CPV mixing angle measurement in Higgs to $\tau\tau$ decays at 240 GeV CEPC

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Motivation - additional sources of CP violation

- CP violation is one of the three Sakharov conditions necessary in order to explain the matter-antimatter asymmetry observed in the Universe.
- The Standard Model provides sources of CP violation: CKM, PMNS matrices. However, the experimentally observed size of CP violation is insufficient to account for baryon asymmetry.

1. **Exploring CP violation in the Higgs sector could give an answer to the baryon asymmetry of the Universe as well as to provide a sign of a physics beyond the Standard Model.**
2. **One way of doing it is by measuring the shape effects on CP−sensitive observables.**
3. **A place to probe CPV in the Higgs sector are Higgs decays (and production) modes.**

- In the SM, the Higgs boson is a CP even state. In more general models, a Higgs mass eigenstate h_{125} can be a superposition of a scalar (CP-even) state H and a pseudoscalar (CP-odd) state A, via a mixing angle ψ_{CP}:

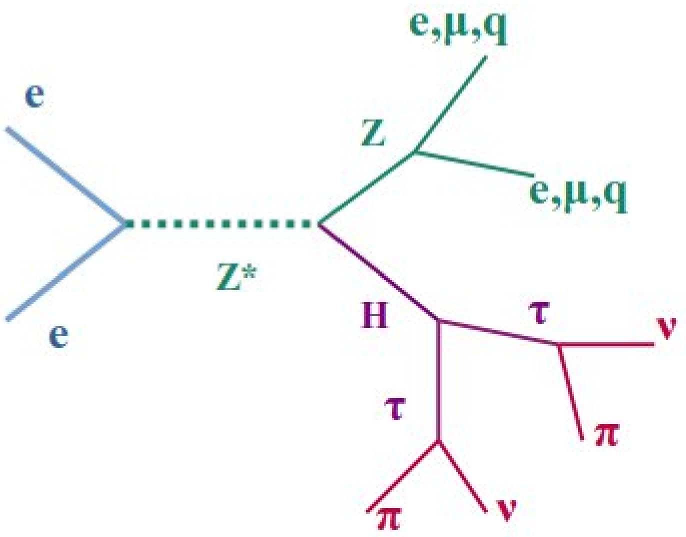
$$h_{125} = H \cdot cos(\psi_{CP}) + A \cdot sin(\psi_{CP})$$

- The CP mixing angle is determined by measuring Higgs decays to τ-pairs.

Processes of interest

SIGNAL

- Higgsstrahlung (HZ) at 240 GeV, σ_{HZ} = 196.9 fb
- $Z \rightarrow l^+l^-$, $H \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^- + E_{miss}$ – leptonic channel
- $Z \rightarrow q\bar{q}$, $H \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^- + E_{miss}$ – hadronic channel
- 5.6 ab^{-1} of integrated luminosity

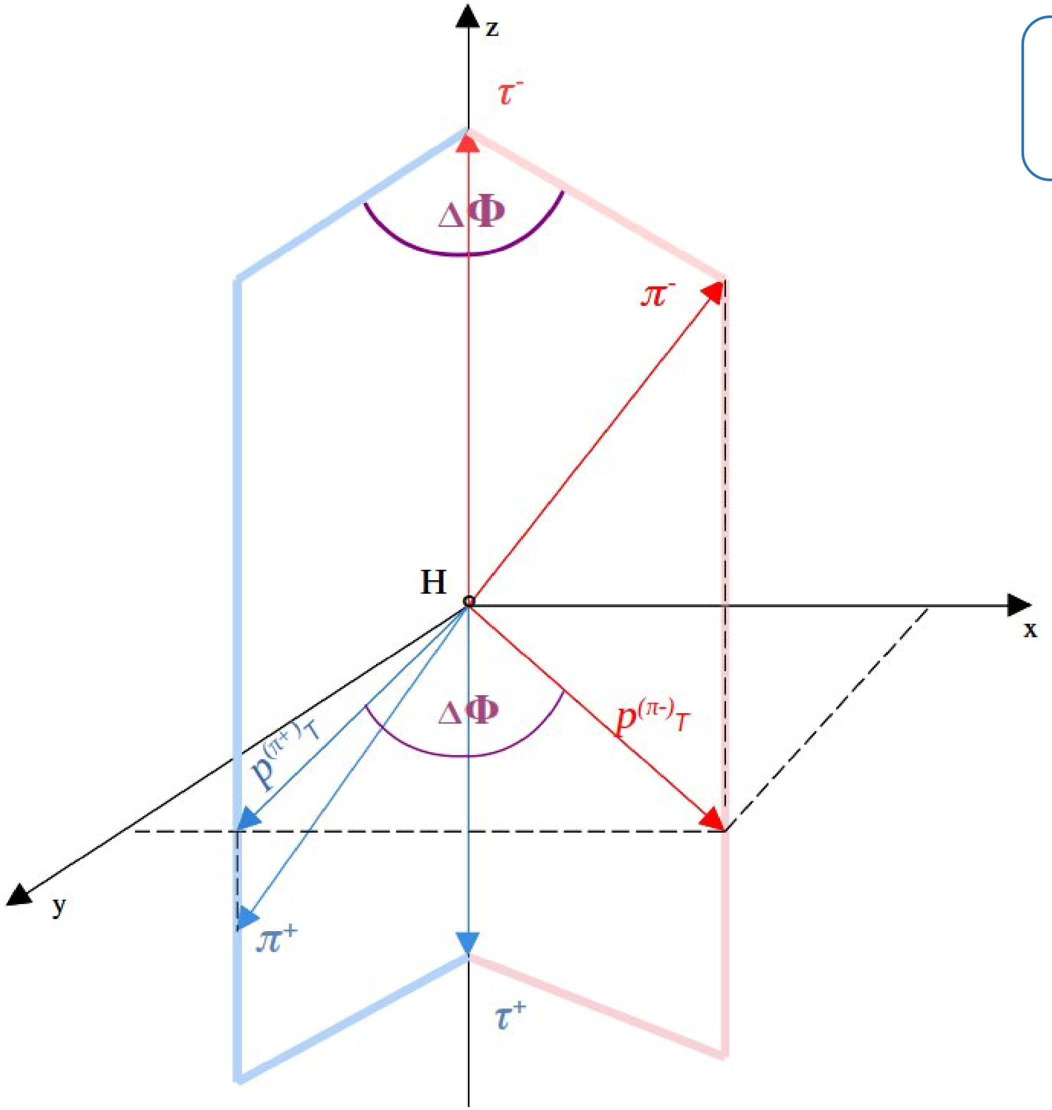


Feynman diagram of the signal process

- **WHIZARD 3.1.4** event generator.
- **PYTHIA 8.3** was used to model Final State Radiation (FSR), hadronize quarks, and decay τ leptons.
- **Delphes 3.5.0**, a fast simulation framework, with the detector response modeled using the CEPC detector card. The anti-k_T (AKT) algorithm was used for jet clustering.

240 GeV	Expected in 5.6ab^{-1}	Simulated (DELPHES)
Signal: $ee \rightarrow HZ$; $Z \rightarrow ll$; $H \rightarrow \tau\tau \rightarrow \pi\nu\pi\nu$	56	100 267
Signal: $ee \rightarrow HZ$; $Z \rightarrow qq$; $H \rightarrow \tau\tau \rightarrow \pi\nu\pi\nu$	560	102 348
llH; $H \rightarrow others$	$1.1 \cdot 10^5$	$2.7 \cdot 10^6$
qqH; $H \rightarrow others$	$7.6 \cdot 10^5$	$9 \cdot 10^5$
$2f$	$5 \cdot 10^9$	$9.4 \cdot 10^6$
$4f$	$1.13 \cdot 10^8$	$8.3 \cdot 10^6$
S/B ~ 10^{-8}		

CP−Sensitive Observable ΔΦ



ΔΦ can be retrieved as the angle between the planes defined by taus' decay products.

Higgs rest frame, τ^- defines z-axis,
n_1, n_2 − unit vectors ⊥ to decay planes

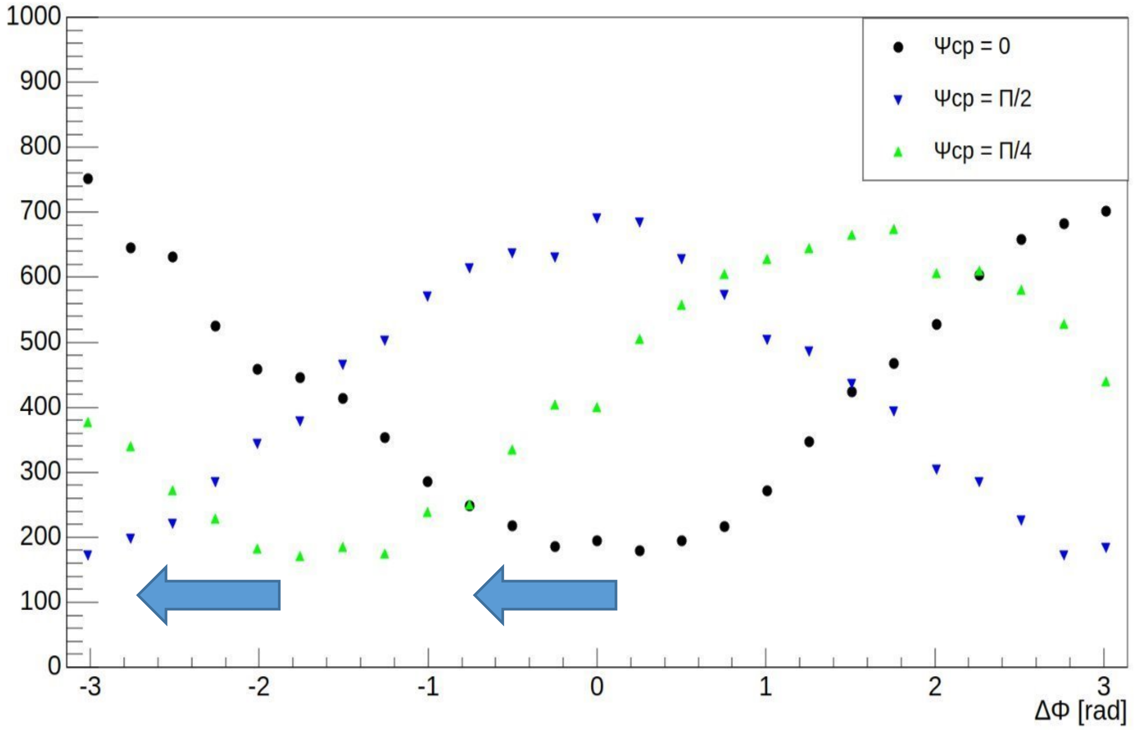
$$\Delta\Phi = \mathrm{sgn}(\sin(\phi)) \cdot \arccos(\cos(\phi))$$

$$\boldsymbol{\Delta\Phi = \begin{cases} \arccos(\cos(\phi)), & \sin(\phi) \geq 0 \\ 2\pi - \arccos(\cos(\phi)), & \sin(\phi) < 0 \end{cases}}$$

$$\cos(\phi) = p_T^{\pi^+} \cdot p_T^{\pi^-} = n_1 \cdot n_2$$

$$\sin(\phi) = \frac{p_{\tau^-} \cdot (p_T^{\pi^+} \times p_T^{\pi^-})}{\left| p_{\tau^-} \cdot (p_T^{\pi^+} \times p_T^{\pi^-}) \right|}$$

- *generator level WHIZARD V3.1.4*
- *PYTHIA V8.3 – tau decay + mixing angle*



Distribution of the CP-sensitive observable $\Delta\phi$ for different mixing ψ_{CP}

Minimum $\Delta\phi$ shifts for non-zero ψ_{CP}

Shape of the sensitive observable $\Delta\phi$ can be modeled with the function:

$$f(\Delta\phi, \psi_{CP}) = A + B \cdot \cos(\Delta\phi - 2 \cdot \psi_{CP})$$

ψ_{CP} can be measured
from the reconstructed $\Delta\phi$ distribution

Tau lepton reconstruction

- $H \to \tau^+\tau^- \to \pi^+\pi^- + E_{miss}$ ($Z \to l^+l^-$) is a rare process (56 evt. in 5.6 ab^{-1}) ➡ **requires precise and efficient reconstruction of tau leptons.**
- tau leptons are reconstructed using ***collinear approximation***.
- ***tau lepton and its visible decay product (a charged pion) are emitted collinearly.***
- ***This assumption, together with the conservation of the event transverse momentum, allows to determine the intensities of tau leptons' momenta.***

Equations are resolved to give the intensity of tau momentum:

$$\boxed{\begin{aligned} -p^x_{ff} &= \boldsymbol{p}_{\tau^-} \cdot a_1 + \boldsymbol{p}_{\tau^+} \cdot a_2 \\ -p^y_{ff} &= \boldsymbol{p}_{\tau^-} \cdot b_1 + \boldsymbol{p}_{\tau^+} \cdot b_2 \end{aligned}} \Rightarrow$$

$$p_{\tau^-} = \frac{p^x_{ff} \cdot b_2 - p^y_{ff} \cdot a_2}{a_2 \cdot b_1 - a_1 \cdot b_2}$$

$$p_{\tau^+} = \frac{p^x_{ff} \cdot a_1 - p^x_{ff} \cdot b_1}{a_2 \cdot b_1 - a_1 \cdot b_2}$$

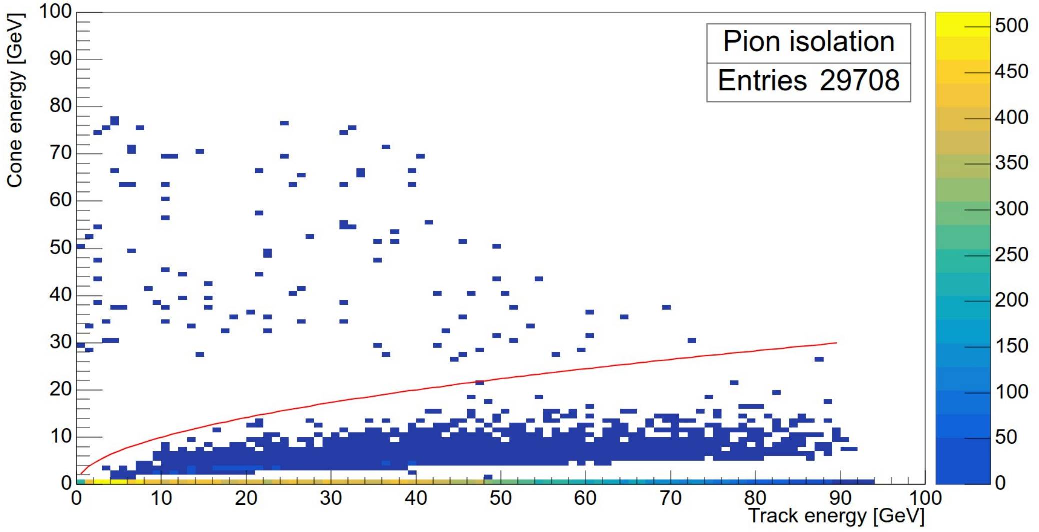
$$\begin{aligned} a_1 &= \sin\theta_{\pi^-} \cdot \cos\phi_{\pi^-} \\ a_2 &= \sin\theta_{\pi^+} \cdot \cos\phi_{\pi^+} \\ b_1 &= \sin\theta_{\pi^-} \cdot \sin\phi_{\pi^-} \\ b_2 &= \sin\theta_{\pi^+} \cdot \sin\phi_{\pi^+} \end{aligned}$$

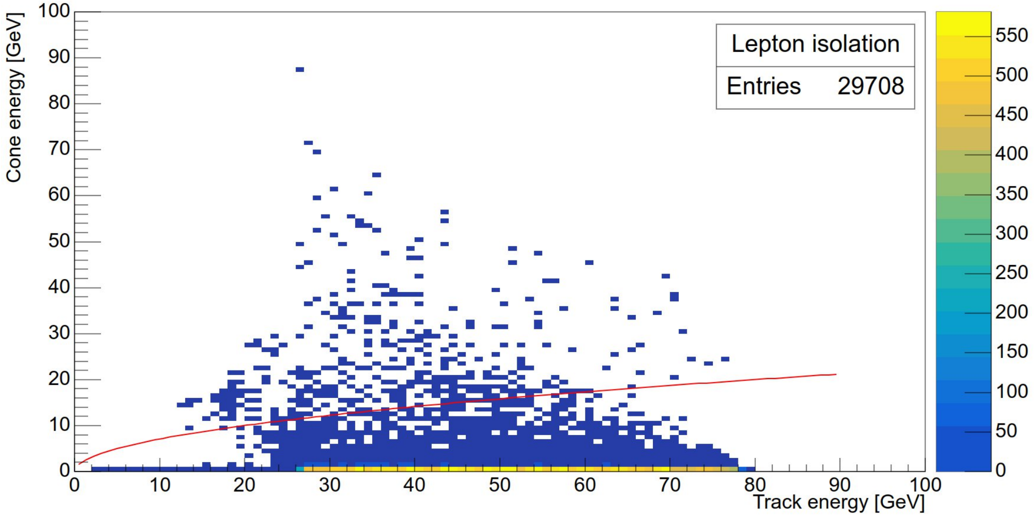
$p_{\tau^\pm}$ – momentum of reconstructed tau
$p^{x,y}_{ff}$ – momentum of Z^0 decay products
$\theta_{\pi^\pm}$, $\phi_{\pi^\pm}$ – polar and azimuthal angle of tau decay

Preselection - leptonic primary Z decays

Preselection:
- Identifies pions for reconstruction of taus' directions
- Suppresses high cross section backgrounds

- Pion isolation;
- Isolation of leptons from primary Z^0 decay;
- Selection cuts:
  - 60 GeV < m_{ll} < 110 GeV
  - 10 GeV < $m_{\tau\tau}$ < 240 GeV
  - 25 GeV < $p_{\tau^\pm}$ < 120 GeV
  - E_{miss} > 5 GeV





Pion isolation requires:

- 8-degree cone around the pion:

$$E_{cone} < \sqrt{AE_{track}^2 + BE_{track} + C}$$

$$m_{cone} < 2 \text{ GeV}$$

E_{cone} – cone energy, E_{track} – track energy, A = 0, B = 10, C = 0 – free parameters of the fit, m_{cone} – cone invariant mass

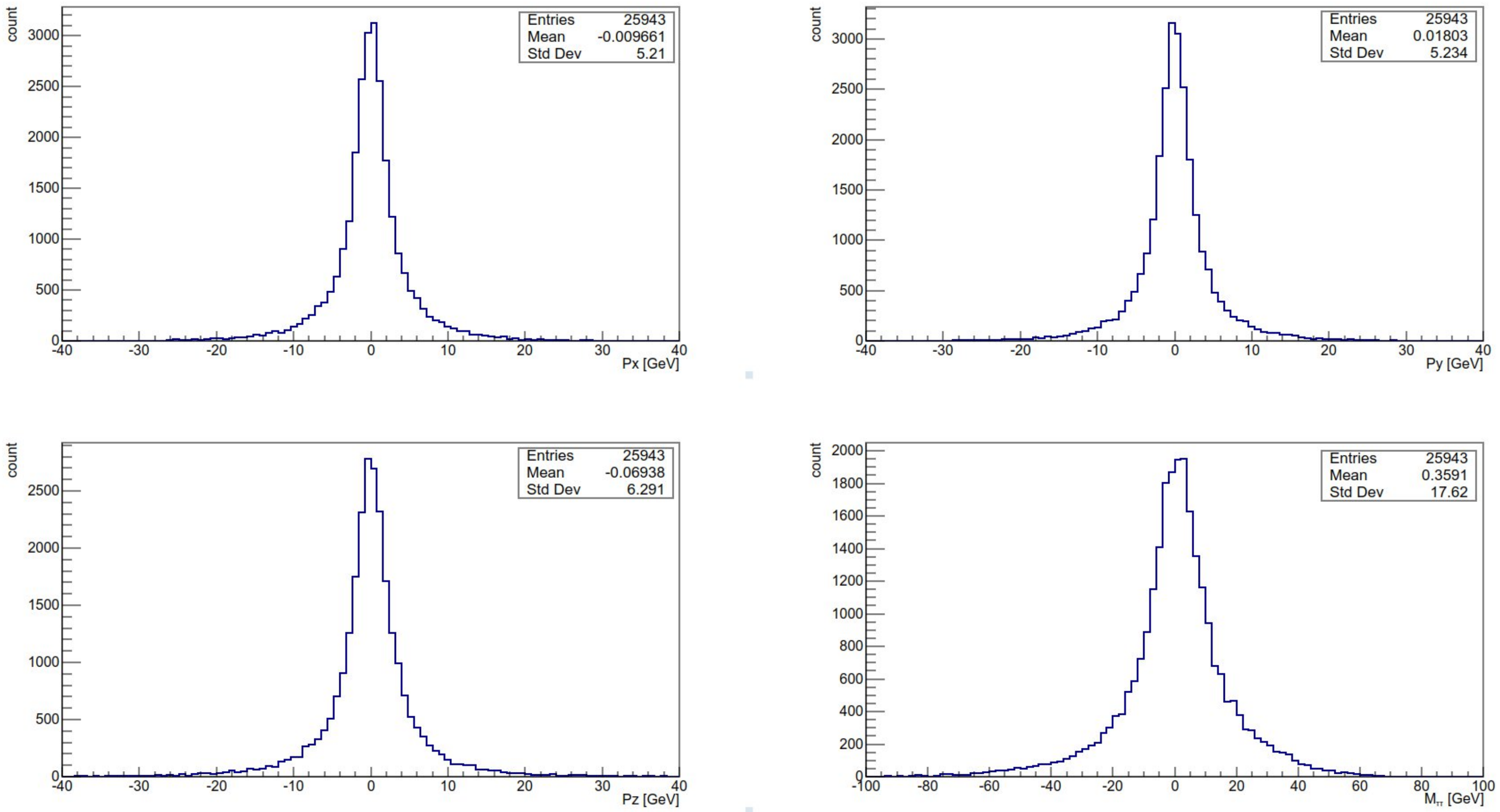
Lepton isolation requires:

- 6-degree cone around the lepton:

$$E_{cone} < \sqrt{AE_{track}^2 + BE_{track} + C}$$

E_{cone} – cone energy, E_{track} – track energy, A = 0, B = 5, C = 0 – free parameters of the fit

tau momentum reconstruction with the colinear approximation



tau momentum resolution (per component) : 6.5 GeV
tau lepton reconstruction efficiency: **86%**

Signal and background after preselection – leptonic Z decays

SIGNAL

Preselection efficiency: **85%**

240 GeV	Expected in $5.6 ab^{-1}$	Simulated	Events in $5.6\ ab^{-1}$
Signal: $ee \to HZ$; $Z \to ll$; $H \to \tau\tau \to \pi\nu\pi\nu$	56	85 462	47
llH; $H \to others$	$1.1 \cdot 10^5$	5 434	217
qqH; $H \to others$	$7.6 \cdot 10^5$	0	0
$2f$	$5 \cdot 10^9$	0	0
$4f$	$1.13 \cdot 10^8$	1 561	35 700

$S/B \sim 10^{-3}$

Corrective function for the collinear approximation

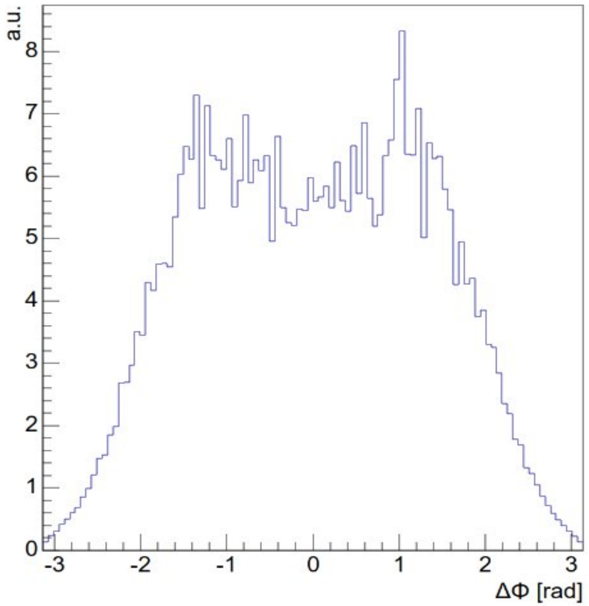
Correction applied to background will disturb its CP-flat shape

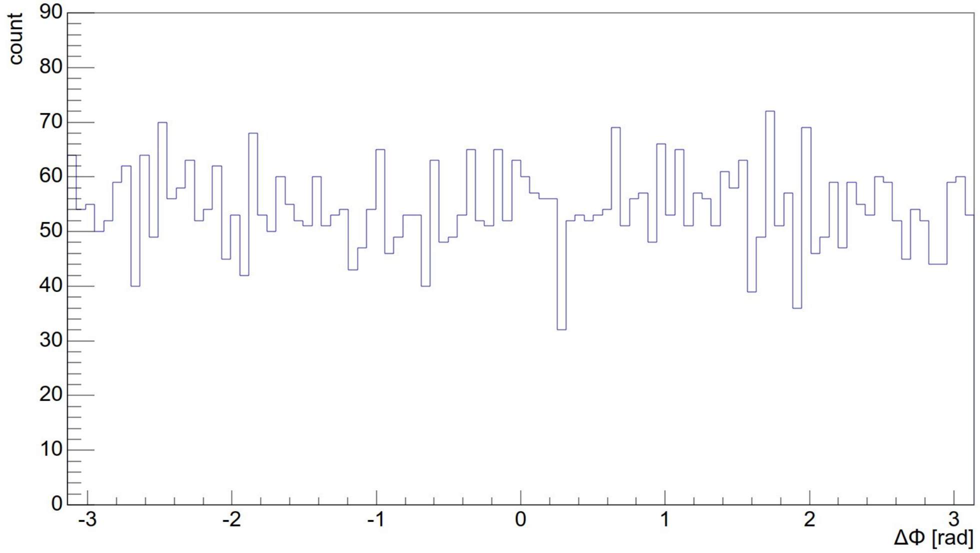
background must be maximally suppressed

The collinear approximation introduces a distortion in the shape of the sensitive observable

(tau direction is approximated with the reconstructed pion)

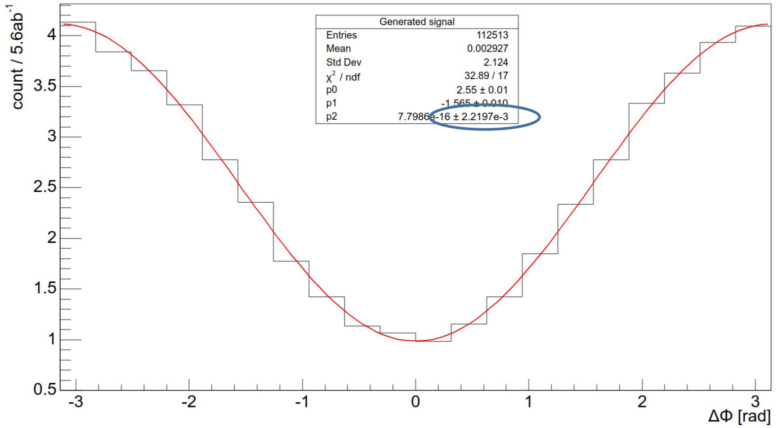
Correction function is determined in simulation





Angular observable ΔΦ, zero mixing (SM), no background – leptonic Z decays

Signal at the generator level:

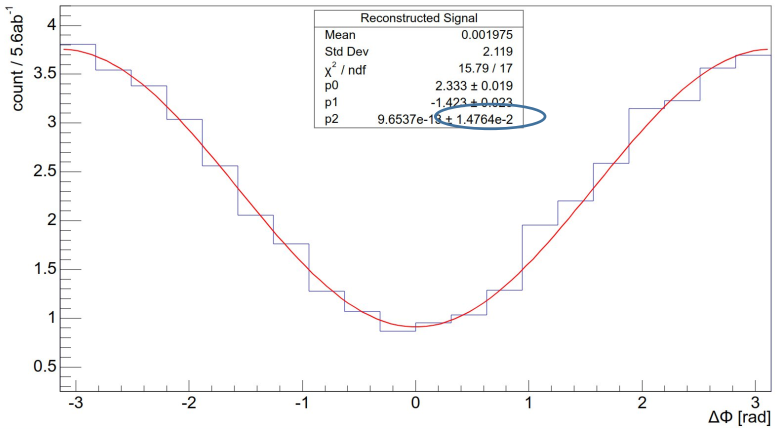


- Determine ψ_{CP} from fit with f (p_2 parameter) :

$$f(\Delta\phi, \psi_{CP}) = A + B \cdot \cos(\Delta\phi - 2 \cdot \psi_{CP})$$

Single fit at a **generator level** (pure signal) returns
ψ_{CP} = (0± **2**) mrad

Reconstructed signal after collinear approximation, preselection + correction for colinear approximation:

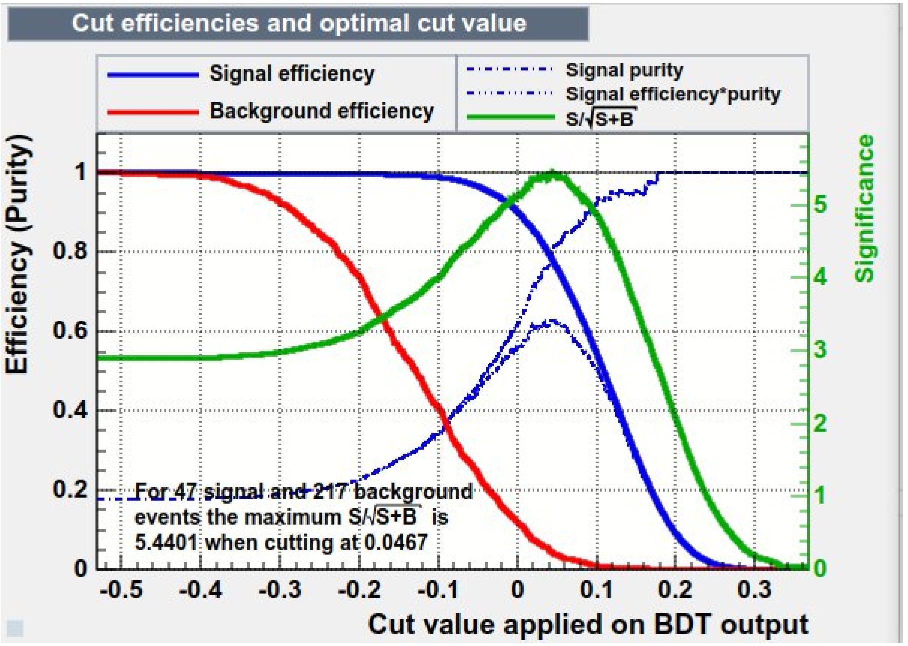


Single fit after **fast simulation** returns
ψ_{CP} = (0± **15**) mrad

MVA– leptonic Z decays

- BDTcut: 0.05
- Signal efficiency: **77%**
- Background rejection: **99.98 %** ($\sim 2 \cdot 10^{-4}$)
- Remaining background events: *llH; H → others*, **6** evt./5.6 ab^{-1}
- post–MVA suppression of *llH; H→others*:
  - Pt_jet > 20 GeV
  - jet multiplicity < 3

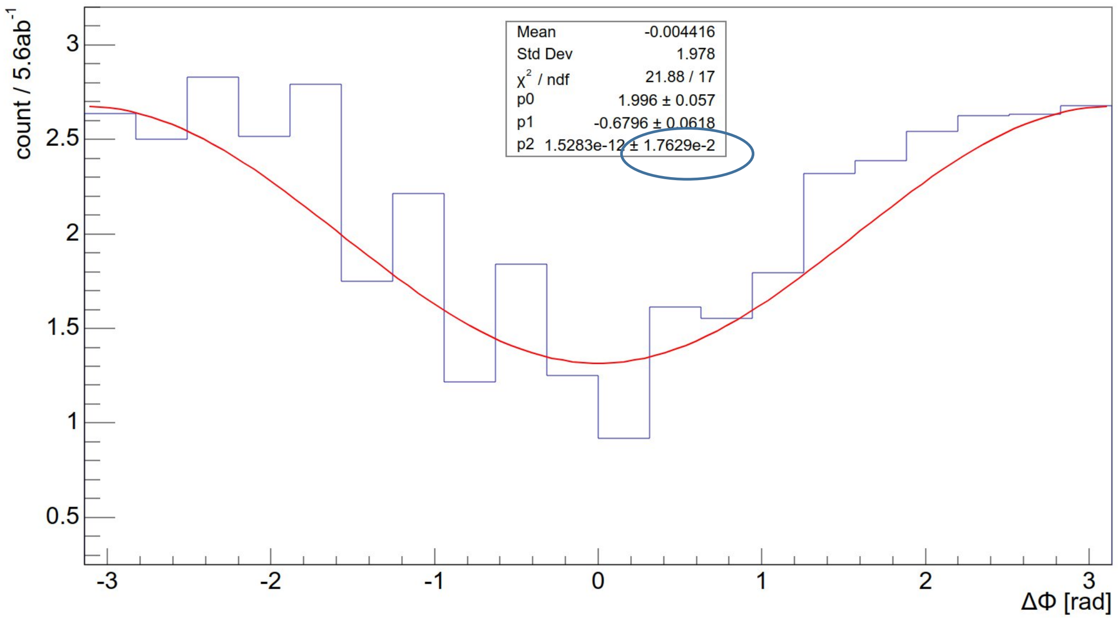
→ **2 evt./5.6 ab^{-1}**



- Signal after selection: 35 evt. /5.6 ab^{-1}
- Background effectively suppressed: 2 evt./5.6 ab^{-1}

ψ_{CP} pseudo-data measurement, zero mixing (SM)

Signal + Background after MVA + correction for colinear approximation
leptonic primary Z decays



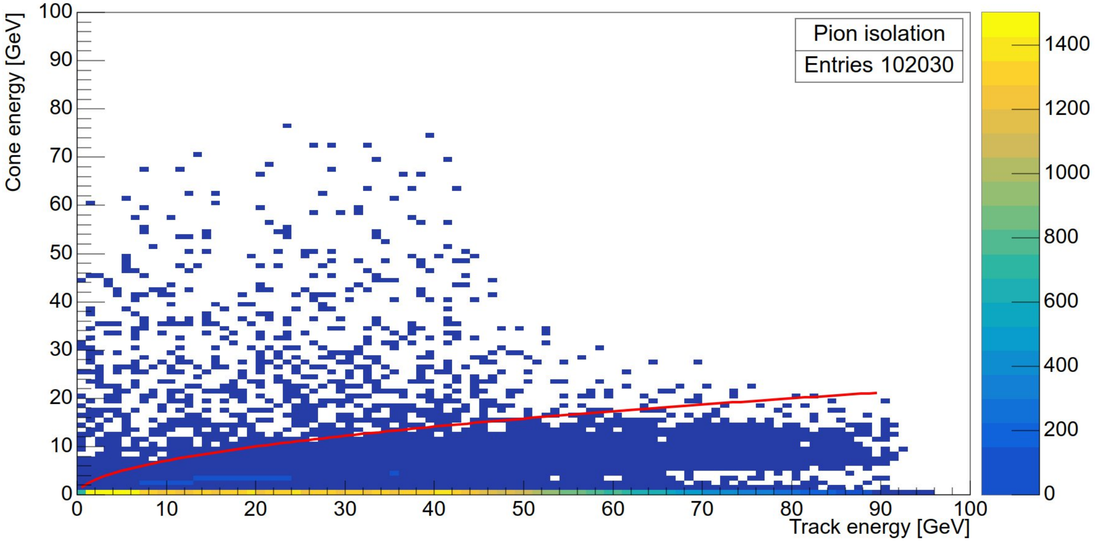
- Fit of reconstructed and selected signal and background
  - Primary Z leptonic decays

$$\psi_{CP} = (\ \mathbf{0 \pm 18}\ )\mathbf{mrad}$$

Preselection - hadronic primary Z decays

- **Similar methodology to leptonic channel**
- **Preselection:**
- Identify pions for reconstruction of taus directions
- Suppress high cross section backgrounds

- Pion isolation;
- 2 most energetic isolated pions per event
- 2 jets per event
- Selection cut: $0 \text{ GeV} < p_{\tau^{\pm}} < 240 \text{ GeV}$



Pion isolation requires:

- 8-degree cone around the pion:

$$E_{cone} < \sqrt{AE_{track}^2 + BE_{track} + C}$$

$$m_{cone} < 2 \text{ GeV}$$

E_{cone} – cone energy, E_{track} – track energy, A = 0, B = 5, C = 0 – free parameters of the fit, m_{cone} – cone invariant mass

Signal and background after preselection – hadronic Z decays

SIGNAL

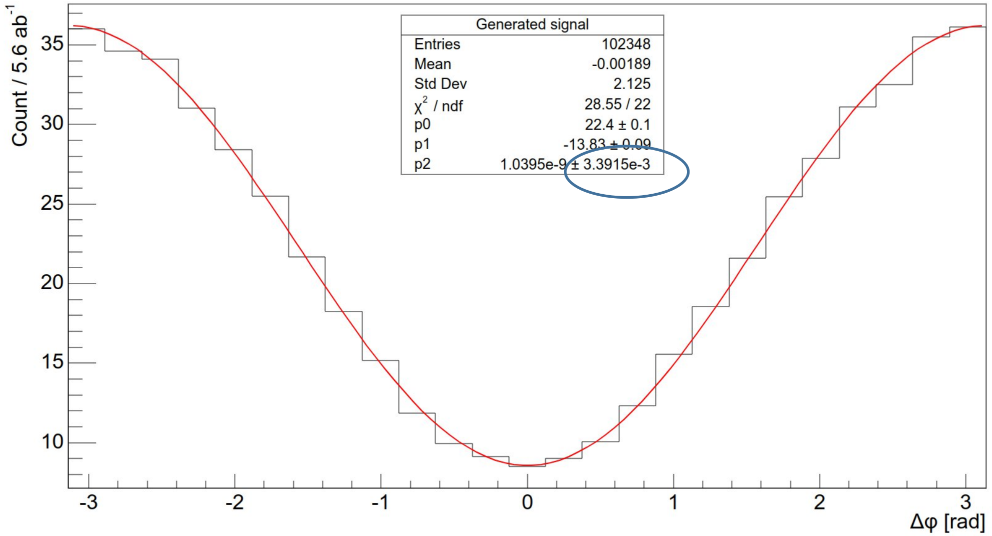
Preselection efficiency: **73%**

240 GeV	Expected in 5.6ab^{-1}	Preselection in 5.6 ab^{-1}	Simulated
Signal: $ee \to HZ;$ $Z \to qq;$ $H \to \tau\tau \to \pi\nu\pi\nu$	560	410	*74 991*
$llH;\ H \to others$	$1.1 \cdot 10^5$	38 973	1 570
$qqH;\ H \to others$	$7.6 \cdot 10^5$	5 515	4 616
$2f$	$5 \cdot 10^9$	7 288 474	93 203
$4f$	$1.13 \cdot 10^8$	25 498	2 357 930

$S/B \sim 10^{-5}$

Angular observable ΔΦ, zero mixing (SM), no background – hadronic Z decays

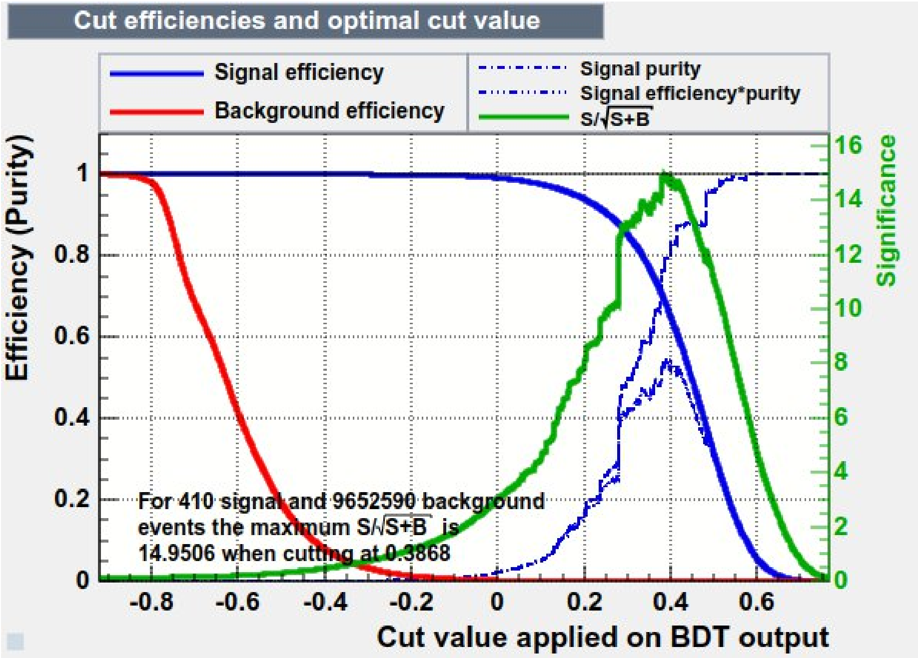
Signal at the generator level:



Fit at a **generator level** (pure signal) returns
$\boldsymbol{\psi_{CP} = (0 \pm 3)}$ **mrad**

MVA– background suppression in hadronic channel

- BDTcut: **0.57**
- Signal efficiency: **31%**

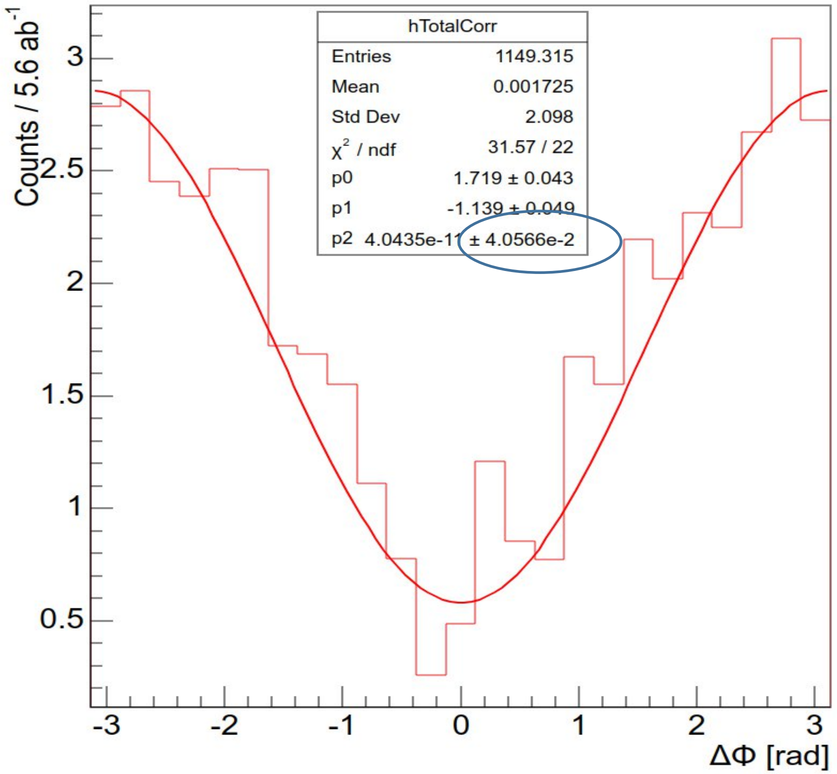


➡ **BDT cut applied to fully suppress the background**

- Signal after selection: **44** evt. /5.6 ab^{-1}
- Background after selection: **0** evt./5.6 ab^{-1}

ψ_{CP} pseudo-data measurement measurement, zero mixing (SM)

Signal + Background after MVA + correction for colinear approximation
hadronic primary Z decays



- Fit for reconstructed and selected signal and background
  - Primary Z hadronic decays

ψ_{CP} = (0± 40) mrad

Discussion

- CP violation in the Higgs sector may occur via scalar-pseudoscalar mixing with the mixing angle ψ_{CP}
- This is a preliminary result **to demonstrate feasibility of ψ_{CP} measurement** based on angular observable in Higgs to tau-pair decays at 240 GeV CEPC

Fit of the Standard Model pseudo-data returns zero mixing angle with ± **18 mrad** uncertainty for leptonic primary Z decays and ± **40 mrad** for hadronic primary Z decays. As two channels are uncorrelated, their combination improves the projected precision of the mixing angle measurement to approximately ± **16 mrad,** for the Standard Model Higgs.

- Further steps can possibly include impact of detailed (full) event reconstruction instead of the one with a fast simulation (although tau reconstruction efficiency and resolution should be comparable to TAURUS)
- Full (tau) reconstruction will remove dependencies introduced by the collinear approximation

Back up

MVA– hadronic Z decays

- Single BDT method
- 37 variables, best ranked ($m_{\tau\tau}$, $\alpha_{\tau\tau}$,$E_{\pi^{\pm}}$, $P_{T\pi^{\pm}}$, $P_{T_{\tau\tau}}$, $m_{Hrecoil}$, $E_{visible\_dijet}$)

Best ranked variables: