DPG Spring Meeting 2019, Aachen

CP measurement in $H \rightarrow \tau\tau$

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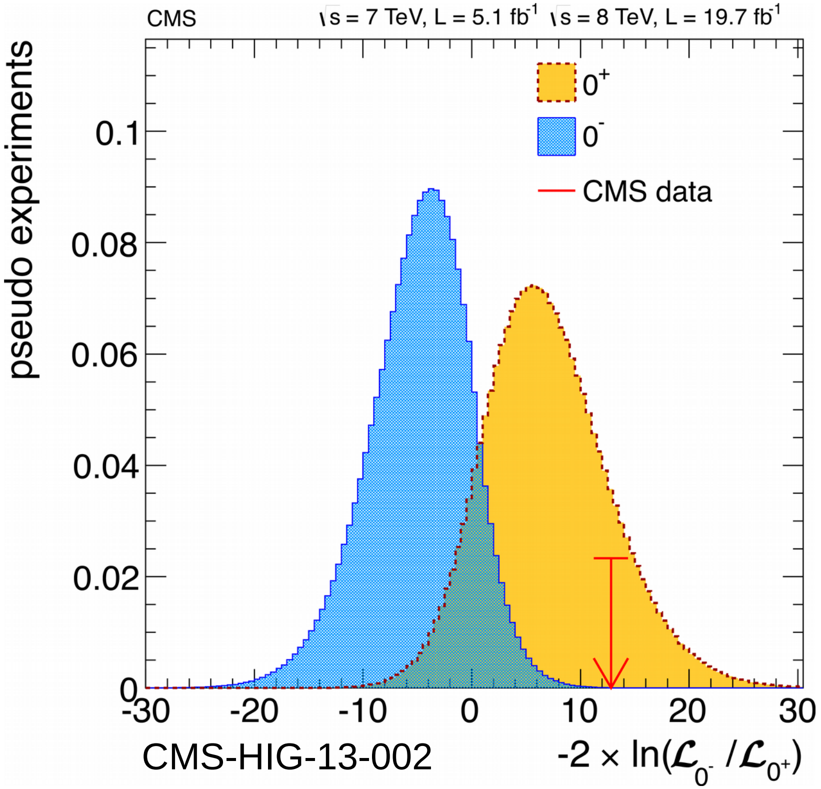
Higgs CP nature

- The SM predicts only one Higgs boson, with spin-parity 0^+
- Run 1 constraints from H→VV excluded a pseudoscalar Higgs

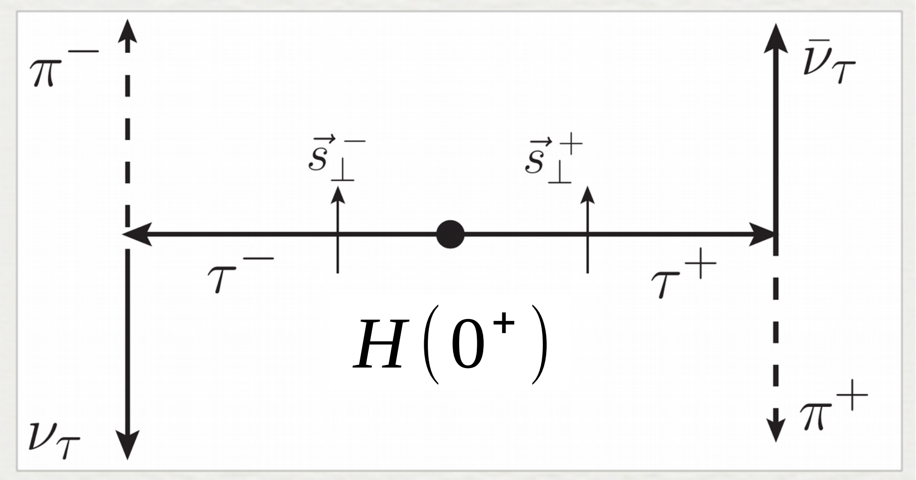


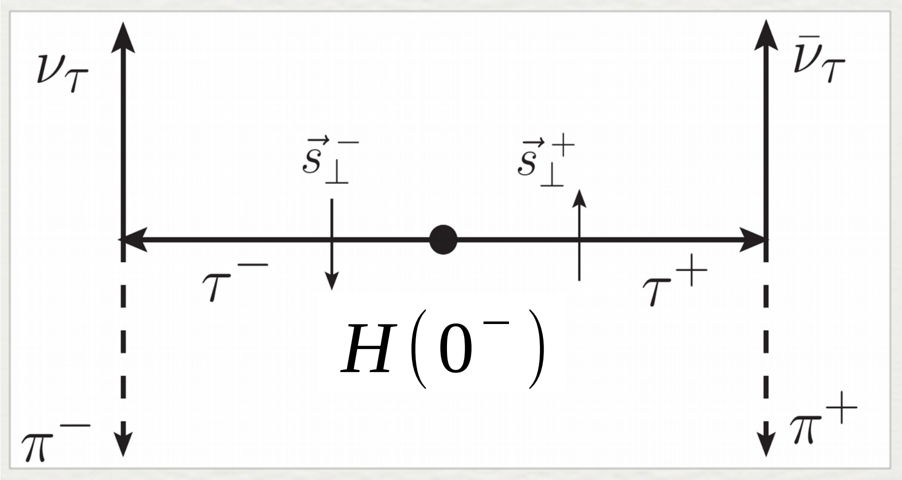
- The VBF H→4l + VBF H→ττ studies from Run2 [CMS-PAS-HIG-17-034] placed tight constraints on a CP-odd anomalous coupling in HVV
- However a CP-odd coupling in the Yukawa interactions is not excluded yet

The possibility of a small CP-mixing is still open and could appear in fermionic decays

CP measurement in H→τ τ

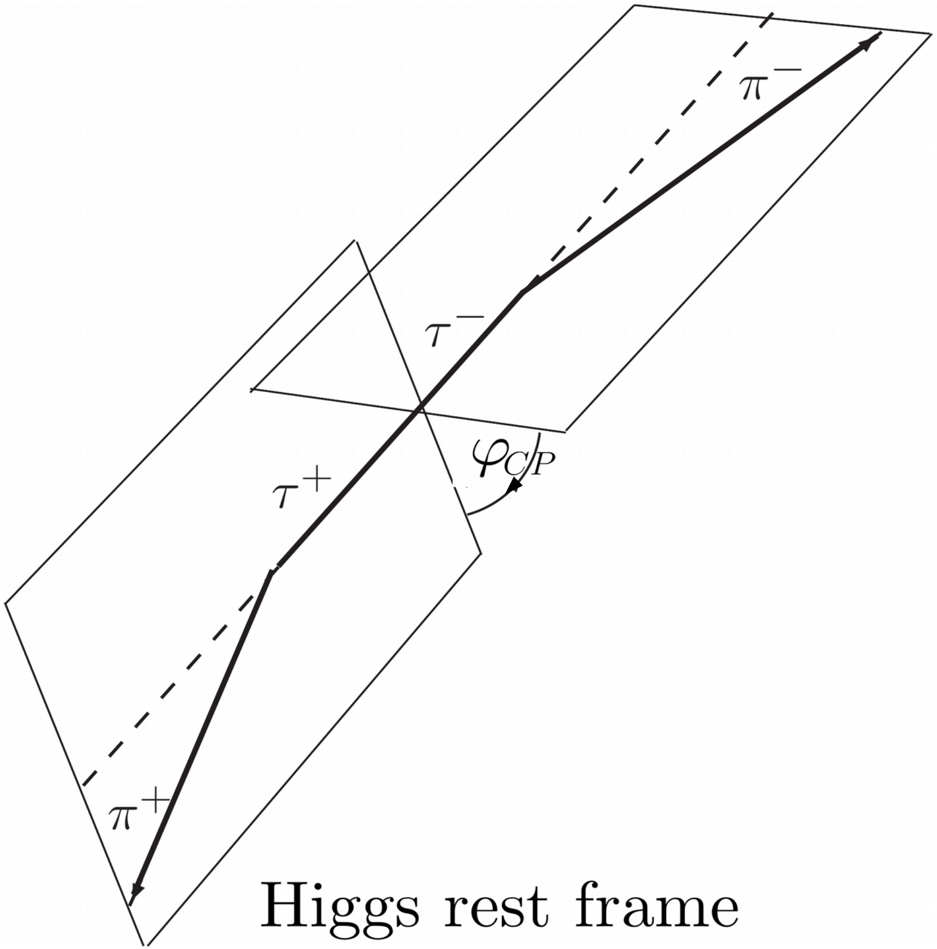
- CP-mixing may appear in the H→τ τ coupling at leading order:
  - $L_Y = -\frac{m_\tau}{v} k_\tau (\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau} i \gamma_5 \tau) h$
  - SM prediction: $\phi_\tau = 0$
- To measure ϕ_τ we need to look at the spin correlation of tau decay products:





The acoplanarity angle

- To access the spin correlation we need to measure the angle between the τ decay planes
- In the Higgs rest frame this angle would be preferably either 0 or π in the case of pure CP states
- The Higgs rest frame is generally not accessible at LHC
  ⟹ the ZMF of the charged decay products is used instead



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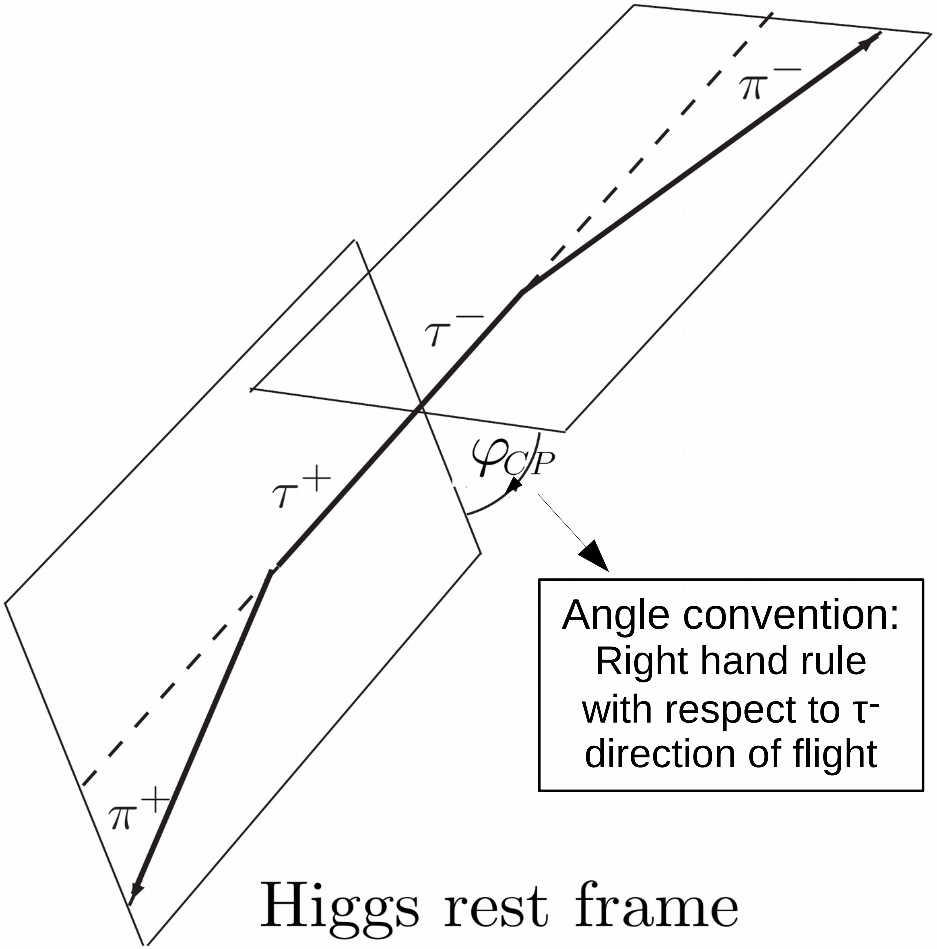
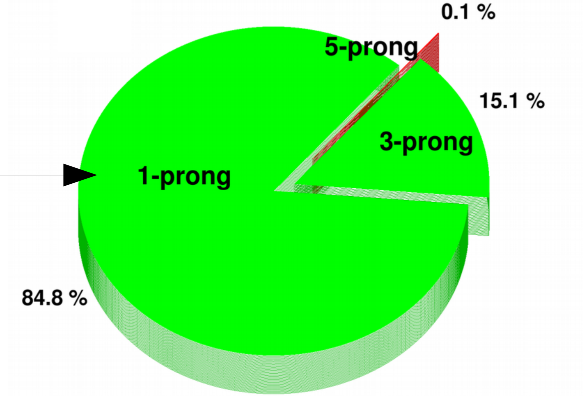


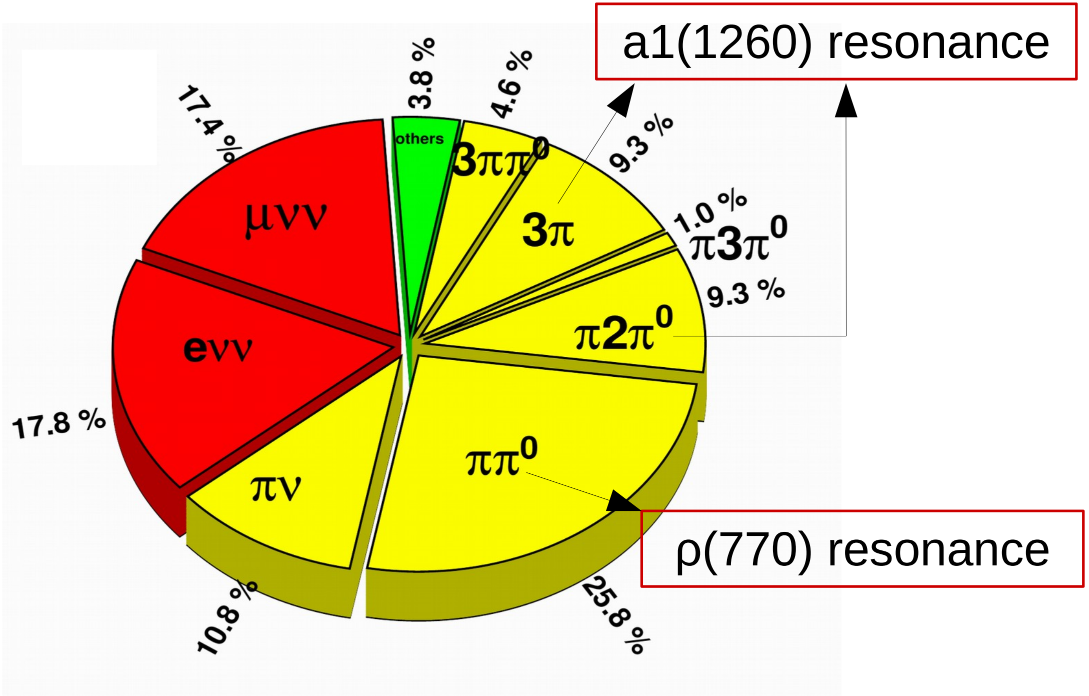
τ branching ratios

Number of prongs
(charged decay products)



$$\tau \rightarrow l + \nu_l + \nu_\tau\,,$$
$$\tau \rightarrow \pi + \nu_\tau\,,$$
$$\tau \rightarrow \rho + \nu_\tau \rightarrow \pi + \pi^0 + \nu_\tau\,,$$
$$\tau \rightarrow a_1 + \nu_\tau \rightarrow \pi + 2\pi^0 + \nu_\tau\,,$$
$$\tau \rightarrow a_1^{L,T} + \nu_\tau \rightarrow 2\pi^\pm + \pi^\mp + \nu_\tau\,.$$

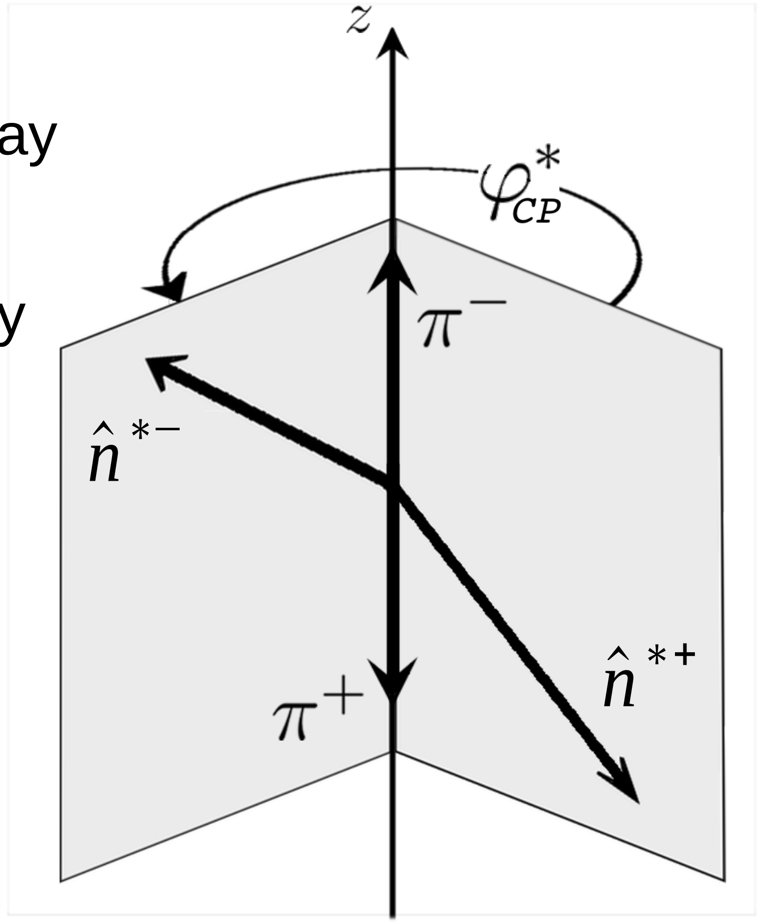
Main exclusive decay channels



The acoplanarity angle

Each plane is identified by 2 vector:

- One is the the momenta of the charged decay product ($\pi^{\pm}$,$\mu^{\pm}$,$e^{\pm}$,a_1)
- The other is chosen depending on the decay channel:
  - 1 Prong: IP vector
  - 1 Prong + π^0s: momenta of the π^0s
  - 3 Prong: vector connecting PV and SV



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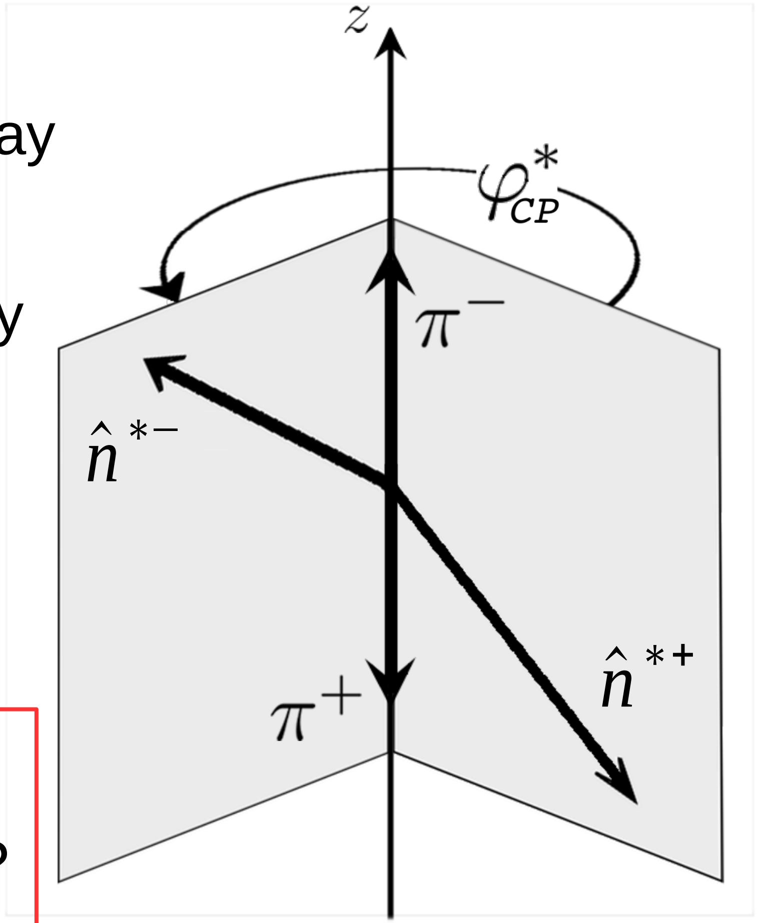


The acoplanarity angle is thus reconstructed, but how do we extract the **CP-mixing angle**?

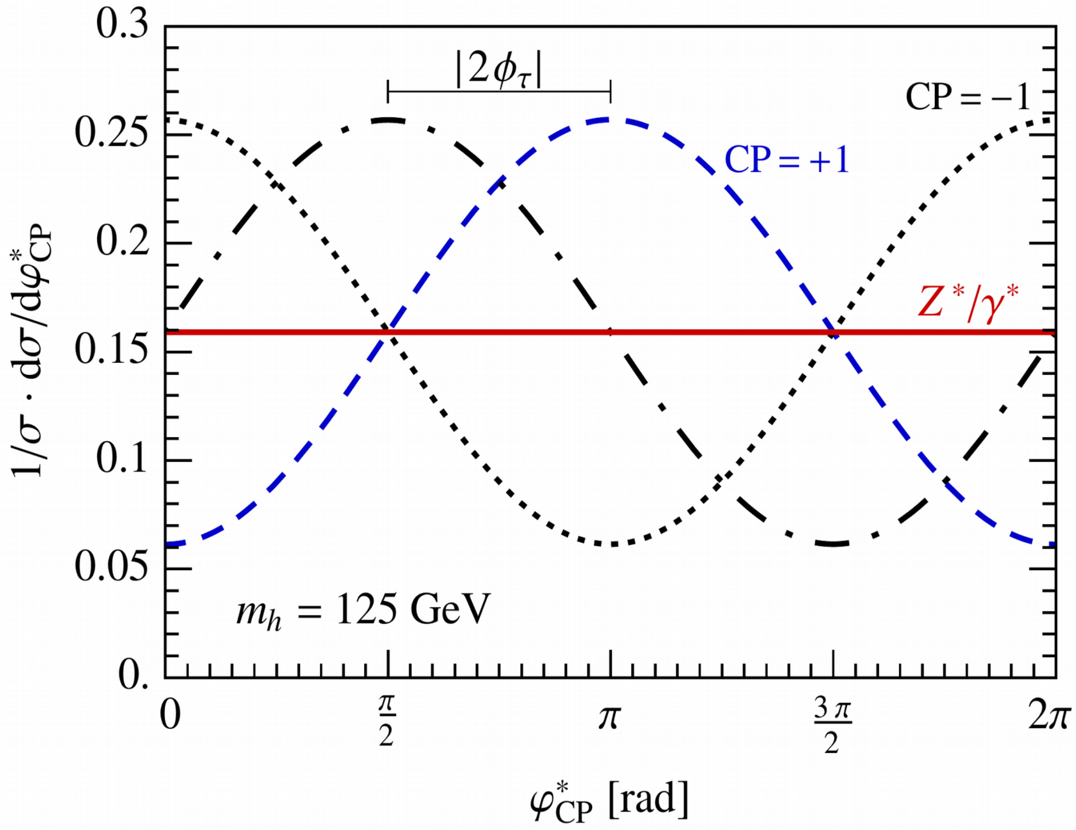
CP mixing angle

The mixing angle will appear as a phase shift with respect to the CP-even distribution

H→ τ τ cross section:

$$\frac{d\sigma}{d\varphi^*_{CP}} \propto -\cos(\varphi^*_{CP} - 2\phi_t)$$

"Determination of the Higgs CP mixing angle in the tau decay channels at the LHC including the Drell-Yan background", S. Berge et al.



CP angle at generator level

Boost reference vector $\hat{n}^{*\pm}$ in ZMF of charged decay products

Use transverse components with respect to the charged prong momenta in that frame: $\hat{n}^{*\pm}_{\perp}$

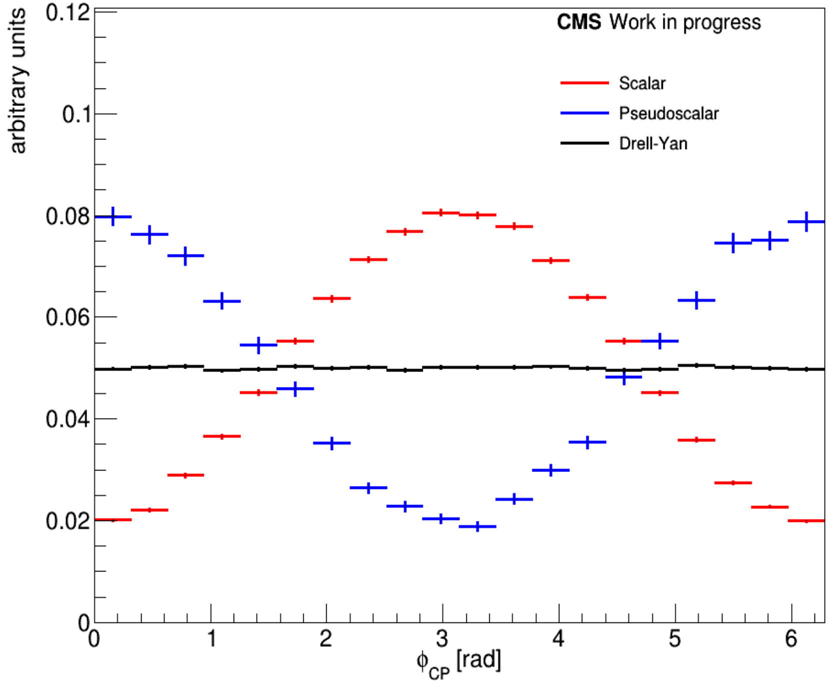
$$\phi^* = \arccos(\hat{n}^{*+}_{\perp} \cdot \hat{n}^{*-}_{\perp})$$

$$O^*_{CP} = \hat{q}^{*-} \cdot (\hat{n}^{*+}_{\perp} \times \hat{n}^{*-}_{\perp})$$

$$\phi_{CP} = \begin{cases} \phi^* & if \;\; O^*_{CP} \geqslant 0 \\ 2\pi - \phi^* & if \;\; O^*_{CP} < 0 \end{cases}$$

Tau 1 decay mode: $\tau^{\pm} \rightarrow \pi^{\pm}$

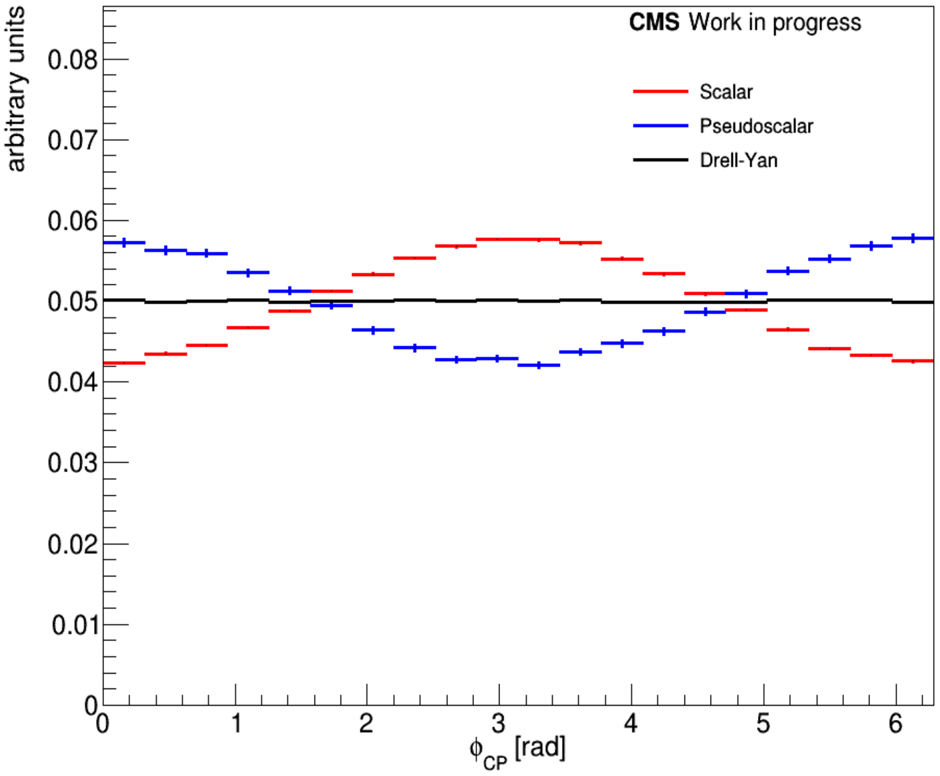
Tau 2 decay mode: $\tau^{\pm} \rightarrow \pi^{\pm}$

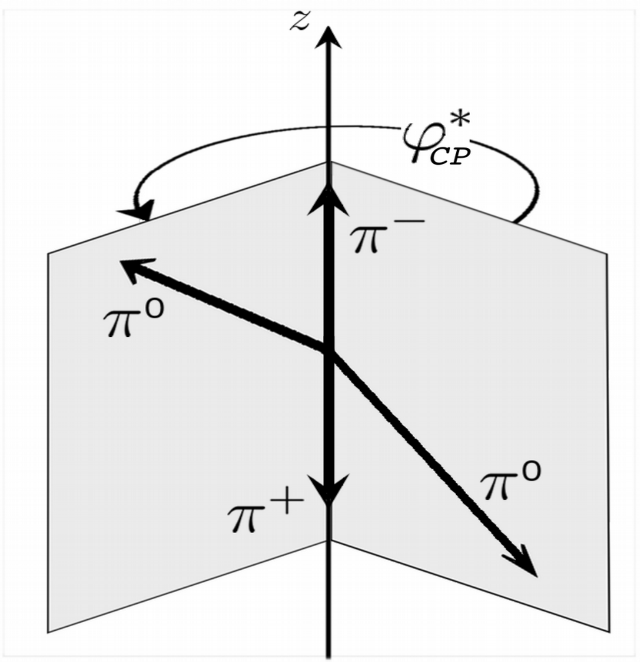


No cuts are applied for these gen level studies
Results at reconstruction level will be shown later

Results using π^0s

Tau 1 decay mode: $\tau^{\pm} \rightarrow \pi^{\pm} + \pi^0$
Tau 2 decay mode: $\tau^{\pm} \rightarrow \pi^{\pm} + \pi^0$

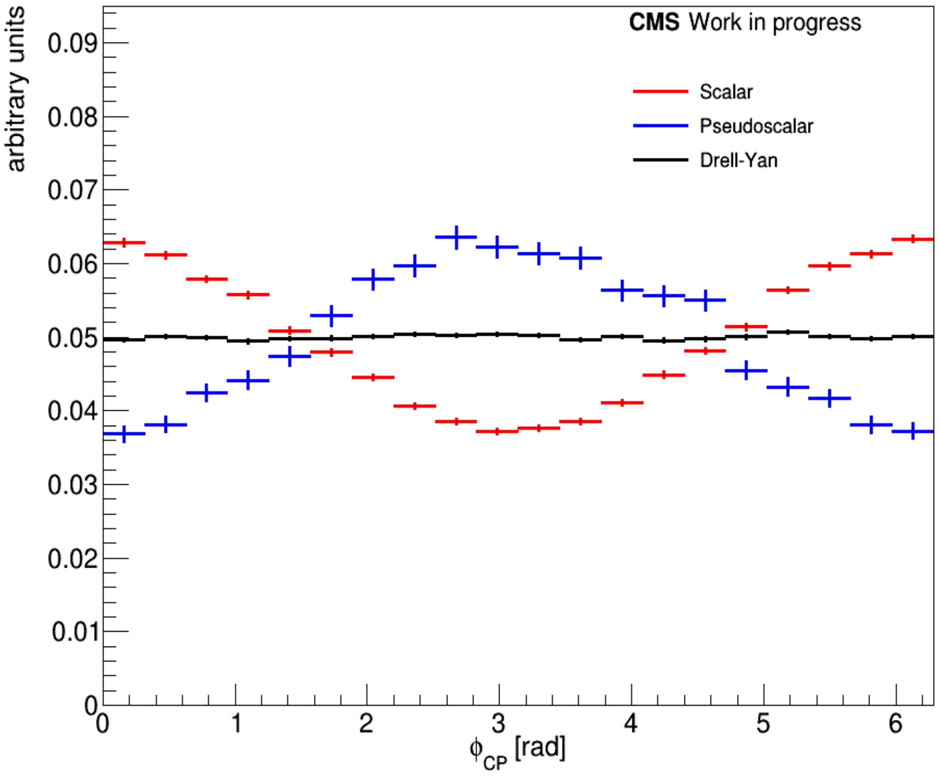




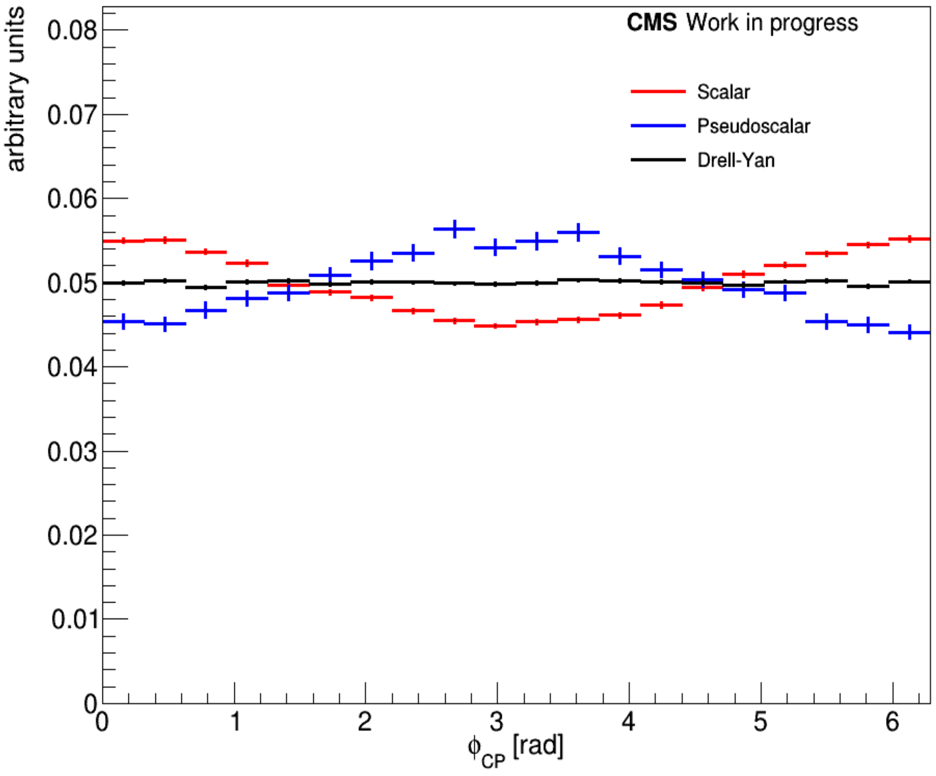
The π^0 momenta is boosted in the ZMF of the charged π.
The acoplanarity angle is calculated in a similar way.

Using a lepton as prong

Tau 1 decay mode: $\tau^{\pm} \rightarrow \mu^{\pm}$
Tau 2 decay mode: $\tau^{\pm} \rightarrow \pi^{\pm}$



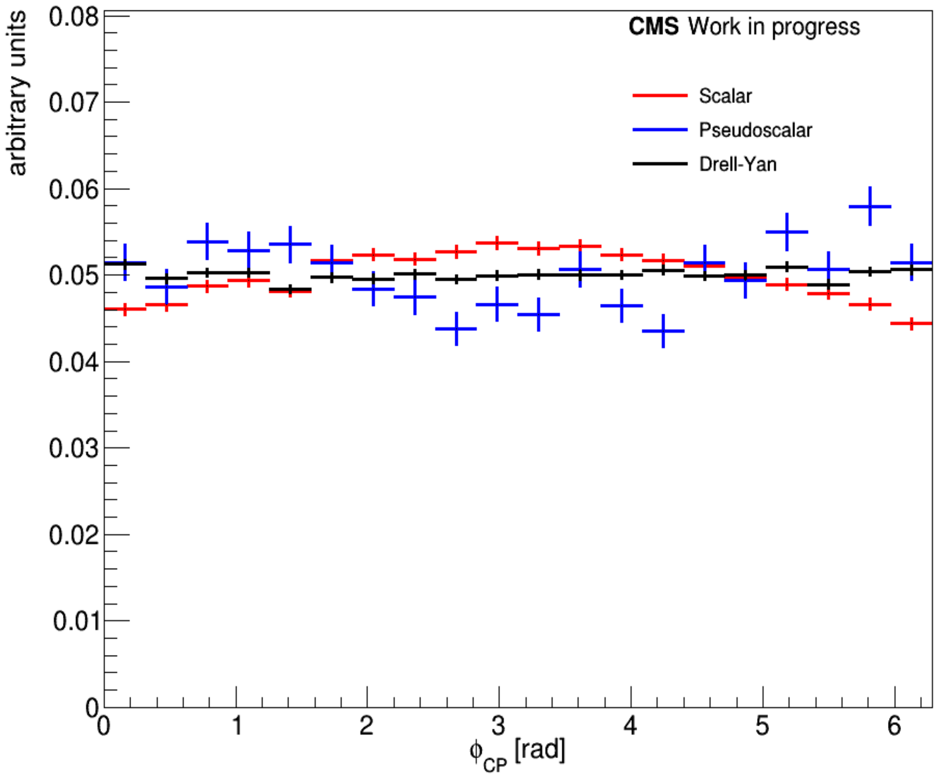
Tau 1 decay mode: $\tau^{\pm} \rightarrow e^{\pm}$
Tau 2 decay mode: $\tau^{\pm} \rightarrow \pi^{\pm} + \pi^{0}$

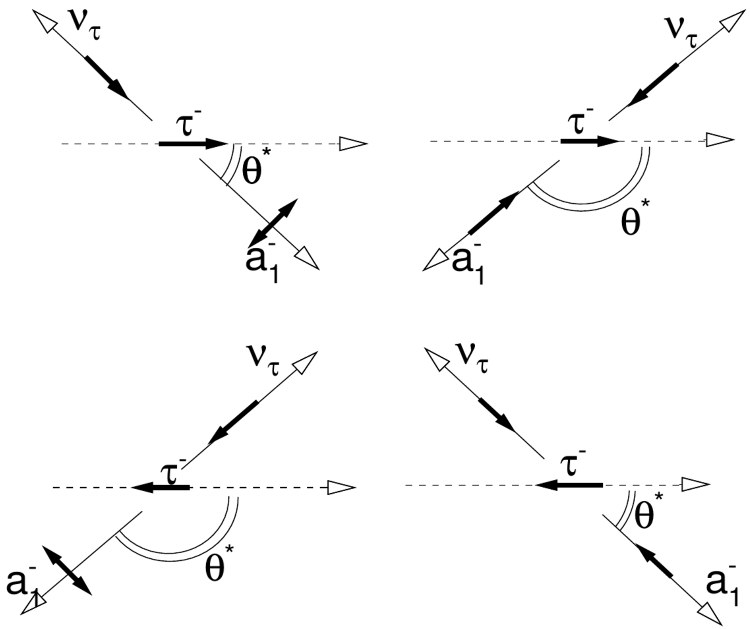


3 Prong channel

Tau 1 decay mode: $\tau^{\pm} \rightarrow \pi^{\pm}$

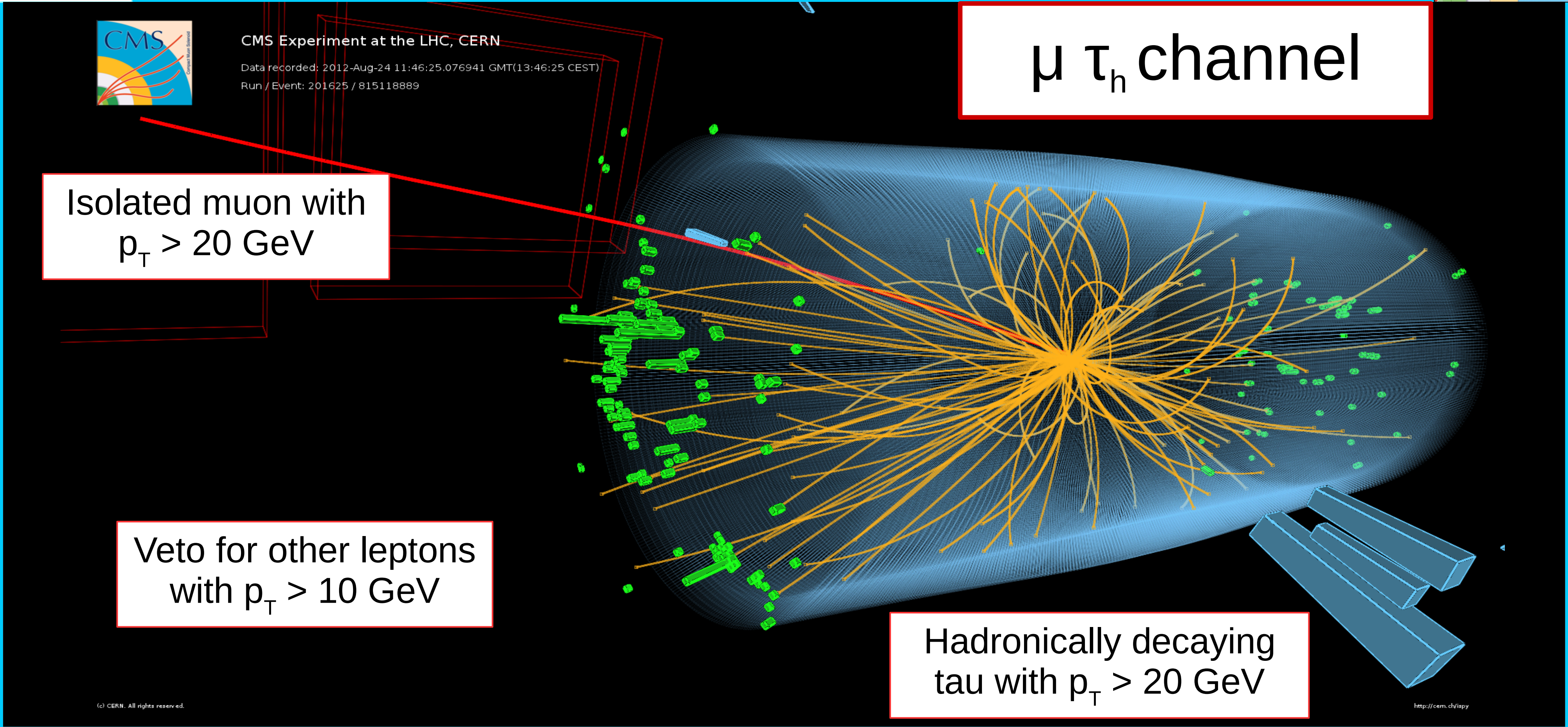
Tau 2 decay mode: $\tau^{\pm} \rightarrow a_1$ inclusive





The spin correlation changes depending on the polarization of the a_1 meson.
A categorization based on the a_1 polarization is thus currently being developed.

Reconstruction level



$\mu\ \tau_h$ channel

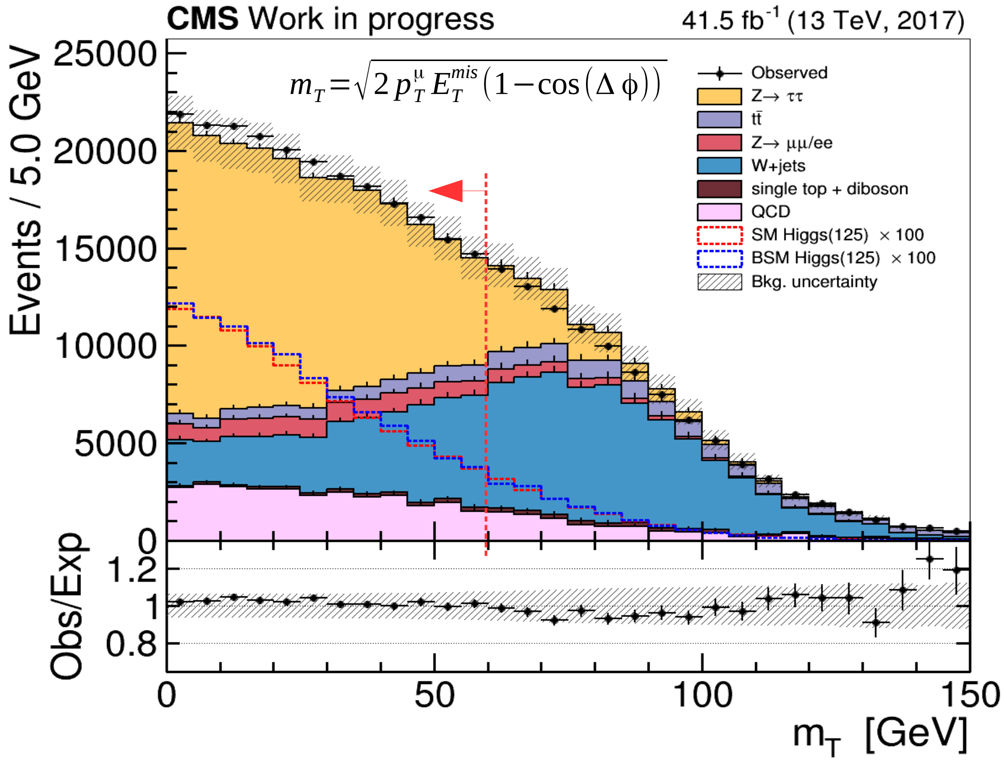
Isolated muon with p_T > 20 GeV

Veto for other leptons with p_T > 10 GeV

Hadronically decaying tau with p_T > 20 GeV

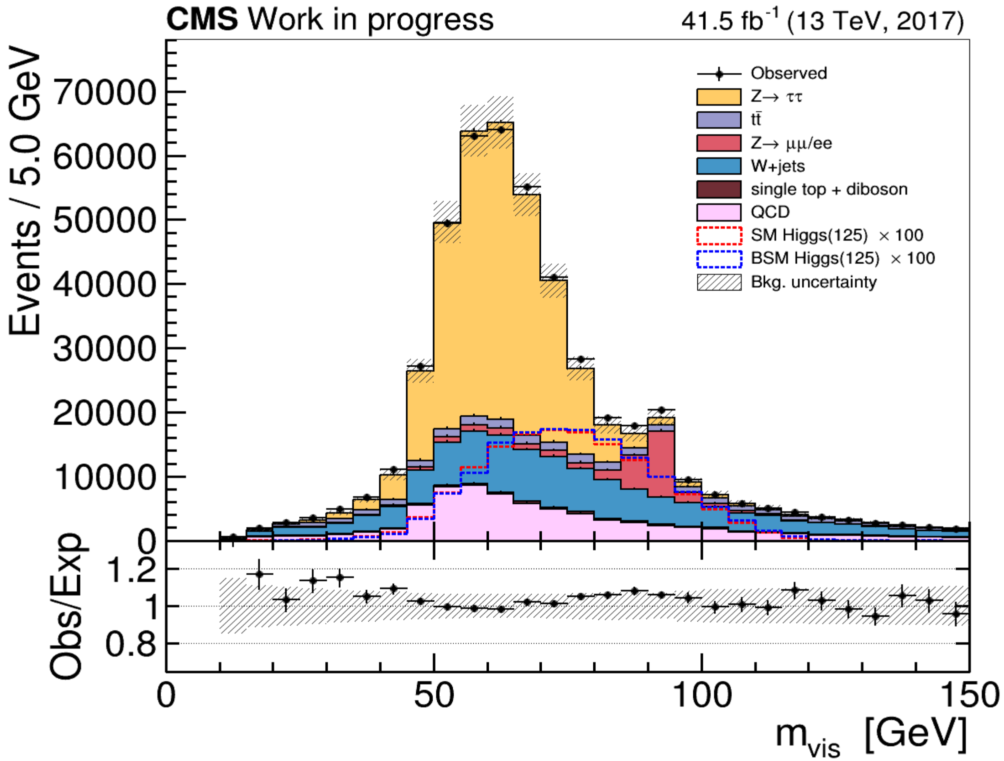
Inclusive selection region

Transverse mass



A cut on m_T is used to reduce the W+jets bkg

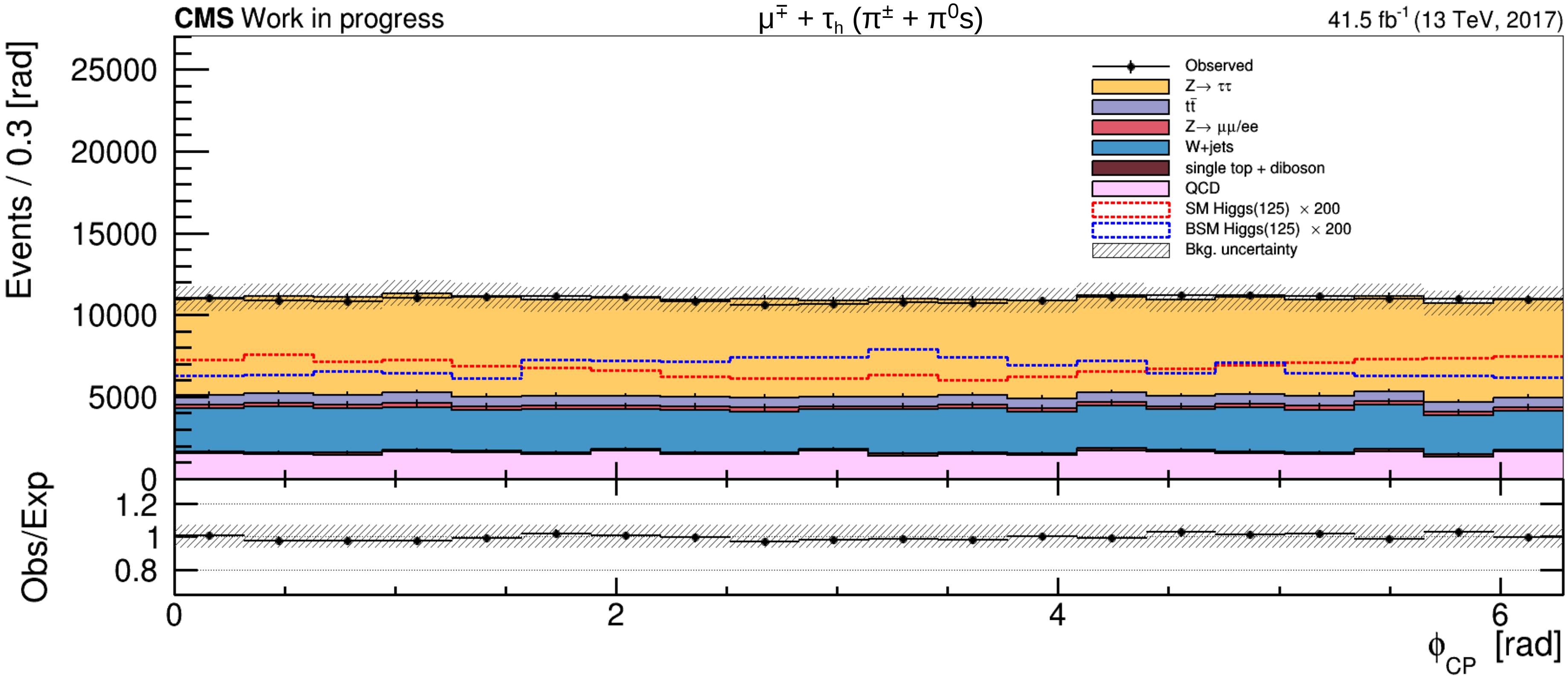
Visible mass



Both plots show a good data / MC agreement

Inclusive selection region

Acoplanarity angle

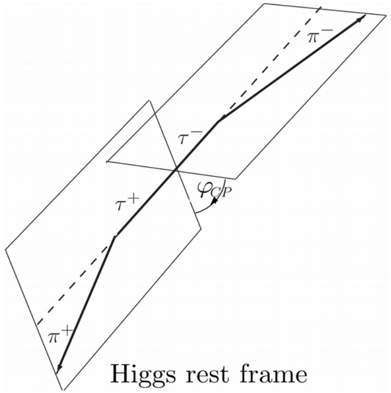


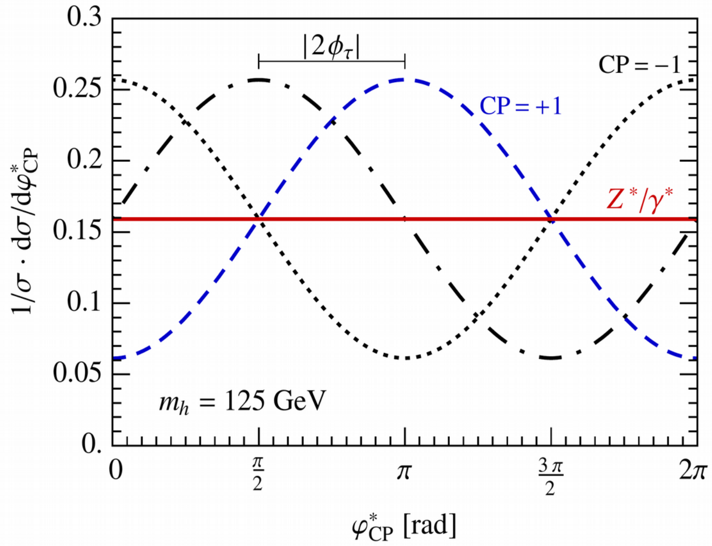
As expected, the backgrounds appear flat, while a modulation can be seen for the signal.

Summary and prospects

- Gen level studies look promising for the measurement of the CP-mixing angle

- At reco level the good Data/MC agreement is a good starting point for the measurement





- The studies will be carried on at reco level in the most sensitive channels to maximize the sensitivity to CP-mixing

- To further improve the sensitivity the use of Machine Learning could prove decisive

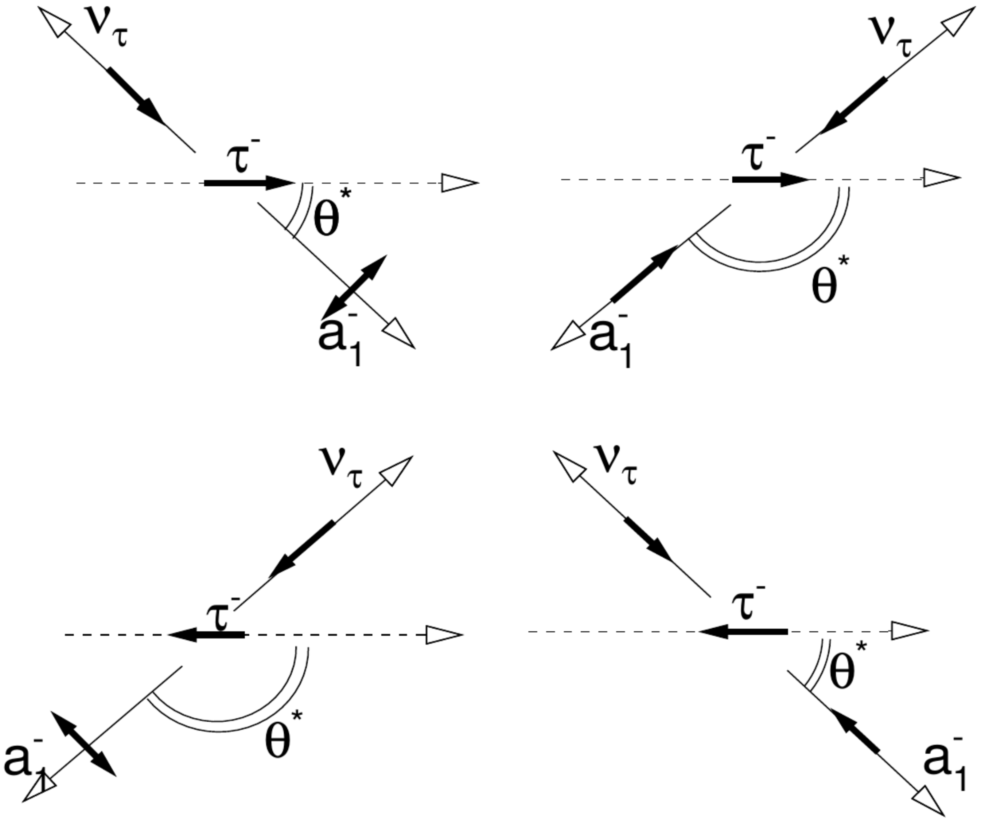
CP measurement in $H \rightarrow \tau\tau$

Andrea Cardini

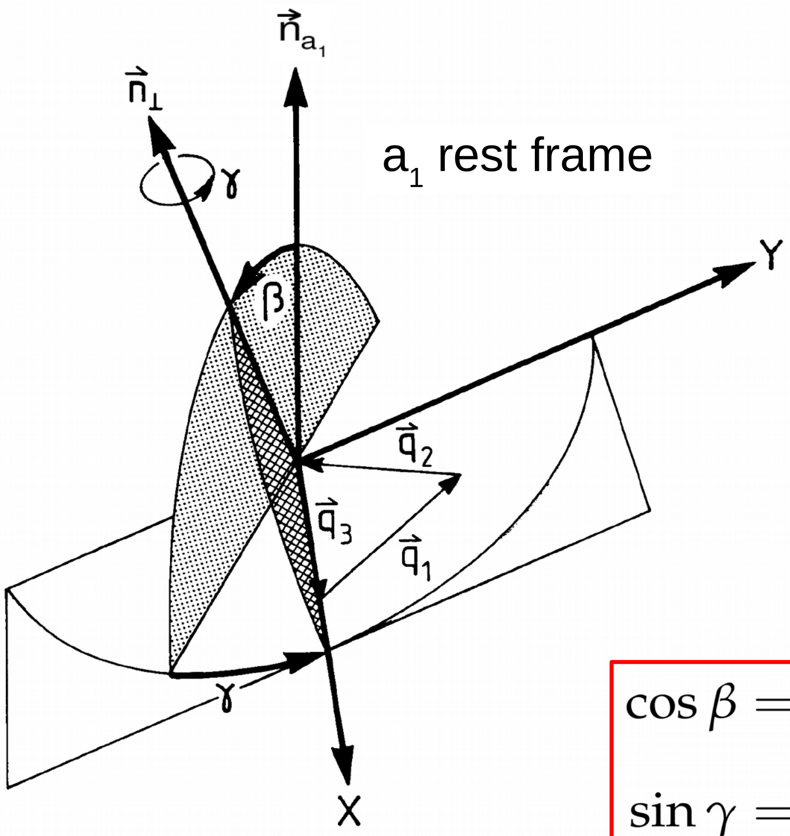
Questions?

Quick recap for 3-prong

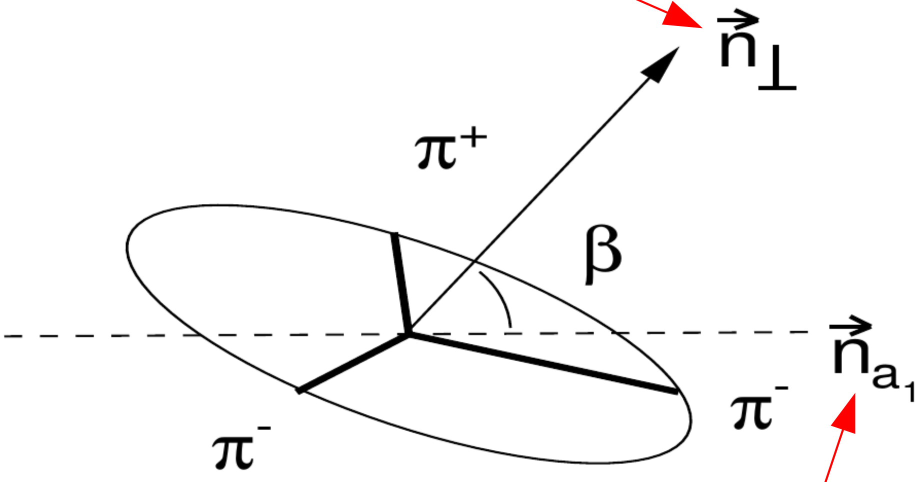
- The 3-prong channel is dominated by the a_1 resonance
- However the a_1 meson has spin 1 ⇒ L and T polarization have opposite spin correlation with the τ
- A categorization based on the a_1 polarization may be needed to study the spin correlation



$a_1 \rightarrow 3\pi$



normal to the π decay plane in the a_1 f.o.r.
(it coincides with the a_1 spin)



direction of motion of a_1

$$\cos\beta = \vec{n}_\perp \vec{n}_{a_1}$$

$$\sin\gamma = \frac{(\vec{n}_\perp \times \vec{n}_{a_1})\vec{q}_3}{|\vec{n}_\perp \times \vec{n}_{a_1}|}$$

Polarization measurement

$$cos\beta = \frac{\vec{p}_3(\vec{p}_1 \times \vec{p}_2)}{|\vec{p}_{3\pi}|T}$$

where:

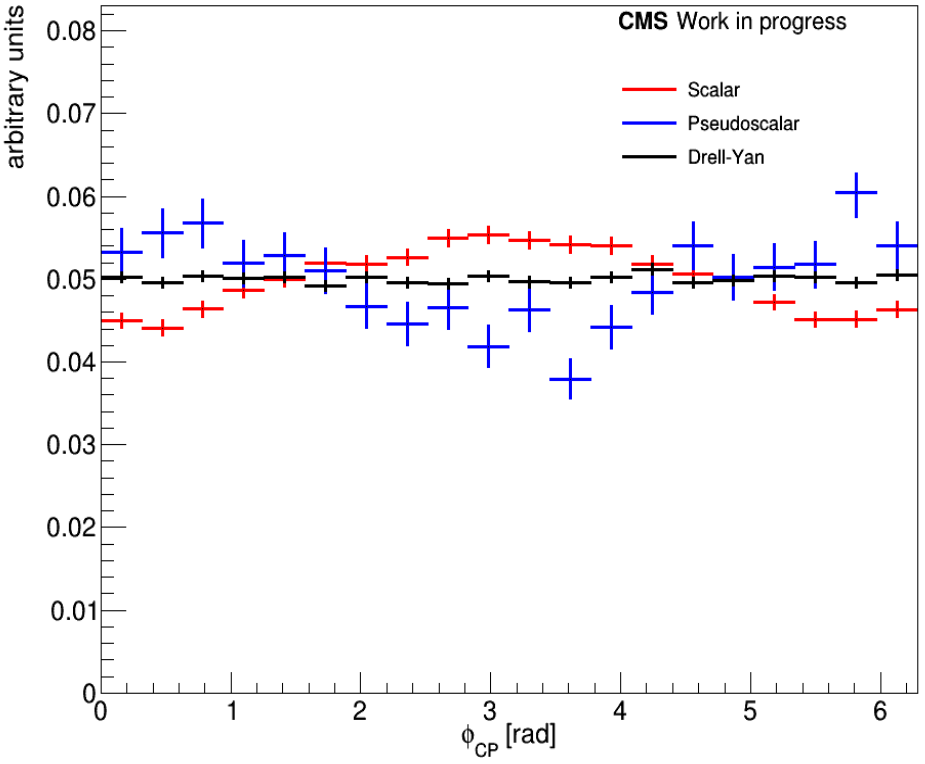
$$T = \frac{1}{2}\sqrt{-\lambda(B_1, B_2, B_3)}$$

$$\lambda(B_1, B_2, B_3) = B_1^2 + B_2^2 + B_3^2 - 2B_1B_2 - 2B_1B_3 - 2B_2B_3$$

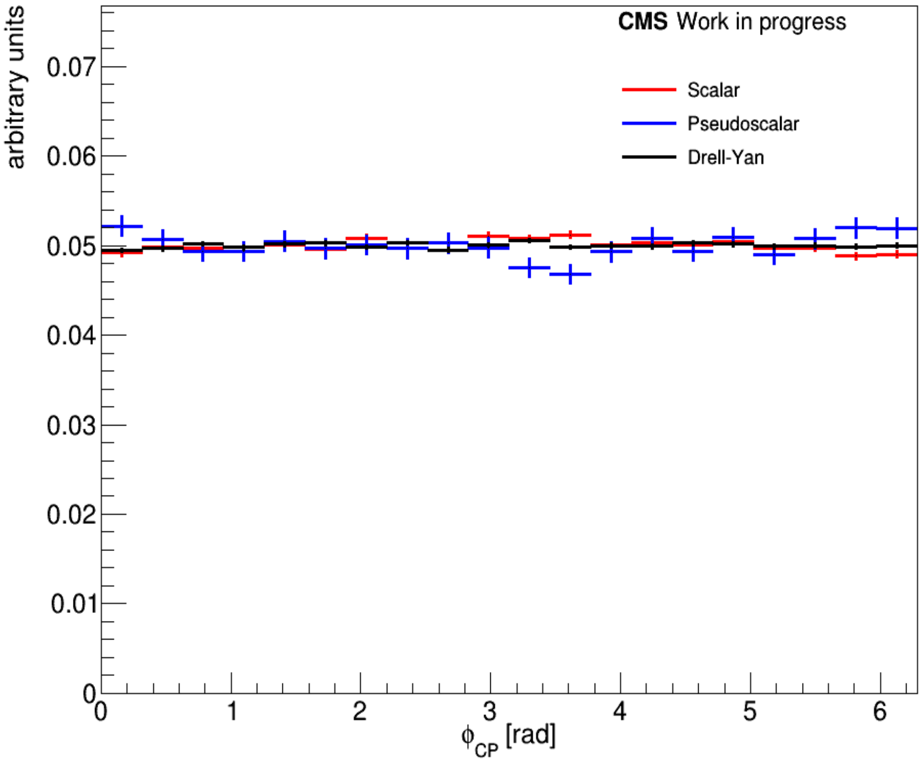
$$B_i = \frac{(E_iE_{3\pi} - \vec{p}_{3\pi}\vec{p}_i)^2 - Q^2m_\pi^2}{Q^2}$$

3 Prong channel

Tau 1 decay mode: $\tau^{\pm} \rightarrow a_1$ transv. pol.
Tau 2 decay mode: $\tau^{\pm} \rightarrow \pi^{\pm}$

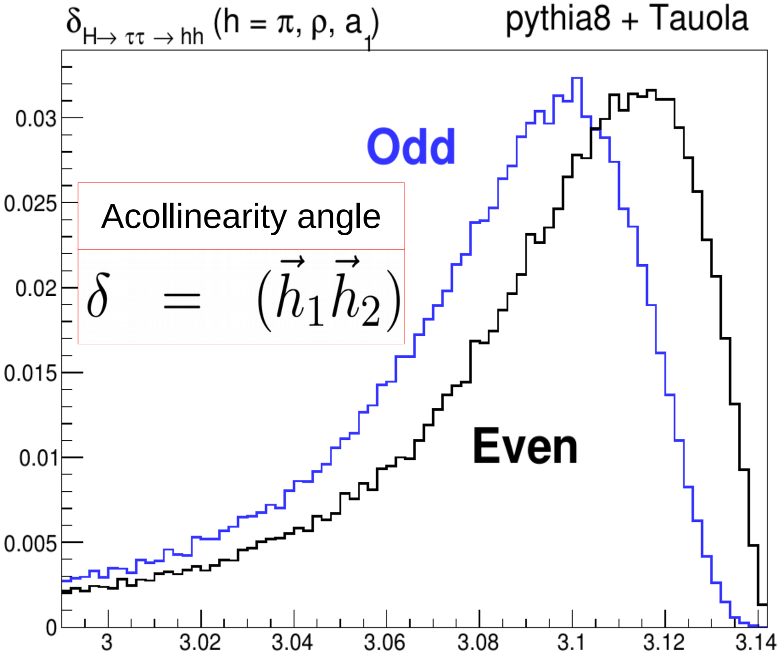


Tau 1 decay mode: $\tau^{\pm} \rightarrow a_1$ long. pol.
Tau 2 decay mode: $\tau^{\pm} \rightarrow \pi^{\pm} + \pi^0$



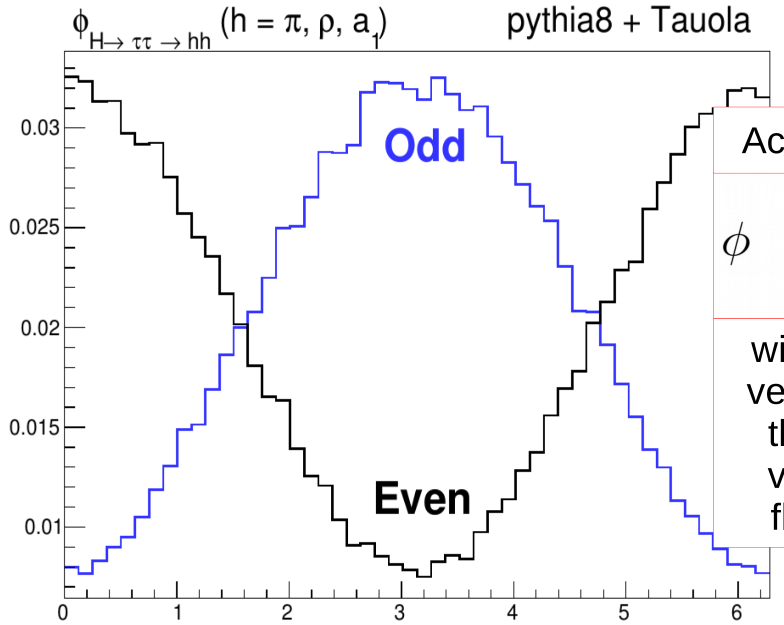
Polarimetric vectors

- The polarimetric vector are computed by a routine in TauSpinner (which is part of the TAUOLA tool)
- Using these vectors it is possible to define define 2 interesting observables:



Acollinearity angle

$$\delta = (\vec{h}_1 \vec{h}_2)$$



Acoplanarity angle

$$\phi = \frac{\vec{k}_1 \times \vec{k}_2}{|\vec{k}_1 \times \vec{k}_2|}$$

with k normalized vector products of the polarimetric vectors and tau flight directions

“Monte Carlo, fitting and Machine Learning for Tau leptons”, Vladimir Cherepanov, Elzbieta Richter-Was, Zbigniew Was