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

I. Bozovic , I. Vidakovic

VINCA Institute of Nuclear Sciences, University of Belgrade



Overview

- Motivation and goal
- CP−sensitive observable
- Method of the analysis
  - tau reconstruction
  - preselection & MVA
- Discussion



Motivation and goal

- The Standard Model does not provide sources of CP violation sufficient to explain BA
- **CP can be violated in Higgs interactions (production and decay)**

- Let us assume in the most generic way that the Higgs mass eigenstate h_{125} is a superposition of scalar *H* (CP-even) and pseudoscalar *A* (CP-odd state), with a mixing angle ψ_{CP}:

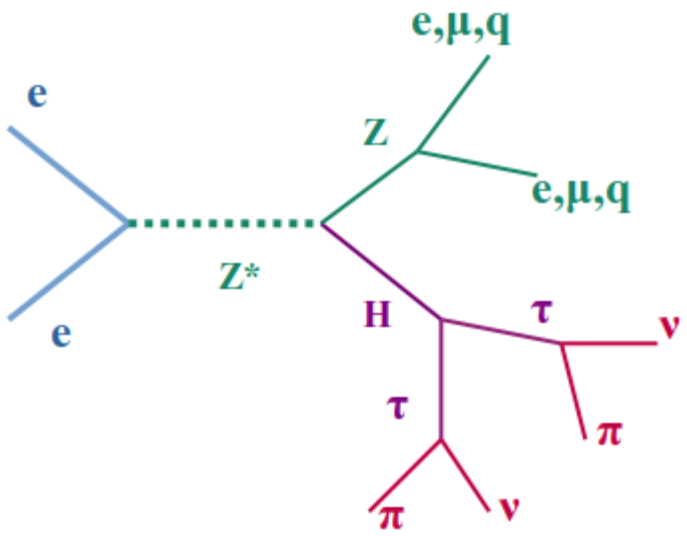
$$h_{125} = H \cdot cos(\psi_{CP}) + A \cdot sin(\psi_{CP})$$

- The CP mixing angle will be determined by measuring Higgs decays to τ-pairs

- In the following we'll use collinear approximation (CA) to reconstruct tau in fast simulation
- The goal is to demonstrate feasibility of ψ_{CP} measurement and not to apply CA in real experiment – it will be substituted by real tau finder
- The estimate is conservative in two aspects:
  - Single one-prong tau decay is considered ($\tau \to \pi\nu$), rare process 56 (560) evt./5.6 ab^{-1}
  - Due to CA background is highly suppressed, what may not be statistically optimal



Signal and background

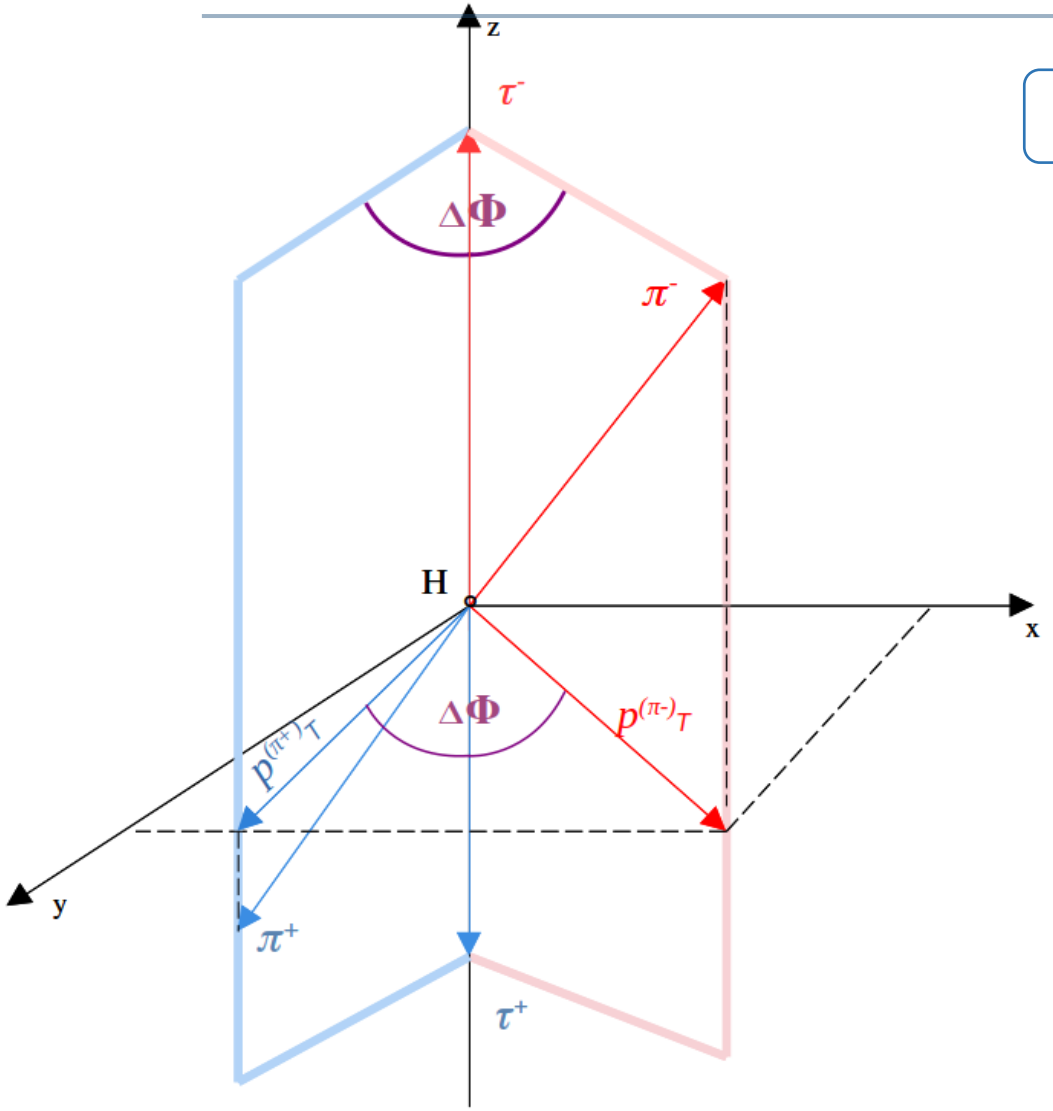


240 GeV	Expected in 5.6ab^{-1}	Simulated (DELPHES)
Signal: *ee → HZ; Z → ll; H → ττ → πνπν*	**56**	100 267
Signal: *ee → HZ; Z → qq; H → ττ → πνπν*	**560**	102 348
llH; H → others	$1.1 \cdot 10^5$	$2.7 \cdot 10^6$
qqH; H → others	$7.6 \cdot 10^5$	$9 \cdot 10^5$
2f	$5 \cdot 10^9$	$9.4 \cdot 10^6$
4f	$1.13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

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

- **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, CEPC detector card

Angular observable ΔΦ



ΔΦ is the (azimuthal) angle between the tau decay planes

Higgs rest frame, τ^- defines z-axis,
n_1, n_2 – unit vectors $\perp$ to decay planes

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

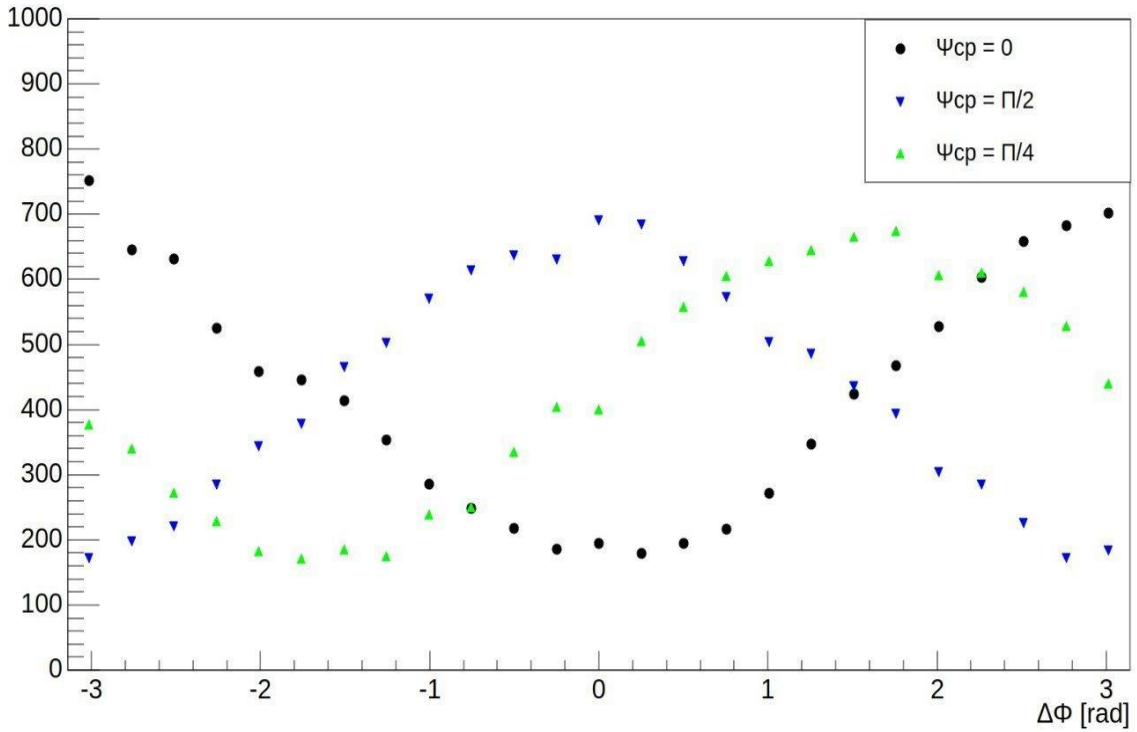
$$\Delta\Phi = \begin{cases} \arccos(\cos(\phi)), \sin(\phi) \geq 0 \\ 2\pi - \arccos(\cos(\phi)), \sin(\phi) < 0 \end{cases}$$

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

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

Angular observable ΔΦ

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



$\Delta\boldsymbol{\phi}$ shape can be modeled with the function:

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

$\boldsymbol{\psi_{CP}}$ can be measured
from the reconstructed $\Delta\boldsymbol{\phi}$ minimum

From the fit parameters of $f(\Delta\phi, \psi_{CP})$, we can estimate Fisher information $I = 4\,(1 - \sqrt{(1-a^2)})$ where $a = |B|/A$

and corresponding uncertainty $\Delta\psi_{CP} = 1/(\sqrt{(N \cdot I)})^{-1}$
where N is the number of selected events

Collinear approximation

- $H \to \tau^+\tau^- \to \pi^+\pi^- + E_{miss}$ is not abundant (56/560 evt. in 5.6 ab^{-1}) ➡ **tau reconstruction must be efficient and precise; In DELPHES (CEPC card) tau reconstruction efficiency is ~ 40%**
- **Collinear approximation:**

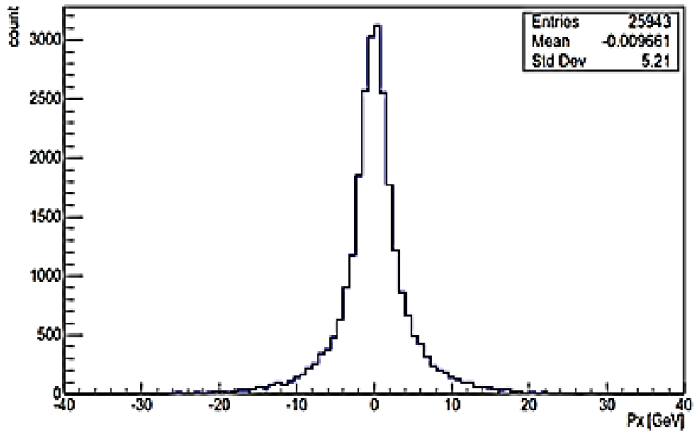
1. **tau lepton and a charged pion are emitted collinearly**
2. **event transverse momentum is conserved**

These allow to find intensity of tau momentum (while pion gives its direction)

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

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

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



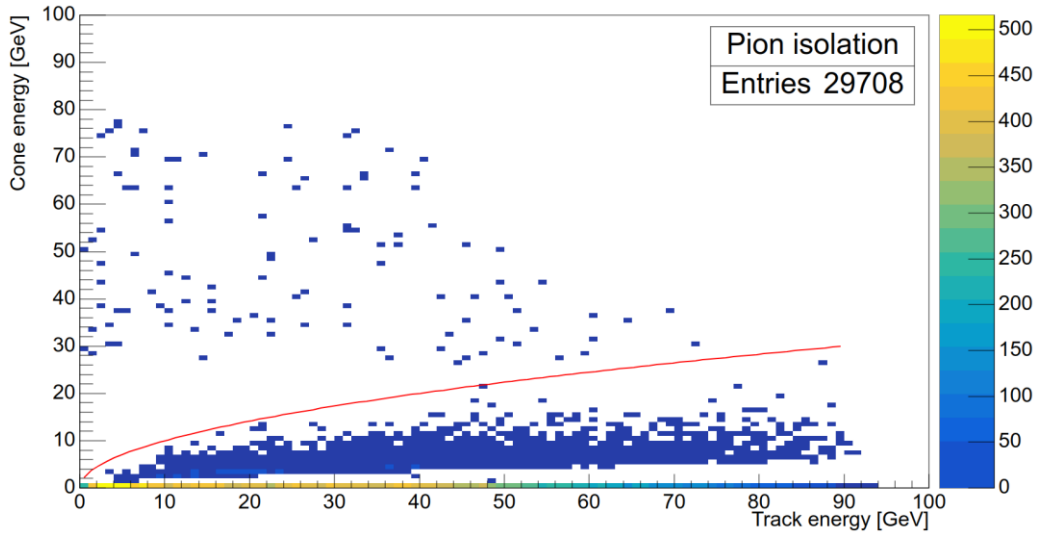
$p_{\tau^\pm}$ – momentum of reconstructed tau
$p^{x,y}_{\bar{f}f}$ – momentum of Z^0 decay products
$\theta_{\pi^\pm}, \phi_{\pi^\pm}$ – polar and azimuthal angle of tau decay

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

tau momentum resolution (per component) ~ **6 GeV**
tau reconstruction efficiency: **86%**

π isolation

$ll\pi\nu\pi\nu$ final state



Pion isolation:

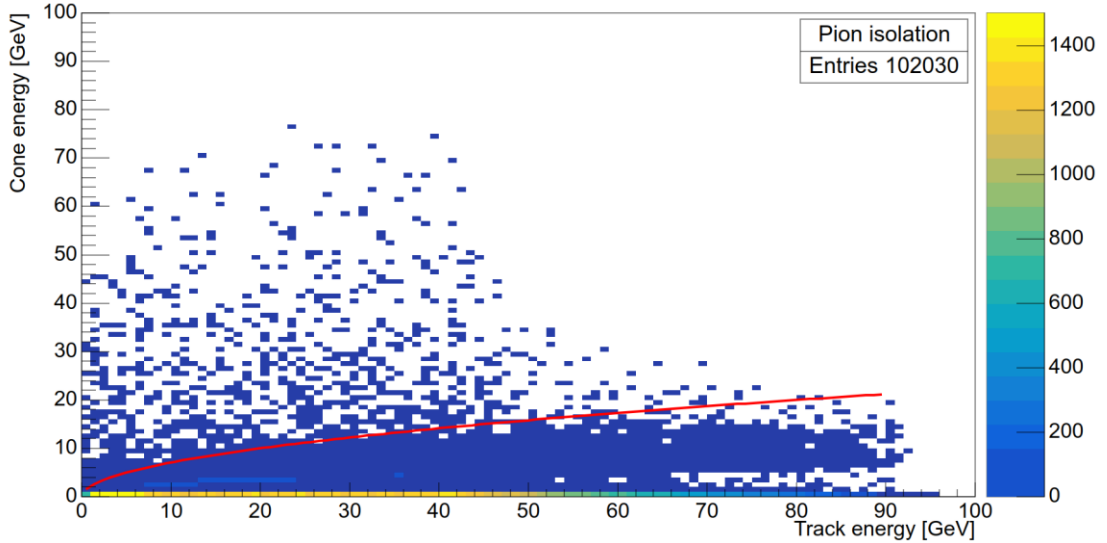
- 8-degree cone around the pion:

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

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

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

$qq\pi\nu\pi\nu$ final state



Pion isolation:

- 8-degree cone around the pion:

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

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

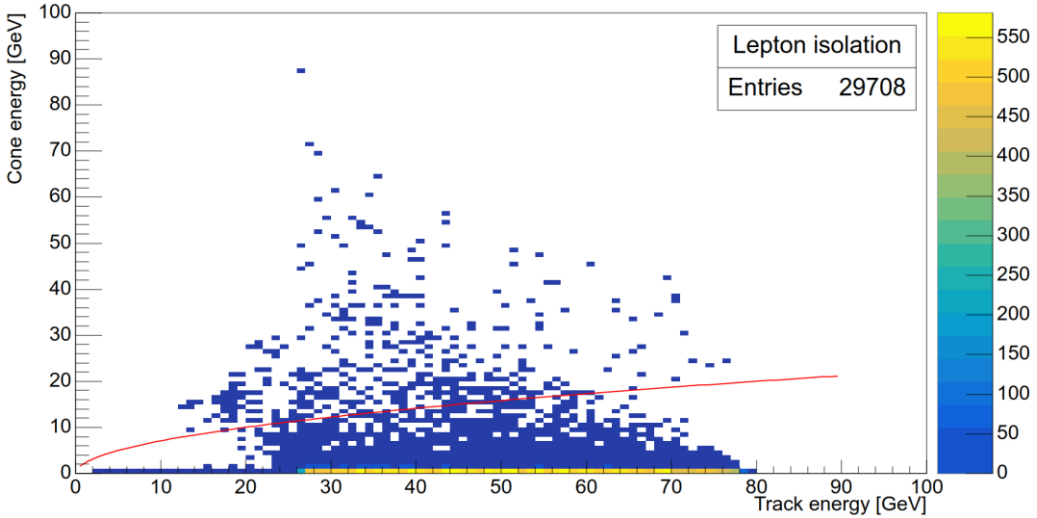
E_{cone} – cone energy, E_{track} – track energy, A = 0, B = 5, C = 0 – free parameters of the fit, m_{cone} – cone invariant mass

Preselection

$ll\pi\nu\pi\nu$ final state

Preselection aims to suppresses high cross-section backgrounds

- Pion isolation;
- Isolation of leptons from primary Z^0 decay;



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

- Selection cuts:
  - 60 GeV < m_{ll} < 110 GeV
  - 25 GeV < $p_{\tau^\pm}$ < 120 GeV
  - E_{miss} 5 < GeV

Preselection efficiency: **85%**
S/B ~ 10^{-3}

240 GeV	Expected in 5.6ab^{-1}	Simulated	Preselected in 5.6 ab^{-1}
Signal: *ee → HZ; Z → ll; H → ττ → πνπν*	56	85 462	47
llH; H → others	$1.1 \cdot 10^5$	5 434	217
qqH; H → 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

Preselection

$qq\pi\nu\pi\nu$ final state

Preselection aims to suppresses high cross-section backgrounds

- Pion isolation;
- 2 most energetic isolated pions per event
- 2 jets per event

Preselection efficiency: **73%**
S/B ~ 10^{-5}

240 GeV	Expected in 5.6ab^{-1}	Preselected in 5.6 ab^{-1}	Simulated
Signal: *ee → HZ; Z → qq; H → ττ → πνπν*	560	410	*74 991*
llH; H → others	$1.1 \cdot 10^5$	38 973	1 570
qqH; H → 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

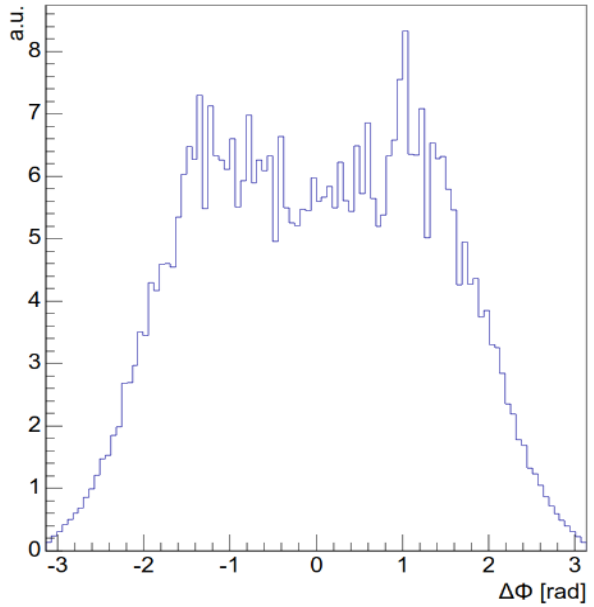


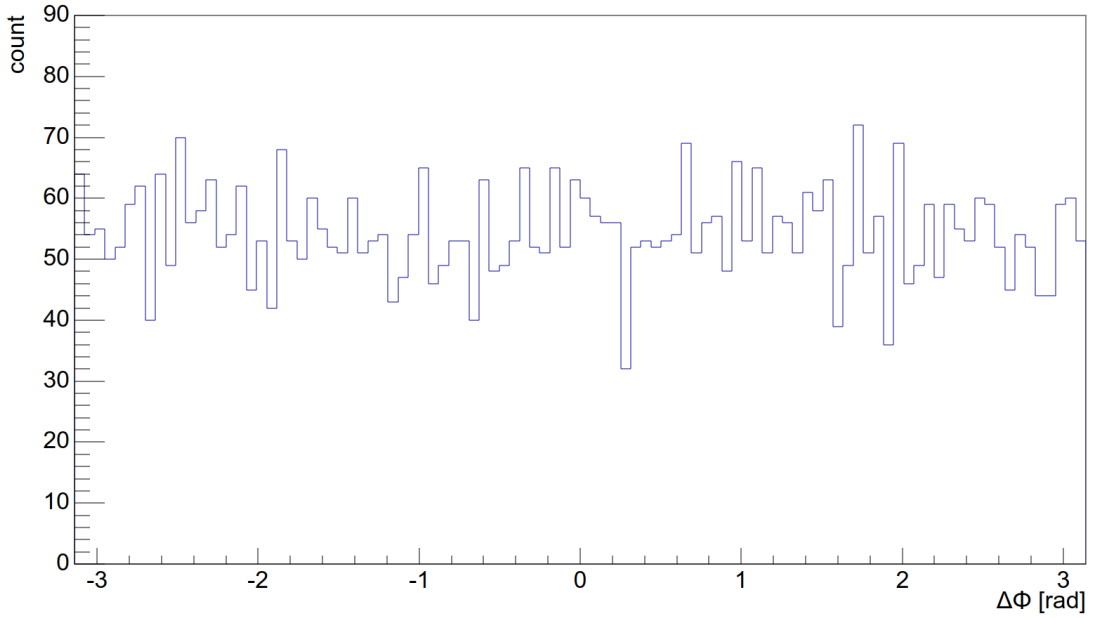
Corrective function for the collinear approximation

- The collinear approximation introduces a distortion in the shape of $\Delta\phi$ (tau direction is approximated with the reconstructed pion)
- Correction function is determined in simulation
- Were we are conservative (to be improved) – the **same** correction function is applied to signal and background

➡ *background must be maximally suppressed*

It is worth noting that this correction will not exist in real experiment (tau reconstruction)

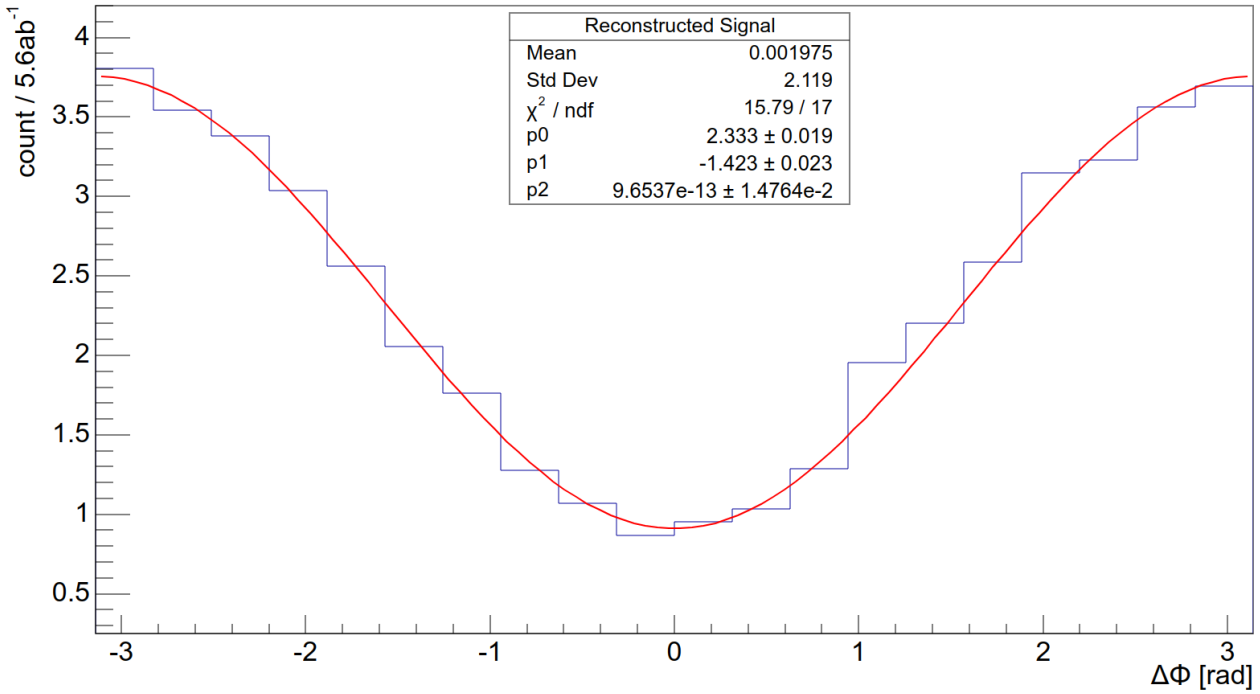




Angular observable ΔΦ, zero mixing (SM), no background

$ll\pi\nu\pi\nu$ final state

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



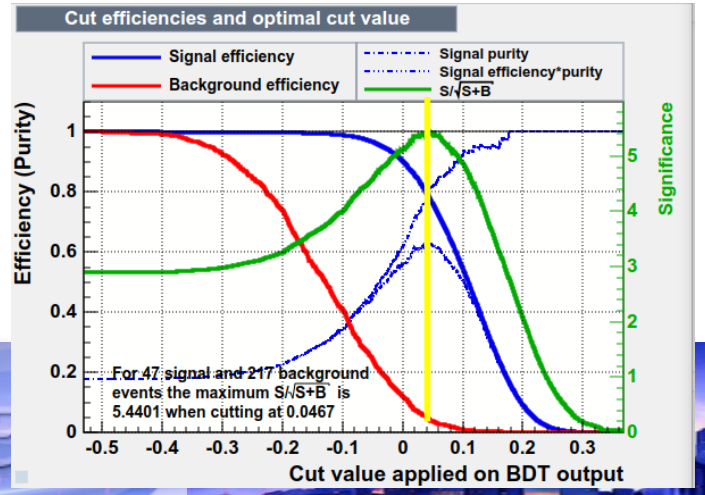
- N=85227
- N(5.6 ab^{-1}) = 47
- a= 0.610
- I = 1.977
- $\Delta\psi_{CP(5.6\ ab^{-1})} \approx 104$ mrad, no background
- But, with background times $\sqrt{(1+B/S)}$

Background suppression with MVA

$ll\pi\nu\pi\nu$ final state

- **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

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

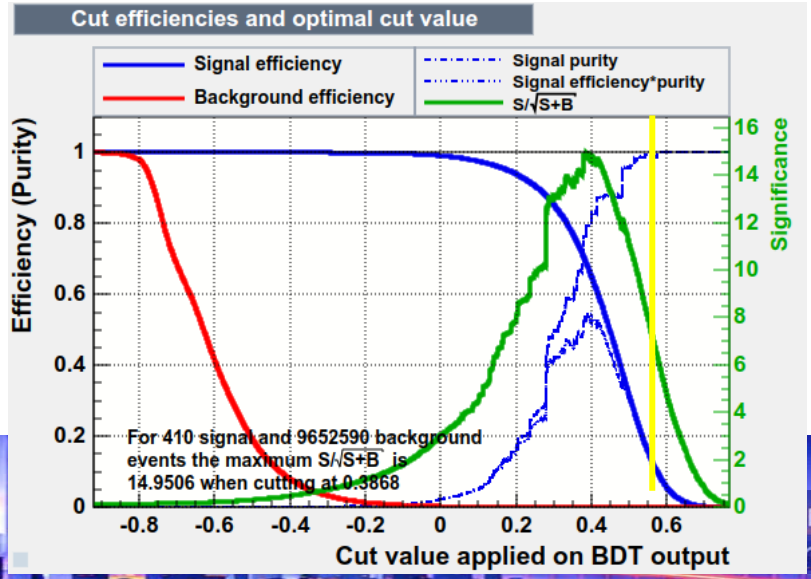


$qq\pi\nu\pi\nu$ final state

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

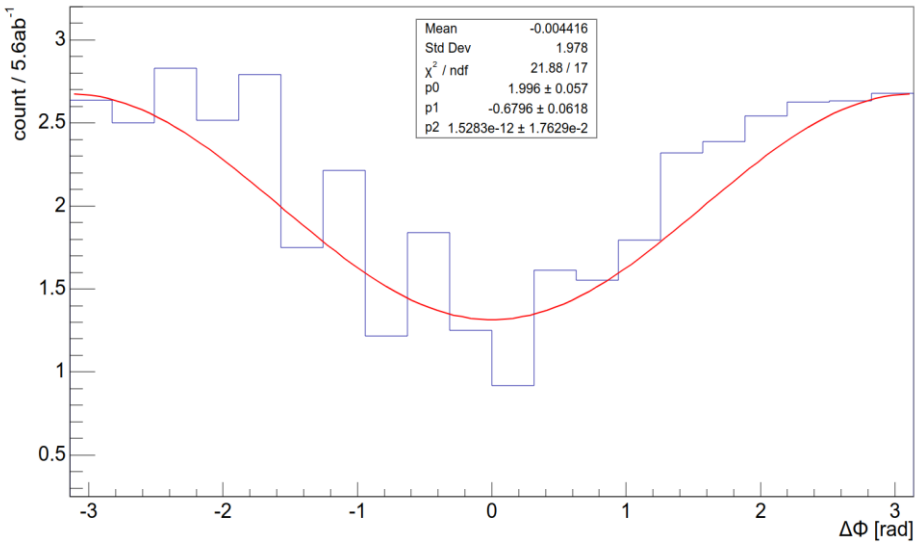
BDT cut fully suppresses the background

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



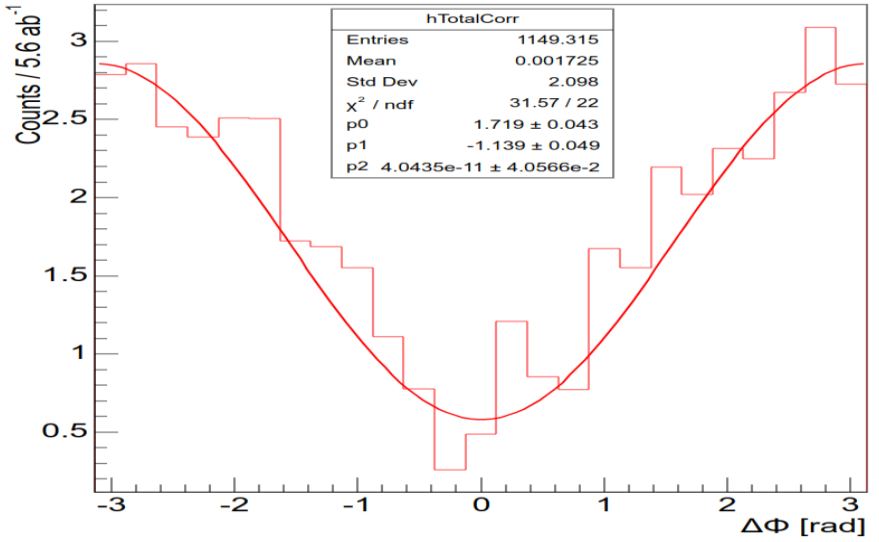
ψ_{CP} pseudo-data measurement, zero mixing (SM)

$ll\pi\nu\pi\nu$ final state



- N(5.6 ab^{-1}) = 35
- a= 0.340
- I = 0.239
- $\Delta\psi_{CP(5.6\ ab^{-1})} \approx 345$ mrad

$qq\pi\nu\pi\nu$ final state



- N(5.6 ab^{-1}) = 44
- a= 0.663
- I = 1.977
- $\Delta\psi_{CP(5.6\ ab^{-1})} \approx 107$ mrad

COMBINED

- $\Delta\psi_{CP(5.6\ ab^{-1})} \approx 102$ mrad
- $\Delta\psi_{CP(21.6\ ab^{-1})} \approx 81$ mrad

Discussion

- This result gives conservative estimate of the challenging ψ_{CP} measurement at 240 GeV CEPC (5.6 ab^{-1}) in $H \rightarrow \tau\tau \rightarrow \pi\pi\nu\nu$ decays with only 56 (560) events in total
- Preliminary estimated precision of the absolute uncertainty of the scalar-pseudoscalar mixing angle amounts to 102 mrad, combined for leptonic and hadronic primary Z decays, with projected 81 mrad for 21.6 ab^{-1}
- It demonstrates feasibility of this measurement, with a room for following improvements:
  - Background can be corrected with a separate function than signal;
  - Background suppression can be optimized w.r.t. the Fisher information in different channels
  - Final precision should be established by repeated pseudo-experiments
  - Finally, colinear approximation should be replaced by realistic tau reconstruction including the shift to the full simulation

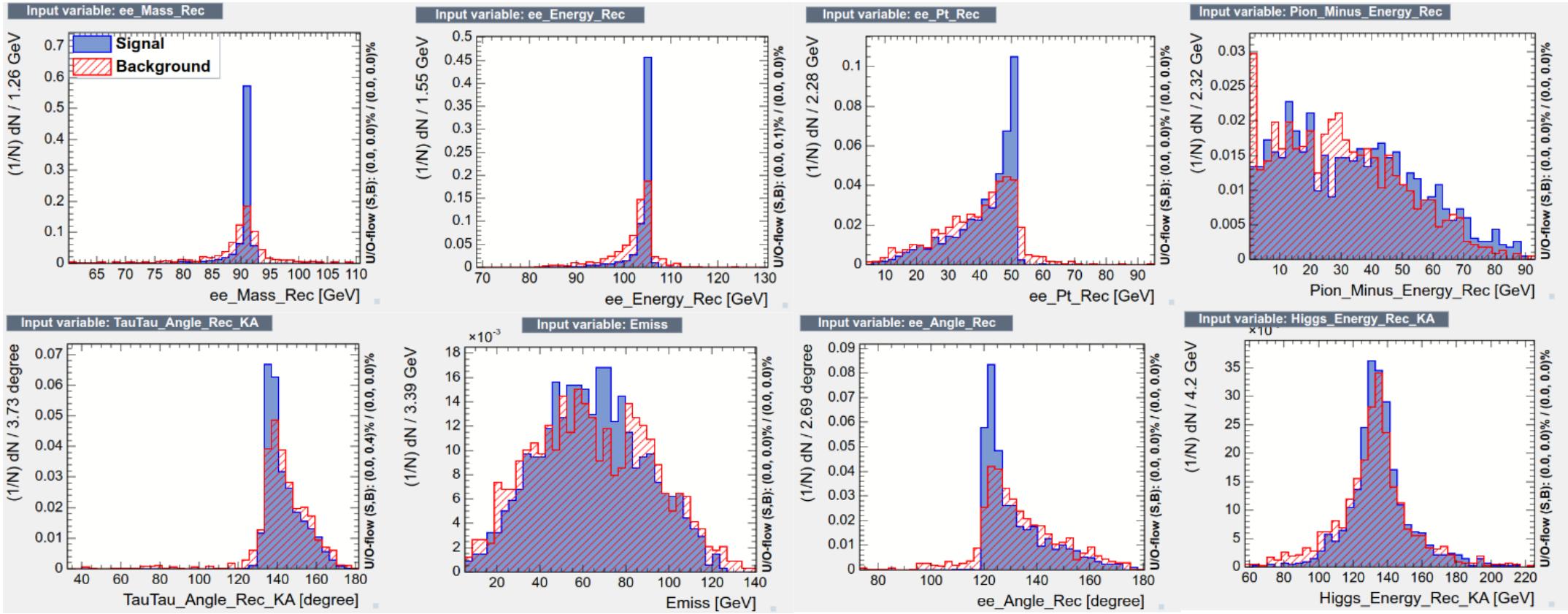
Backup


CEPC
The 2026 International Workshop on the
High Energy Circular Electron Positron Collider

Leptonic Z decays

- 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



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

