

# Measurement of the Higgs CP in its decay to $\tau$ leptons

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# Motivation and theory



- The Standard Model (SM) Higgs boson is even under charge-parity (CP) inversion. Some of the extensions of the SM predict the existence of a CP-odd component of the Higgs.
- A pure CP-odd scenario was excluded by measuring the Higgs coupling to gauge bosons (CMS and ATLAS).
- But a mixed CP scenario is still possible and is more accessible through the fermionic coupling of the Higgs.
- This study is the **first direct measurement** of the CP structure of the Yukawa coupling between the Higgs and  $\tau$  leptons. The measurement is performed in the  $H \rightarrow \tau^+ \tau^-$  decay.
- The  $H\tau\tau$  coupling can be decomposed into CP-even and CP-odd terms:

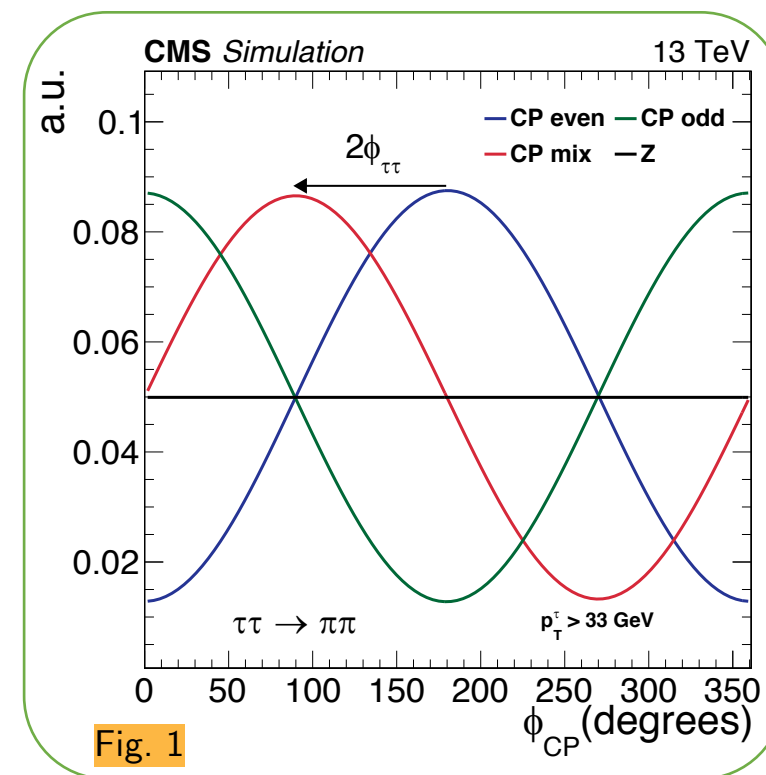
$$L_Y = -\frac{m_\tau}{v} (\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau}i\gamma_5\tau) \quad , \quad m_\tau = \text{mass of } \tau, \quad v = \text{V.E.V.} = 246 \text{ GeV}$$

- Defining the CP mixing angle as  $\tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$

- $\phi_{\tau\tau} = 0^\circ$  : CP-even Higgs
- $\phi_{\tau\tau} = 90^\circ$  : CP-odd Higgs
- $\phi_{\tau\tau} = 45^\circ$  : maximum-mixing CP Higgs

- $\phi_{\tau\tau}$  can be measured using the variable,  $\phi_{CP}$ , which is defined from the angle between the decay products of  $\bar{\tau}\tau$ :

$$\frac{d\sigma}{d\phi_{CP}} \propto \cos(\phi_{CP} - 2\phi_{\tau\tau}), \quad [\text{arXiv: 1308.2674}]$$



# $\phi_{CP}$ measurement and optimizations



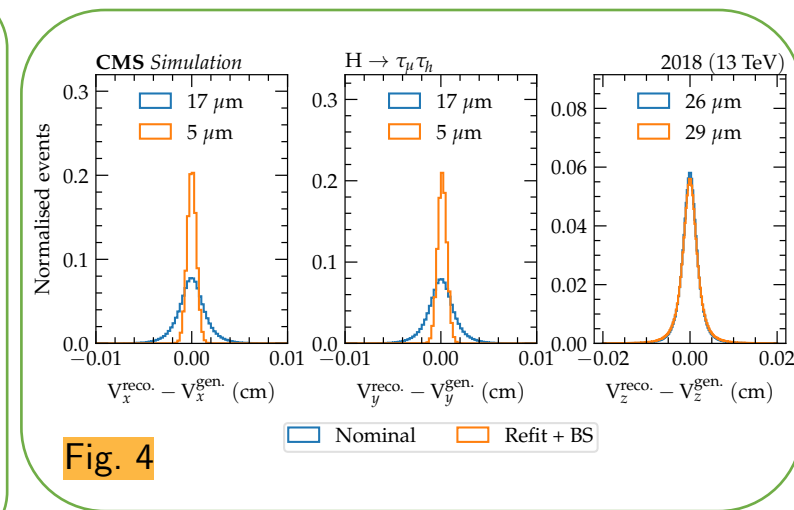
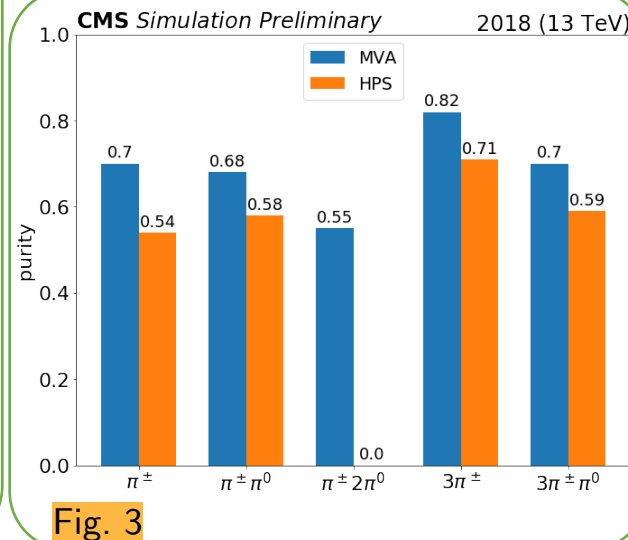
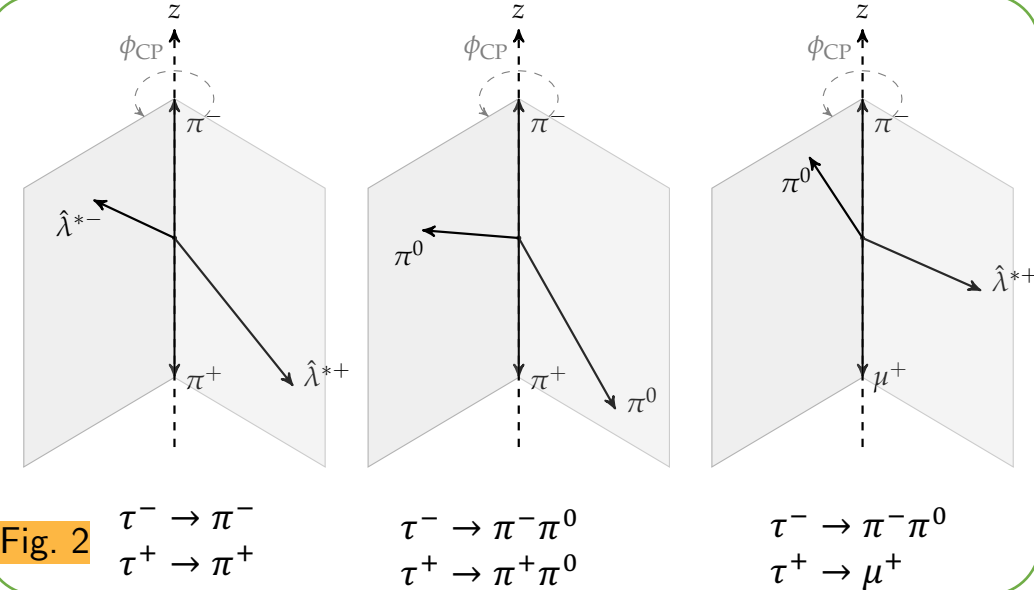
## $\phi_{CP}$ measurement

- The  $\phi_{CP}$  is the angle between two planes, each defined by the “visible” products of  $\tau^+$  and  $\tau^-$  (Fig. 2)
  - “visible” means neutrinos excluded
  - In a single visible particle decay (e.g.  $\pi^\pm$ ), the plane is defined with the help of its impact parameter (more on arXiv: 1510.03850)

## Optimizations

- Identify signal ( $H \rightarrow \tau^- \tau^+$ ) from background: Machine learning (ML) techniques
- Identify  $\tau$  hadronic decays: ML techniques (Fig. 3)
  - 10 to 55 %-points improvement in purity of decay channels and ~20% improvement in CP sensitivity
- Primary vertex (PV) reconstruction (Fig. 4)
  - Exclude  $\tau$  tracks from the PV fit + use beamspot constraints. Transverse resolution improved by O(3)
- Impact parameter (IP):
  - 3D reconstruction + Exclude events with low IP significance

Main visible $\tau^-$ decay products
$e^-$
$\mu^-$
$\pi^-$
$\pi^- \pi^0$
$\pi^- 2\pi^0$
$\pi^- \pi^+ \pi^-$
$\pi^- \pi^+ \pi^- \pi^0$



# Result



- The observed (expected) sensitivity to distinguish between CP-even and CP-odd scenario is  $3.2 \sigma$  ( $2.3 \sigma$ ).
- Fig. 5 shows the negative log-likelihood scan of  $\phi_{\tau\tau}$ . The observed (expected)  $\phi_{\tau\tau}$  is found to be  $4^\circ \pm 17^\circ$  ( $0^\circ \pm 23^\circ$ ) at 68% CL.
- Fig. 6 shows a 2D negative log-likelihood scan of  $\kappa_\tau$  and  $\tilde{\kappa}_\tau$ .
- The next-to-minimal supersymmetric model (NMSSM) allows up to  $\pm 27^\circ$  CP violation [arXiv: 1508.03255]. Our result exclude a part of the phase space in this model at 68% CL.
- The  $\phi_{CP}$  distribution for the three most sensitive decay channels can be seen in Fig. 7. “A” is a measure showing asymmetry between CP-even and CP-odd
 
$$A = \frac{|C_{P\text{even}} - C_{P\text{odd}}|}{C_{P\text{even}} + C_{P\text{odd}}}, \quad (\text{averaged over all bins})$$
- **Conclusion:** The result is compatible with the SM prediction within uncertainties. The pure CP-odd scenario is rejected by  $3.2 \sigma$ .

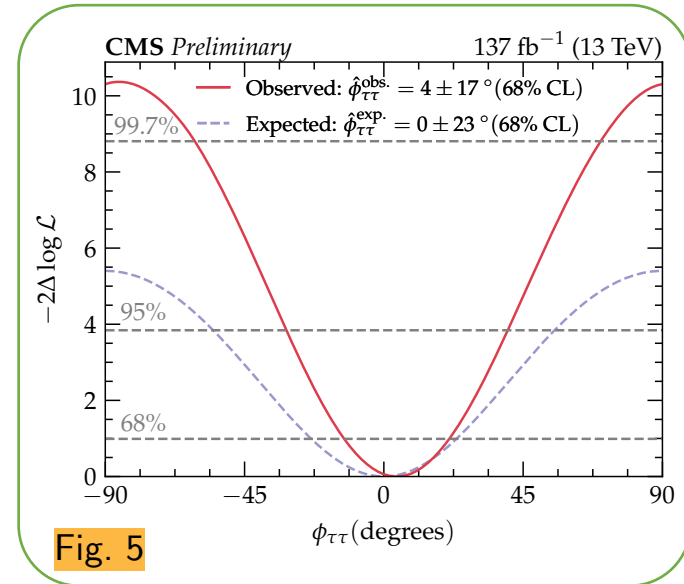


Fig. 5

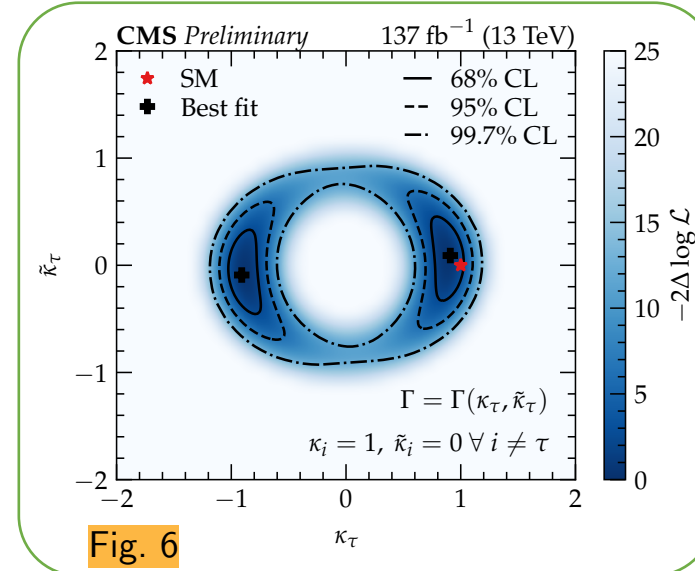


Fig. 6

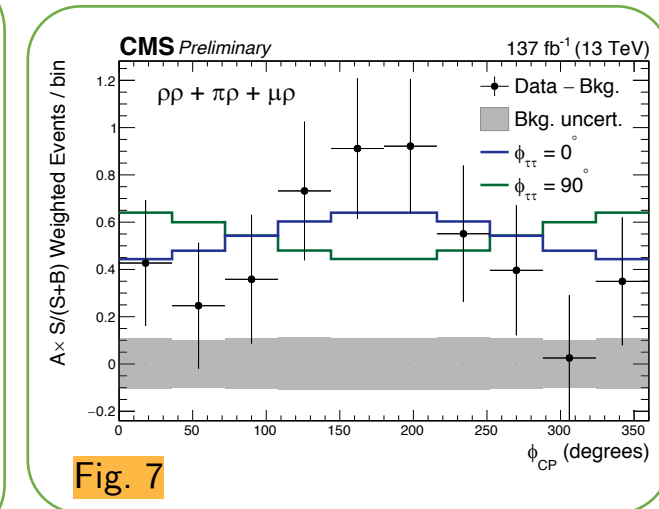


Fig. 7