H_{1,A}|^2).$$

6 of these 9 functions are independent

—	0 in assumption
 	EFT CP-odd term
Others	CP-even contribution

Optimal variable approach

Differential cross section could be represented as:

$$\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2 d\phi} = N \times \left(J_{\text{even}}(\theta_1, \theta_2, \phi) + \hat{\alpha}_{A\tilde{Z}} \times J_{\text{odd}_1}(\theta_1, \theta_2, \phi) + \hat{\alpha}_{Z\tilde{Z}} \times J_{\text{odd}_2}(\theta_1, \theta_2, \phi) \right)$$

where $\hat{\alpha}_{A\tilde{Z}}$ and $\hat{\alpha}_{Z\tilde{Z}}$ are CP-violating parameters.

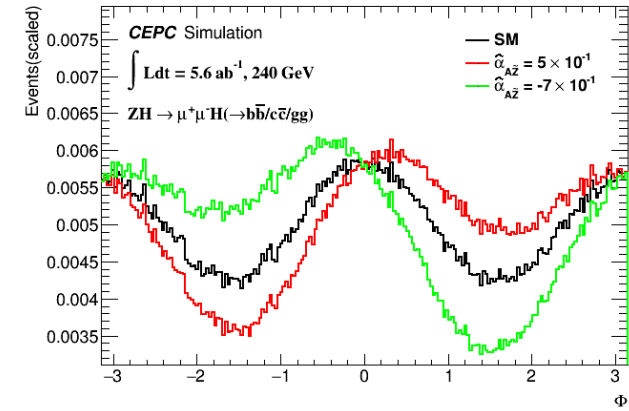
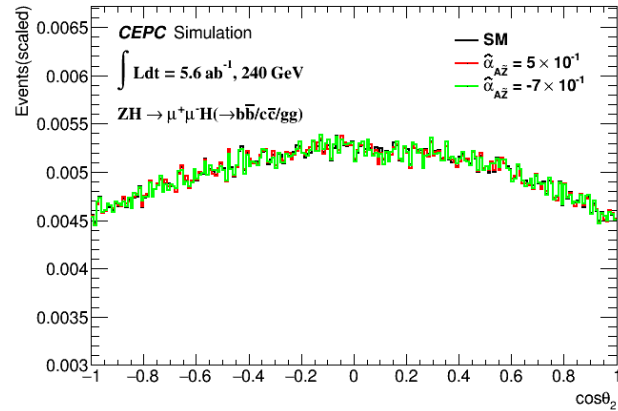
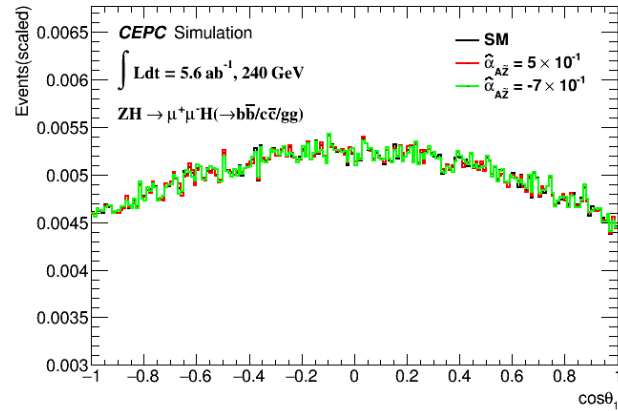
Optimal variable approach

Differential cross section could be represented as:

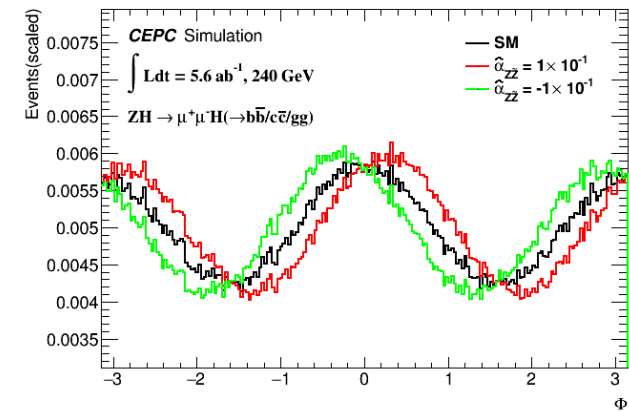
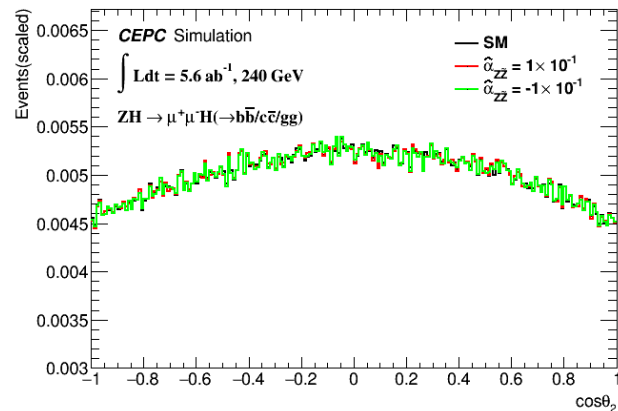
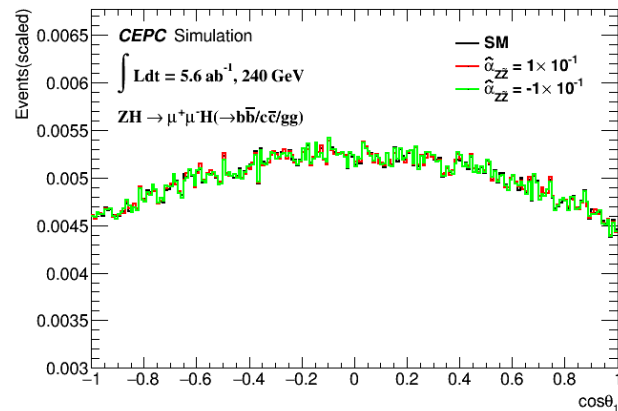
$$\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2 d\phi} = N \times \left(J_{\text{even}}(\theta_1, \theta_2, \phi) + \hat{\alpha}_{A\tilde{Z}} \times J_{\text{odd}_1}(\theta_1, \theta_2, \phi) + \hat{\alpha}_{Z\tilde{Z}} \times J_{\text{odd}_2}(\theta_1, \theta_2, \phi) \right)$$

where $\hat{\alpha}_{A\tilde{Z}}$ and $\hat{\alpha}_{Z\tilde{Z}}$ are CP-violating parameters.

$\hat{\alpha}_{A\tilde{Z}}$



$\hat{\alpha}_{Z\tilde{Z}}$



Optimal variable approach

$$\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2 d\phi} = N \times \left(J_{\text{even}}(\theta_1, \theta_2, \phi) + \hat{\alpha}_{A\tilde{Z}} \times J_{\text{odd}_1}(\theta_1, \theta_2, \phi) + \hat{\alpha}_{Z\tilde{Z}} \times J_{\text{odd}_2}(\theta_1, \theta_2, \phi) \right)$$

In this formation, we could define **Optimal Variable ω** which combines the information from $\{\theta_1, \theta_2, \phi\}$:

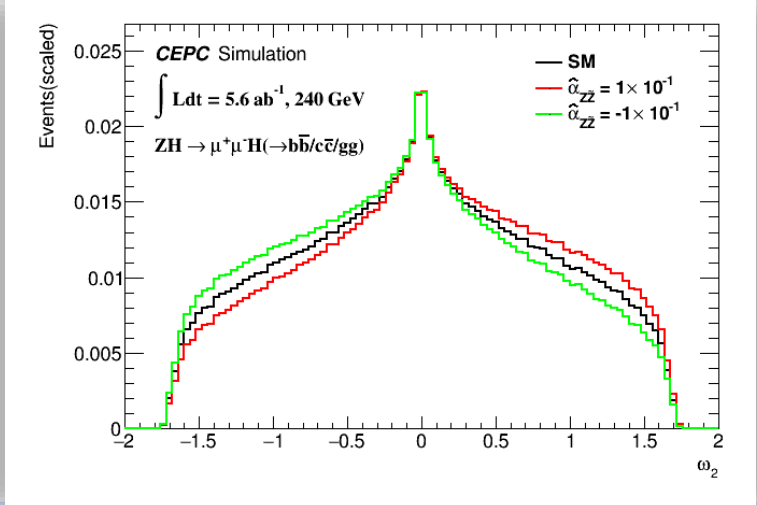
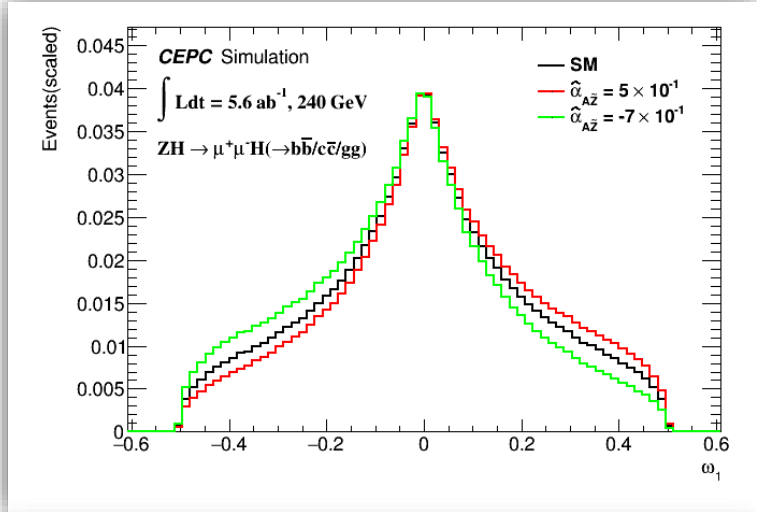
$$\omega_1 = \frac{J_{\text{odd}_1}(\theta_1, \theta_2, \phi)}{J_{\text{even}}(\theta_1, \theta_2, \phi)} \text{ to measure } \hat{\alpha}_{A\tilde{Z}}$$

$$\omega_2 = \frac{J_{\text{odd}_2}(\theta_1, \theta_2, \phi)}{J_{\text{even}}(\theta_1, \theta_2, \phi)} \text{ to measure } \hat{\alpha}_{Z\tilde{Z}}$$

Benefits:

- Only use the one-dimensional distribution of the single variable ω to substitute the 3-dimension distribution without any loss of information.

[PLB 306 \(1993\) 411-417](#)



Monte Carlo samples

Samples:

- The SM Higgs and background samples: generate with Whizard 1.95 and full simulated based on the CEPC baseline detector design. (Used to calculate the selection efficiencies and study background.)
- CP-mixing Higgs samples: generate according to differential cross section for $e^+e^- \rightarrow ZH \rightarrow llH$:

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

- $\sqrt{s} = 240\text{GeV}$
- The mass of Higgs boson is set to be 125GeV and the couplings are set to the SM predictions.
- All the generations are normalized to the expected yields in data with an integrated luminosity of 5.6ab^{-1} .

Event selection

(Using the SM Higgs and background samples)

- **Signal:** $e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^-H(\rightarrow b\bar{b}/c\bar{c}/gg)$ channel.
- **Background:** Irreducible background which contains the same final states as that in signal.

Choose selections by the best significance:

	variable	Selection value
Lepton pair selection	$ \cos\theta_{\mu^+\mu^-} $	(-1,0.81)
	$M_{\mu\mu}$	(77.5GeV, 104.5GeV)
	$M_{recoil_{\mu\mu}}$	(124GeV, 140GeV)
Jets pair selection	$ \cos\theta_{jet} $	(-1,0.96)
	M_{jj}	(100GeV, 150GeV)

Where $M_{recoil_{\mu\mu}}^2 = (\sqrt{s} - E_{\mu\mu})^2 - p_{\mu\mu}^2 = s - 2E_{\mu\mu}\sqrt{s} + m_{\mu\mu}^2$

- **Signal:** $e^+e^- \rightarrow ZH \rightarrow e^+e^-H(\rightarrow b\bar{b}/c\bar{c}/gg)$ channel
- **Background:** Irreducible background which contains the same final states as that in signal.

Choose selections by the best significance:

	variable	Selection value
Lepton pair selection	$ \cos\theta_{e^+e^-} $	(-1,0.81)
	M_{ee}	(85GeV, 95GeV)
	$M_{recoil_{ee}}$	(124GeV, 140GeV)
	$ \cos\varphi_{e^+} $	(-1,0.95)
Jets pair selection	$ \cos\varphi_{e^-} $	(-1,0.95)
	$ \cos\theta_{jet} $	(-1,0.96)
	M_{jj}	(110GeV, 145GeV)

Cut-flow checks

$ZH \rightarrow \mu^+ \mu^- + b\bar{b}/c\bar{c}/gg$ channel

	Signal	Irreducible Background
Original	2.62×10^4	1.25×10^6
Lepton pair selection	1.59×10^4 (efficiency:60.67%)	9.91×10^3 (efficiency:0.79%)
All selection	1.48×10^4 (efficiency:56.42%)	5.60×10^3 (efficiency:0.45%)

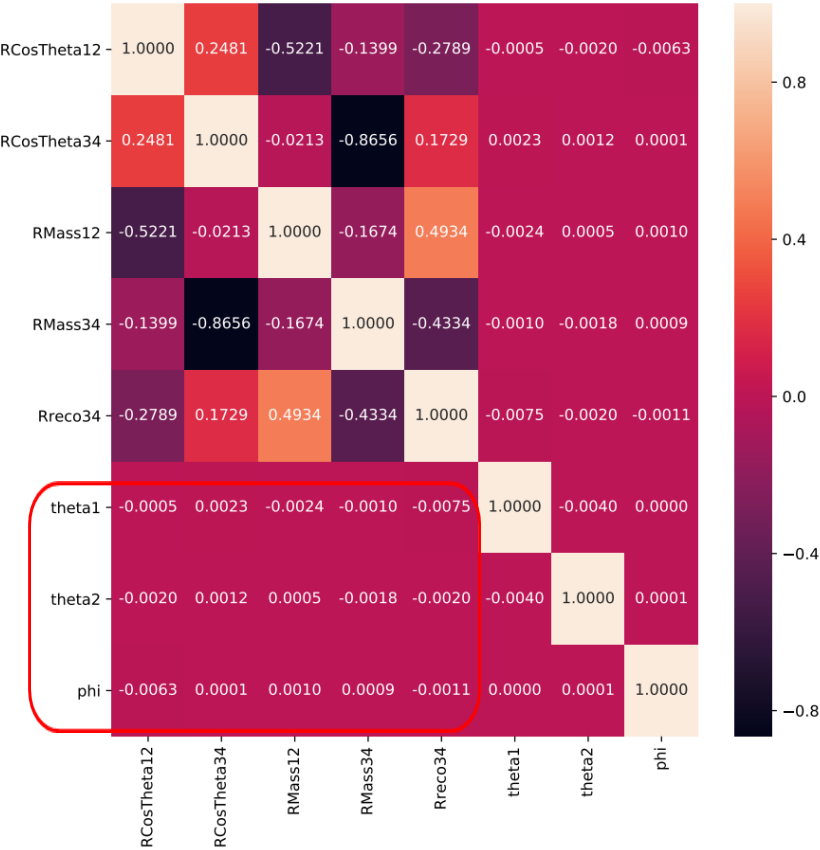
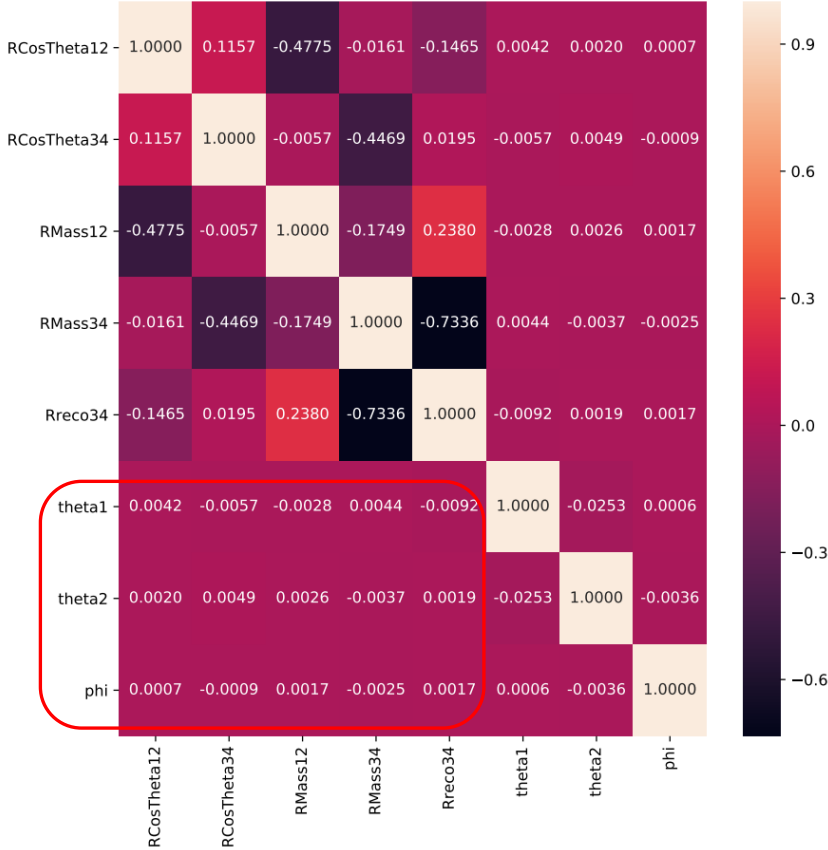
$ZH \rightarrow e^+ e^- + b\bar{b}/c\bar{c}/gg$ channel

	Signal	Irreducible Background
Original	2.72×10^4	1.77×10^6
Lepton pair selection	8.76×10^3 (efficiency:32.2%)	8.77×10^4 (efficiency:0.50%)
All selection	7.15×10^3 (efficiency:26.3%)	4.59×10^3 (efficiency:0.25%)

Event selection

Correlation:

- We can see that θ_1, θ_2, ϕ have little correlation with $\cos\theta_{l+l^-}, \text{Mass}_{ll}, M_{recoil_{ll}}, \cos\theta_{jet}, \text{Mass}_{jj}$.



- So we can ignore the impact of event selections to $\theta_1, \theta_2, \text{ and } \phi$.

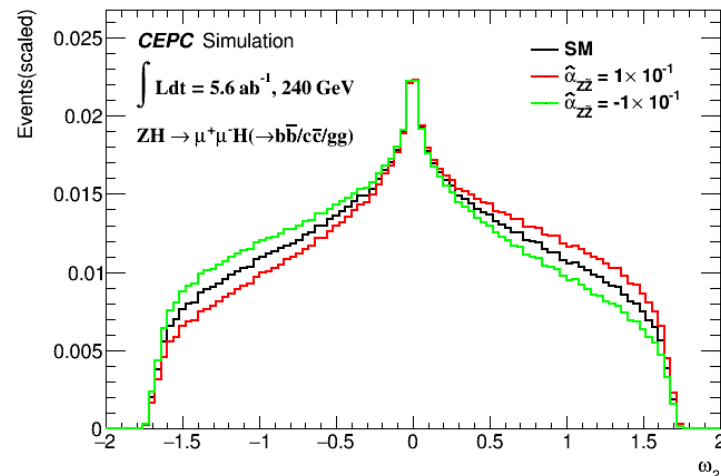
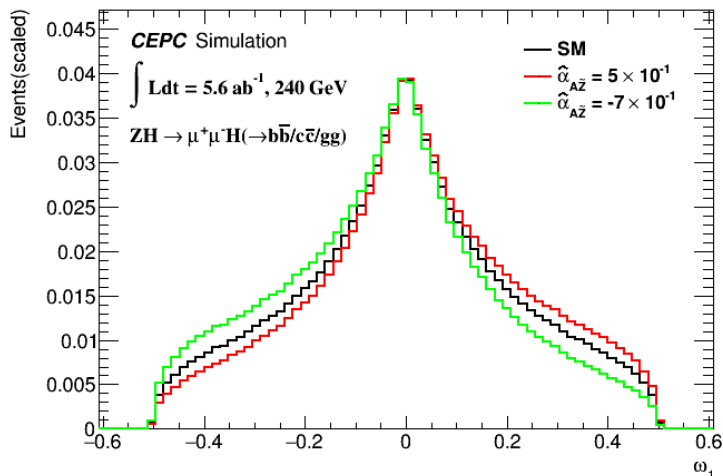
Fitting strategy and result

Fit strategy: Maximum-likelihood fit

$$f^{\vec{\alpha}}(\omega) = N_{\text{sig}} * f_{\text{sig}}^{\vec{\alpha}}(\omega) + N_{\text{bkg}} * f_{\text{bkg}}^{\vec{\alpha}}(\omega)$$

where $\vec{\alpha}$ means $\hat{\alpha}_{AZ}$ and $\hat{\alpha}_{ZZ}$, ω represents ω_1 and ω_2 .

- Fit ω to get $f_{\text{sig}}^{\vec{\alpha}}(\omega)$ and $f_{\text{bkg}}^{\vec{\alpha}}(\omega)$
- Fit $M_{\text{recoil}_{\mu\mu}}$ to get N_{sig} and N_{bkg}
- Evaluate likelihood function for each $\vec{\alpha}$ value hypothesis and construct a ΔNLL as a function of $\vec{\alpha}$.



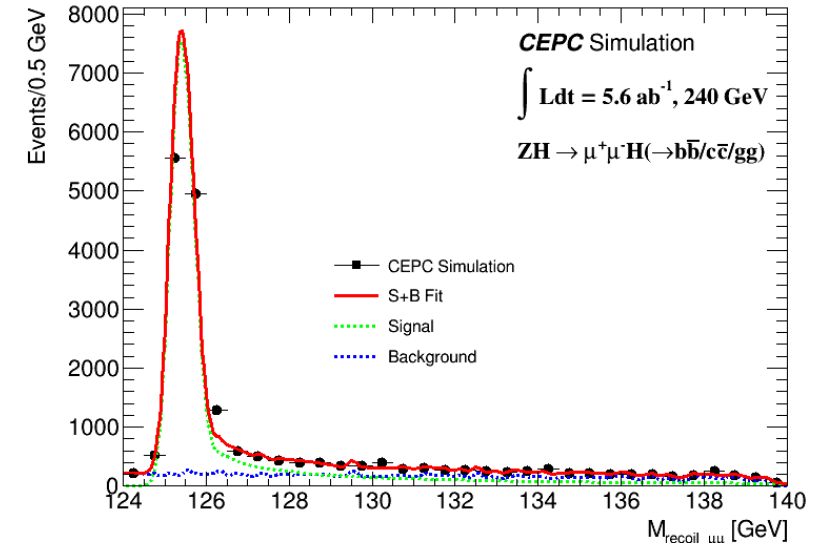
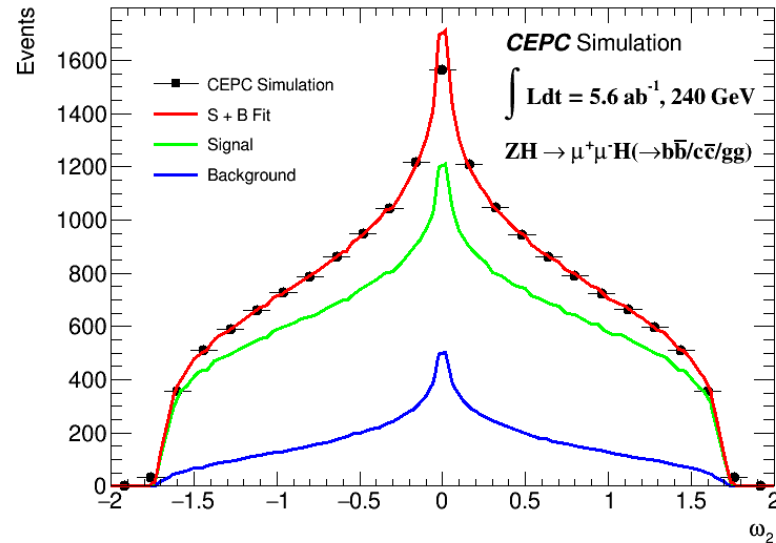
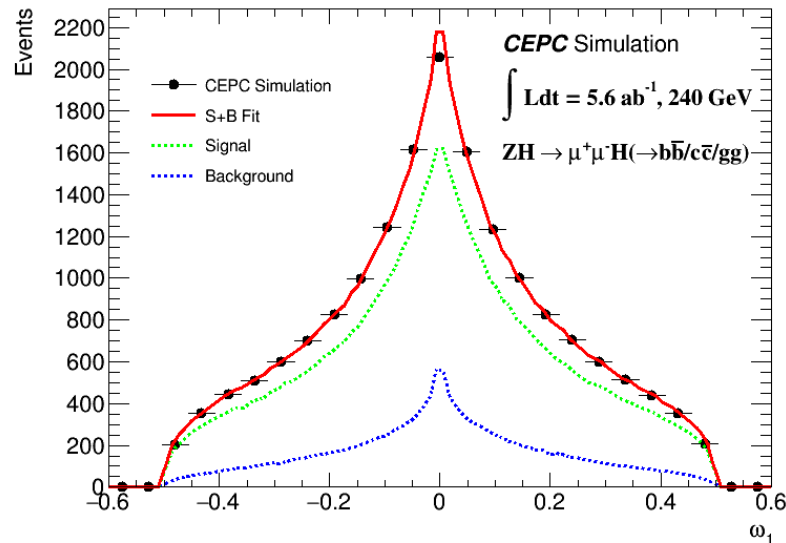
Fitting strategy and result

Fit ω :

- Use histogram pdf to fit **MC signal and background sample**.
- The red curve is global fit, the green curve is signal events, the blue curve is background events.

Fit $M_{recoil_{\mu\mu}}$:

- The signal modeled by the Crystal Ball function.
- The background modeled by a second-order polynomial.
- Using **ISR sample** can simulate the small exponential tail (which corresponding to the expected distribution.)



Individual Fit

Extract maximum-likelihood fit p-value and interval

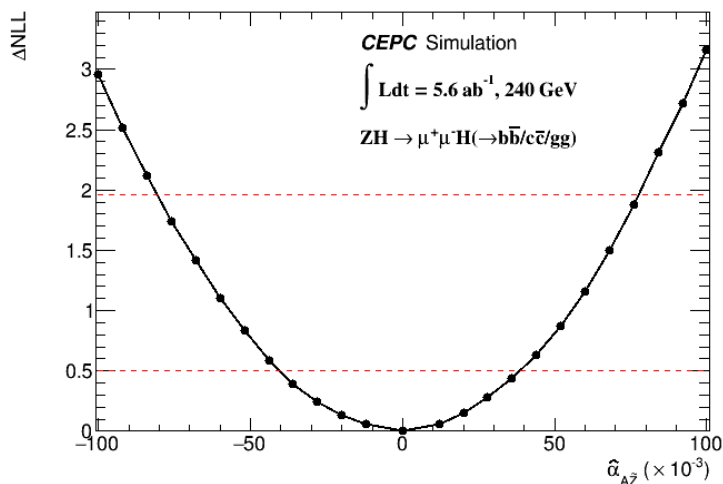
- In $\mu^+ \mu^- H$ channel.
- Fit ΔNLL curve with a quadratic function $\Delta NLL(\vec{\alpha}) = a \cdot (\vec{\alpha} - \vec{\alpha}_0)^2$
- 68%(95%) CL interval corresponds to $\Delta NLL=0.5(1.96)$.
- Set: fit to $\hat{\alpha}_{A\tilde{Z}}, \hat{\alpha}_{Z\tilde{Z}} = 0$.

$$\Delta NLL(\hat{\alpha}_{A\tilde{Z}}|\omega_1) = 2.93 \times 10^{-4} (\hat{\alpha}_{A\tilde{Z}} + 8.68 \times 10^{-1})^2$$

For $\hat{\alpha}_{A\tilde{Z}}$:

68% CL: $[-4.16 \times 10^{-2}, 3.88 \times 10^{-2}]$

95% CL: $[-8.10 \times 10^{-2}, 7.82 \times 10^{-2}]$



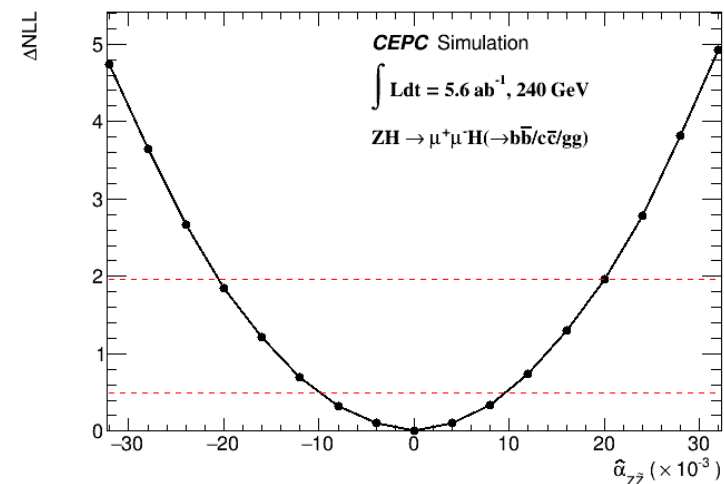
- Set: fit to $\hat{\alpha}_{Z\tilde{Z}}, \hat{\alpha}_{A\tilde{Z}} = 0$.

$$\Delta NLL(\hat{\alpha}_{Z\tilde{Z}}|\omega_2) = 4.51 \times 10^{-3} (\hat{\alpha}_{Z\tilde{Z}} + 6.36 \times 10^{-1})^2$$

For $\hat{\alpha}_{Z\tilde{Z}}$:

68% CL: $[-1.06 \times 10^{-2}, 1.00 \times 10^{-3}]$

95% CL: $[-2.06 \times 10^{-2}, 2.01 \times 10^{-2}]$



Fit to phi

ϕ has the most information among the three kinematic variables (θ_1, θ_2, ϕ)

straight-forward to fit ϕ .

In $\mu^+ \mu^- H$ channel.

	$\hat{\alpha}_{AZ}(\times 10^{-2})$	$\hat{\alpha}_{ZZ}(\times 10^{-2})$
	ω -fitting	
68% CL(1σ)	[-4.16, 3.88]	[-1.06, 1.00]
95% CL(2σ)	[-8.10, 7.82]	[-2.06, 2.01]
	ϕ -fitting	
68% CL(1σ)	[-4.42, 4.21]	[-1.35, 1.24]
95% CL(2σ)	[-8.66, 8.45]	[-2.62, 2.51]

The results of ϕ -fitting is slight worse than those of the ω -fitting.

- θ_1 and θ_2 have less information.

Combined results

$5.6ab^{-1}$	$\hat{\alpha}_{A\bar{Z}}(1\sigma)$	$\hat{\alpha}_{Z\bar{Z}}(1\sigma)$	$\hat{\alpha}_{A\bar{Z}}(2\sigma)$	$\hat{\alpha}_{Z\bar{Z}}(2\sigma)$
$\mu^+\mu^-(\times 10^{-2})$	[-4.16, 3.88]	[-1.06, 1.00]	[-8.10, 7.82]	[-2.06, 2.01]
$e^+e^-(\times 10^{-2})$	[-5.97, 5.43]	[-1.48, 1.48]	[-11.6, 11.0]	[-2.93, 2.93]
<i>combine</i> ($\times 10^{-2}$)	[-3.47, 3.10]	[-0.850, 0.827]	[-6.69, 6.32]	[-1.67, 1.65]

Combined results

	5.6 ab^{-1}		20 ab^{-1}	
	$\bar{c}_{Z\gamma}$	\bar{c}_{ZZ}	$\bar{c}_{Z\gamma}$	\bar{c}_{ZZ}
	$\mu^+ \mu^- H$ channel			
68% CL(1σ)	[−0.36, 0.33]	[−0.08, 0.07]	[−0.19, 0.17]	[−0.04, 0.04]
95% CL(2σ)	[−0.70, 0.67]	[−0.15, 0.15]	[−0.37, 0.35]	[−0.08, 0.08]
	$e^+ e^- H$ channel			
68% CL(1σ)	[−0.51, 0.47]	[−0.11, 0.11]	[−0.28, 0.24]	[−0.06, 0.06]
95% CL(2σ)	[−1.00, 0.95]	[−0.21, 0.21]	[−0.53, 0.49]	[−0.11, 0.11]
	Combined results			
68% CL(1σ)	[−0.30, 0.27]	[−0.06, 0.06]	[−0.16, 0.14]	[−0.03, 0.03]
95% CL(2σ)	[−0.58, 0.55]	[−0.12, 0.12]	[−0.31, 0.28]	[−0.06, 0.06]

Consider CEPC Higgs operation can be upgraded to 20 ab^{-1} .

- Normalize samples to the expected yields in data with an integrated luminosity of 20 ab^{-1} .
- This result is about **two times** better than that of 5.6 ab^{-1}

Result compare --> Compared with HL-LHC

In order to compare our study with HL-LHC, some conversion is necessary. (show in backup.)

In HL-LHC: (1sigma)

Parameter	$\tilde{c}_{Z\gamma}$	\tilde{c}_{ZZ}	Case
HL-LHC ($A\ell$, incl.)	[-0.22,0.22]	[-0.33,0.33]	1P
	[-0.25,0.25]	[-0.27,0.27]	1P _{marg.}
HL-LHC ($A\ell$, diff.)	[-0.10,0.10]	[-0.31,0.31]	1P
	[-0.13,0.13]	[-0.22,0.22]	1P _{marg.}
HE-LHC ($A\ell$, incl.)	[-0.18,0.18]	[-0.17,0.17]	1P
	[-0.23,0.23]	[-0.20,0.20]	1P _{marg.}
HE-LHC ($A\ell$, diff.)	[-0.05,0.05]	[-0.13,0.13]	1P
	[-0.06,0.06]	[-0.10,0.10]	1P _{marg.}

[arXiv:1902.00134](https://arxiv.org/abs/1902.00134)

Result compare --> Compared with HL-LHC

In order to compare our study with HL-LHC, some conversion is necessary. (show in backup.)

In HL-LHC: (1sigma)

Parameter	$\tilde{c}_{Z\gamma}$	\tilde{c}_{ZZ}	Case
HL-LHC (4ℓ , incl.)	[-0.22,0.22]	[-0.33,0.33]	1P
	[-0.25,0.25]	[-0.27,0.27]	1P _{marg.}
HL-LHC (4ℓ , diff.)	[-0.10,0.10]	[-0.31,0.31]	1P
	[-0.13,0.13]	[-0.22,0.22]	1P _{marg.}
HE-LHC (4ℓ , incl.)	[-0.18,0.18]	[-0.17,0.17]	1P
	[-0.23,0.23]	[-0.20,0.20]	1P _{marg.}
HE-LHC (4ℓ , diff.)	[-0.05,0.05]	[-0.13,0.13]	1P
	[-0.06,0.06]	[-0.10,0.10]	1P _{marg.}

[arXiv:1902.00134](https://arxiv.org/abs/1902.00134)

Collider	pp	e^+e^-	e^+e^-	e^+e^-
E (GeV)	14000	3000	240	240
\mathcal{L} (fb ⁻¹)	3000	5000	5600	20000
$\tilde{c}_{Z\gamma}$ (1 σ)	[-0.22, 0.22]	[-0.18, 0.18]	[-0.30, 0.27]	[-0.16, 0.14]
\tilde{c}_{ZZ} (1 σ)	[-0.33, 0.33]	[-0.12, 0.12]	[-0.06, 0.06]	[-0.03, 0.03]

HL-LHC

CLIC

CEPC

The results in $5.6ab^{-1}$ are **significantly better** than HL-LHC on the \tilde{c}_{ZZ} and comparable on the $\tilde{c}_{Z\gamma}$.

◦ For $5.6ab^{-1}$: $f_{CP}^{HZZ} < 9.16 \times 10^{-6}$

Summary

An EFT based Higgs CP-mixing test is performed.

- Set up some basic assumptions to have a simplest CP-mixing model.
- Introduced optimal variable with better performance.
- Used ML-fit in ω and ϕ distribution to extract $\hat{\alpha}_{A\tilde{Z}}$ and $\hat{\alpha}_{Z\tilde{Z}}$.
- Result: 68% CL $\tilde{c}_{Z\gamma} \in [-0.30, 0.27]$ and $\tilde{c}_{ZZ} \in [-0.06, 0.06]$; $f_{CP}^{HZZ} < 9.16 \times 10^{-6}$.
- Consider CEPC Higgs operation can be upgraded to $20ab^{-1}$, the results is about **two times** better. In \tilde{c}_{ZZ} , the sensitivities is improved by about **one order of magnitude** compared with pp collider.

Collider	pp	e^+e^-	e^+e^-	e^+e^-
E (GeV)	14000	3000	240	240
\mathcal{L} (fb $^{-1}$)	3000	5000	5600	20000
$\tilde{c}_{Z\gamma}$ (1σ)	$[-0.22, 0.22]$	$[-0.18, 0.18]$	$[-0.30, 0.27]$	$[-0.16, 0.14]$
\tilde{c}_{ZZ} (1σ)	$[-0.33, 0.33]$	$[-0.12, 0.12]$	$[-0.06, 0.06]$	$[-0.03, 0.03]$

Thank you!

Backup

Result compare --> Compared with HL-LHC

In HL-LHC: [arXiv:1902.00134](https://arxiv.org/abs/1902.00134)

$$\mathcal{L}_{\text{CPV}} = \frac{H}{v} \left[\tilde{c}_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} \tilde{A}^{\mu\nu} + \tilde{c}_{Z\gamma} \frac{e\sqrt{g_1^2 + g_2^2}}{2} Z_{\mu\nu} \tilde{A}^{\mu\nu} + \tilde{c}_{ZZ} \frac{g_1^2 + g_2^2}{4} Z_{\mu\nu} \tilde{Z}^{\mu\nu} + \tilde{c}_{WW} \frac{g_2^2}{2} W_{\mu\nu}^+ \tilde{W}^{\mu\nu} \right]$$

Compare theory model in P5, we can get that the value in red frame are same:

$$(g_1=0.358, g_2=0.648, e=0.313, v = 1/\sqrt{\sqrt{2}G_F^0} = 2M_W/g \approx 246.22\text{GeV})$$

$$(\sqrt{2}G_F)^{1/2} \hat{\alpha}_{ZZ} H Z_{\mu\nu} \tilde{Z}^{\mu\nu} = \frac{H}{v} \tilde{c}_{ZZ} \frac{g_1^2 + g_2^2}{4} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \quad \frac{g_1^2 + g_2^2}{4} = 0.137$$

$$(\sqrt{2}G_F)^{1/2} \hat{\alpha}_{AZ} H Z_{\mu\nu} \tilde{A}^{\mu\nu} = \frac{H}{v} \tilde{c}_{Z\gamma} \frac{e\sqrt{g_1^2 + g_2^2}}{2} Z_{\mu\nu} \tilde{A}^{\mu\nu} \quad \frac{e\sqrt{g_1^2 + g_2^2}}{2} = 0.116$$