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

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Abstract

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

Keywords: the Higgs Boson, CP violation, CEPC

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Introduction

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

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 $\sqrt{s} = 7\&8$ 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.

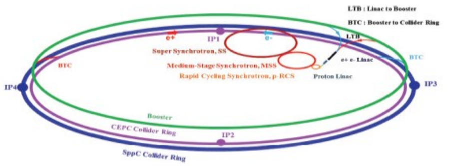
- We need new facilities to achieve more precise measurement.

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

Introduction

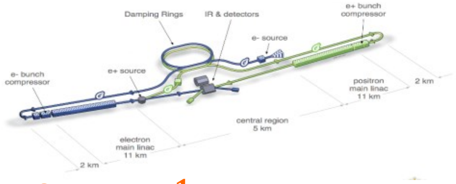
Future e^+e^- collider experiment as Higgs factory :

- At a center of mass energy of $\sqrt{s}{\sim}240GeV$ 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.

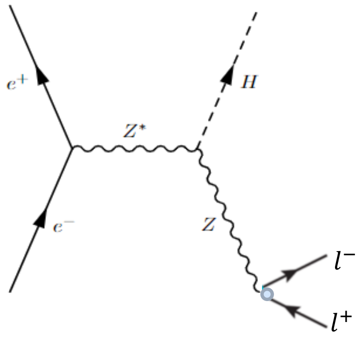


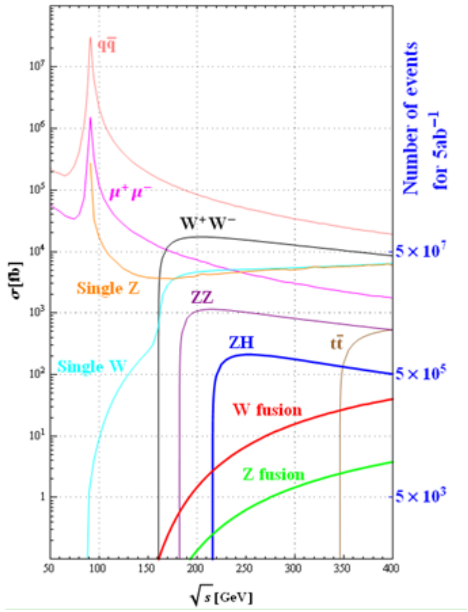
CEPC, 5.6 ab^{-1} @ 240GeV

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



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





Theory framework

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

$c_{AZ} = (\sqrt{2}G_F)^{1/2}\hat{\alpha}_{AZ}$, $c_{A\tilde{Z}} = (\sqrt{2}G_F)^{1/2}\hat{\alpha}_{A\tilde{Z}}$.

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

  $m_z = m_{Z0}(1+\delta_Z)$, $G_F = G_{F0}\left(1+\delta_{G_F}\right)$, $\alpha_{em} = \alpha_{em0}(1+\delta_A)$

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

m_{Z0} = 91.1876

G_{F0} = 1.166367e-5

α_{em0} = 1/127.940

Theory framework

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The $H \to Zll$ matrix element:

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

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

  And the parameters in the function are following:

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

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

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

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

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

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

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

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

(red box) : SM term

Others : EFT contribution

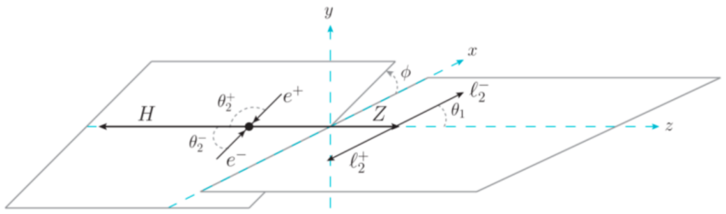
Theory framework

[JHEP 03(2016) 050] [JHEP 11(2014) 028]

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

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

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



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

Variables for studying distribution: θ_1,θ_2,ϕ

Theory framework

JHEP 03(2016) 050 JHEP 11(2014) 028

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

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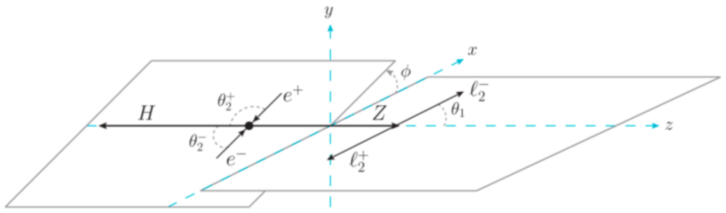
$$\mathcal{N}_\sigma(q^2) = \frac{1}{2^{10}(2\pi)^3}\cdot\frac{1}{\sqrt{r}\gamma_Z}\cdot\frac{\sqrt{\lambda(1,s,r)}}{s^2}$$



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

Variables for studying distribution: θ_1, θ_2, ϕ

Assumption for simplification:

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

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

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

$$J_3 = 32\,r\,s\,g_A\,g_V\,\mathrm{Re}\,(H_{1,V}\,H_{1,A}^*)\,,$$

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

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

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

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

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

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

6 of these 9 functions are independent

(red strike line)	0 in assumption
(blue box)	EFT CP-odd term
Others	CP-even contribution

Optimal variable approach

Differential cross section could be represented as:

$$\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2 d\phi} = N \times \left(J_{\text{even}}\,(\theta_1, \theta_2, \phi) + \hat{\alpha}_{A\tilde{Z}} \times J_{odd_1}(\theta_1, \theta_2, \phi) + \hat{\alpha}_{Z\tilde{Z}} \times J_{odd_2}(\theta_1, \theta_2, \phi)\right)$$

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

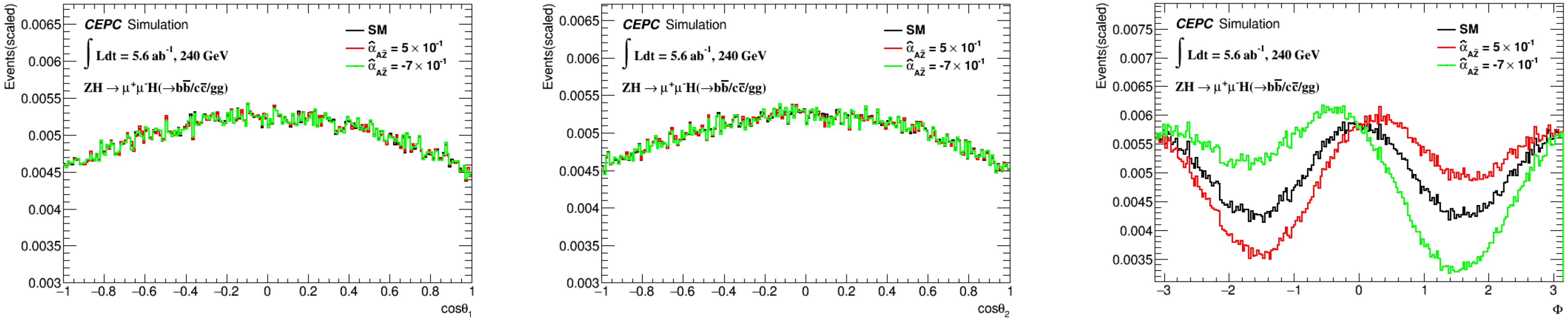
Optimal variable approach

Differential cross section could be represented as:

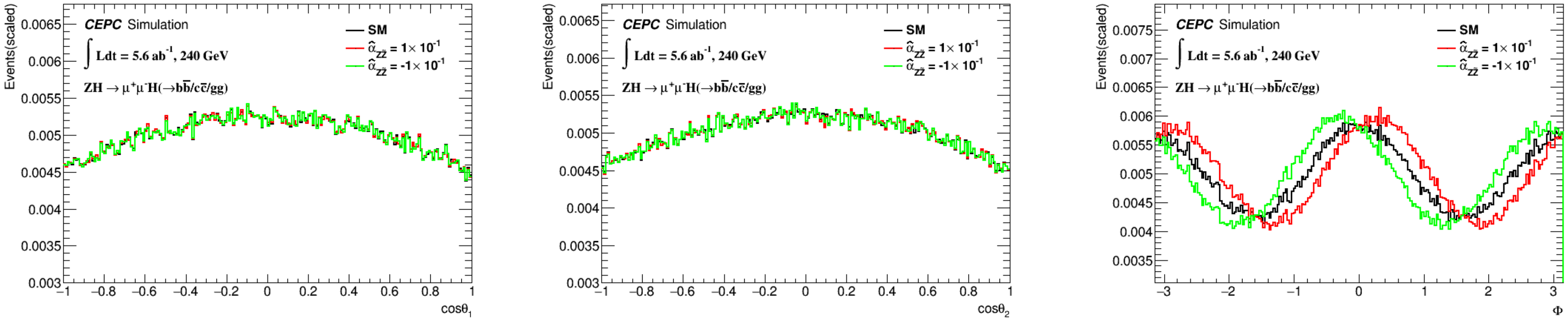
$$\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2 d\phi} = N \times \left(J_{\text{even}}\,(\theta_1,\theta_2,\phi) + \hat{\alpha}_{A\tilde{Z}} \times J_{odd_1}(\theta_1,\theta_2,\phi) + \hat{\alpha}_{Z\tilde{Z}} \times J_{odd_2}(\theta_1,\theta_2,\phi)\right)$$

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

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



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



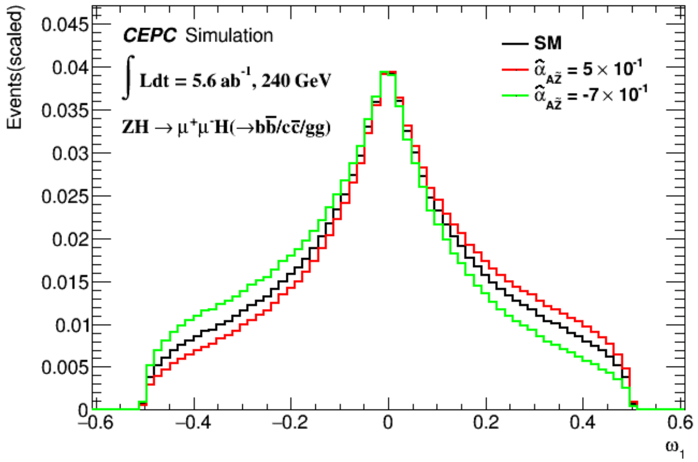
Optimal variable approach

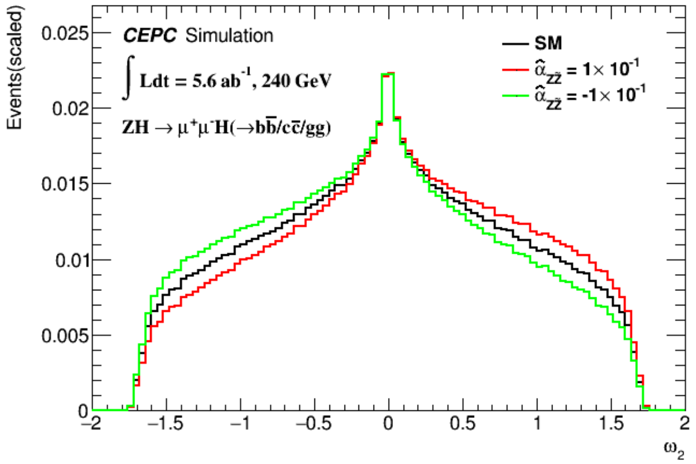
$$\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2 d\phi} = N \times \left(J_{even}(\theta_1, \theta_2, \phi) + \hat{\alpha}_{A\tilde{Z}} \times J_{odd_1}(\theta_1, \theta_2, \phi) + \hat{\alpha}_{Z\tilde{Z}} \times J_{odd_2}(\theta_1, \theta_2, \phi)\right)$$

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

$$\omega_1 = \frac{J_{odd_1}(\theta_1,\theta_2,\phi)}{J_{even}(\theta_1,\theta_2,\phi)}$$ to measure $\hat{\alpha}_{A\tilde{Z}}$

$$\omega_2 = \frac{J_{odd_2}(\theta_1,\theta_2,\phi)}{J_{even}(\theta_1,\theta_2,\phi)}$$ 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 $e^+e^- \to ZH \to llH$:

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

- $\sqrt{s} = 240GeV$
- 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	$\lvert cos\theta_{\mu^+\mu^-}\rvert$	$(-1,0.81)$
	$M_{\mu\mu}$	$(77.5GeV, 104.5GeV)$
	$M_{recoil\_\mu\mu}$	$(124GeV, 140GeV)$
Jets pair selection	$\lvert cos\theta_{jet}\rvert$	$(-1,0.96)$
	M_{jj}	$(100GeV, 150GeV)$

Where $M^2_{recoil\_\mu\mu} = (\sqrt{s} - E_{\mu\mu})^2 - p^2_{\mu\mu} = s - 2E_{\mu\mu}\sqrt{s} + m^2_{\mu\mu}$

- **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	$\lvert cos\theta_{e^+e^-}\rvert$	$(-1,0.81)$
	M_{ee}	$(85GeV, 95GeV)$
	M_{recoil_ee}	$(124GeV, 140GeV)$
	$\lvert cos\varphi_{e^+}\rvert$	$(-1,0.95)$
	$\lvert cos\varphi_{e^-}\rvert$	$(-1,0.95)$
Jets pair selection	$\lvert cos\theta_{jet}\rvert$	$(-1,0.96)$
	M_{jj}	$(110GeV, 145GeV)$

Event selection

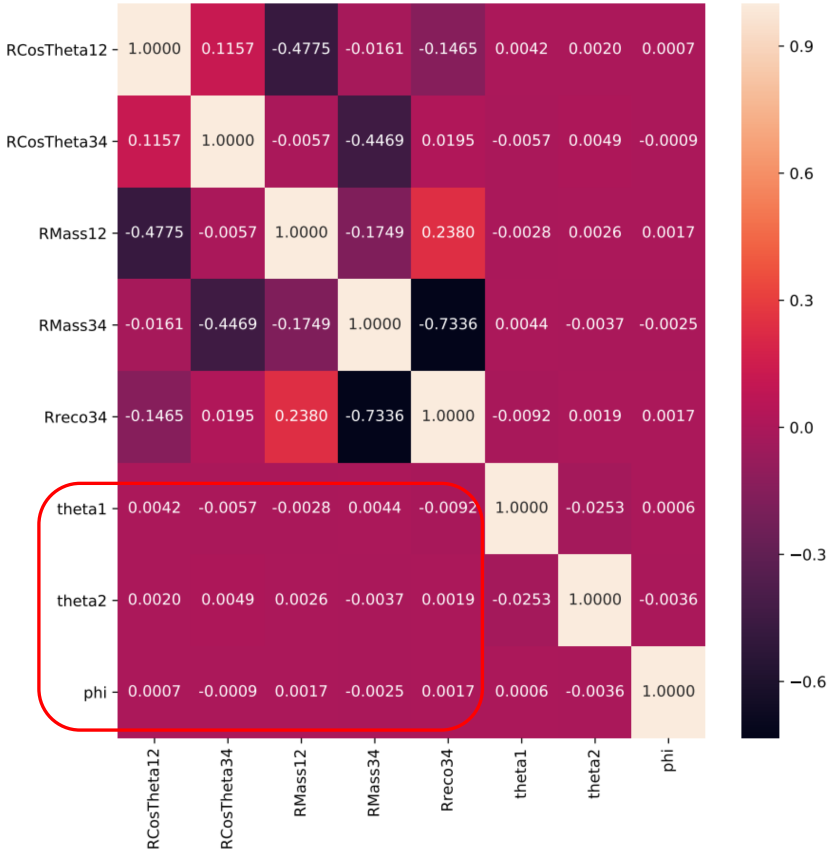
$ZH \to \mu^+\mu^- + b\bar{b}/c\bar{c}/gg$ **channel**		
	Signal	Irreducible Background
Original	2.62×10^4	1.25×10^6
Lepton pair selection	1.59×10^4 (efficiency:60.67%)	9.91×10^3 (efficiency:0.79%)
All selection	1.48×10^4 (efficiency:56.42%)	5.60×10^3 (efficiency:0.45%)

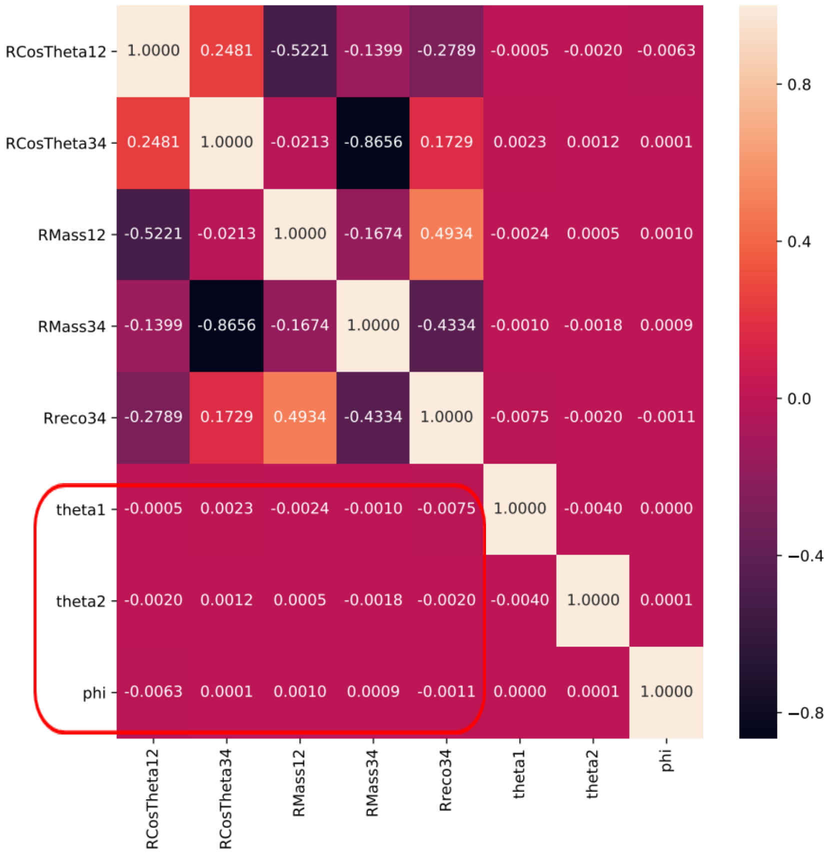
$ZH \to e^+e^- + b\bar{b}/c\bar{c}/gg$ **channel**		
	Signal	Irreducible Background
Original	2.72×10^4	1.77×10^6
Lepton pair selection	8.76×10^3 (efficiency:32.2%)	8.77×10^4 (efficiency:0.50%)
All selection	7.15×10^3 (efficiency:26.3%)	4.59×10^3 (efficiency:0.25%)

Event selection

Correlation:

- We can see that $\theta_1,\ \theta_2, \phi$ have little correlation with $cos\theta_{l^+l^-}$, Mass_{ll}, M_{recoil_ll}, $cos\theta_{jet}$, Mass_{jj}.





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

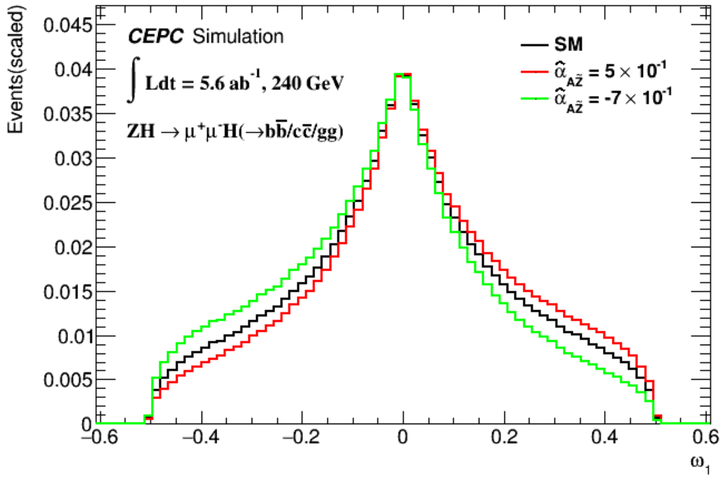
Fitting strategy and result

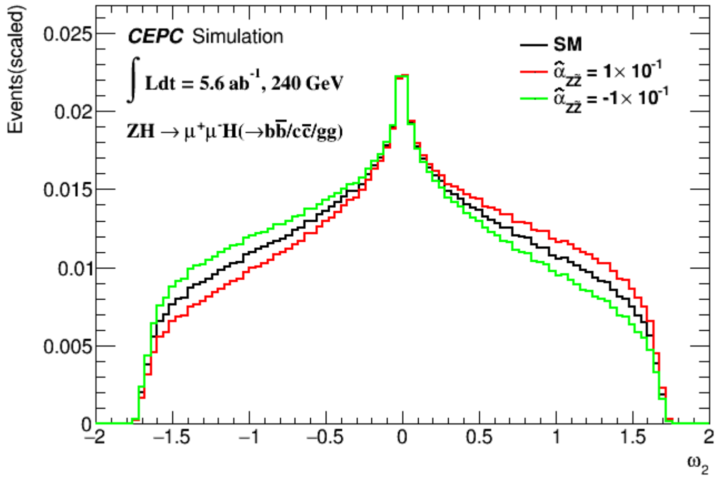
Fit strategy: Maximum-likelihood fit

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

where $\vec{\alpha}$ means $\hat{\alpha}_{A\tilde{Z}}$ *and* $\hat{\alpha}_{Z\tilde{Z}}$, ω represents ω_1 and ω_2.

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





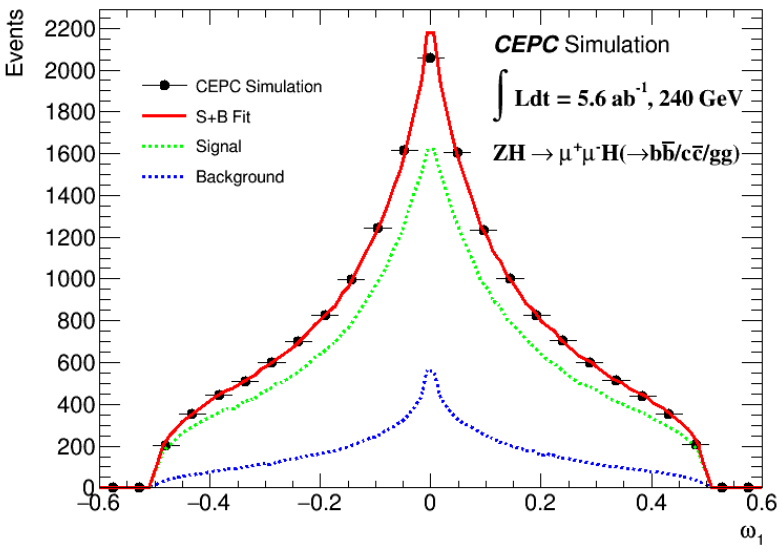
Fitting strategy and result

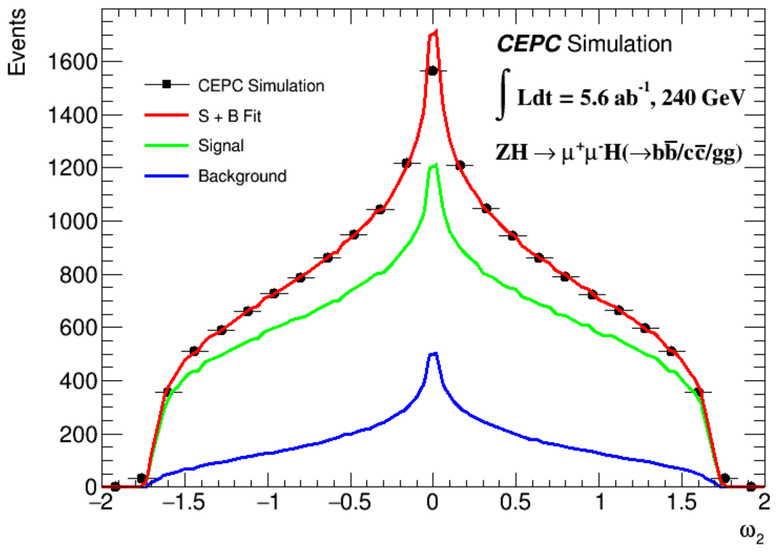
Fit ω:

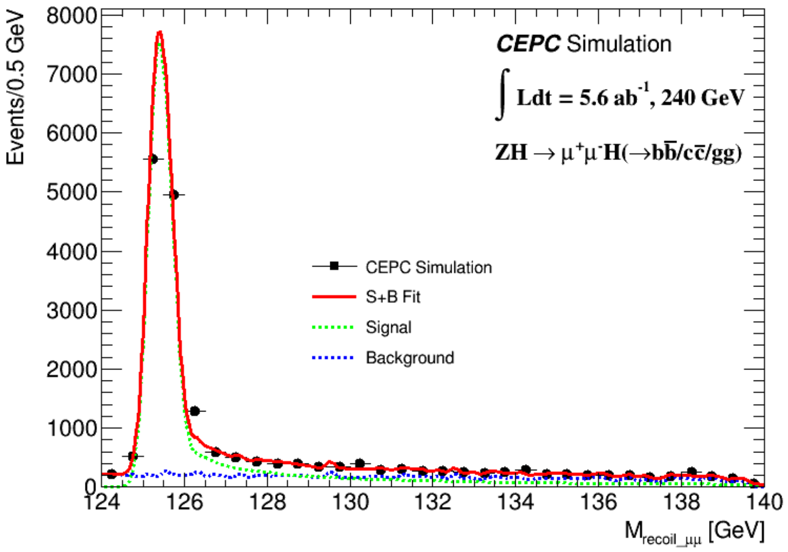
- Use histogram pdf to fit **MC signal and background sample.**
- The red curve is global fit, the green curve is signal events, the blue curve is background events.

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.)







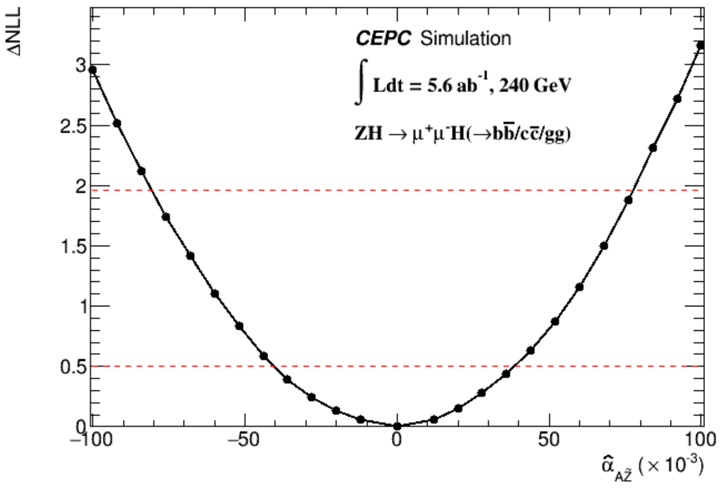
Individual Fit

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 ΔNLL=0.5(1.96).
- Set: $fit\ to\ \hat{\alpha}_{A\tilde{Z}}, \hat{\alpha}_{Z\tilde{Z}} = 0.$

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

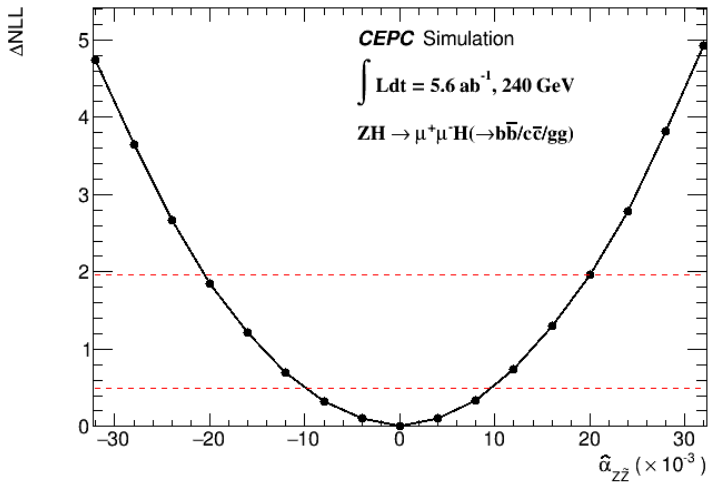
For $\hat{\alpha}_{A\tilde{Z}}$:
68% CL: $[-4.16 \times 10^{-2}, 3.88 \times 10^{-2}]$
95% CL: $[-8.10 \times 10^{-2}, 7.82 \times 10^{-2}]$



- 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 $(\theta_1, \theta_2, \phi)$

straight-forward to fit ϕ.

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

	$\hat{\alpha}_{A\tilde{Z}}(\times 10^{-2})$	$\hat{\alpha}_{Z\tilde{Z}}(\times 10^{-2})$
	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

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

Combined results

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

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

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

$20ab^{-1}$	$\hat{\alpha}_{A\tilde{Z}}(1\sigma)$	$\hat{\alpha}_{Z\tilde{Z}}(1\sigma)$	$\hat{\alpha}_{A\tilde{Z}}(2\sigma)$	$\hat{\alpha}_{Z\tilde{Z}}(2\sigma)$
$\boldsymbol{\mu^+\mu^-\mu^-}(\times 10^{-2})$	$[-2.19, 2.03]$	$[-0.538, 0.516]$	$[-4.26, 4.04]$	$[-1.05, 1.03]$
$\boldsymbol{e^+e^-\mu^-}(\times 10^{-2})$	$[-3.22, 2.75]$	$[-0.763, 0.785]$	$[-6.15, 5.68]$	$[-1.52,1.54]$
$\boldsymbol{combine\mu^-}(\times 10^{-2})$	$[-1.85,1.59]$	$[-0.420, 0.430]$	$[-3.54, 3.27]$	$[-0.836, 0.846]$

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)

arXiv:1902.00134

Analysis \ 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]	$1P_{marg.}$

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)

arXiv:1902.00134

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	[-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]	$1P_{marg.}$

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)	$[-0.33, 0.33]$	$[-0.12, 0.12]$	$[-0.06, 0.06]$	$[-0.03, 0.03]$

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)	$[-0.33, 0.33]$	$[-0.12, 0.12]$	$[-0.06, 0.06]$	$[-0.03, 0.03]$

Status: Accepted by EPJC

Thank you!

Backup

Result compare --> Compared with HL-LHC

In HL-LHC: arXiv:1902.00134

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

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

(g1=0.358, g2=0.648, e=0.313, $v = 1/\sqrt{\sqrt{2}G_F^0} = 2M_W/g \approx 246.22\text{GeV}$)

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

$$\frac{g_1^2+g_2^2}{4} = 0.137$$

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

$$\frac{e\sqrt{g_1^2+g_2^2}}{2} = 0.116$$