IMPERIAL

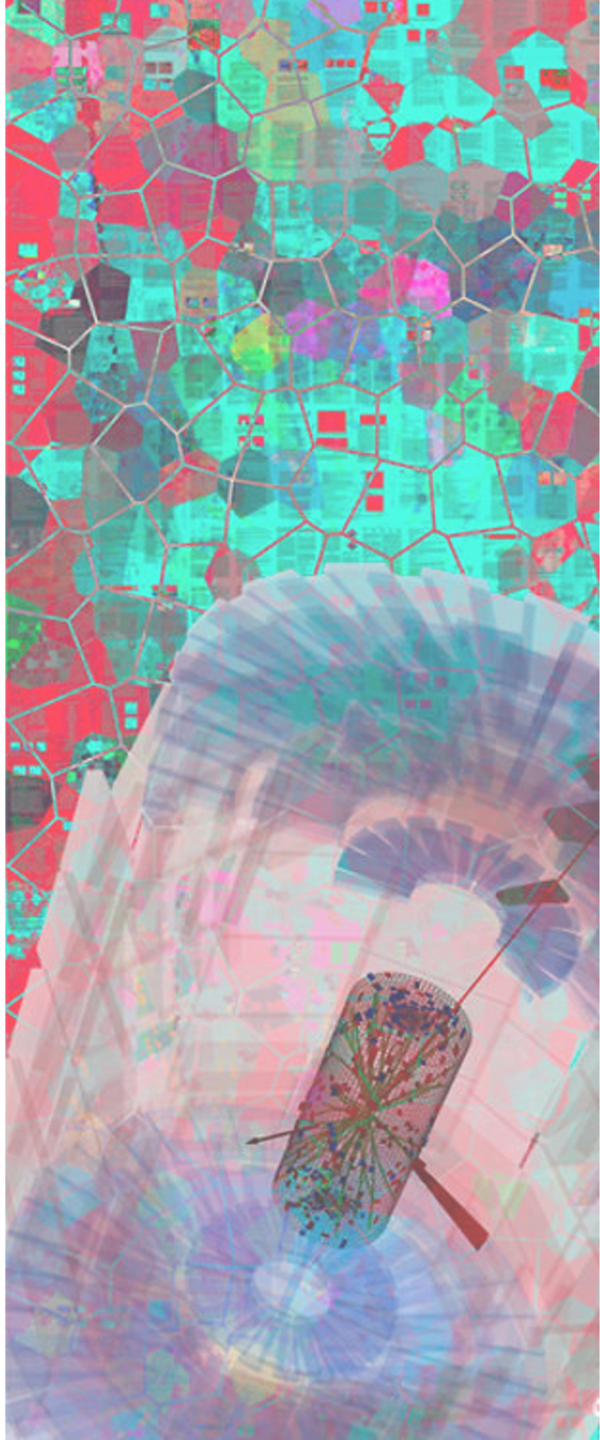
Measurement of the CP structure of the Higgs boson to tau lepton Yukawa coupling at $\sqrt{s}$ =13.6 TeV

Higgs Hunting

16th September 2026

Lucas Russell

on behalf of the CMS collaboration

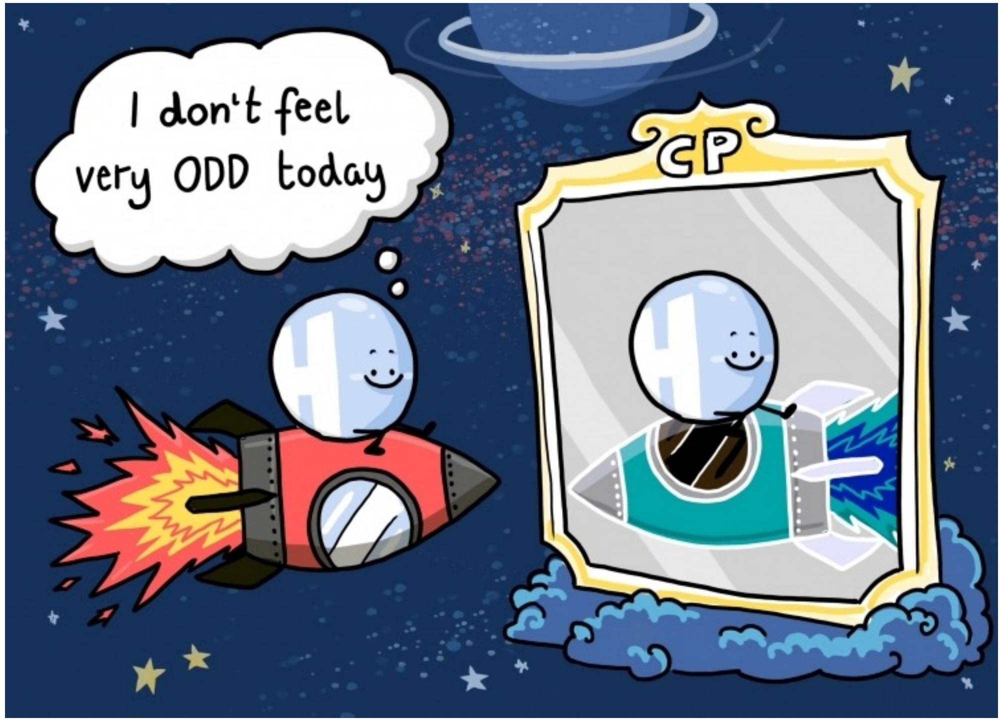


Introduction

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

- There is **no tree-level** CP-odd coupling between the Higgs and **vector bosons**

- The couplings to **fermions** can have CP-even and CP-odd components **at tree level**
  → Anomalous **tau lepton** or top quark Yukawa couplings could in principle generate the BAU (although top is more heavily constrained)



- Will present the latest CMS measurement of the **CP structure of the tau lepton Yukawa coupling** (using data recorded at $\sqrt{s} = 13.6$ TeV in 2022/23)
  → Accepted for publication in JHEP: arXiv:2606.03510

CP measurement in H→ $\tau\tau$

- 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:

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

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

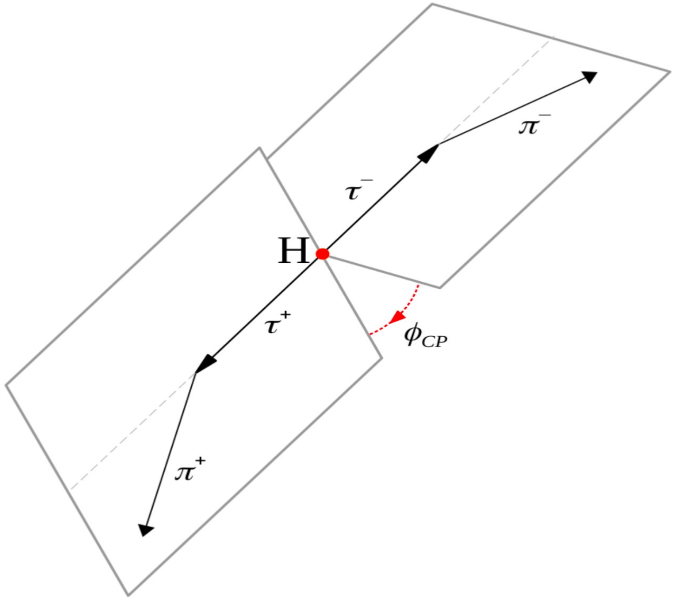
- If $|\alpha^{\mathrm{H}\tau\tau}|$ is between ~ 5° and 15°, could generate enough CP violation to explain the baryon asymmetry, whilst remaining compatible with experimental constraints (model-dependent) [1]

→ Previous measurement [2] ($\sqrt{s} = 13$ TeV): $\alpha^{\mathrm{H}\tau\tau} = -1 \pm 19°$

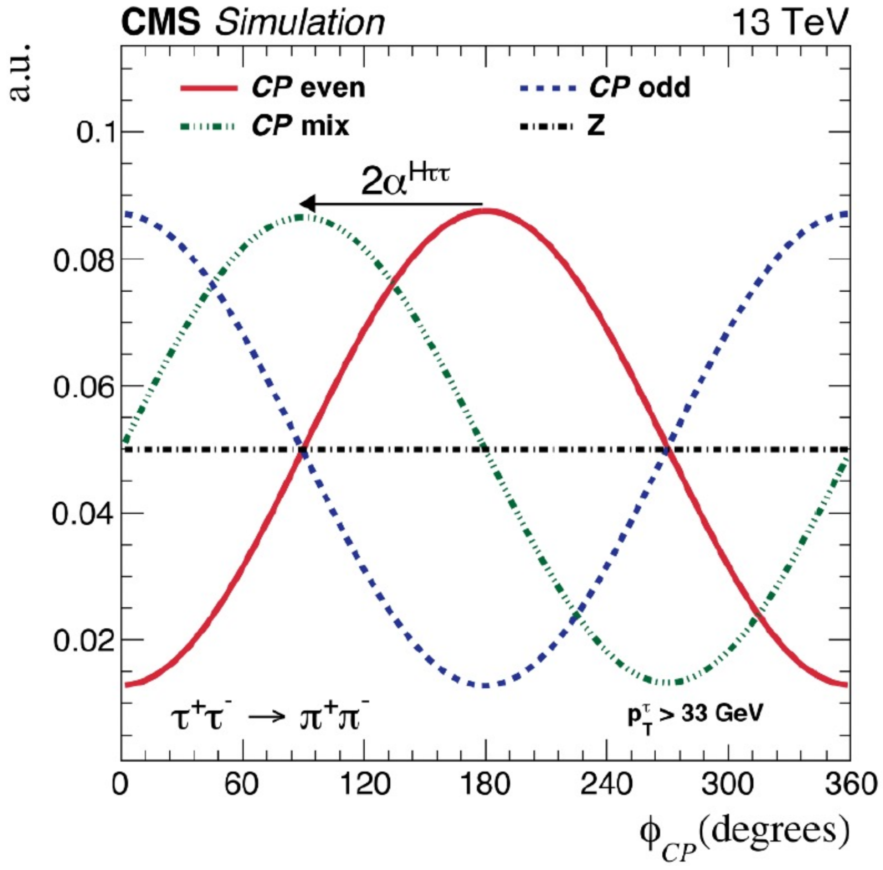
[1]: EPJC 82 (2022) 604
[2]: JHEP 06 (2022) 12

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



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



Modulation in ϕ_{CP} for different signal scenarios [1]

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

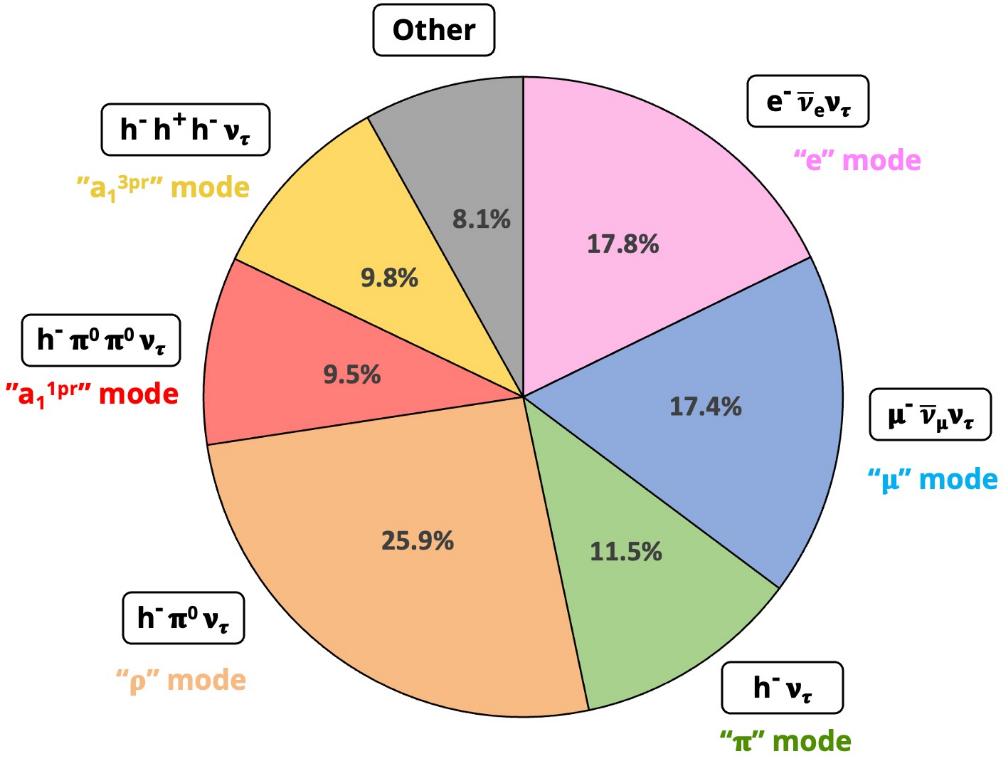
[1]: JHEP 06 (2022) 12

Tau lepton topologies

- Tau leptons are unstable, and can decay either hadronically (τ_h) or leptonically (τ_e/τ_μ)
  → In this analysis, we consider $\boldsymbol{\tau_h\tau_h}$, $\boldsymbol{\tau_\mu\tau_h}$ and $\boldsymbol{\tau_e\tau_h}$ final states

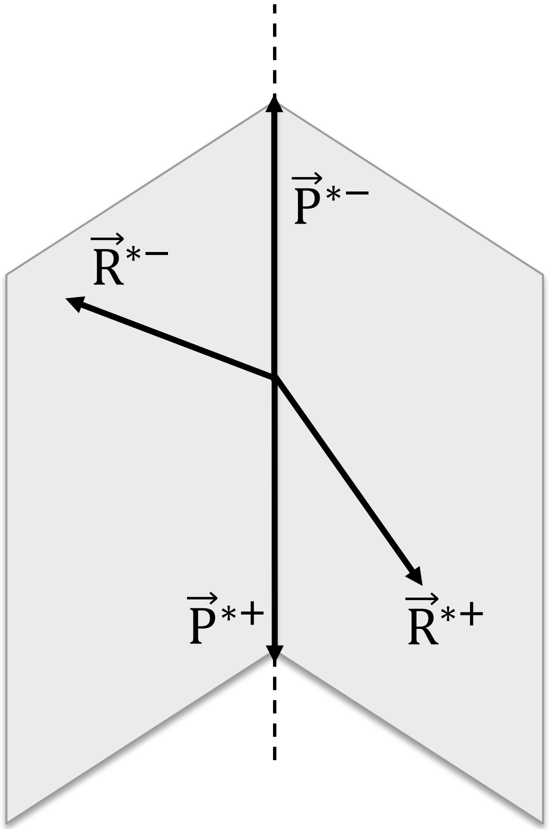
- Require an oppositely charged, and well separated pair of leptons, that pass identification algorithms

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)



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

Reconstruction of the ϕ_{CP} observable



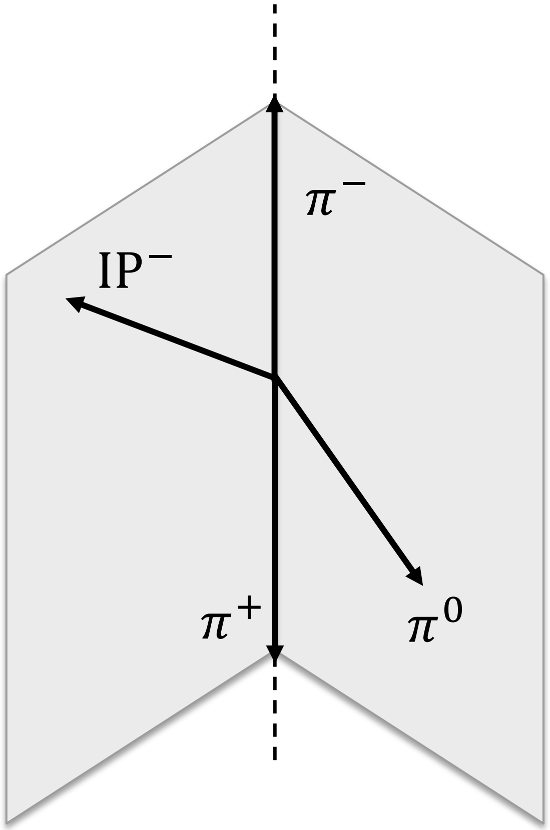
- Work in the **zero-momentum frame** of the charged decay products *(except $a_1^{3pr}a_1^{3pr}$ where Higgs rest-frame used)*

- **Define $\vec{R}^{*\pm}$ and $\vec{P}^{*\pm}$ depending on τ decay topology**

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

- $\pi^\pm$, $\mu^\pm$, $e^\pm$, 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



- Work in the **zero-momentum frame** of the charged decay products *(except $a_1^{3pr}a_1^{3pr}$ where Higgs rest-frame used)*

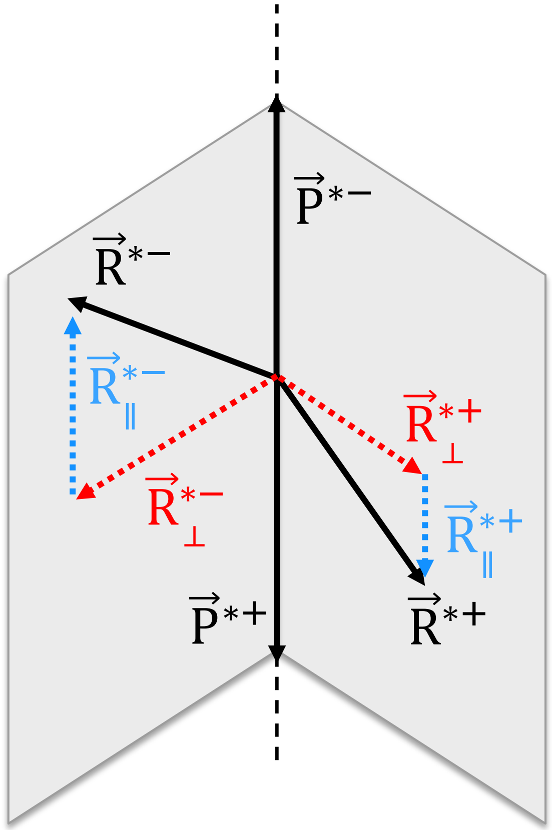
- **Define $\vec{\mathbf{R}}^{*\pm}$ and $\vec{\mathbf{P}}^{*\pm}$ depending on τ decay topology**

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

- $\pi^\pm$, $\mu^\pm$, $e^\pm$, 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

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



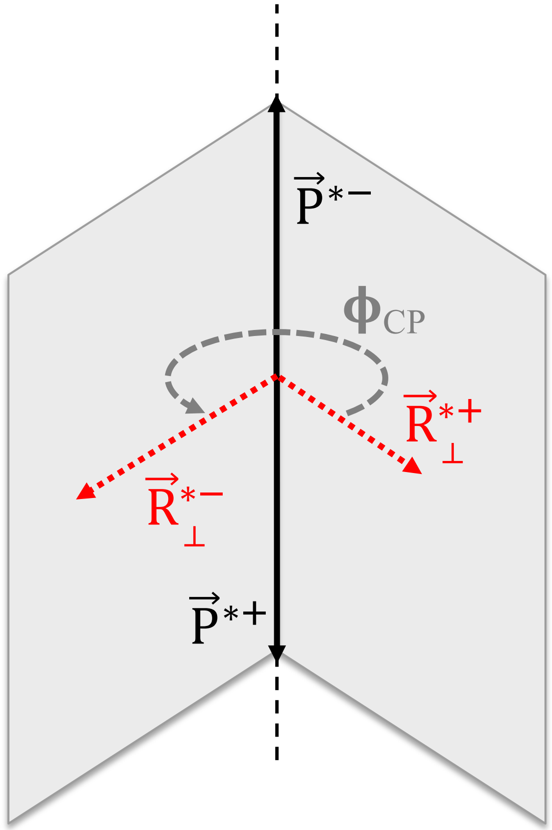
- Work in the **zero-momentum frame** of the charged decay products *(except $a_1^{3pr}a_1^{3pr}$ where Higgs rest-frame used)*
- **Define $\vec{\mathbf{R}}^{*\pm}$ and $\vec{\mathbf{P}}^{*\pm}$ depending on τ decay topology**

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

- $\pi^{\pm}$, $\mu^{\pm}$, $e^{\pm}$, 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

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

Reconstruction of the ϕ_{CP} observable

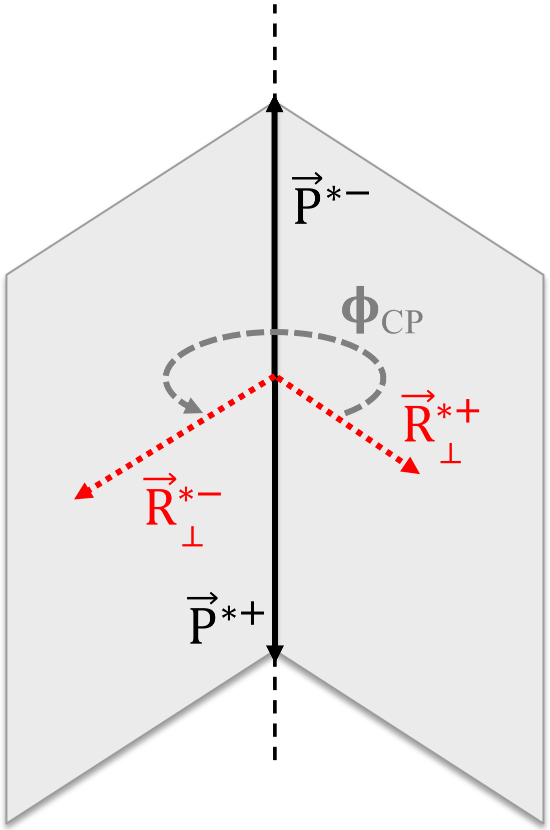


→ Define: $\Phi^* = \cos^{-1}(\hat{R}_{\perp}^{*+} \cdot \hat{R}_{\perp}^{*-})$

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



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

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

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

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

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

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

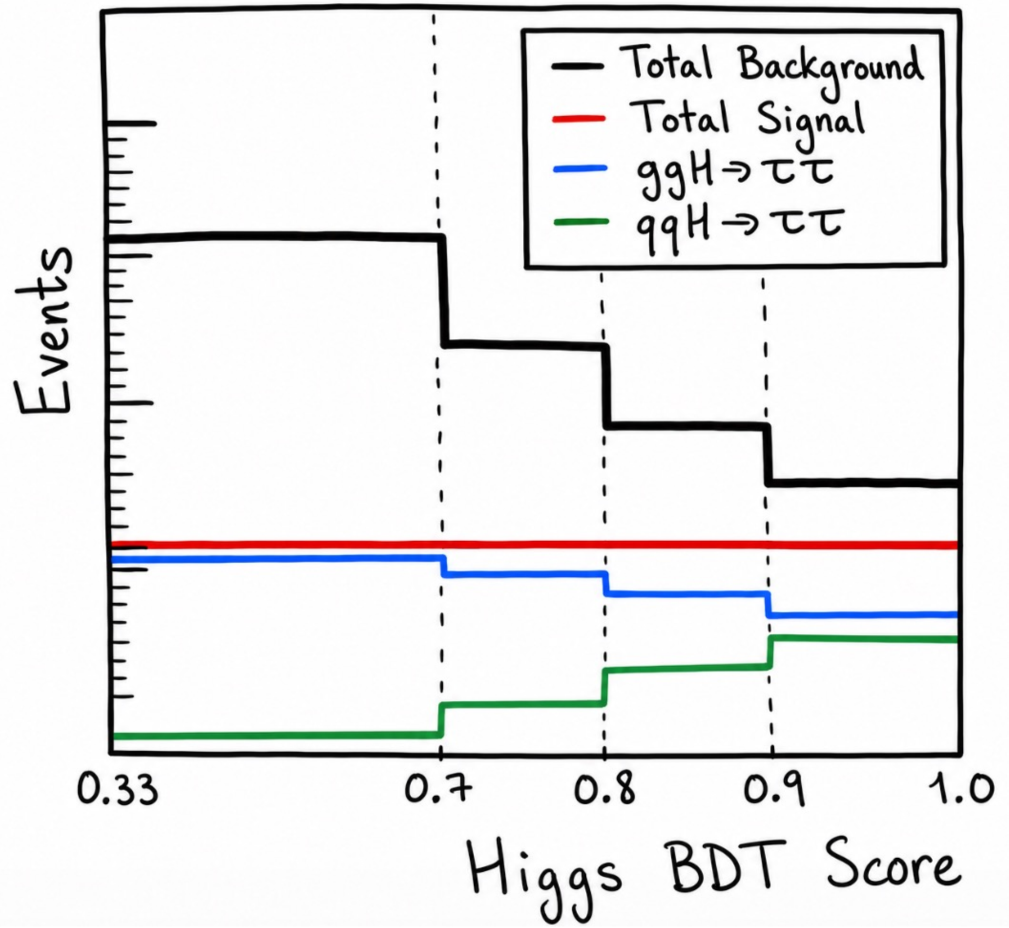
Event classification

- 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 $Z\rightarrow\tau\tau$
  - **Mis-ID Tau Background:** Jets/light leptons mis-reconstructed as τ

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

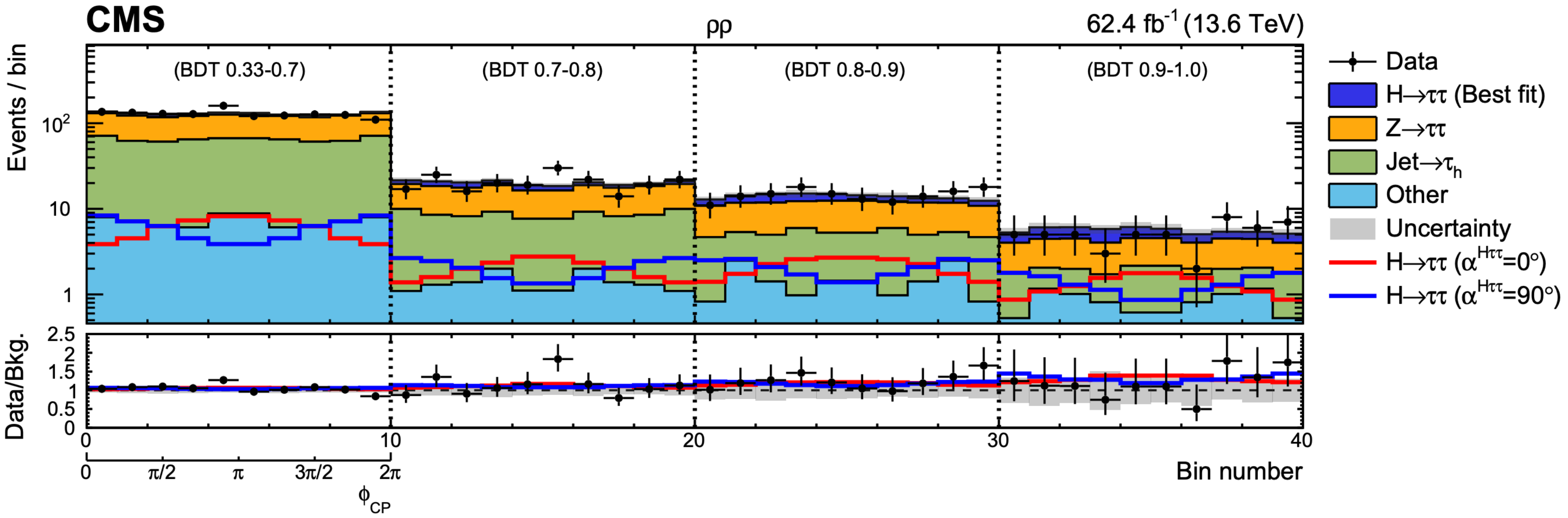
→ Higgs BDT score separates signal from background events (and has a different shape for the ggH and qqH production mechanisms)



Simplified sketch of signal BDT score distribution

Fit inputs

- A simultaneous binned maximum likelihood fit for $\alpha^{H\tau\tau}$ is performed, profiling μ_{ggH} and μ_{qqH}
  - Fit inputs are **ϕ_{CP} distributions for the signal category in windows of Higgs BDT score**
  - → Determine signal rates μ_{ggH} and μ_{qqH} from shape of BDT score, and $\alpha^{H\tau\tau}$ from shape of ϕ_{CP}



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

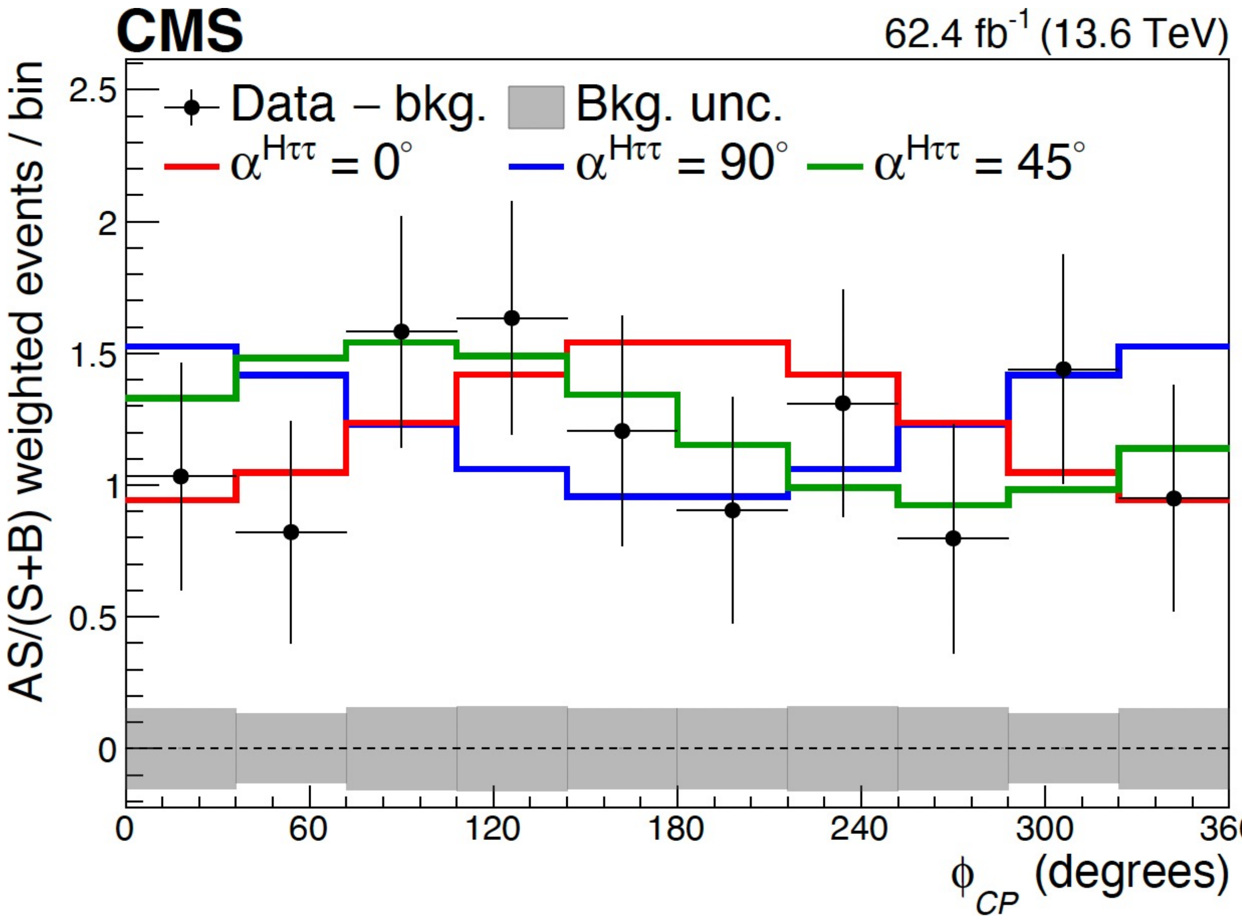
Background subtracted ϕ_{CP} distribution ($\sqrt{s} = 13.6$ TeV)

- 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:

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

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)

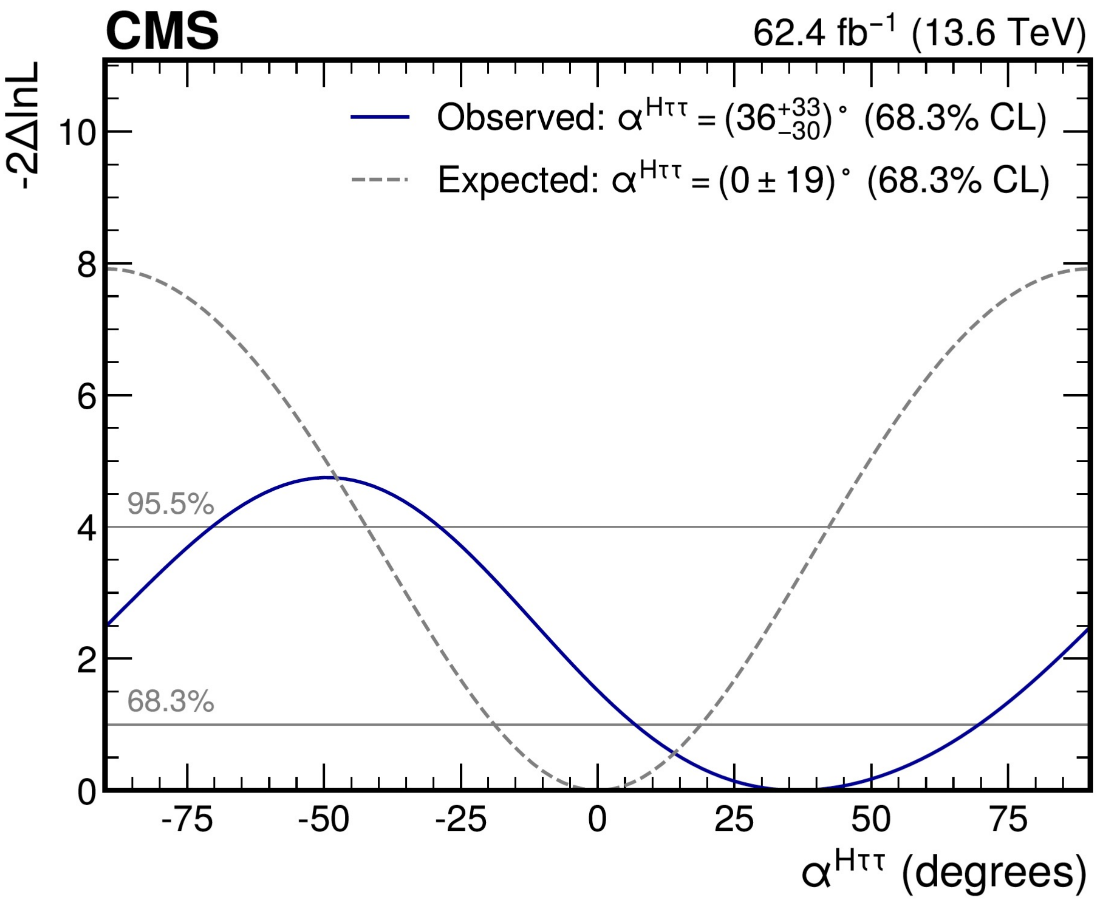
Results at $\sqrt{s} = 13.6$ TeV

- **Observed:**

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

- CMS $\sqrt{s} = 13$ TeV analysis [1] observed $\alpha^{H\tau\tau} = -1 \pm 19^\circ$, with expected $\alpha^{H\tau\tau} = 0 \pm 21^\circ$
  - → **Significant improvement in the expected uncertainty at $\sqrt{s} = 13.6$ TeV**: 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
  - Optimised cuts and ϕ_{CP} reconstruction
  - Higgs production cross section increase



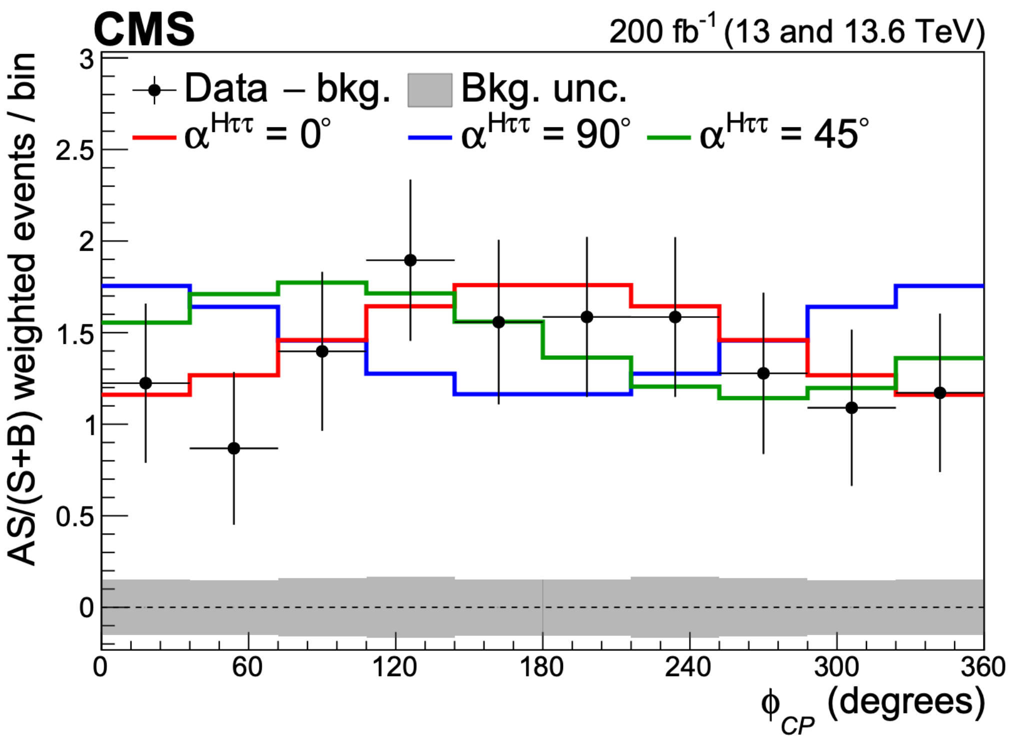
Likelihood scan of $\alpha^{H\tau\tau}$ ($\sqrt{s} = 13.6$ TeV)

[1]: JHEP 06 (2022) 12

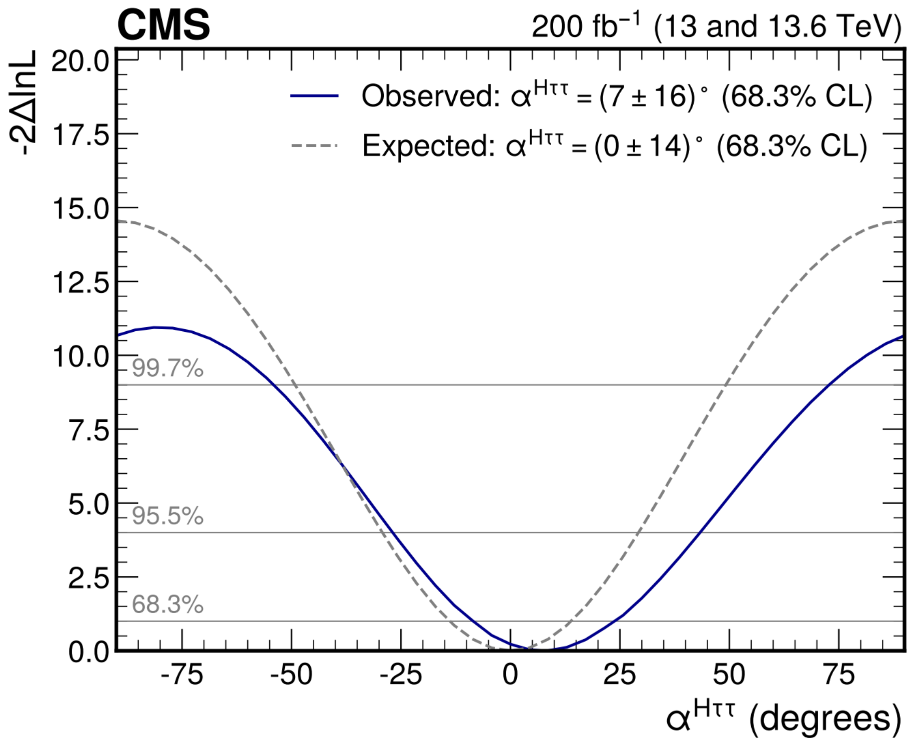
Combined results at $\sqrt{s} = 13$ and $\sqrt{s} = 13.6$ TeV

- Combination with $\sqrt{s} = 13$ TeV analysis [1]:

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



Background-subtracted ϕ_{CP} distribution (combined)

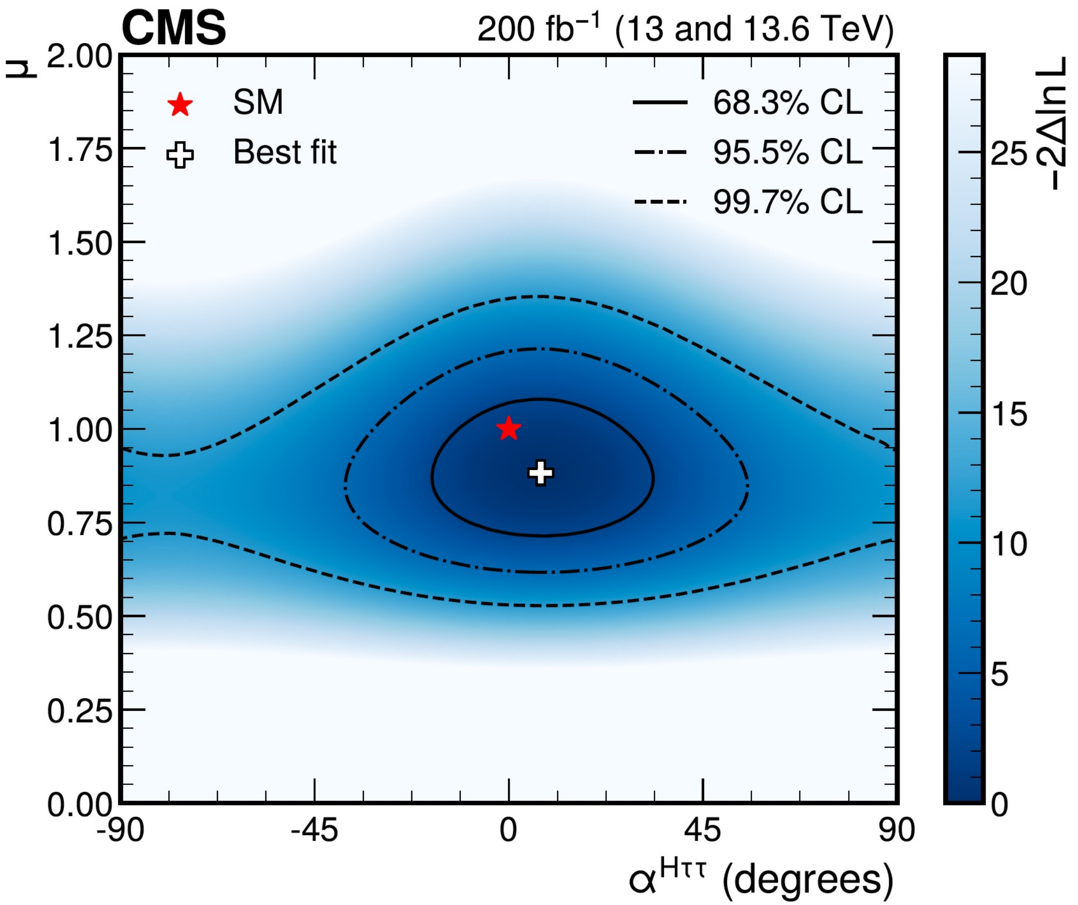


Likelihood scan of $\alpha^{H\tau\tau}$ (combined)

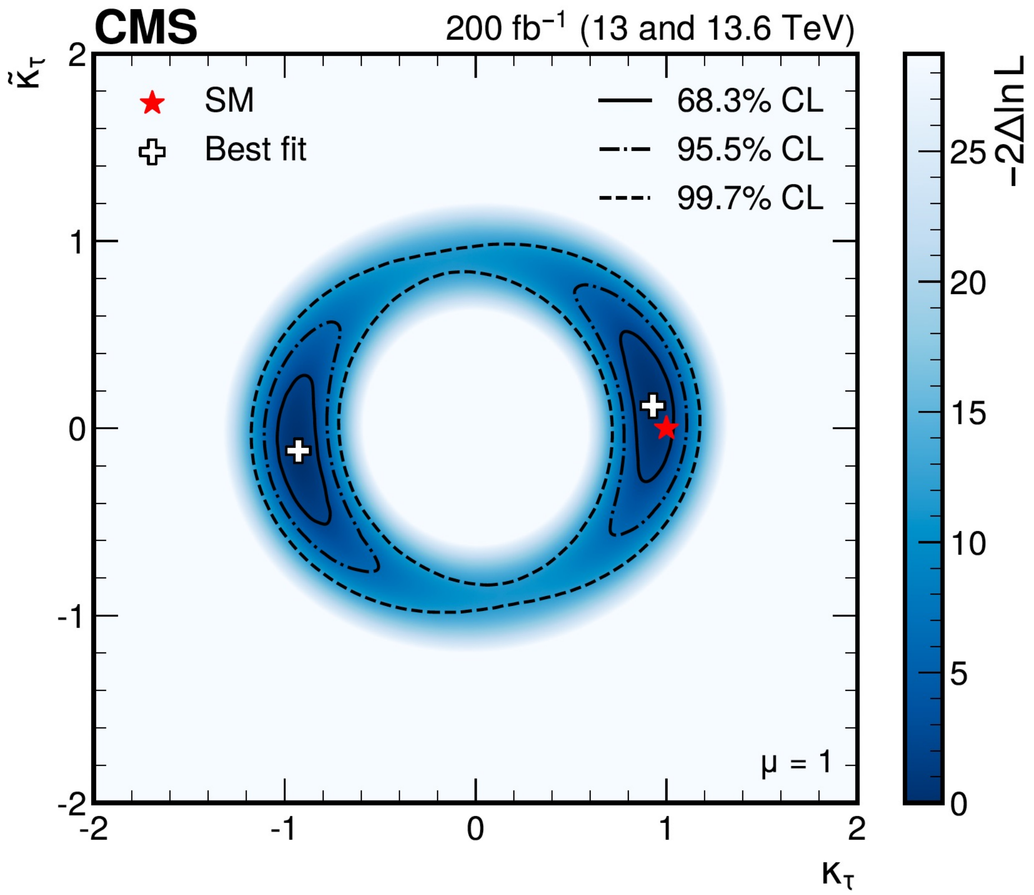
- **Most precise measurement by CMS** to date of the CP nature of the Higgs to τ lepton coupling, and the **best expected precision by any experiment** (*ATLAS $\sqrt{s} = 13$ TeV: Obs. 9 ± 16°, Exp 0 ± 28°* [2])

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

- Alternative fits are also performed:



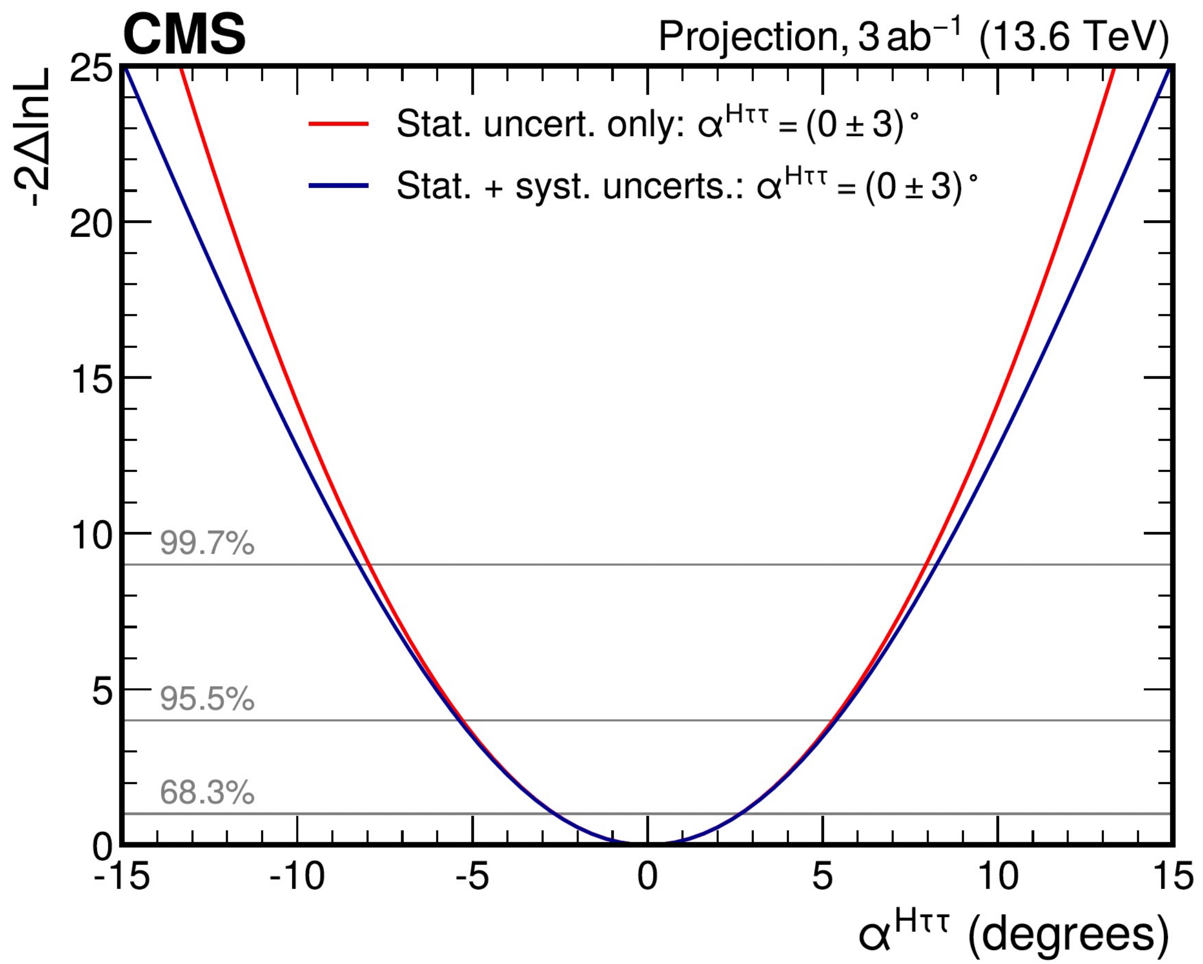
Scan of total signal strength vs $\alpha^{\mathrm{H}\tau\tau}$



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

Extrapolation to the end of the 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
  → Improved compared with the prediction in previous result (5°)



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, accepted for publication in JHEP: [arXiv:2606.03510]

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

- Combination with $\sqrt{s} = 13$ TeV: $\boldsymbol{\alpha^{H\tau\tau} = 7 \pm 16}°$ (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 are important to further reduce the uncertainty on $\alpha^{H\tau\tau}$, allowing precise probes of BSM scenarios which predict small mixing angles
  → **Currently limited by statistical uncertainties**, many improvements to come with additional LHC data, and refined analysis techniques

BACKUP

Event selection

- Events are selected online by the CMS trigger system:

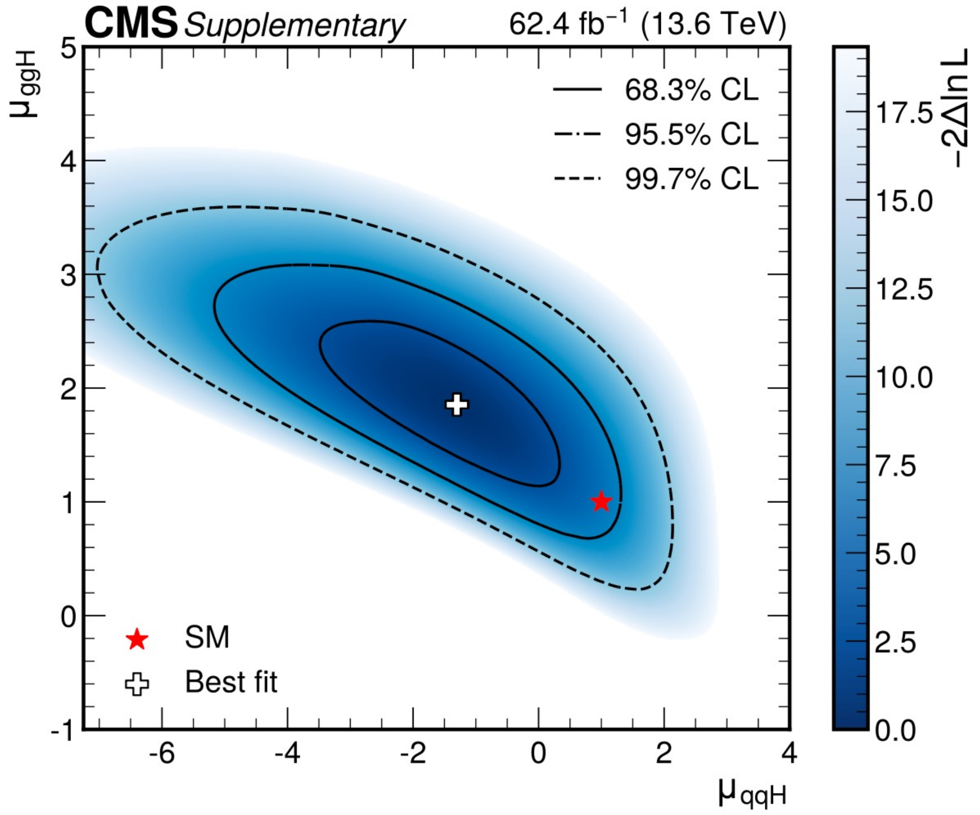
Channel	Trigger	Trigger requirement (GeV)	Offline requirement (GeV)
$\tau_h\tau_h$	di-τ	$\tau_h(35)$ & $\tau_h(35)$	$\tau_h(40)$ & $\tau_h(40)$
	di-τ +jet	$\tau_h(30), \tau_h(30)$& jet(60)	$\tau_h(35), \tau_h(35)$& jet(60)
$\tau_\mu\tau_h$	single μ	$\mu(24)$	$\mu(26)$
$\tau_e\tau_h$	single e	$e(30)$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

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

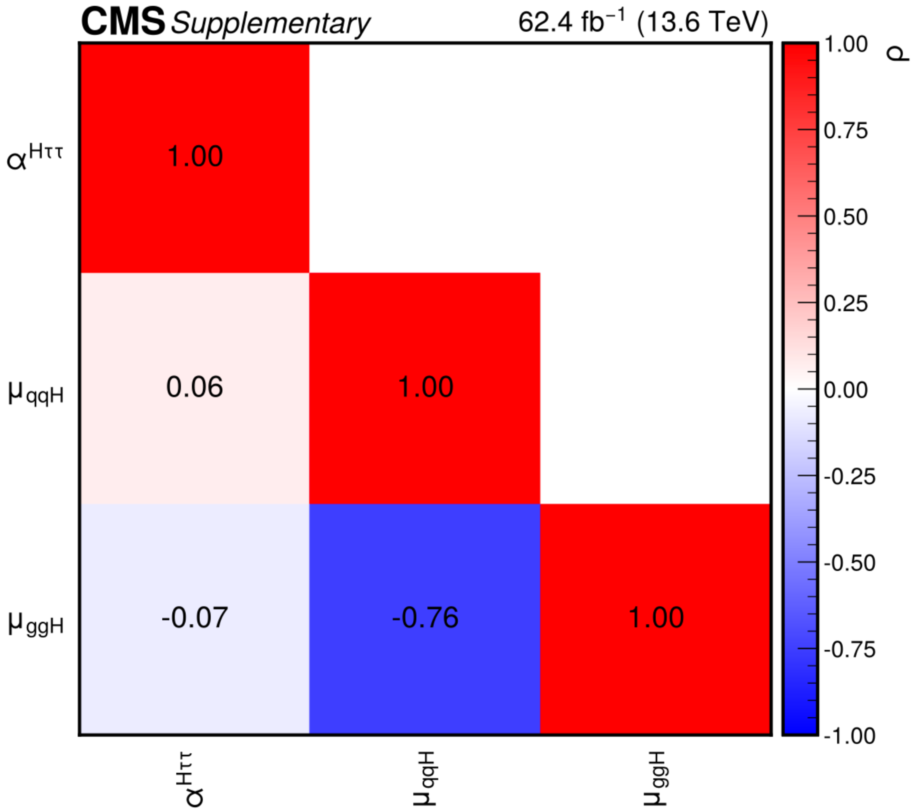
- Additional cuts are applied depending on the tau decay topology to optimise sensitivity
  → Well reconstructed IP required for π, e and μ modes
  → Energy splitting cut for ρ and a_1^{1pr} modes: $E_{split} = \left|\frac{E(\pi^0) - E(\pi^\pm)}{E(\pi^0) + E(\pi^\pm)}\right|$
  → Presence of a secondary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

Signal strength modifiers ($\sqrt{s} = 13.6$ TeV)

- Best-fit signal strength modifiers : $\mu_{\text{ggH}} = 1.86^{+0.48}_{-0.47}$ and $\mu_{\text{qqH}} = -1.3^{+1.1}_{-1.4}$
  - Alternative fit with one signal strength parameter in good agreement with SM ($\mu = 0.94^{+0.28}_{-0.22}$)



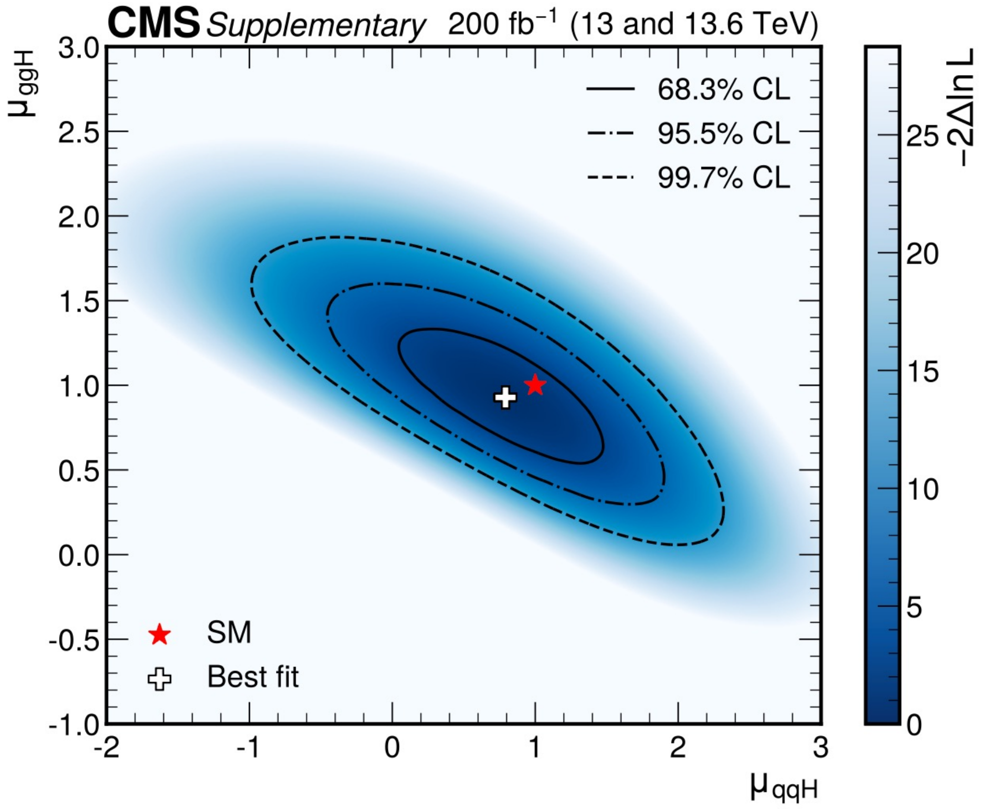
2D likelihood scan of the signal strength modifiers for ggH and VBF+VH



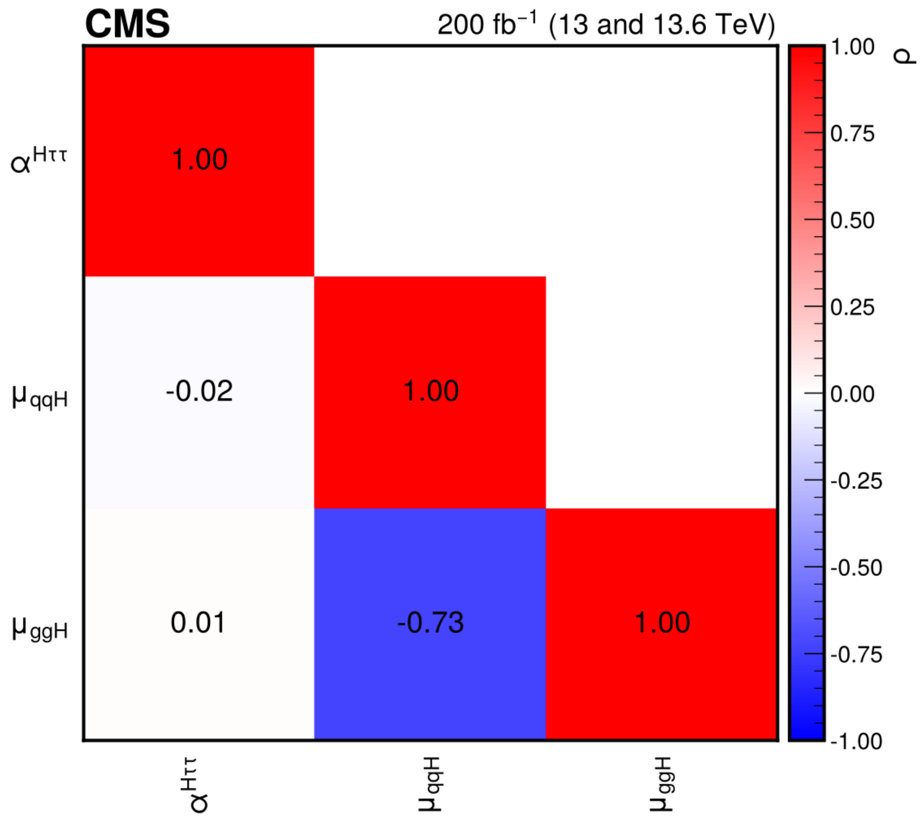
Correlation between $\alpha^{\text{H}\tau\tau}$ and the signal strength modifiers

Signal strength modifiers ($\sqrt{s}$ = 13 and 13.6 TeV)

- Best-fit signal strength modifiers: $\mu_{\mathrm{ggH}} = 0.93^{+0.29}_{-0.25}$ and $\mu_{\mathrm{qqH}} = 0.79^{+0.50}_{-0.47}$



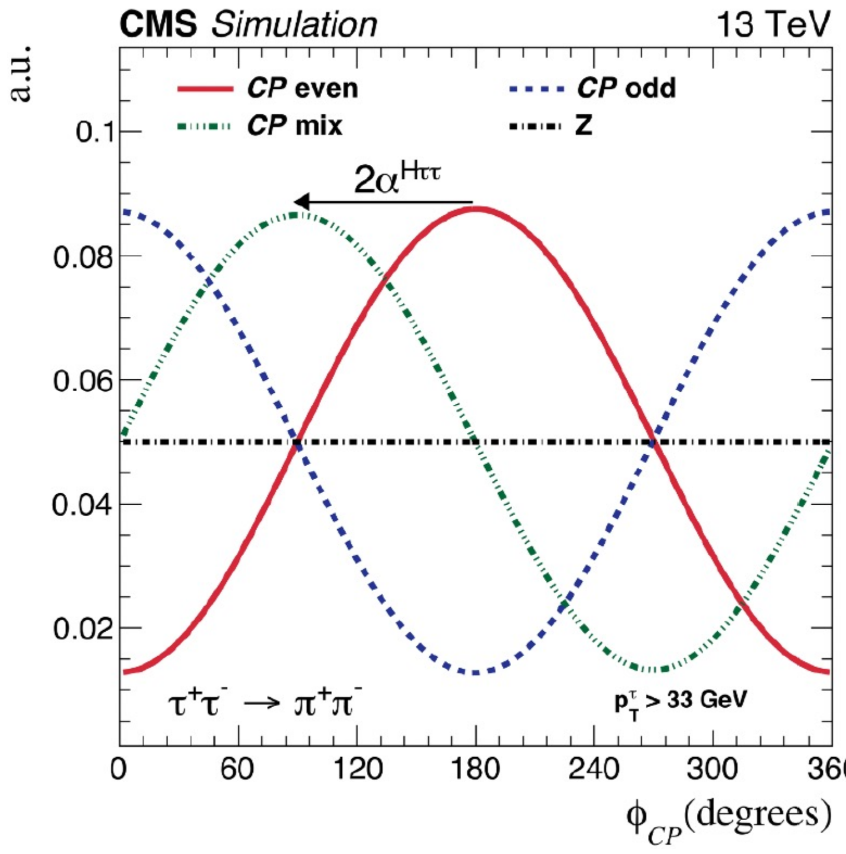
2D likelihood scan of the signal strength modifiers for ggH and VBF+VH



Correlation between $\alpha^{\mathrm{H}\tau\tau}$ and the signal strength modifiers

H$\rightarrow\tau\tau$: Signal Modelling

- Generate ggH and qqH (VBF + VH) samples using Powheg+Pythia8
- Samples are simulated with uncorrelated τ lepton spin, and reweighted using the TauSpinner
  - Event weights to model CP-even ($\alpha^{H\tau\tau} = 0°$), CP-odd ($\alpha^{H\tau\tau} = 90°$) and CP-mixed ($\alpha^{H\tau\tau} = 45°$) scenarios
  - → Every other value of $\alpha^{H\tau\tau}$ can be modelled using a linear sum of these contributions
- We are **not sensitive to the CP-nature of the Higgs production** interaction in our measurement of $\alpha^{H\tau\tau}$
  - In ggH, CP-odd top couplings modify $\Delta\phi_{jj}$ for VBF-like events, therefore not included as a variable in the BDT
  - In qqH, in principle large amounts of CPV could impact CP-even variables such as p_T^H, which *could* affect the BDT output, but these scenarios are heavily constrained experimentally ($\mathcal{O}\sim10^{-3}$)
  - → Higgs production mechanism in the generator is configured to only produce scalar Higgs bosons



Generator-level modulation for different CP scenarios [1]

BDT input features

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

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

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

ΔR, $\Delta\varphi$, 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

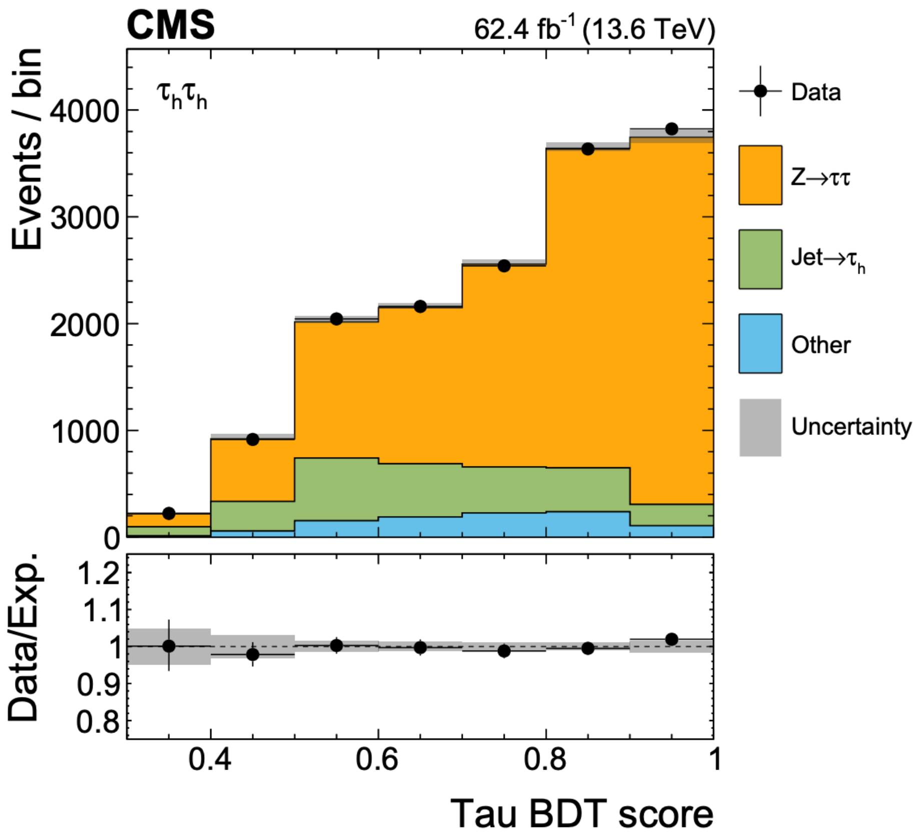
p_T^{jet1}, p_T^{jet2}, η^{jet1}, η^{jet2} # individual jet kinematics

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

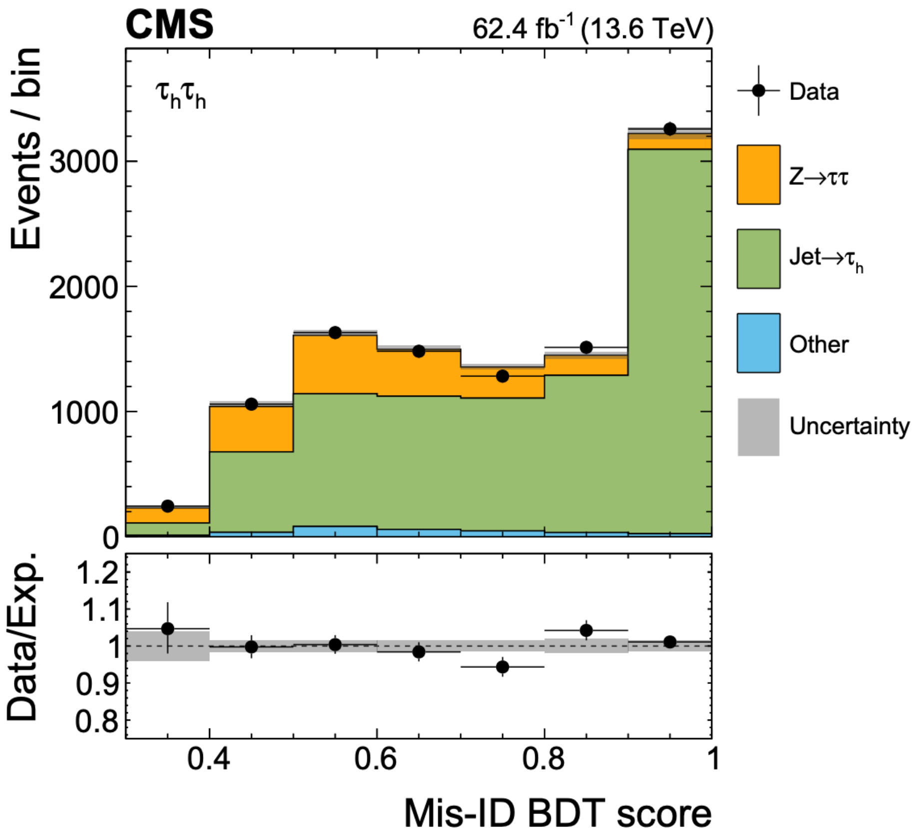
N_{jets} # global jet information

Background category BDT distributions

- Background category score distributions are used to constrain systematics in the fit:



BDT classifier score for the genuine tau background category



BDT classifier score for the misidentified tau background category

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

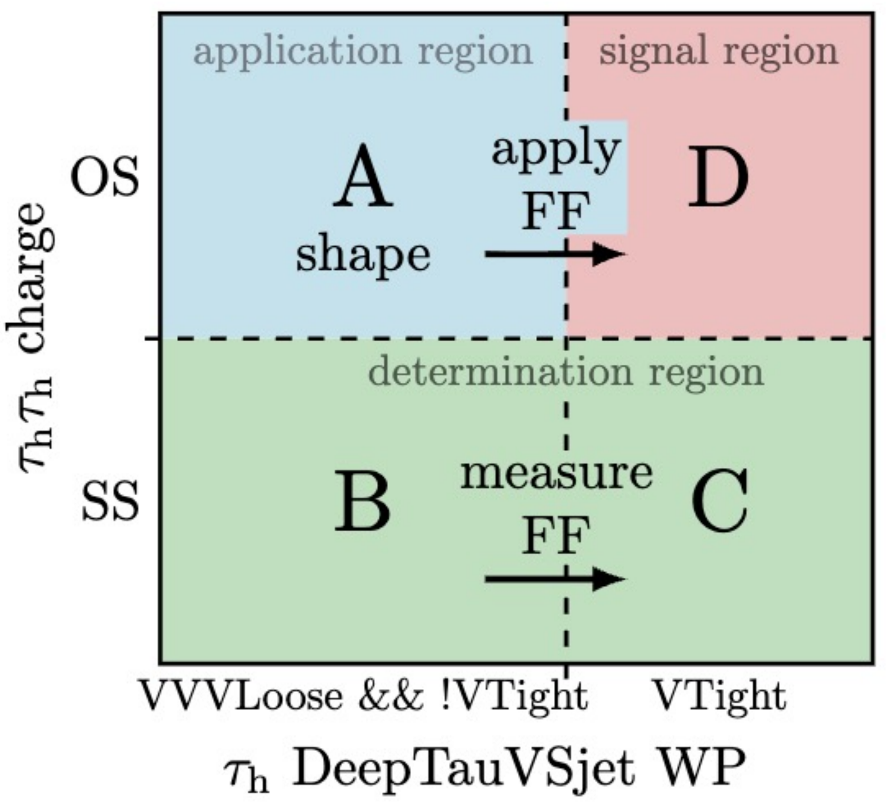
Background Estimation

- 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)

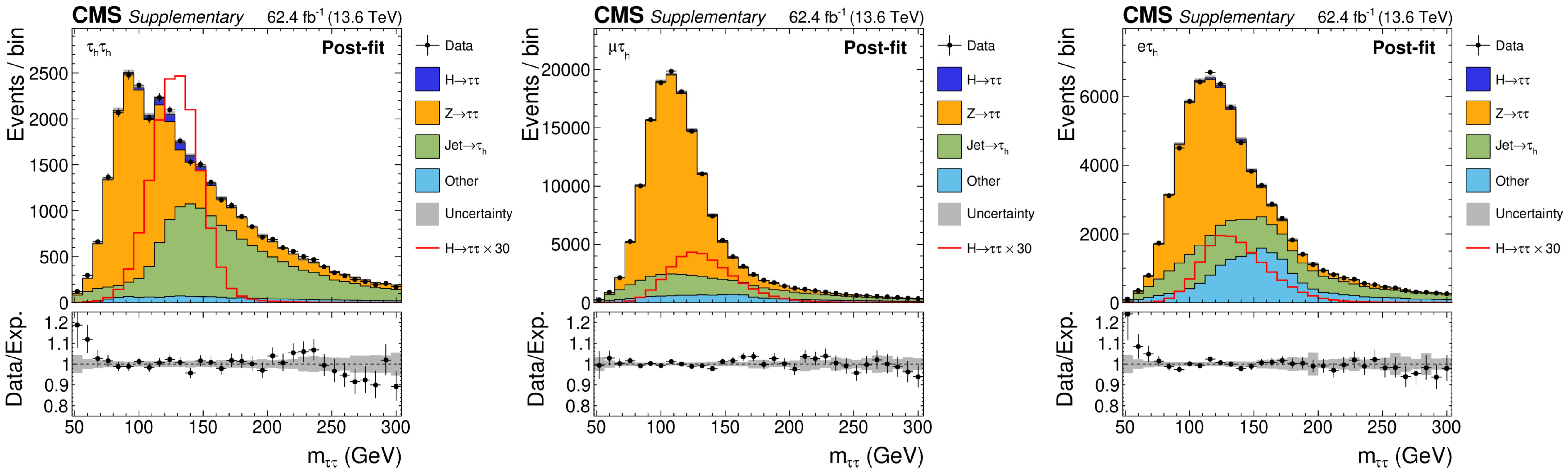
➢ Other backgrounds are estimated from simulation



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

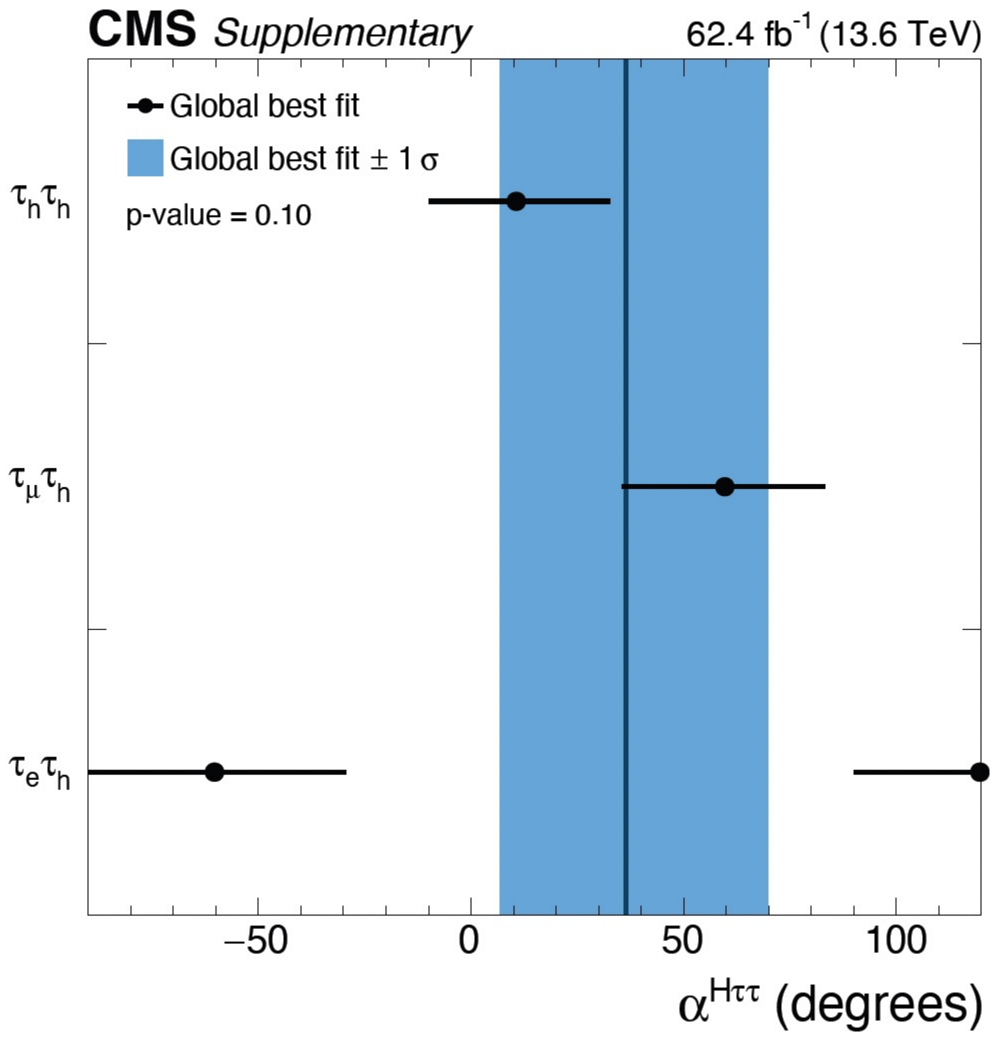
Invariant mass distributions

- Di-tau invariant mass estimated with the FastMTT algorithm:



Channel Compatibility

- Tested the compatibility of the different analysis channels: $\tau_h\tau_h$, $\tau_\mu\tau_h$ and $\tau_e\tau_h$
- Performed two fits to the data:
  - Nominal model where each has same $\alpha^{H\tau\tau}$
  - Alternate where each has its own $\alpha^{H\tau\tau}_{channel}$
- Obtain a χ^2-like variable for the observed data and determine p-value from toys
  - ➢ Channels compatible, with p-value of 10%



NB: $\alpha^{H\tau\tau}$ is cyclical (i.e. $\alpha^{H\tau\tau}$ = -60° is equivalent to $\alpha^{H\tau\tau}$ = 120°)

Expected sensitivity per channel

- Performed 1D expected scans of $\alpha^{H\tau\tau}$ (with SM $\alpha^{H\tau\tau}$ i.e. 0°), and determine the expected exclusion of the CP-odd scenario

- Expected sensitivity is compared across all channels considered in the analysis
  - $\tau_h\tau_h$ is the most sensitive channel, followed by $\tau_\mu\tau_h$, then $\tau_e\tau_h$
  - $\rho\rho$, $\pi\rho$ and ρa_1^{3pr} are the most sensitive final states

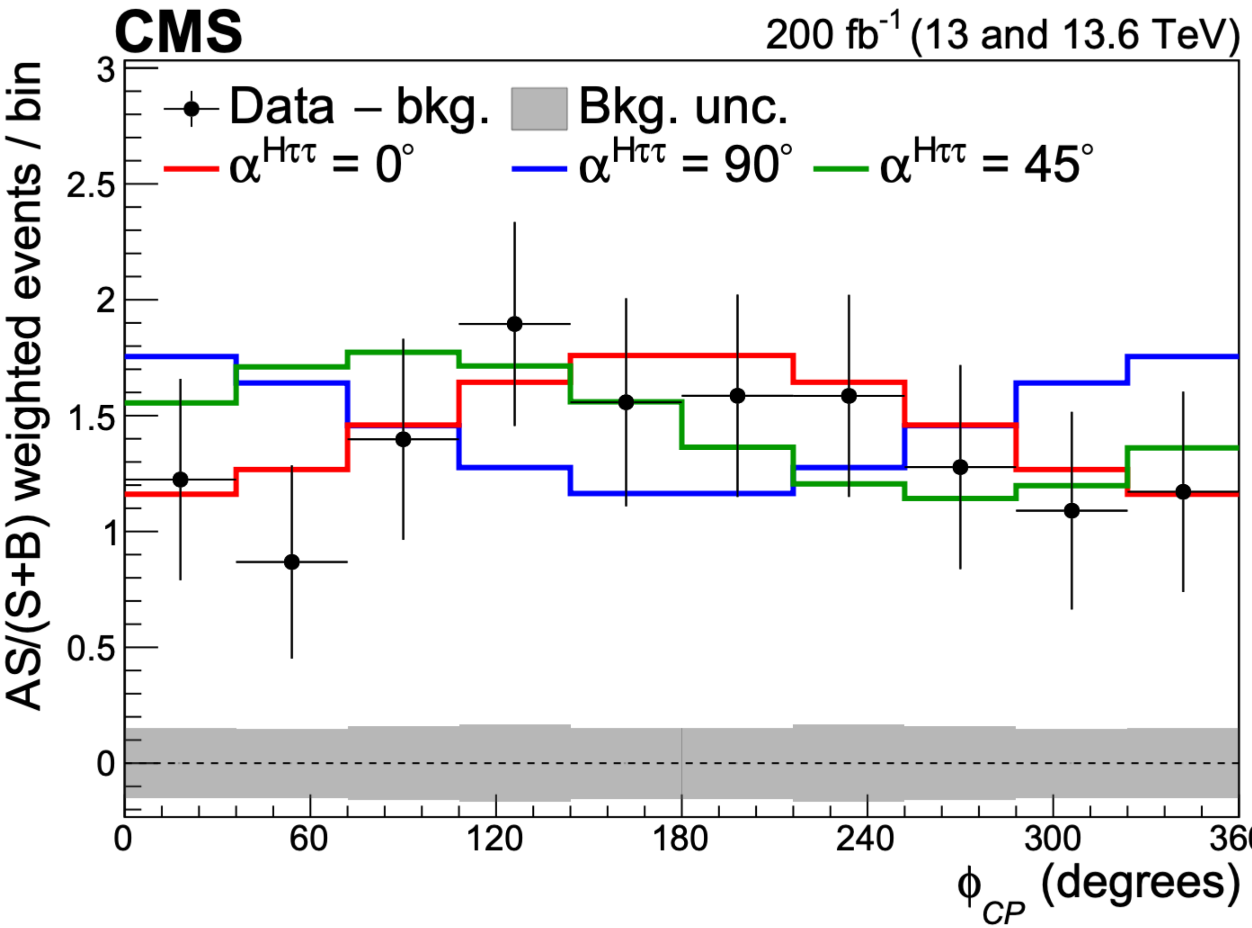
Decay mode	Expected sensitivity (σ)
$\tau_h\tau_h$	2.38
$\rho\rho$	1.31
$\rho\pi$	1.18
ρa_1^{3pr}	1.17
πa_1^{3pr}	0.70
$\pi\pi$	0.43
$a_1^{1pr}\rho$ and $a_1^{1pr}a_1^{1pr}$	0.47
$a_1^{3pr}a_1^{3pr}$	0.41
πa_1^{1pr}	0.29
$a_1^{3pr}a_1^{1pr}$	0.27
$\tau_\mu\tau_h$	1.34
$\mu\rho$	1.00
$\mu\pi$	0.58
μa_1^{3pr}	0.61
μa_1^{1pr}	0.24
$\tau_e\tau_h$	0.66
$e\rho$	0.47
$e\pi$	0.31
$e a_1^{3pr}$	0.34
$e a_1^{1pr}$	0.09
Combined	2.82

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)

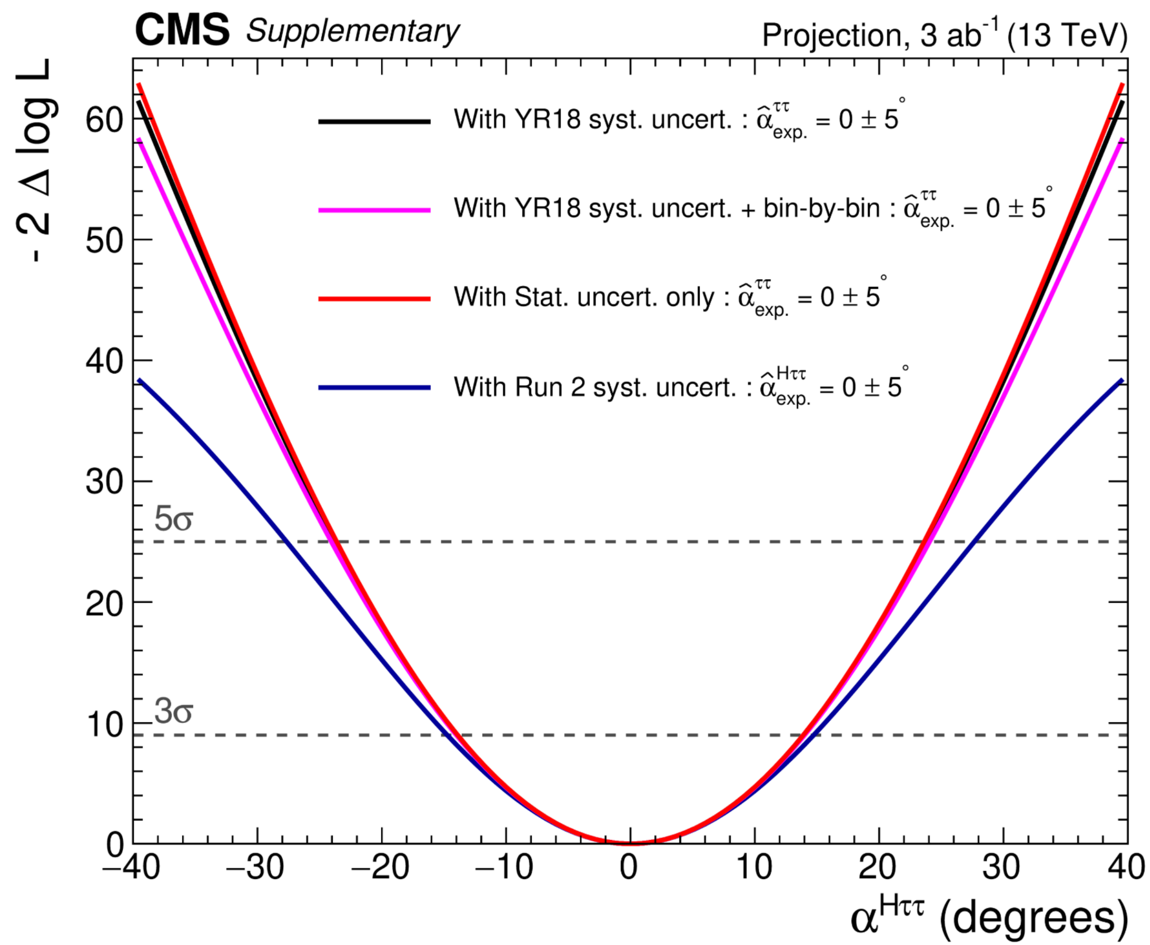
* *Included for* $\sqrt{s} = 13.6$ TeV *measurement only (these used a different binning at* $\sqrt{s} = 13$ TeV*)*



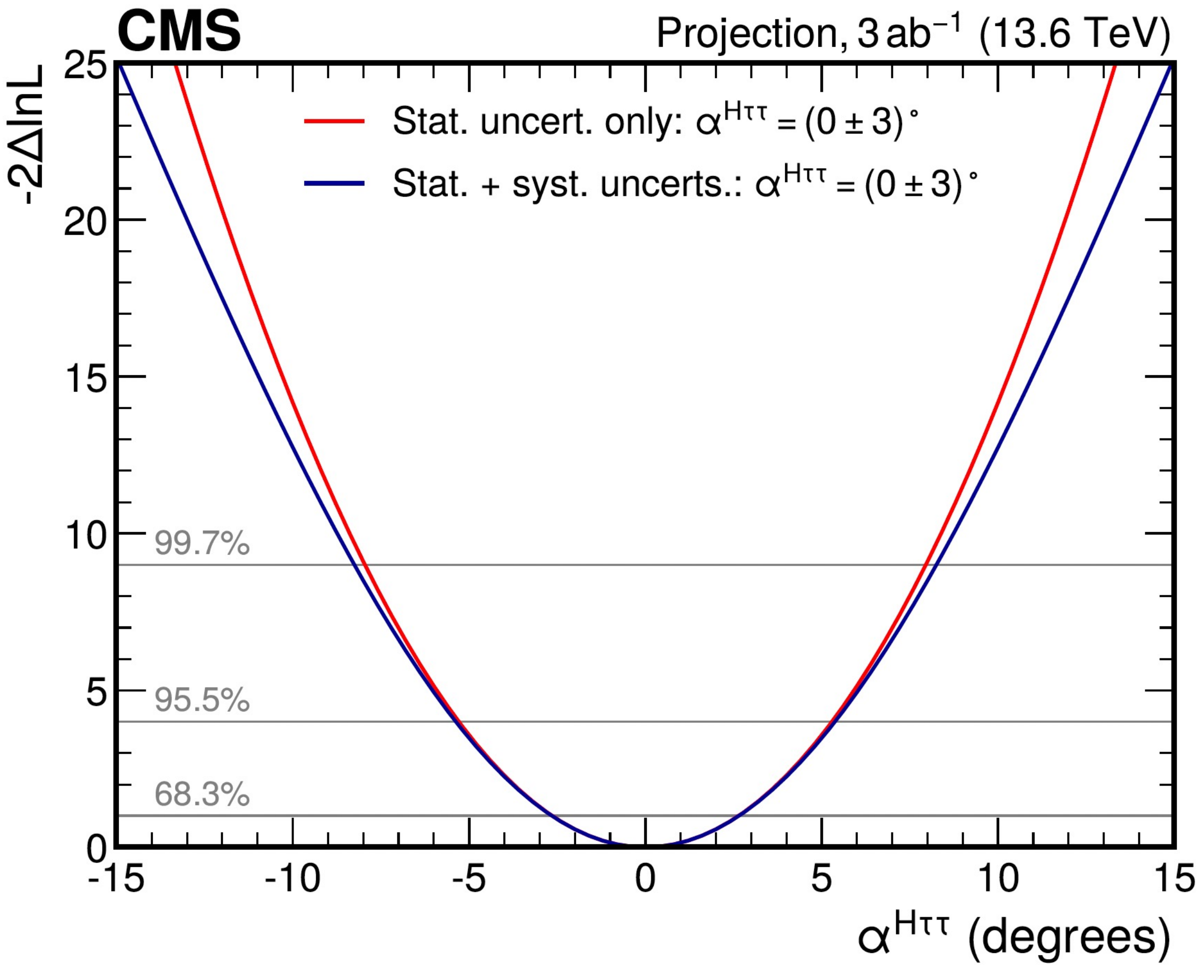
Background-subtracted ϕ_{CP} distribution ($\sqrt{s} = 13.6$ TeV and $\sqrt{s} = 13$ TeV)

[1]: JHEP 06 (2022) 12

Projections for HL-LHC $\alpha^{H\tau\tau}$ (previous vs new)



Expected sensitivity at the HL-LHC after the previous measurement ($\sqrt{s} = 13$ TeV) [1]

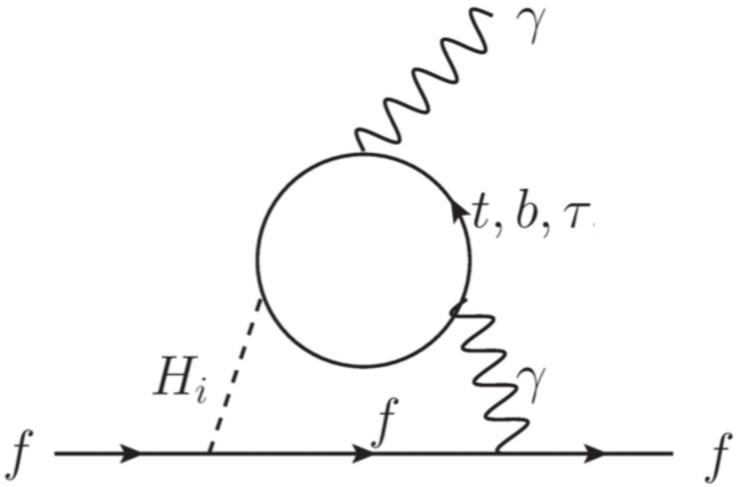


Expected sensitivity at the HL-LHC after the latest result ($\sqrt{s} = 13.6$ TeV)

[1]: JHEP 06 (2022) 12

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: arXiv:2202.11753

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

- BAU models also constrain: PhysRevLett.124.181801

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

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

Anomalous couplings in HVV

- The anomalous interactions of the Higgs with gauge bosons can be written as:

Kinetic Terms

$$\mathcal{A}(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

SM tree level (CP-even) CP-even (dim-6) CP-odd (dim-6)

- Measure parameters from effective fractional cross sections:

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \operatorname{sign}\left(\frac{a_i}{a_1}\right)$$

  - Some systematics cancel in the ratio (theory, luminosity)

  → Represents the fraction of the cross section originating from coupling a_i

- Can be measured in **production** (VBFH, VH) and **decay** ($\mathrm{H} \to \mathrm{VV}$)

Most recently in $H \to \gamma\gamma$ arXiv:2605.14245	Most recently in $H \to 4\ell$ CMS-PAS-HIG-25-011

CP Measurement in H-top couplings

- The top quark coupling can be expressed in terms of **CP-even** and **CP-odd** terms:

$$\mathcal{A}(\mathrm{Hff}) = -\frac{m_f}{v}\bar{\psi}_\mathrm{f}\left(\boxed{\kappa_\mathrm{f}} + \boxed{i\,\tilde{\kappa}_\mathrm{f}\gamma_5}\right)\psi_\mathrm{f}$$

→ Define effective fractional cross section:

$$f_{CP}^{\mathrm{Hff}} = \frac{|\tilde{\kappa}_\mathrm{f}|^2}{|\kappa_\mathrm{f}|^2 + |\tilde{\kappa}_\mathrm{f}|^2}\,\mathrm{sgn}\left(\frac{\tilde{\kappa}_\mathrm{f}}{\kappa_\mathrm{f}}\right)$$

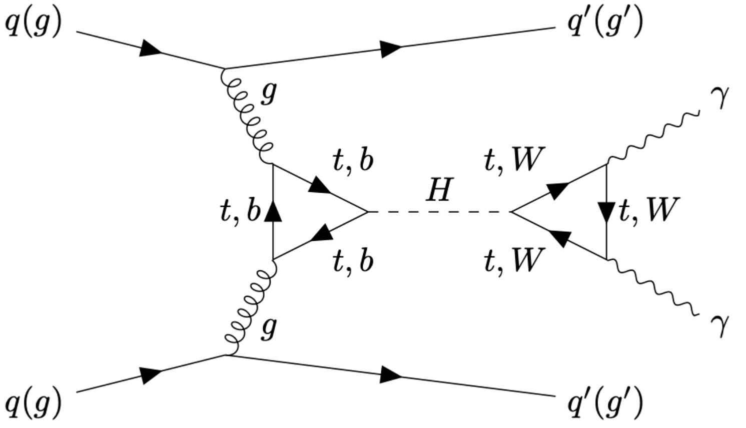
- Can be measured in $\mathrm{t\bar{t}H}$ (and tH), as well as ggH (in ”$\mathrm{VBF\text{-}like}$” events)

→Probe the Hgg coupling: $$f_{a3}^{\mathrm{ggH}} = \frac{|a_3^{\mathrm{gg}}|^2}{|a_2^{\mathrm{gg}}|^2 + |a_3^{\mathrm{gg}}|^2}\,\mathrm{sgn}\left(\frac{a_3^{\mathrm{gg}}}{a_2^{\mathrm{gg}}}\right)$$

CP-odd

CP-even

then: $$|f_{CP}^{\mathrm{Htt}}| = \left(1 + 2.38\left[\frac{1}{|f_{\mathrm{a3}}^{\mathrm{ggH}}|} - 1\right]\right)^{-1}$$



Most recently in $H \to \gamma\gamma$
arXiv:2605.14245

CP in production

- Previous results, probing the CP nature in production (PRD 108 (2023) 032013):