Higgs CP measurement with EFT model in lepton collider

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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 ATLAS and CMS at >99% CL in $\sqrt{s} = 7\&8$ TeV, 25fb-1 data.
- SM+BSM Higgs CP mixing model is still under testing.

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

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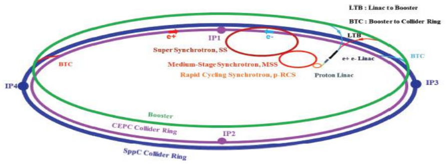
Any observation of CPV in Higgs would be New Physics!

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

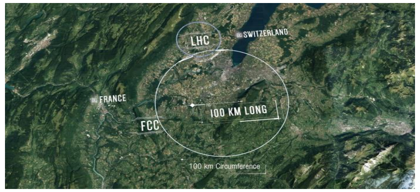
Introduction

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

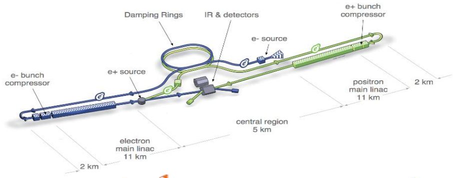
- At a center of mass energy of $\sqrt{s}\sim 240GeV$ which maximizes the Higgs boson production cross section through $e^+e^- \rightarrow ZH$ process.
- Cleaner environment and more events produced than (HL)-LHC.
- More precise Higgs-gauge boson coupling study.



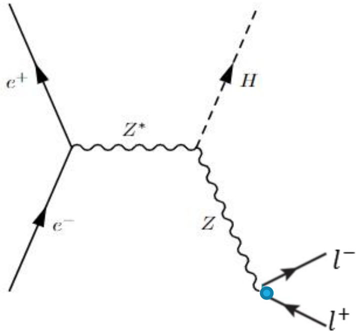
CEPC, 5.6 ab^{-1} @ 240GeV

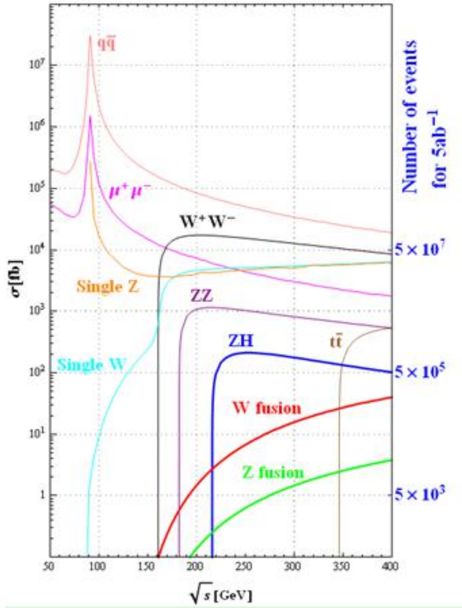


FCC-ee, 5 ab^{-1} @240GeV



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





Theory model

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

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

Theory model

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

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:

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

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

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

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

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

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

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

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

(red box) **: SM term**

Others : EFT contribution

Theory model

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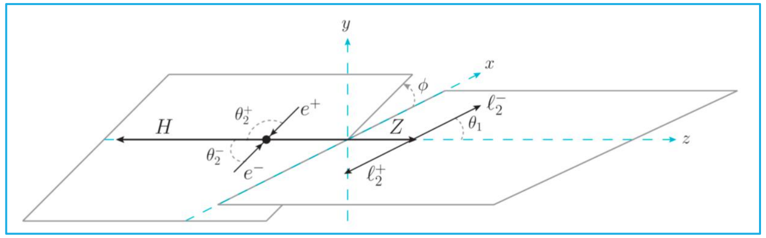
Differential cross section for $ee \to ZH \to llH$:

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

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



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

Variables for studying distribution: θ_1, θ_2, ϕ

Theory model

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

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

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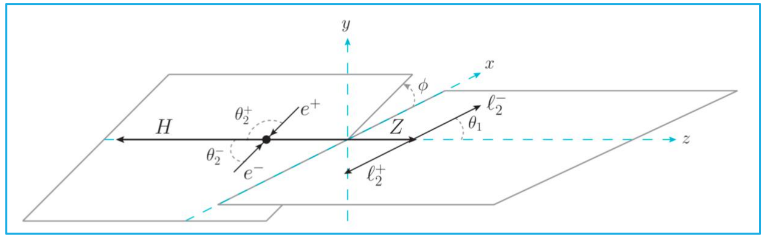


$$\begin{aligned}\mathcal{J}(q^2,\theta_1,\theta_2,\phi) = & J_1(1+\cos^2\theta_1\cos^2\theta_2+\cos^2\theta_1+\cos^2\theta_2) \\ & + J_2\sin^2\theta_1\sin^2\theta_2 + J_3\cos\theta_1\cos\theta_2 \\ & + (J_4\sin\theta_1\sin\theta_2 + J_5\sin 2\theta_1\sin 2\theta_2)\sin\phi \\ & + (J_6\sin\theta_1\sin\theta_2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

Variables for studying distribution: θ_1, θ_2, ϕ

Assumption for simplification:

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

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

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

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

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

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

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

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

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

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

6 of these 9 functions are independent

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

Optimal variable approach

PLB 306（1993）411-417

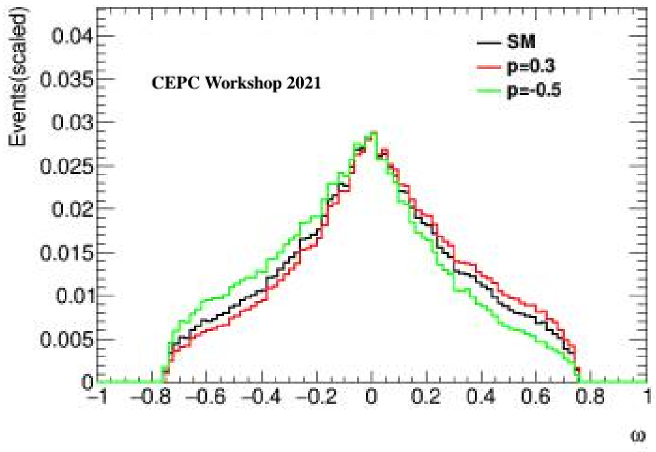
Differential cross section could be represent as:

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

where p is an additional global CP-mixing parameter.

In this formation, we could define an Optimal Variable ω 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



Benefits:

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

Previous review

Previous Result : 95% CL $p \in [-5.70 \times 10^{-3}, 6.33 \times 10^{-3}]$, corresponding to $\delta G_F, \hat{\alpha}_{\phi l}^{V}, \hat{\alpha}_{\phi l}^{A}, \hat{\alpha}_{A\tilde{Z}}, \hat{\alpha}_{Z\tilde{Z}} < 10^{-6}$. Higgs CP measurement analyses

Previous comment: not consider the decay modes of Higgs & study on truth level.

Update: consider simulation and Higgs decay to $b\bar{b}/c\bar{c}/gg$.

MC: Whizard 1.95 in CEPC, $ee \to ZH \to \mu\mu H$.

Two samples:

- Simulation: fast simulation based on CEPC-v4 detector design
- Truth level: simulate the physical process of $ee \to ZH$ directly in dynamics

Higgs CP-mixing measurement

Event selection: (using Monte Carlo simulation sample)

- $\sqrt{s} = 240GeV, \int Ldt = 5.6ab^{-1}$
- **Signal**: $ee \to ZH \to \mu\mu H(\to b\bar{b}/c\bar{c}/gg)$ channel
- **Background**: Irreducible background which contains the same final states as that in signal.

- Muon pair selection:

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

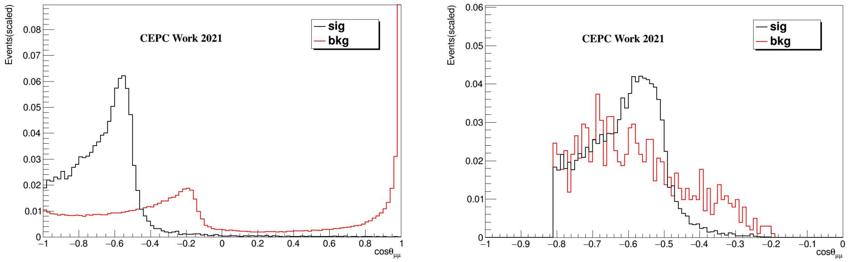
Where $M^2_{recoil\_\mu\mu} = (\sqrt{s} - E_{\mu\mu})^2 - p^2_{\mu\mu} = s - 2E_{\mu\mu}\sqrt{s} + m^2_{\mu\mu}$

- Jets pair selection:

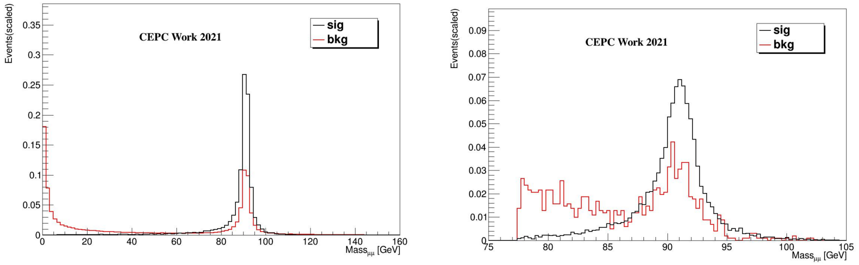
$|cos\theta_{jet}| < 0.96$; Mass$_{jj}$ ϵ (100GeV, 150GeV).

Higgs CP-mixing measurement

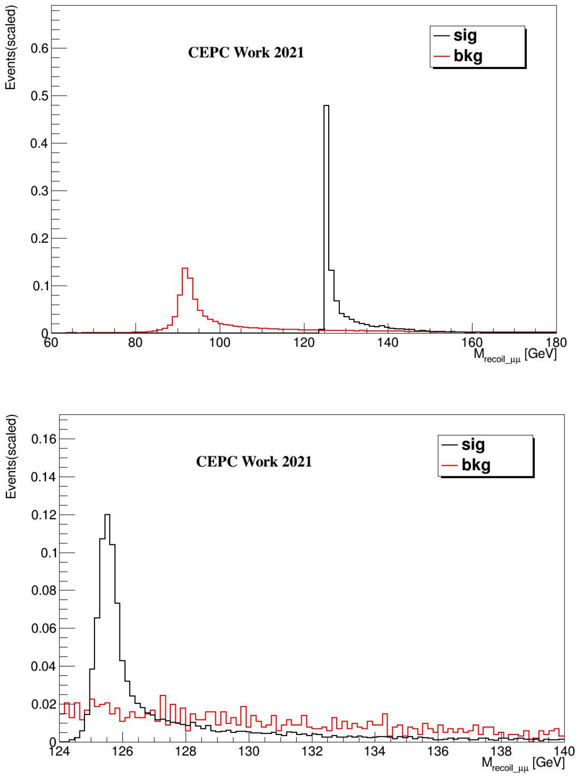
$|cos\theta_{\mu\mu}|<0.81$



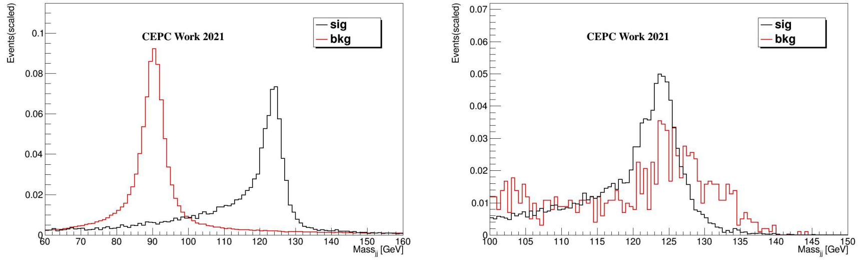
$\text{Mass}_{\mu\mu}\ \epsilon\ (77.5GeV, 104.5GeV)$



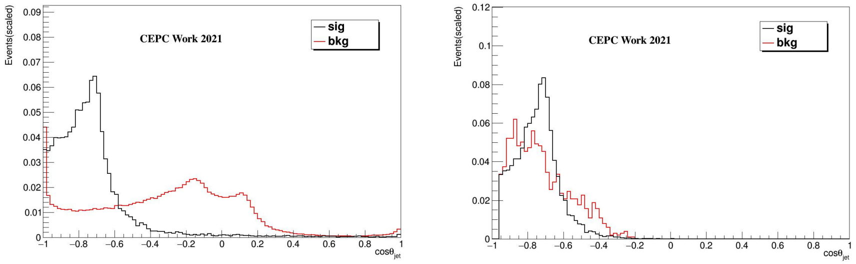
$M_{recoil\_\mu\mu}\ \epsilon\ (124GeV, 140GeV)$



$\text{Mass}_{jj}\ \epsilon\ (100GeV, 150GeV)$



$|cos\theta_{jet}|<0.96$



Higgs CP-mixing measurement

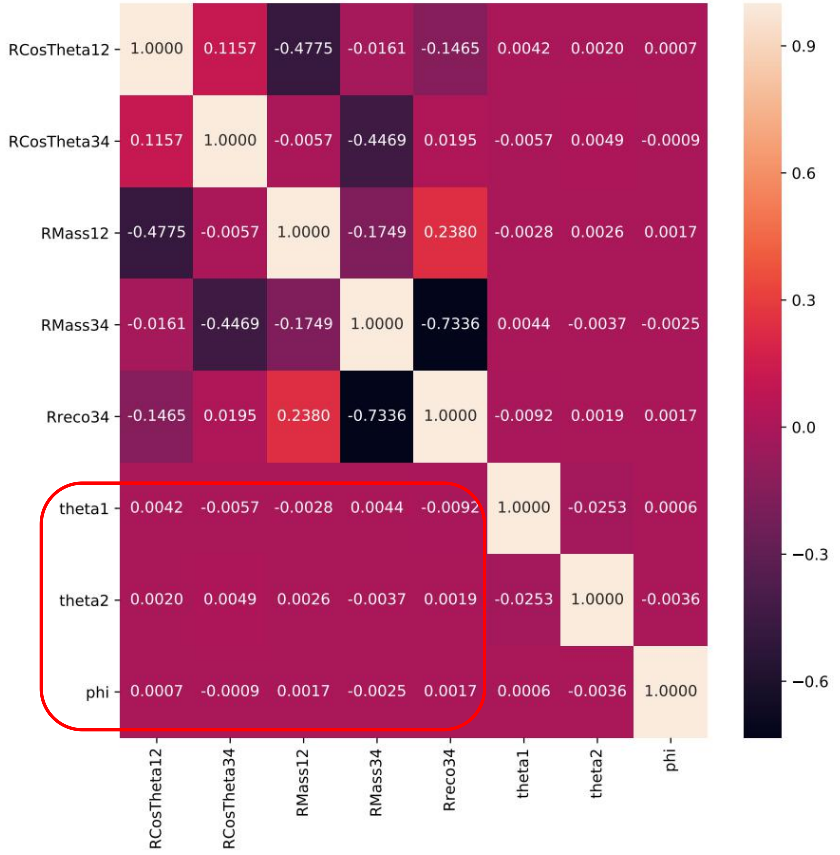
Cut Flow:

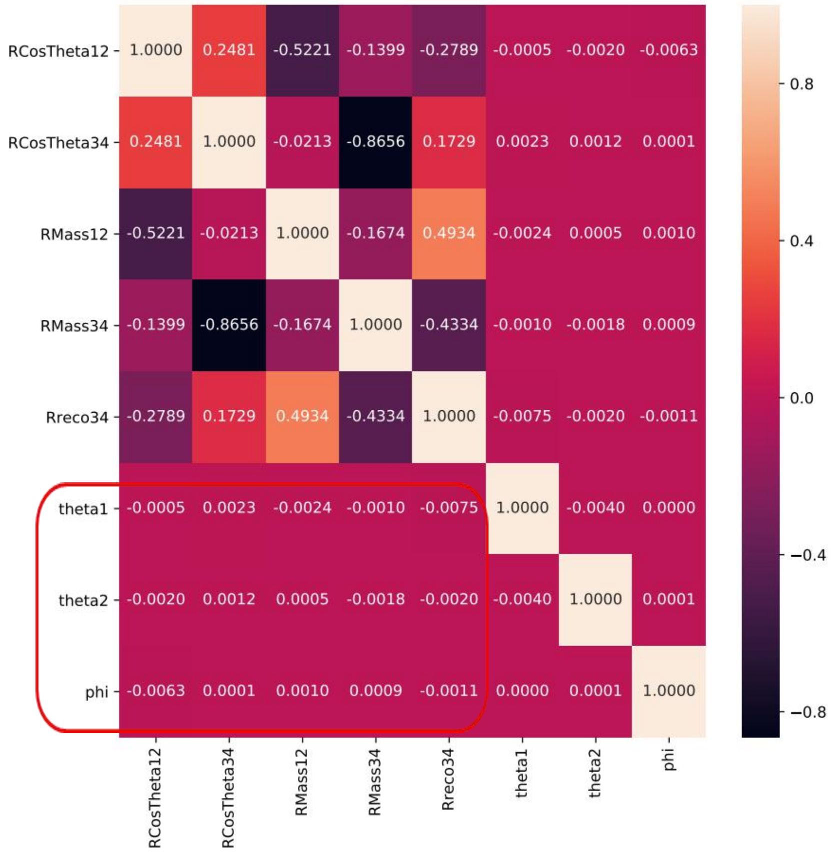
$ZH \to \mu^+\mu^- + b\bar{b}/c\bar{c}/\tau\tau/gg$ channel		
	Signal	Irreducible Background
Original	28627	1251768
Muon pair selection	18420(efficiency:64.82%)	11370(efficiency:0.91%)
All selection	13312(efficiency:46.83%)	3610(efficiency:0.29%)

Higgs CP-mixing measurement

Correlation:

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



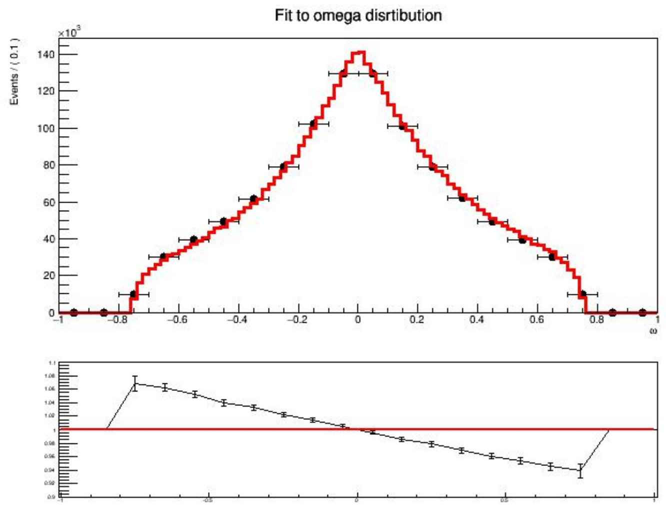


- So we can ignore the impact of event selections to $\theta_1, \ \theta_2, and \ \phi$.

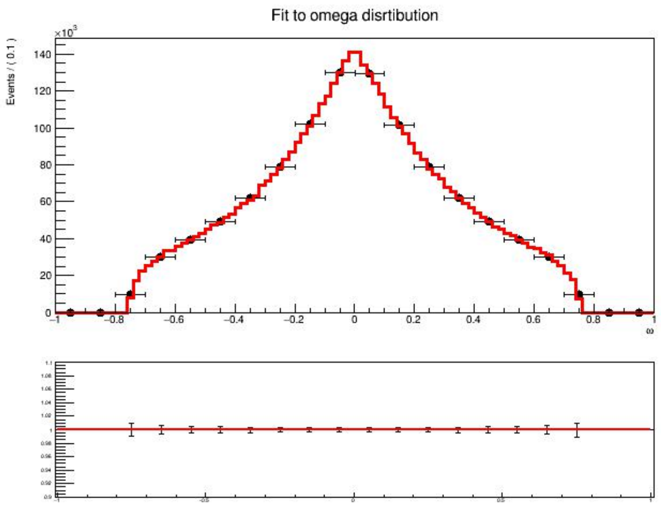
Higgs CP-mixing measurement

Fit strategy: Maximum-likelihood fit

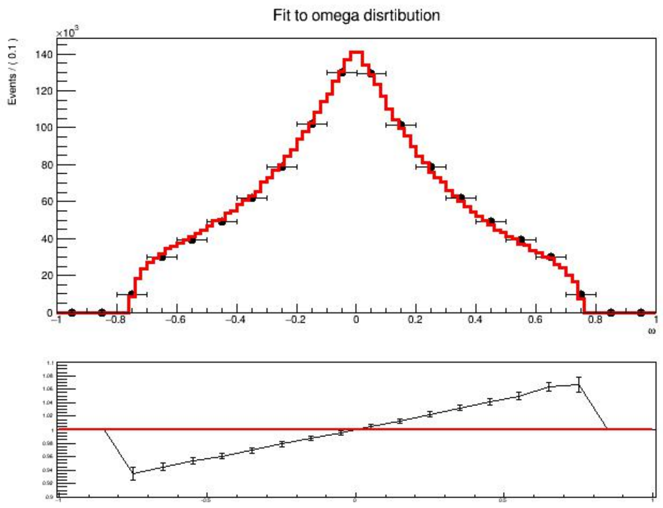
- $f^{p}(\omega) = N_{sig} * f_{sig}^{p}(\omega) + N_{bkg} * f_{bkg}^{p}(\omega)$
- **Fit ω to get $f_{sig}^{p}(\omega)$ and $f_{bkg}^{p}(\omega)$**
- **Fit $M_{recoil\_\mu\mu}$ to get N_{sig} and N_{bkg}**
- Evaluate likelihood function for each p value hypothesis, and construct a ΔNLL as a function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



P= 0.09 compare p= 0



P= 0 compare p= 0



P= -0.09 compare p= 0

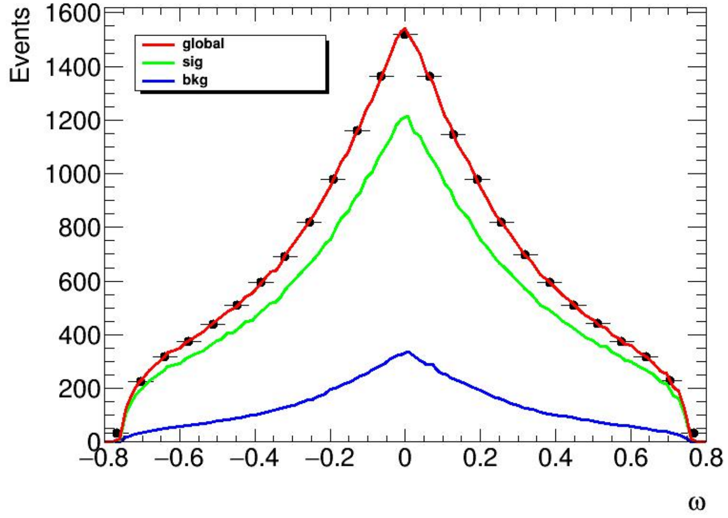
Higgs CP-mixing measurement

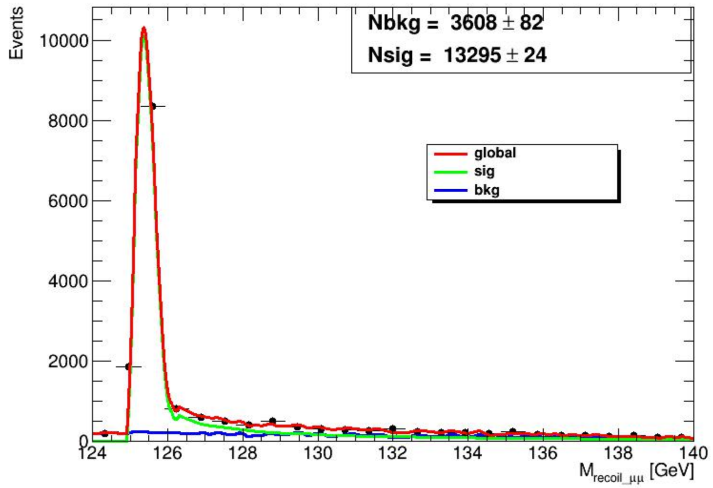
Fit ω :

- 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 $M_{recoil\_\mu\mu}$:

- Use histogram pdf to fit the $M_{recoil\_\mu\mu}$ of signal(the signal is **on truth level** after **doing the smear to simulate detector error** and **considering the ISR** to simulate the small exponential tail).
- The $M_{recoil\_\mu\mu}$ distribution of the combinatorial background (dominated by the $e^+e^- \to ZZ \to llq\bar{q}$) is modeled by a second order polynomial.

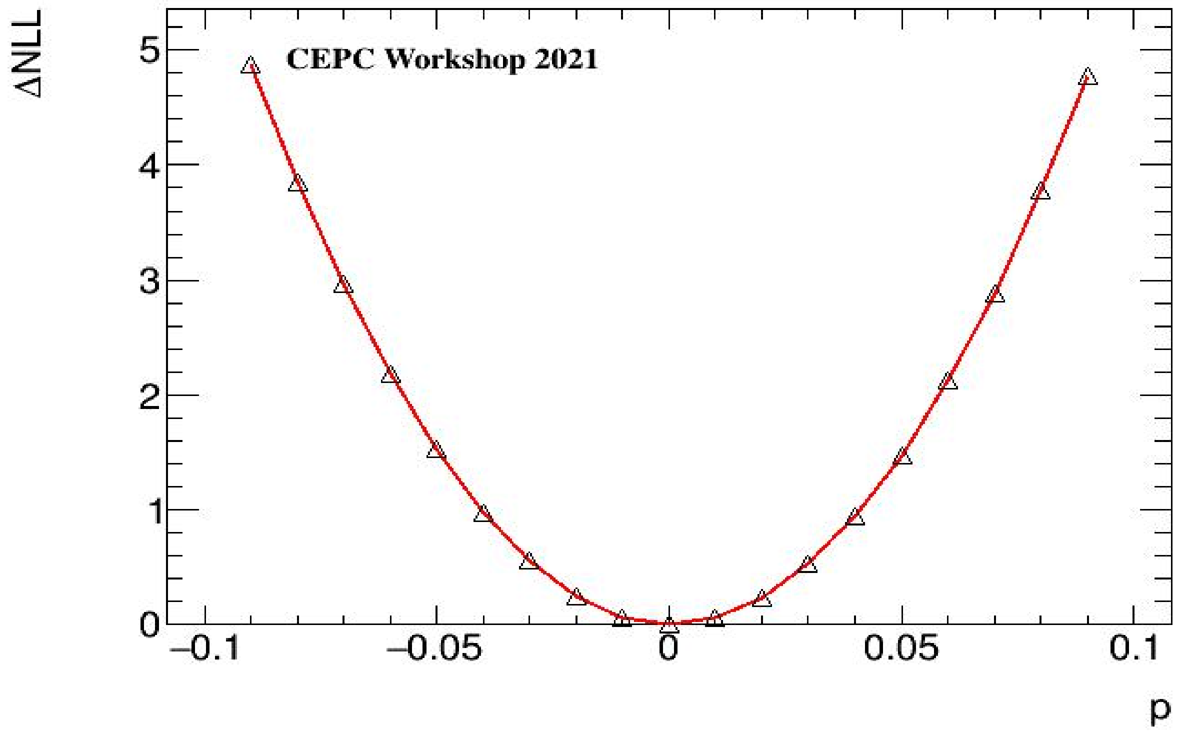




Higgs CP-mixing measurement

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).



$$\boldsymbol{\Delta NLL(p|\omega) = 595.4(p - 4.2 \times 10^{-4})^2}$$

For ω:
68% CL: $[-2.9 \times 10^{-2}, 2.9 \times 10^{-2}]$
95% CL: $[-5.7 \times 10^{-2}, 5.7 \times 10^{-2}]$

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 distribution to extract p.
- Result: 95% CL $p \in [-5.7 \times 10^{-2}, 5.7 \times 10^{-2}]$, corresponding to $\delta G_F, \hat{\alpha}_{\phi l}^{V}, \hat{\alpha}_{\phi l}^{A}, \hat{\alpha}_{A\tilde{Z}}, \hat{\alpha}_{Z\tilde{Z}} < 10^{-5}$.

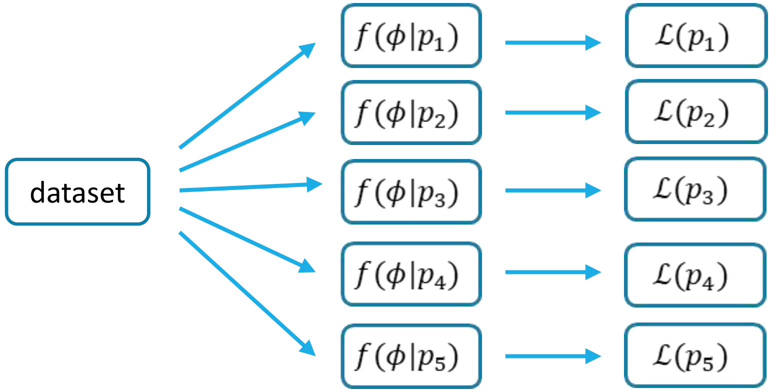
Backup

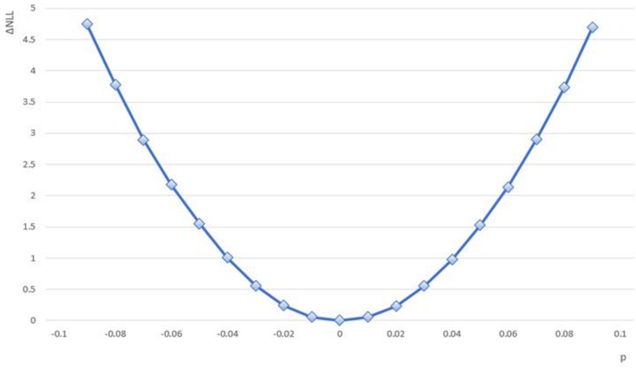
Maximum likelihood fit

Construct a likelihood function

- $\mathcal{L}(\vec{x}|p,\vec{\theta}) = \prod_{data} f(x_i\,|p,\vec{\theta})$

  $\vec{\theta}$: nuisance parameter. p: POI, CP-mixing parameter. x_i: dataset (ω).
- When statistics is large enough, we suppose $\mathcal{L}(\vec{x}|p,\vec{\theta}) \sim Gaus(\hat{p},\sigma_p^2)$, so $ln\mathcal{L}(p) = ln\mathcal{L}_{max} - \frac{1}{2}\left(\frac{p-\hat{p}}{\sigma_p}\right)^2$
- From $\Delta NLL = NLL - NLL_{\min}$ (negative log likelihood) we can extract maximum likelihood estimate $\hat{p}$ and its CL interval.

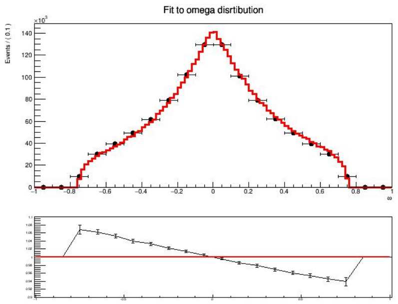




Maximum likelihood fit

Sample modelling

- ω modelling: Histogram pdf. Highly depends on the sample statistics used to build histogram and HistPdf.



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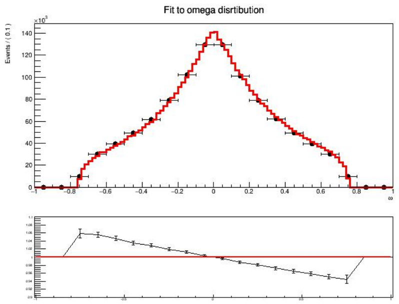

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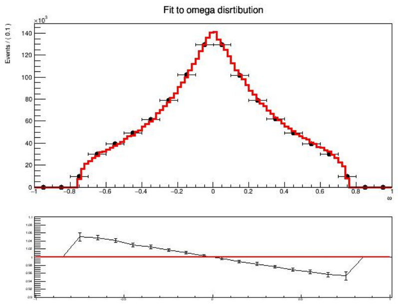

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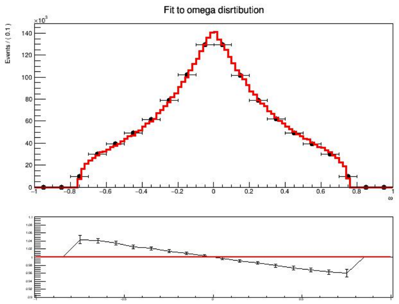

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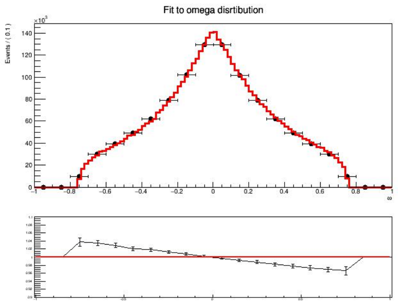

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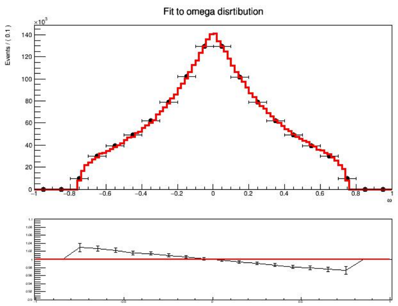

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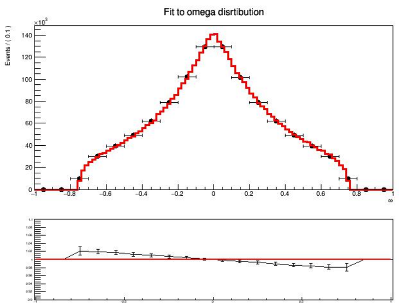

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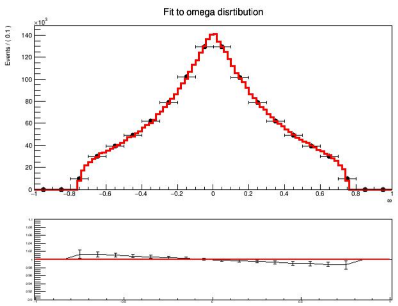

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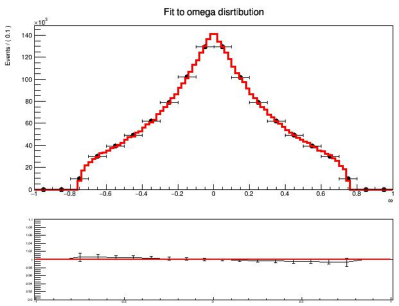

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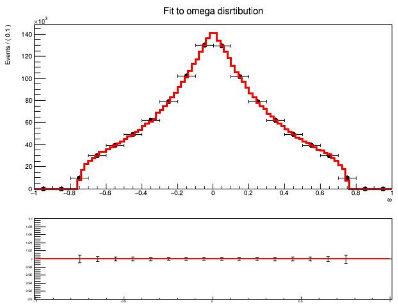

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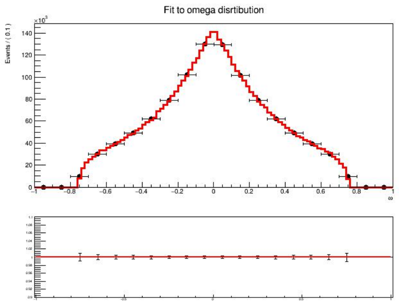
Maximum likelihood fit

Sample modelling

- ω modelling: Histogram pdf. Highly depends on the sample statistics used to build histogram and HistPdf.



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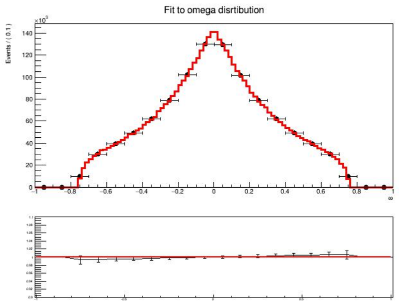

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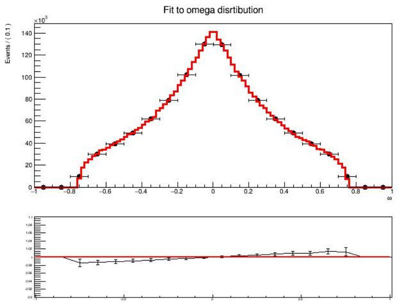

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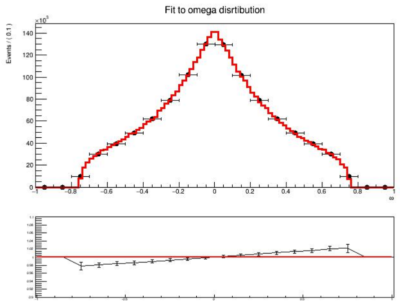

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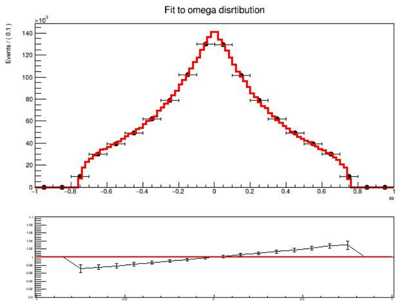

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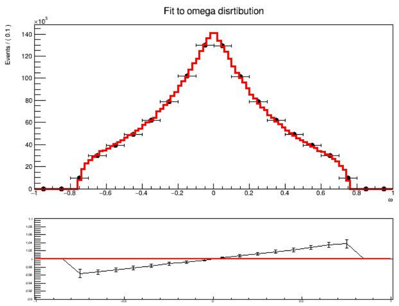

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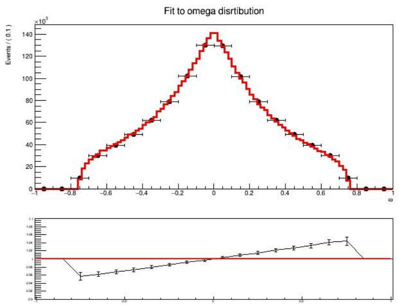

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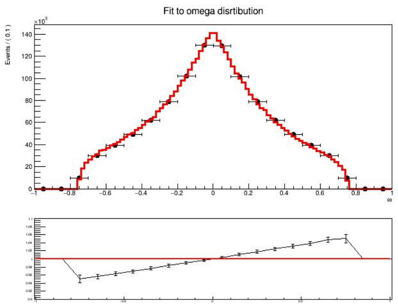

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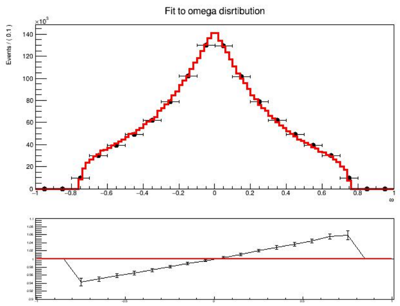

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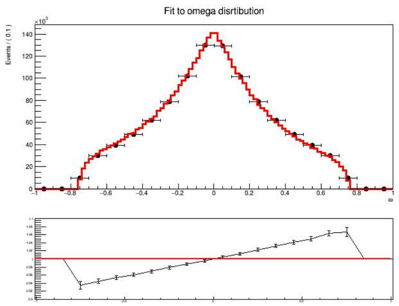

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