CP violation in Higgs to tautau decays at the CEPC

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Overview

- Motivation
- CP−sensitive observable
- Method of the analysis
  - tau−lepton reconstruction
  - Preselection
  - MVA selection
- Discussion

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.

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.

One way of doing it is by measuring the shape effects on CP−sensitive observables.

A way to probe CPV in the Higgs sector are Higgs decays.

- 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}:

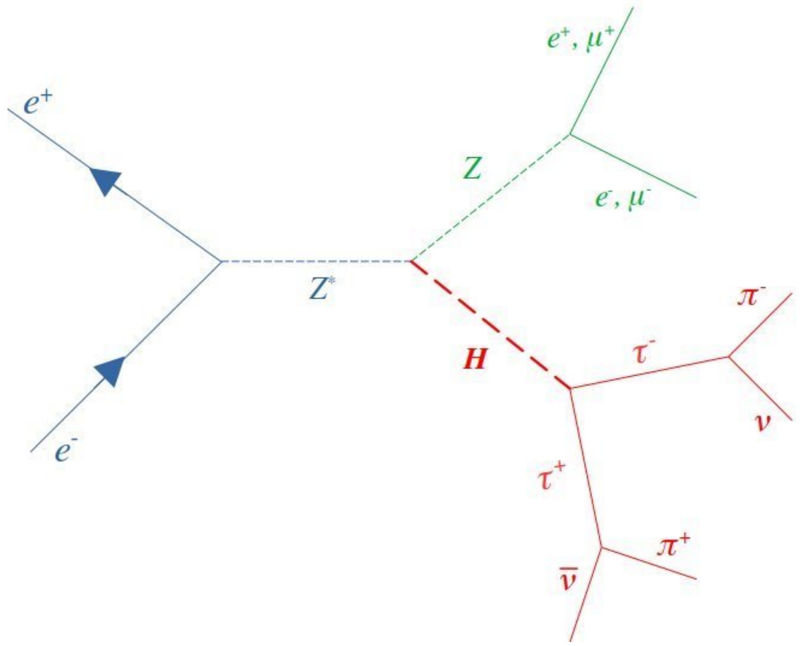
$$h_{125} = H \cdot cos(\psi_{CP}) + A \cdot sin(\psi_{CP})$$

- The CP mixing angle can be probed by measuring Higgs decays to τ lepton pairs.

Processes of interest

SIGNAL

- Higgsstrahlung (HZ) at 240 GeV, $\sigma_{HZ} = 196.9$ fb
- $Z \to l^+l^-,\ H \to \tau^+\tau^- \to \pi^+\pi^- + E_{miss}$
- 5.6 ab^{-1} of integrated luminosity

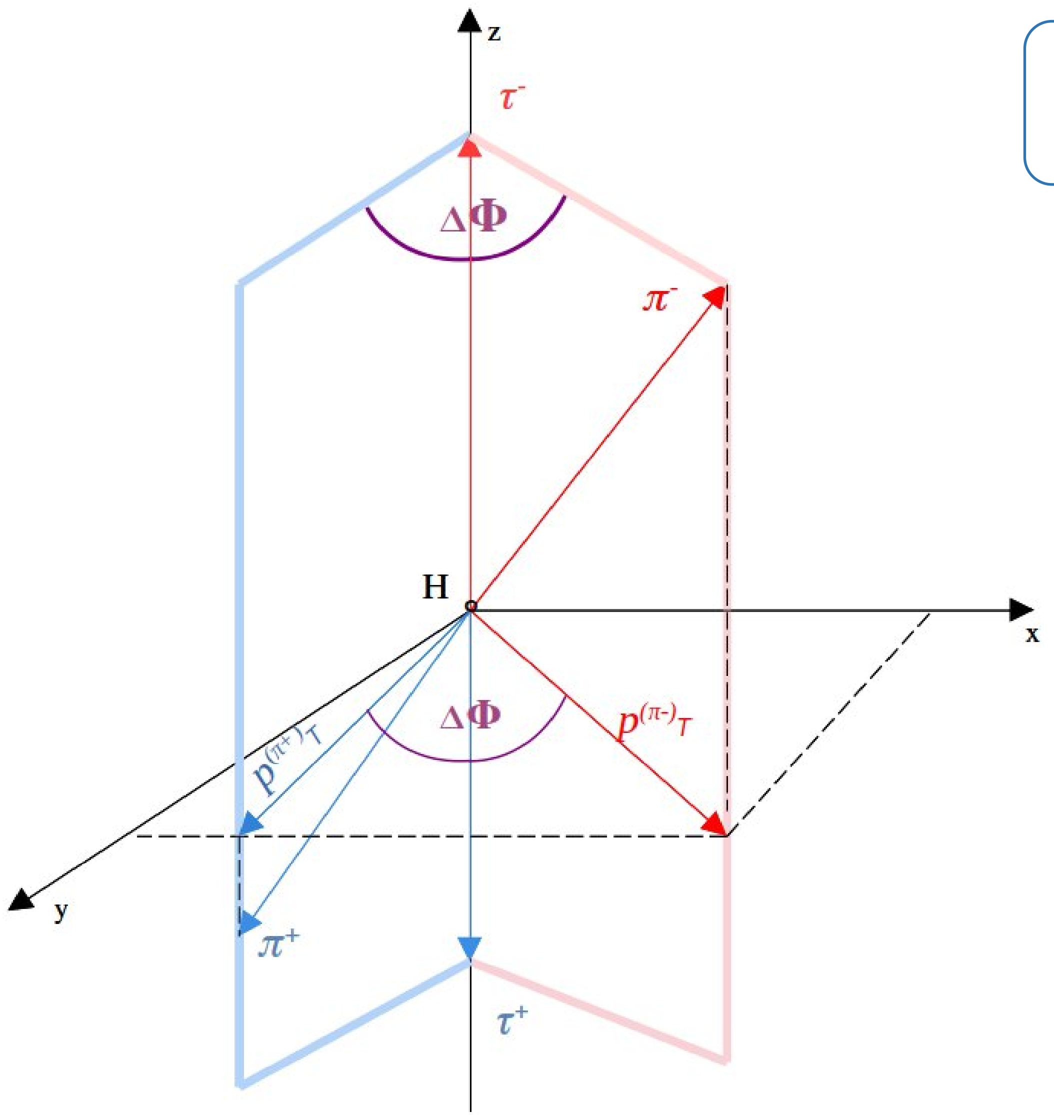


Feynman diagram of the signal process

- **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.

240 GeV	**Expected in 5.6ab^{-1}**	**Simulated (DELPHES)**
Signal: $ee \to HZ$; $Z \to ll$; $H \to \tau\tau \to \pi\nu\pi\nu$	56	100 267
$llH;\ H \to others$	$1.1 \cdot 10^5$	2 752 170
$qqH;\ H \to others$	$7.6 \cdot 10^5$	200 000
$2f$	$8 \cdot 10^8$	4 837 473
$4f$	$1.8 \cdot 10^8$	7 875 488

CP–Sensitive Observable ΔΦ



ΔΦ can be retrieved as the angle between the planes defined by the decay products of the tau leptons.

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

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

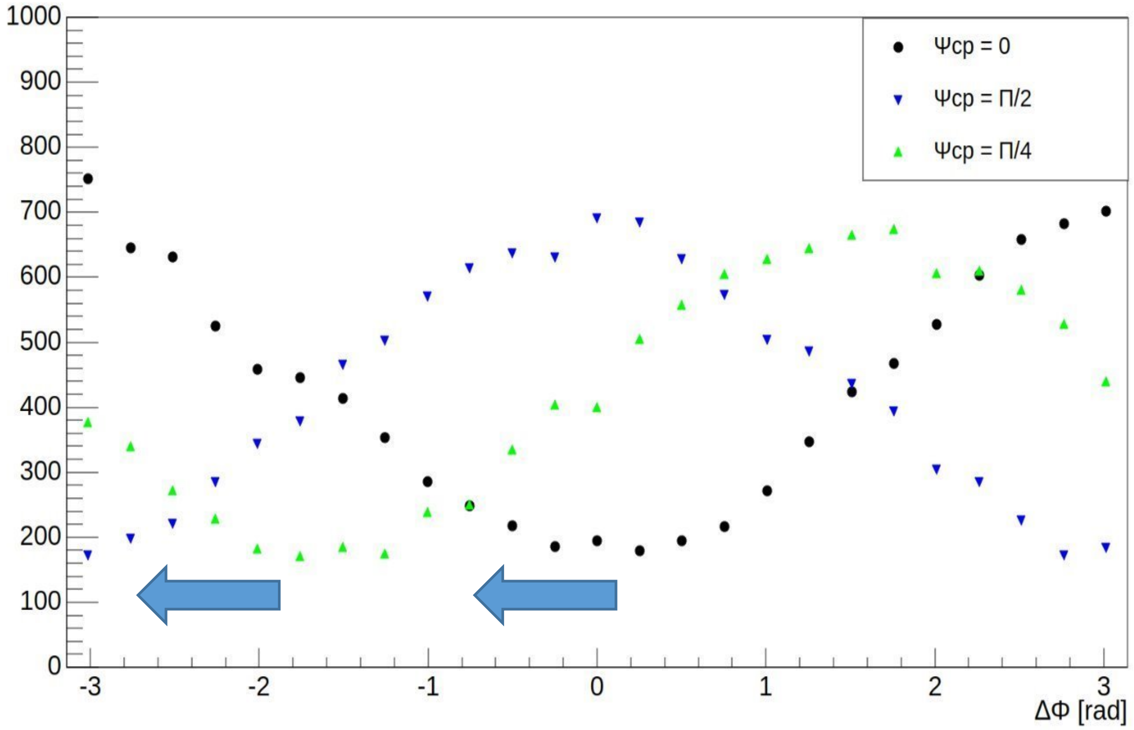
$$\Delta\Phi = \begin{cases} \arccos(\cos(\phi)), & \sin(\phi) \geq 0 \\ 2\pi - \arccos(\cos(\phi)), & \sin(\phi) < 0 \end{cases}$$

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

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

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

- *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}:
phase shift w.r.t. ψ_{CP}, maximal mixing $\psi_{CP} = \pi/4$

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

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

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.**
- Standard tau finder efficiency ~ 30%.
- tau leptons had to be reconstructed in another way − ***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:

$$-p^x_{\bar{f}f} = \boldsymbol{p}_{\tau^-} \cdot a_1 + \boldsymbol{p}_{\tau^+} \cdot a_2$$
$$-p^y_{\bar{f}f} = \boldsymbol{p}_{\tau^-} \cdot b_1 + \boldsymbol{p}_{\tau^+} \cdot b_2$$

⟹

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

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

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

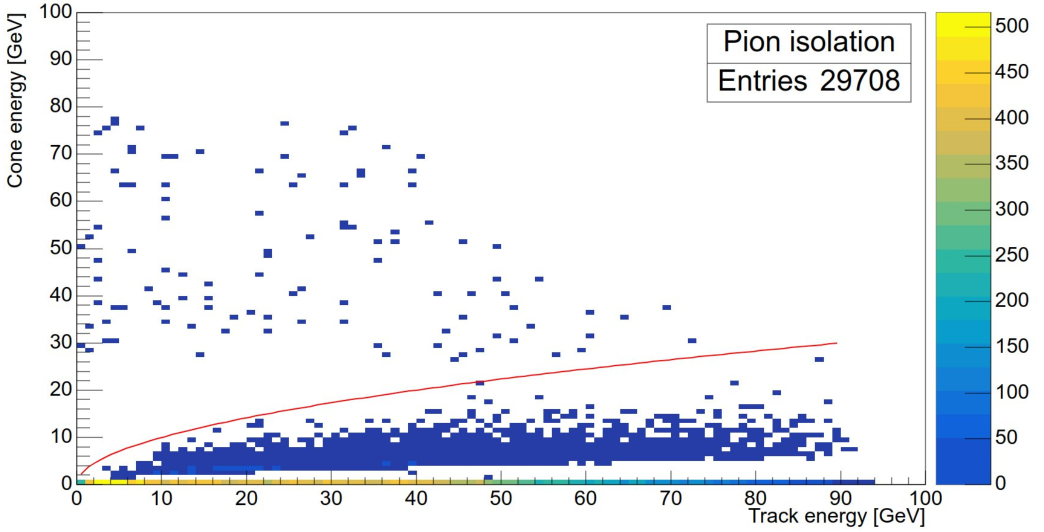
$p_{\tau^\pm}$ – momentum of reconstructed tau
$p^{x,y}_{\bar{f}f}$ – momentum of Z^0 decay products
$\theta_{\pi^\pm}, \phi_{\pi^\pm}$ – polar and azimuthal angle of tau decay

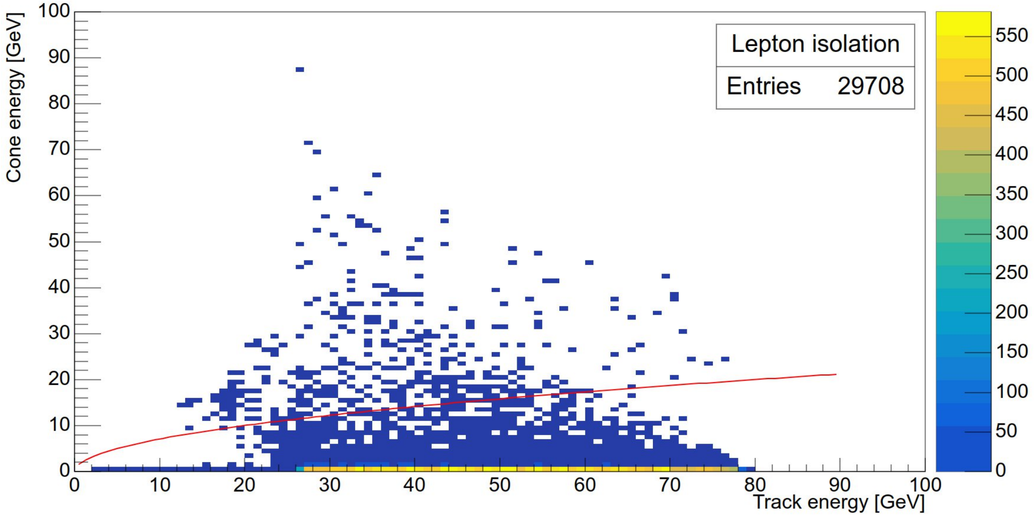
Preselection

Preselection is performed to:

- Identify pions for reconstruction of taus directions
- Suppress high cross section backgrounds

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





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 = 10, C = 0 – free parameters of the fit, m_{cone} – cone invariant mass

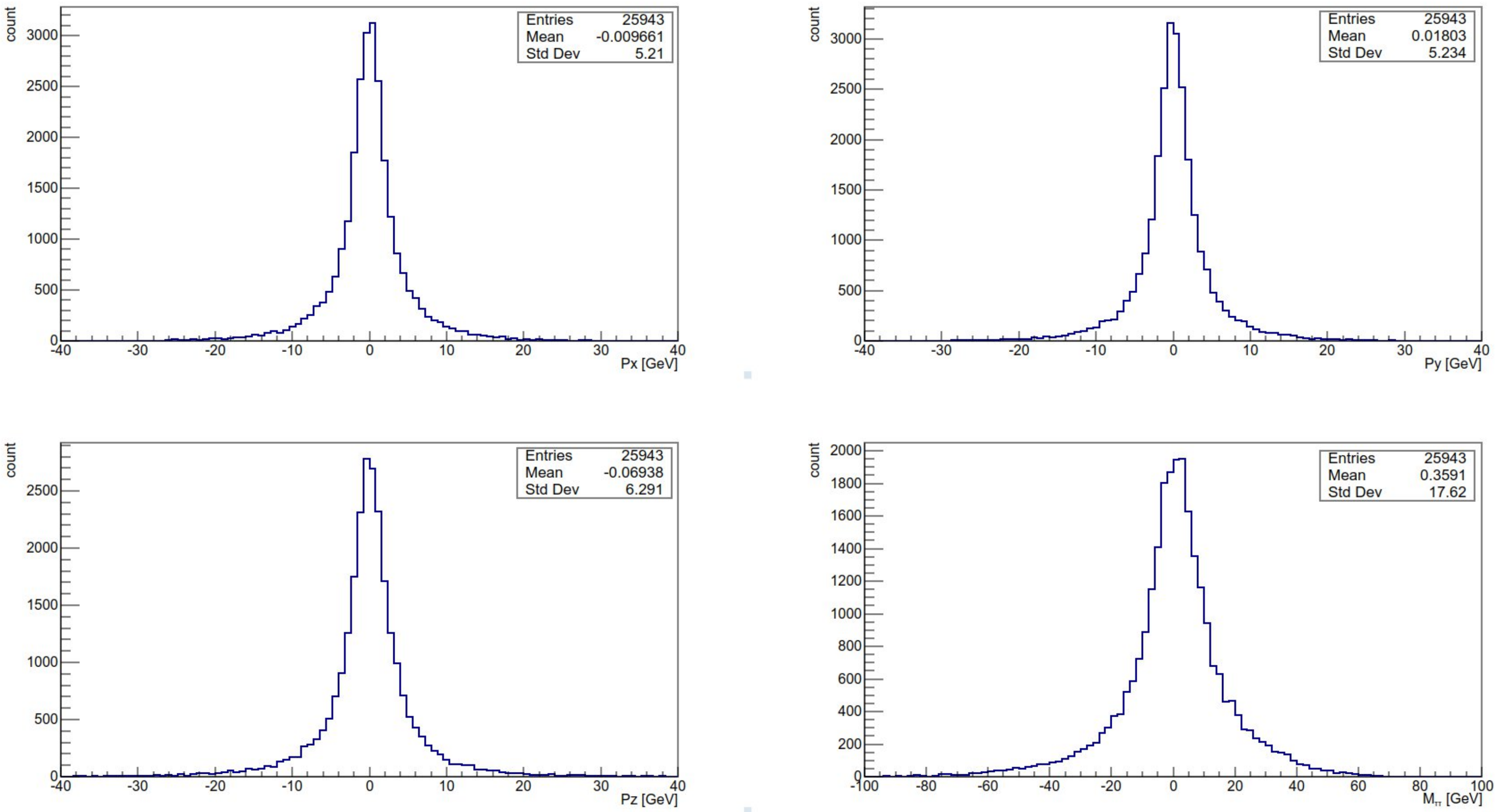
Lepton isolation requires:

- 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 is **86%**.

Signal and background after preselection

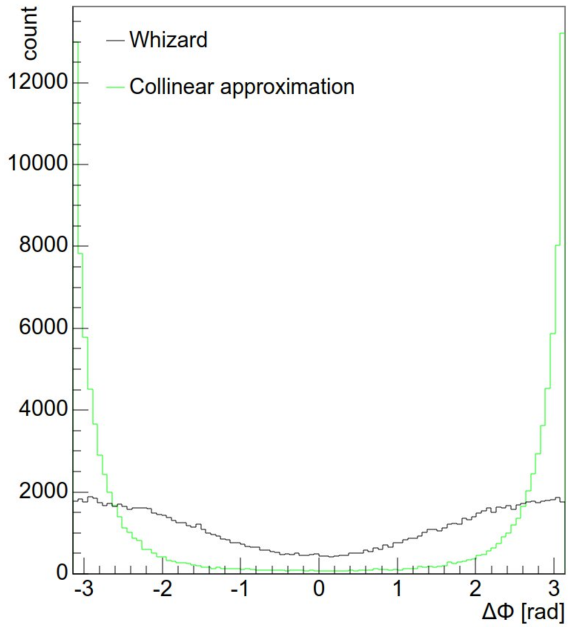
SIGNAL

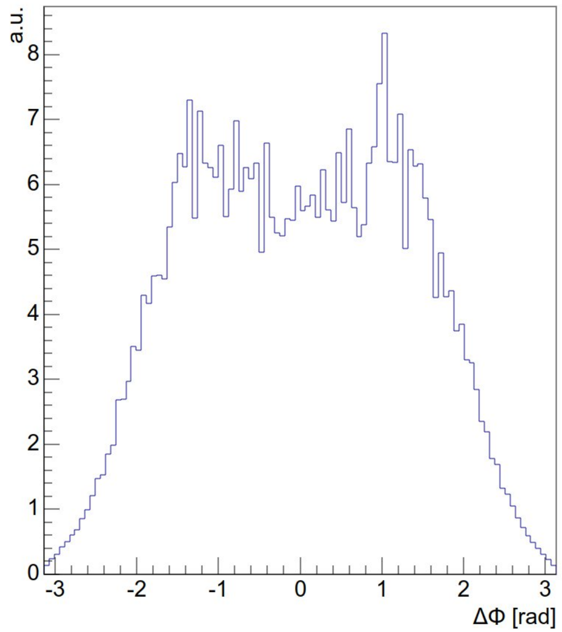
Preselection efficiency: **85%**
Purity (truth linked) : **99%**
Efficiency * Purity: **84.3%**

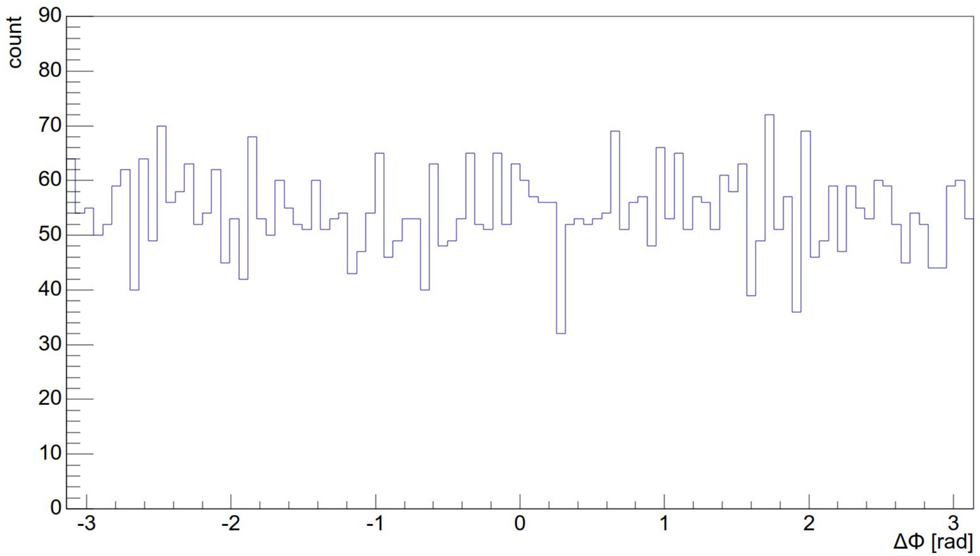
240 GeV	**Expected in 5.6ab^{-1}**	**Simulated**	**Events in 5.6 ab^{-1}**
Signal: $ee \to HZ$; $Z \to ll$; $H \to \tau\tau \to \pi\nu\pi\nu$	56	85462	47
llH; $H \to others$	$1.1 \cdot 10^5$	5434	217
qqH; $H \to others$	$7.6 \cdot 10^5$	0	0
$2f$	$8 \cdot 10^8$	0	0
$4f$	$1.8 \cdot 10^8$	1561	35700

Corrective function for the collinear approximation

- The collinear approximation introduces a distortion in the shape of the sensitive observable since the real tau direction is approximated with the reconstructed pion.



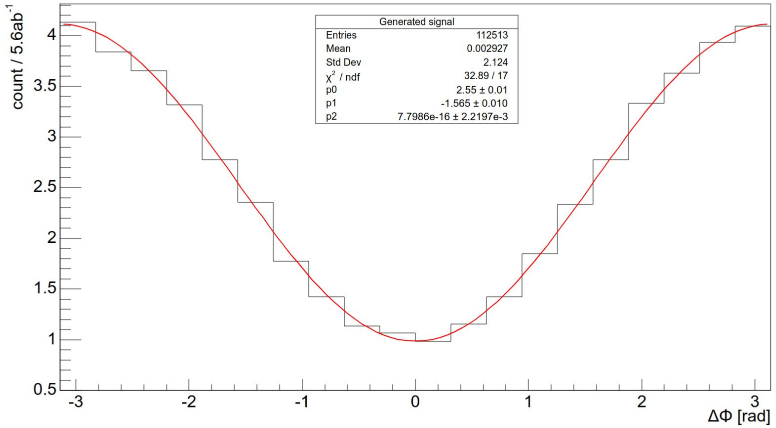




- Correction should be applied to all selected events, changing the CP-flat shape of background ➡ superior background suppression

Angular observable ΔΦ, zero mixing (SM), no background

Signal at the generator level:

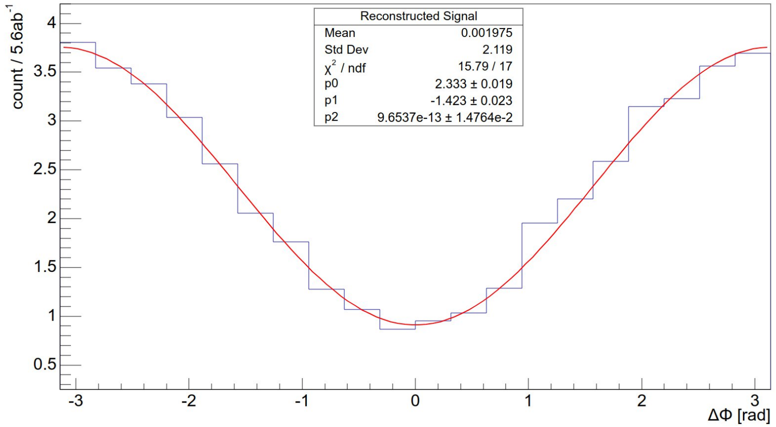


- Determine position of the local minimum with the function:

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

- Single fit at a **generator level** (pure signal) returns $\psi_{CP} = 0$ with uncertianty of ± 2.2 mrad

Reconstructed signal after collinear approximation + correction for colinear approximation:

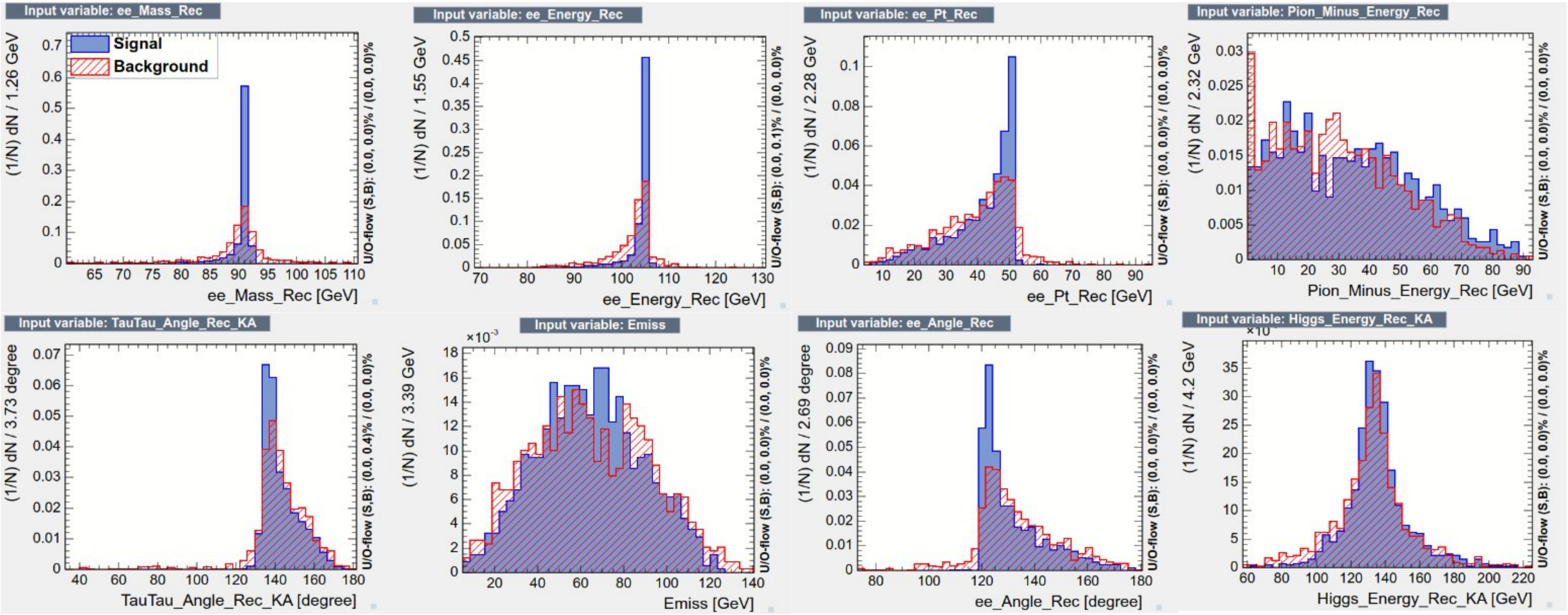


- Single fit after **fast simulation** returns $\psi_{CP} = 0$ with uncertianty of ± 15 mrad

MVA

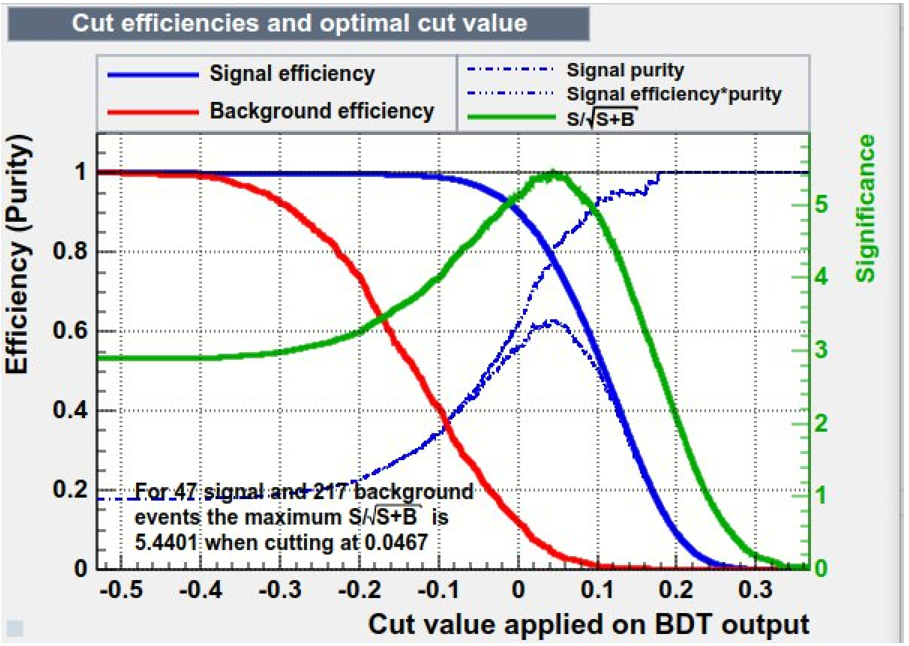
- Single BDT method
- 30 variables, best ranked (m_{ll}, E_{ll}, α_{ll}, $P_{T_{ll}}$, $\alpha_{\tau\tau}$, $E_{\pi^\pm}$, $P_{T\pi^\pm}$, $m_{\tau\tau}$, $E_{\tau\tau}$, E_{miss})

Best ranked variables:



MVA

- BDTcut: 0.05
- Signal efficiency: **77%**
- Background rejection: **99.98 %**
- Remaining background events: *llH->others*, 6 evt./5.6 ab^{-1}



Size of the simulated background sample 139 ab^{-1} , (about 160 remaining events) allows to develop post–MVA suppression of *llH; H→others*:

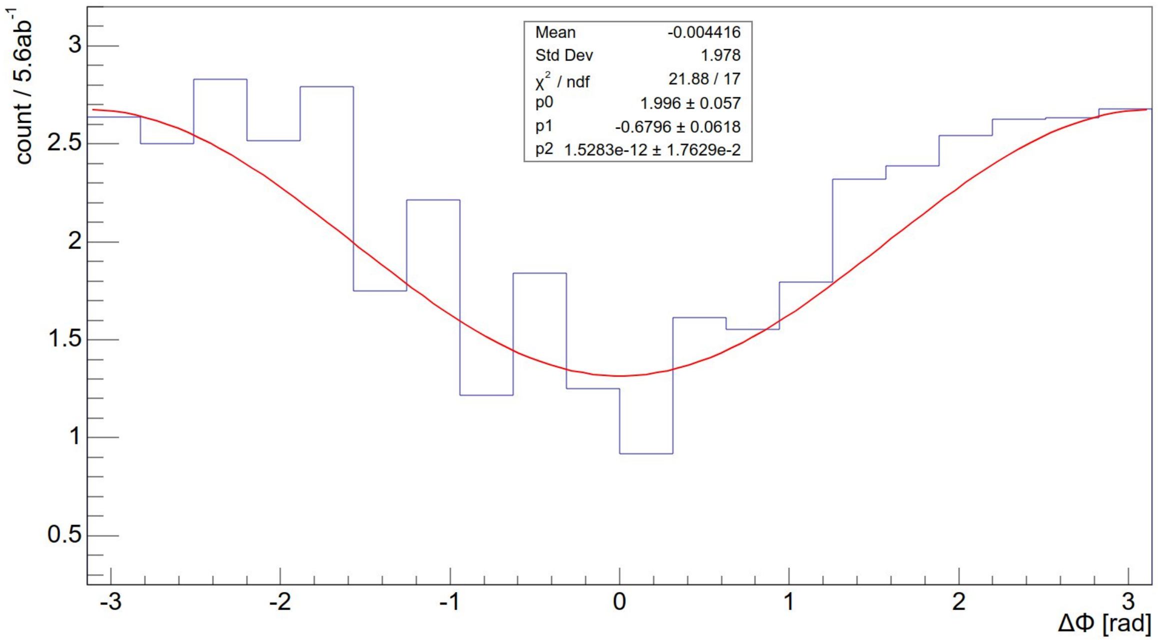
- **Pt_jet** > 20 GeV
- **jet multiplicity** < 3

→ 2 evt./5.6 ab^{-1}

- Signal events after MVA + cuts: 35 evt. /5.6 ab^{-1}
- Background events after MVA + cuts: 2 evt./5.6 ab^{-1}

ψ_{CP} measurement, zero mixing (SM)

Signal + Background after MVA + correction for colinear approximation



- Fit after **fast simulation** returns $\psi_{CP} = 0$ with uncertainty of ± **17.6** mrad
- Reduced χ^2 is: 1.29

Discussion

- This is a very preliminary result,
- to demonstrate feasibility of ψ_{CP} measurement based on angular observable in Higgs to tautau decays at 240 GeV CEPC.

- Very many possible further steps:
  - Include hadronic primary Z decays
  - Include fully reconstructed backgrounds – thanks to Kaili Zhang and Manqi Ruan!
  - Better tau reconstruction (full simulation instead of fast)
  - Include other tau decays ($\tau^{\pm} \rightarrow \pi^{\pm} \pi^{0} \nu$)
  - Play around with background suppression (if needed, more methods)
  - Play around with polarization (transverse, longitudinal)
  - Possibly introduce optimal observable