Higgs CP measurement with EFT model in lepton collider

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Introduction

Standard Model Higgs: $m_H = 125.03GeV, J^{PC} = 0^{++}$

Related experiments in LHC:

- The hypothesis of spin-1 or spin-2 Higgs has been excluded by ATLAS and CMS at >99% CL in $\sqrt{s} = 7\&8$ TeV, 25fb-1 data.
- Totally CP-even Higgs also has been excluded, the CL depends on theory model (>95%).
- SM+BSM Higgs CP mixing model is still under testing.

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

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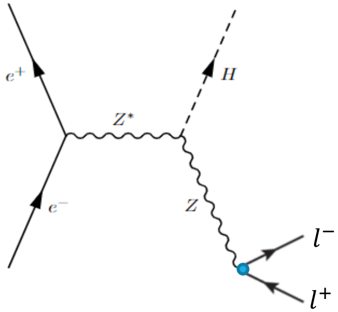
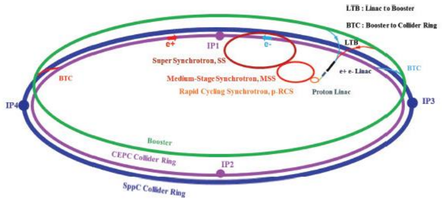
Any observation of CPV in Higgs would be New Physics!

Introduction

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

- $e^+e^- \to ZH$ process @ $\sqrt{s}\sim 240GeV$
- A opportunity for Higgs-gauge boson coupling study.

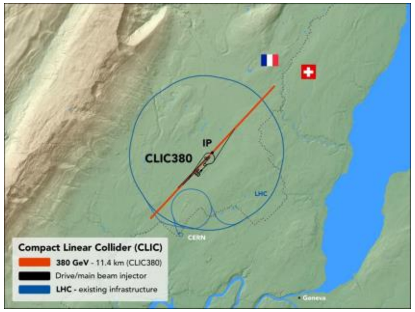




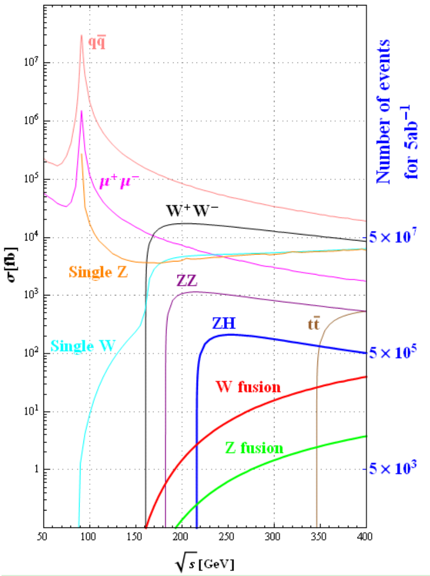
CEPC, 5.6 ab^{-1} @ 240GeV

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

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



CLIC, 380GeV for Higgs & top



Theory model

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

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

- So the $H \to Zll$ matrix element:

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

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

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

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

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

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

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

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

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

Red box: SM term

Others EFT contribution

Theory model

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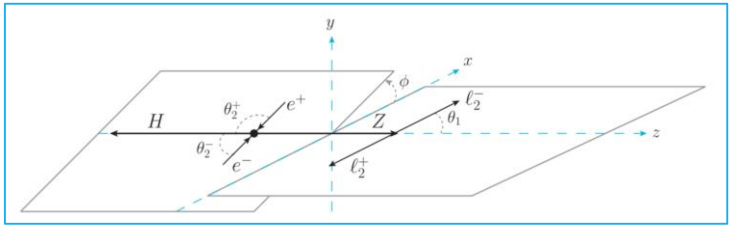
Assumption for simplification:

- $\delta_{G_F} = \hat{\alpha}_{\phi l}^{V} = \hat{\alpha}_{\phi l}^{A} = \hat{\alpha}_{A\tilde{Z}} = \hat{\alpha}_{Z\tilde{Z}} = 10^{-3}$,others are set to 0, so $H_{2,V/A} = 0$.

Differential cross section for $ee \to ZH \to llH$

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

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



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

Variables for studying distribution: θ_1, θ_2, ϕ

Theory model

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

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

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

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

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

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

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

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

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

0 in assumption

EFT CP-odd term

Others CP-even contribution

6 of these 9 functions art independent, CP-even and CP-odd terms are fully decoupled:

$$\frac{d\sigma}{dcos\theta_1 dcos\theta_2 d\phi} = N \times (J_{CP-even}(\theta_1, \theta_2, \phi) + J_{CP-odd}(\theta_1, \theta_2, \phi)).$$

Optimal variable approach

Cross section could be represent as: PLB 306（1993）411-417

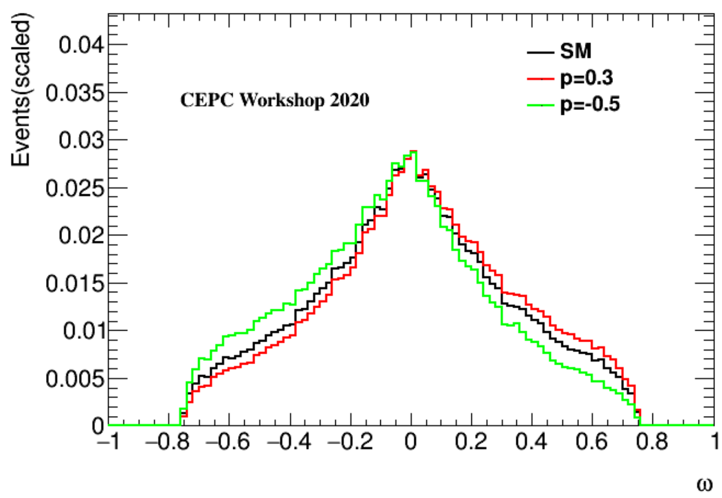
$$\frac{d\sigma}{dcos\theta_1 dcos\theta_2 d\phi} = N \times (J_{CP-even}(\theta_1,\theta_2,\phi) + p \times J_{CP-odd}(\theta_1,\theta_2,\phi)).$$

where p is an additional global CP-mixing parameter.

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

$$\omega = \frac{J_{CP-odd}(\theta_1,\theta_2,\phi)}{J_{CP-even}(\theta_1,\theta_2,\phi)}$$ to measure p

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



Higgs CP-mixing measurement

Preliminary test in CEPC condition https://arxiv.org/abs/1905.12903

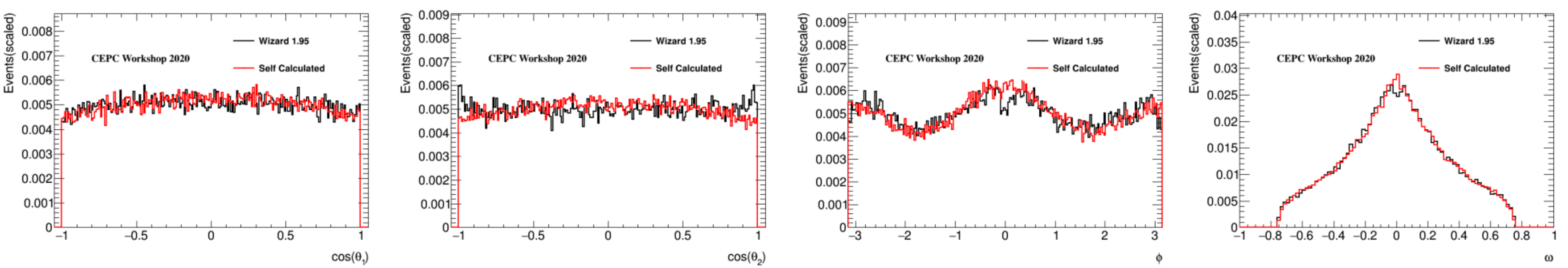
- $\sqrt{s} = 240GeV$, $\int Ldt = 5ab^{-1}$, $ee \to ZH \to \mu\mu bb$ channel.
- Irreducible SM background is not considered.
- Detector simulation and reconstruction, selection efficiency, flavor tagging efficiency are not considered. Perform this analysis in truth level.
- Event yields are not considered, only compare the distribution difference

$\mu^+\mu^- H \to \mu^+\mu^- + b\bar{b}/c\bar{c}/gg$ Channel					
	Signals	$\mu^+\mu^- H$ Background	Other Higgs Background	Irreducible Background	Other SM Background
Original	2.45×10^4	1.10×10^4	1.01×10^6	1.05×10^6	4.96×10^8
Lepton pair selection without recoil mass cut	1.51×10^4	6.56×10^3	227	1.09×10^4	2.79×10^4
Jets pair selection and lepton pair recoil mass cut for fit region	1.32×10^4	1.80×10^3	108	7.75×10^3	43.6
Signal Region	1.31×10^4	1.80×10^3	96.1	5.78×10^3	38.4
$e^+e^- H \to e^+e^- + b\bar{b}/c\bar{c}/gg$ Channel					
	Signals	$e^+e^- H$ Background	Other Higgs Background	Irreducible Background	Other SM Background
Original	2.63×10^4	1.17×10^4	1.01×10^6	1.62×10^6	4.95×10^8
Lepton pair selection without recoil mass cut	9.17×10^3	3.53×10^3	128	9.00×10^3	7.11×10^4
Jets pair selection and recoil lepton pair mass cut of fit region	7.14×10^3	917	56.1	8.63×10^3	69.4
Signal Region	7.13×10^3	913	36.4	4.14×10^3	67.4

Higgs CP-mixing measurement

Sample simulation

- Simulate $ee \rightarrow ZH \rightarrow llH$ decay chain in full phase space with TGenPhaseSpace
- The joint angular distribution is realized with accept-reject method by calculated differential cross section $\frac{d\sigma}{dcos\theta_1 dcos\theta_2 d\phi}$, and validate with official MC (Whizard 1.95 in CEPC, $ee \rightarrow ZH \rightarrow \mu\mu H$).
- All the parameters in EFT could be easily modified.
- Possible to switch to full simulation in future.

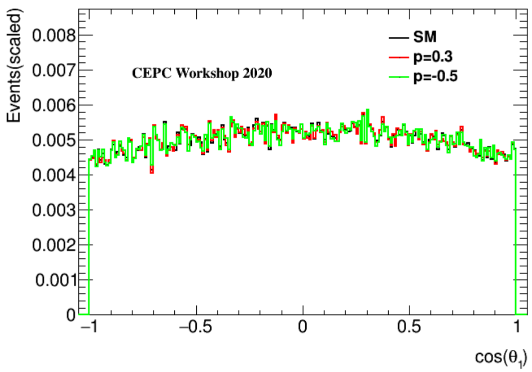


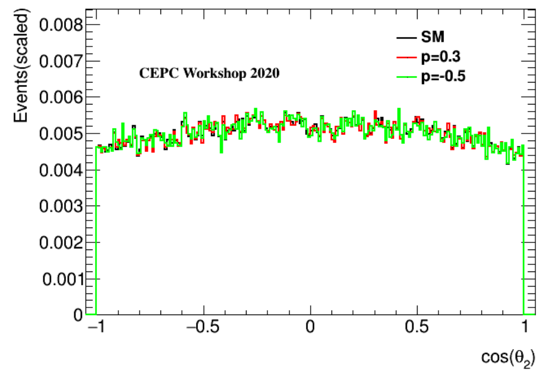
Distribution of $\cos\theta_1$, $\cos\theta_2$, ϕ, ω. $\cos\theta_2$ has some mismatch, but is not used in analysis (next page).

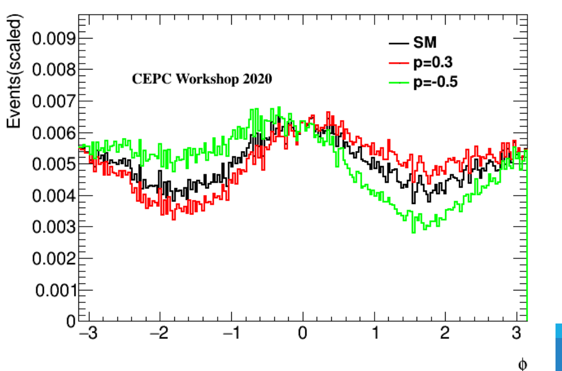
Higgs CP-mixing measurement

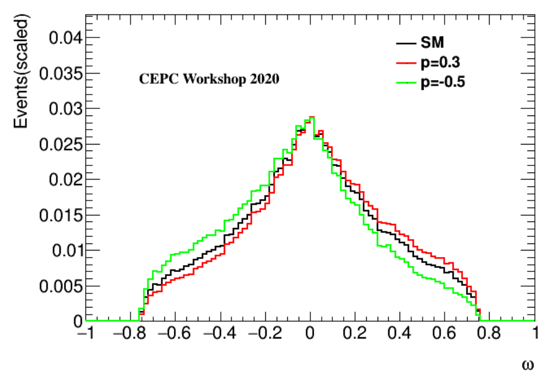
The CP-mixing would influence those variables

Parameters chosen for CP-mixing extraction: $\boldsymbol{\phi}, \boldsymbol{\omega}$. θ_1/θ_2 are not used due to low separation power.









Separation power:

$$< S^2 >= \frac{1}{2}\int \frac{(\hat{y}_s(y) - \hat{y}_b(y))^2}{\hat{y}_s(y) + \hat{y}_b(y)} dy.$$

SM vs. p=-0.5:

$cos\theta_1$: 1.3×10^{-4}

$cos\theta_2$: 1.8×10^{-4}

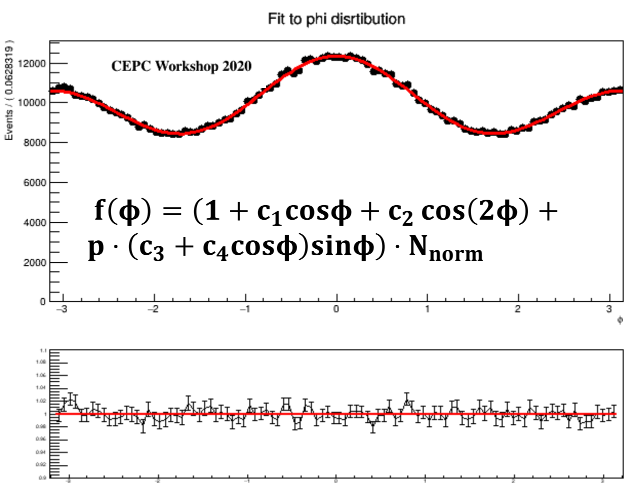
ϕ: 0.012

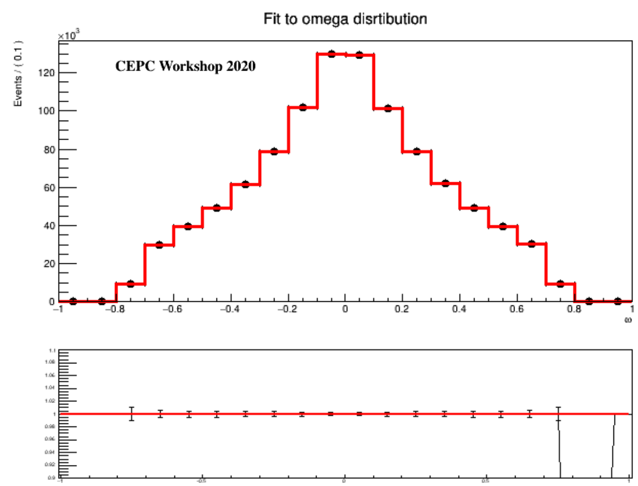
ω: 0.014

Higgs CP-mixing measurement

Fit strategy: Maximum-likelihood fit

- Use high statistic templates to remove statistics fluctuation (1M events).
- ϕ modelling: $f(\phi|\, p) = \int \frac{d\sigma}{dcos\theta_1 dcos\theta_2 d\phi} dcos\theta_1 dcos\theta_2$
- ω modelling: Histogram pdf.
- Evaluate likelihood function for each p value hypothesis, and construct a ΔNLL (Negative Log Likelihood) as a function of p.

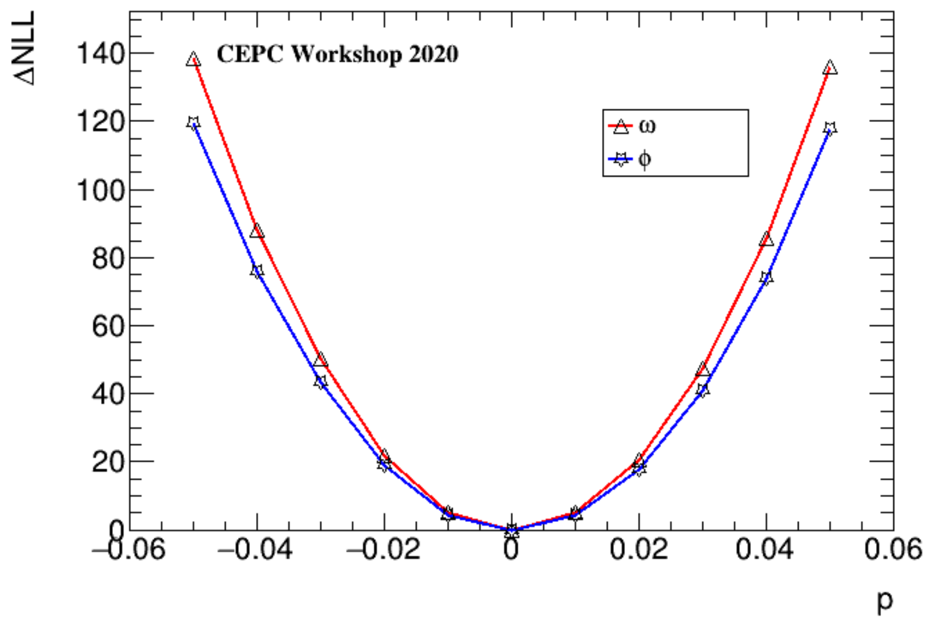




Higgs CP-mixing measurement

Extract maximum-likelihood fit p-value and interval

- Fit ΔNLL curve with a quadratic function $\Delta NLL(p) = a \cdot (p - p_0)^2$
- 68%(95%) CL interval corresponds to ΔNLL=0.5(1.96).
- Expect limit for SM (no statistics fluctuation in shape).



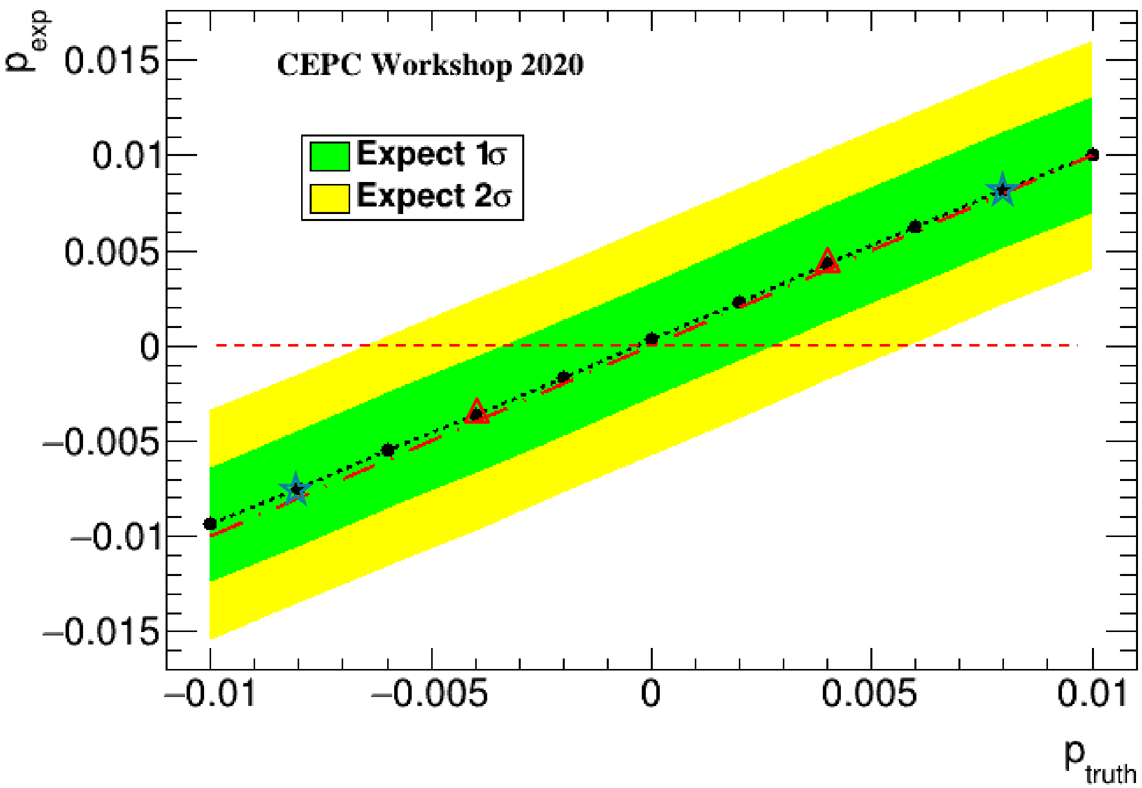
$$\boldsymbol{\Delta NLL(p|\omega) = 54164(p - 3\times 10^{-4})^2}$$
$$\boldsymbol{\Delta NLL(p|\phi) = 46779(p - 3\times 10^{-4})^2}$$

For ω:
68% CL: $[-2.72\times 10^{-3}, 3.35\times 10^{-3}]$
95% CL: $[-5.70\times 10^{-3}, 6.33\times 10^{-3}]$

For ϕ:
68% CL: $[-2.97\times 10^{-3}, 3.57\times 10^{-3}]$
95% CL: $[-6.17\times 10^{-3}, 6.78\times 10^{-3}]$

Higgs CP-mixing measurement

For other CP-mixing p hypothesis, a similar result could be derived with ω



△ 1σ exceed beyond SM

☆ 2σ exceed beyond SM

A bit shift in input truth p and measured p. Needs some further understanding.

Summary and conclusion

A 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 ϕ and ω distribution to extract p, while event yield is not considered.
- Result: 95% CL $p \in [-5.70 \times 10^{-3}, 6.33 \times 10^{-3}]$, corresponding to $\delta G_F, \hat{\alpha}_{\phi l}^{V}, \hat{\alpha}_{\phi l}^{A}, \hat{\alpha}_{A\tilde{Z}}, \hat{\alpha}_{Z\tilde{Z}} < 10^{-6}$.

Remaining problem and next plan:

- Fluctuation is not considered. Shape modelling would introduce the dominant uncertainty in the future real high energy ee collider experiment.
- Include the background processes, consider full simulation.
- A matrix element based Optimal Observable might provide better significance in CP test.