Measurements of Higgs boson properties (mass, width, and Spin/CP) with the ATLAS detector

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on behalf of the ATLAS Collaboration

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Introduction

Since its discovery in 2012, the Higgs boson has been scrutinized at the LHC…

- to test compliance with SM prediction,
- to look for possible deviations that could highlight BSM physics.

In this talk: Latest ATLAS measurements of:

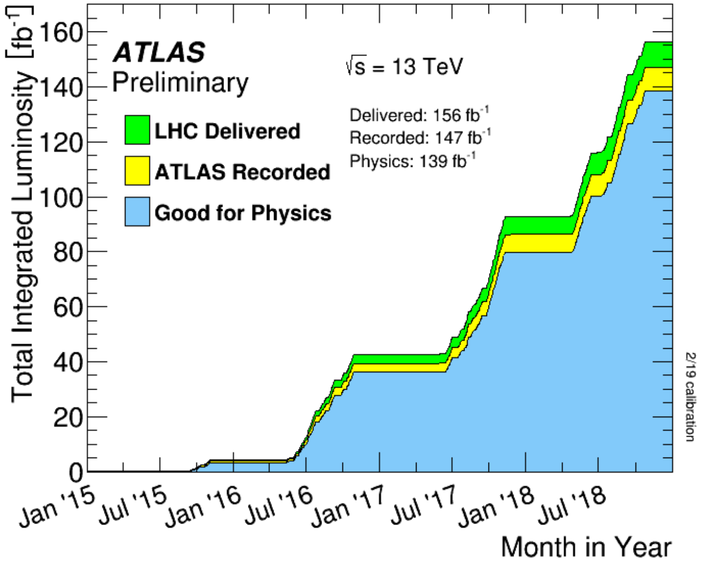
- Higgs mass
- Higgs width
- Higgs spin/CP

using the full ATLAS dataset from LHC Run-2

More ATLAS studies of the Higgs boson today by:

- Maria Teresa Camerlingo (cross-sections, couplings)
- Angela Maria Burger (di-Higgs)

ATLAS public online estimates



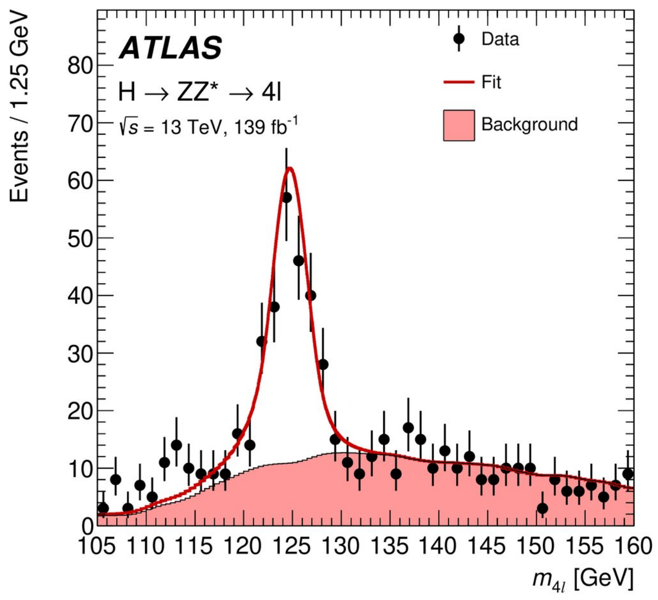
1 Higgs Mass

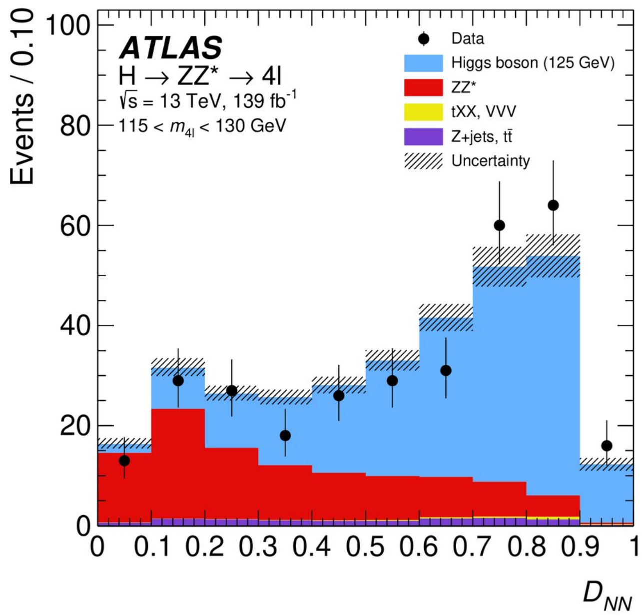
- Free parameter of the SM
- Important for theoretical predictions
- Studied with $H \to ZZ^* \to 4\ell$ & $H \to \gamma\gamma$ decays

Higgs mass ($H \to ZZ \to 4\ell$)

arXiv: 2207.00320 (sub. to PLB)

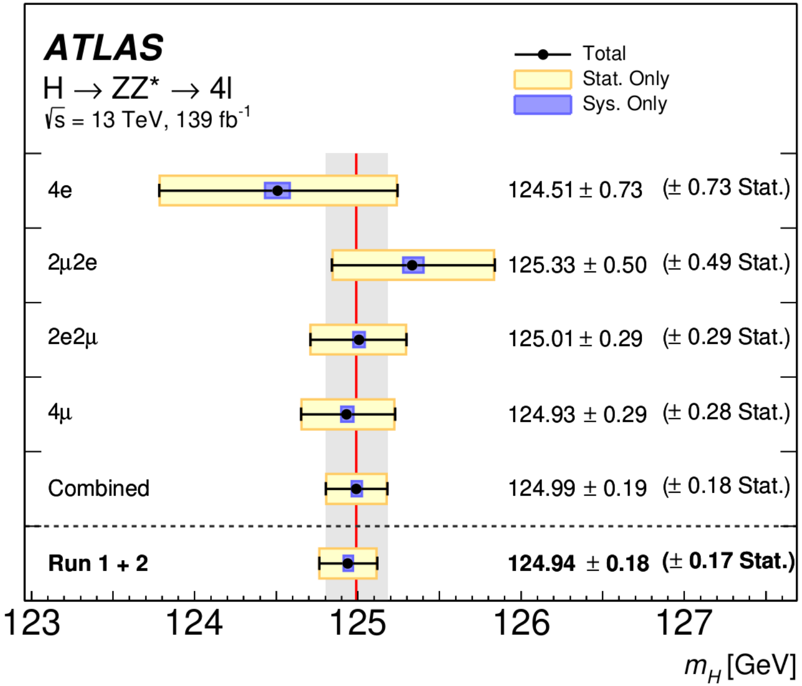
- **4 final states:** 4μ, $4e$, $2\mu 2e$, $2e2\mu$ (primary pair is the closest to m_Z).
- **Kinematic fit** of primary pair to m_Z → improves $m_{4\ell}$ resolution.
- **2 observables:** $m_{4\ell}$, D_{NN} (additional separation from non-resonant $ZZ^* \to 4\ell$).
- Unbinned fit to the data with **event-by-event $m_{4\ell}$ resolution estimates** (QRNN trained on MC).





Higgs mass ($H \to ZZ \to 4\ell$)

arXiv: 2207.00320 (sub. to PLB)

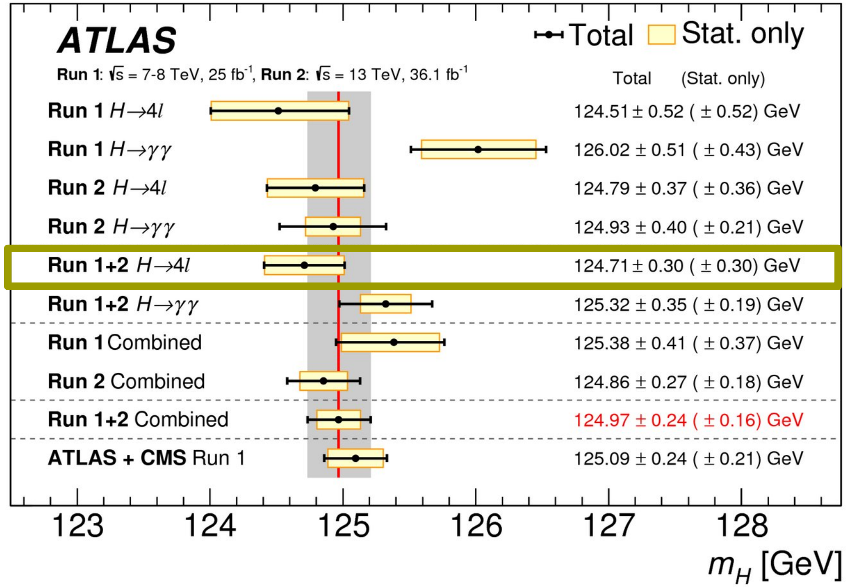


Combination of 7, 8 and 13 TeV data sets:

m_H = 124.94 ± 0.17(stat.) ± 0.03(syst.) GeV

dominant

28 MeV from muon p_T scale, greatly benefitted by the improved muon momentum-scale calibration → described in Marco's talk in this session



Substantial improvement w.r.t. previous results

Futher improvement expected with addition of H→γγ study (and combination with CMS).

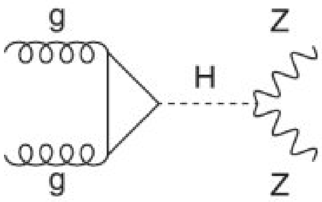
2 Higgs Width

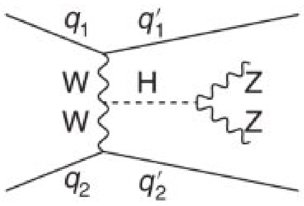
- Predicted by SM (4.1 MeV)
- Inaccessible via direct measurement due to experimental resolution
- Indirect methods exploit the relationship between
  Higgs coupling constants in the on-shell and off-shell regimes

Higgs width *(H→ZZ→4ℓ / 2ℓ2ν)*

arXiv: 2304.01532 (sub. to PLB)

- According to SM: $\sigma^{\text{on-shell}}_{gg\to H\to VV} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{m_H \Gamma_H}$ $\sigma^{\text{off-shell}}_{gg\to H\to VV} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{m^2_{ZZ}}$
- Assuming SM ratios of on-shell/off-shell couplings, we can obtain Γ_H from the ratio of the rates in the two regimes.
- Destructive interference: *gg* → (*H**→) *ZZ* is less than *gg*→*H**→*ZZ* + *gg* → *ZZ*.





Analysis strategy (outline)

H→ZZ→4ℓ

- Final states: 4*μ*, 4*e*, 2*μ*2*e*, 2*e*2*μ*
- $m_{12} \in [50, 106]$ GeV
  $m_{34} \in$ variable window
- 3 SRs: ggF, VBF, mixed
- **$m_{4\ell} > 220$ GeV**
- **Observable:** NN-based discriminant:
  - off-shell signal
  - interfering background
  - non-interfering background

H→ZZ→2ℓ2ν

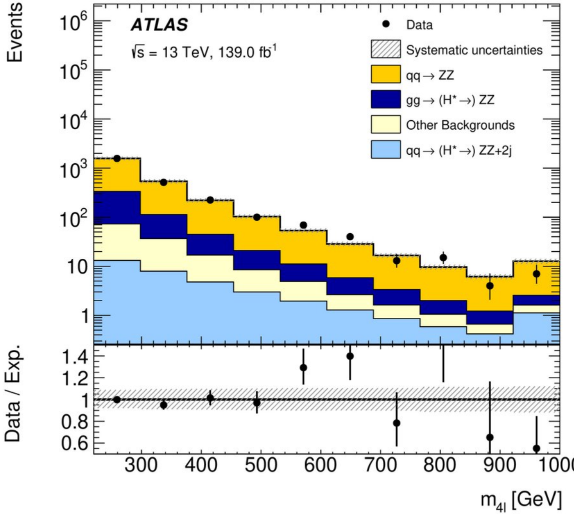
- Final states: 2*μ*/2*e* + $E_{\text{T,miss}}$
- $m_{\ell\ell} \in [76, 106]$ GeV
- **Observable:** transverse mass of the Z-pair:

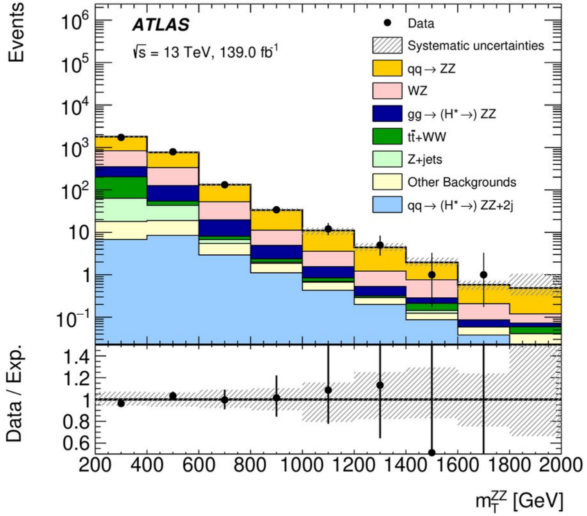
$$m_{\text{T}}^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_{\text{T}}^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_{\text{T}}^{\text{miss}}\right)^2}\right]^2 - \left|\vec{p}_{\text{T}}^{\,\ell\ell} + \vec{E}_{\text{T}}^{\text{miss}}\right|^2}$$

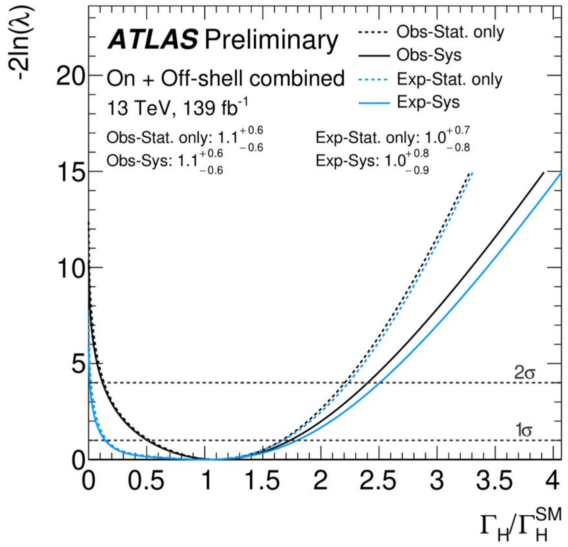
Higgs width (*H→ZZ→4ℓ / 2ℓ2ν*)

arXiv: 2304.01532 (sub. to PLB)

Comparisons between data and the SM prediction in the inclusive SR of each analysis.







$\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV

$\Gamma_{SM} = 4.1^{+3.2}_{-3.5}$ MeV

$\Gamma_H/\Gamma_{SM} = 1.1^{+0.7}_{-0.6}$

- Observed (expected) 95% CL limits: 0.5(0.1) < Γ_H < 10.5(10.9) MeV
- Background-only hypothesis rejected with 3.2σ (2.2σ) observed (expected) significance.

- Measurement of VBF off-shell signal strength.
- Alternative interpretation constrains the on-shell / off-shell ratios of Higgs coupling (κ_g,κ_V).

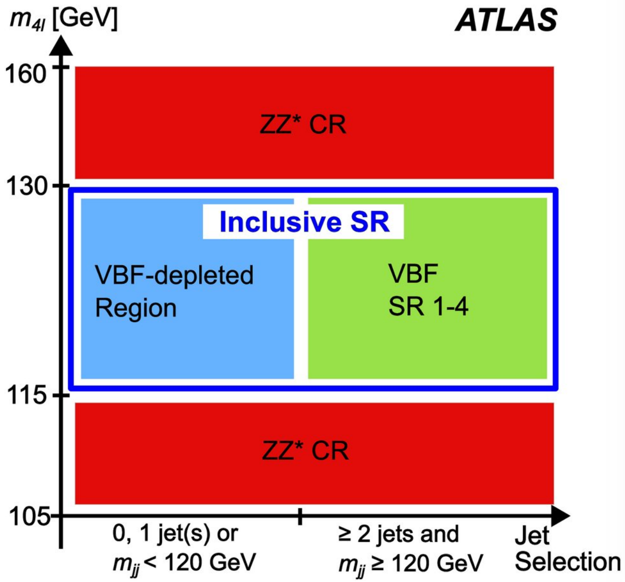
3 Higgs spin - CP

- Predicted CP-violation is too small to explain the observed baryon asymmetry
- Sign of CP-violation in the Higgs sector → indication of BSM phenomena
- ATLAS and CMS have excluded pure spin-parity states 0^-, $1^\pm$, $2^\pm$ at over 99% CL
- Recent searches target CP-even / CP-odd admixtures in the Higgs couplings

CP: Higgs – vector boson ($H \to ZZ \to 4\ell$)

arXiv: 2304.09612 (sub. to JHEP)

- SMEFT introduces CP-odd HVV couplings: $\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$
- Matrix-Element-based Optimal Observables (OOs) defined to maximize sensitivity to coupling constants c_i (Wilson coefficients).
- Each OO is most sensitive to a specific coefficient.

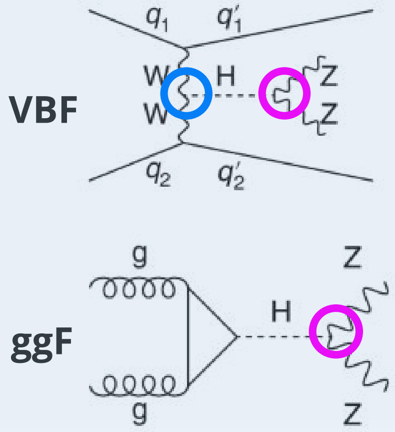


Signal and control regions for the 3 analysis strategies

HVV at decay and production (VBF)

→ 3 independent analysis strategies: (optimize sensitivity to specific OOs)

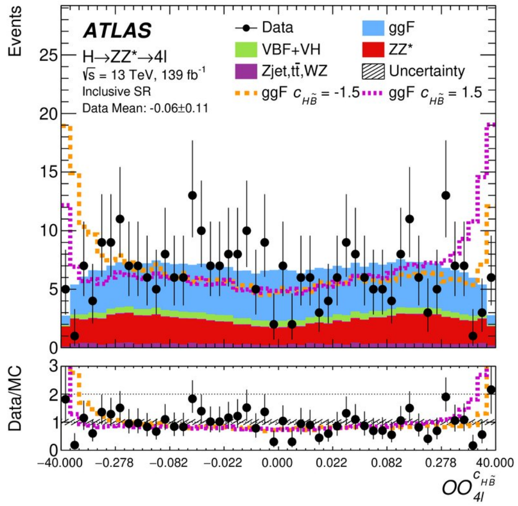
- production-only (VBF),
- decay-only (VBF, ggF),
- combined (VBF)

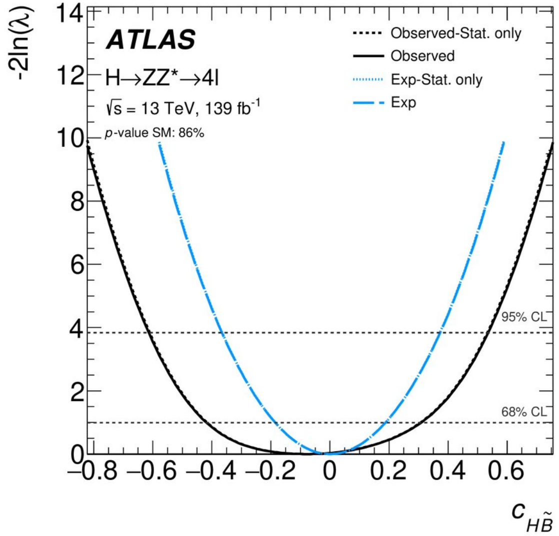


CP: Higgs – vector boson ($H \to ZZ \to 4\ell$)

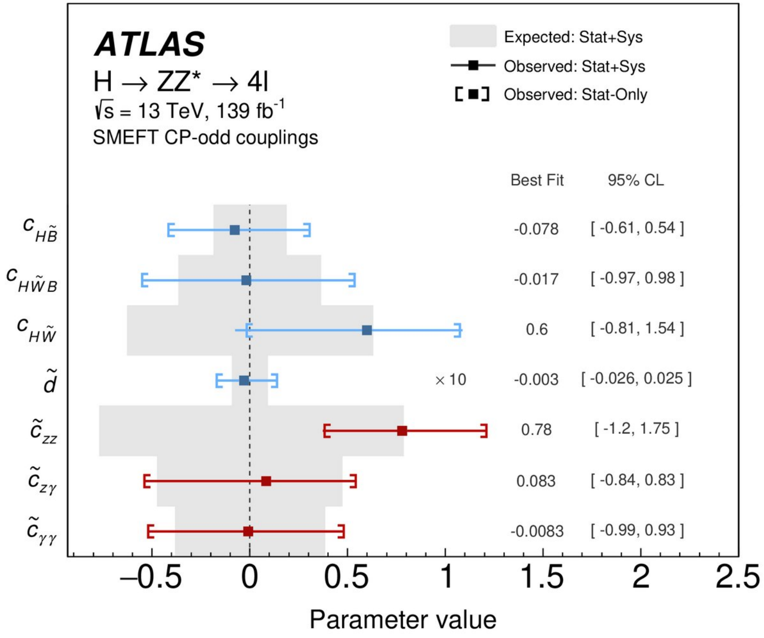
arXiv: 2304.09612 (sub. to JHEP)

Direct optimal-observable fits:





Best fit results - Wilson coefficients
Warsaw basis / Higgs Basis



No significant deviation from SM predictions.

CP: Higgs – vector boson ($H \to \gamma\gamma$)

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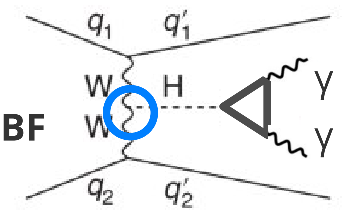
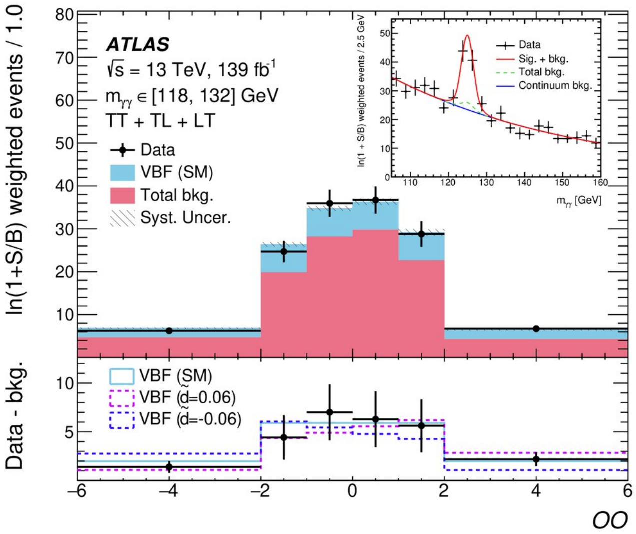
arXiv: 2208.02338 (sub. to PRL)

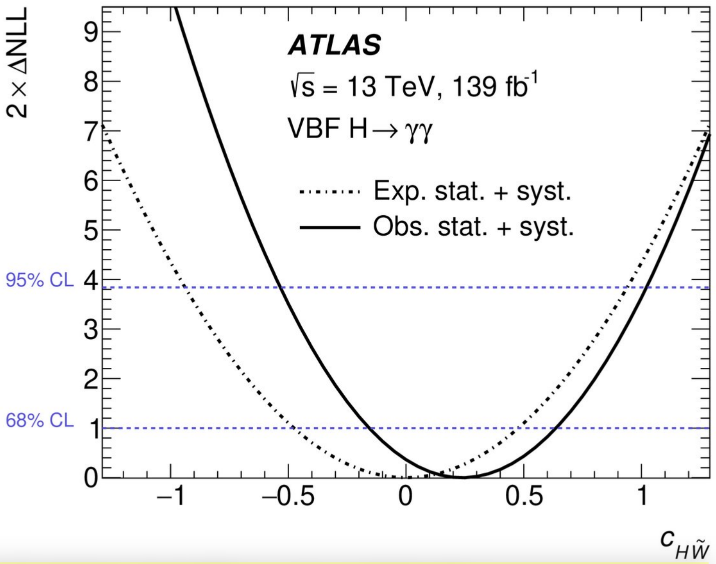
The VBF topology is sensitive to $c_{HW\sim}$ → single OO.

- Dominant backgrounds: ggF (MC), γγ (MC), γj/jj (data-driven)
- 2 BDTs to discriminate VBF / ggF and VBF / continuum
- 3 signal regions (excl. case where both BDT cuts fail)

VBF







$c_{HW} \in$ [−0.53, 1.02] (obs.), [−0.94, 0.94](exp.) at 95%CL

Most stringent to date constraints on CP-violating effects in the HVV coupling.

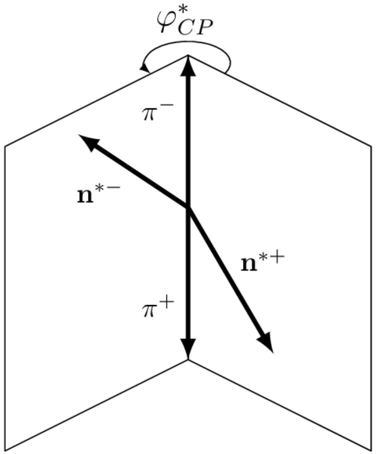
CP: Higgs – τ ($H\to\tau\tau$)

arXiv: 2212.05833 (sub. to EPJC)

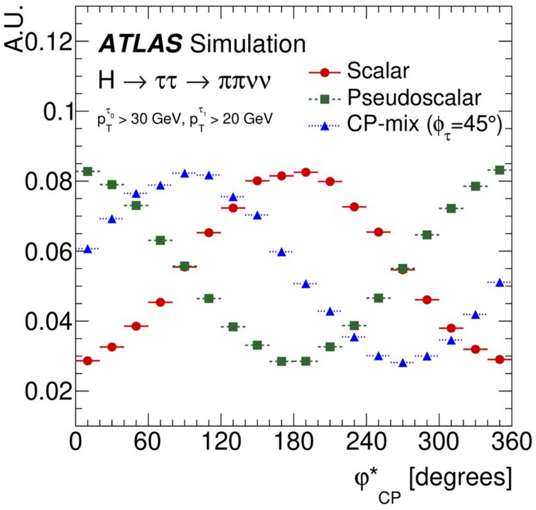
Probing the Yukawa coupling for CP-mixing: $\mathcal{L}_{H\tau\tau} = -\frac{m_t}{\upsilon}\kappa_\tau \bar{\tau}(\cos\varphi_\tau + i\gamma_5 \sin\varphi_\tau)\tau$

- **Boosted topology:** reconstructed $\tau^+\tau^-$ with small angular separation (rejects non-resonant $\tau\tau$ background).
- **110 < $m_{\tau\tau}^{MMC}$ < 150 GeV** (sidebands used to control the normalization of $Z(\to\tau\tau)$+jets background).
- **Analysis channels:** (a) $\tau_{lep}\,\tau_{had}$, (b) $\tau_{had}\,\tau_{had}$ + categorization according to τ_{had} final states.
- **Signal regions:** 2 x VBF (defined by BDT), 2 x ggF (defined by the Higgs-boson boost).

Observable: signed acoplanarity φ^*_{CP} between tau decay planes. (depending on the decay mode).



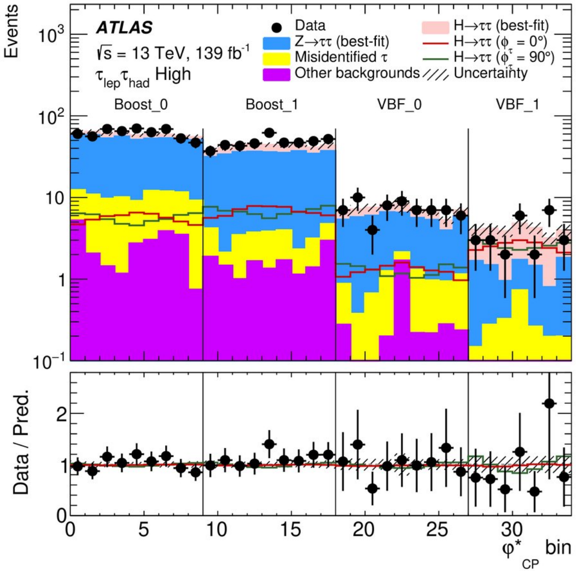
sensitive to φ_τ



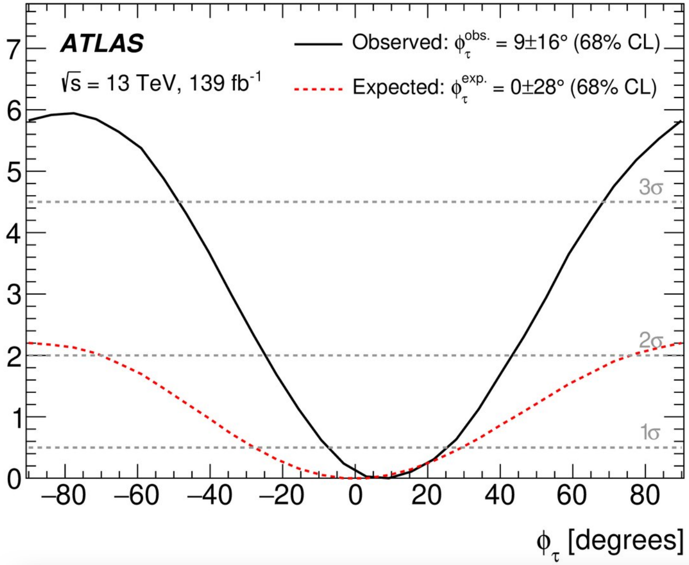
MMC: advanced likelihood-based algorithm named the Missing Mass Calculator ised tp calculate the invariant mass of the τ-lepton-pair system

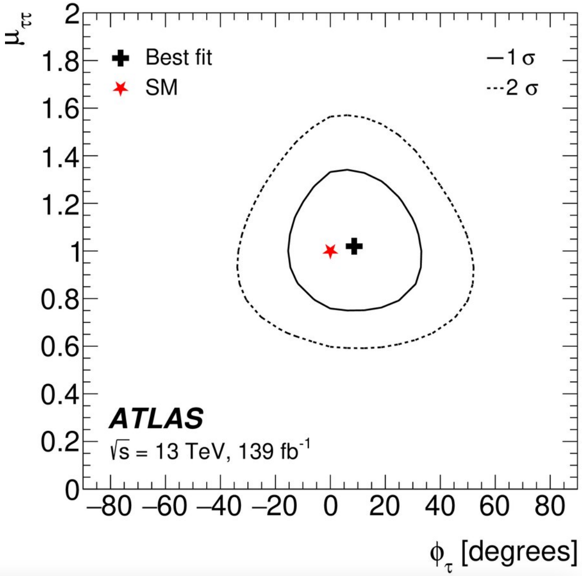
CP: Higgs – τ (H→ττ)

arXiv: 2212.05833 (sub. to EPJC)



Post-fit event yields in signal-enriched regions.





Best-fit value: $\varphi_\tau = 9^o \pm 16^o$ (expected: of $0^o \pm 28^o$) at 68% CL.

The pure CP-odd hypothesis is disfavoured at a level of 3.4σ.

CP: Higgs – top quark (*ttH, H→bb*)

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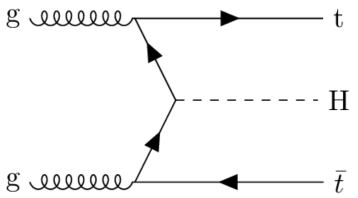
arXiv: 2303.05974 (sub. to PLB)



Pure CP-odd coupling has been excluded at 3σ.

Probing the Yukawa coupling for CP-mixing: $\mathscr{L}_{t\bar{t}H} = -\kappa_t' y_t \varphi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$

Analysis Strategy exploiting the high jet and *b*-tagged jet multiplicity in the final state:

DNN

1L + jets

2L(OS) + jets

$TR_{\text{boosted H}}$	Training Region	CRs ($t\bar{t}$+jets)	Training Region	CRs ($t\bar{t}$+jets)

Reconstruction BDTs → full reconstruction of final state particles (employing $E_{T miss}$)

Classification BDTs → Refine TRs into SRs and additional CRs
→ control the modelling of CP-sensitive observables.

Observables:	BDT score	$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{\|\vec{p}_1\|\|\vec{p}_2\|}$,	Yield	$b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{\|\vec{p}_1\|\|\vec{p}_2\|}$ (2SRs)	$\Delta R_{bb,avg}$

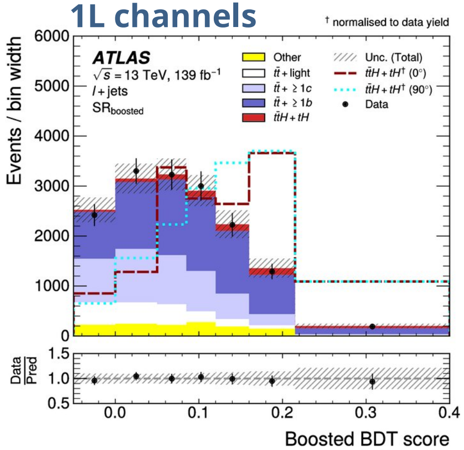
$\boldsymbol{p}_{1,2}$: spatial-momenta of the top-quarks

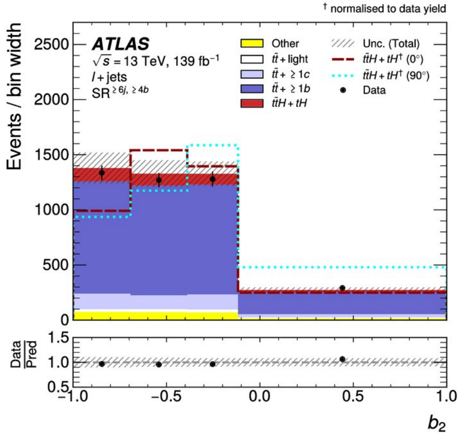
CP: Higgs – top quark (*ttH, H→bb*)

arXiv: 2303.05974 (sub. to PLB)

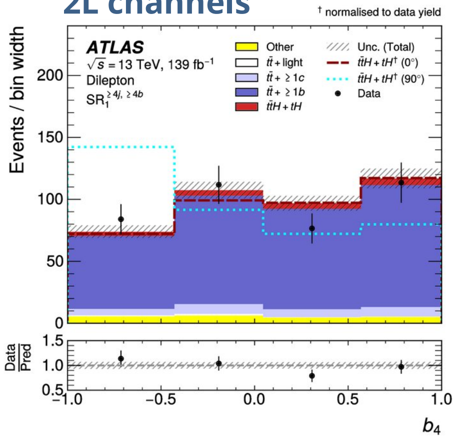
Post-fit distributions of CP-sensitive observables.

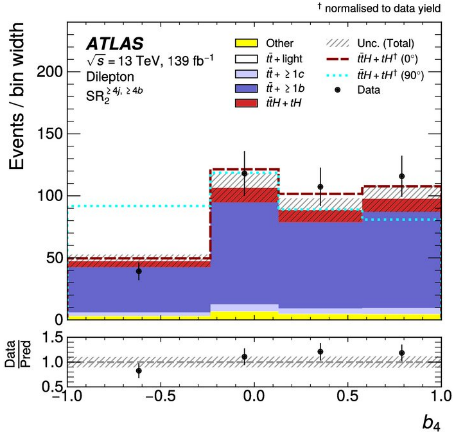
1L channels

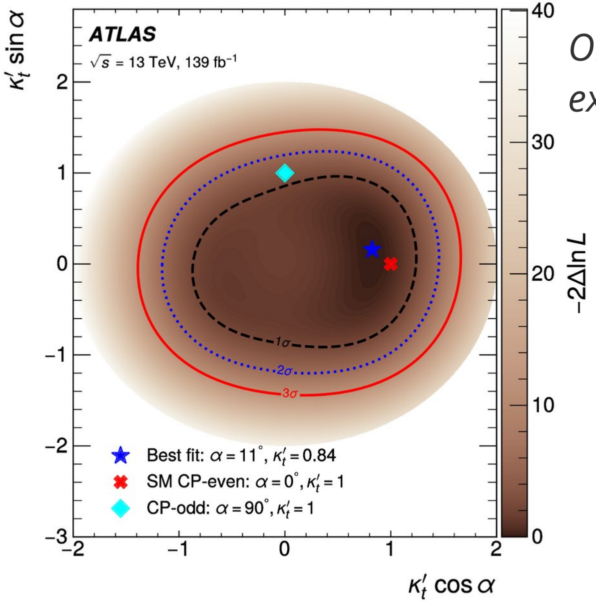




2L channels







Observed 2D exclusion contours.

Best Fit Values: $\alpha = 11^{o\,+56^{o}}_{\;\,-77^{o}}$, $\kappa'_t = 0.84^{+0.30}_{-0.46}$

consistent with SM (α=0°, κ'_t=1)

Pure CP-odd hypothesis disfavoured with 1.2σ.

Conclusions

- **Precision era for Higgs property measurements:**
  - Most precise measurement on the mass m_H = 124.94 ± 0.17(stat.) ± 0.03(syst.) GeV (4l/2l2v channels).
  - Evidence for off-shell Higgs production.
  - Defined observed (expected) upper limit 10.5 (10.9) MeV on Γ_H, at 95% CL.
- **Starting to probe the structure of Higgs interactions:**
  - 95% CL upper limits defined for CP-odd contributions to Higgs-Vector Boson couplings.
  - CP-odd contributions to Higgs-fermion couplings are now being constrained too.
- **No deviation from the SM observed so far.**
- **Run3 and HL-LHC will significantly increase the available dataset → large boost to precision reach.**

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Backup Material

Higgs mass ($H \to ZZ \to 4\ell$)

arXiv: 2207.00320 (sub. to PLB)

Final state	Higgs	ZZ, tXX, VVV	Reducible backgrounds	Expected total yield	Observed yield	S/B
4μ	78 ± 5	38.7 ± 2.2	2.84 ± 0.17	120 ± 5	115	1.89
$2e2\mu$	53.4 ± 3.2	26.7 ± 1.4	3.02 ± 0.19	83.1 ± 3.5	94	1.80
$2\mu 2e$	41.2 ± 3.0	17.9 ± 1.3	3.4 ± 0.5	62.5 ± 3.3	59	1.93
$4e$	36.2 ± 2.7	15.7 ± 1.6	2.83 ± 0.35	54.8 ± 3.2	45	1.95
Total	209 ± 13	99 ± 6	12.2 ± 0.9	321 ± 14	313	1.88

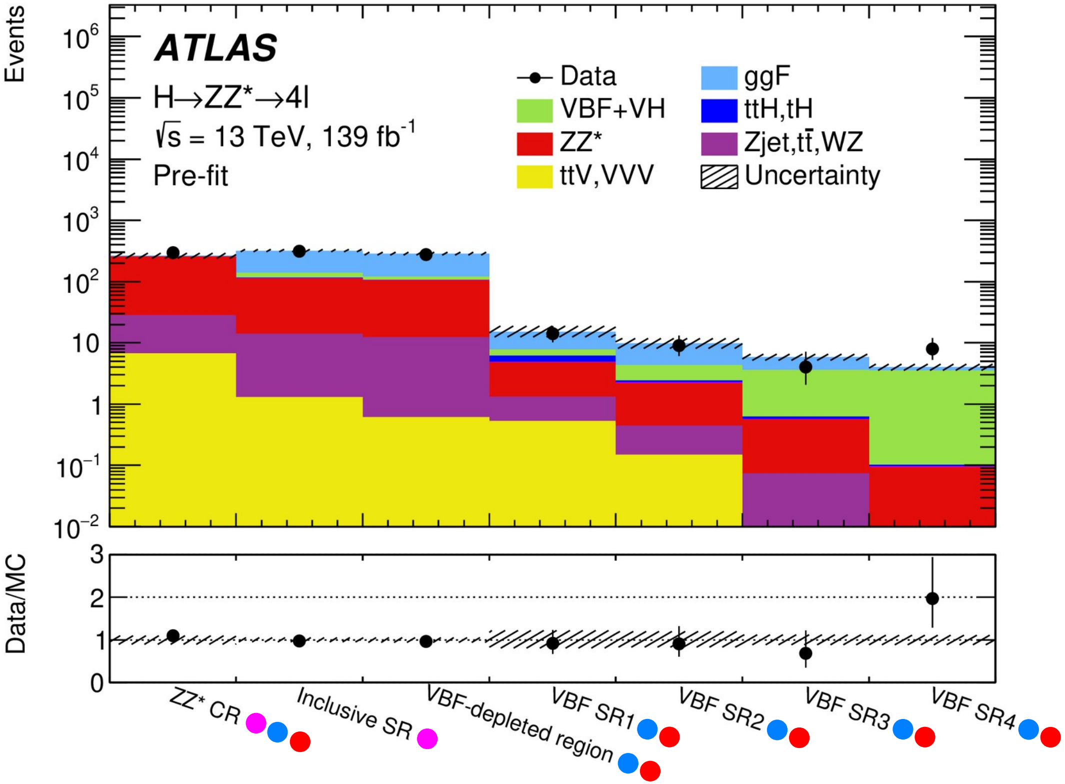
observed and expected (pre-fit) yields for the different decay final states in the region with $m_{4\ell}$ between 115 and 130 GeV.

Systematic Uncertainty	Contribution [MeV]
Muon momentum scale	± 28
Electron energy scale	± 19
Signal-process theory	± 14

Largest contributions to the systematic uncertainty of m_H.

CP $(H \to ZZ \to 4\ell)$

arXiv: 2304.09612 (sub. to JHEP)



CP $(H \to ZZ \to 4\ell)$

arXiv: 2304.09612 (sub. to JHEP)

EFT coupling parameter	Expected 68% CL	Expected 95% CL	Observed 68% CL	Observed 95% CL	Best-fit value	SM p-value	Fit type
$c_{H\tilde{B}}$	[−0.18, 0.19]	[−0.37, 0.37]	[−0.42, 0.31]	[−0.61, 0.54]	−0.078	0.86	decay
$c_{H\widetilde{W}B}$	[−0.36, 0.36]	[−0.72, 0.72]	[−0.56, 0.53]	[−0.97, 0.98]	−0.017	0.99	decay
$c_{H\widetilde{W}}$	[−0.63, 0.63]	[−1.26, 1.28]	[−0.07, 1.09]	[−0.81, 1.54]	0.60	0.37	comb
$\tilde{d}$	[−0.009, 0.009]	[−0.018, 0.018]	[−0.017, 0.014]	[−0.026, 0.025]	−0.003	0.86	decay
$\tilde{c}_{zz}$	[−0.77, 0.79]	[−2.4, 2.4]	[0.37, 1.21]	[−1.20, 1.75]	0.78	0.11	prod
$\tilde{c}_{z\gamma}$	[−0.47, 0.47]	[−0.76, 0.76]	[−0.54, 0.54]	[−0.84, 0.83]	0.083	0.93	decay
$\tilde{c}_{\gamma\gamma}$	[−0.38, 0.38]	[−0.76, 0.77]	[−0.52, 0.48]	[−0.99, 0.93]	−0.01	0.99	decay

CP ($H \to \tau\tau$)

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arXiv: 2212.05833 (sub. to EPJC)

Classification of dominant (high) and sub-dominant (medium/low) final states

Channel	Signal region	Decay mode combination	Selection criteria
$\tau_{lep}\tau_{had}$	High	ℓ–1p0n	$\lvert d_0^{sig}(e)\rvert > 2.5$ or $\lvert d_0^{sig}(\mu)\rvert > 2.0$ $\lvert d_0^{sig}(\tau_{1p0n})\rvert > 1.5$
		ℓ–1p1n	$\lvert d_0^{sig}(e)\rvert > 2.5$ or $\lvert d_0^{sig}(\mu)\rvert > 2.0$ $\lvert y^{\rho}(\tau_{1p1n})\rvert > 0.1$
	Medium	ℓ–1pXn	$\lvert d_0^{sig}(e)\rvert > 2.5$ or $\lvert d_0^{sig}(\mu)\rvert > 2.0$ $\lvert y^{\rho}(\tau_{1pXn})\rvert > 0.1$
		ℓ–3p0n	$\lvert d_0^{sig}(e)\rvert > 2.5$ or $\lvert d_0^{sig}(\mu)\rvert > 2.0$ $\lvert y^{a_1}(\tau_{3p0n})\rvert > 0.6$
	Low	All above	Not satisfying selection criteria

Channel	Signal region	Decay mode combination	Selection criteria
$\tau_{had}\tau_{had}$	High	1p0n–1p0n	$\lvert d_0^{sig}(\tau_1)\rvert > 1.5$ $\lvert d_0^{sig}(\tau_2)\rvert > 1.5$
		1p0n–1p1n	$\lvert d_0^{sig}(\tau_{1p0n})\rvert > 1.5$ $\lvert y^{\rho}(\tau_{1p1n})\rvert > 0.1$
		1p1n–1p1n	$\lvert y^{\rho}(\tau_1)y^{\rho}(\tau_2)\rvert > 0.2$
	Medium	1p0n–1pXn	$\lvert d_0^{sig}(\tau_{1p0n})\rvert > 1.5$ $\lvert y^{\rho}(\tau_{1pXn})\rvert > 0.1$
		1p1n–1pXn	$\lvert y^{\rho}(\tau_{1p1n})y^{\rho}(\tau_{1pXn})\rvert > 0.2$
		1p1n–3p0n	$\lvert y^{\rho}(\tau_{1p1n})\rvert > 0.1$ $\lvert y^{a_1}(\tau_{3p0n})\rvert > 0.6$
	Low	All above	Not satisfying selection criteria

Other decay combinations are not considered in this analysis because their respective φ_{CP} observables perform relatively poorly in discriminating between different CP scenarios.

Notation	Decay mode	Branching fraction
ℓ	$\ell^{\pm}\bar{\nu}\nu$	35.2%
1p0n	$h^{\pm}\nu$ $(\pi^{\pm}\nu)$	11.5% (10.8%)
1p1n	$h^{\pm}\pi^0\nu$ $(\pi^{\pm}\pi^0\nu)$	25.9% (25.5%)
1pXn	$h^{\pm} \geq 2\pi^0\nu$ $(\pi^{\pm}2\pi^0\nu)$	10.8% (9.3%)
3p0n	$3h^{\pm}\nu$ $(3\pi^{\pm}\nu)$	9.8% (9.0%)

CP $(H \to \tau\tau)$

arXiv: 2212.05833 (sub. to EPJC)

Contributing uncertainties

Set of nuisance parameters	Impact on ϕ_τ [degrees]
Jet energy scale	3.4
Jet energy resolution	2.5
Pile-up jet tagging	0.5
Jet flavour tagging	0.2
E_T^{miss}	0.4
Electron	0.3
Muon	0.9
τ_{had} reconstruction	1.0
Misidentified τ	0.6
τ_{had} decay mode classification	0.3
π^0 angular resolution and energy scale	0.2
Track ($\pi^\pm$, impact parameter)	0.7
Luminosity	0.1
Theory uncertainty in $H \to \tau\tau$ processes	1.5
Theory uncertainty in $Z \to \tau\tau$ processes	1.1
Simulated background sample statistics	1.4
Signal normalisation	1.4
Background normalisation	0.6
Total systematic uncertainty	5.2
Data sample statistics	15.6
Total	16.4

CP (ttH, $H \rightarrow bb$)

arXiv: 2303.05974 (sub. to PLB)

Contributing uncertainties

Uncertainty source	$\Delta\alpha\,[^\circ]$	
Process modelling		
Signal modelling	+8.8	-14
$t\bar{t} + \geq 1b$ modelling		
$t\bar{t} + \geq 1b$ 4V5 FS	+23	-37
$t\bar{t} + \geq 1b$ NLO matching	+22	-33
$t\bar{t} + \geq 1b$ fractions	+14	-21
$t\bar{t} + \geq 1b$ FSR	+5.2	-9.9
$t\bar{t} + \geq 1b$ PS & hadronisation	+16	-24
$t\bar{t} + \geq 1b$ $p_{\mathrm{T}}^{b\bar{b}}$ shape	+5.4	-4.6
$t\bar{t} + \geq 1b$ ISR	+14	-24
$t\bar{t} + \geq 1c$ modelling	+6.6	-11
$t\bar{t}$ + light modelling	+2.5	-4.7
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+8.7	-15
c-mis-tag rates	+6.7	-11
l-mis-tag rates	+2.3	-2.7
Jet energy scale and resolution		
b-jet energy scale	+1.6	-3.8
Jet energy scale (flavour)	+7.8	-11
Jet energy scale (pileup)	+5.2	-7.9
Jet energy scale (remaining)	+8.1	-13
Jet energy resolution	+5.7	-9.3
Luminosity	$\leq \pm 1$	
Other sources	+4.9	-8
Total systematic uncertainty	+41	-54
$t\bar{t} + \geq 1b$ normalisation	+8.2	-13
κ_t'	+17	-33
Total statistical uncertainty	+32	-49
Total uncertainty	+52	-73

CP (ttH, $H \rightarrow bb$)

arXiv: 2303.05974 (sub. to PLB)

Post-fit event yields in the analysis regions.

Agreement between fitted model and data

S/B composition