Probing Higgs CP properties at the CEPC

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FIRST PAN-AFRICAN ASTRO-PARTICLE AND COLLIDER PHYSICS WORKSHOP

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Abstract

In the Circular Electron Positron Collider (CEPC), a measurement of the Higgs CP mixing through $e^+e^- \to ZH \to \mu^+\mu^- H(\to b\bar{b}/c\bar{c}/gg)$ 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 $\tilde{\alpha}_{A\tilde{Z}}$ is constrained between the region of -8.27×10^{-2} and 8.09×10^{-2} and $\tilde{\alpha}_{Z\tilde{Z}}$ between -2.15×10^{-2} and 2.02×10^{-2} at 95% 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.

Higgs-gauge vector boson interaction lacks precise measurement in all inclusive Higgs production mode(i.e. ggF dominant).

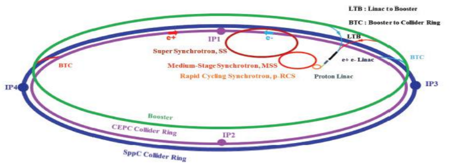
Any observation of CP violation in Higgs would be New Physics!

What we want to study is the Higgs CP mixing model aiming to find the CP-odd Higgs.

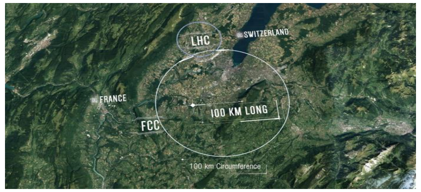
Introduction

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

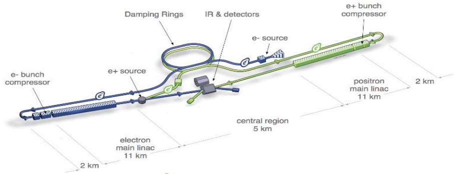
- At a center of mass energy of $\sqrt{s}\sim 240GeV$ which maximizes the Higgs boson production cross section through $e^+e^- \rightarrow ZH$ process.
- Cleaner environment and more events produced than (HL)-LHC.
- More precise Higgs-gauge boson coupling study.



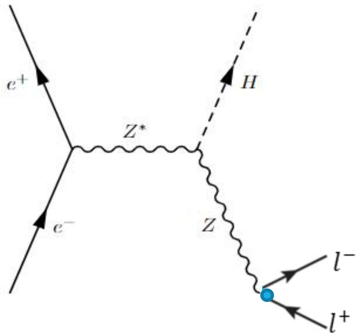
CEPC, 5.6 ab^{-1} @ 240GeV

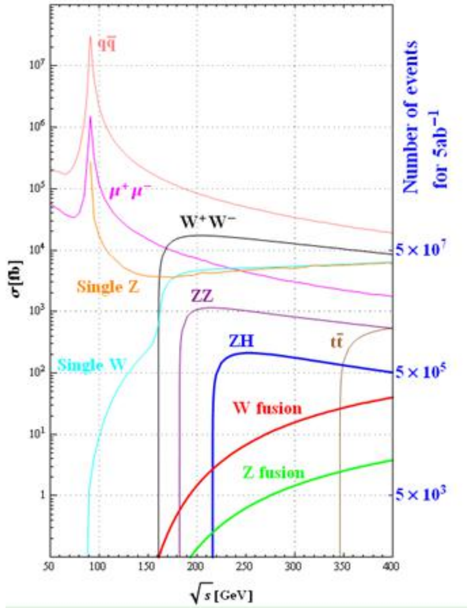


FCC-ee, 5 ab^{-1} @240GeV



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





Theory framework

JHEP 03 (2016) 050　JHEP 11(2014) 028

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

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

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

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

- 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:

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

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

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

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

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

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

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

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

: SM term

Others : EFT contribution

Theory framework

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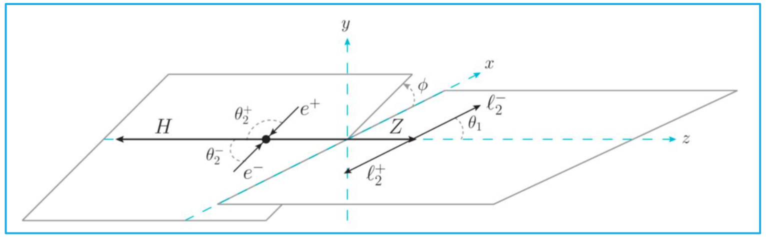
Differential cross section for $e^+e^- \to ZH \to llH$:

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

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



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

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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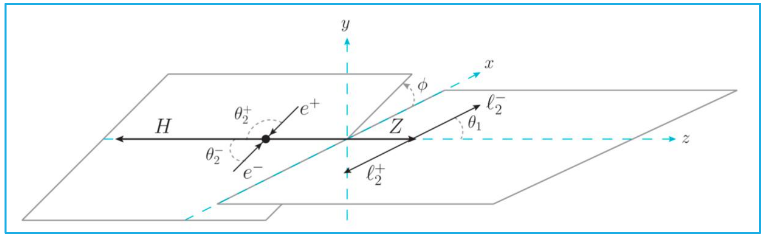


$$\begin{aligned}\mathcal{J}(q^2,\theta_1,\theta_2,\phi) = \; & J_1(1+\cos^2\theta_1\cos^2\theta_2+\cos^2\theta_1+\cos^2\theta_2) \\ & + J_2\sin^2\theta_1\sin^2\theta_2 + J_3\cos\theta_1\cos\theta_2 \\ & + (J_4\sin\theta_1\sin\theta_2 + J_5\sin 2\theta_1\sin 2\theta_2)\sin\phi \\ & + (J_6\sin\theta_1\sin\theta_2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

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 $H_{2,V/A} = 0$.

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

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

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

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

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

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

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

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

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

6 of these 9 functions are independent

0 in assumption

EFT CP-odd term

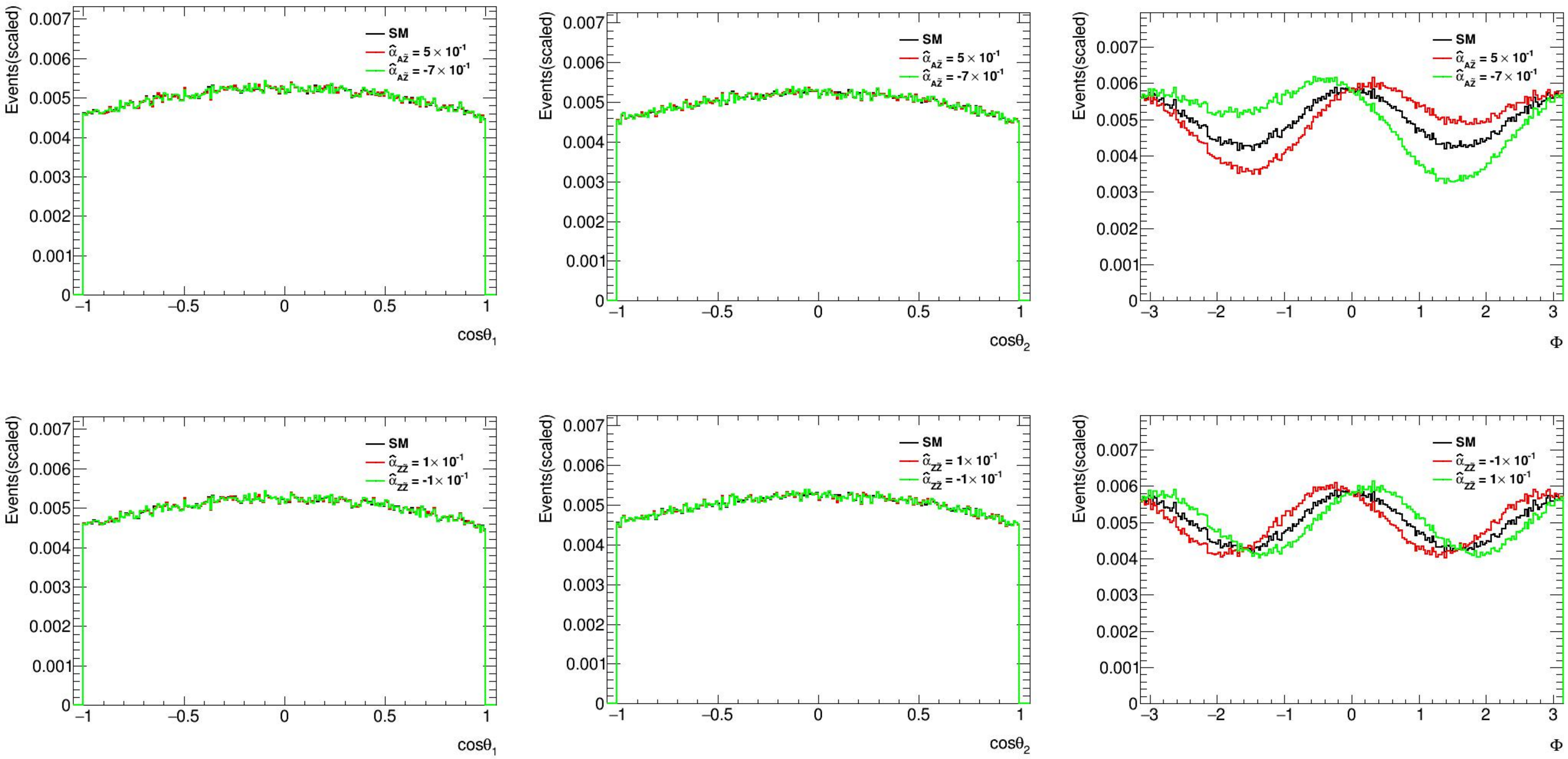
Others CP-even contribution

Optimal variable approach

Differential cross section could be represent 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

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

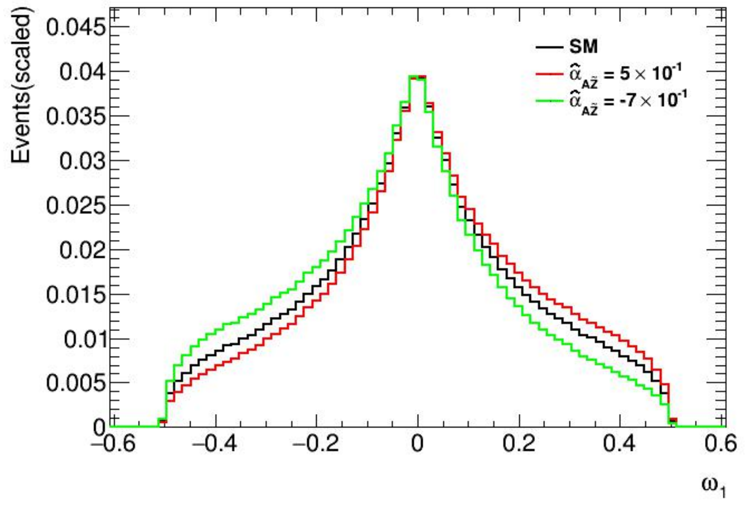
$$\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2 d\phi} = N \times \left(J_{\text{even}}\,(\theta_1,\theta_2,\phi) + \hat{\alpha}_{A\tilde{Z}} \times J_{odd_1}(\theta_1,\theta_2,\phi) + \hat{\alpha}_{Z\tilde{Z}} \times J_{odd_2}(\theta_1,\theta_2,\phi)\right)$$

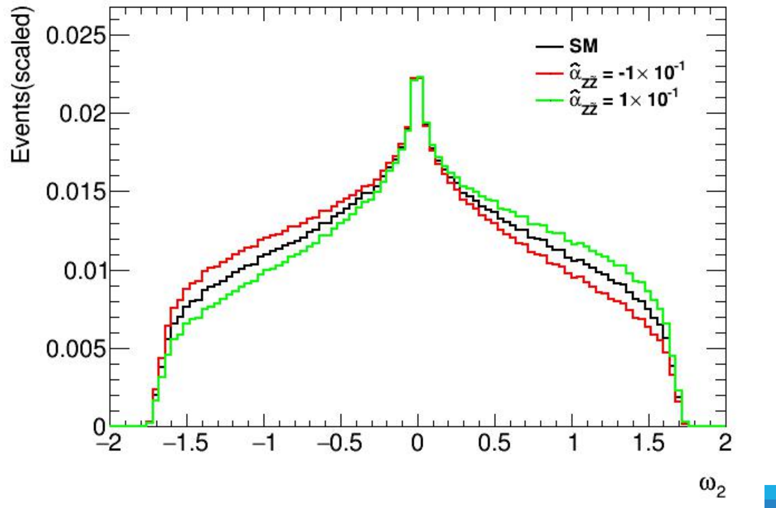
In this formation, we could define Optimal Variable ω which combines the information from $\{\theta_1,\ \theta_2,\phi\}$:

$$\omega_1 = 1000 \times \frac{J_{odd_1}(\theta_1,\theta_2,\phi)}{J_{\text{even}}\,(\theta_1,\theta_2,\phi)}$$ to measure $\hat{\alpha}_{A\tilde{Z}}$

$$\omega_2 = 1000 \times \frac{J_{odd_2}(\theta_1,\theta_2,\phi)}{J_{\text{even}}\,(\theta_1,\theta_2,\phi)}$$ to measure $\hat{\alpha}_{Z\tilde{Z}}$

(The factor of 1000 is included here only for numerical convenience)





Benefits:

- Combine the information from 3-dimension phase space
- Easier to study

Monte Carlo samples

Samples:

- The SM Higgs and background samples: generate with Whizard 1.95 and fast simulated based on the CEPC baseline detector design.
- 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**: $e^+e^- \to ZH \to \mu^+\mu^- H(\to b\bar{b}/c\bar{c}/gg)$ channel
- **Background**: Irreducible background which contains the same final states as that in signal.

Choose selections by the best significance:

- Muon pair selection:

  $|cos\theta_{\mu^+\mu^-}| < 0.81$; $\mathrm{Mass}_{\mu\mu} \in (77.5GeV, 104.5GeV)$; $M_{recoil\_\mu\mu} \in (124GeV, 140GeV)$.

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

- Jets pair selection:

  $|cos\theta_{jet}| < 0.96$; $\mathrm{Mass}_{jj} \in (100GeV, 150GeV)$.

Event selection

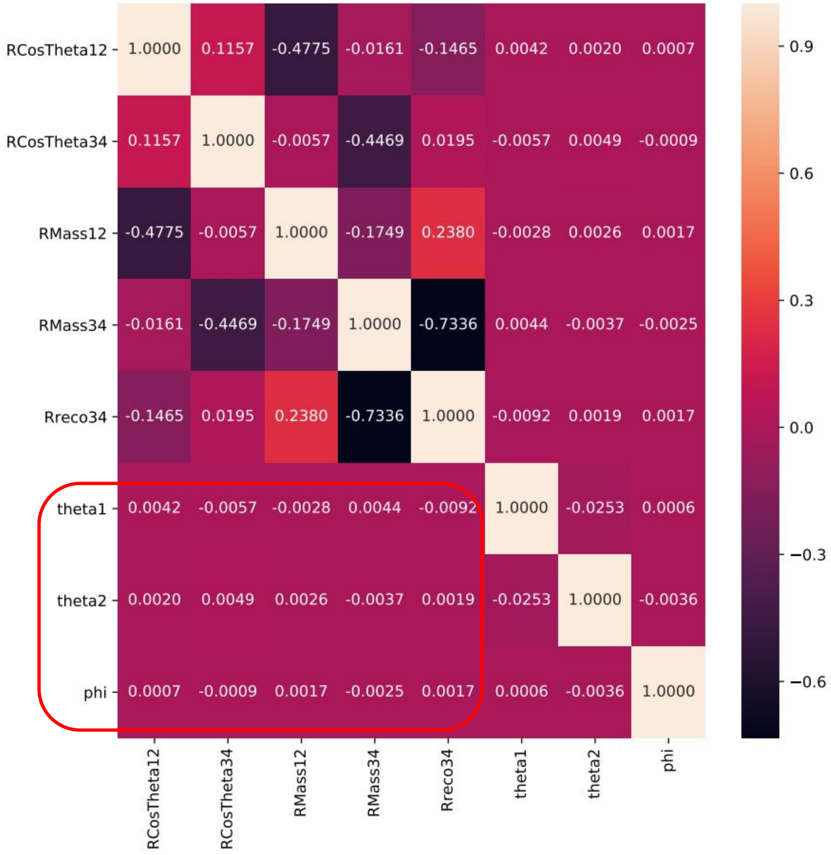
Cut Flow:

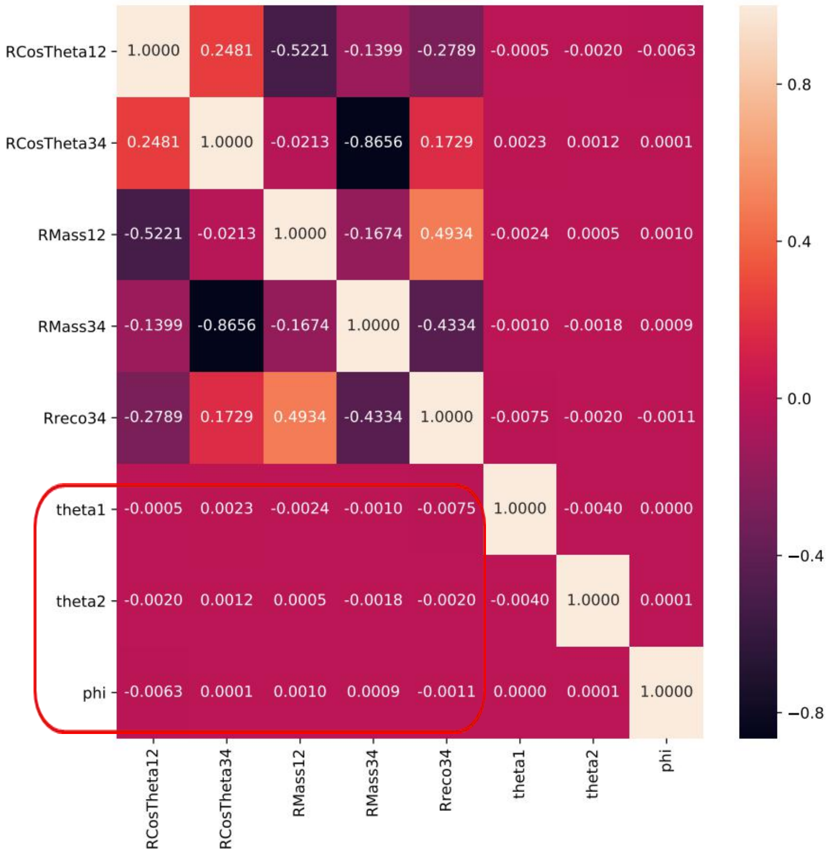
$ZH \to \mu^+\mu^- + b\bar{b}/c\bar{c}/gg$ channel		
	Signal	Irreducible Background
Original	2.86×10^6	1.25×10^6
Muon pair selection	1.84×10^4 (efficiency:64.33%)	1.14×10^4 (efficiency:0.91%)
All selection	1.33×10^4 (efficiency:46.50%)	3.61×10^3 (efficiency:0.29%)

Event selection

Correlation:

- We can see that $\theta_1,\ \theta_2, \phi$ have little correlation with $cos\theta_{\mu^+\mu^-}$, $\text{Mass}_{\mu\mu}$, $M_{recoil\_\mu\mu}$, $cos\theta_{jet}$, Mass_{jj}.





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

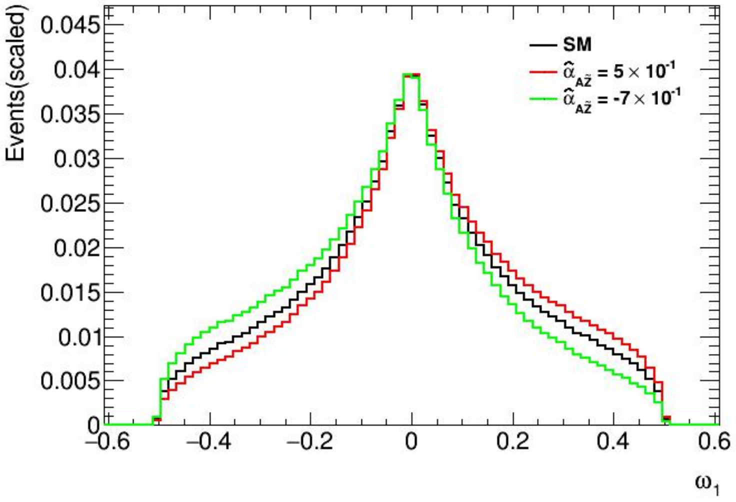
Fitting strategy and result

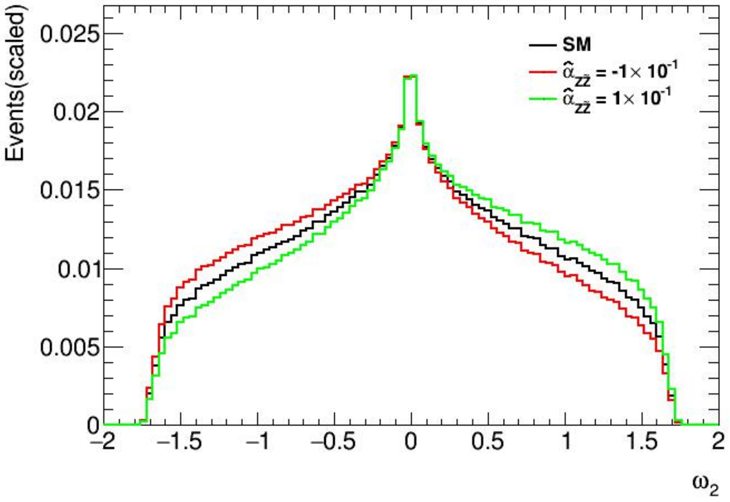
Fit strategy: Maximum-likelihood fit

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

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 $f_{\text{sig}}^{\vec{\alpha}}(\omega)$ and $f_{bkg}^{\vec{\alpha}}(\omega)$**
- **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 $\vec{\alpha}$.





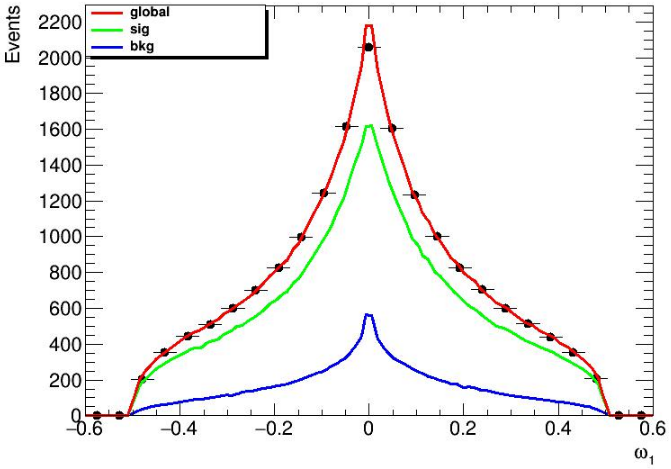
Fitting strategy and result

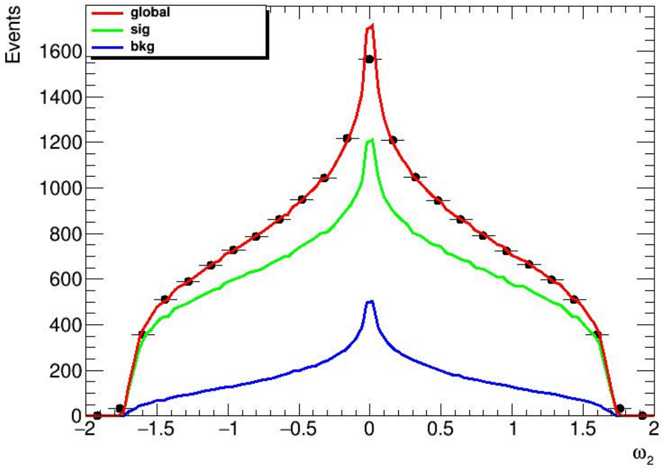
Fit ω :

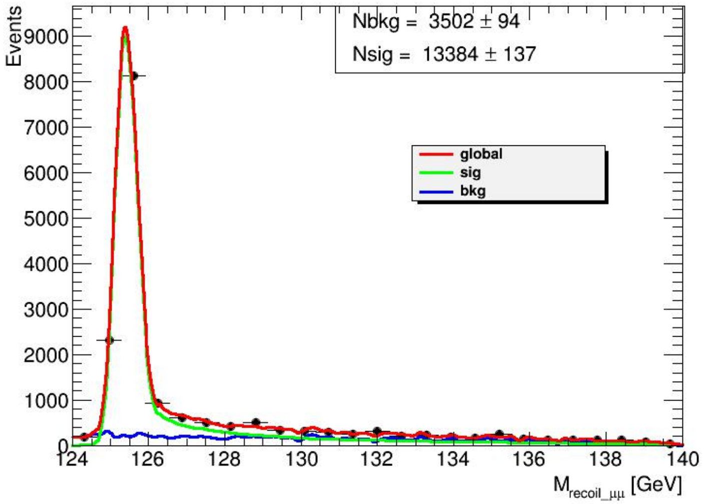
- Use histogram pdf to fit **MC signal and background sample**.
- The red curve is global fit, the green curve is signal events, the blue curve is background events.

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.)







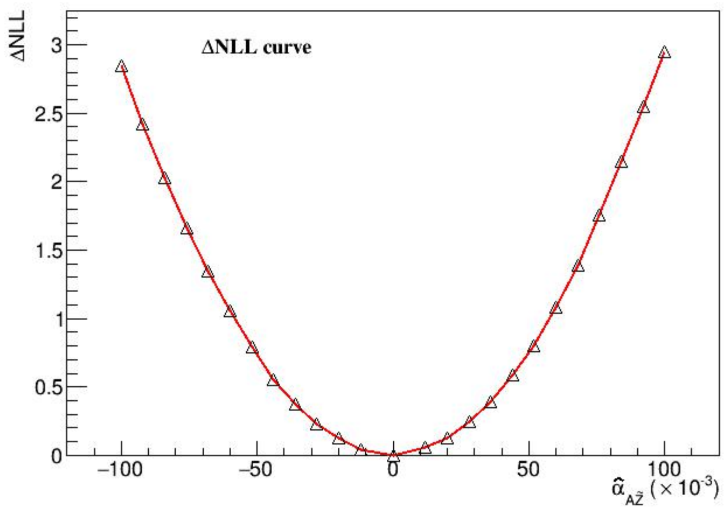
Individual Fit

Extract maximum-likelihood fit p-value and interval

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

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

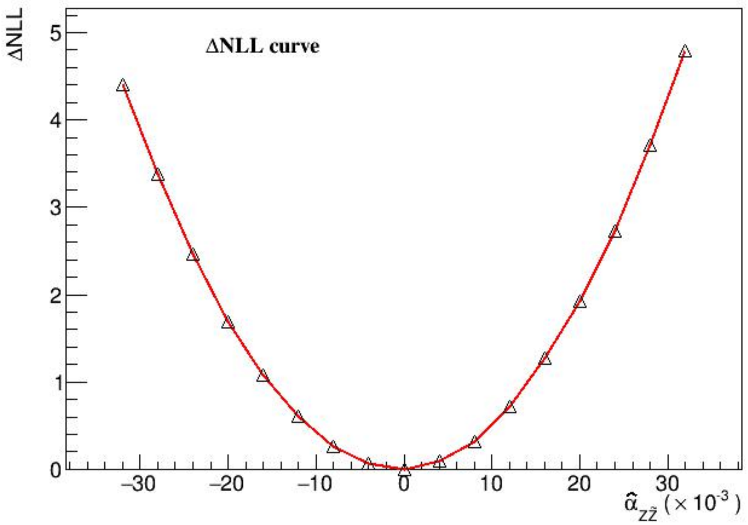
For $\hat{\alpha}_{A\tilde{Z}}$:
68% CL: $[-4.22 \times 10^{-2}, 4.04 \times 10^{-2}]$
95% CL: $[-8.27 \times 10^{-2}, 8.09 \times 10^{-2}]$



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

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

For $\hat{\alpha}_{Z\tilde{Z}}$:
68% CL: $[-1.12 \times 10^{-2}, 9.89 \times 10^{-3}]$
95% CL: $[-2.15 \times 10^{-2}, 2.02 \times 10^{-2}]$



Fit to phi

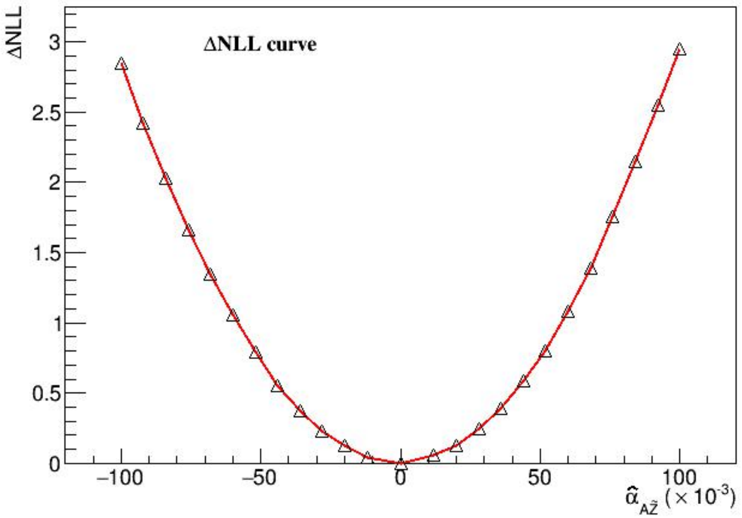
ϕ has the most information among the three kinematic variables $(\theta_1, \theta_2, \phi)$

straight-forward to fit ϕ.

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

$\boldsymbol{\Delta NLL}(\hat{\alpha}_{A\tilde{Z}}|\phi) = \mathbf{2.68 \times 10^{-4}}(\hat{\alpha}_{A\tilde{Z}} + \mathbf{1.05})^2$

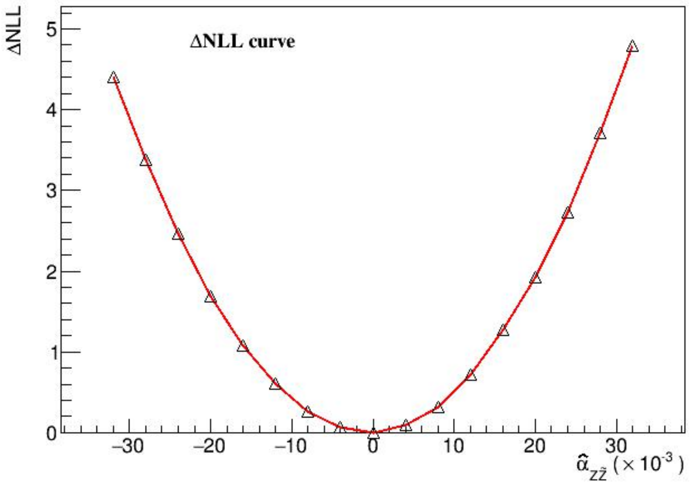
For $\hat{\alpha}_{A\tilde{Z}}$:
68% CL: $[-4.42 \times 10^{-2}, 4.21 \times 10^{-2}]$
95% CL: $[-8.66 \times 10^{-2}, 8.45 \times 10^{-2}]$



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

$\boldsymbol{\Delta NLL}(\hat{\alpha}_{Z\tilde{Z}}|\phi) = \mathbf{2.98 \times 10^{-3}}(\hat{\alpha}_{Z\tilde{Z}} + \mathbf{5.53 \times 10^{-1}})^2$

For $\hat{\alpha}_{Z\tilde{Z}}$:
68% CL: $[-1.35 \times 10^{-2}, 1.24 \times 10^{-2}]$
95% CL: $[-2.62 \times 10^{-2}, 2.51 \times 10^{-2}]$



The results of ϕ-fitting is slight worse than those of the ω-fitting
- $\theta_1\ and\ \theta_2$ have less information.

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)

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]	$1P_{marg.}$

arXiv:1902.00134

In CEPC (fit to ω):

	$\tilde{c}_{Z\gamma}$	$\tilde{c}_{ZZ}$
68% CL(1σ)	$[-0.36, 0.35]$	$[-0.08, 0.07]$
95% CL(2σ)	$[-0.71, 0.70]$	$[-0.16\ \ 0.15]$

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 $\widehat{\alpha}_{A\tilde{Z}}$ and $\widehat{\alpha}_{Z\tilde{Z}}$.
- Result: 95% CL $\widehat{\alpha}_{A\tilde{Z}} \in [-8.27 \times 10^{-2}, 8.09 \times 10^{-2}]$ and $\widehat{\alpha}_{Z\tilde{Z}} \in [-2.15 \times 10^{-2}, 2.02 \times 10^{-2}]$

For future

- Increasing luminosity like $20ab^{-1}$.
- More processes such as $ZH \rightarrow e^{+}e^{-}H$.

- The sensitivities to new physics could be improved by about one order of magnitude.

Thank you!

Backup

Result compare --> Compared with HL-LHC

In HL-LHC: arXiv:1902.00134

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

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

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

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

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

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

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