Measurements of Higgs Boson Properties in Decays to Two Tau Leptons with the ATLAS Detector

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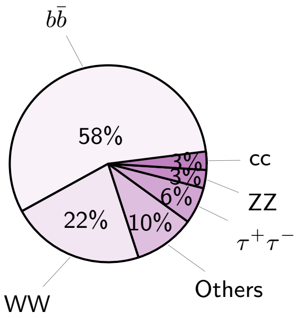
Higgs 2023 Conference

Motivation

- The characterization of the Higgs boson continued during the Run-2 data-taking period between 2015 and 2018.
- Full Run-2 dataset ($\int \mathcal{L}dt = 139$ fb^{-1}, $\sqrt{s}$ =13 TeV) contains about 30 times more Higgs Bosons than its Run-1 counterpart[a], which is used for the measurements of Higgs boson production and decay rates.
- $H \to \tau\tau$ (branching ratio: 6%) channel is particularly sensitive to the Higgs boson's Yukawa coupling
- ATLAS observed $H \to \tau\tau$ for the first time in 36 fb^{-1} analysis [b] and measured
  - total cross-section
  - cross-sections for ggF and VBF

This talk:

- Cross-section measurements
- Higgs boson $\mathcal{CP}$ property

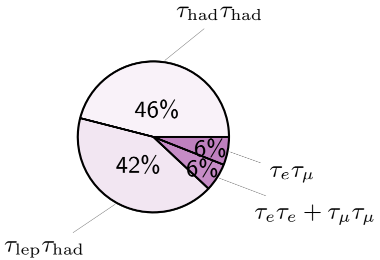


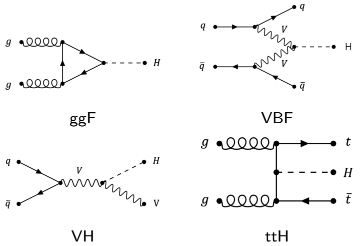
[a] Nature 607, 52–59 (2022)
[b] PhysRevD.99.072001

Cross-section Measurements

Overview and Highlights of Cross-section Measurements

- $H \to \tau\tau$ cross-section measurement with ATALS full Run-2 dataset [a].
- 4 Higgs production modes: ggF, VBF, V($\to$qq)H, ttH($\tau_{\text{had}}\tau_{\text{had}}$)
- STXS[b]: physical cross sections that are defined in mutually exclusive regions of phase space ("bins").
- Various improvements compared to previous measurement with 36 fb^{-1}:
  - VBF, VH, ttH are further split with Boost Decision Tree (BDT) taggers into two subcategories: suffixed_1/0
  - STXS measurement performed in six bins for ggF
  - Kinematic embedding to control $Z \to \tau\tau$ using $Z \to \ell\ell$
  - Not including $\tau_e\tau_e + \tau_\mu\tau_\mu$ to prevent from large uncertainties in Z+jets background modeling

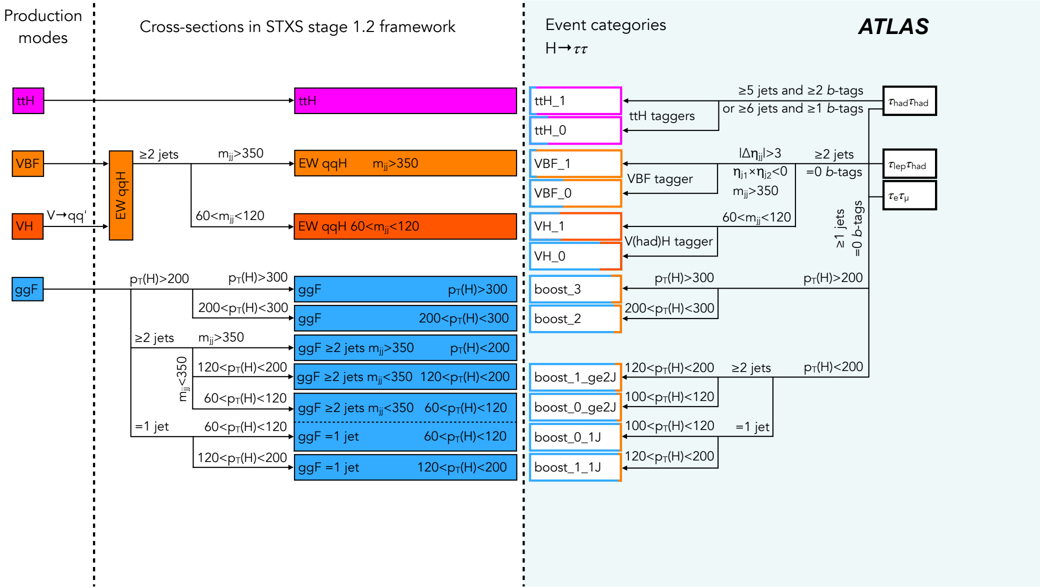




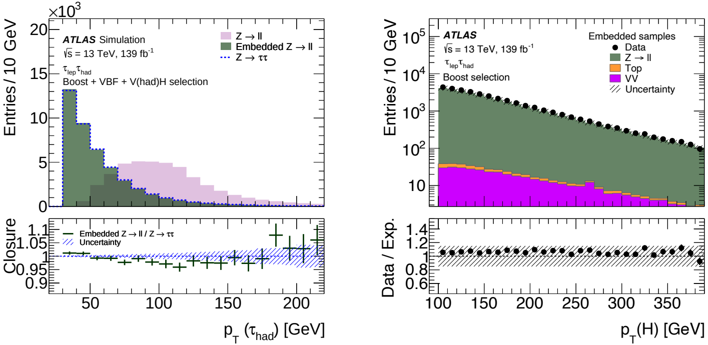
[a] JHEP08(2022)175

[b] https://arxiv.org/abs/1906.02754

STXS Stage 1.2 and Event Categorization

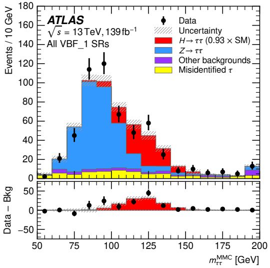


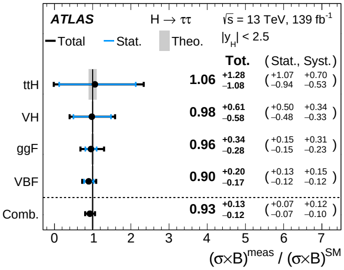
- $Z \to \tau\tau$ + jets is the dominant background in this analysis
- Better resolution of kinematics in the $Z \to \ell\ell$ than in the $Z \to \tau\tau$ one due to the absence of ν and the excellent momentum resolution for electrons and muons
- Kinematic embedding to control $Z \to \tau\tau$ modeling using control regions based on $Z \to \ell\ell$ process
- The embedded $Z \to \ell\ell$ control regions are used in the fit to scale $Z \to \tau\tau$ background.

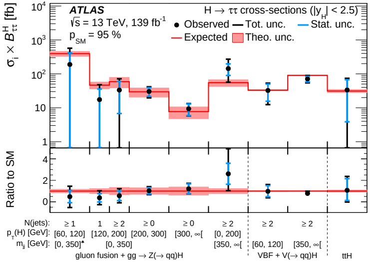


Measured Cross-sections

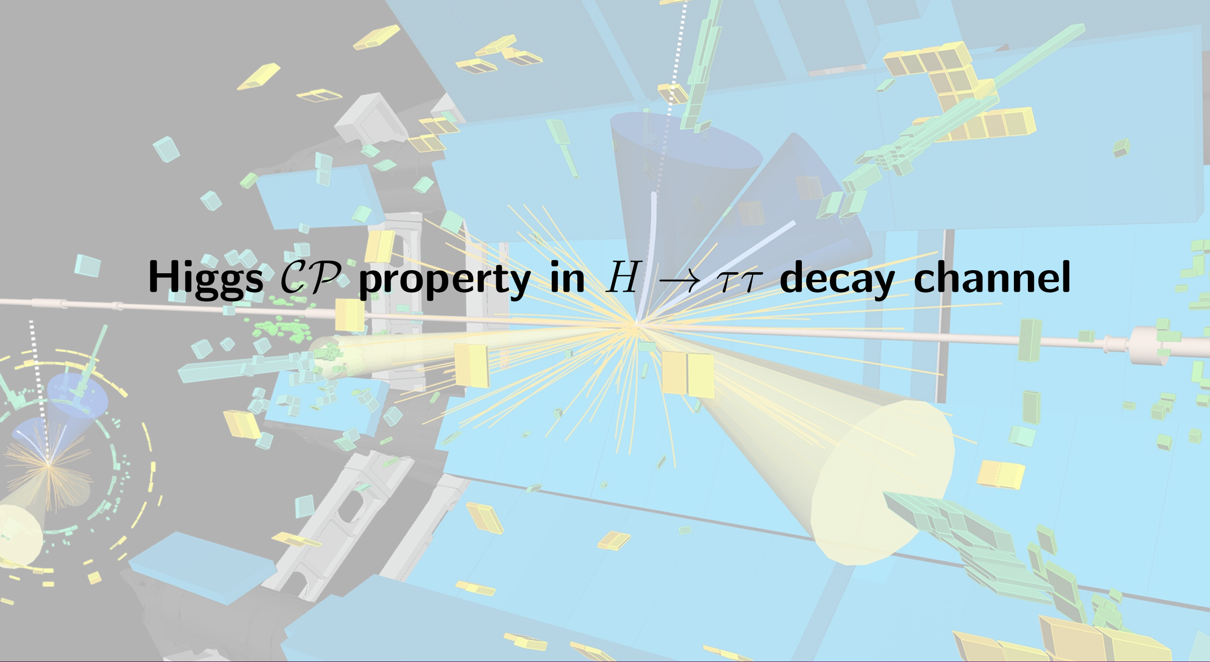
- Cross-sections measured inclusively, per production mode and in STXS bins
- Among the measured production modes, highest precision on **VBF**
- In the SXTS ggF measurement, better precision at high $p_T(H)$
- Similar statistic/systematic uncertainty contribution
- Dominant systematic uncertainty: **Signal modeling**
- The observed uncertainty in the cross-section determination achieved $\pm 13.9\%$ ($^{+28}_{-25}\%$ for 36 fb^{-1} measurement).
- All results are in **agreement with the Standard Model predictions**.







Higgs $\mathcal{CP}$ property in $H \to \tau\tau$ decay channel



Theoretical Motivation

The problem of baryon asymmetry in the universe (BAU):

- The net surplus of matter over antimatter throughout the universe

Sakharov Conditions (1967):

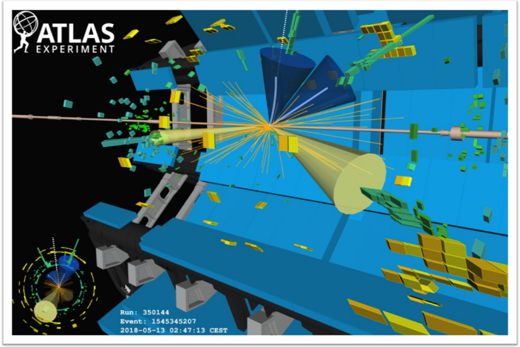
- Baryon number B violation
- **$\mathcal{C}$-symmetry and $\mathcal{CP}$-symmetry violation**
- No thermal equilibrium

- Although LHC data strongly prefer that Higgs boson is a $\mathcal{CP}$-even (scalar) particle, it is not yet excluded that Higgs boson has $\mathcal{CP}$-odd (pseudoscalar) component $\Rightarrow$ Sign of new physics
- Previous studies of the $\mathcal{CP}$ properties of Higgs boson interactions with gauge bosons ($H \to VV$[1,2], $H \to \gamma\gamma$[3]) have shown no deviation from the SM predictions.
- $\mathcal{CP}$-odd Higgs bosons couple to fermions at tree-level $\Rightarrow$ This way to go!

[1] JHEP03(2018)095
[2] Phys. Rev. D 100, 112002
[3] Phys. Rev. D 98, 052005

Overview and Highlights of $H \to \tau\tau$ Decay $\mathcal{CP}$ Run 2 Analysis

- Performing the first ATLAS measurement of Higgs $\mathcal{CP}$ nature in Yukawa coupling with $H \to \tau\tau$ decay vertex with ATLAS full Run-2 dataset [4]
- $\mathcal{CP}$-**sensitive angular observable** ϕ^*_{CP} is defined by the visible decay products of τ lepton decays, which requires reconstruction of τ **decay products** and **decay modes**.



[4] Eur. Phys. J. C 83, 563 (2023)

- Effective Lagrangian for $\mathcal{CP}$-mixed Higgs, parameterised with **mixing angle** ϕ_τ

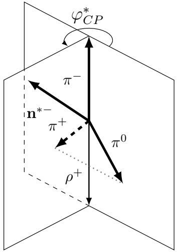
$$\mathcal{L}_{h\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + sin\phi_\tau\bar{\tau}i\gamma_5\tau)h \quad (1)$$

ϕ_τ : the "$\mathcal{CP}$-mixing" angle $\in [-\frac{\pi}{2}, \frac{\pi}{2}]$

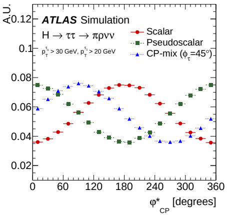
  - $|\phi_\tau| = 0$: Pure $\mathcal{CP}$-even, SM hypothesis
  - $|\phi_\tau| = \frac{\pi}{2}$: Pure $\mathcal{CP}$-odd, Pseudo-scalar hypothesis
  - $0 < |\phi_\tau| < \frac{\pi}{2}$: $\mathcal{CP}$-admixture

- Observable ϕ^*_{CP} related to ϕ_τ constructed as signed angle between τ decay planes spanned by decay products ($\pi^\pm$, π^0, light leptons) and / or impact parameter defined in the visible di-tau zero momentum frame (ZMF)

$$d\Gamma_{H\to\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16}\cos(\phi^*_{CP} - 2\phi_\tau) \quad (2)$$



τ decay planes for constructing ϕ^*_{CP} in 1p0n-1p1n decay



ϕ^*_{CP} distribution for 1p0n-1p1n decay in Higgs boson samples for different CP hypotheses

Observable Reconstruction and Decay Channels

Methods of constructing τ decay planes and ϕ^*_{CP} [a]:

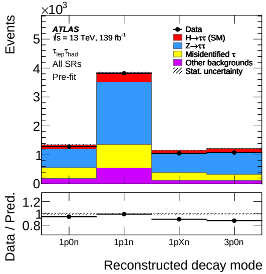
- **IP method (for $\ell = e, \mu$ and 1p0n)**
  - Charged tracks and impact parameter ($\mathbf{n}^{*\pm}$)
- **ρ decay plane method (1p1n, 1pXn)**
  - Charged pion and neutral pion (π^0)
- **a_1 decay method (3p0n)**
  - An extension of ρ method[b]
- **Combined**
  - Combination of the methods above according to different decay modes

τ decay product reconstruction and τ decay mode classification are implemented by **"Tau Particle Flow"** (from Run 1[c]).

[a] Phys. Rev. D 92, 096012
[b] Phys. Rev. D 94, 093001
[c] Eur. Phys. J. C 76, 295 (2016)

Decay channel	Decay mode combination	Method	Fraction in all τ-lepton-pair decays
$\tau_{lep}\tau_{had}$	ℓ–1p0n	IP	8.1%
	ℓ–1p1n	IP–ρ	18.3%
	ℓ–1pXn	IP–ρ	7.6%
	ℓ–3p0n	IP–a_1	6.9%
$\tau_{had}\tau_{had}$	1p0n–1p0n	IP	1.3%
	1p0n–1p1n	IP–ρ	6.0%
	1p1n–1p1n	ρ	6.7%
	1p0n–1pXn	IP–ρ	2.5%
	1p1n–1pXn	ρ	5.6%
	1p1n–3p0n	ρ–a_1	5.1%

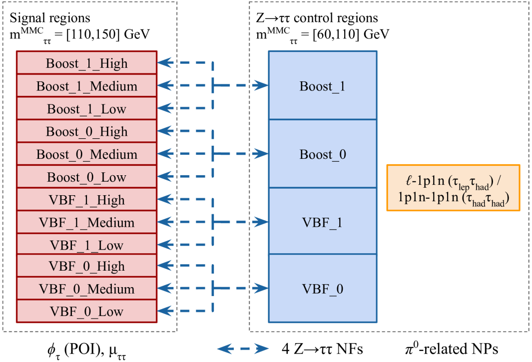
di-τ decay mode combinations considered in the analysis



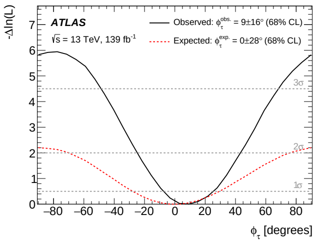
Reconstructed τ_{had} decay modes

Event Selection

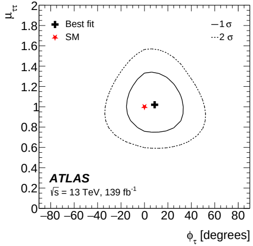
- Preselection criteria and trigger requirement (single lepton and di-tau trigger) for $\tau_{\rm lep}\tau_{\rm had}$ and $\tau_{\rm had}\tau_{\rm had}$ final states largely follow ATLAS Run-2 $H \to \tau\tau$ cross-section measurement[5].
- **24 Signal Regions**
- **8 $Z(\to \tau\tau)+$ jets Control Regions**
- **2 ρ constraint $Z \to \tau\tau+$ jets Control Regions**



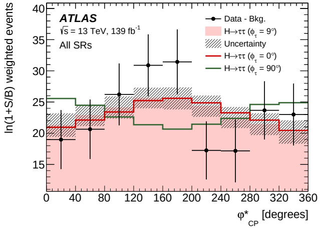
5 JHEP08(2022)175



1D likelihood scan



2D likelihood scan



Combined post-fit distribution of ϕ^*_{CP} from all signal regions

	CP-odd exclusion	**Best Esti. $\hat{\phi}_\tau$ (°)**	**1 σ limit (°)**
Observed	3.4 σ	9	± 16
Expected	2.1 σ	0	± 28

- Best fit value of ϕ_τ is compatible with SM
- Measured signal strength compatible with SM and ATLAS Run-2 $H \to \tau\tau$ cross-section measurement
- The total uncertainties are **dominated by statistical uncertainty in data**.
- The dominant contributions to the **systematic uncertainties** are from **jet energy scale and resolution**.

Summary

- Full Run-2 dataset contains about 30 times more Higgs Bosons than its Run-1 counterpart, which is used for the measurements of Higgs boson production and decay rates.

Cross-section measurement:

- The observed uncertainty in the inclusive cross-section determination achieved $\pm 13.9\%$ ($^{+28}_{-25}\%$ for previous measurement).
- Cross-section measurements include 4 main Higgs production modes and in STXS 1.2 framework.
- All results are **consistent** with the Standard Model predictions.

Higgs boson $\mathcal{CP}$ property in $H \to \tau\tau$ decay channel:

- The mixing angle ϕ_τ is measured to be $9^\circ \pm 16^\circ$.
- The pure $\mathcal{CP}$-odd hypothesis is disfavoured at a level of 3.4 σ.
- The $\mathcal{CP}$ measurement for Run 2 is **consistent** with the Standard Model expectation.
- The measurement is statistically-limited.

`Thank you for your attention!`

Backup

Outlook for Run 3

Improvements:

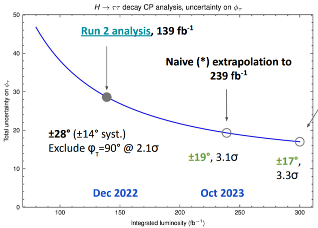
- Statistical uncertainty (plan to combine Run 2 & partial Run 3)
- Experimentally limited by Jet energy scale effects (both in shape and acceptance)
- Potential improvement on the sensitivity in 3 prong ($\tau^{\pm} \to a_1^{\pm}\nu$, $a_1^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$) channel based on observables trained by neural network (NN)
- Signal region categorization
- More decay mode combinations (1pXn-1pXn, 3p0n-3p0n, etc.)?
- Including $\tau_{lep}\tau_{lep}$ decay channel?

Improvements from Data Statistics

- Measurement uncertainty is largely dominated by data sample statistics
- 2022+2023 Run 3 (HLep GRL $56.3 = 29.0 + 27.2\ \text{fb}^{-1}$) + Run 2 ($140\ \text{fb}^{-1}$): $28\ \text{deg} \rightarrow 23\ \text{deg}$, uncertainty reduced by $\sim 20\%$

Impact on analyses : H→ττ decay CP analysis

(*) Doesn't account for XS changes



Run 2 analysis extrapolated to 300 fb^{-1}

Uncertainty **reduced by ~30%** with data available at the end of this year

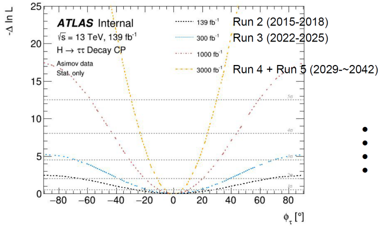
⇒ Interesting result for next year

Challenge is to understand the data! (e.g. τ ID)

Assumes combination with Run 2…

HLep workshop: Higgs groups and plans, 2023

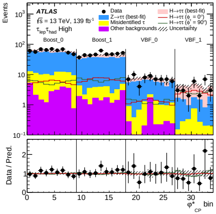
Htautau CP: sensitivity projection



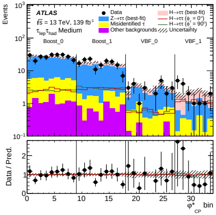
- 139 fb-1 (28°)
- 300 fb-1 (17°)
- 1000 fb-1 (10°)
- 3000 fb-1 (6°)

ATLAS Week: HCP Talk, 2022

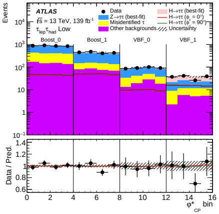
Post-fit Distribution of Observable



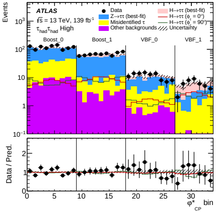
$\tau_{\rm lep}\tau_{\rm had}$ High SR



$\tau_{\rm lep}\tau_{\rm had}$ Medium SR



$\tau_{\rm lep}\tau_{\rm had}$ Low SR



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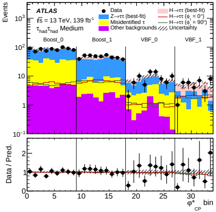

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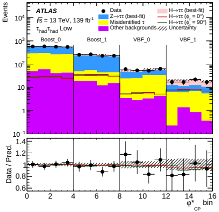

$\tau_{\rm had}\tau_{\rm had}$ Low SR