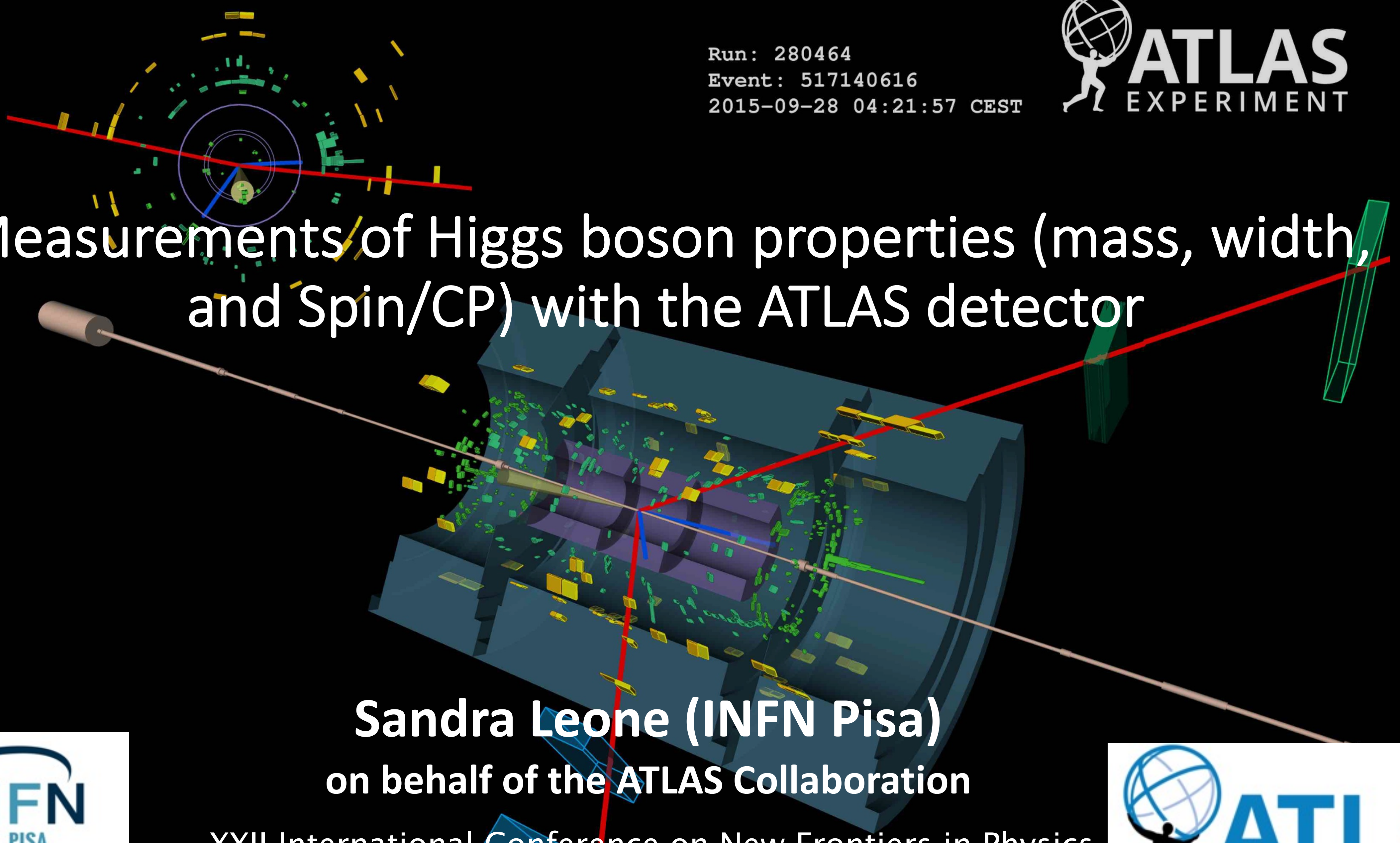
Measurements of Higgs boson properties (mass, width, and Spin/CP) with the ATLAS detector



Sandra Leone (INFN Pisa)

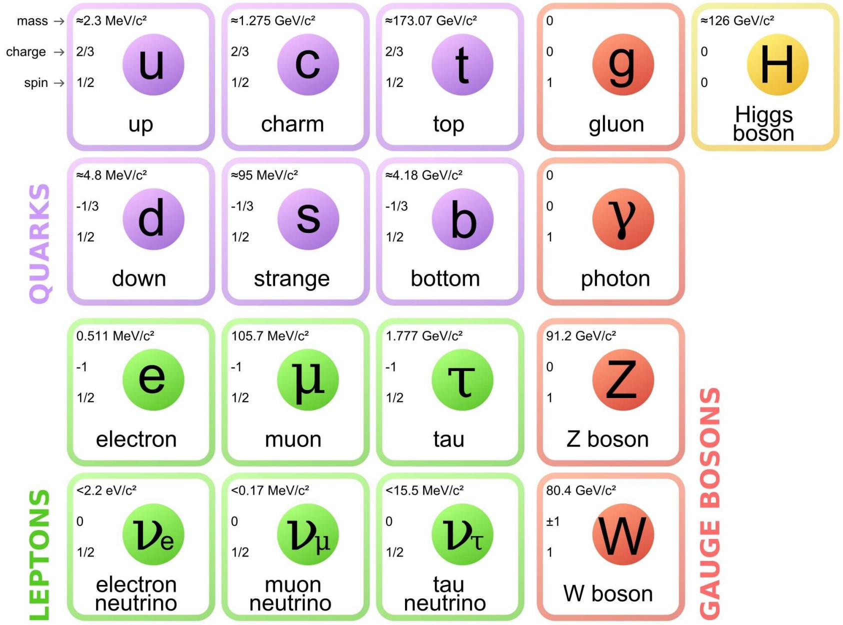
on behalf of the ATLAS Collaboration

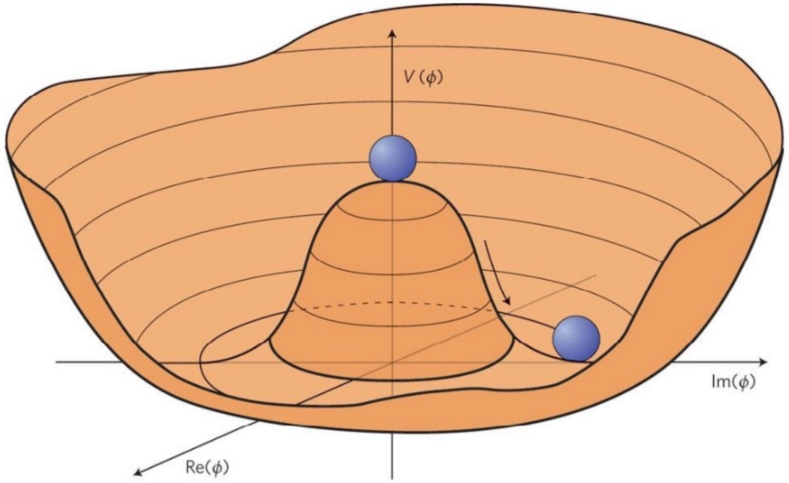
XXII International Conference on New Frontiers in Physics (ICNFP 2023) July 10-23, 2023

The Higgs boson in the Standard Model (SM) of particle physics

- The Higgs boson plays a unique role in the SM giving masses to other particles via the EW spontaneous symmetry breaking
- The discovery of the Higgs boson was announced in 2012 by ATLAS and CMS
- Since then, the Higgs boson has been scrutinized at the LHC to precisely determine its properties

  → The observation of any deviation could imply new physics
- In this talk the latest ATLAS measurements are presented, using the full dataset from LHC Run-2 at 13 TeV (139 fb^{-1}) , about Higgs:
  - Mass
  - Width
  - Spin/CP structure





- More Higgs ATLAS results at this conference:
- **David Reikher** (Higgs boson production and decay rates)
- **Daariimaa Battulga** (Higgs boson pairs)

Higgs boson mass measurement

- The Higgs boson mass is a free parameter in the SM
- It determines the strength of interaction with other SM particles
- $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ are the most sensitive channels:
  - Clear signature final states
  - High mass resolution 1-2 %
  - Main uncertainties: Electron/photon energy scale and muon momentum scale
- The combined ATLAS and CMS measurement with Run-I data is:

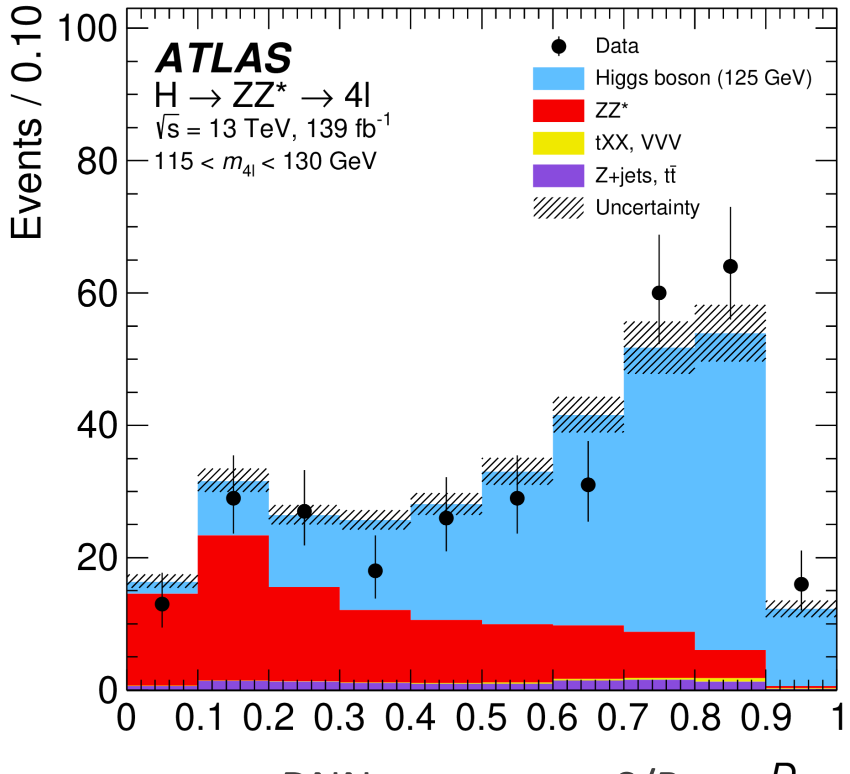
$m_H = 125.09 \pm 0.24\ [\pm 0.21\ (\text{stat.}) \pm 0.11\ (\text{syst.})]$ GeV Phys. Rev. Lett. 114 (2015)

Statistical uncertainty is dominant

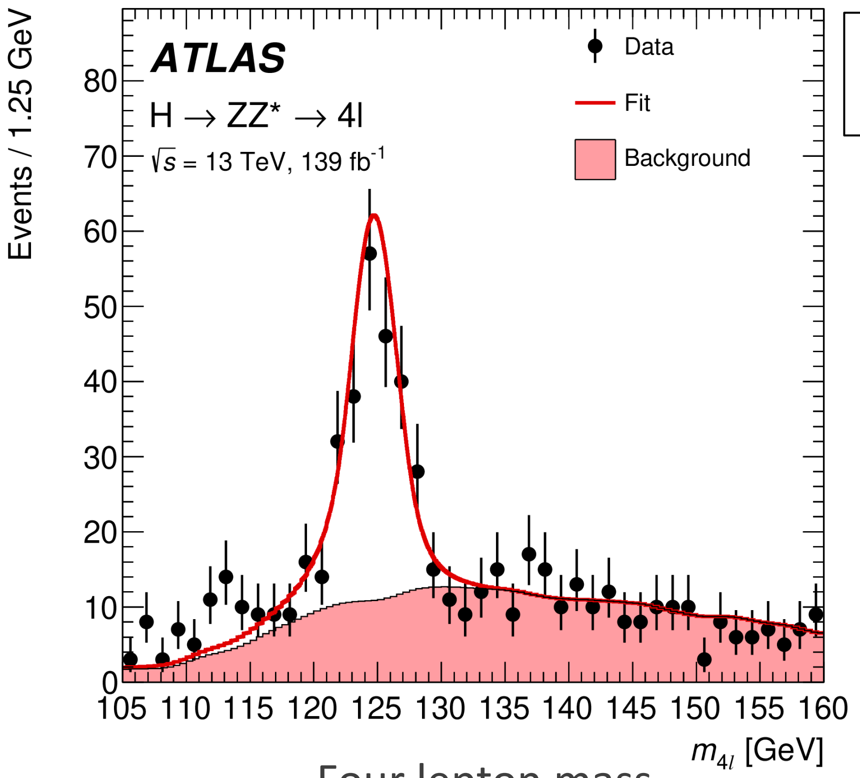
Higgs boson mass measurement ($H \to ZZ^* \to 4\ell$)

Phys. Lett. B 843 (2023) 137880

- Analysis performed in 4 final states: 4μ, 4e, 2μ2e, 2e2μ (primary pair is the closest to m_Z).
- Deep Neural Network (DNN) used to separate signal from main non-resonant $ZZ^* \to 4\ell$ background
- 2 observables are used in the fit: $m_{4\ell}$, DNN.
- Unbinned fit to the data with event-by-event $m_{4\ell}$ resolution estimates (QRNN* trained on MC).

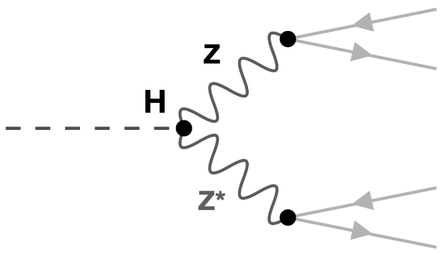


DNN to separate S/B



Four lepton mass

*Quantile Regression Neural Network

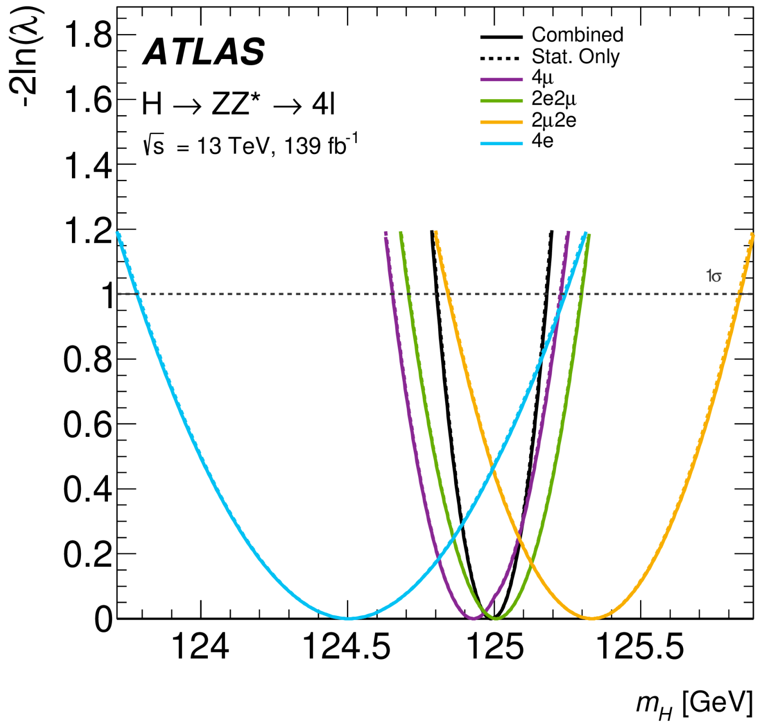


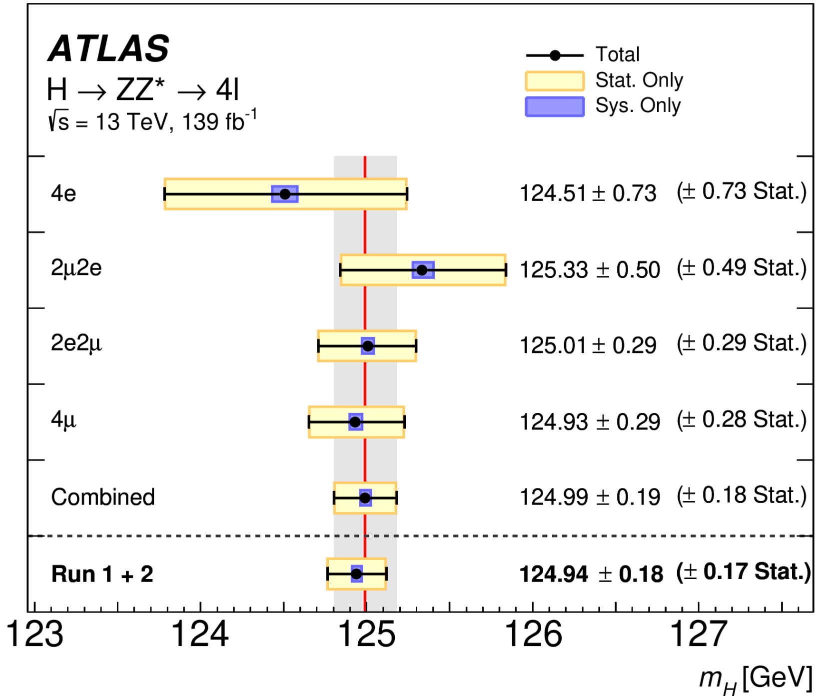
Higgs boson mass measurement ($H \to ZZ^* \to 4\ell$)

Phys. Lett. B 843 (2023) 137880

Systematics under control → uncertainties related to muon and electron reconstruction ~ O(10-20) MeV

-2ln(λ) values as a function of m_H





Combination of 7, 8 and 13 TeV data sets:

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

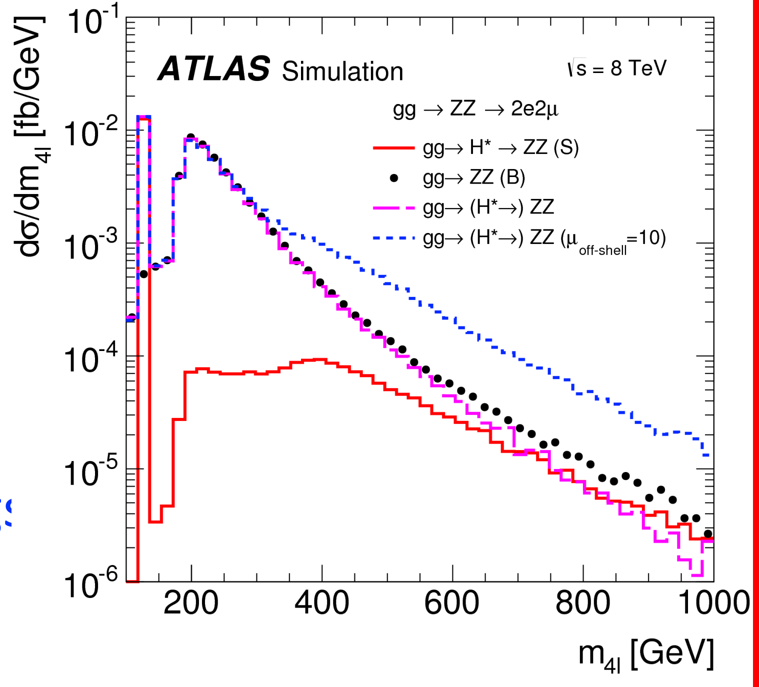
Still dominated by statistical uncertainty:
→ will improve with more data

Further improvement expected with addition of H→γγ analysis

Higgs boson width measurement

- Higgs boson width is predicted by SM (~4.1 MeV @ 125 GeV)
  - ✓ Much smaller than experimental resolution O(1 GeV)
  - → Impossible to be directly measured from signal shape
- Can be indirectly extracted from the ratio of on-shell and off-shell signal strengths, exploiting the relationship between Higgs coupling constants:

$$\sigma^{\mathrm{on-shell}}_{pp\to H\to VV^*} \sim \frac{g^2_{\mathrm{gluon}} g^2_V}{m_H \Gamma_H} \qquad \sigma^{\mathrm{off-shell}}_{pp\to H^*\to VV} \sim \frac{g^2_{\mathrm{gluon}} g^2_V}{m^2_{VV}}$$



Eur. Phys. J. C (2015) 75:335

- ✓ assuming same strength of the on-shell and off-shell effective couplings we can obtain Γ_H from the ratio of the rates in the two regimes :

$$\Longrightarrow \quad \frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}} = \frac{\mu_{\mathrm{off-shell}}}{\mu_{\mathrm{on-shell}}}$$

- ✓ Destructive interference with continuum gg/VV→VV production in the off-shell region
  → *a negative impact for total yield*

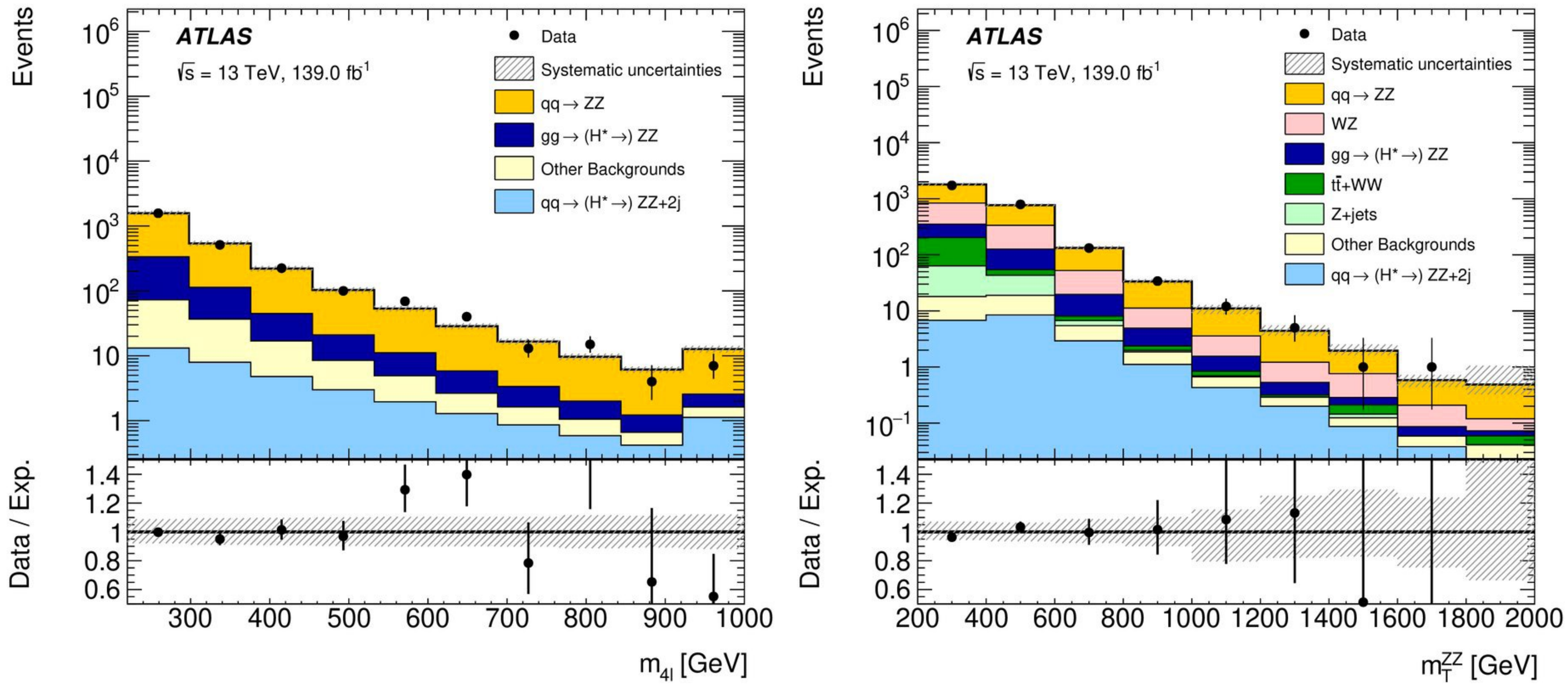
Higgs boson width measurement ($H \rightarrow ZZ^* \rightarrow 4\ell/2\ell 2\nu$)

arXiv:2304.01532 (Sub. to PLB)

- Analysis Performed in $H \rightarrow ZZ \rightarrow 4\ell/2\ell 2\nu$ channels
  - ✓ 4ℓ final state: the discriminator is the output of neural network (O_{NN}) used to separate signal from backg.
  - ✓ $2\ell 2\nu$ final state: the discriminator is the transverse mass of the ZZ system: M_T^{ZZ}
- Three Signal Regions are defined for each channel:
  - ✓ggF, Mixed, EW (VBF)

Uncertainty from modelling of signal and backgrounds is the dominant systematic

4ℓ channel: $m_{4\ell}$ — $2\ell 2\nu$ channel: M_T^{ZZ}

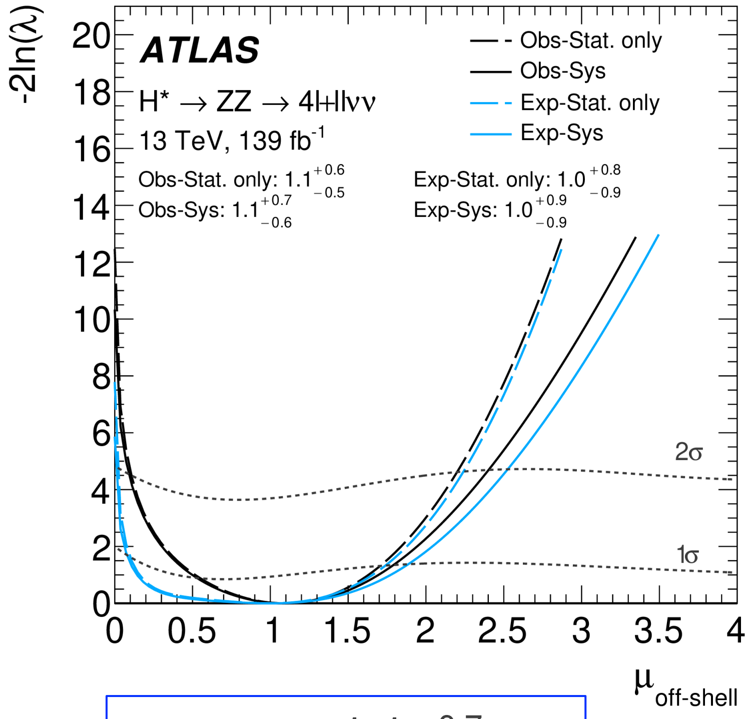


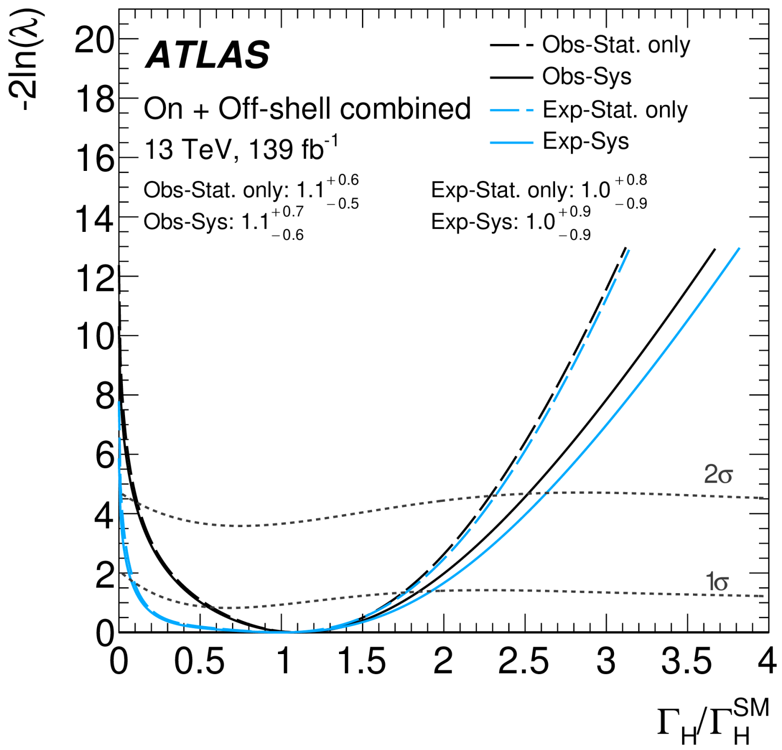
Comparisons between data and SM prediction for the inclusive SR of the two channels

Higgs boson width measurement ($H \to ZZ^* \to 4\ell/2\ell 2\nu$)

arXiv:2304.01532 (Sub. to PLB)

- $2\ln\lambda$, as a function of the off-shell Higgs signal strength, for the combination of the $ZZ\to 4\ell$ and $ZZ\to 2\ell 2\nu$ off-shell analyses





$\mu_{off-shell} = 1.1\ ^{+0.7}_{-0.6}$

$\Gamma_H/\Gamma_{SM} = 1.1\ ^{+0.7}_{-0.6}$ $\Gamma_{SM} = 4.1\ ^{+3.2}_{-3.5}$ MeV

Background-only hypothesis ($\mu_{off-shell} = 0$) rejected with 3.3σ (2.2σ) observed (expected) significance.

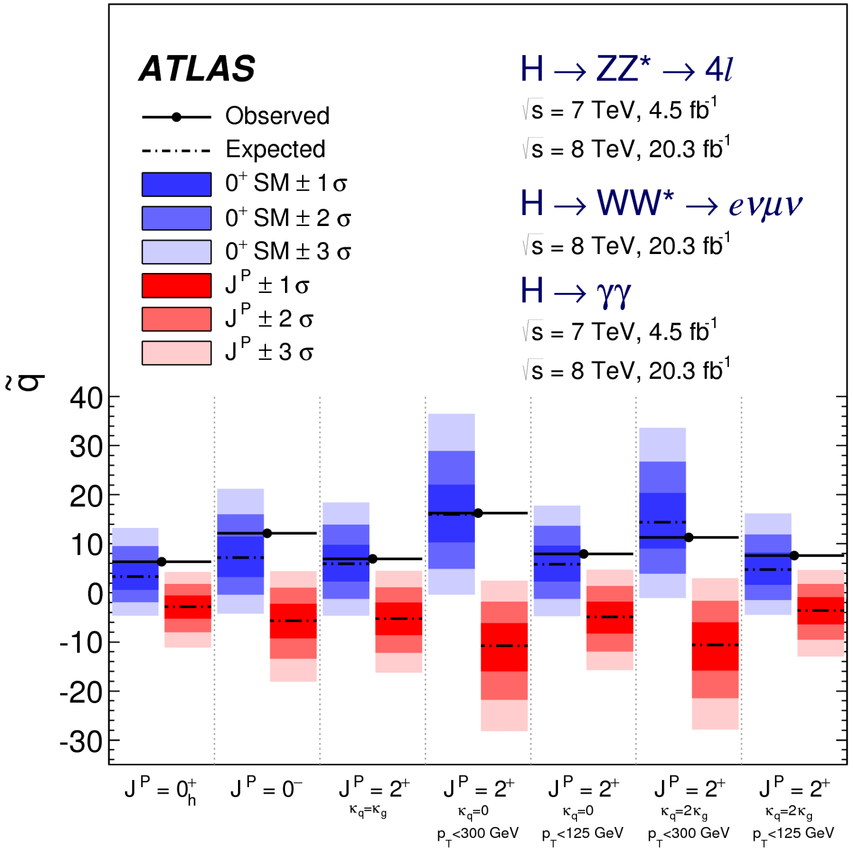
$\Gamma_H = 4.5\ ^{+3.3}_{-2.5}$ MeV

$\mu_{on-shell} = 1.01 \pm 0.11$ from Eur. Phys. J. C 80 (2020) 957

Observed (expected) 95% CL limits:
$0.5\ (0.1) < \Gamma_H < 10.5\ (10.9)$ MeV

Higgs boson CP and anomalous coupling

- The Higgs boson couplings have been measured by ATLAS and CMS
  - → agree with the SM predictions
- In the SM, the Higgs is predicted to be **spin 0 and CP-even:** $J^{CP}=0^{++}$
- Pure CP-odd states already excluded from its observed decays
- Here I'll focus on searches for mixture of CP-even / CP-odd in the Higgs couplings (still allowed):
  - → Could represent a new source of CP violation
- Use of observables optimized to discriminate different CP hypothesis:
  - → Rate cannot disentangle anomalous CP-even or CP-odd effects, while observable shape does



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HVV anomalous coupling and CP structure

- SMEFT introduces CP-odd HVV couplings: $\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$ → 3 independent dim-6 operators, for CP-odd

$$\mathcal{M}_{\text{Mix}}(\boldsymbol{c}) = \mathcal{M}_{\text{SM}} + \mathcal{M}_{\text{BSM}}(\boldsymbol{c})$$
$$\Longrightarrow |\mathcal{M}_{\text{Mix}}(\boldsymbol{c})|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2\Re(\mathcal{M}_{\text{SM}}\mathcal{M}^*_{\text{BSM}}(\boldsymbol{c})) + |\mathcal{M}_{\text{BSM}}(\boldsymbol{c})|^2$$

CP-even

CP-odd

$$\mathcal{OO}(\boldsymbol{c}) = \frac{2\Re(\mathcal{M}_{\text{SM}}\mathcal{M}^*_{\text{BSM}}(\boldsymbol{c}))}{|\mathcal{M}_{\text{SM}}|^2}$$

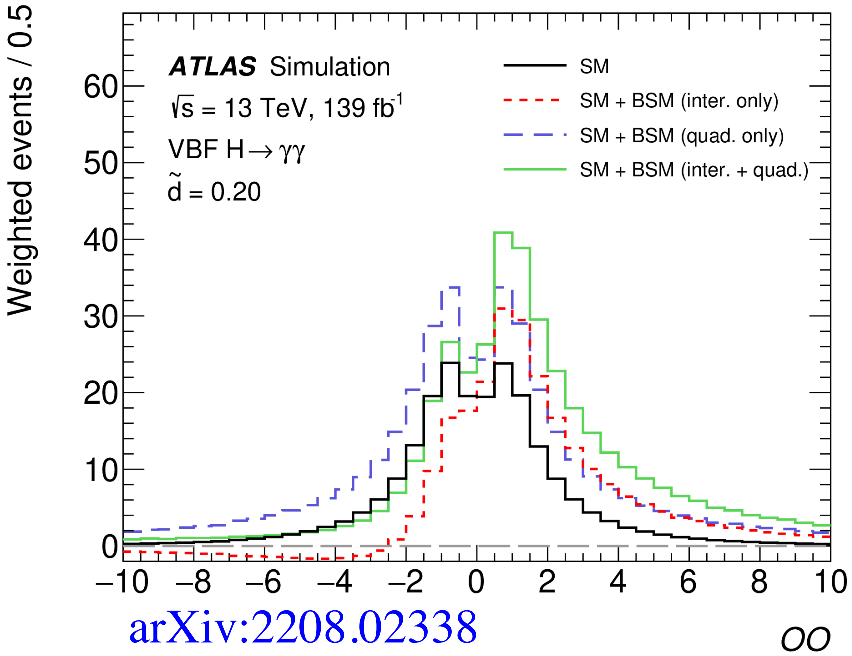
Symmetric for CP-even (SM)
Asymmetric for CP-odd (BSM)

- Matrix-Element-based **Optimal Observables** (OOs) are defined to maximize sensitivity to coupling constants c_i (Wilson coefficients):
  → each OO is most sensitive to a specific coefficient.

- Two parametrization used: **Warsaw basis** and **Higgs basis,** and a simpler parametrization:

$$\tilde{d} : \; c_{H\widetilde{W}B} = 0, c_{H\widetilde{W}} = c_{H\widetilde{B}} = \frac{\Lambda^2}{v^2}\tilde{d}, \quad \tilde{c}_{z\gamma} = 0, \quad \tilde{c}_{\gamma\gamma} = \sin^2\theta_W \cos^2\theta_W \tilde{c}_{zz} \propto \tilde{d}$$

Operator	Structure	Coupling
	Warsaw Basis	
$O_{\Phi\widetilde{W}}$	$\Phi^\dagger\Phi\widetilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\widetilde{W}B}$	$\Phi^\dagger\tau^I\Phi\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\widetilde{B}}$	$\Phi^\dagger\Phi\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{B}}$
	Higgs Basis	
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$

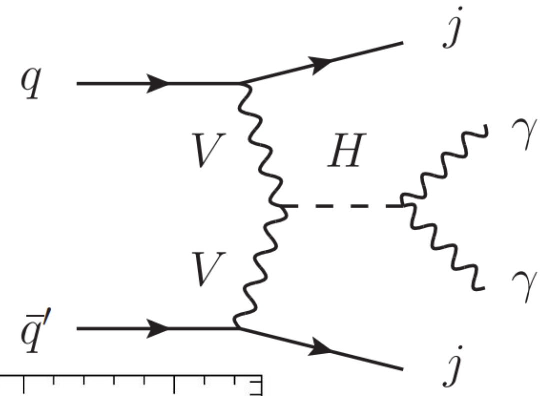


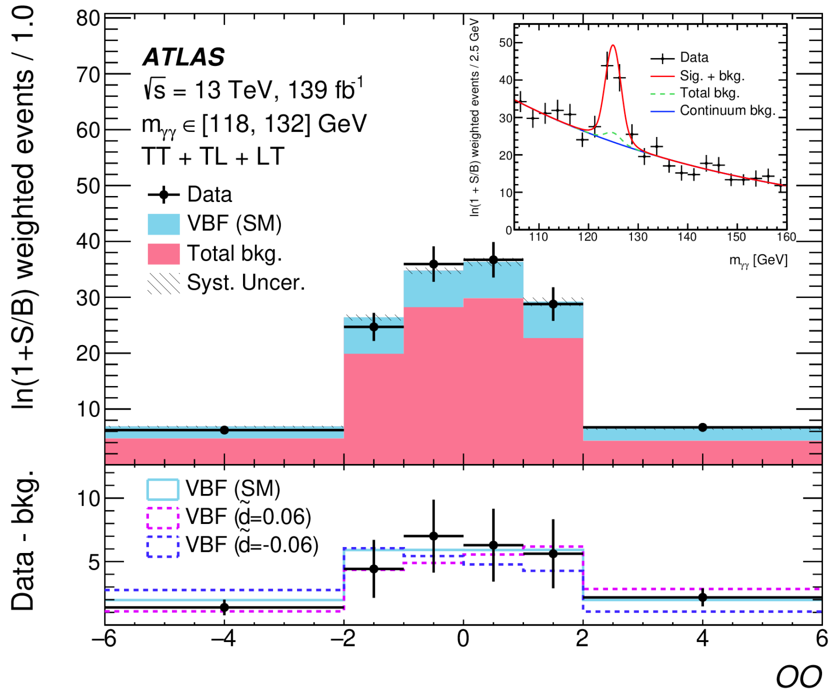
arXiv:2208.02338

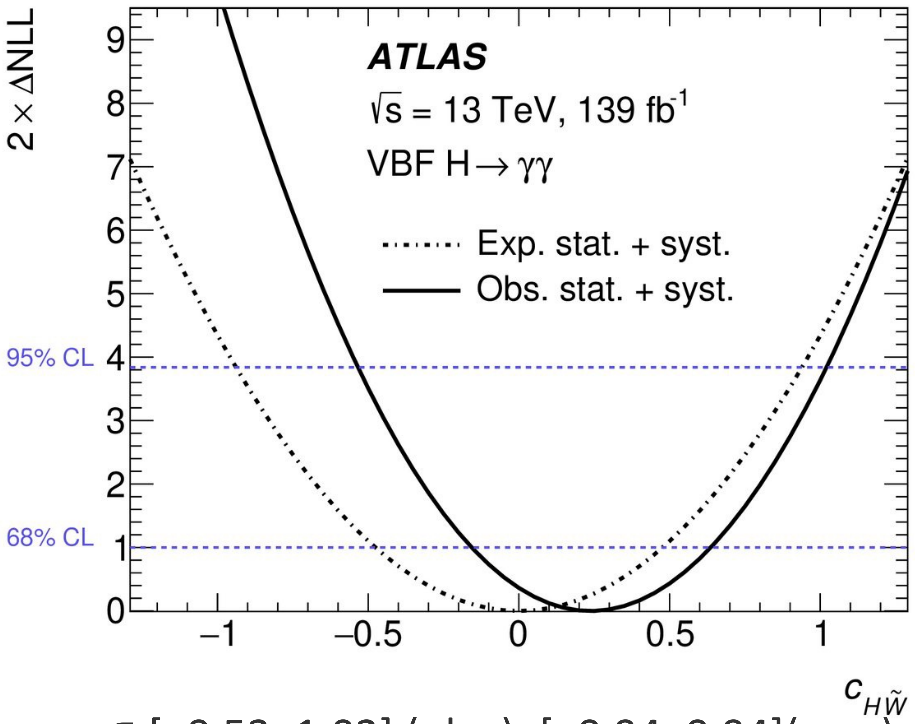
HVV anomalous coupling: VBF $H\to\gamma\gamma$

arXiv:2208.02338 (Sub. to PRL)

- The VBF topology in this analysis is mainly sensitive to $c_{H\tilde{W}}$
- Use 2 BDTs to discriminate VBF/ggF and VBF/continuum background
- Define three signal regions (excluding case when both BDT cuts fail)
- Fit $m_{\gamma\gamma}$ distributions on each *OO* bin for each SR to extract signal contribution







Results are compatible with the SM: no sign of CP violation in the Optimal Observable distributions.

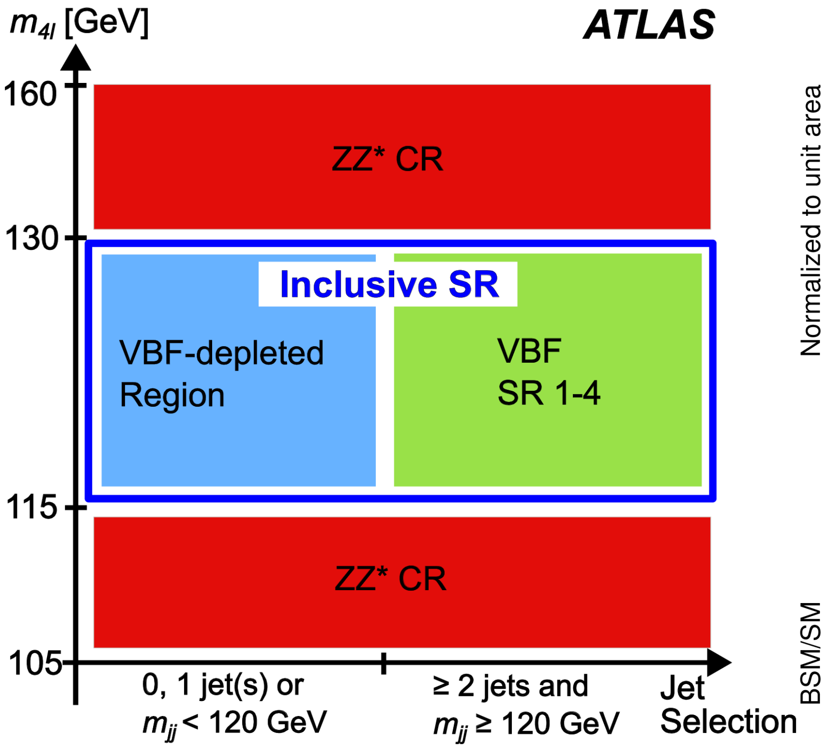
$c_{HW} \in [-0.53, 1.02]$ (obs.), $[-0.94, 0.94]$(exp.) at 95%CL

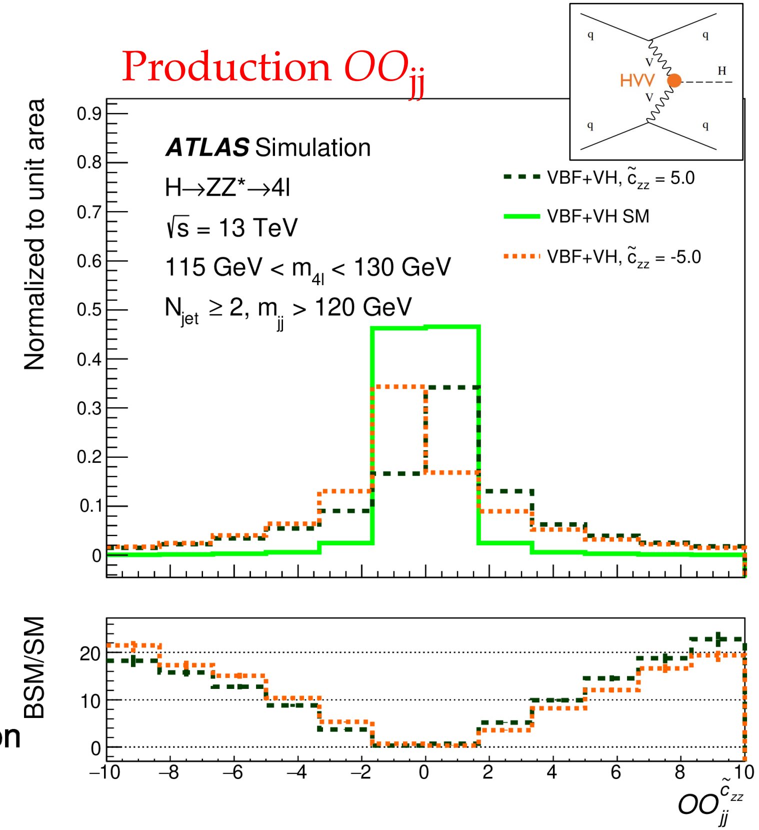
Most stringent constraint on CP-violating effects in HVV coupling to date .

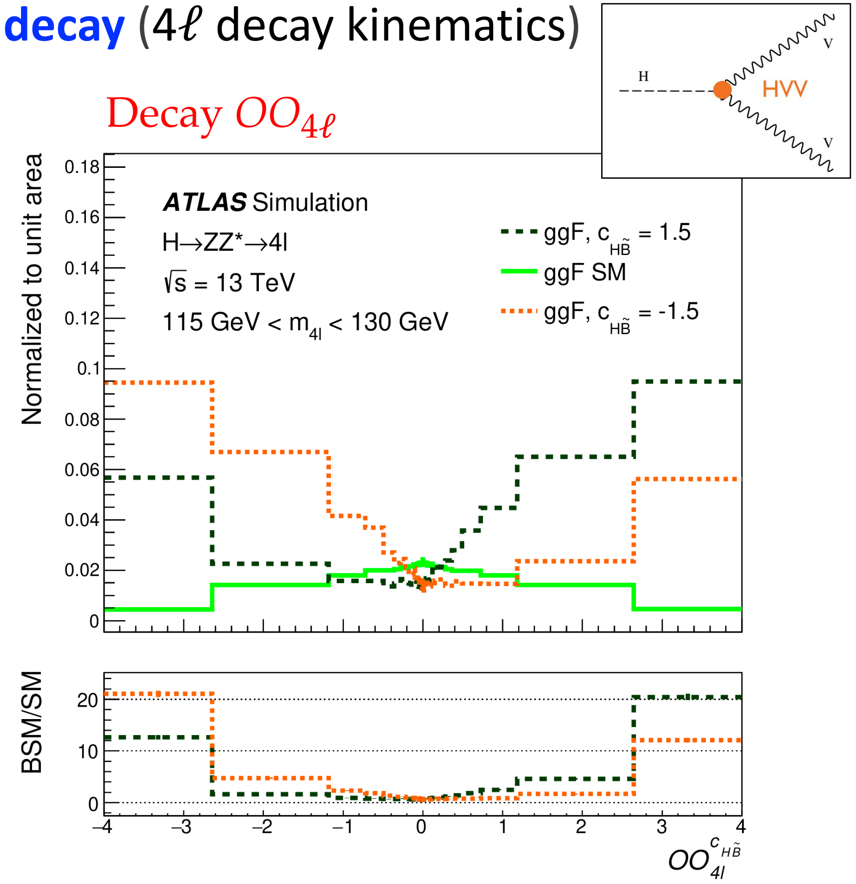
HVV anomalous coupling: H→ZZ→ 4ℓ

arXiv:2304.09612 (Sub. to JHEP)

- Use Optimal Observable (*OO*) to probe CP-odd component
- Only changes in the shape of the optimal-observable distributions are used to estimate BSM couplings
- Define two *OO*s: for **production** (VBF enriched, 2 jets kinematic) and for **decay** (4ℓ decay kinematics)





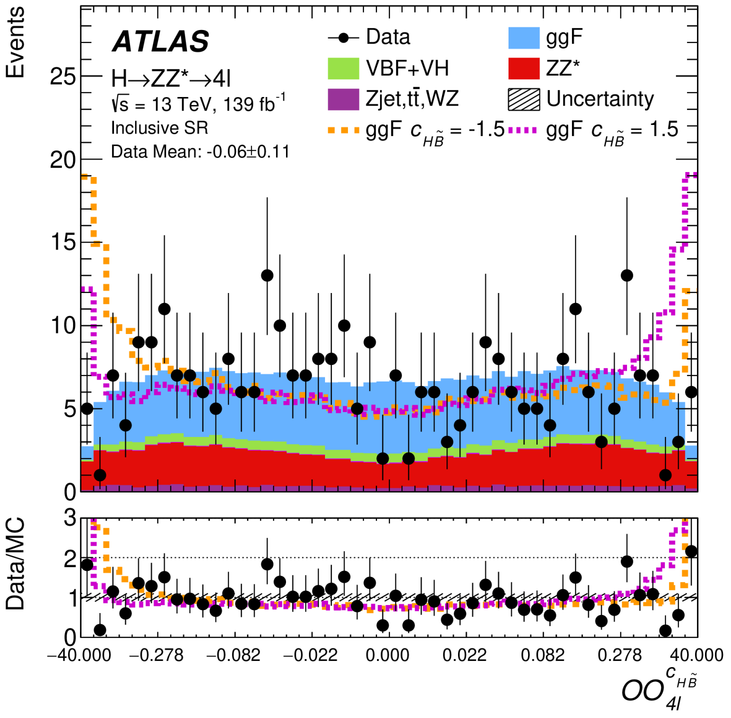


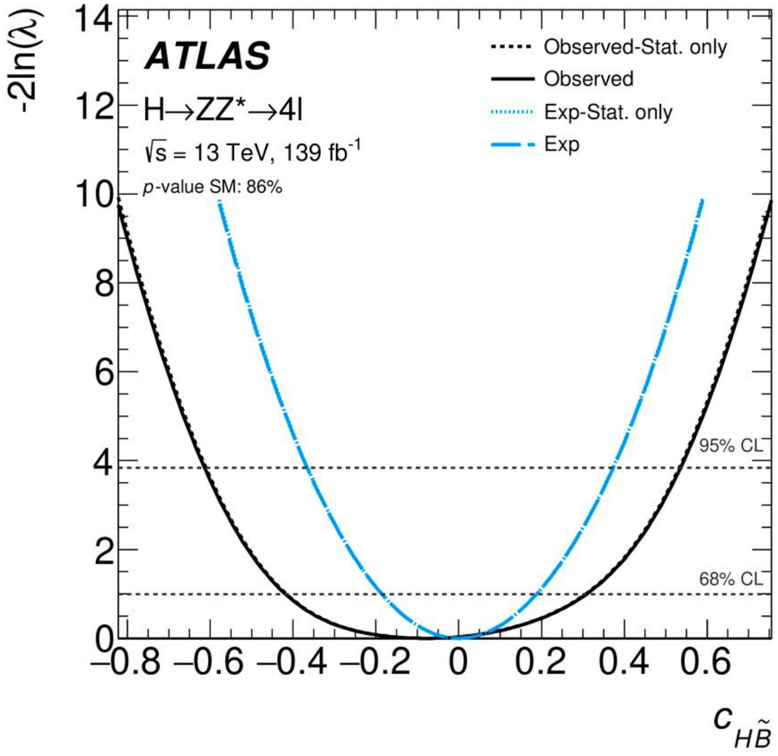
- Three types of fits are performed: *1) decay-only, 2) production-only, 3) and combined fit*
- 1) *decay-only* targets CP-violating effects in the Higgs decay. 2) *production-only* searches for signs of CP-violation at the VBF production vertex. 3) *combined* targets BSM signatures in both production and decay vertices.

HVV anomalous coupling: H→ZZ→ 4ℓ

arXiv:2304.09612 (Sub. to JHEP)

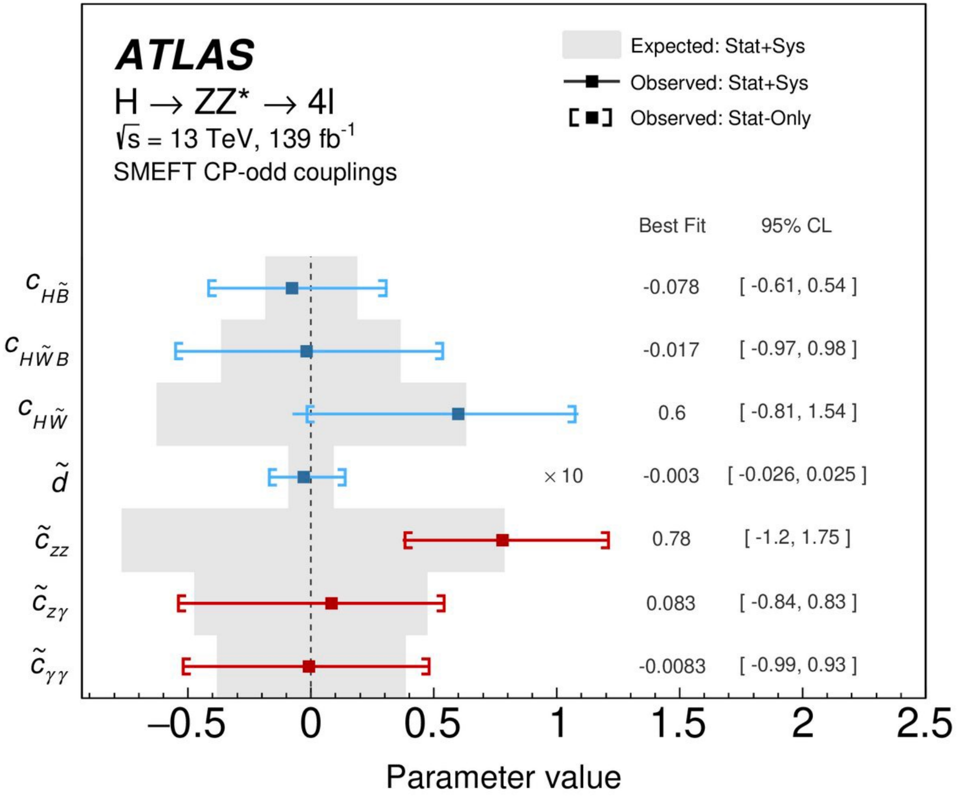
One of the OO fits (decay level observable)





Best fit results - Wilson coefficients

Warsaw basis / Higgs Basis



No significant deviation from SM predictions.

All measurements are in agreement with the Standard Model prediction of a CP-even Higgs boson.

CP structure: $H \to \tau\tau$

Eur. Phys. J. C (2023) 83:563

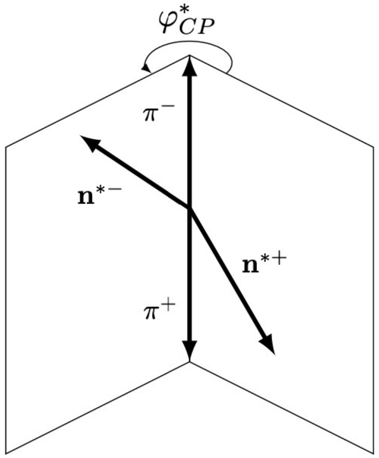
Probing the Yukawa coupling for CP-mixing: $\mathcal{L}_Y = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau} i\gamma_5 \tau)h$, [PRD 92, 096012 (2015)]

- CP-sensitive angular observables defined using the geometry of the visible τ decay products
- 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).

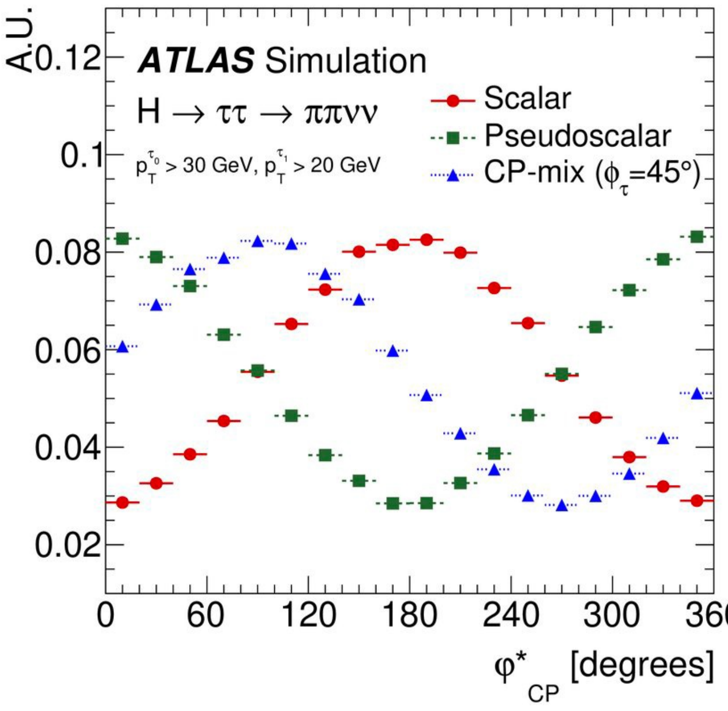
Observable: signed acoplanarity ϕ^*_{CP} between tau decay planes.

Depending on tau decay modes: several methods developed to reconstruct ϕ^*_{CP}

Example:
Impact parameter method



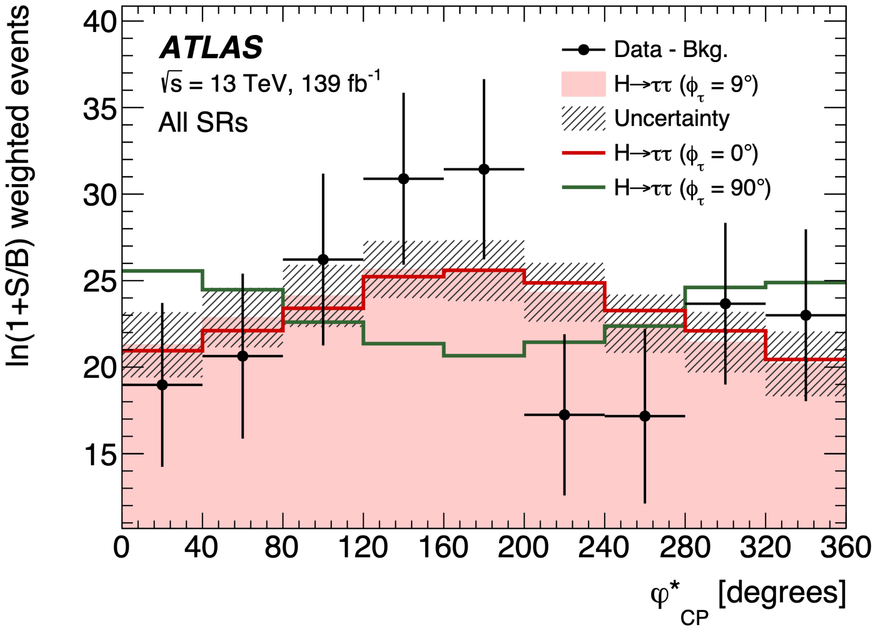
$H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$

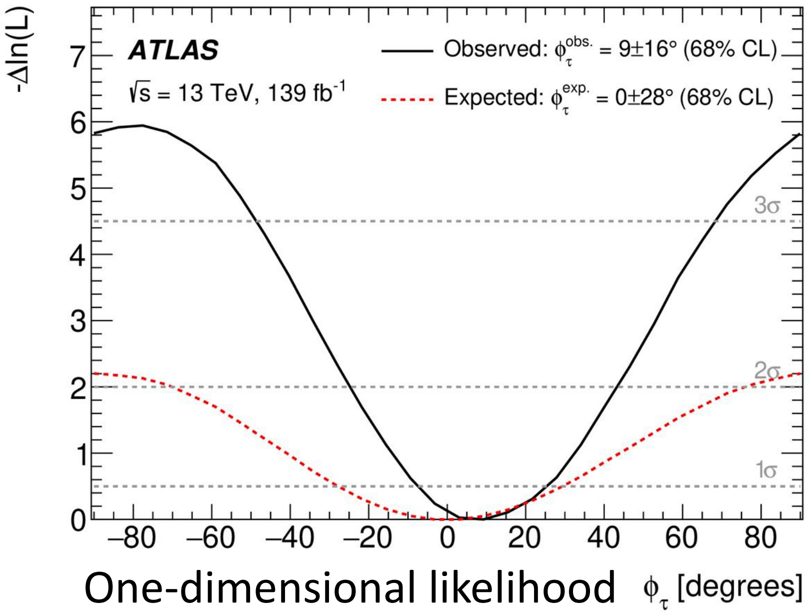


CP structure: H→$\tau\tau$

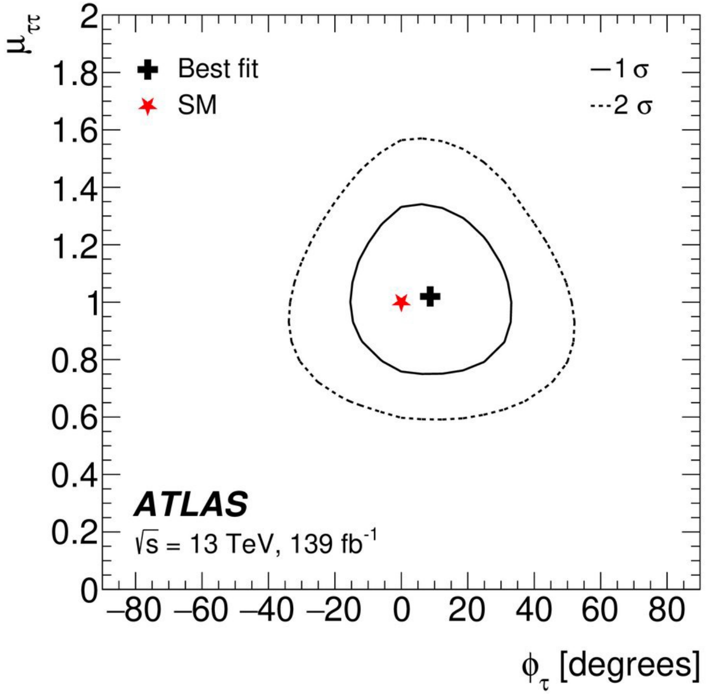
Eur. Phys. J. C (2023) 83:563

Combined post-fit distribution of φ^*_{CP} from all signal regions in both the $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels.





One-dimensional likelihood scan of the CP-mixing angle ϕ_τ



2D likelihood scan of the observed signal strength $\mu_{\tau\tau}$ versus the CP-mixing angle ϕ_τ

Best-fit value: $\phi_\tau = 9 \pm 16$ deg. (expected: 0 ± 28 deg.) at 68% CL

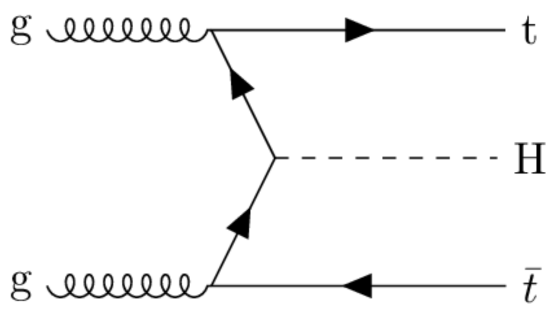
Pure CP-odd hypothesis disfavored at a level of 3.4σ

CP structure in Higgs-Top interaction (ttH, H→bb)

arXiv:2303.05974 (sub. to PLB)

- The top–Higgs interaction can be extended beyond the SM as:

$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$



- Pure CP-odd coupling has been excluded at 3.9σ in ttH→γγ [PRL 125, 061802 (2020)]
- This study measures the values of κ'_t and α with a binned profile likelihood fit.
- It uses 1ℓ+jets (including boosted region) and 2ℓ channels
- 2 BDTs are used: one for reconstruction of final state particles and one for classification (to discriminate the ttH signal against the backgrounds)
- Two dedicated CP sensitive observables defined with top quark kinematic information:

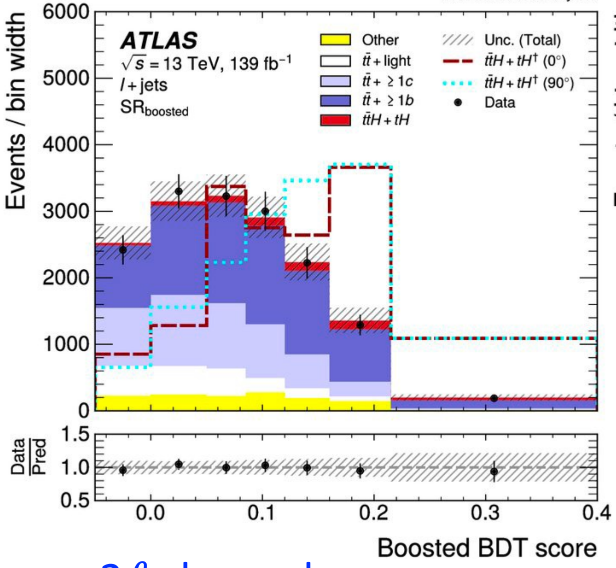
$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|}, \quad \text{and} \quad b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

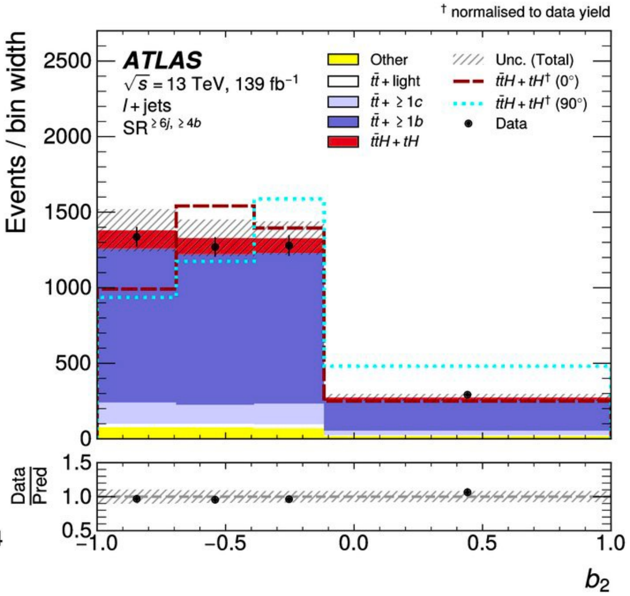
CP structure in Higgs-Top interaction (ttH,H→bb)

Post-fit distributions of CP-sensitive observables.

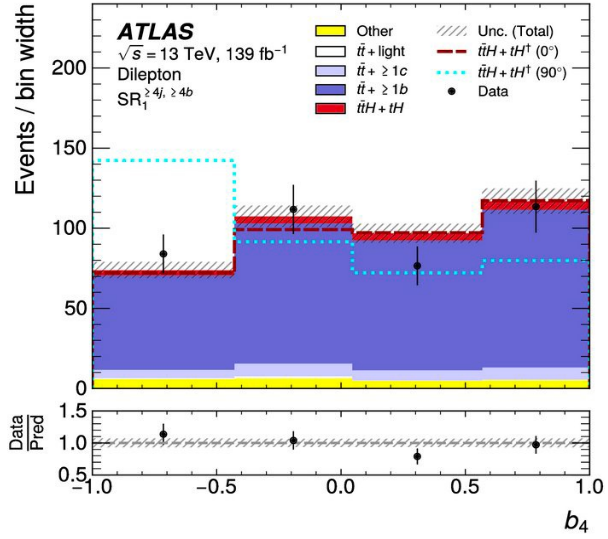
arXiv:2303.05974 (sub. to PLB)

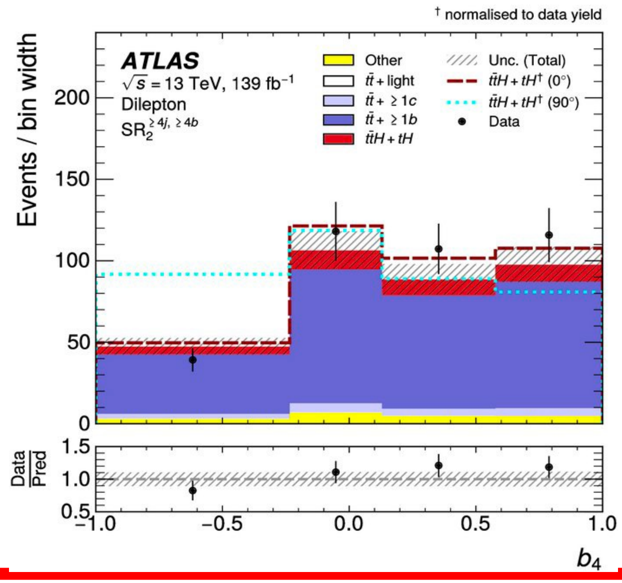
1ℓ channel



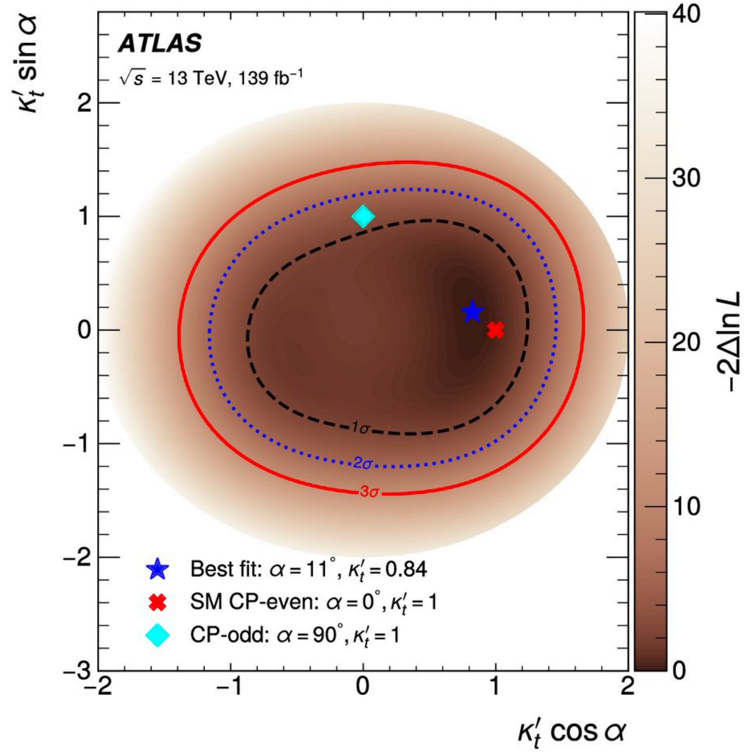


2ℓ channel





Observed 2D exclusion contours.



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

consistent with SM (α=0 deg., κ'_t = 1)

The data disfavour the pure CP-odd hypothesis with a 1.2 σ significance

Conclusions

- Thanks to LHC Run2 data, 11 years after the Higgs discovery we are now in the Higgs precision era
- Higgs boson mass is m_H = 124.94 ± 0.18 GeV from $H \rightarrow ZZ^* \rightarrow 4\ell$ channel with full RunI and Run-II datasets.
- Evidence of off-shell Higgs boson is found with an observed significance of 3.3σ in $H \rightarrow ZZ^* \rightarrow 4\ell/2\ell 2\nu$
  - ✓ Higgs boson width is: $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV (constrained to $0.5 < \Gamma_H < 10.5$ MeV @95% CL)
- The CP properties of the Higgs boson have been studied in various channels
  - ✓ No significant deviation from the SM observed so far
- Run3, well ongoing, and later HL-LHC, will significantly increase the available dataset:

→ will boost the precision reach

Public results from the ATLAS Higgs Working Group can be found here:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults