Measurements of Higgs boson properties with the ATLAS detector

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High Energy Physics in the LHC Era

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on behalf of the ATLAS collaboration

Overview

Studying the properties of the Higgs boson is a key component of the LHC physics program

Observation of deviations between these measurements and Standard Model (SM) predictions would be a sign of possible new phenomena beyond the SM

Recent public ATLAS results to be discussed in this talk:

- Measurement of the Higgs boson mass in the $H \to ZZ^* \to 4\ell$ decay channel (and $H \to \gamma\gamma$) — arXiv:2207.00320, Phys. Lett. B 784 (2018) 345
- Constraints on the total width of the Higgs boson in the $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$ channels — ATLAS-CONF-2022-068
- CP properties of the Higgs boson coupling to electroweak bosons with the VBF $H \to \gamma\gamma$ channel — arXiv:2208.02338
- CP properties of the Higgs boson coupling to fermions
    - tau-Higgs interaction with $H \to \tau^+\tau^-$ — arXiv:2212.05833
    - top-Higgs Yukawa coupling in tH and $t\bar{t}H$ events with $H \to b\bar{b}$ and with $H \to \gamma\gamma$ — ATLAS-CONF-2022-016, Phys. Rev. Lett. 125 (2020) 061802

Higgs mass (I)

- intimately related to the Higgs potential
  → its value is not predicted by the SM
  (only mild correlations with heavy fermion and boson masses)

$$V(\Phi) = -\mu^2 \Phi^* \Phi + \lambda (\Phi^* \Phi)^2$$

$$= V_0 + \frac{1}{2} m_H^2 H^2 + \lambda \langle v \rangle H^3 + \frac{1}{4} \lambda H^4$$

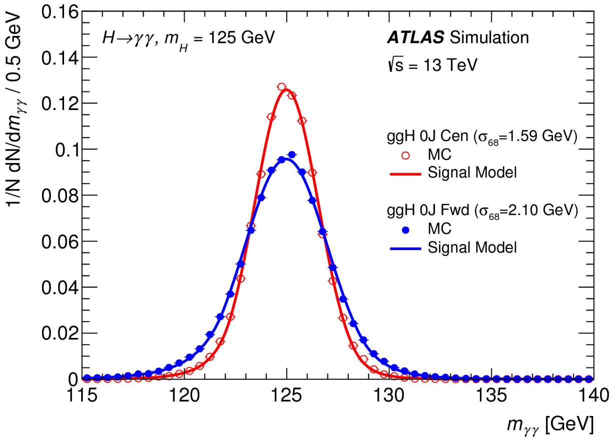
- the Higgs couplings are defined by the m_H value
- access to the fundamental μ^2 parameter:
  → at the center of the naturalness problem
- precision measurements via fully-reconstructed final states in $H\to\gamma\gamma$, $H\to ZZ^*\to 4\ell$
- understanding of detector is crucial:

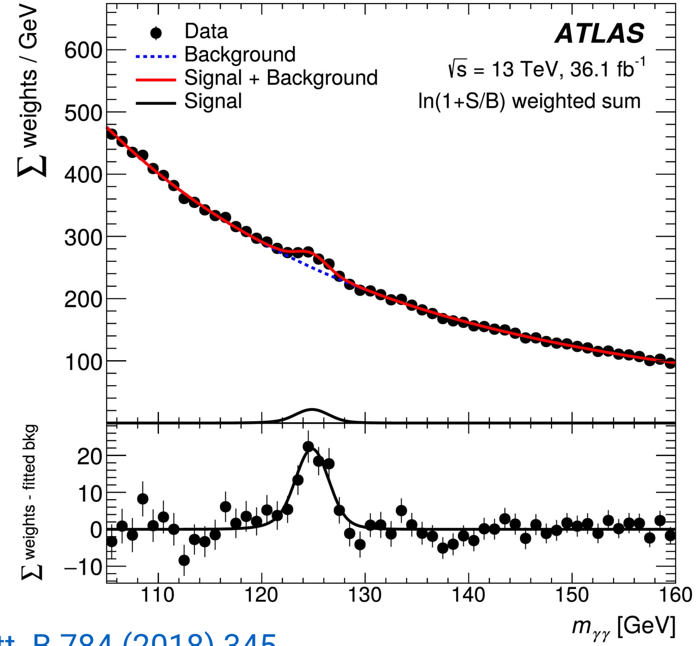
→ precise calibrations of γ, $\mu^\pm$ and $e^\pm$ energy and momentum scales are needed
→ also, precise understanding of detector resolution

Mass measurement with $H\to\gamma\gamma$:

m_H = 124.93 ± 0.21 (stat.) ± 0.34 (syst.) GeV
(36.1 fb^{-1}, subset of Run 2 data)

Systematics dominated by knowledge of EM calorimeter and material





Phys. Lett. B 784 (2018) 345

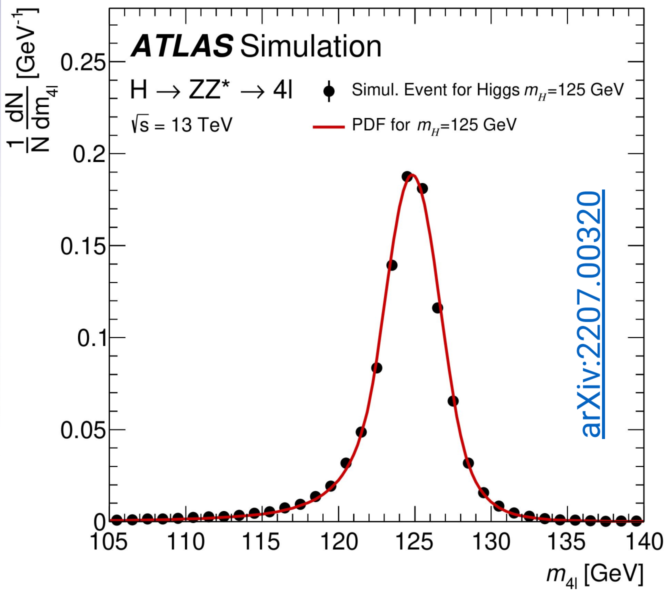
Higgs mass (II)

Mass measurement in the H→ZZ*→4ℓ channel:

Categorise events per Z boson decay channel : 4μ, 2μ2e, 2e2μ, 4e
Recover final state radiation, kinematic constraint of leading lepton pairs
Simultaneous fit in 4 the final state categories (4μ, 4e, 2μ2e, 2e2μ)

Discriminant variables :

- $m_{4\ell}$, the four-lepton invariant mass
- D_{NN}, a signal–to-background discriminant
  input: 4ℓ p_T & η, trained separately for each final state
- σ_i the per-event resolution

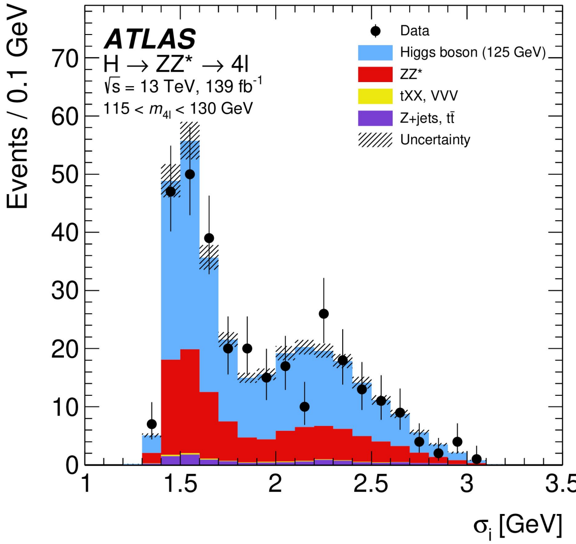


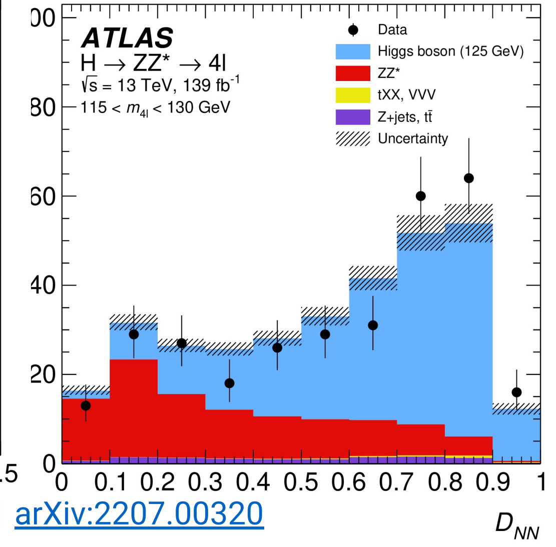
PDF for signal:

$$\mathcal{P}(m_{4\ell}, D_{NN}, \sigma_i | m_H) = \mathcal{P}(m_{4\ell}|D_{NN}, \sigma_i, m_H)\cdot\mathcal{P}(D_{NN}|\sigma_i, m_H)\cdot\mathcal{P}(\sigma_i|m_H)$$
$$\simeq \mathcal{P}(m_{4\ell}|D_{NN}, \sigma_i, m_H)\cdot\mathcal{P}(D_{NN}|m_H),$$

Dependence of D_{NN} and σ_i on m_H :
→ interpolated from fits to samples generated at various m_H

PDF for background: $P_b = P_b(m_{4\ell}, D_{NN})$
→ 2D probability density function using kernel estimation





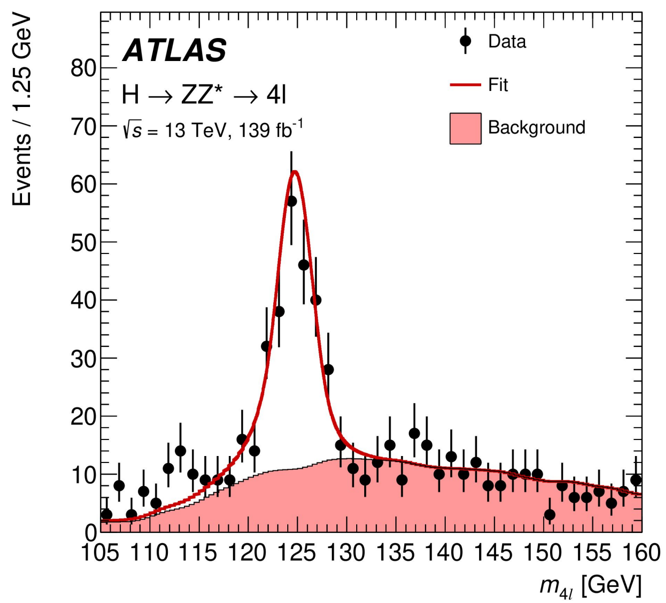
arXiv:2207.00320

Higgs mass (III)

Mass measurement in the H→ZZ*→4ℓ channel:
(139 fb^{-1}, full Run 2 data)

m_H = 124.99 ± 0.18 (stat.) ± 0.04 (syst.) GeV

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



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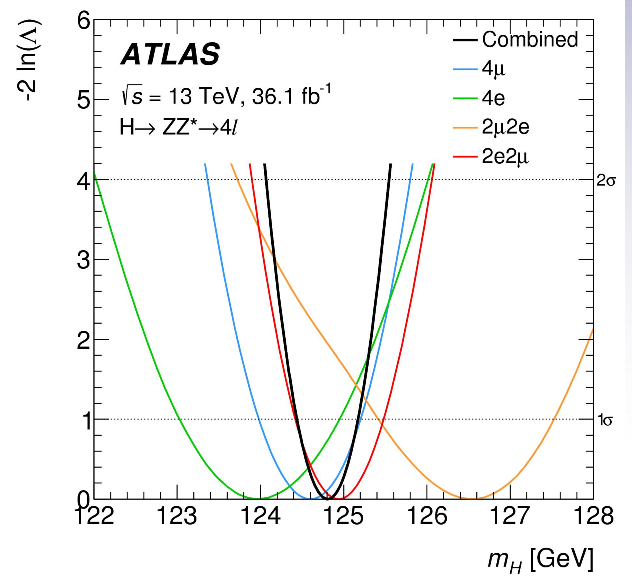


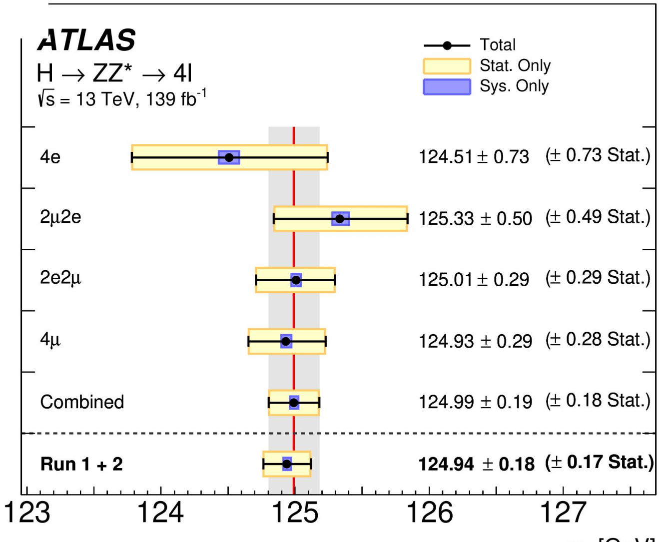
Most precise ATLAS measurement of m_H:
total uncertainty slightly below 1.5 per mille

Significantly improved muon p_T-scale uncertainty wrt previous published result

Result dominated by channels with sub-leading dimuons (4μ and 2e2μ)

Combining this measurement with the Run 1 ATLAS result gives :

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



arXiv:2207.00320

Higgs Width (I)

- SM prediction: $$\Gamma_{\mathrm{H}}^{\mathrm{SM}} = 4.1\ \mathrm{MeV}$$
  → makes it sensitive to non-SM contributions to the total width
  → too small for detector resolution of the LHC experiments

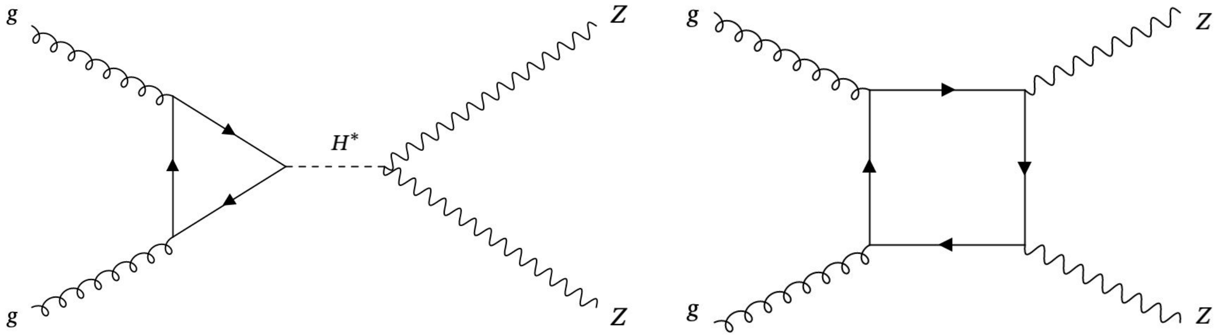
- access via the ratio of on-shell and off-shell Higgs production to extract Γ_{H}
  → exploits enhanced off-shell production, unique to H → VV
  → assumes no significant contributions from new physics below ~2 TeV

$$\sigma_{gg\to H\to VV}^{(\mathrm{onshell})} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_H \Gamma_H}$$

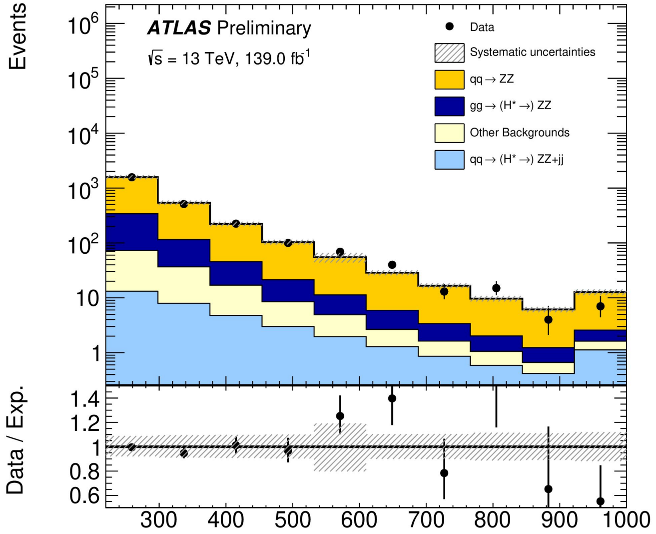
$$\sigma_{gg\to H^*\to VV}^{(\mathrm{offshell})} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_{ZZ}^2}$$

- the off-shell Higgs signal and gg → ZZ background cannot be distinguished
  → large, destructive interference effects

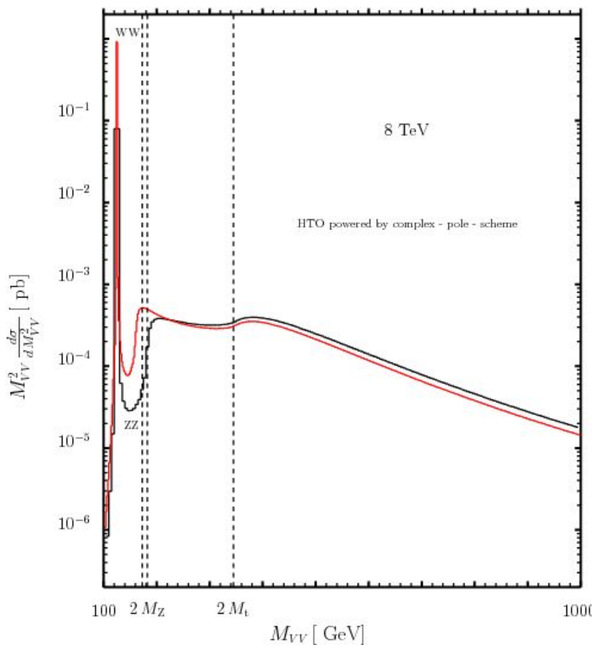
N. Kauer and G. Passarino, JHEP 08 (2012) 116



(a similar interference effect at play in EW production)



ATLAS-CONF-2022-068



Higgs Width (II)

- three signal regions in the analysis, targeting both ggF- and VBF- enriched selections
- the measurement is performed in two complementary channels:

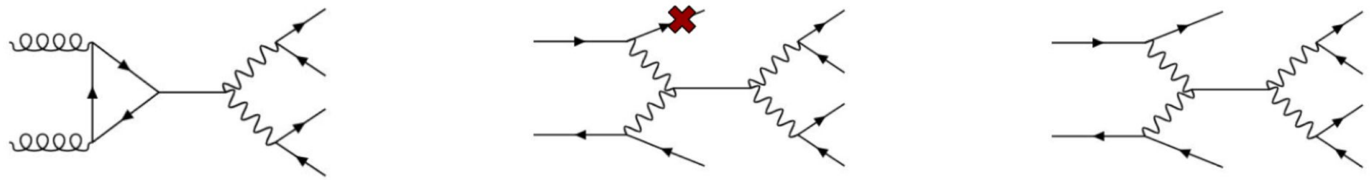
- $ZZ^* \to 4\ell$
  advantages:
    - clean signal
    - fully reconstructed

  observable:
    - neural net discriminant $O^{\mathrm{ggF}}_{\mathrm{NN}}$

- $ZZ^* \to 2\ell 2\nu$
  advantage:
    - six times higher branching ratio

  observable:
    - transverse ZZ mass m_{T}^{ZZ}

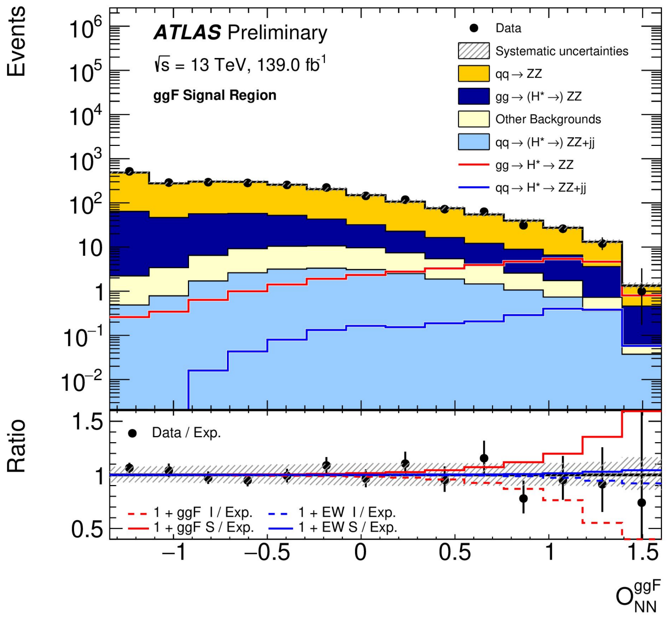
ggF Signal region | 1 jet mixed signal region | EW signal region

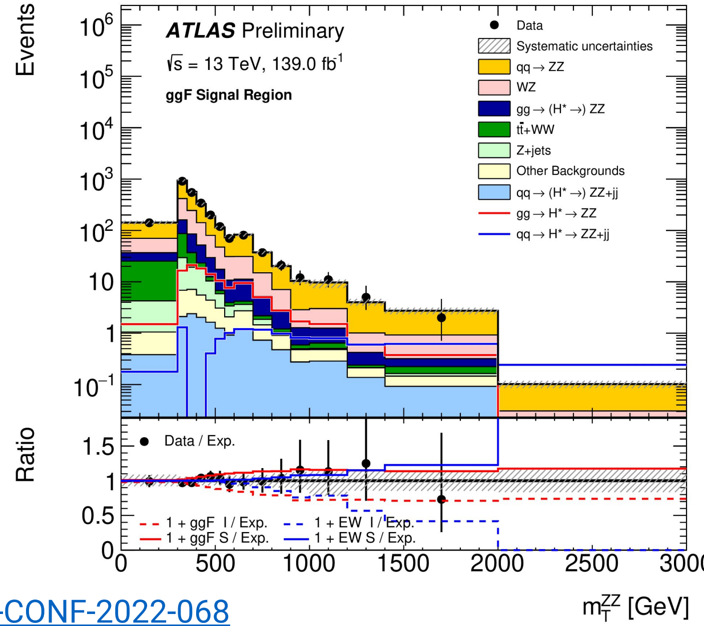


ggF Signal region:
$n_{\mathrm{jets}} = 0$
$n_{\mathrm{jets}} = 1 \text{ and } \eta_j < 2.2$
$n_{\mathrm{jets}} \geq 2 \text{ and } \Delta\eta_{jj} < 4.0$

1 jet mixed signal region: $n_{\mathrm{jets}} = 1 \text{ and } \eta_j \geq 2.2$

EW signal region: $n_{\mathrm{jets}} \geq 2 \text{ and } \Delta\eta_{jj} \geq 4.0$





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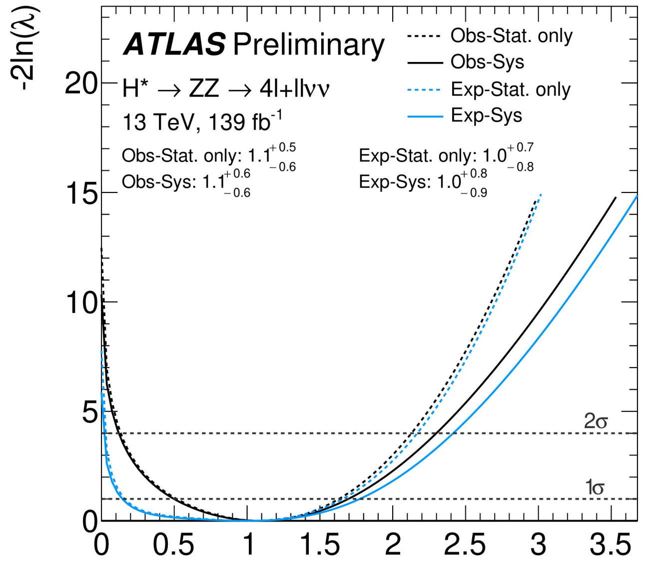
Higgs Width (III)

- Off-shell signal strength from a simultaneous fit to the six signal regions
- observed signal strength : $\mu_{(\text{offshell})} = 1.1^{+0.6}_{-0.6}$

  → background-only hypothesis rejected at 3.2σ observed (2.4σ expected)
- combination with the 4ℓ on-shell signal strength to find the Higgs boson total width : $\frac{\Gamma_H}{\Gamma_H^{SM}} = 1.1^{+0.6}_{-0.6}$
- i.e. in terms of the Higgs boson width $\Gamma_H = 4.6^{+2.6}_{-2.5}$ MeV

Results are preliminary (asymptotic confidence bands) but not expected to change significantly



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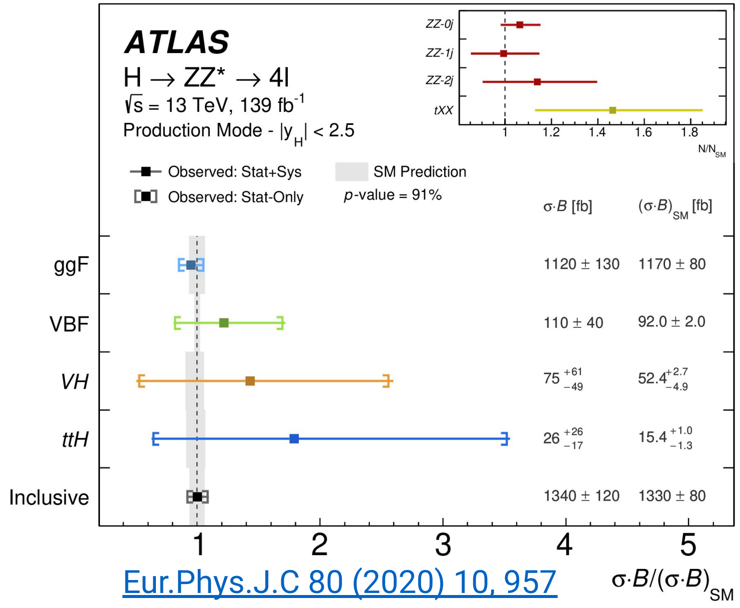
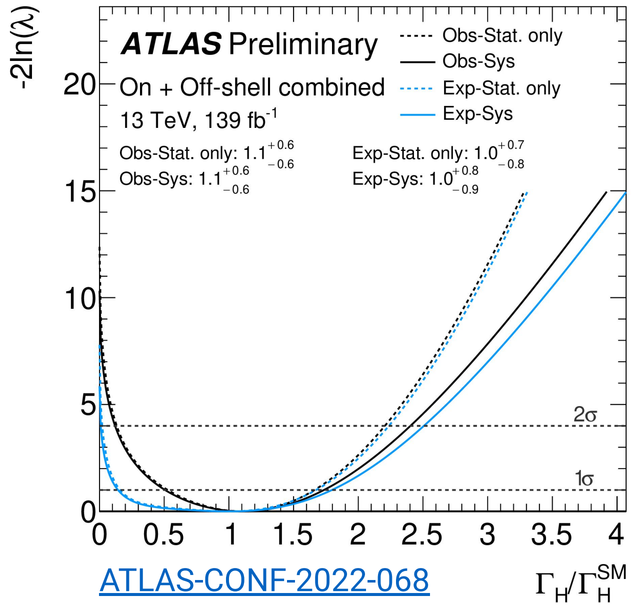


Eur.Phys.J.C 80 (2020) 10, 957



ATLAS-CONF-2022-068

Higgs spin and CP

- SM Higgs has spin 0 and positive (even) parity ($J^{CP} = 0^{++}$)
- legacy Run 1 result : spin 1 and 2 hypotheses excluded at > 99.9% CL using $H\rightarrow\gamma\gamma$, $H\rightarrow ZZ^*$, and $H\rightarrow WW^*$
- known sources of CP violation in the SM: complex phases in CKM quark and PMNS neutrino mixing matrices

  → SM CPV by itself insufficient to generate the observed matter-antimatter asymmetry in the Universe
  → clear motivation to study the CP properties on the Higgs boson

- strategy : measure shape (and rate) effects on CP-sensitive observables
  → specific studies for bosonic or fermionic couplings

- effect of CP-odd components on bosonic couplings:

$$\mathscr{L}_{\mathrm{VVH}} = \mathscr{L}_{\mathrm{VVH,SM}} + \frac{1}{\Lambda^2} cH\tilde{V}_{\mu\nu}V_{\mu\nu}$$

  → parametrized as expansion with higher order terms
  → suppressed by powers of scale of new physics Λ

- fermionic couplings are affected at tree level:

$$\mathscr{L}_{Y,f} = -\frac{m_f}{\langle v \rangle}\bar{\psi}_f\left(\kappa_f + i\gamma_5\tilde{\kappa}_f\right)H\psi_f$$

  → measure mixing angle between CP-even and CP-odd components
  → study the Higgs interactions with heavier fermions to benefit from their enhanced coupling

Higgs HVV coupling in VBF (I)

- study of bosonic couplings using VBF $H\to\gamma\gamma$

- effective HVV Lagrangian augmented with dimension six CP-odd operators
- strength of CP violation in VBF matrix element via a single parameter:

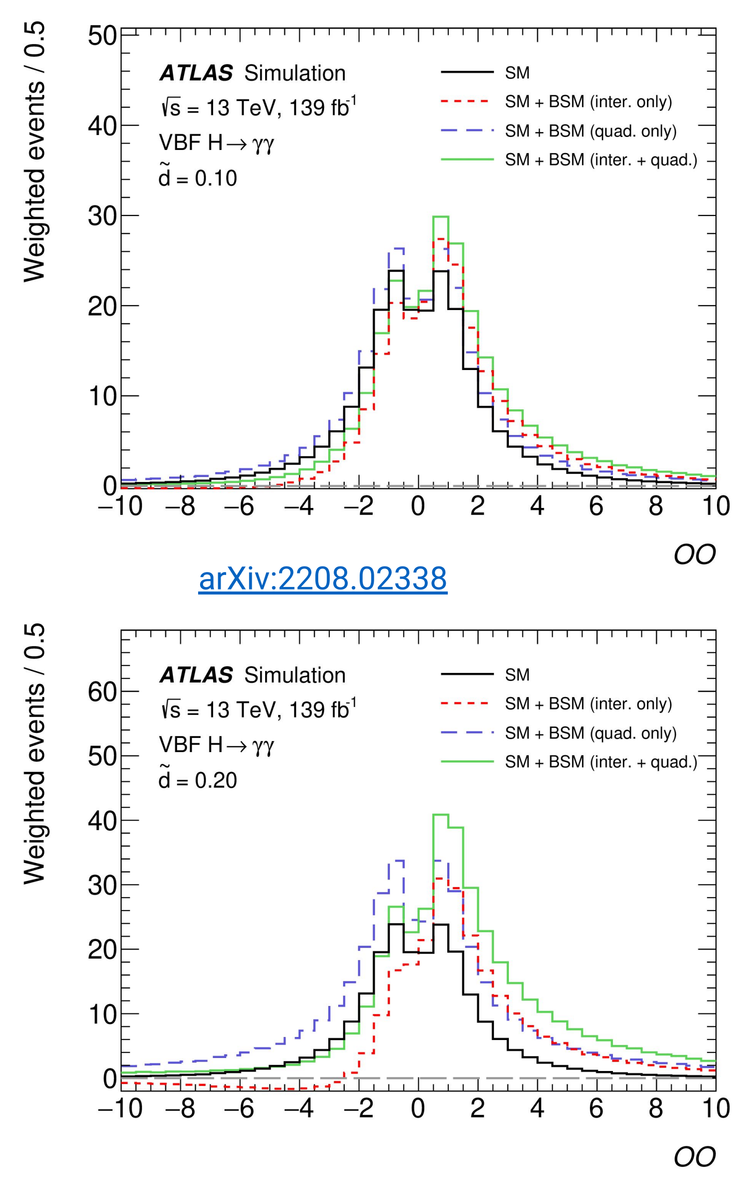
$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\tilde{d}\,\Re\left(\mathcal{M}_{SM}^{*}\mathcal{M}_{CP-odd}\right) + \tilde{d}^2|\mathcal{M}_{CP-odd}|^2$$

(more precisely: $\tilde{d}$ parameter for HISZ basis, $c_{H\tilde{W}}$ for SMEFT Warsaw basis)

- calculate LO matrix elements using 4-momenta of Higgs and VBF jets
- derive initial-state parton momentum fractions from jet momenta
- use the Optimal Observable OO:

$$OO = \frac{2\Re e\left(\mathcal{M}_{SM}^{*}\mathcal{M}_{CP-odd}\right)}{|\mathcal{M}_{SM}|^2}$$

→ no-CP violation scenario : OO symmetric
→ increasingly CP strength : larger OO asymmetry and non-zero mean value



arXiv:2208.02338

Higgs HVV coupling in VBF (II)

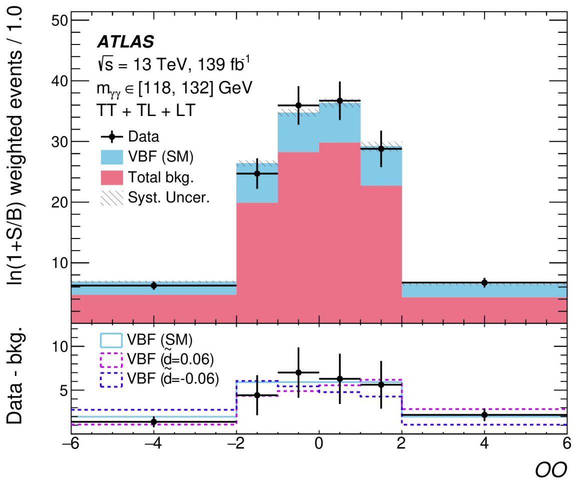
- select events with ≥2 photons and ≥2 tag jets , maximise signal purity using 2 BDTs:

  → BDT(VBF/ggF): separate VBF signal from gluon-fusion Higgs production
  → BDT(VBF/Continuum): separate VBF signal from continuum diphoton background

- split into signal regions using BDT output: Tight-Tight (TT); Loose-Tight (LT); Tight-Loose (TL)

- pure shape analysis – signal normalisation is left floating in the fit to depend only on interference term

→ follows standard ATLAS $H \to \gamma\gamma$ analysis strategies
→ unbinned likelihood fits
→ background analytical function
selected to minimize *spurious signal*



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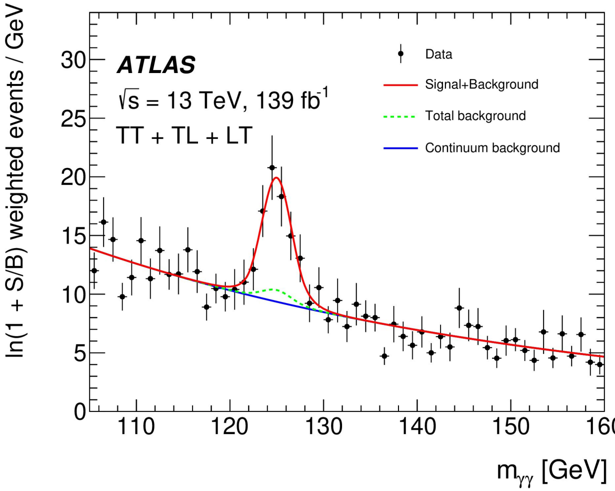

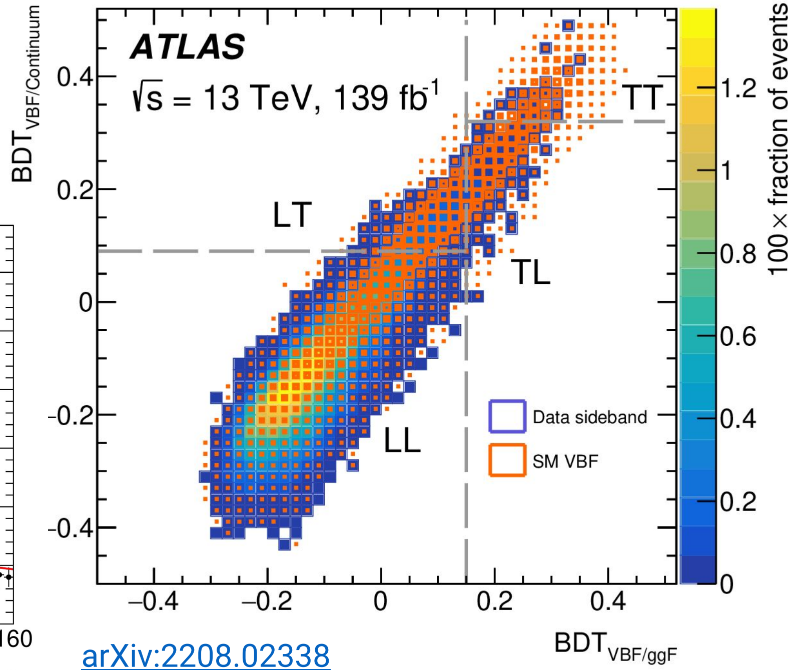

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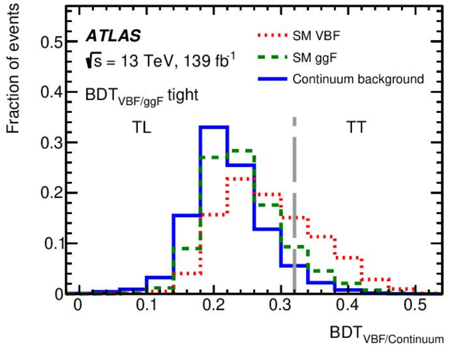
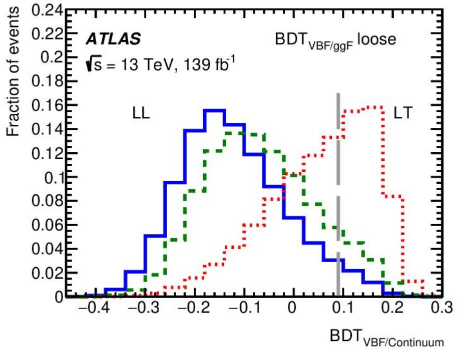


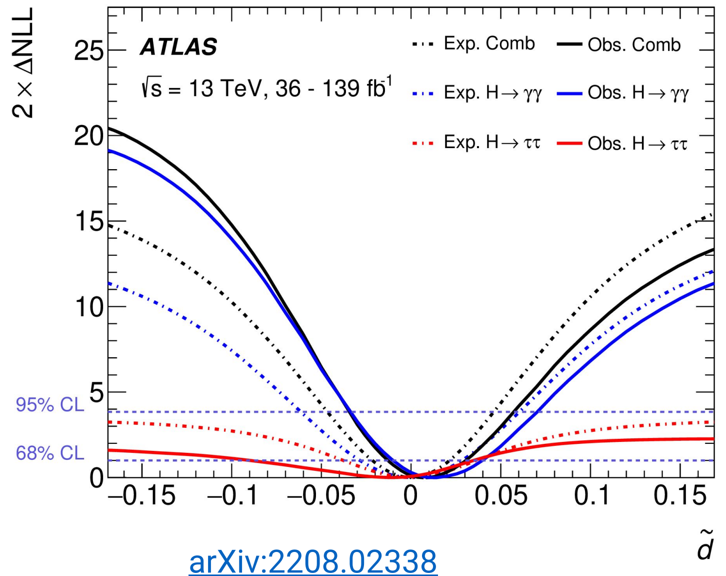


Higgs HVV coupling in VBF (III)

- baseline interpretation of the result using the HISZ EFT operator basis (further tightened through combination with results from the $H \to \tau\tau$ channel)
- results using the Warsaw basis also extracted (for future combinations)
- sensitivity essentially driven by the interference term
  - no change in results from the quadratic term
- results are the strongest existing bounds on CP violation in HVV

Table 1: Observed and expected 68% and 95% confidence intervals for $\tilde{d}$ and $c_{H\tilde{W}}$. Results for scenarios with the interference-only (noted as 'inter. only') term and interference-plus-quadratic terms (noted as 'inter.+quad.') are both presented. Combined results for $\tilde{d}$ including the $H \to \tau\tau$ analysis are shown. The expected results of $H \to \tau\tau$ are slightly different from Ref. due to the different correlation scheme between their signal region and control region.

	68% (exp.)	95% (exp.)	68% (obs.)	95% (obs.)
$\tilde{d}$ (inter. only)	[−0.027, 0.027]	[−0.055, 0.055]	[−0.011, 0.036]	[−0.032, 0.059]
$\tilde{d}$ (inter.+quad.)	[−0.028, 0.028]	[−0.061, 0.060]	[−0.010, 0.040]	[−0.034, 0.071]
$\tilde{d}$ from $H \to \tau\tau$	[−0.038, 0.036]	–	[−0.090, 0.035]	-
Combined $\tilde{d}$	[−0.022, 0.021]	[−0.046, 0.045]	[−0.012, 0.030]	[−0.034, 0.057]
$c_{H\tilde{W}}$ (inter. only)	[−0.48, 0.48]	[−0.94, 0.94]	[−0.16, 0.64]	[−0.53, 1.02]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.48, 0.48]	[−0.95, 0.95]	[−0.15, 0.67]	[−0.55, 1.07]



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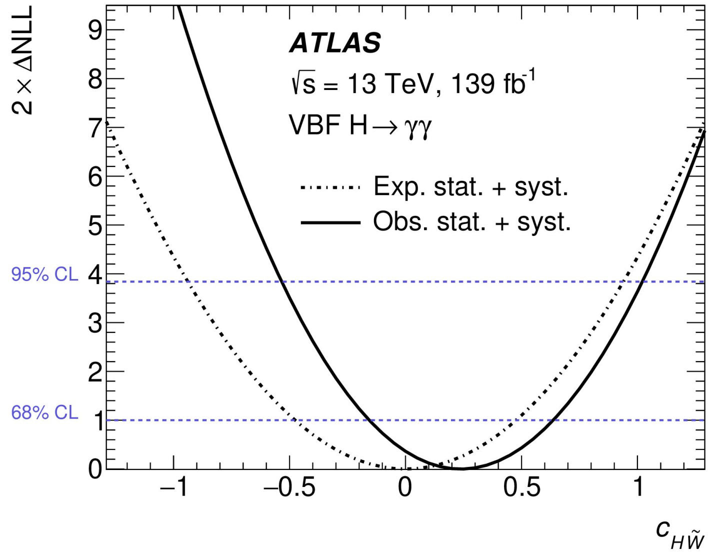


Higgs Yukawa couplings

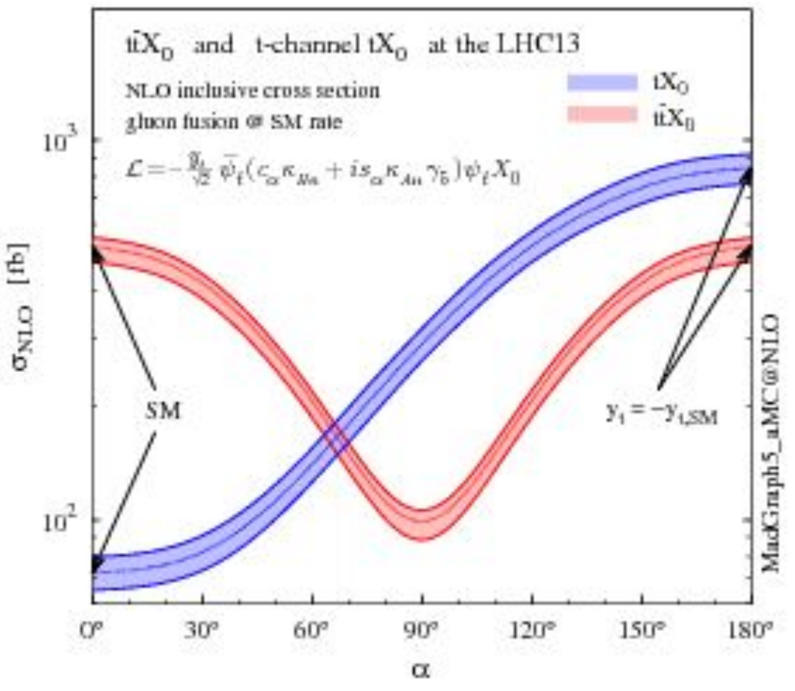
- Higgs Yukawa couplings generically decomposed into CP-even (κ_f) and CP-odd ($\tilde{\kappa}_f$) contributions:

$$\mathscr{L}_{Y,f} = -\frac{m_f}{\langle v \rangle} \bar{\psi}_f \left(\kappa_f + i\gamma_5 \tilde{\kappa}_f \right) H \psi_f$$

- fraction of CP violation in these Yukawa interactions parameterised by a CP mixing angle α

$$f_{CP}^{Hff} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2} = \sin^2\alpha$$

F. Demartin, F. Maltoni, K. Mawatari and M. Zaro, Eur.Phys.J.C 75 (2015) 6, 267



- CP violation in Yukawa interactions probed via top quarks and tau leptons

→ $H \to \tau^+\tau^-$:
sensitivity to the CP mixing angle *α* probed through angular/spin correlations

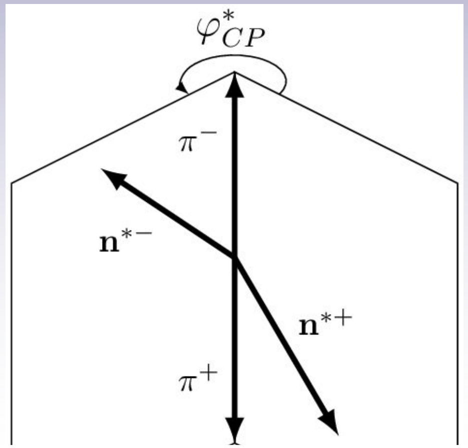
→ Higgs-top:
access via ttH and tH production using both rates and CP-sensitive observables

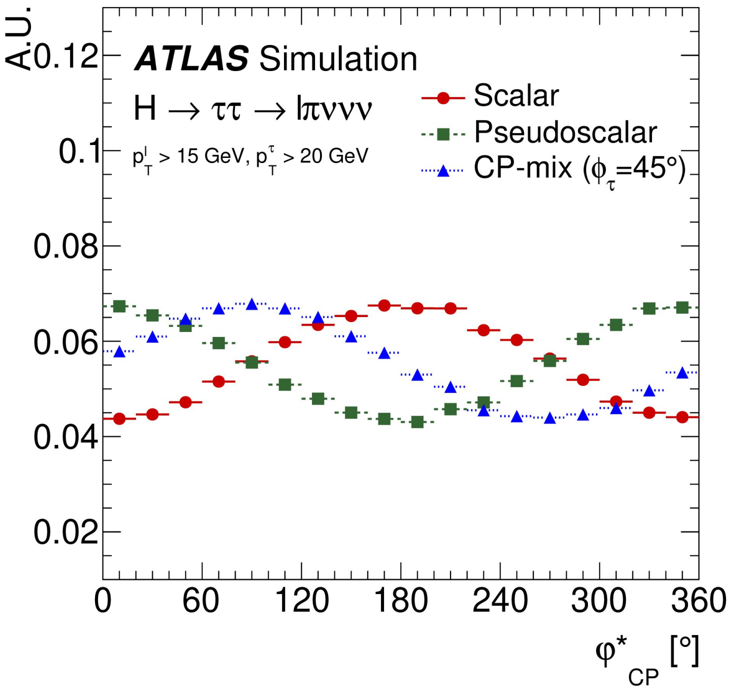
Higgs CP with H→τ⁺τ⁻ (I)

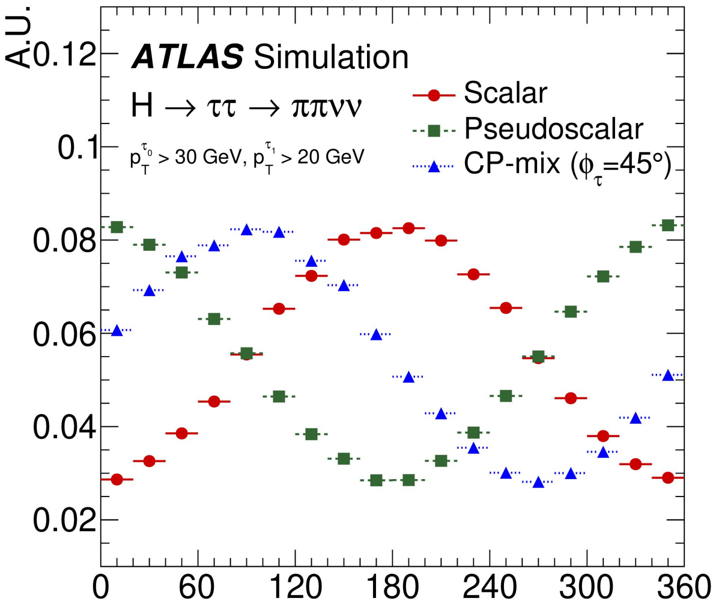
Sensitivity to CPV from measurement of angle between τ lepton decay planes: φ_{CP}
→ using φ* as proxy (due to neutrinos)

Measurement performed in 24 signal categories and 10 control regions
→ targeting different decay modes

Decay plane reconstruction using either IP or " ρ plane" methods (decays with/without π^0)







arXiv:2212.05833

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%)

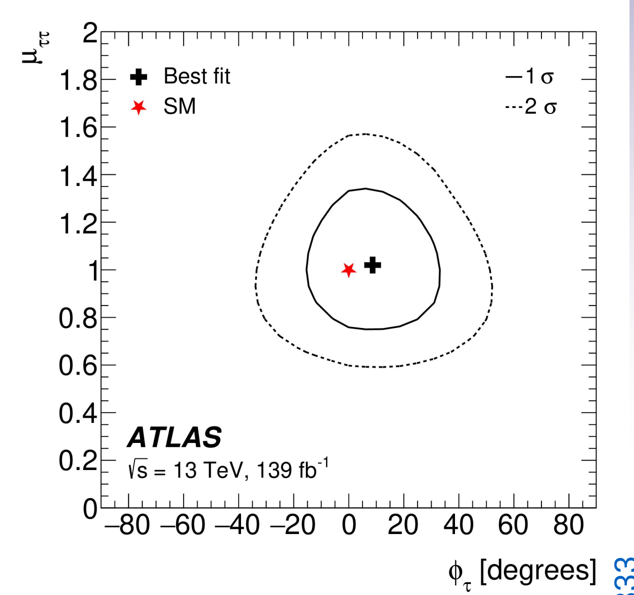
Decay channel	Decay mode combination	Method	Fraction in all τ-lepton-pair decays
$\tau_{lep}\tau_{had}$	ℓ–1p0n	IP	8.1%
	ℓ–1p1n	IP–ρ	18.3%
	ℓ–1pXn	IP–ρ	7.6%
	ℓ–3p0n	IP–a_1	6.9%
$\tau_{had}\tau_{had}$	1p0n–1p0n	IP	1.3%
	1p0n–1p1n	IP–ρ	6.0%
	1p1n–1p1n	ρ	6.7%
	1p0n–1pXn	IP–ρ	2.5%
	1p1n–1pXn	ρ	5.6%
	1p1n–3p0n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

Higgs CP with $H\to\tau^+\tau^-$ (II)

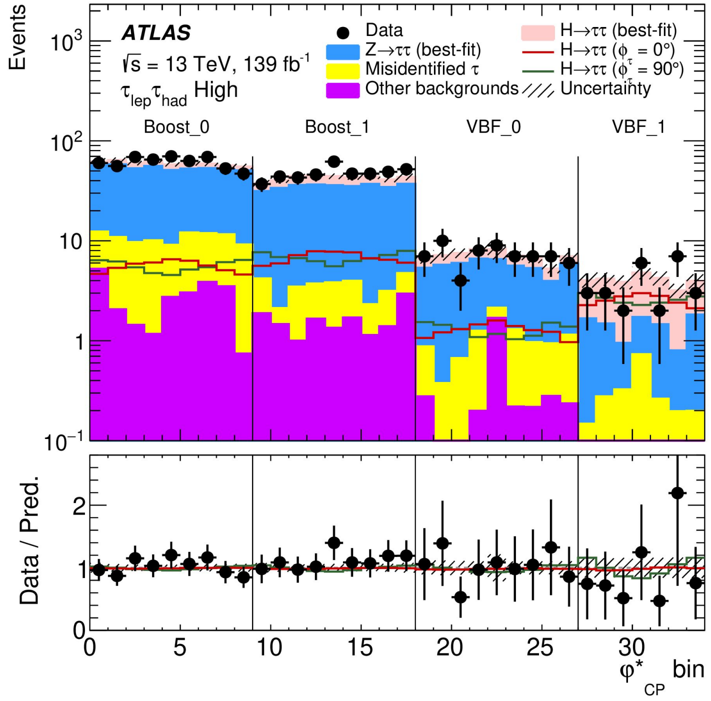
- CP mixing angle extracted from a simultaneous fit to all regions
  → exploits shape only information : signal strength floated
- dominant background ($Z\to\tau^+\tau^-$) from dedicated control regions
- results statistically limited
  → leading systematic uncertainty from jet calibration

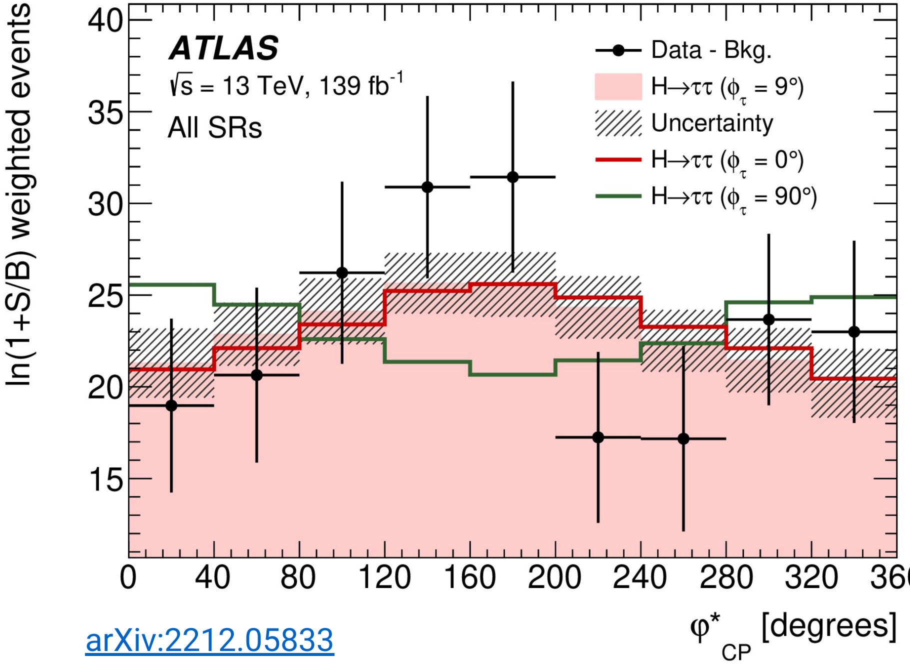
- best fit value for φ_τ = 9 ± 16 degrees at 1σ (compatible with SM)

  → pure CP-odd hypothesis (φ_τ = 90 degrees) excluded at 3.4 σ



arXiv:2212.05833





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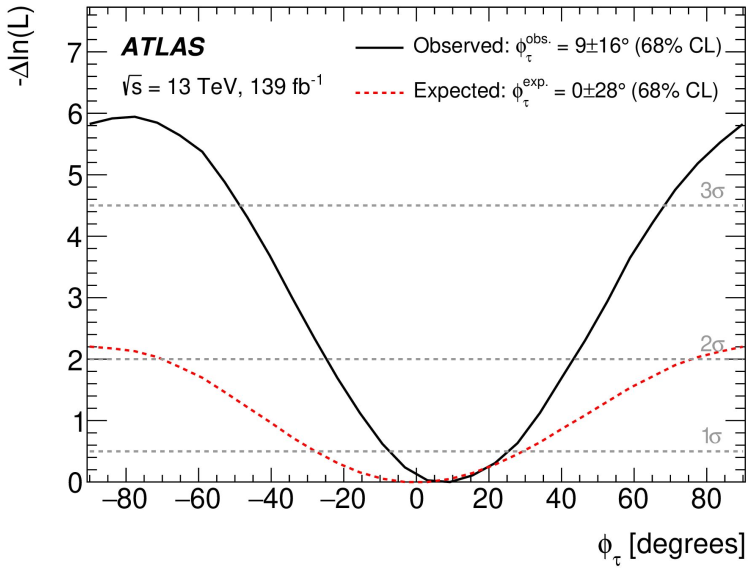


CP measurements in $t\bar{t}H/tH$ ($H\to b\bar{b}$) (I)

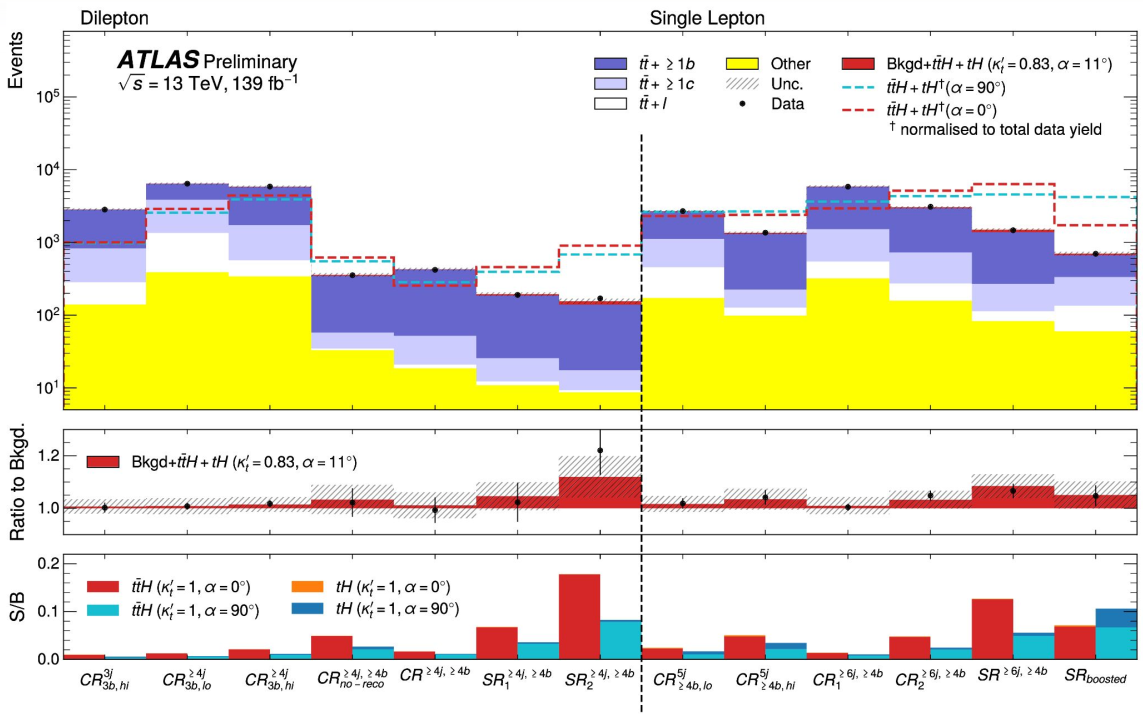
- explore CP violation in Higgs-top coupling CP using $t\bar{t}H$ and tH production
  → tWH and tHjb considered as signal
- analysis strategy: event categorisation:
  → step I: control (CR) and preliminary signal regions (PSR) defined
  → step II: classification BDT ($t\bar{t}H$ vs tt+jets) used to define final SR ($t\bar{t}H$-enrich region) from PSRs
- CP sensitive observables used in PSRs
  → exploit angular and kinematic differences in events caused by CP effects

Channel (PSR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton (PSR$^{\geq 4j,\geq 4b}$)	$\mathrm{CR}^{\geq 4j,\geq 4b}_{\text{no-reco}}$	–	$\Delta\eta_{\ell\ell}$
	$\mathrm{CR}^{\geq 4j,\geq 4b}$	BDT∈ [−1, −0.086)	b_4
	$\mathrm{SR}^{\geq 4j,\geq 4b}_1$	BDT∈ [−0.086, 0.186)	b_4
	$\mathrm{SR}^{\geq 4j,\geq 4b}_2$	BDT∈ [0.186, 1]	b_4
ℓ+jets (PSR$^{\geq 6j,\geq 4b}$)	$\mathrm{CR}^{\geq 6j,\geq 4b}_1$	BDT∈ [−1, −0.128)	b_2
	$\mathrm{CR}^{\geq 6j,\geq 4b}_2$	BDT∈ [−0.128, 0.249)	b_2
	$\mathrm{SR}^{\geq 6j,\geq 4b}$	BDT∈ [0.249, 1]	b_2
ℓ+jets (PSR$_{\text{boosted}}$)	SR$_{\text{boosted}}$	BDT∈ [−0.05, 1]	Classification BDT score

- sensitivity to α and κ_t from CP- sensitive observables:

$$b_2 = \frac{(\vec{p}_1 \times \hat{n}) \cdot (\vec{p}_2 \times \hat{n})}{|\vec{p}_1||\vec{p}_2|}, \quad \text{and} \quad b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|}$$

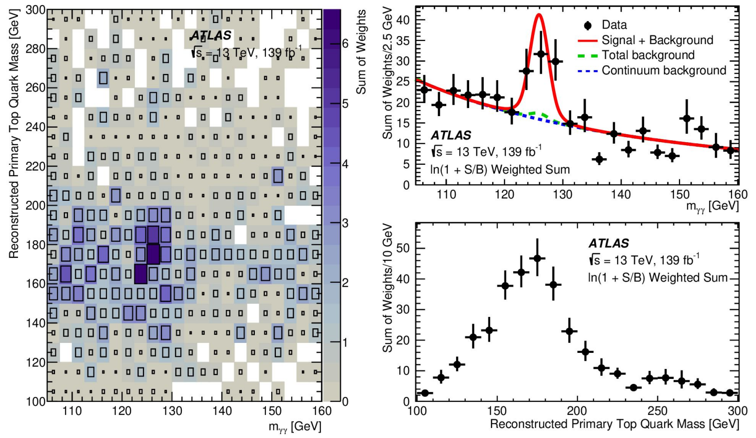
(and a BDT for the SR$_{\text{boosted}}$ region)



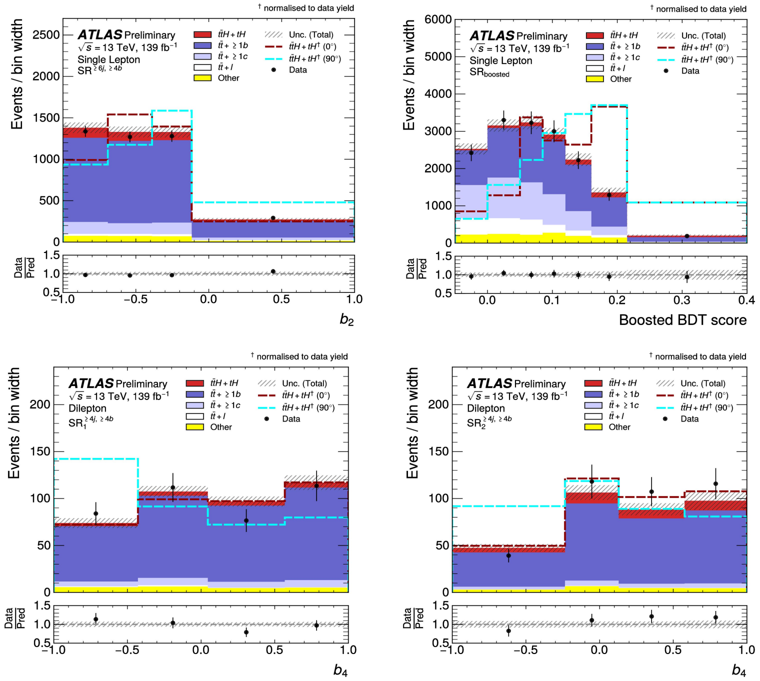
ATLAS-CONF-2022-016

CP measurements in $t\bar{t}H/tH$ ($H \to b\bar{b}$) (II)

- CP mixing angle α and coupling strength extracted from a profile likelihood fit
  → uncertainty on the mixing angle dominated by $t\bar{t}$+≥1b modelling
- CP-even scenario : $$\alpha = \left(11^{+56}_{-77}\right)^{\circ}, \; \kappa_t' = \left(0.83^{+0.30}_{-0.46}\right)$$
  → pure CP-odd scenario disfavoured at 1.2 σ
- this result is complementary and compatible to previous $t\bar{t}H(H \to \gamma\gamma)$ analysis
  → allows for a future combined result



Phys. Rev. Lett. 125 (2020) 061802



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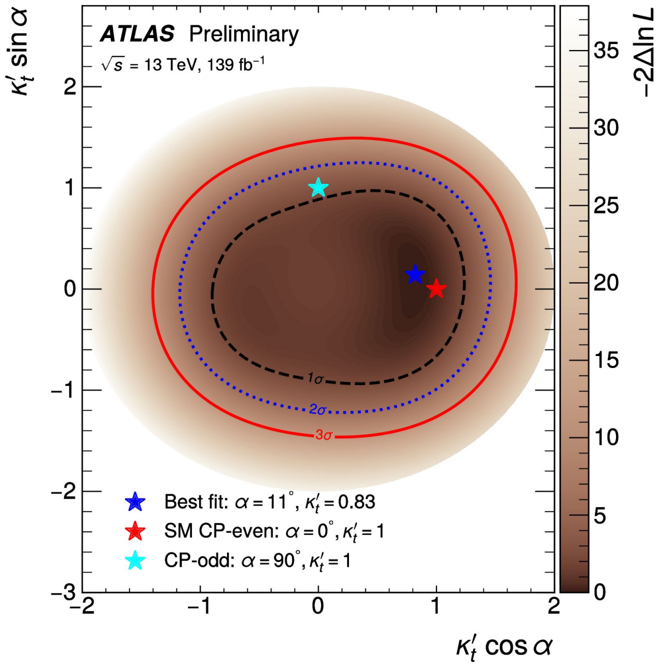

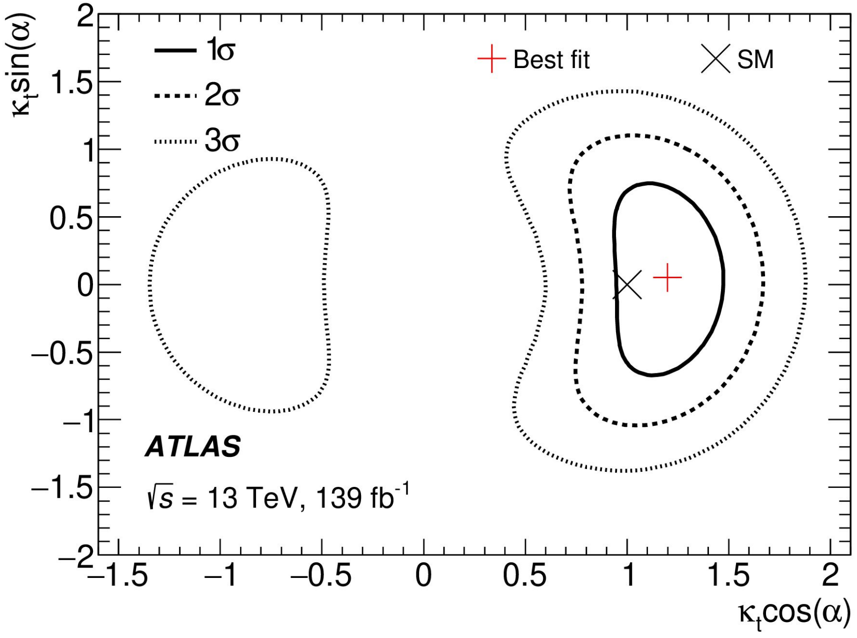

Conclusions

On the Higgs boson mass:

- important effort to calibrate leptons in Run 2 → impressive reduction of systematic uncertainties in $H \to ZZ^* \to 4\ell$
- the statistical uncertainty remains dominant (as in Run 1)
- will further improve with combination with $H \to \gamma\gamma$ using full Run 2 dataset
    - ongoing effort towards the final Run 2 photon calibration
- improvements in calibration remain motivated by needs in other physics studies
    - i.e. search for new, narrow resonances

On the Higgs boson width:

- room for improvements in the systematic uncertainties (i.e. on background)
- off-shell yields are still limited by statistics
- still room for new physics contributions to the total Higgs width Γ

Search for CP violation in the Higgs sector is very active

- analyses are probing anomalous contributions in fermionic and boson couplings
- measurements in several decay channels accessing CPV effects both in production and decay
- all current limits are compatible with SM predictions
- some CP-odd couplings are excluded at ≥ 3σ (by combinations of multiple measurements)
- as a general rule, constraints are statistically limited

Stay tuned for more Run-2 measurements and combination and for Run-3!