Update on $H \to \tau\tau$ CP at FCC-ee with $\sqrt{s} = 240$ GeV

Sofia Giappichini, Matteo Presilla

ETP FCC meeting
17 Apr. 2025

Signal samples

- Effective field theory (EFT) approach to introduce CPV in the SM

$$\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\text{SM}} + \sum_d \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathscr{O}_i^{(d)},$$

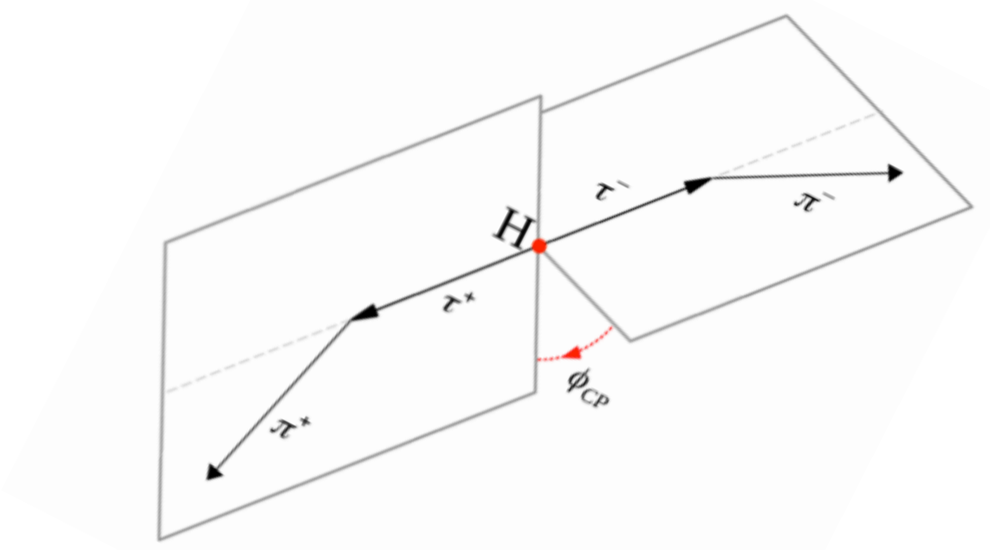
- Relevant operators to modify the $H \to \tau\tau$ vertex:

$$\boxed{\mathscr{O}_{eH} = (H^\dagger H)(\bar{L}_L \tilde{H} e_R) + \text{h.c.},} \qquad \mathscr{O}_{eW} = (\bar{L}_L \sigma^{\mu\nu} e_R)\tau^I H W^I_{\mu\nu}, \qquad \mathscr{O}_{eB} = (\bar{L}_L \sigma^{\mu\nu} e_R) H B_{\mu\nu}\,.$$

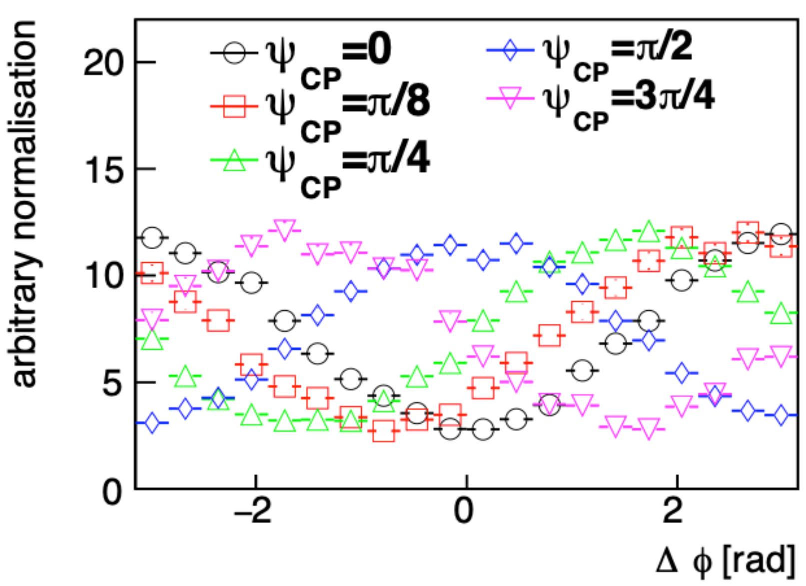
- Generation in Madgraph with TauDecay UFO arxiv:1212.6247v2 to have spin correlations and specific tau decay modes
- For now, only tested $Z \to ee$ samples
- Wilson Coefficients ± 1 for the first operator in SMEFT@LO under the topU3L flavor assumption
- The imaginary part of the operator is responsible for CPV

General idea

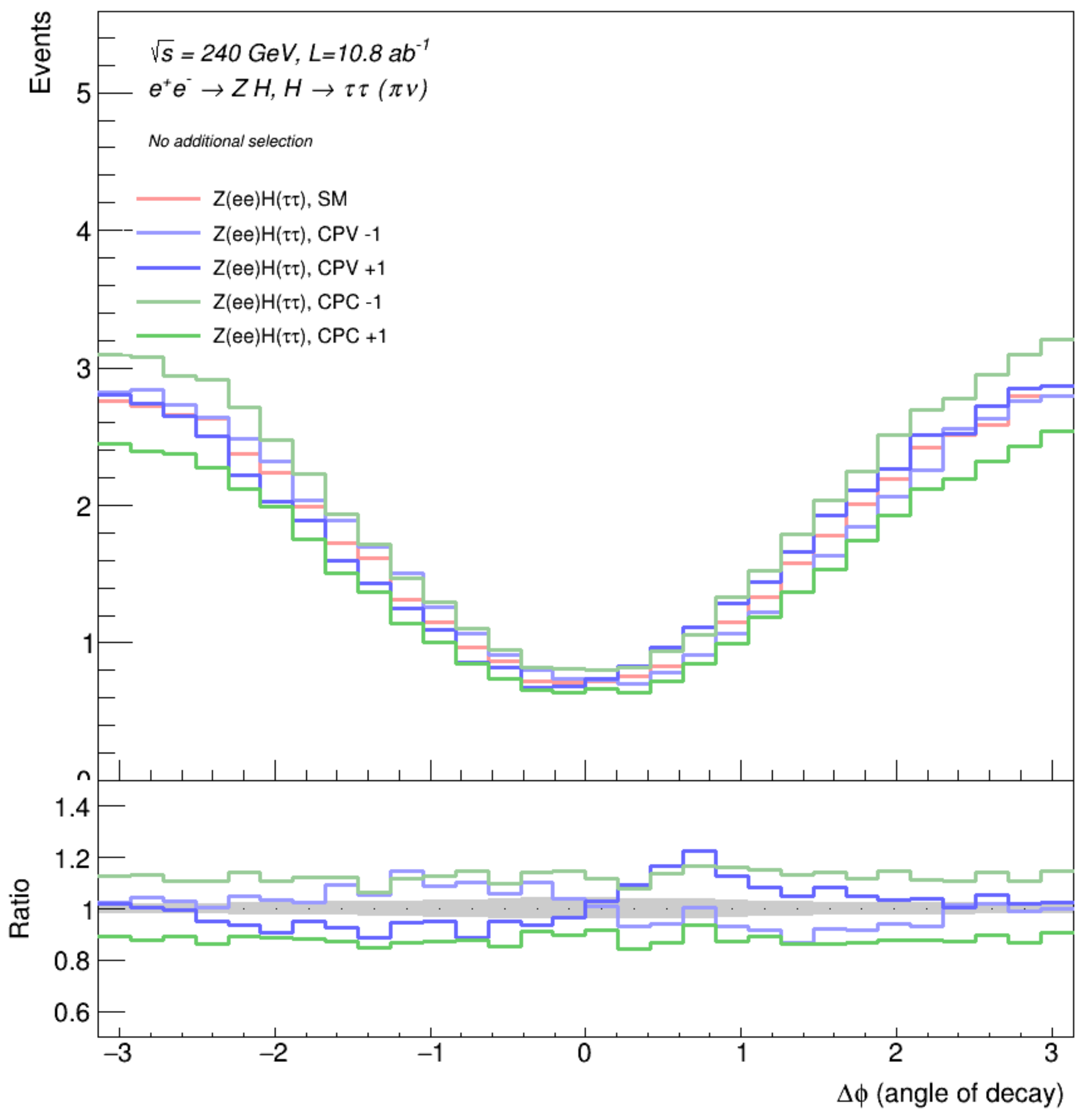
- SM Higgs is a spin 0, CPC, particle
- Any indication of CPV in the Higgs interactions with SM particles is related to BSM physics
- Pure CP odd Higgs is excluded by ATLAS and CMS ~3 σ, from the top and tau couplings

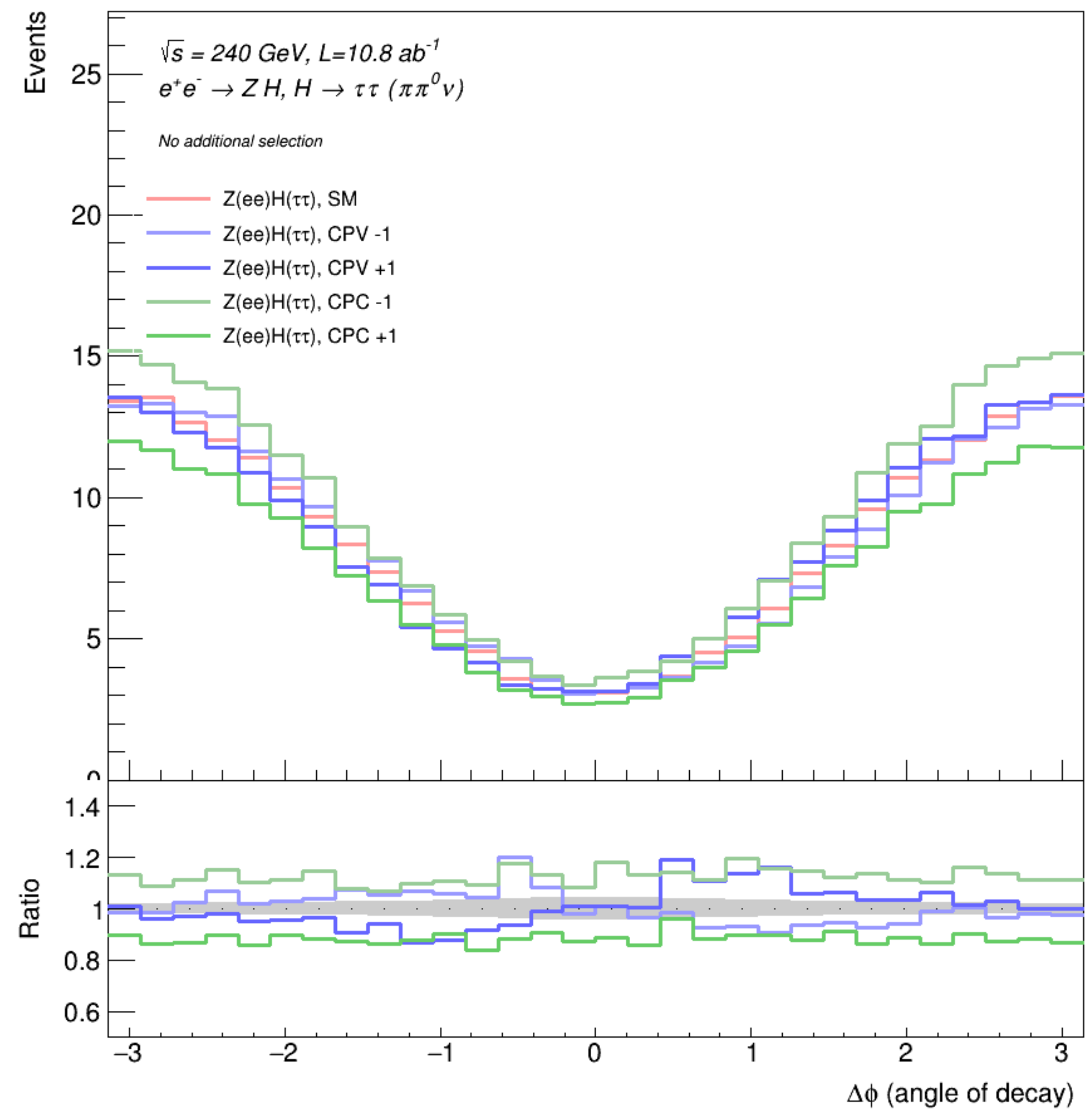


- The angle between the tau decay planes is sensitive to the CP state
- To reconstruct this, we need to know the tau daughters very well, neutrino included, or take some other proxy for the tau direction
  - "ILC" method: reconstruct the neutrinos directly
  - "CMS" method: use the impact parameter vector and the charged pion track
- The visible taus are reconstructed with the explicit function on R5 jets



Angle between planes





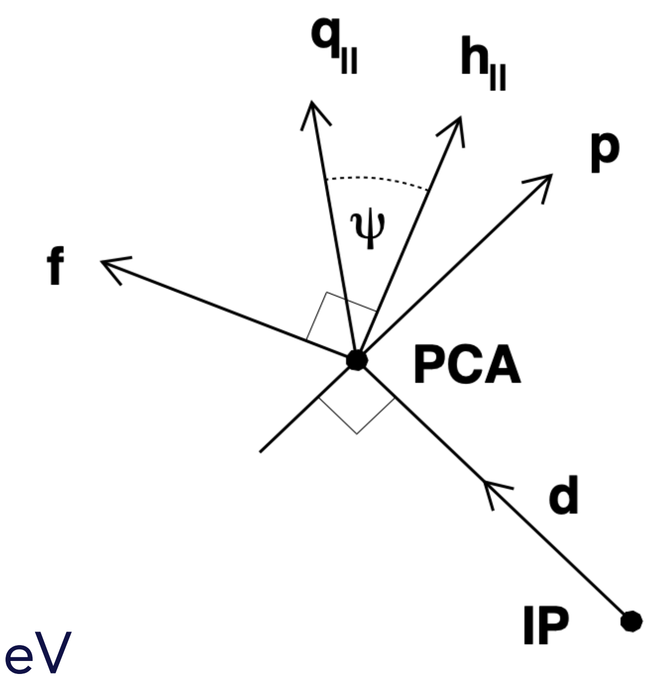
Impact parameter

- The main issue so far for both methods to fail was the imprecise knowledge of the impact parameter vector
- The one saved in the samples is **not** perpendicular to the pion track (direction of the momentum, assuming straight tracks in the relevant region), both considering it from the origin or the IP (common vertex of the primary tracks)

- The procedure that works is:
  - Use the d_0 and z_0 from the track class to get the position of the track/momentum from the origin
  - Use the momentum phi angle to get the direction of d_0 in the xy plane ($\phi_\pi + \pi/2$)
  - Find the point closest to the IP on this track (from the origin point of view)
  - Get the vector pointing from the IP to the point of closest approach ➜ this is the impact parameter vector

ILC method - tau

arxiv:1507.01700



- Full tau reconstruction based on the impact parameter vector of the single charged prong:
  - Build the decay plane with the impact vector d and the track p
  - $h = p + k$ visible tau, where k is the neutral part of the tau
  - $q_\perp = -k_\perp$ neutrino momentum perpendicular to the plane
  - Get $|q_{||}|$ by considering the energy balance with $m_\tau = 1.777$ GeV
  - Two solutions per tau are possible in general (quadratic solution)
    - If the discriminant is negative, **assume it's zero**
    - Find the crossing point between the pion track and the tau track
    - **Weight the solutions** by the likelihood that the interaction is compatible with the mean tau decay length (~87 μm), the weight is zero if the point is in the opposite direction of the tau
    - Minimize (**ROOT Minuit2**) the total transverse momentum in quadrants for $\psi_{1,2}$ $[-\pi/2,0] \times [0,\pi/2]$

ILC method - angle

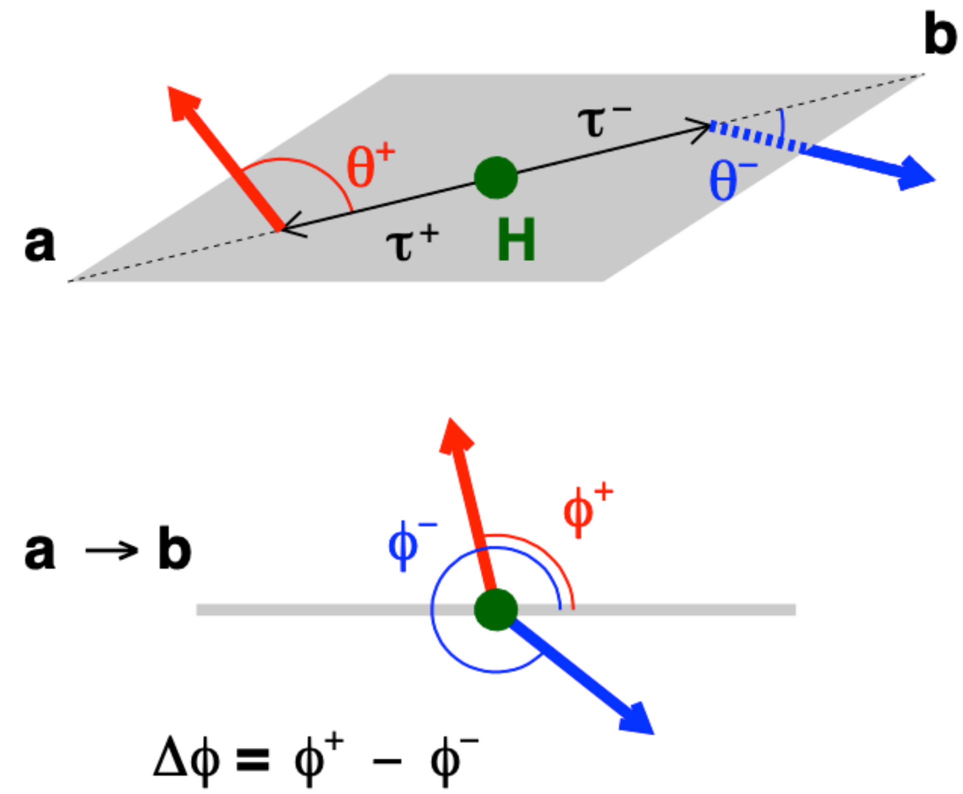
arxiv.org:1804.01241

- For $\tau \to \pi\nu$ and $\tau \to \rho\nu \to \pi\pi^0\nu$ the spin information is carried by the **polarimeters**:

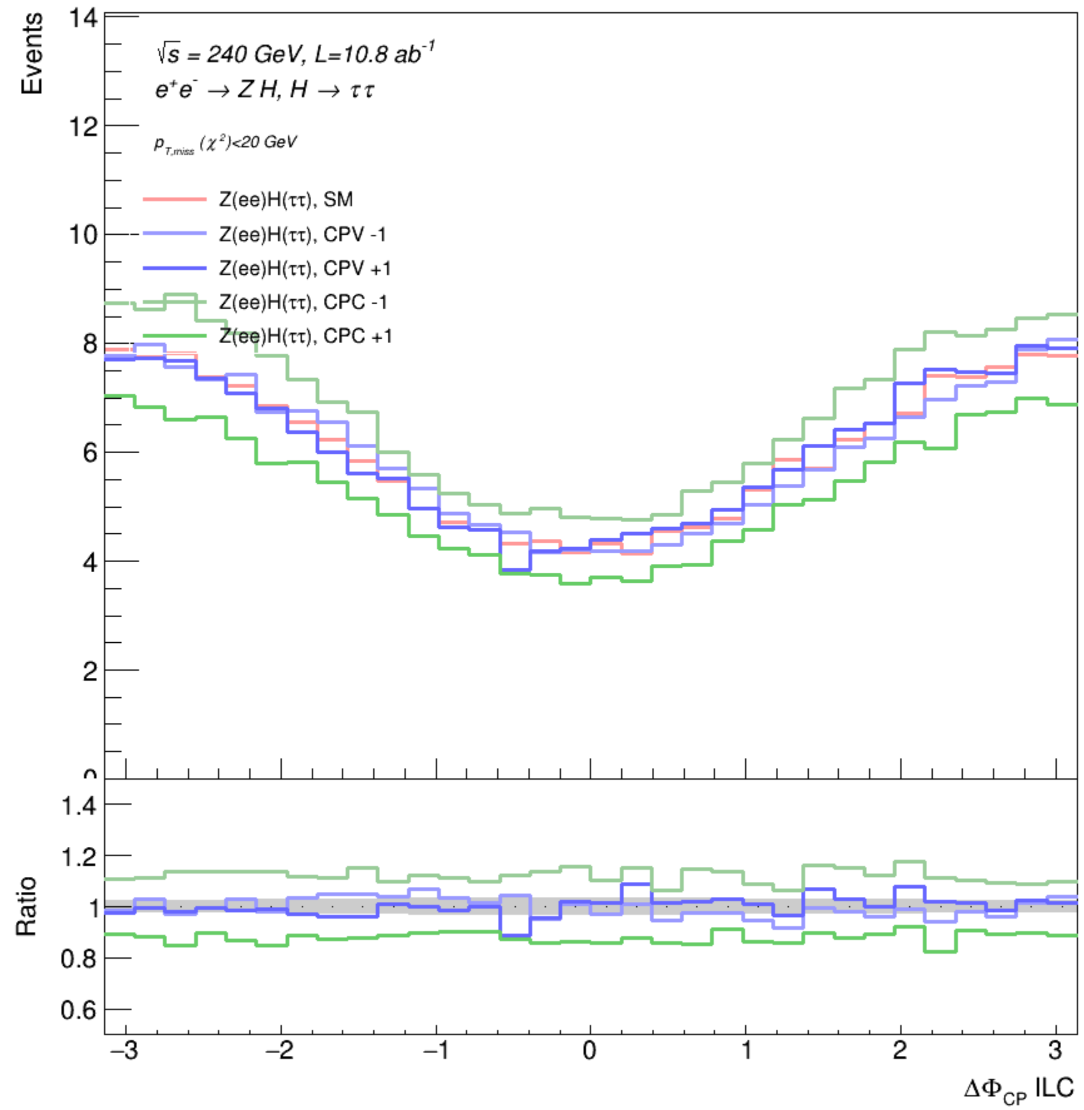
$$\vec{h}_{\tau\to\pi\nu} \propto \overrightarrow{p_\pi}, \qquad \vec{h}_{\tau\to\rho\nu} \propto m_\tau(E_\pi - E_{\pi^0})(\overrightarrow{p_\pi} - \overrightarrow{p_{\pi^0}}) + \frac{1}{2}(p_\pi + pi_{\pi^0})^2\overrightarrow{p_\nu}$$

- We use them to define the angle between the decay planes, ϕ_{CP}, by boosting them in the respective tau rest frame and taking the τ^- direction in the Higgs rest frame as reference

- **Cons**: only works on few decay modes and the recoil system needs to be well known too



ILC method - plot

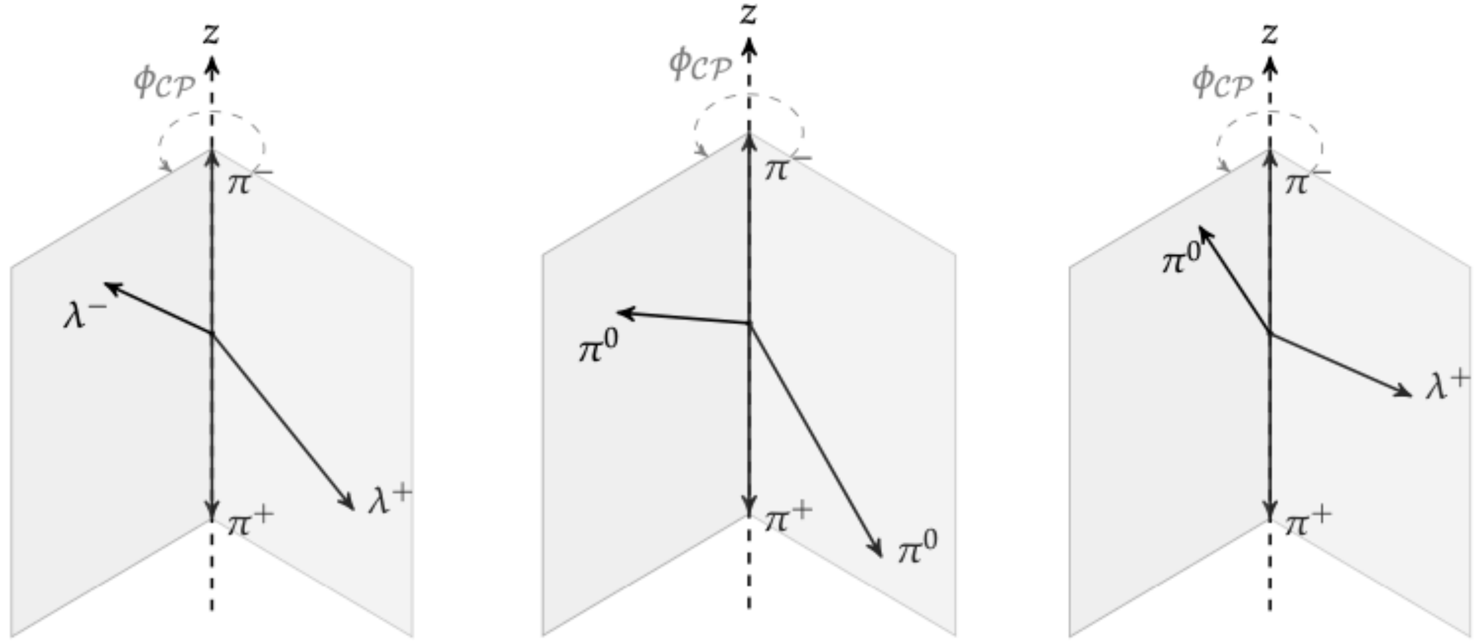


- $\tau \to \pi\nu + \tau \to \rho\nu$ in both taus
- There is a loss of events from the minimization, ~10% of the total, worse for $\tau \to \rho\nu$
- A cut on $p_T^{miss} < 20$ GeV is applied as it's needed to clean the $\tau \to \pi\nu$
- Total efficiency is about 58-60% (like ILC)

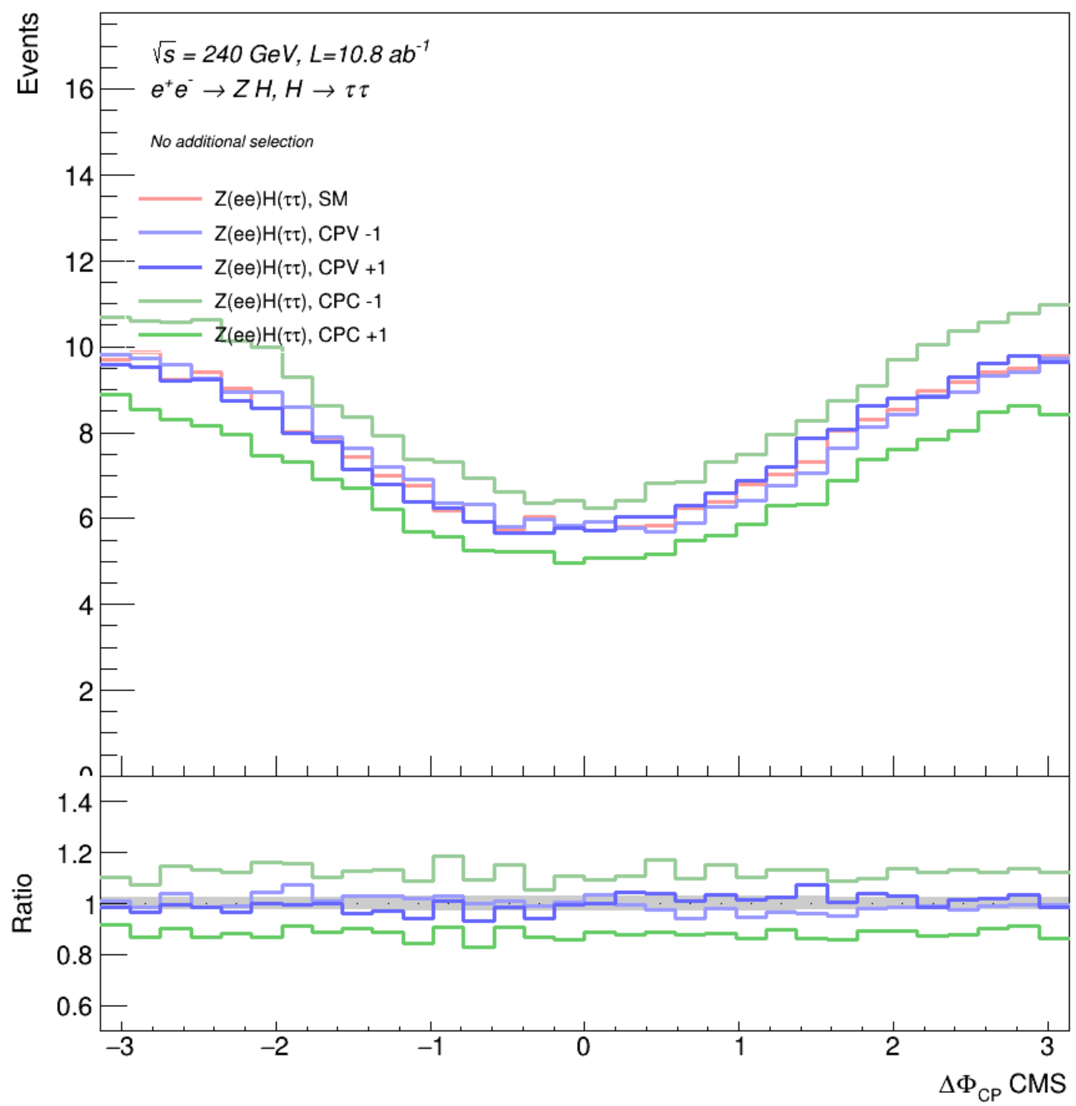
CMS method - angle

arxiv:2110.04836

- No direct reconstruction of the tau/neutrino, works on **all decay modes** (with adaptations)
- Take the impact parameter vector from the IP and boost it with the pion momentum to the zero momentum frame (ZMF, sum of the charged pions)
- Use the perpendicular vector to the tracks to build the angle ψ $[0,\pi]$
- If $\frac{E_{\pi^+} - E_{\pi^0}}{E_{\pi^+} + E_{\pi^0}} \cdot \frac{E_{\pi^-} - E_{\pi^0}}{E_{\pi^-} + E_{\pi^0}} > 0 \ \rightarrow \phi_{CP,temp} = \psi$, otherwise $\phi_{CP,temp} = \psi - \pi$
- If $\hat{\pi}^{ZMF} \cdot (\hat{\lambda}_\perp^{-ZMF} \times \hat{\lambda}_\perp^{+ZMF}) > 0 \ \rightarrow \phi_{CP} = \phi_{CP,temp}$, otherwise $\phi_{CP} = -\phi_{CP,temp}$
- For better accuracy, if neutral pions are present, take that instead of the impact parameter

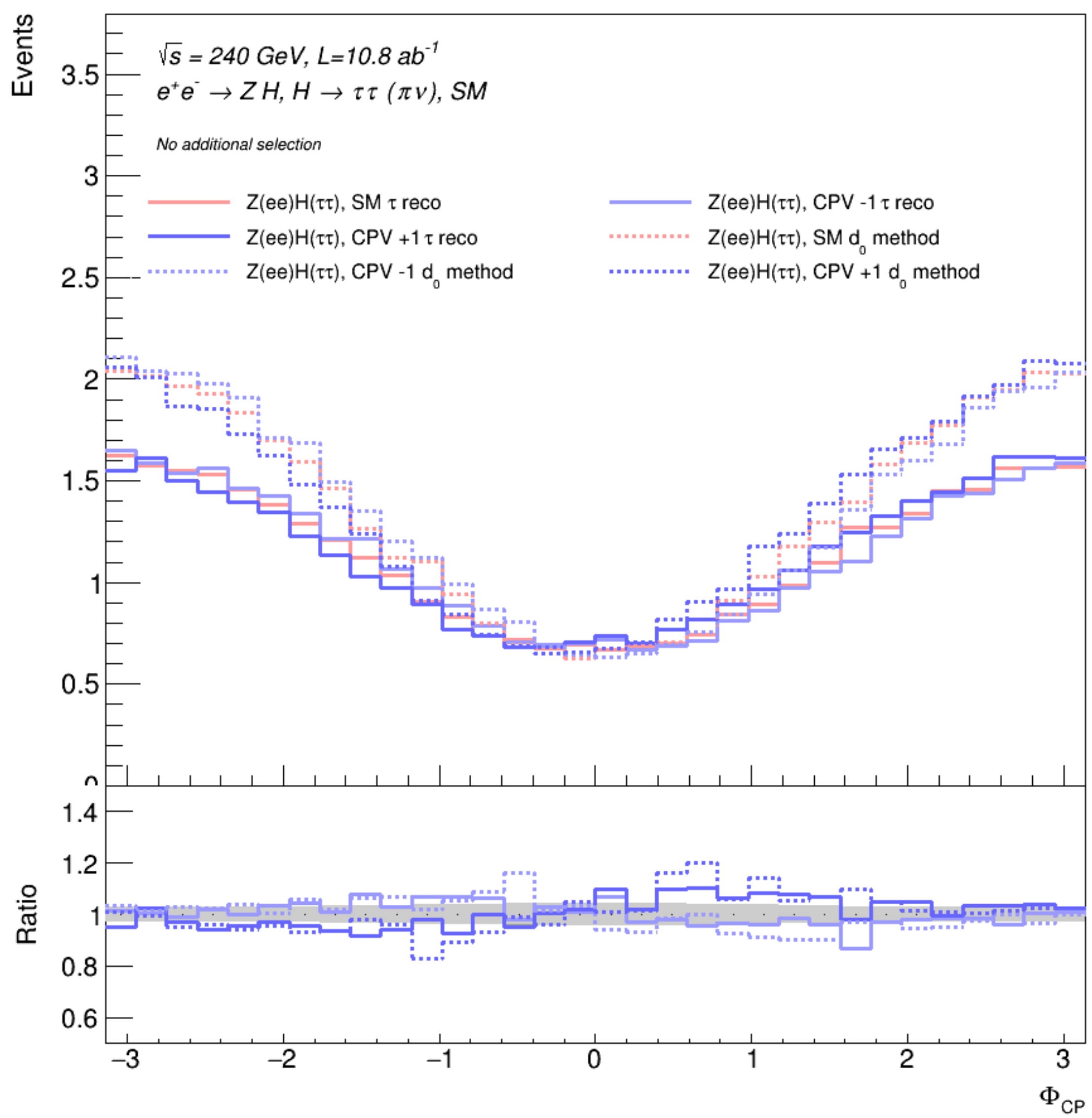


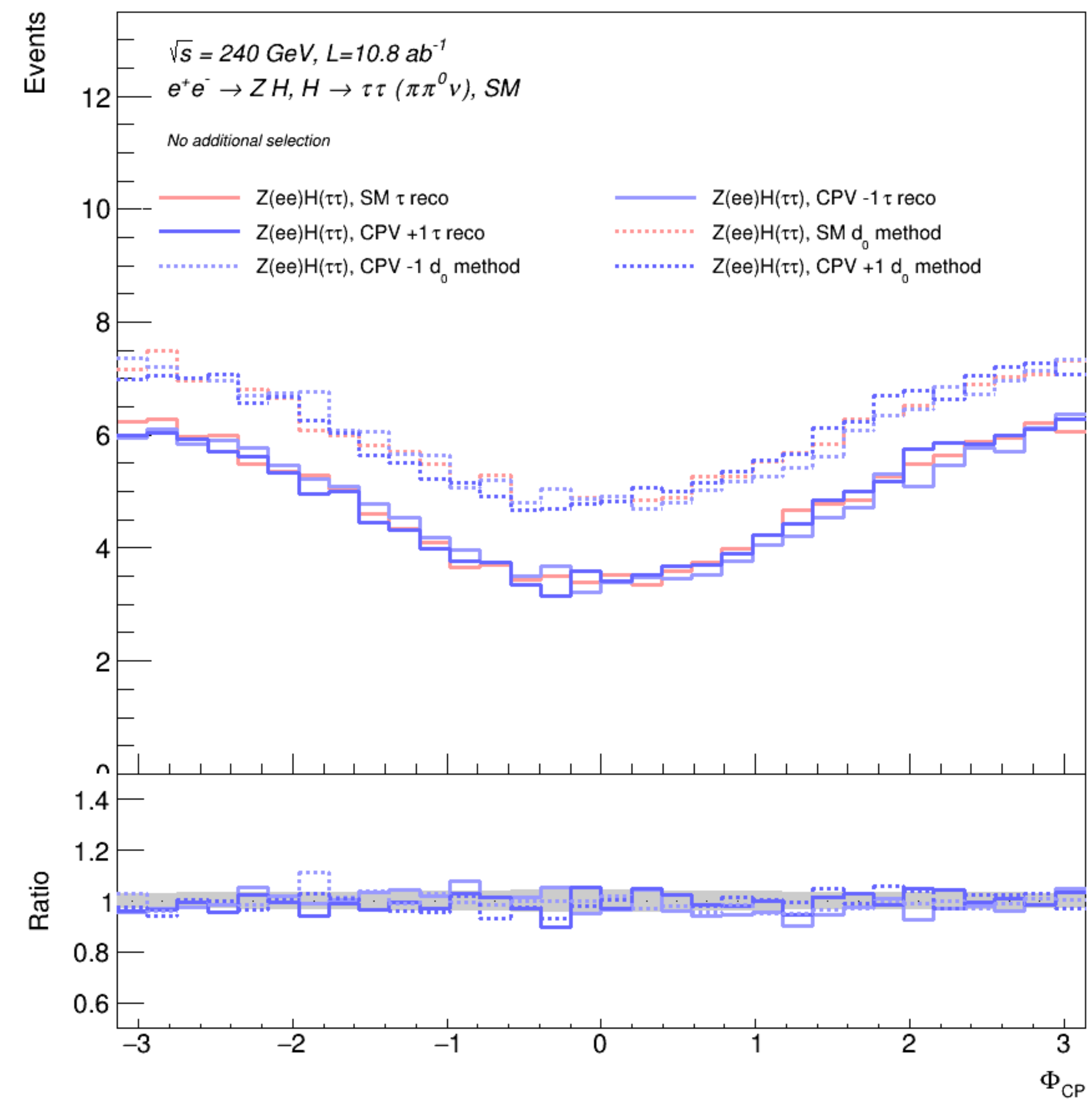
CMS method - plot



- Efficiency is the one for the object selection, ~70%

Comparison

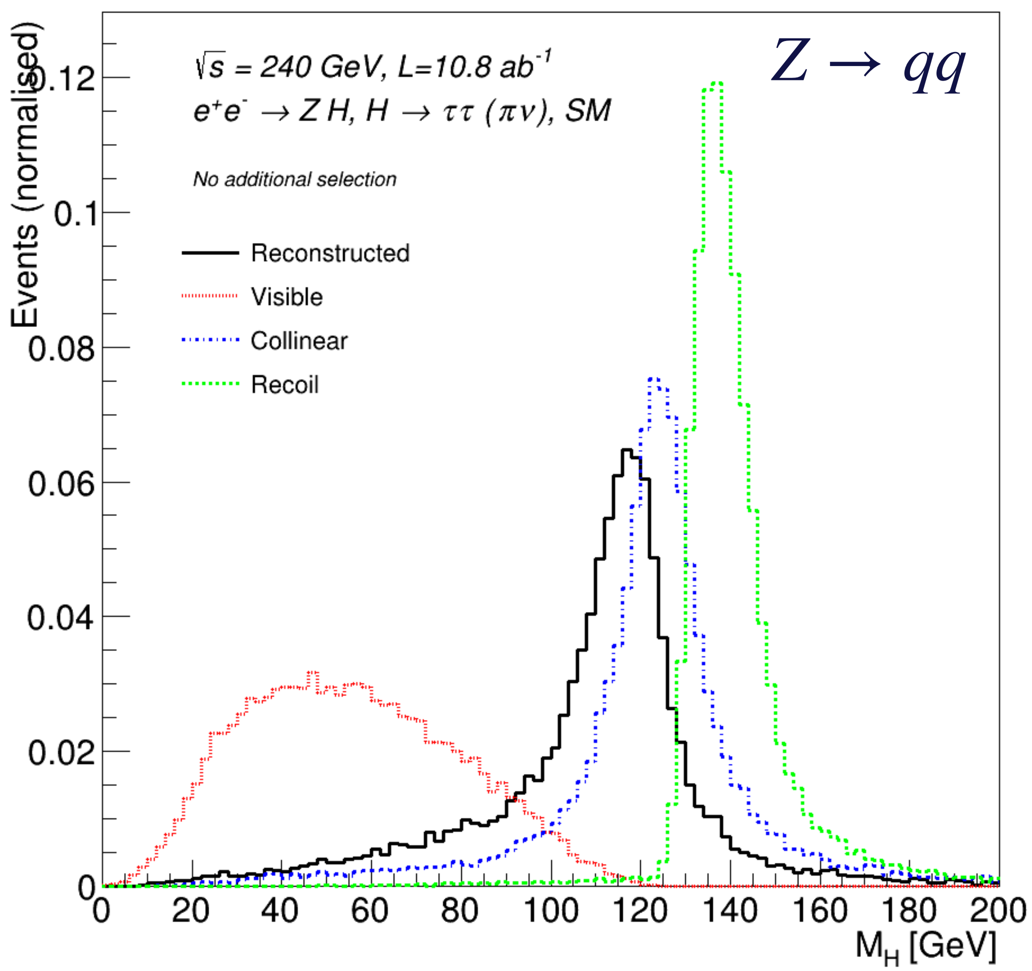


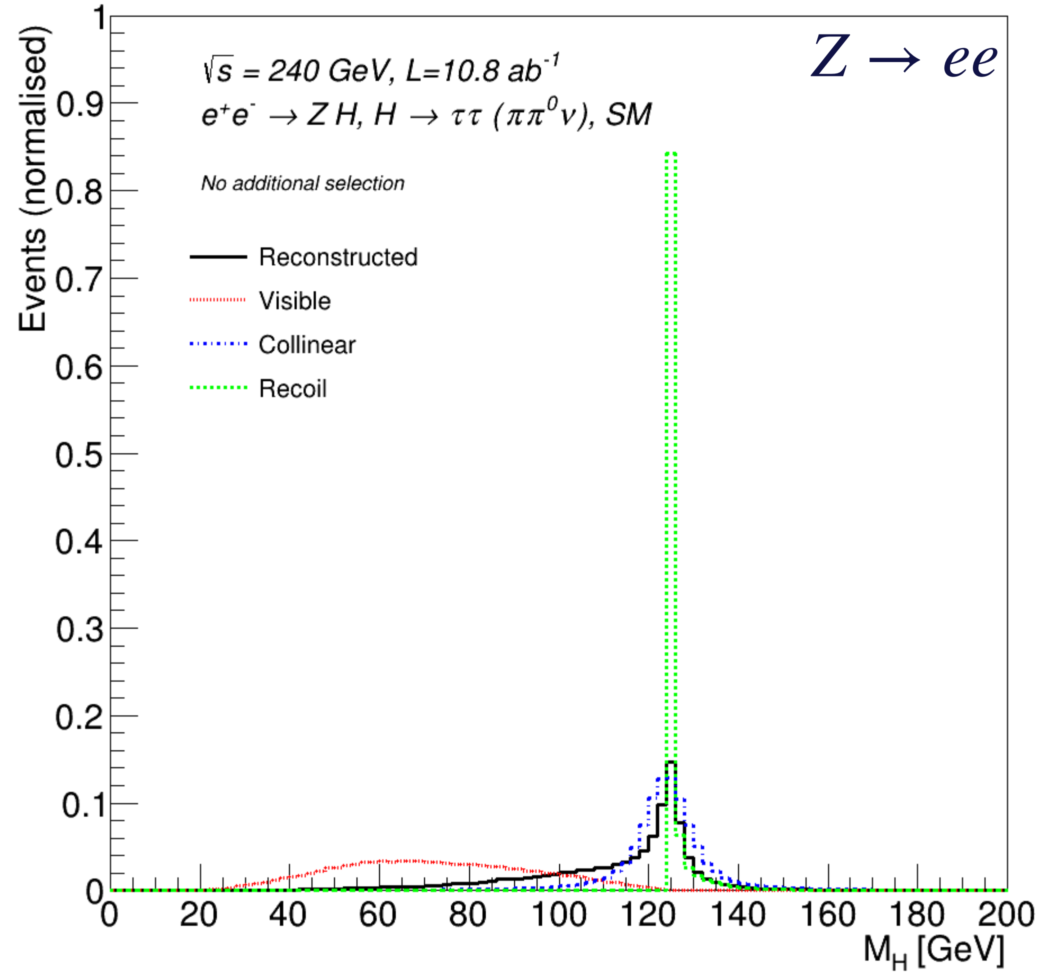


- CMS method is better in terms of efficiency and discrimination power for the $\tau \rightarrow \pi\nu$ channel
- For $\tau \rightarrow \rho\nu$ there is only an efficiency advantage

Higgs mass

- The reconstructed (ILC) Higgs mass in the $Z \to ee$ decay is more precise than the collinear approximation but the recoil mass is definitely better at discriminating
- For $Z \to qq$ there is a shift at lower values in the reconstructed because the **Z mass is off** (~80 GeV), which results in the minimization thinking $\sqrt{s} < 240$ GeV otherwise it would peak at 125 (from ILC papers), it affects everything but the collinear mass





Semi-conclusions

- CMS method is arguably better, both in efficiency and decay modes it can be applied to
- But it still needs to be tested on the other tau decay modes
- The ILC method could potentially work with the three-prong decay too if the polarimeters can be generalised but not with leptonic decays and $Z \to \nu\nu$

- It's worth figuring out why the Z mass resolution for the hadronic decays is so bad in general, for what we've seen so far the jet algorithms tested (R5 and ktN) have the same problem
- In any case, having the reconstructed tau as per ILC method is not worth the effort it takes to implement it in the cross-section analysis since the improvement it can give with respect to the collinear mass is almost zero and compared to the recoil is just worst
- This is the opposite conclusion as in the paper, so maybe they can get better precision out of the method (better and proper impact parameter vector would help a lot)

Backup

IP vertex

- Numbers taken from some other analysis a long time ago, most likely the exotic Higgs decay that used DVs a lot

```
.Define("PrimaryTracks",  "VertexFitterSimple::get_PrimaryTracks( EFlowTrack_1, true, 4.5, 20e-3, 300, 0., 0., 0.)")
.Define("n_PrimaryTracks",  "ReconstructedParticle2Track::getTK_n( PrimaryTracks )")
.Define("PrimaryVertexObject", "VertexFitterSimple::VertexFitter_Tk(1, PrimaryTracks, true, 4.5, 20e-3, 300)")
.Define("PrimaryVertex",  "VertexingUtils::get_VertexData( PrimaryVertexObject )")
.Define("RecoIP_p4",        "TLorentzVector(PrimaryVertex.position.x, PrimaryVertex.position.y, PrimaryVertex.position.z, 0.)")

.Define("SecondaryTracks",   "VertexFitterSimple::get_NonPrimaryTracks( EFlowTrack_1, PrimaryTracks )")
.Define("n_SecondaryTracks",  "ReconstructedParticle2Track::getTK_n( SecondaryTracks )" )
.Define("SecondaryVertexObject", "VertexFitterSimple::VertexFitter_Tk(2, SecondaryTracks)")
.Define("SecondaryVertex",  "VertexingUtils::get_VertexData( SecondaryVertexObject )")
```