Analysis of the CP Structure of the Tau Lepton Yukawa coupling at $\sqrt{s} = 13.6$ TeV

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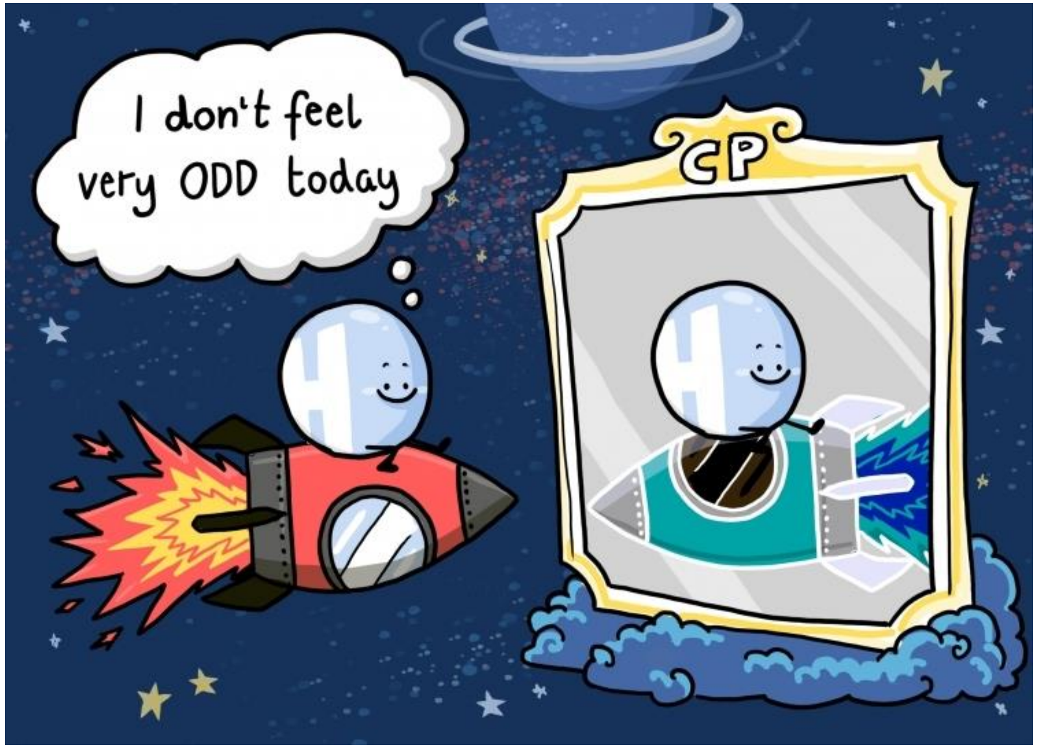
On behalf of the CMS Collaboration

Introduction

- The amount of CP violation in the SM is insufficient to explain the **matter-antimatter asymmetry** of the universe
  → **Extended Higgs sectors** could introduce **additional sources of CP-violation via BSM effects**



- The Yukawa couplings to **fermions** can have CP-even and CP-odd components **at tree level**
  → Tau Yukawa coupling could have a sufficiently large CP-odd component to explain the baryon asymmetry

- Latest CMS measurement of the **CP structure of the tau lepton Yukawa coupling** ($\sqrt{s}$ = 13.6 TeV, 2022/23)
  → Shown for the first time at Moriond, public note: CMS-PAS-HIG-25-012

CP Measurement in H$\rightarrow\tau\tau$

- Tau Lepton Yukawa coupling can be parametrised in terms of **CP-even** and **CP-odd** couplings:

$$\mathcal{L}_\tau = -\frac{m_\tau}{v}\bar{\tau}(\kappa_\tau + i\gamma_5\tilde{\kappa}_\tau)\tau\mathrm{H}$$

→ Define effective mixing angle:

$$\tan\left(\alpha^{\mathrm{H}\tau\tau}\right) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

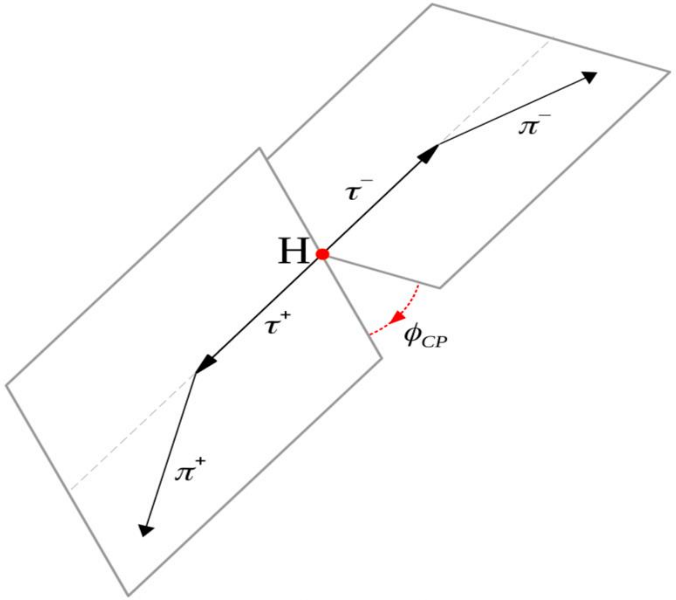
CP-even: $\alpha^{\mathrm{H}\tau\tau} = 0°$ (SM), CP-odd: $\alpha^{\mathrm{H}\tau\tau} = 90°$, CP-mixed: $0° < |\alpha^{\mathrm{H}\tau\tau}| < 90°$

- If $|\alpha^{\mathrm{H}\tau\tau}|$ is between ~ 5° to 15°, could explain the baryon asymmetry of the universe, whilst remaining compatible with experimental constraints (model-dependent) [1]
  → Previous measurement [2] ($\sqrt{s} = 13$ TeV): $\alpha^{\mathrm{H}\tau\tau} = -1 \pm 19°$

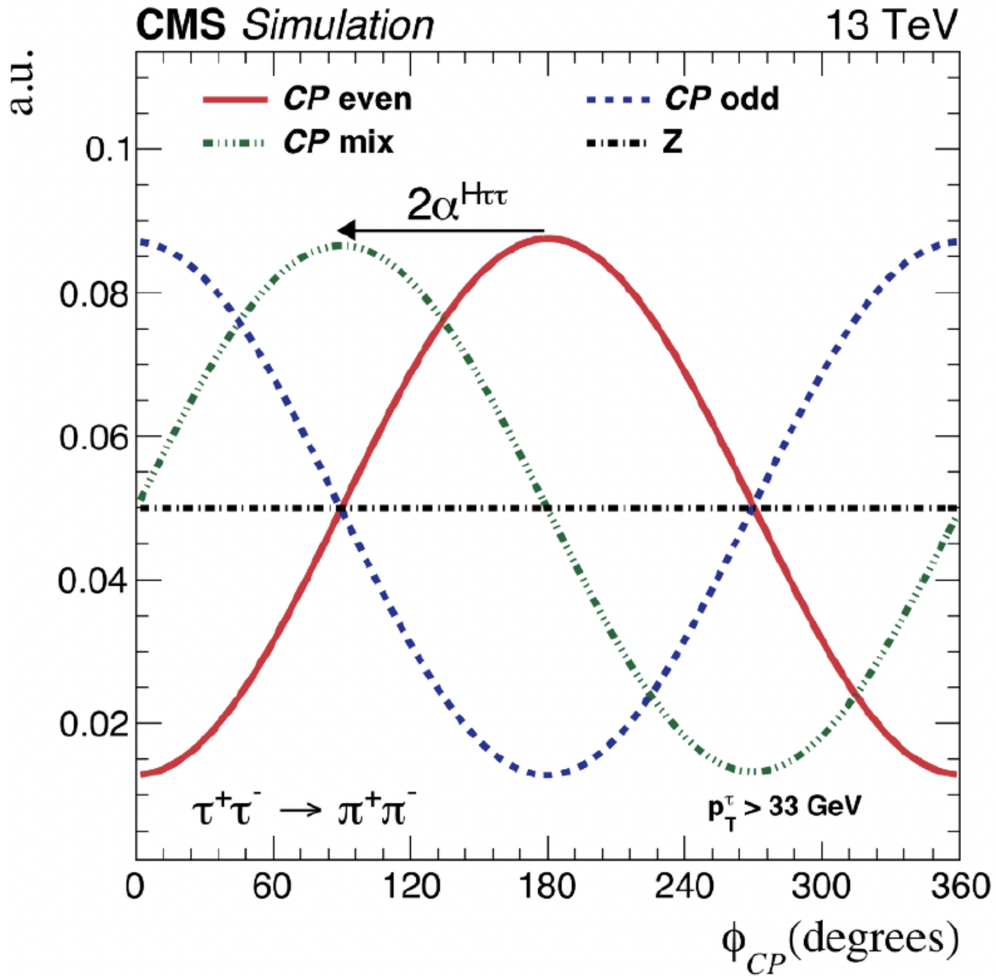
[1]: EPJC 82 (2022) 604
[2]: JHEP 06 (2022) 12

Determining the $\alpha^{H\tau\tau}$ mixing angle

- Relationship between $\alpha^{H\tau\tau}$ and ***"acoplanarity angle"*** $\boldsymbol{\phi_{CP}}$ can be inferred from spin correlations



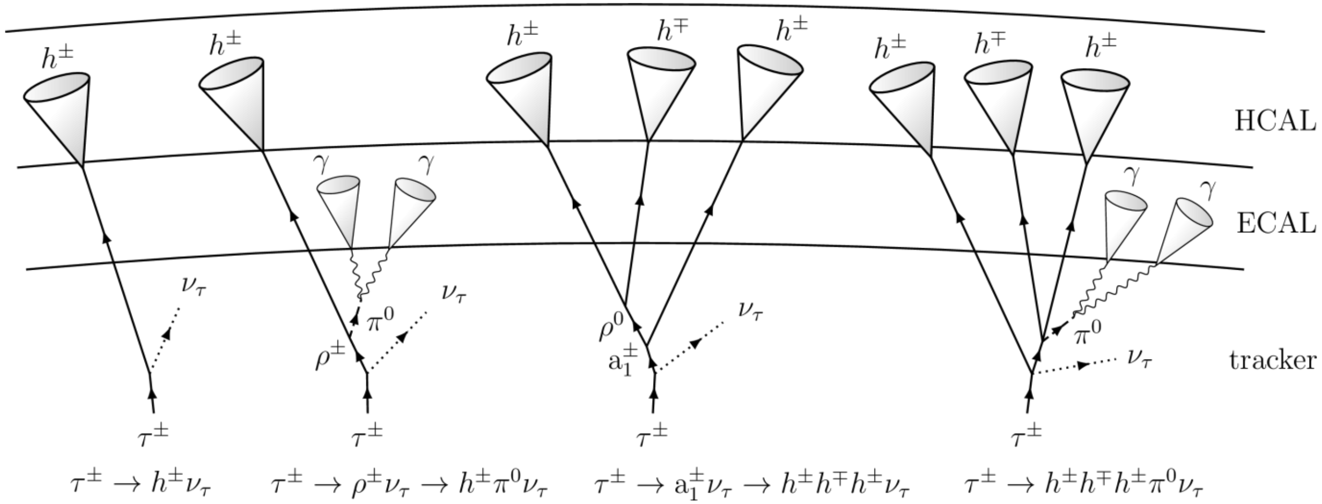
$$\frac{d\Gamma}{d\phi_{CP}}(H \to \tau^+\tau^-) \sim 1 - b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$

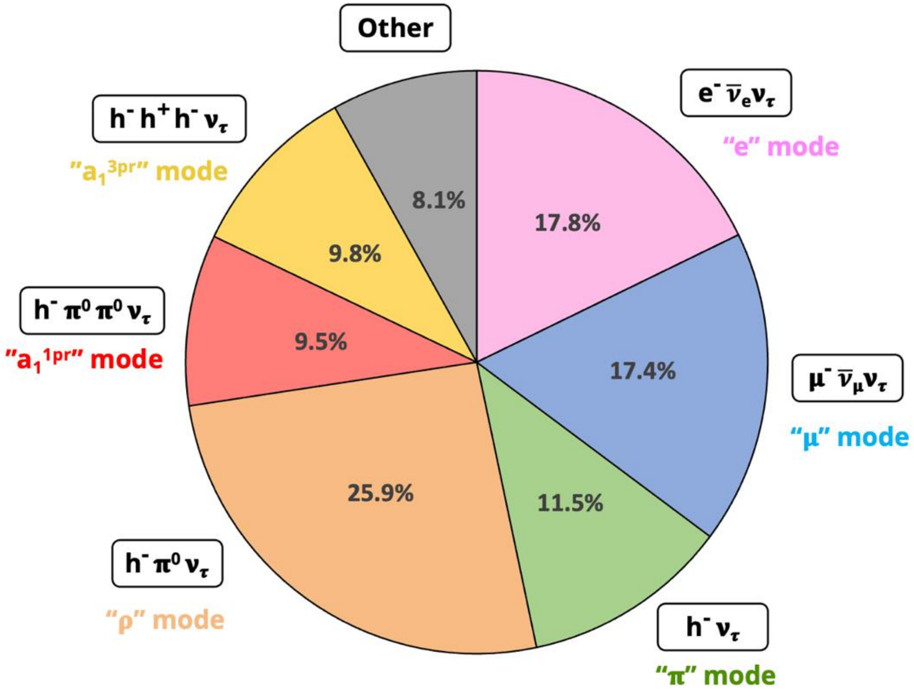


→ However, the reconstruction of decay planes is challenging as the undecayed tau momenta are unknown

Tau Decay Topologies

- Tau leptons are unstable, and can decay either hadronically (τ_h) or leptonically (τ_e/τ_μ)
  - → Leptonic decays are reconstructed as electrons/muons
  - → Hadronic decays are identified using DeepTau algorithm [1]



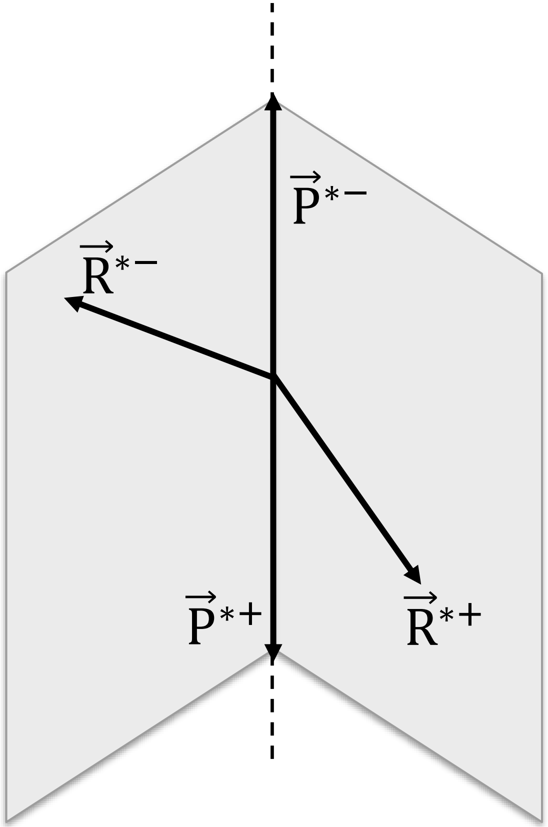


Branching fractions for different τ decays (identical for charge conjugates)

- In this analysis, we consider $\boldsymbol{\tau_\mathrm{h}\tau_\mathrm{h}}$, $\boldsymbol{\tau_\mu\tau_\mathrm{h}}$ and $\boldsymbol{\tau_\mathrm{e}\tau_\mathrm{h}}$ final states

[1]: JINST 20 (2025) 12032

Reconstruction of the ϕ^{CP} observable

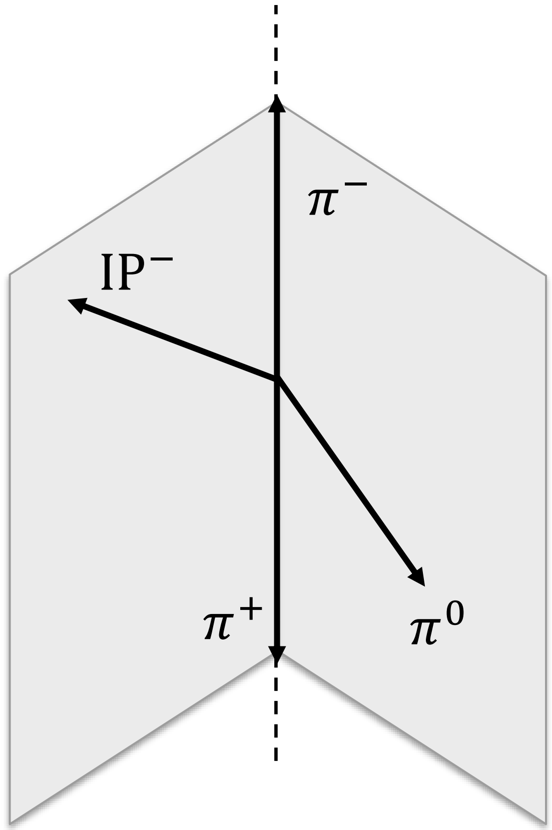


- Work in the **zero-momentum frame** of the charged decay products (except $a_1^{3pr}a_1^{3pr}$ where Higgs rest-frame used)
- **$\vec{R}^{*\pm}$ and $\vec{P}^{*\pm}$ are defined depending on τ decay topology**

Decay	π	ρ/a_1^{1pr}	a_1^{3pr}	e	μ
R	IP	π^0	PVec	IP	IP
P	$\pi^\pm$	$\pi^\pm$	$\tau^\pm$	$e^\pm$	$\mu^\pm$

- $\pi^\pm$, $\mu^\pm$, $e^\pm$, π^0, $\tau^\pm$: Momentum vector
- IP: Vector between the primary vertex and point of closest approach of the charged track
- Polarimetric vector (PVec): Estimate of the most likely direction of the tau spin

Reconstruction of the ϕ^{CP} observable



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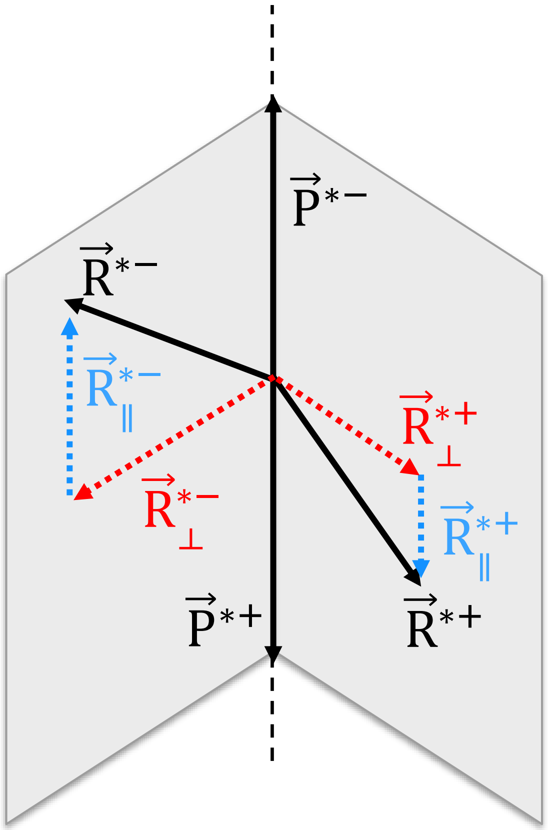
Example:
- **τ^- decays via π mode** $(\tau^- \to \pi^- \nu_\tau)$
- **τ^+ decays via ρ mode** $(\tau^+ \to \pi^+ \pi^0 \nu_\tau)$

Reconstruction of the ϕ^{CP} observable



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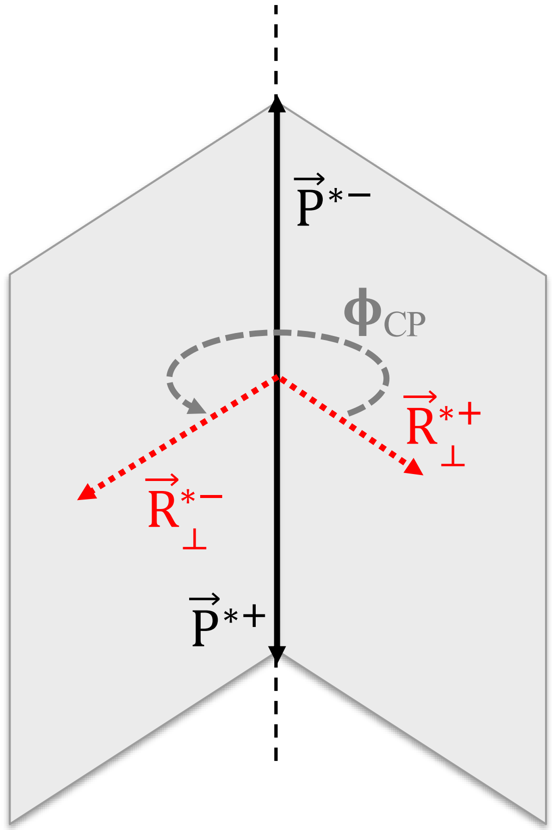
→ Split $\vec{\mathbf{R}}^{*\pm}$ vectors into components parallel and perpendicular to the $\vec{\mathbf{P}}^{*\pm}$

Reconstruction of the ϕ^{CP} observable

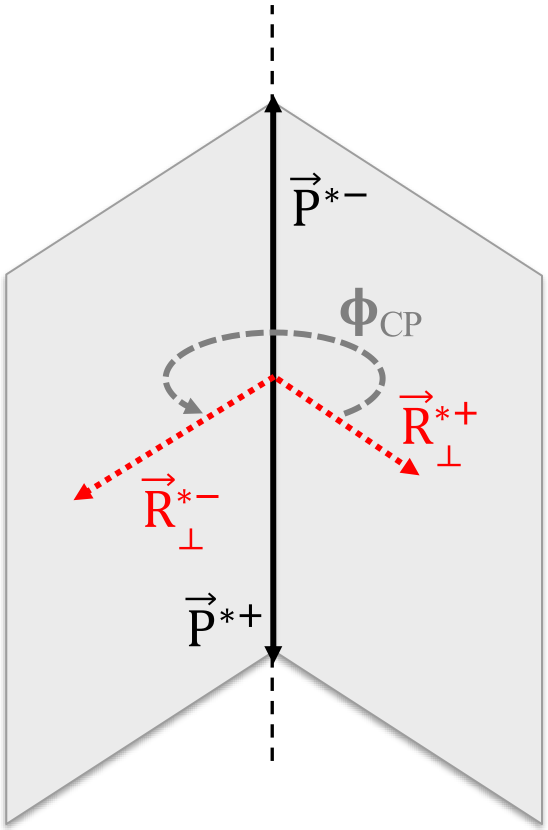


→ Define: $\Phi^{*} = \cos^{-1}(\hat{R}_{\perp}^{*+} \cdot \hat{R}_{\perp}^{*-})$

and: $O^{*} = \hat{P}^{*-} \cdot (\hat{R}_{\perp}^{*+} \times \hat{R}_{\perp}^{*-})$

then: $\Phi_{CP} = \begin{cases} \Phi^{*} & \text{if } O^{*} \geq 0 \\ 2\pi - \Phi^{*} & \text{if } O^{*} < 0 \end{cases}$

Reconstruction of the ϕ^{CP} observable



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NB: If ρ/a_1^{1pr} *mesons are involved, additional shift needed:*

Compute $y^{\tau\pm} = \dfrac{E(\pi^0) - E(\pi^\pm)}{E(\pi^0) + E(\pi^\pm)}$ *for each meson in the pair*

and if the product < 0: $\Phi_{CP}^{New} = \begin{cases} \Phi_{CP} + \pi & \text{if } \Phi_{CP} < \pi \\ \Phi_{CP} - \pi & \text{if } \Phi_{CP} \geq \pi \end{cases}$

Selections

- Events are selected online by the CMS trigger system:

Channel	Trigger	Trigger requirement (GeV)	Offline requirement (GeV)
$\tau_h\tau_h$	di-τ	$\tau_h(35)$ & $\tau_h(35)$	$\tau_h(40)$ & $\tau_h(40)$
	di-τ +jet	$\tau_h(30), \tau_h(30)$& jet(60)	$\tau_h(35), \tau_h(35)$& jet(60)
$\tau_\mu\tau_h$	single μ	$\mu(24)$	$\mu(26)$
$\tau_e\tau_h$	single e	e(30)	e(32)

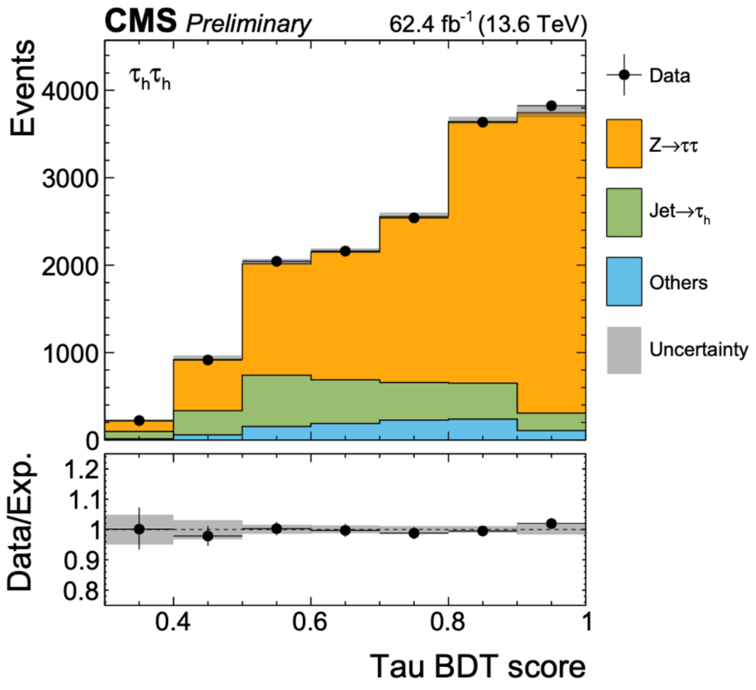
- Require an oppositely charged, and well separated pair of leptons, that pass identification algorithms

- Additional cuts are applied depending on the tau decay topology to optimise sensitivity
  - → Well reconstructed IP required for π, e and μ modes
  - → Energy splitting cut for ρ and a_1^{1pr} modes: $E_{split} = \left|\frac{E\,(\pi^0) - E\,(\pi^{\pm})}{E\,(\pi^0) + E\,(\pi^{\pm})}\right|$
  - → Presence of a secondary decay vertex for the a_1^{3pr} mode

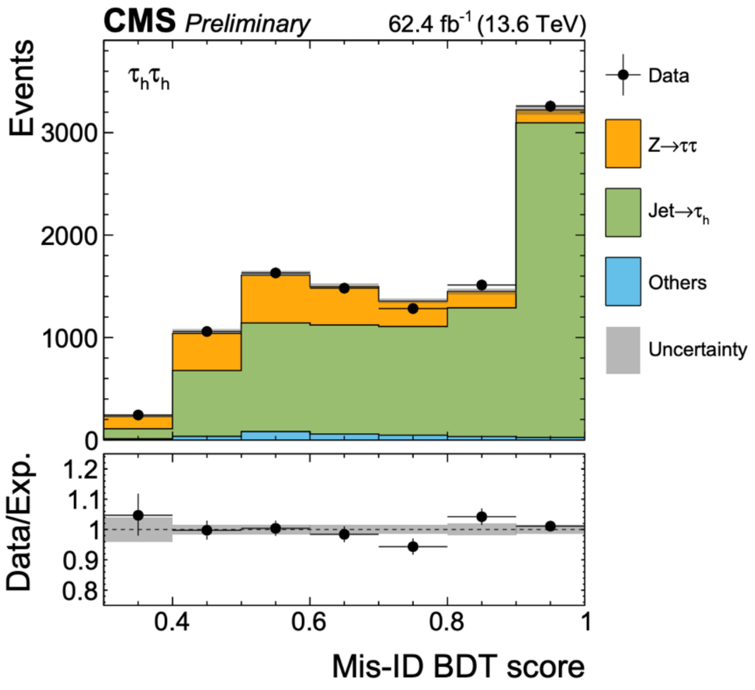
Event Classification

- Train a **multiclass BDT classifier for each channel** ($\tau_h\tau_h$, $\tau_\mu\tau_h$ and $\tau_e\tau_h$)

- Aim to distinguish between 3 classes
  - **Higgs:** VBF, VH ($W^\pm H$, ZH), ggH
  - **Genuine Tau Background:** Mainly $Z\to\tau\tau$
  - **Mis-ID Tau Background:** Jets/light leptons mis-reconstructed as τ



Post-fit genuine tau background category ($\tau_h\tau_h$ channel)

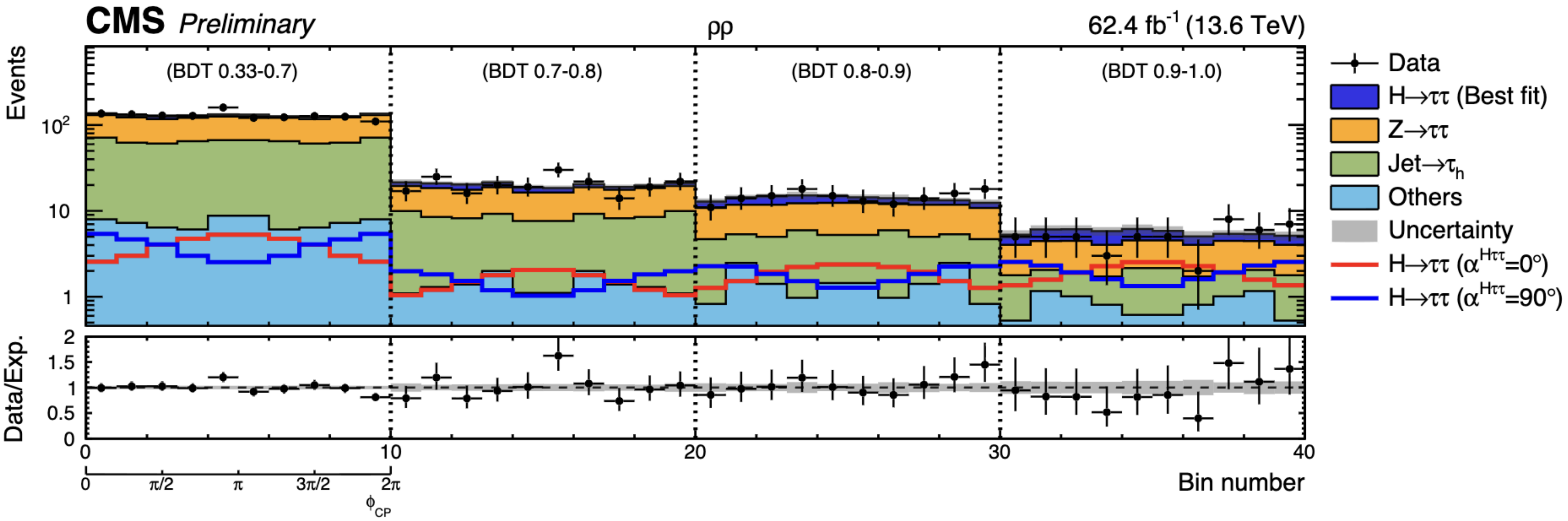


Post-fit mis-identified tau background category ($\tau_h\tau_h$ channel)

→ All events are assigned a class based on the probability output

Fit Inputs

- A **simultaneous binned maximum likelihood fit for $\alpha^{H\tau\tau}$** is performed
  - Fit inputs are Φ_{CP} distributions for the signal category, split into windows of Higgs Category BDT score:



Post-fit distribution for the most sensitive signal category
(both tau leptons decaying via the ρ mode)

  - Background (Genuine and Mis-ID τ) BDT score distributions used to constrain systematic uncertainties

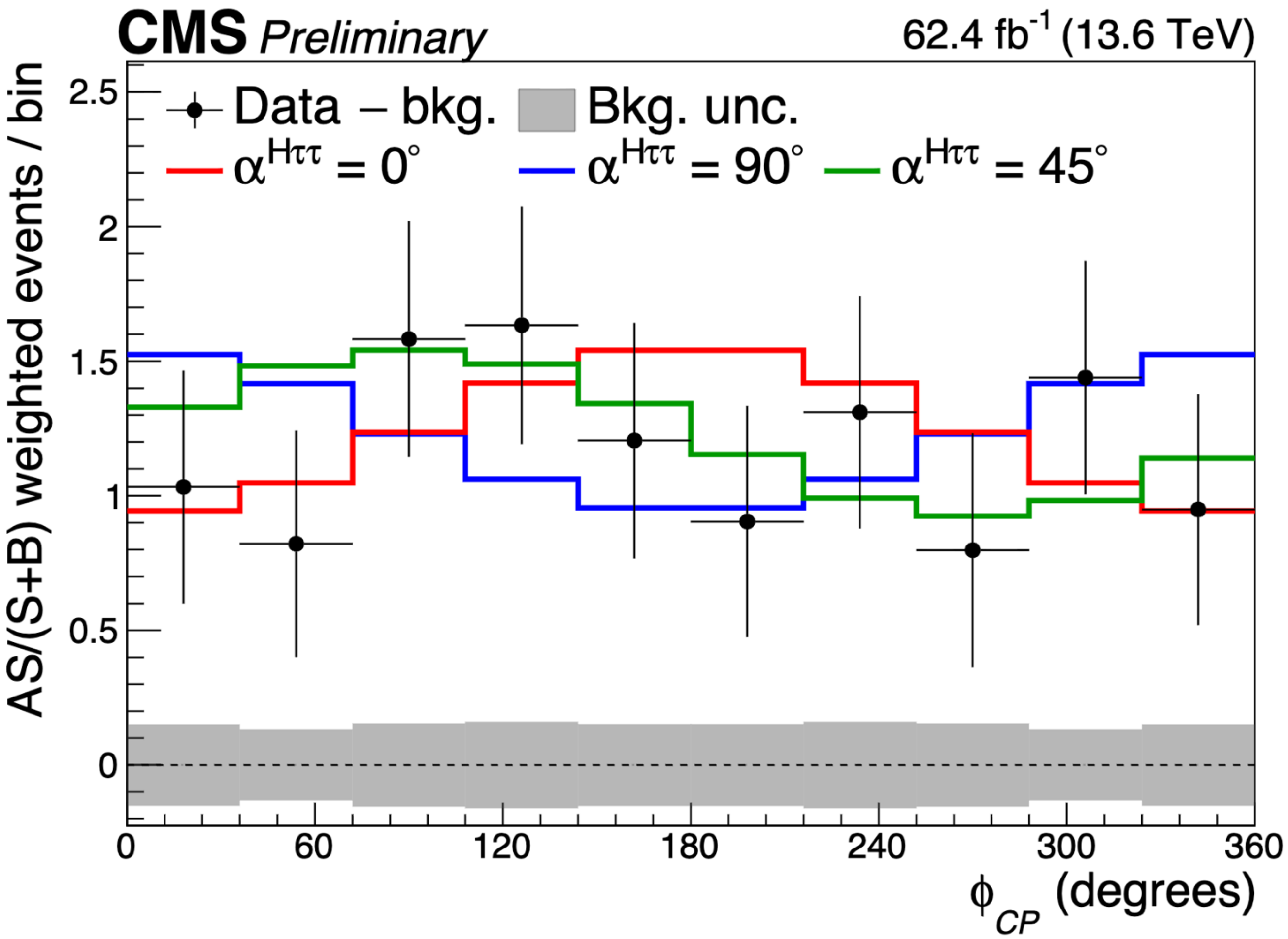
Background Subtracted ϕ_{CP} Distribution ($\sqrt{s} = 13.6$ TeV)

- Background subtracted data for the ρρ, πρ, μρ, eρ, ρa_1^{3pr}, $\rho a_1^{1pr}/a_1^{1pr}a_1^{1pr}$, μa_1^{3pr} and $e a_1^{3pr}$ channels (others use different number of Φ_{CP} bins)

- Each BDT score bin is weighted by AS/(S+B), where S (B) are the signal (background) rates, and A is the average asymmetry per BDT bin:

$$A = \frac{1}{N_{\phi_{CP}}} \sum_{\mathrm{i}}^{N_{\phi_{CP}}} \frac{|N_\mathrm{i}^{\mathrm{even}} - N_\mathrm{i}^{\mathrm{odd}}|}{N_\mathrm{i}^{\mathrm{even}} + N_\mathrm{i}^{\mathrm{odd}}}$$

where N_i^{even} (N_i^{odd}) are the number of even/odd signal events in each Φ_{CP} bin



Background-subtracted ϕ_{CP} distribution ($\sqrt{s} = 13.6$ TeV)

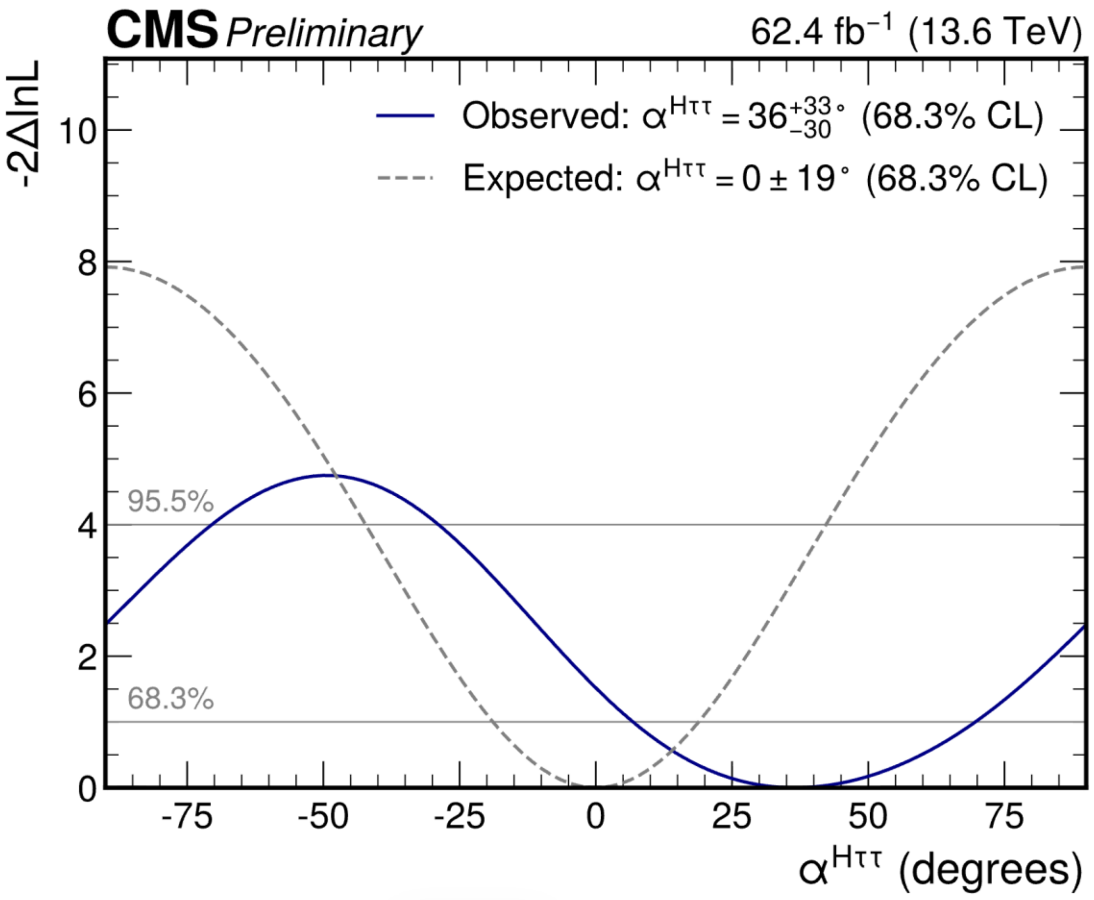
Scan of $\alpha^{H\tau\tau}$ ($\sqrt{s} = 13.6$ TeV)

- **Observed:**

$$\alpha^{H\tau\tau} = 36 \pm 27\,(\text{stat})\,^{+18}_{-11}\,(\text{bbb})\,^{+9}_{-7}\,(\text{syst})^{\circ}$$

- **Significant improvement in expected uncertainty** (better than ±21° achieved at $\sqrt{s} = 13$ TeV, despite using less than half the amount of data: 62 fb^{-1} vs 138 fb^{-1})

  → Sources of improvement include:
  - Improved tau identification/trigger
  - Higgs production Xsec increase
  - Optimised cuts and ϕ_{CP} reconstruction



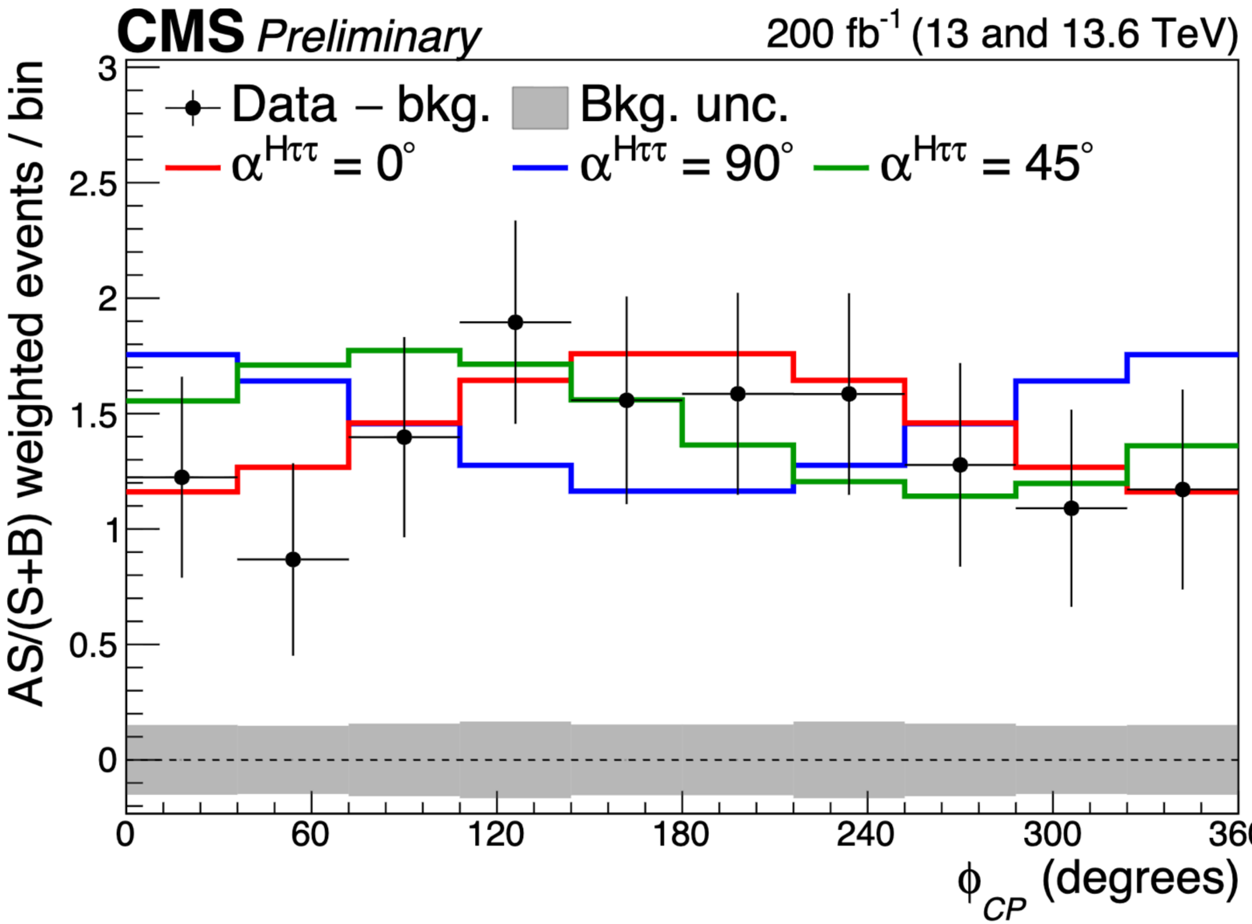
Likelihood scan of $\alpha^{H\tau\tau}$ ($\sqrt{s} = 13.6$ TeV)

Background Subtracted ϕ_{CP} ($\sqrt{s} = 13$ and 13.6 TeV)

- **Combination of $\sqrt{s} = 13.6$ TeV and $\sqrt{s} = 13$ TeV [1] data sets is performed**

- Background subtracted data for the ρρ, πρ, μρ, eρ, ρa_1^{3pr}*, $\rho a_1^{1pr}/a_1^{1pr}a_1^{1pr}$*, μa_1^{3pr}* and $e a_1^{3pr}$* channels (others use different number of Φ_{CP} bins)

* *Included for* $\sqrt{s} = 13.6$ TeV *measurement only (these used a different binning at* $\sqrt{s} = 13$ TeV*)*



Background-subtracted ϕ_{CP} distribution ($\sqrt{s} = 13.6$ TeV and $\sqrt{s} = 13$ TeV)

[1]: JHEP 06 (2022) 12

Scan of $\alpha^{H\tau\tau}$ ($\sqrt{s} = 13$ and 13.6 TeV)

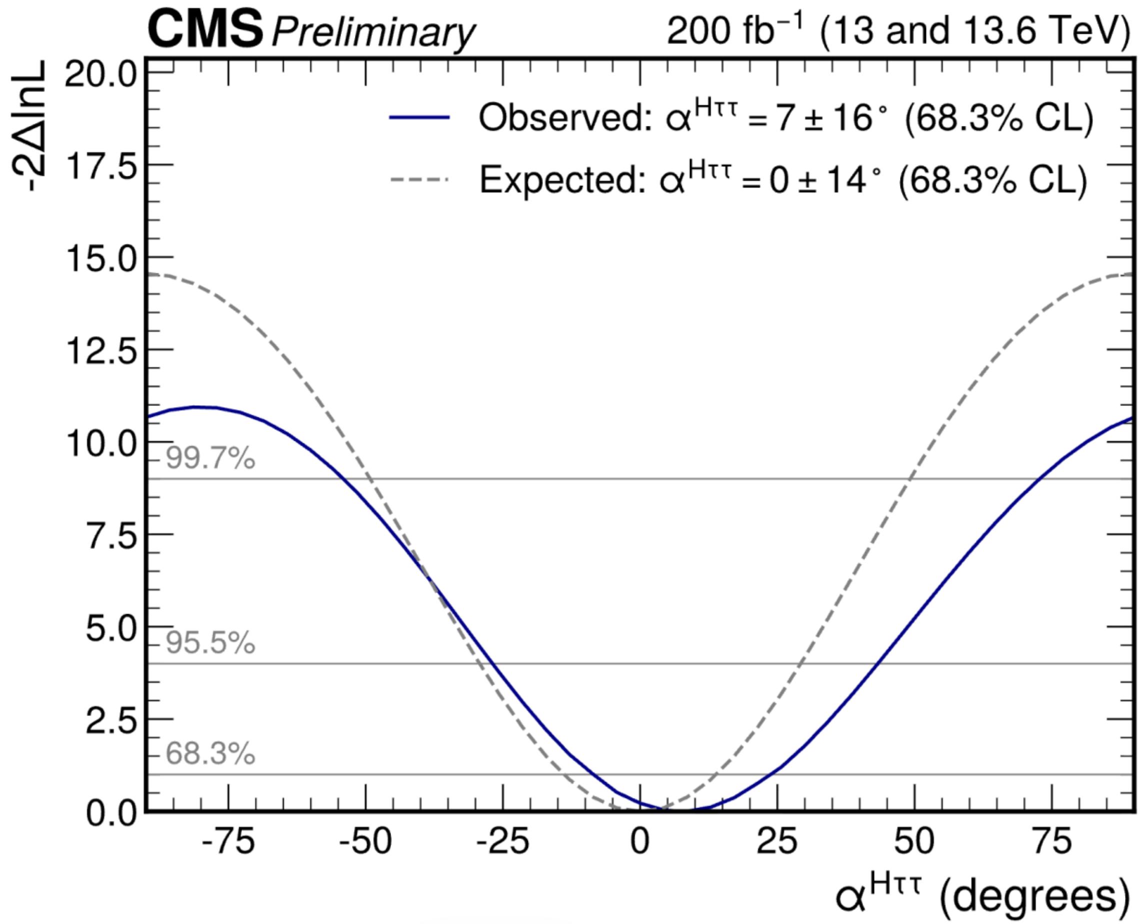
- $\sqrt{s} = 13$ TeV analysis alone [1]:
  - Observed: $\alpha^{H\tau\tau}$ = -1 ± 19° (Expected ± 21°)

- **Combination of the $\sqrt{s} = 13.6$ TeV and $\sqrt{s} = 13$ TeV data sets:**

$$\alpha^{H\tau\tau} = 7 \pm 16\,(\text{stat})\,^{+3}_{-2}\,(\text{bbb})\ \pm 2\,(\text{syst})^{\circ}$$

  - Most precise measurement by CMS to date of the CP nature of the Higgs to τ lepton coupling, and the best expected precision by any experiment

* *ATLAS ($\sqrt{s} = 13$ TeV): Obs. 9 ± 16°, Exp 0 ± 28°* [2]

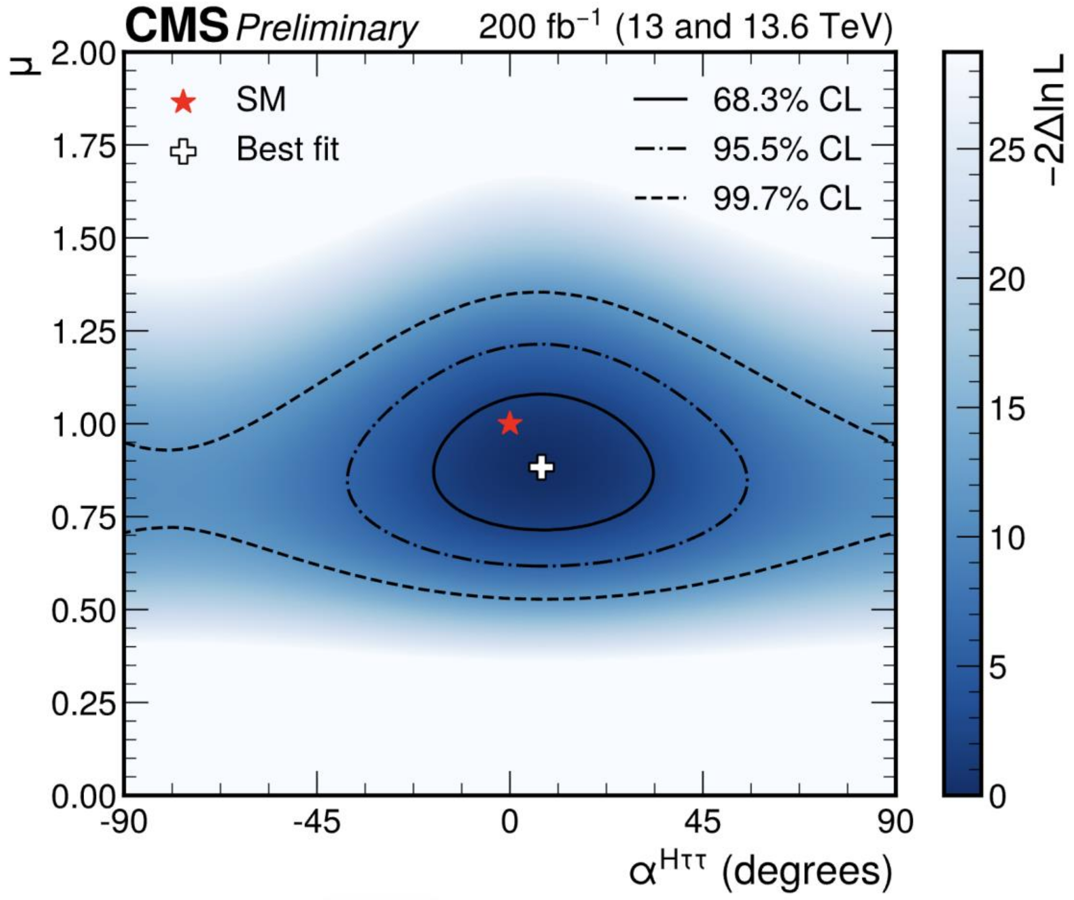


Likelihood scan of $\alpha^{H\tau\tau}$ ($\sqrt{s} = 13.6$ TeV and $\sqrt{s} = 13$ TeV)

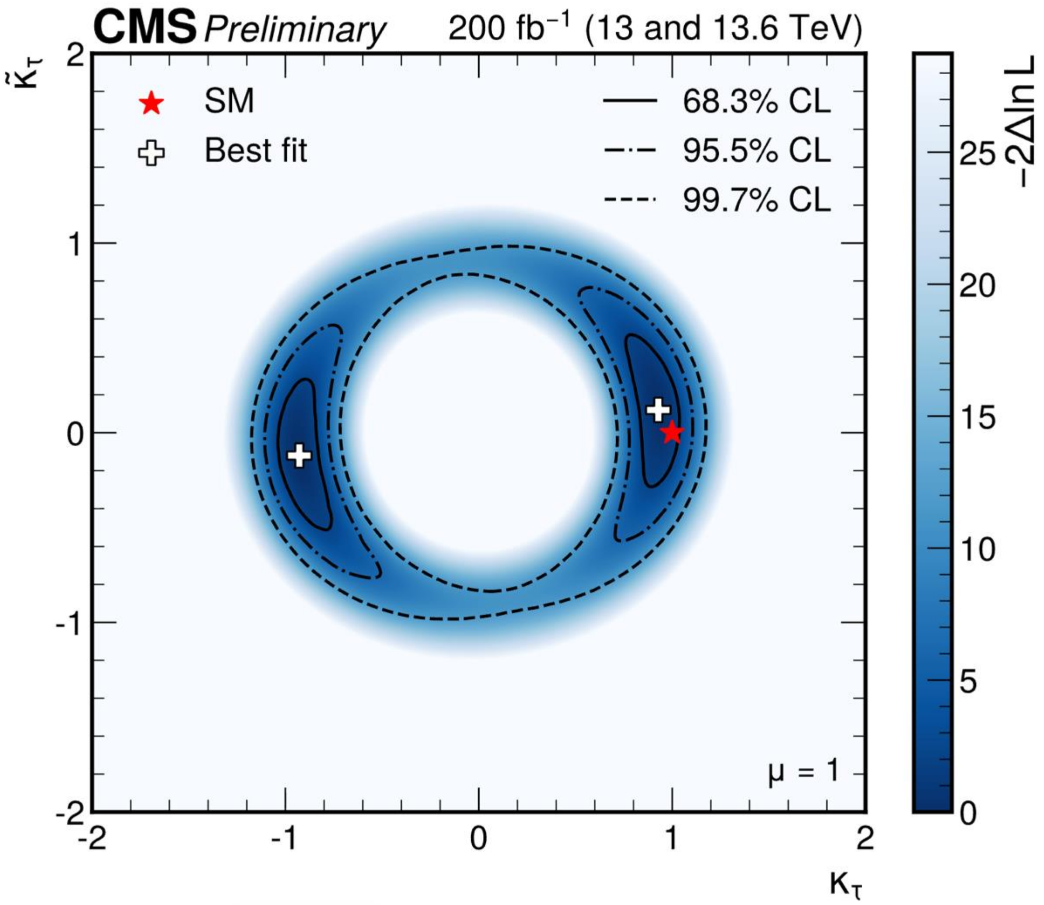
[1]: JHEP 06 (2022) 12
[2]: EPJC 83 (2023) 563

Additional Likelihood Scans ($\sqrt{s} = 13$ and 13.6 TeV)

Likelihood scans for alternate fits are also performed:



Scan of total signal strength vs $\alpha^{H\tau\tau}$



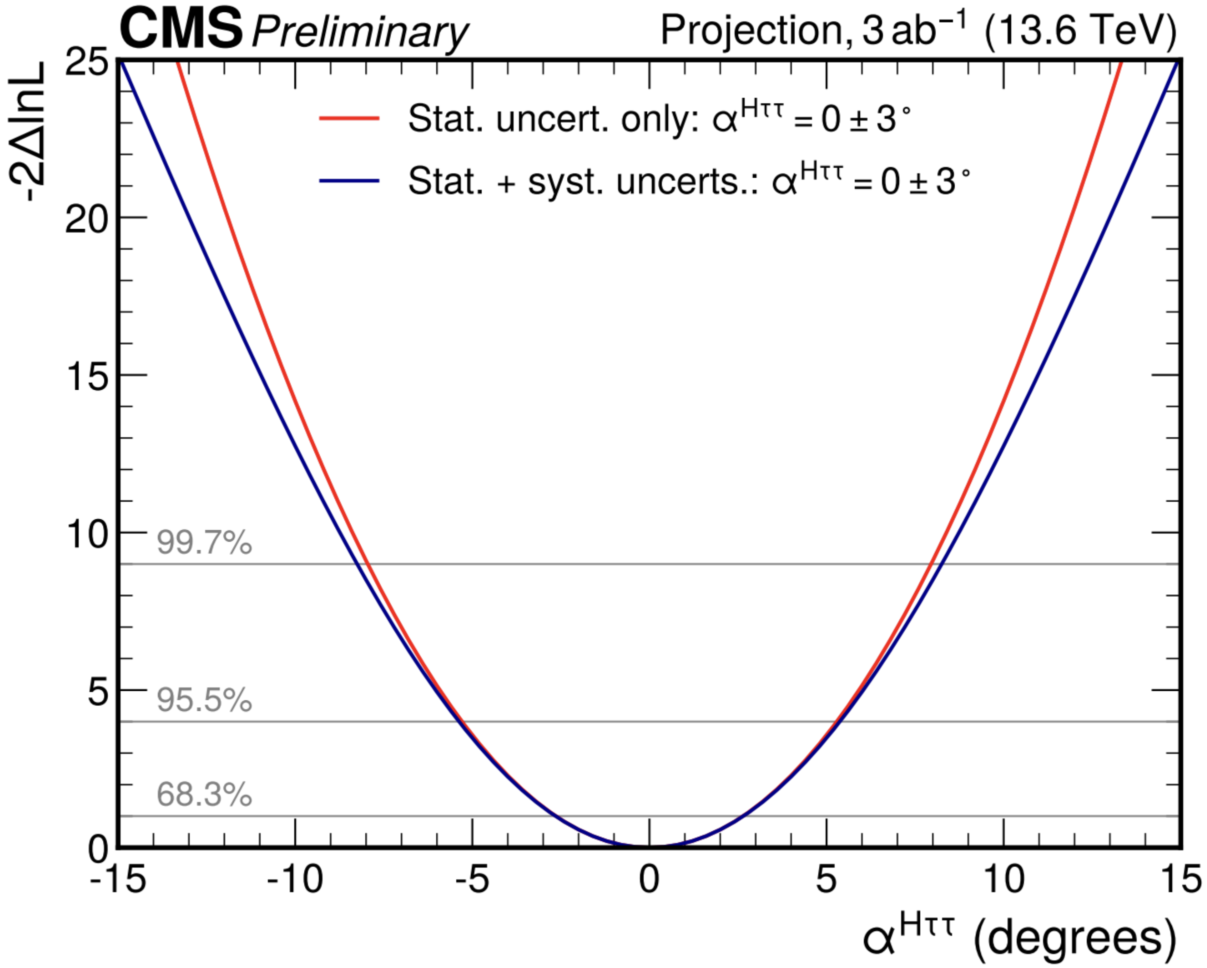
Scan with likelihood parametrised in terms of $\tilde{\kappa}_\tau$ and κ_τ

Extrapolation to the end of HL-LHC

- Extrapolation to the end of the HL-LHC (integrated luminosity of 3 ab^{-1})

- Two systematic uncertainty scenarios are considered:
  - → Systematics the same as in the $\sqrt{s} = 13.6$ TeV analysis
  - → Statistical uncertainties only

- Expected precision on $\alpha^{H\tau\tau}$ is 3° in both scenarios
  - → Probe BSM scenarios that predict small but non-zero mixing angle



Extrapolated likelihood scan of $\alpha^{H\tau\tau}$ to the end of the HL-LHC

Summary

- Presented an overview of the $\sqrt{s} = \mathbf{13.6}$ **TeV (2022+2023)** measurement of the **CP structure of the Yukawa coupling between the Higgs boson and τ leptons at CMS**
  → New result, documented in [CMS-PAS-HIG-25-012]

- $\sqrt{s} = 13.6$ TeV analysis result observed $\boldsymbol{\alpha^{\mathrm{H}\tau\tau} = 36^{+33}_{-30}}{}^\circ$ (expected $0 \pm 19°$)
  → Significantly improved expected sensitivity with respect to $\sqrt{s} = 13$ TeV, despite using less than half the amount of data

- Combination with $\sqrt{s} = 13$ TeV: $\boldsymbol{\alpha^{\mathrm{H}\tau\tau} = 7 \pm 16}°$ (expected $0 \pm 14°$)
  → Most precise measurement by CMS to date of the CP nature of the Higgs to τ lepton coupling, and the best expected precision by any experiment

- Future measurements will further reduce the uncertainty on $\alpha^{\mathrm{H}\tau\tau}$, allowing precise probes of BSM scenarios which predict small mixing angles

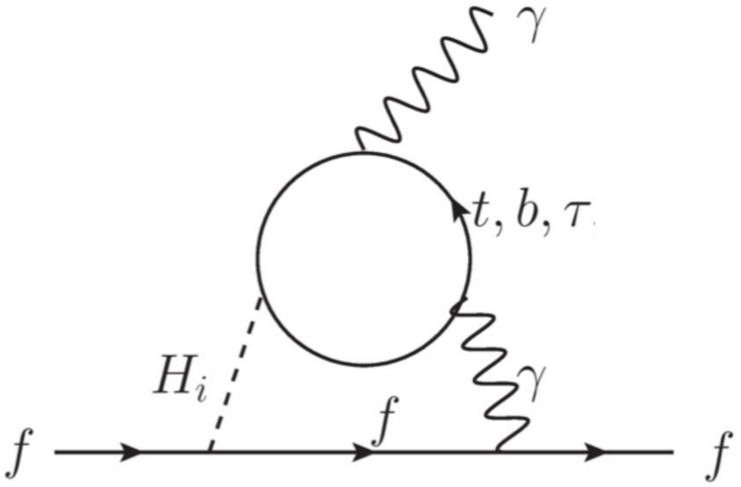
BACKUP

EDM/BAU Constraints

- CP-violating coupling can lead to EDM generation
  - Electron EDM provides tight constraint (model dependent) $d_e \sim 10^{-29}$ e cm (ACME Coll., 2018)

- In simplest models: EPJC 82 (2022) 604

$$|d_e/d_e^{\text{ACME}}| = \kappa_e(870.0\tilde{\kappa}_t + 3.9\tilde{\kappa}_b + 3.4\tilde{\kappa}_\tau + 2.8\tilde{\kappa}_c + \ldots) + \tilde{\kappa}_e(610.1\kappa_t + 3.1\kappa_b + 2.8\kappa_\tau + 2.3\kappa_c + \ldots)$$



- BAU models also constrain:
  PRL 124 (2020) 181801

$$Y_B^{\text{obs}} = (8.59 \pm 0.08) \times 10^{-11}$$

$$Y_B/Y_B^{\text{obs}} = 28\tilde{\kappa}_t - 11\tilde{\kappa}_\tau - 0.2\tilde{\kappa}_b + \ldots$$

Extracting $\alpha^{H\tau\tau}$

- A **simultaneous binned maximum likelihood fit is performed:**

$$L(\mu_{ggH}, \mu_{qqH}, \alpha^{H\tau\tau}, \vec{\theta}) = \prod_{i}^{N_{bin}} P(n_i \mid S_i(\mu_{ggH}, \mu_{qqH}, \alpha^{H\tau\tau}, \vec{\theta}) + B_i(\vec{\theta})) \prod_{m}^{N_{nuisance}} C_m(\vec{\theta})$$

- *P*: Poisson distribution for obs. of n_i events
- $\vec{\theta}$: Nuisance parameters
- μ_{ggH}, μ_{qqH} : Signal strengths for ggH and VBF+VH
- $S_i(\mu_{ggH}, \mu_{qqH}, \alpha^{H\tau\tau}, \vec{\theta})$: Signal expectation
- $B_i(\vec{\theta})$: Background expectation
- $C_m(\vec{\theta})$: Constraints on nuisance parameters

- Fit inputs are:
  - Φ_{CP} distributions for the signal category, split into windows of Higgs Category BDT score
  - Background (Genuine and Misidentified τ) BDT score distributions

BDT Features

--- All channels
--- $\ell\tau_h$ only

p_T^1, p_T^2, $|\eta^1|$ # individual tau (lepton) kinematics

p_T^{MET}, $\Delta\phi^1_{MET}$, $\Delta\phi^2_{MET}$ # met information

ΔR, $\Delta\phi$, m_{vis}, p_T^{vis}, $p_T^{\tau\tau}$, $m_{FastMTT}$ # pair quantities

$m_T(1, MET)$, $m_T(2, MET)$, $m_T(1, 2)$, $\sqrt{m_T(1, MET)^2 + m_T(2, MET)^2 + m_T(1,2)^2}$ # m_T variables

p_T^{jet1}, p_T^{jet2}, η^{jet1}, η^{jet2} # individual jet kinematics

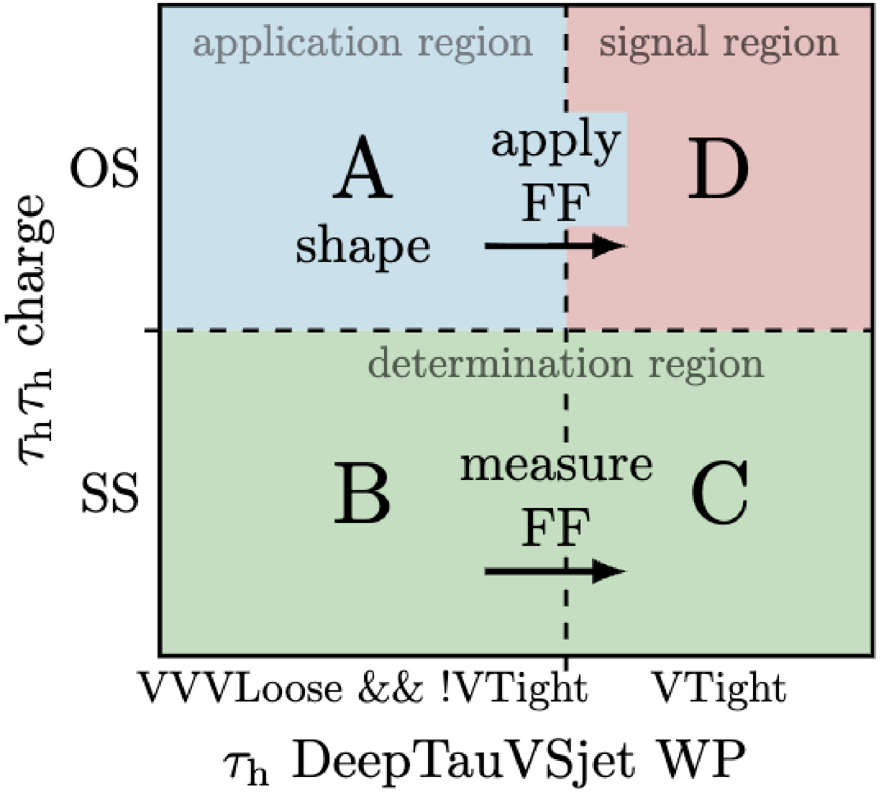
m_{jj}, p_T^{jj}, $\Delta\eta^{jj}$ # dijet quantities

N_{jets} # global jet information

Background Estimation

- Backgrounds where jets are misidentified as τ_h ($j \to \tau_h$) are difficult to simulate accurately
  - Data-driven "Fake factor" (F_F) method is used instead
- Measure the $j \to \tau_h$ fake factor in the determination region, and apply it in the application region to estimate the contribution in the signal region
  - Measured in as a **function of p_T in bins of decay mode and jet multiplicity**
- Sets of FFs:
  - In the $\tau_h\tau_h$ channel: 1 (QCD)
  - In the $\ell\tau_h$ channels: 3 (QCD, W+jets, top pairs)

➢ Other backgrounds are estimated from simulation



Definition of FF regions in $\tau_h\tau_h$ channel