Institute of Experimental Particle Physics

Karlsruher Institut für Technologie

$H \to \tau\tau$ MEASUREMENTS AT FCC-ee IN THE ZH CHANNEL AT 240 GeV

Sofia Giappichini, Markus Klute, Matteo Presilla, Aaron Wiedl, Xunwu Zuo

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$H \to \tau\tau$ CROSS-SECTION

General workflow

- We excluded all isolated electrons and muons ($p_T > 20$ GeV and iso<0.25) from jets
  - **Inclusive e^+e^- generalized kt algorithm** with R=0.5 and $p_{T,j} > 2$ GeV
  - **Exclusive e^+e^- Durham algorithm** with n_{jets} depending on the category

- We define **nine categories** based on the Z and tau decays ($\ell = e, \mu$)
  - $Z \to \ell\ell$
  - $Z \to qq$
  - $Z \to \nu\nu$
  - $H \to \tau_\ell\tau_\ell$
  - $H \to \tau_\ell\tau_h$
  - $H \to \tau_h\tau_h$
- Basic selection requires exactly the objects in each category to be reconstructed

- Leptonic taus are always handled "manually" by selecting the isolated leptons
- Quark jets are differentiated from hadronic tau jets depending on the reconstruction method ➜ next slide

Tau reconstruction

- Both methods are based on jet clustering

Explicit

- Only jets with no electrons or muons
- Gets the leading π
- Adds constituents to it if pt>1 GeV and Δθ<0.2
- Defines a tau ID based on decay modes

ParticleNet

- Trained on di-jets events
- Assigns quark/tau score for each jet
- We select jets with tau score > 0.5

Efficiency compared to true taus

	Explicit tau reconstruction		ParticleNet tau reconstruction	
	Inclusive jets	Exclusive jets	Inclusive jets	Exclusive jets
$Z \to \nu\nu,\ H \to \tau\tau$	90.34%	87.09%	97.60%	94.20%
$Z \to ee,\ H \to \tau\tau$	84.96%	78.07 %	95.15%	83.21 %
$Z \to \mu\mu,\ H \to \tau\tau$	84.96%	79.94%	95.15%	83.21%
$Z \to bb,\ H \to \tau\tau$	77.69%	77.31%	76.23%	65.72%
$Z \to cc,\ H \to \tau\tau$	78.45%	78.07%	76.58%	65.72%
$Z \to ss,\ H \to \tau\tau$	78.82%	78.07%	76.15%	65.50%
$Z \to qq,\ H \to \tau\tau$	78.78%	77.95%	76.57%	65.50%

Results

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- **Combine shape-based fit** arXiv:2404.06614 with 20% lnN background uncertainty and MC statistical uncertainties
  - Cut-based analysis: M_{recoil} for $Z \to \ell\ell$ and $Z \to qq$, M_{vis} for $Z \to \nu\nu$
  - BDT analysis: M_{recoil} for $Z \to \ell\ell$, BDT score for $Z \to qq$ and $Z \to \nu\nu$
- Final numbers for the relative uncertainty (68% CL) of $H \to \tau\tau$ cross section at $\sqrt{s}$=240 GeV, $\mathscr{L}$=10.8 ab^{-1}
- Best result from ParticleNet tau reconstruction using exclusive jets and applying the BDT selection

	Explicit tau reconstruction		ParticleNet tau reconstruction	
	Inclusive jets	Exclusive jets	Inclusive jets	Exclusive jets
Cut-based analysis	-1.28 %, +1.30%	±1.54%	±0.95%	±1.15%
BDT analysis	±1.02%	±0.88	±0.79%	±0.74%

$H \rightarrow \tau\tau$ CP

General info

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- Mapping of EFT Yukawa operator to kappa framework (commonly used in analyses)

$$\mathscr{L}_{\text{Yukawa},\kappa} = -\sum_f \frac{y_f^{\text{SM}}}{\sqrt{2}} \kappa_f \bar{f} \left(\cos\phi_f + i\gamma_5 \sin\phi_f\right) f \, ,$$

$$C_{fH,ij} = \text{Re}[C_{fH,ij}] + i\,\text{Im}[C_{fH,ij}] \equiv C_{fH+,ij} + iC_{fH-,ij} \, .$$

$$\kappa_f \cos\phi_f \doteq 1 - \frac{v}{\sqrt{2}m_f} \frac{v^2}{\Lambda^2} C_{fH+} \, , \qquad \kappa_f \sin\phi_f \doteq -\frac{v}{\sqrt{2}m_f} \frac{v^2}{\Lambda^2} C_{fH-} \, .$$

- Working on mostly gen level information with samples that only have $\tau \to \pi\nu$ decays in SMEFT@LO under the *topU3L* flavor assumption

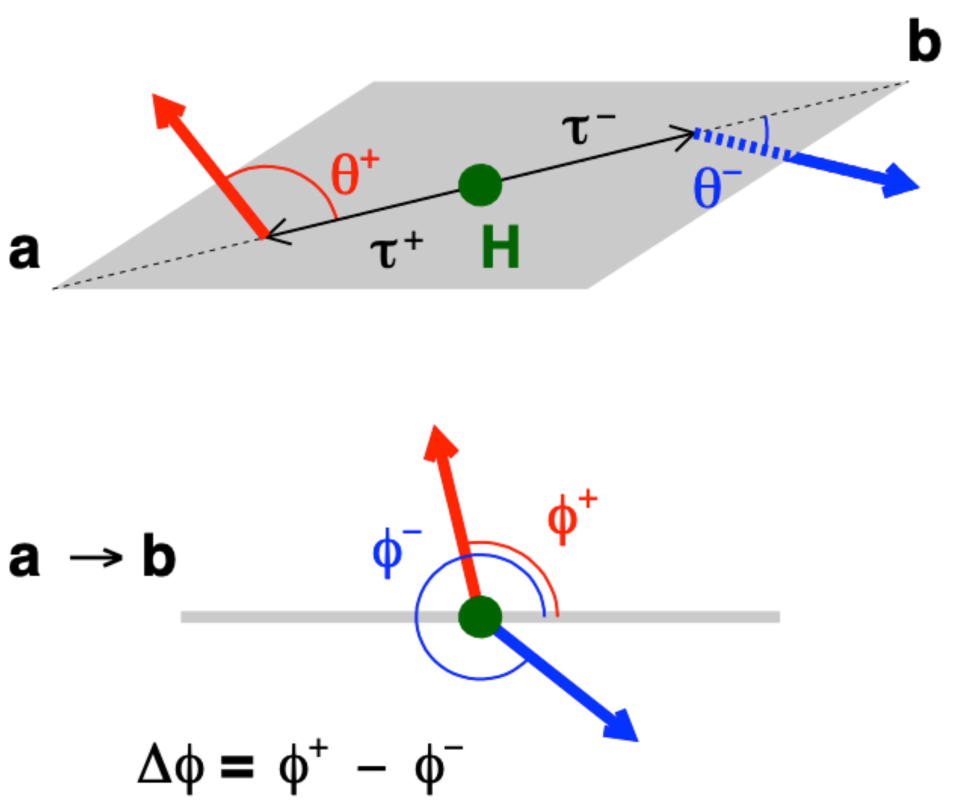
ILC method

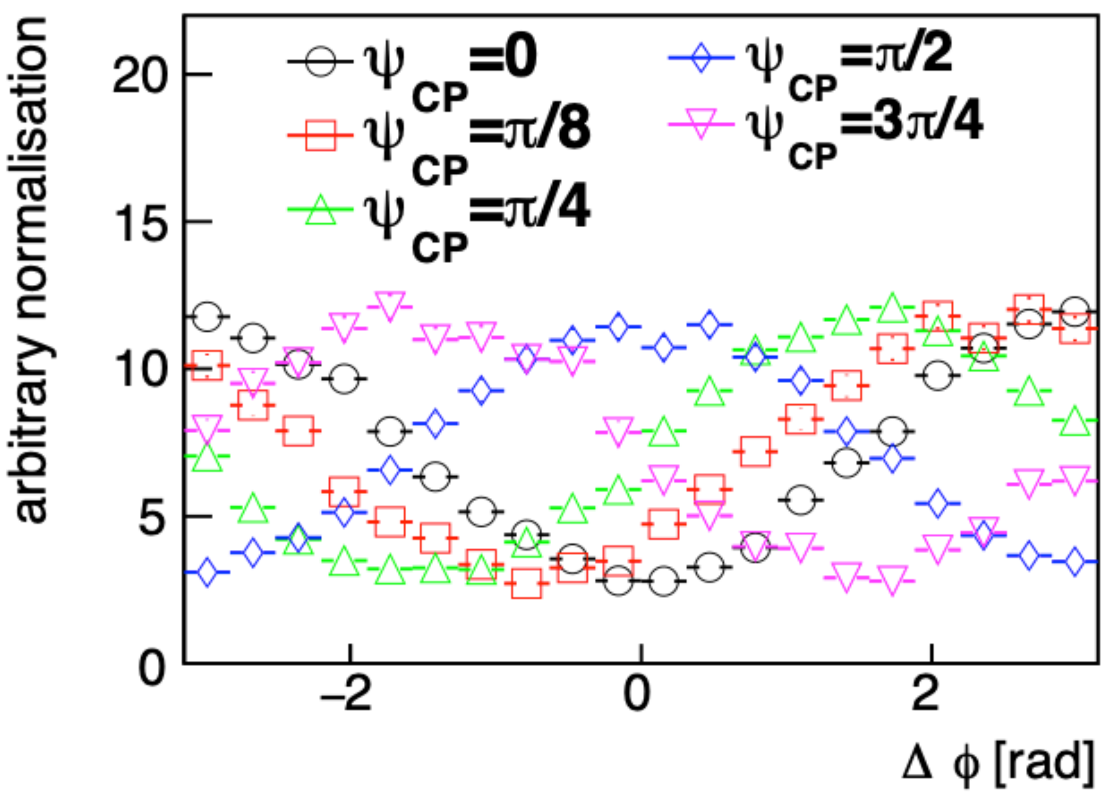
https://arxiv.org/pdf/1804.01241

- Reconstruct the decay plane using polarimeters
- The 4-momenta are boosted in the respective tau rest frame

$$\mathbf{h}(\tau^\pm \to \pi^\pm \nu) \propto \mathbf{p}_{\pi^\pm} \tag{6}$$

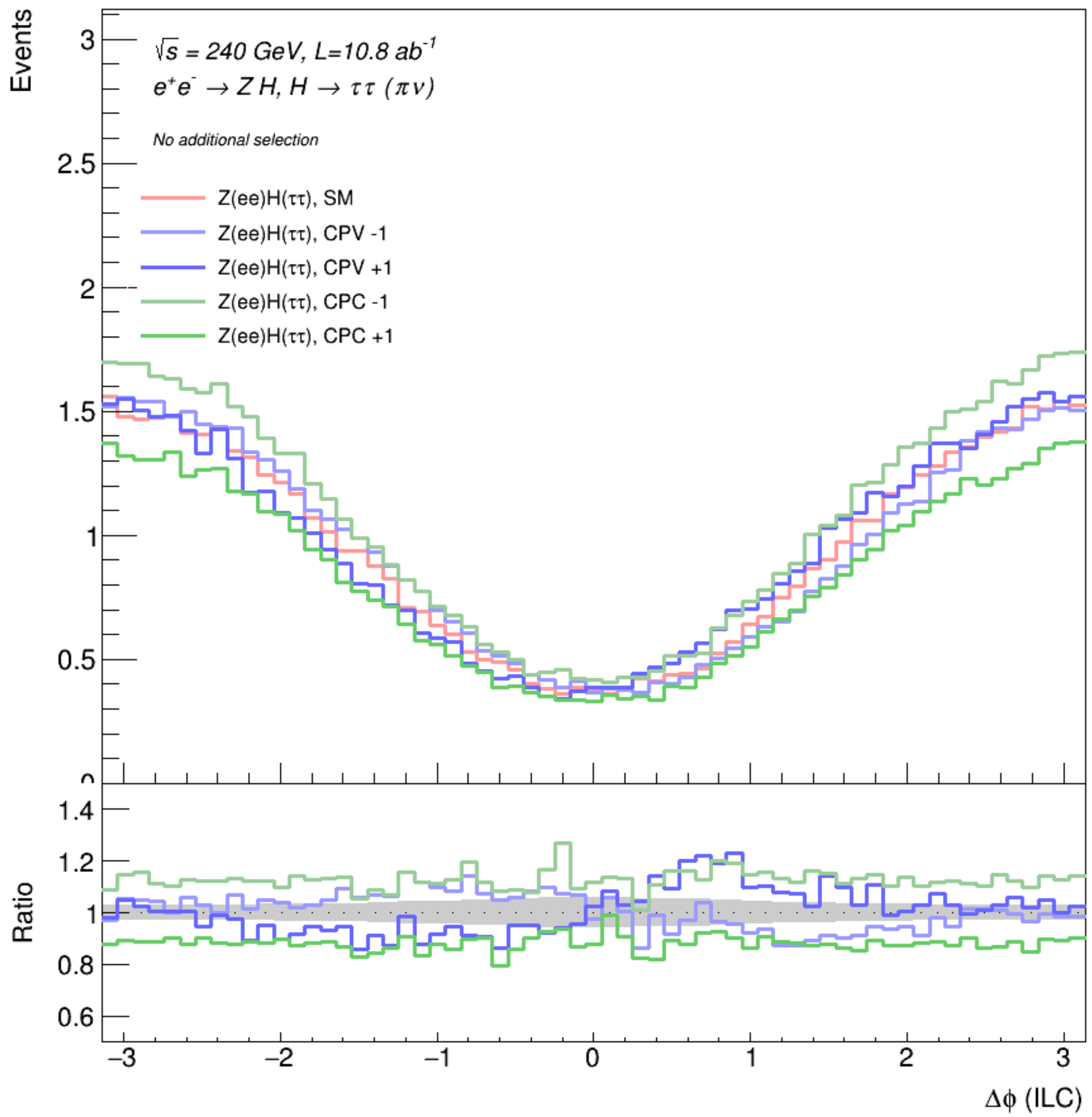
$$\mathbf{h}(\tau^\pm \to \pi^\pm \pi^0 \nu) \propto m_\tau (E_{\pi^\pm} - E_{\pi^0})(\mathbf{p}_{\pi^\pm} - \mathbf{p}_{\pi^0}) + \frac{1}{2}(p_{\pi^\pm} + p_{\pi^0})^2 \mathbf{p}_\nu, \tag{7}$$



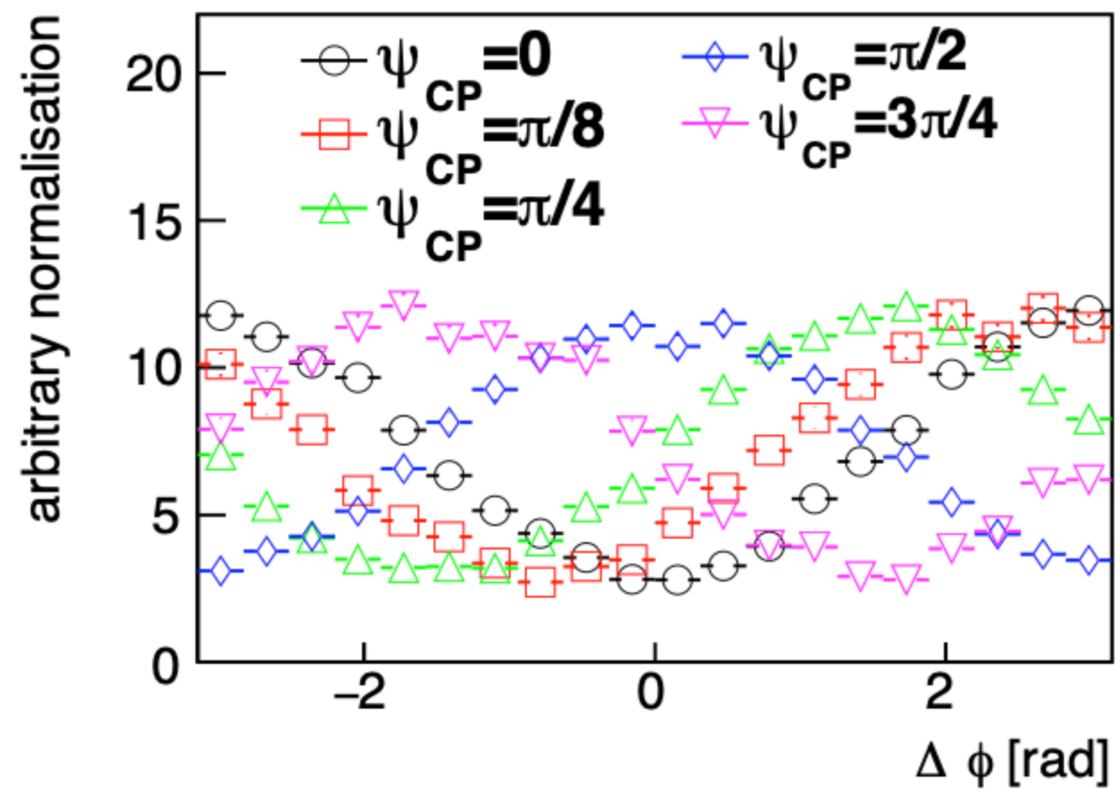


- In the ILC publication, samples with varying Higgs CP properties were simulated by changing the spin correlations applied in the decay of the τ pair by means of Pythia's `HiggsH1:phiParityparameter` to describe ψCP = 0 (i.e. the SM), π/8,π/4,π/2, and 3π/4 rad - we will also test this simulation setup despite should be equivalent to the EFT approach.

ILC method - gen level



ILC Paper



- Very similar to the true angle, the only difference is using the respective tau rest frames instead of the Higgs
- Same as before, whizard sample is flat (not plotted here)

ILC method - reconstruction

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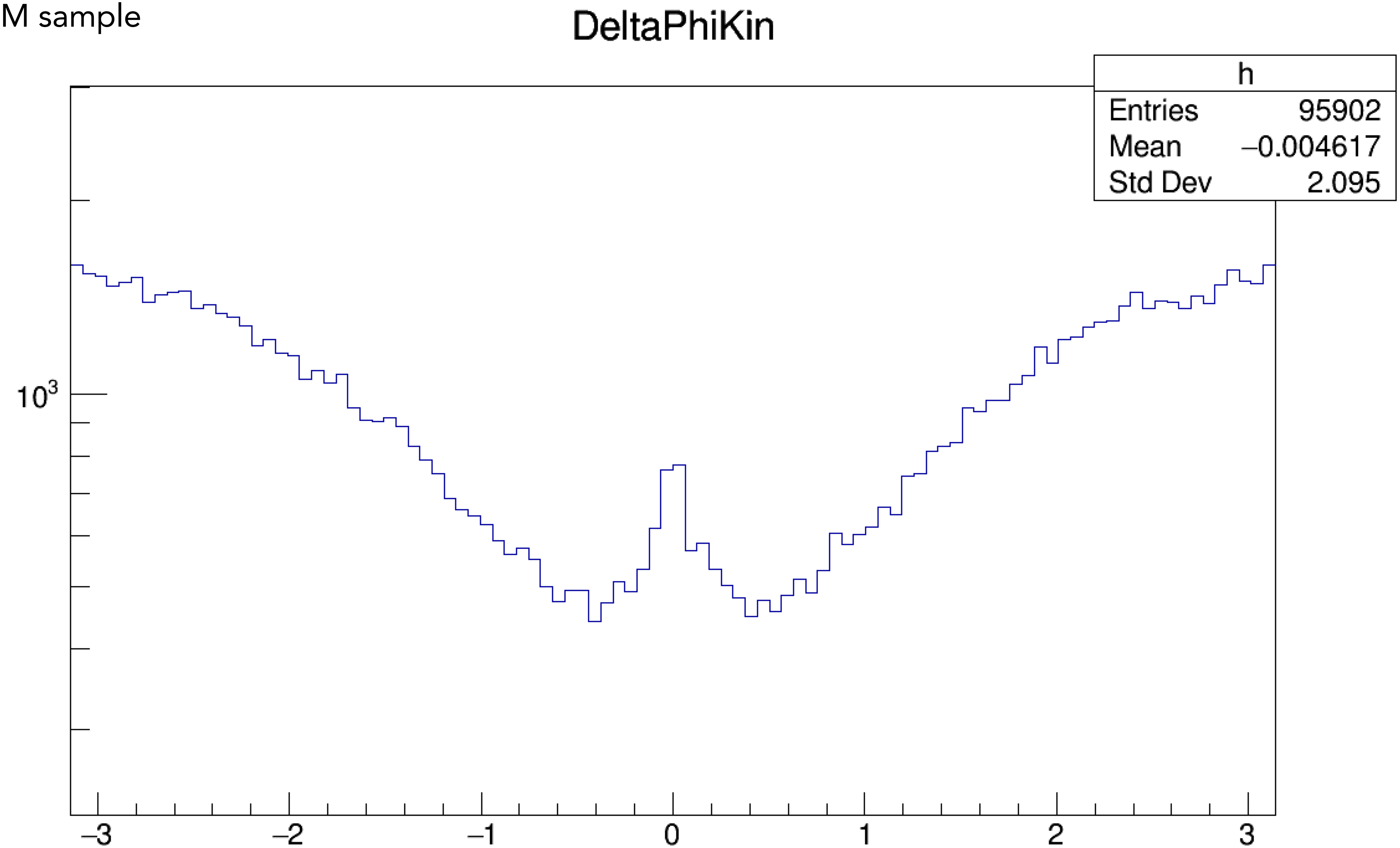
- Using gen Higgs and pions we can test the reconstruction method:
  - Minimize χ^2 function for the tau mass (1 MeV precision), missing 4-vector and recoil 4-vector (10 Mev precision)
  - Uses **ROOT minuit2**, initially we tried minuit but it had trouble properly converging
  - Comparison of the reconstructed taus with the true gen taus is very good ($0 \pm 1\ GeV$ in each component of the 4-vectors)
  - But looking at the $\Delta\phi$ there is an excess of events around 0 which can be eliminated by **constraining the reconstructed mass** to be as close as possible to 1.777 GeV (1.77-1.78)
  - Unfortunately, this is still not enough to show CPV: this could be “solved” with further cuts on the taus, such as pT (suggested from CMS analyses) or better precision in the fit, it will be studied in the next days

- There is also a fitting strategy used by the ILC paper but still needs to be adapted to minuit2 to work porperly

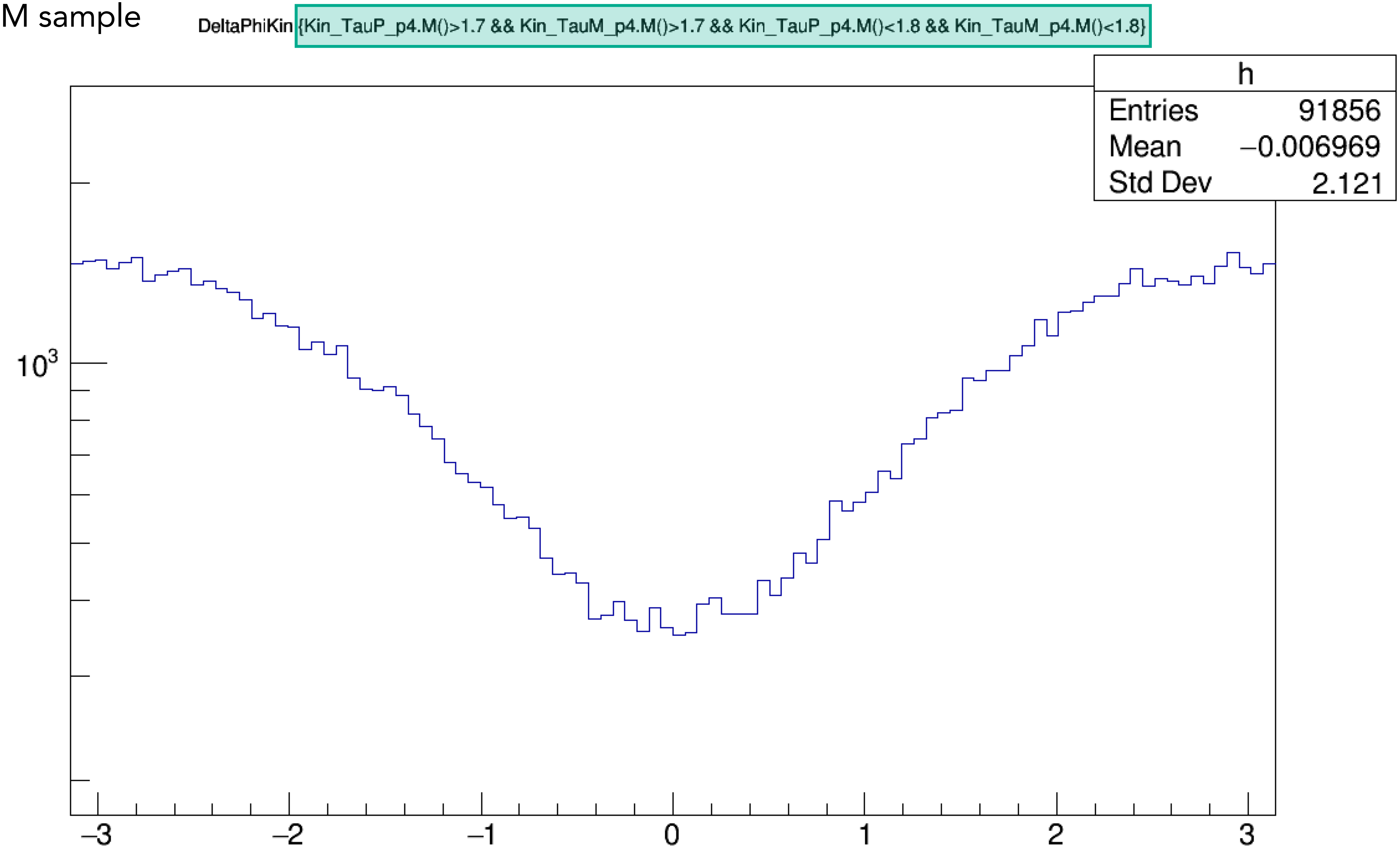
ILC method - reconstruction

SM sample



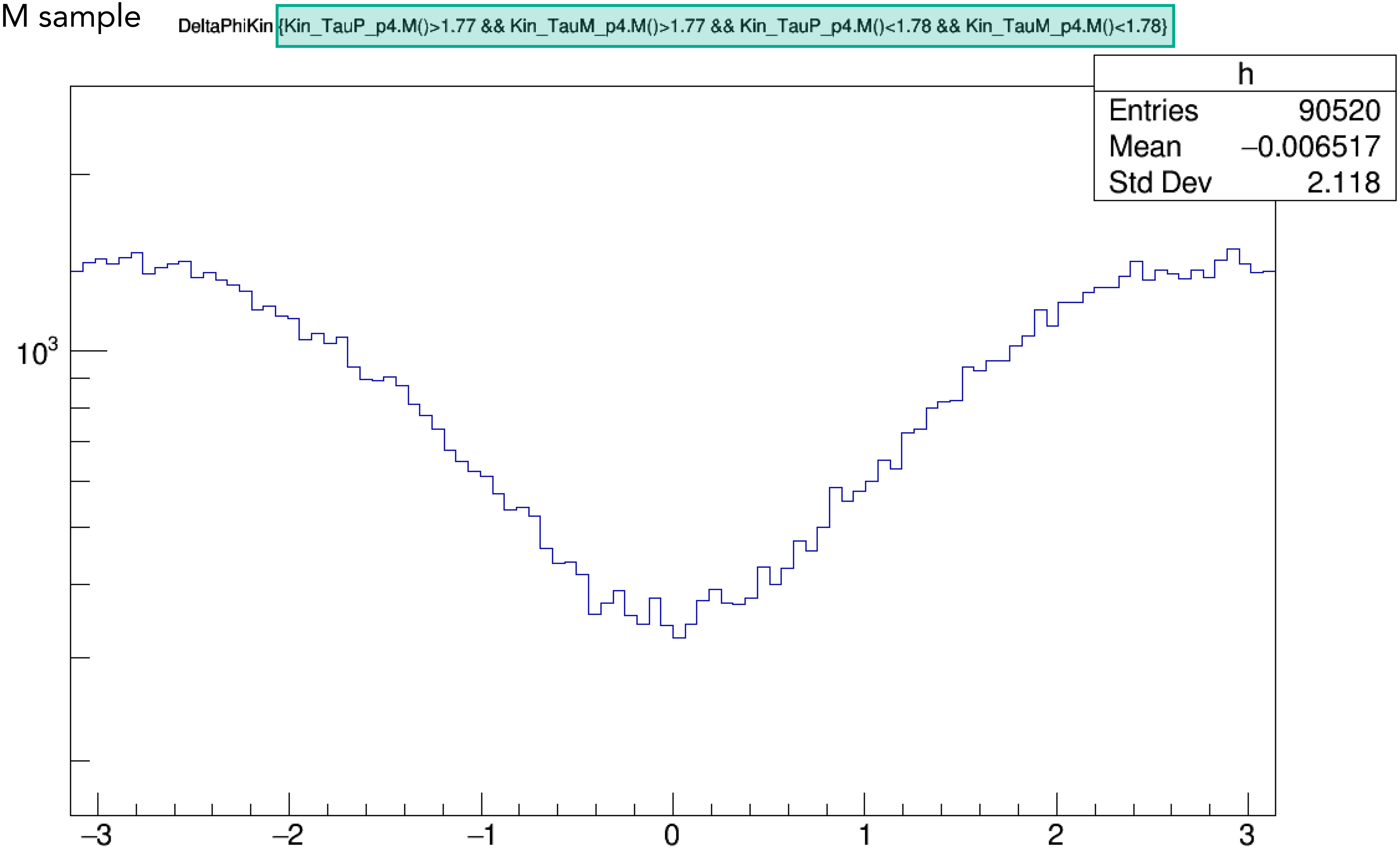
ILC method - reconstruction

SM sample

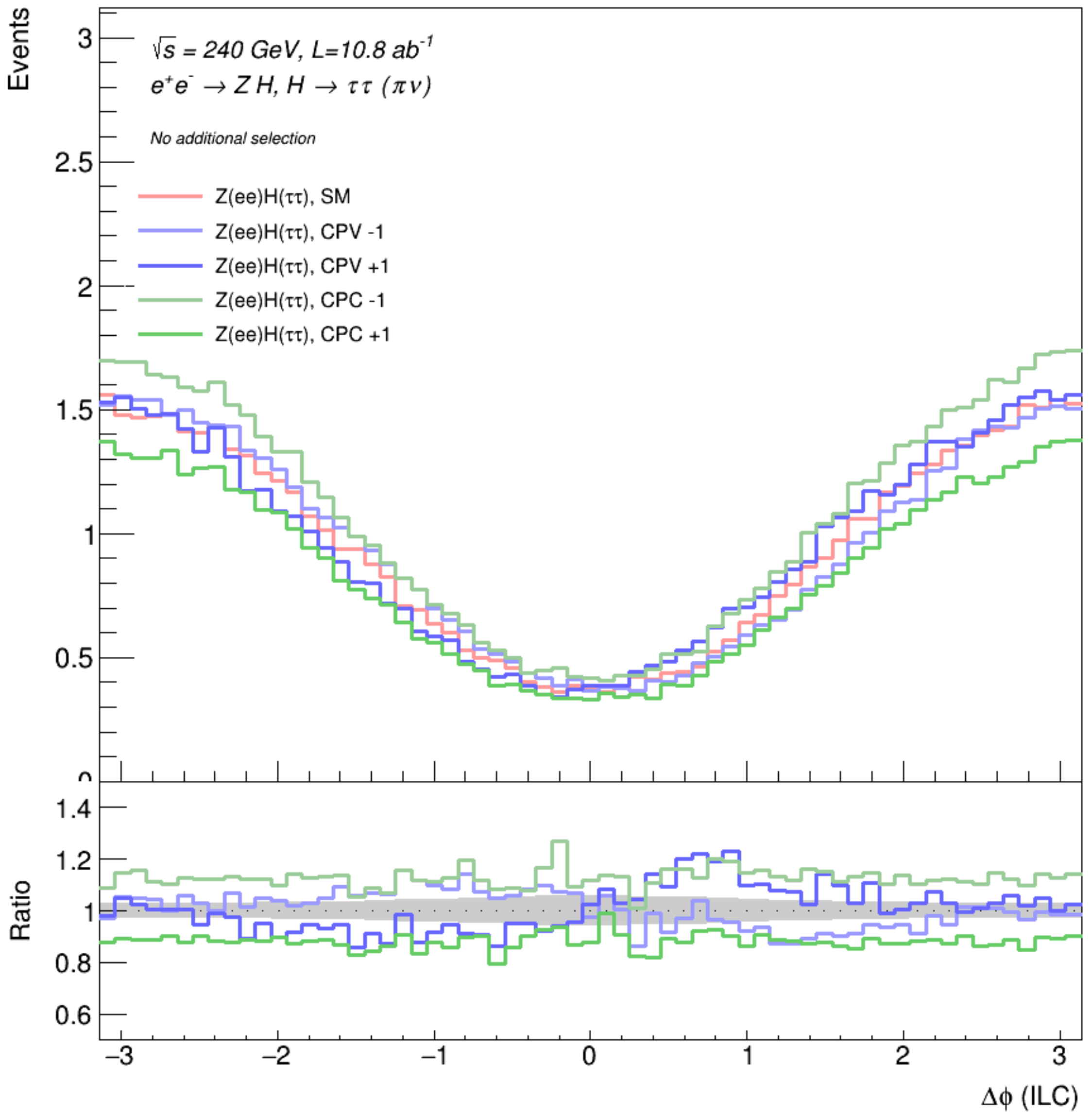


ILC method - reconstruction

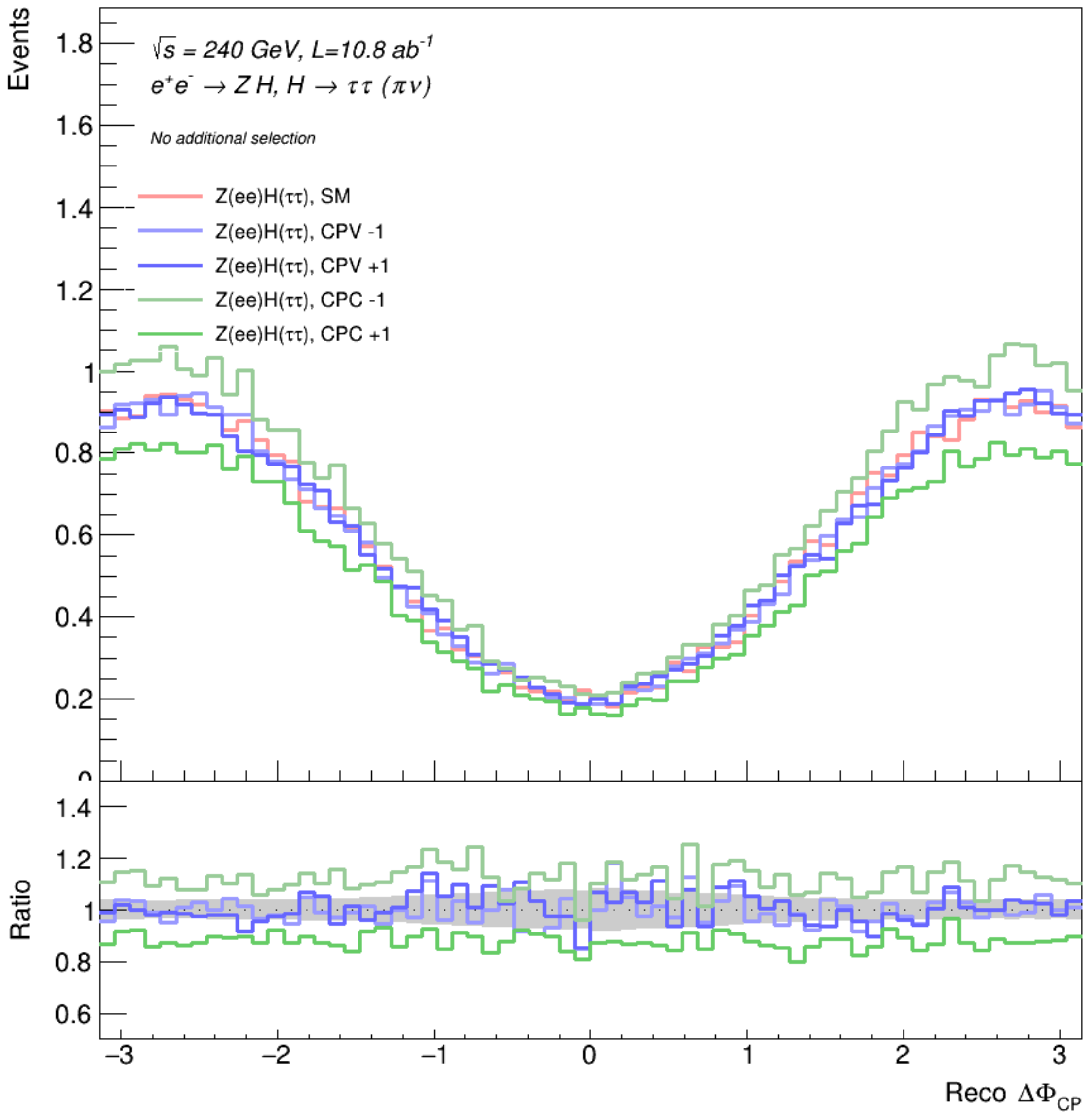
SM sample



ILC method - reconstruction



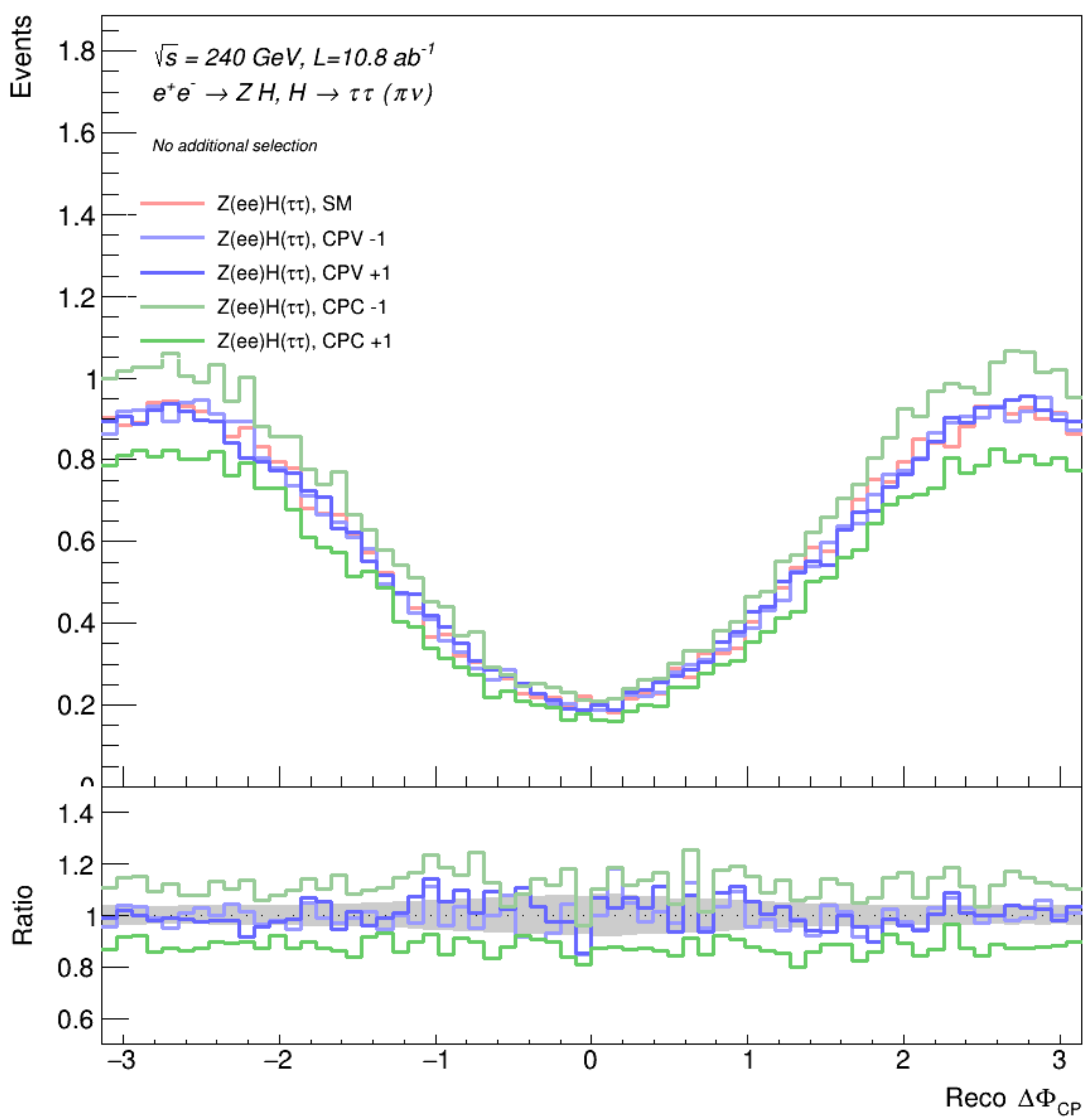
Purely gen



Reconstructed tau with gen info

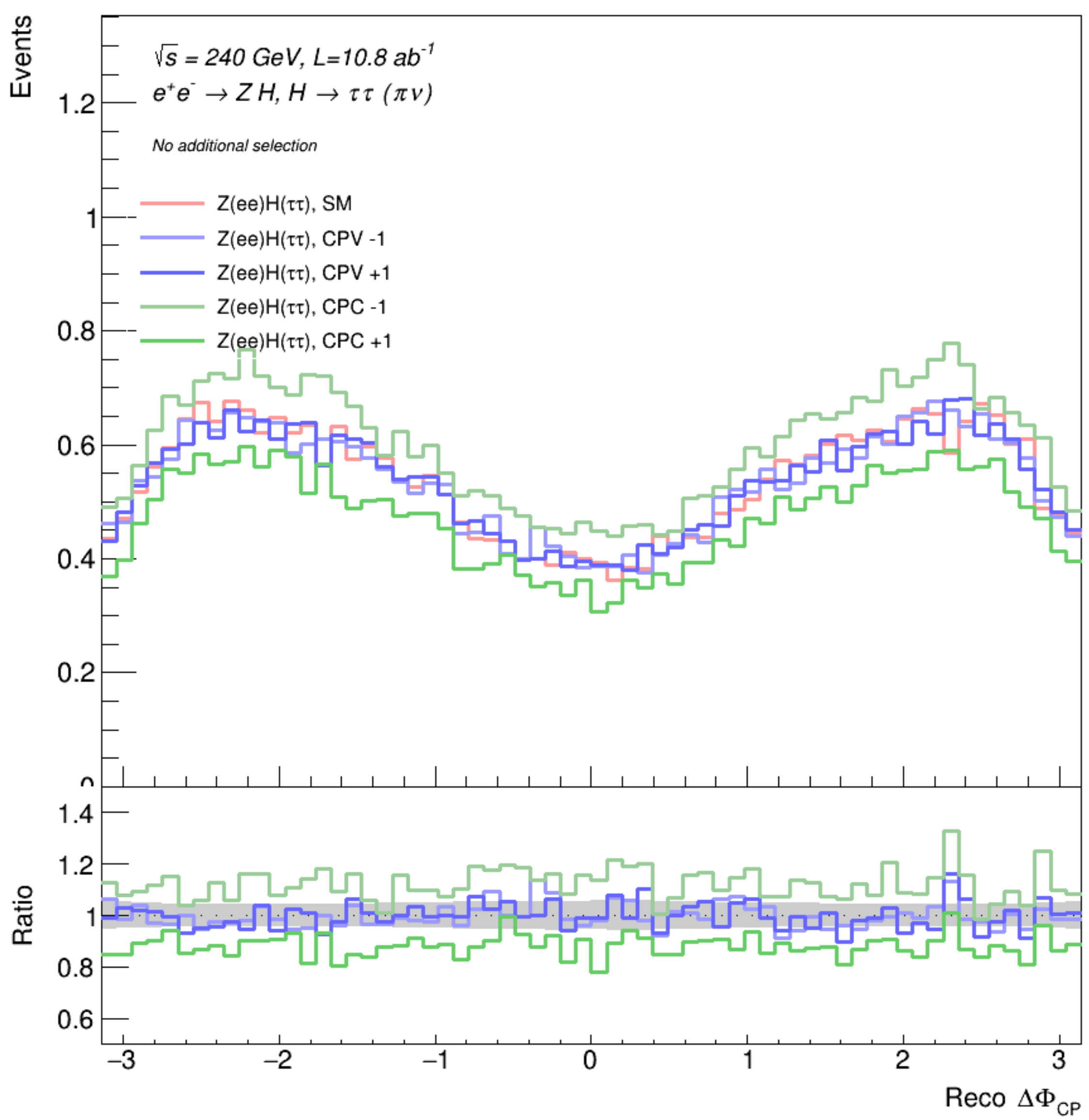
$1.77 < m_\tau < 1.78$

ILC method - full reconstruction



Reconstructed tau with gen info

$1.77 < m_\tau < 1.78$

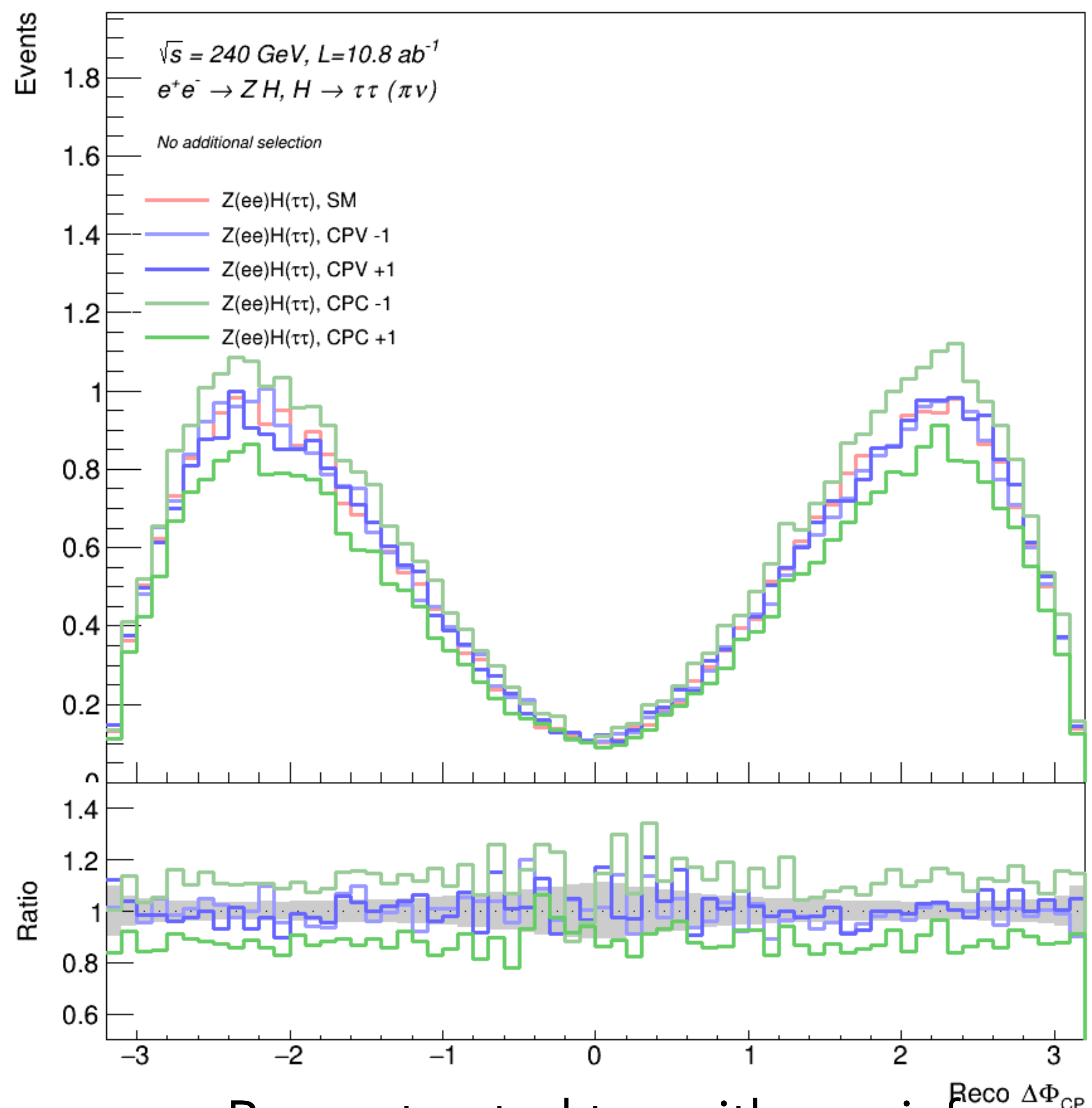


Reconstructed tau with reco info

$1.77 < m_\tau < 1.78$

Belle reconstruction

- We also tried to follow this Belle paper that makes use of the recoil rest frame to reconstruct the tau 4-vectors:
  - Any "analytical" method has a two-fold ambiguity that can be "resolved" with additional considerations such as missing energy and ΔR between tau and neutrino
  - But the method always reconstructs in our case taus with 5 GeV more energy than they should, giving an energy |balance of -10 GeV
  - Also, the boundary bins of $\Delta\phi$ are not well-treated and the CPV is washed out



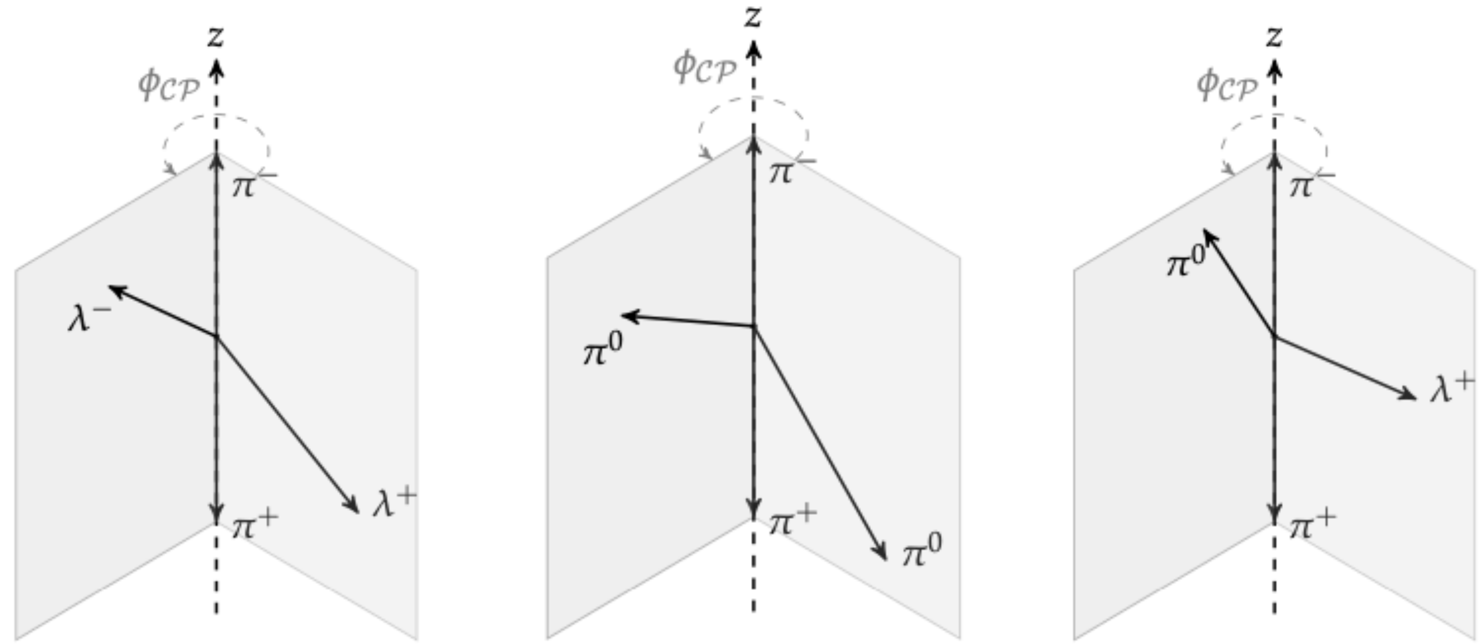
Reconstructed tau with gen info

BACKUP

CMS reconstruction

https://arxiv.org/pdf/2110.04836

- Reconstruct the angle between the decay planes without accessing the tau 4-momentum
- Uses instead the impact parameter vector for one-prong decay or π^0 and π for rho decays (also possible to mix them) with boost in the charged particles zero momentum frame



- If the tau momenta is instead well known (three-prong), they use the polarimetric method and the secondary vertex to determine the a direction

$$|\vec{p}_\tau| = \frac{(m_{a_1}^2 + m_\tau^2)|\vec{p}_{a_1}|\cos\theta_{GJ} \pm \sqrt{(m_{a_1}^2 + |\vec{p}_{a_1}|^2)((m_{a_1}^2 - m_\tau^2)^2 - 4m_\tau^2|\vec{p}_{a_1}|^2\sin^2\theta_{GJ})}}{2(m_{a_1}^2 + |\vec{p}_{a_1}|^2\sin^2\theta_{GJ})}. \quad (9)$$

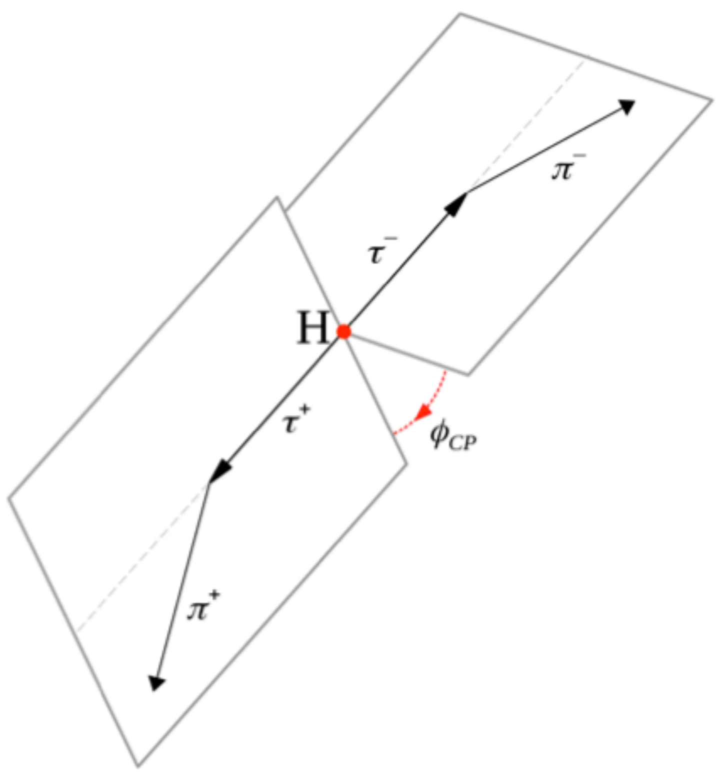
The maximal allowed value θ_{GJ}^{max} of the Gottfried–Jackson angle is defined as

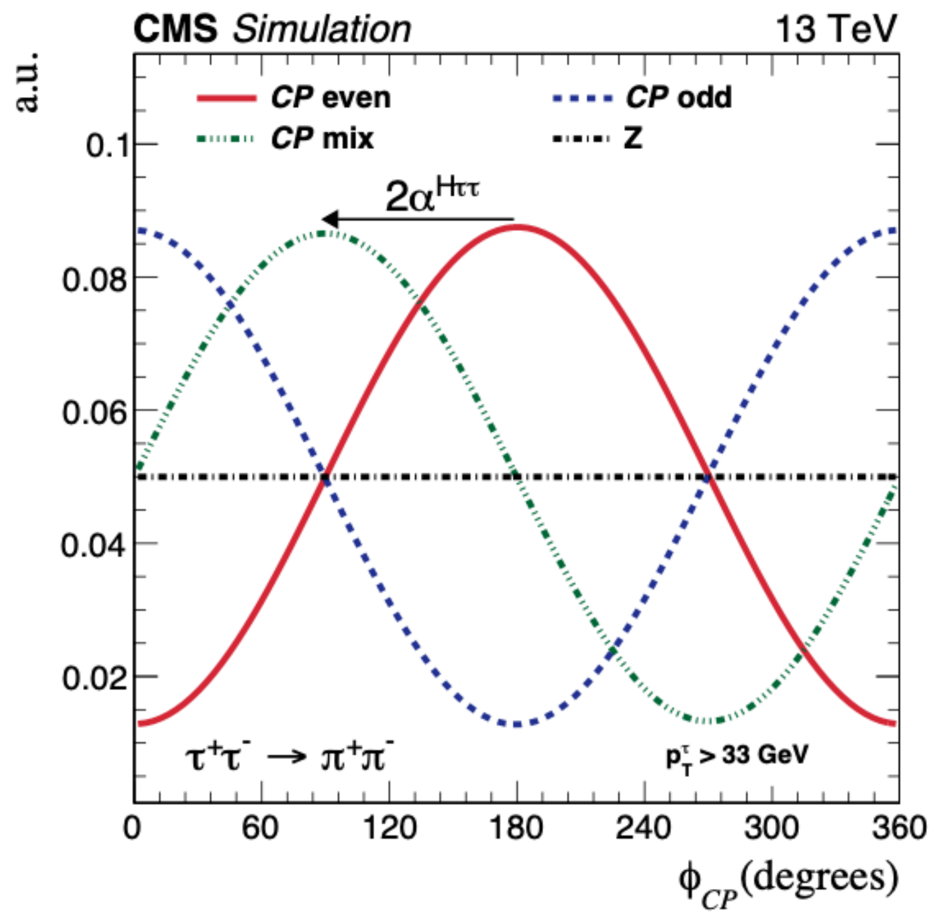
$$\theta_{GJ}^{max} = \arcsin\left(\frac{m_\tau^2 - m_{a_1}^2}{2m_\tau|\vec{p}_{a_1}|}\right). \quad (10)$$

Gen information

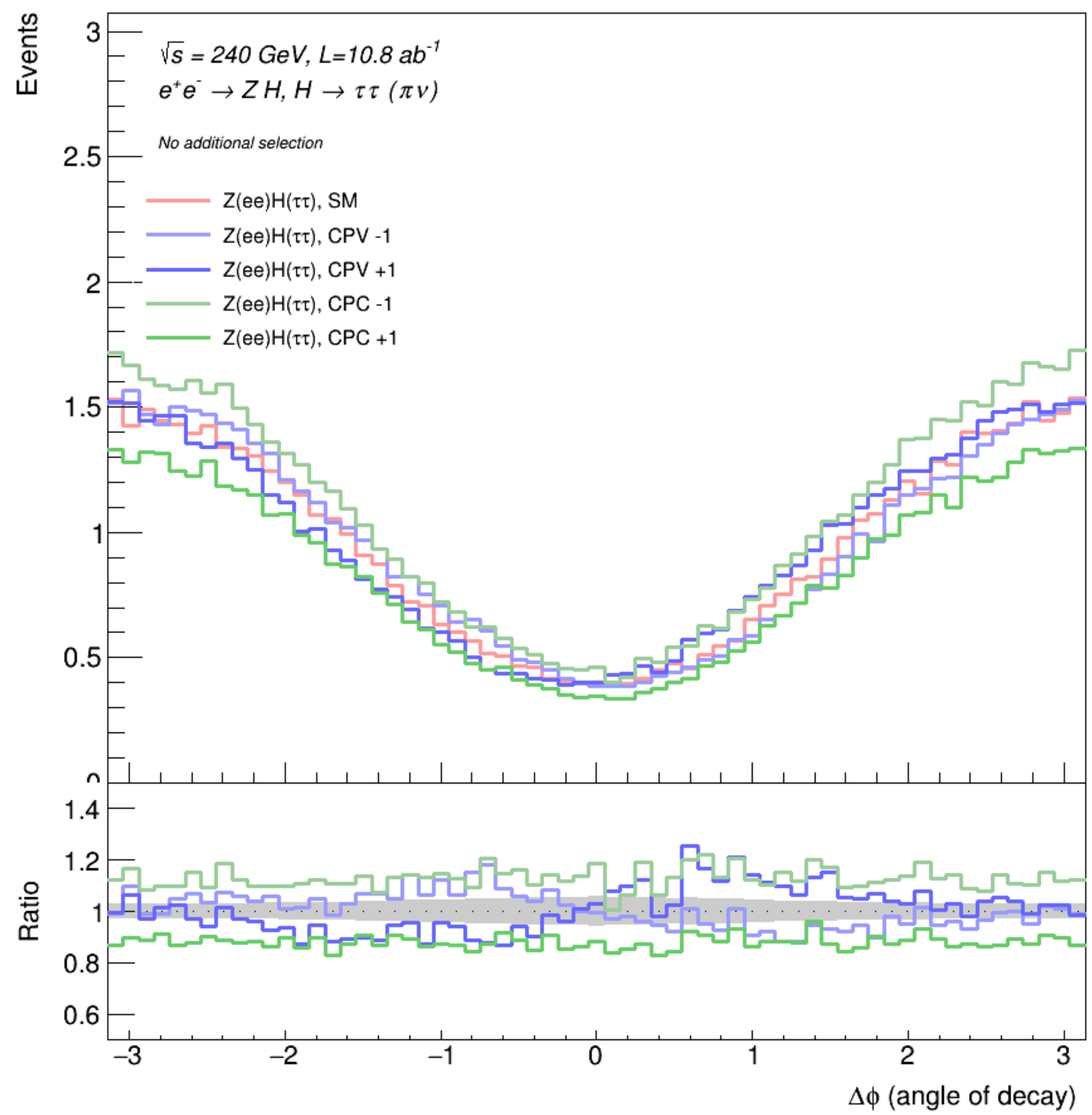
https://arxiv.org/pdf/2110.04836

- The general idea of all the reconstruction methods is to get the **angle between the decay planes** of the tau in the di-tau rest frame
- We can reconstruct the planes directly by knowing the tau and daughters' 4-momenta
- All vectors are boosted in the Higgs rest frame
- We take the direction of the τ^- as reference to get the value of ϕ_{CP}



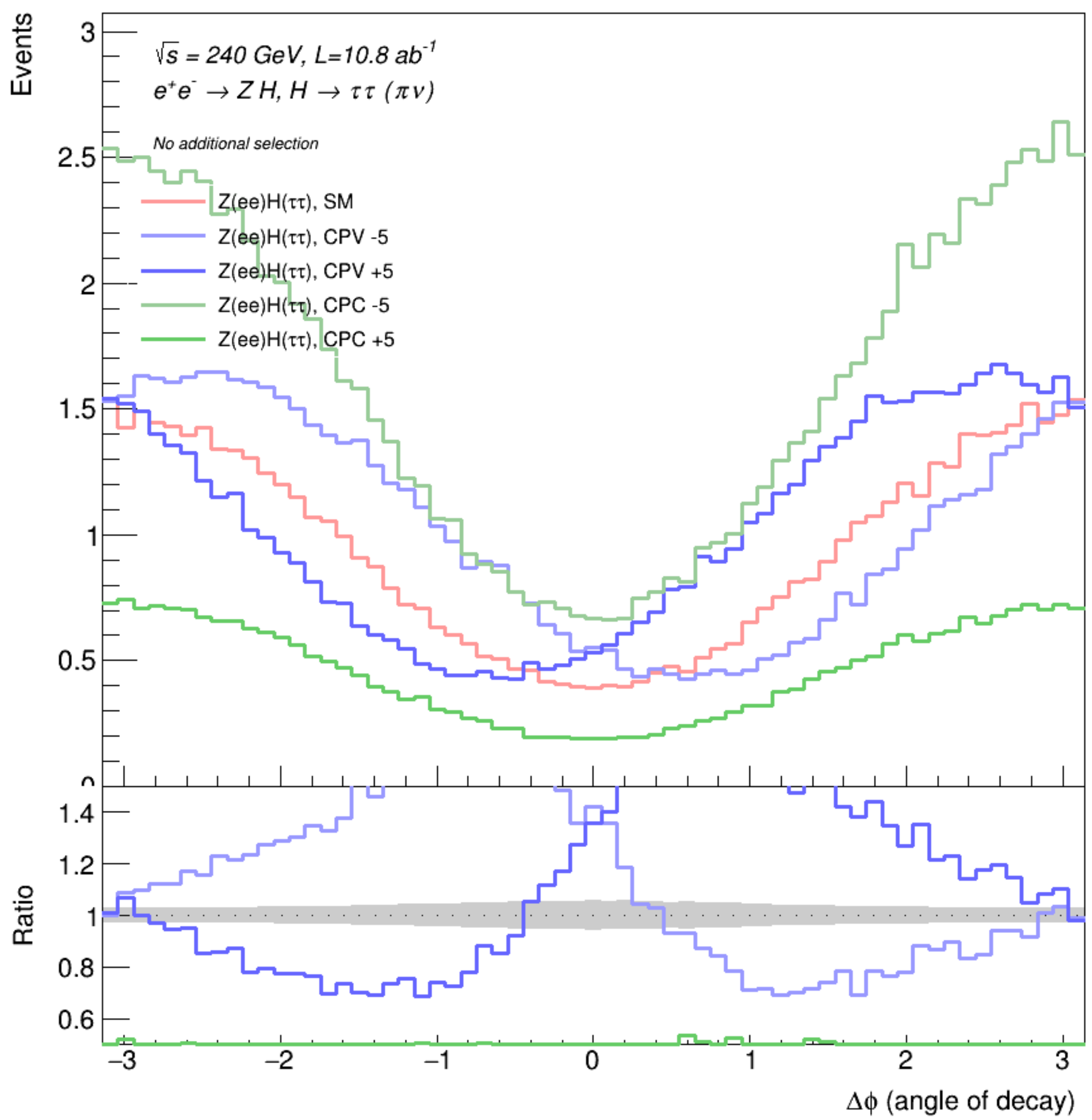


Gen information



- Tested Wilson Coefficients ± 1 for the operators $Re\{\mathcal{O}_{eh}\}, Im\{\mathcal{O}_{eh}\}$ in SMEFT@LO under the *topU3L* flavor assumption
- Only for $\tau \to \pi\nu$, everything is scaled to the appropriate cross-section
- There is a tiny phase shift with CP-violating samples while CP-conserving ones only have a cross-section difference with SM

Gen information



- Tested Wilson Coefficients ±5 for the operators $Re\{\mathcal{O}_{eh}\}, Im\{\mathcal{O}_{eh}\}$ in SMEFT@LO under the *topU3L* flavor assumption
- Only for $\tau \to \pi\nu$, everything is scaled to the appropriate cross-section