Search for CP violation in Higgs boson interactions at the ATLAS experiment

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Windows on the Universe - 30th Anniversary Rencontres du Vietnam
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ATLAS EXPERIMENT

"la Caixa" LIP

Searching for CP violation in Higgs boson interactions

Why?

- Sakharov conditions for a matter-dominated Universe require CP violation.
  - Known SM sources are insufficient to explain the observed asymmetry.
- CP violation in the Higgs sector is an enticing possibility:
  - The Higgs boson is a CP eigenstate with $J^{CP}=0^{+}$ in the Standard Model.
  - A pure $J^{CP}=0^{-}$ boson was ruled out in Run 1.
  - But a **CP-odd admixture** is far from being ruled out!
- Several BSM models predict CP violation in the Higgs sector (e.g. 2HDM).

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Searching for CP violation in Higgs boson interactions

How?

Bosonic couplings:

- CP-odd contributions may enter only at higher orders terms and be suppressed by powers of $1/\Lambda$.
- This could be why it hasn't been observed so far.

$$\mathscr{L}_{VVH} = \mathscr{L}_{VVH,SM} + \frac{1}{\Lambda^2} c\phi\tilde{V}_{\mu\nu}V^{\mu\nu} + \dots$$

Λ ≡ scale of new physics

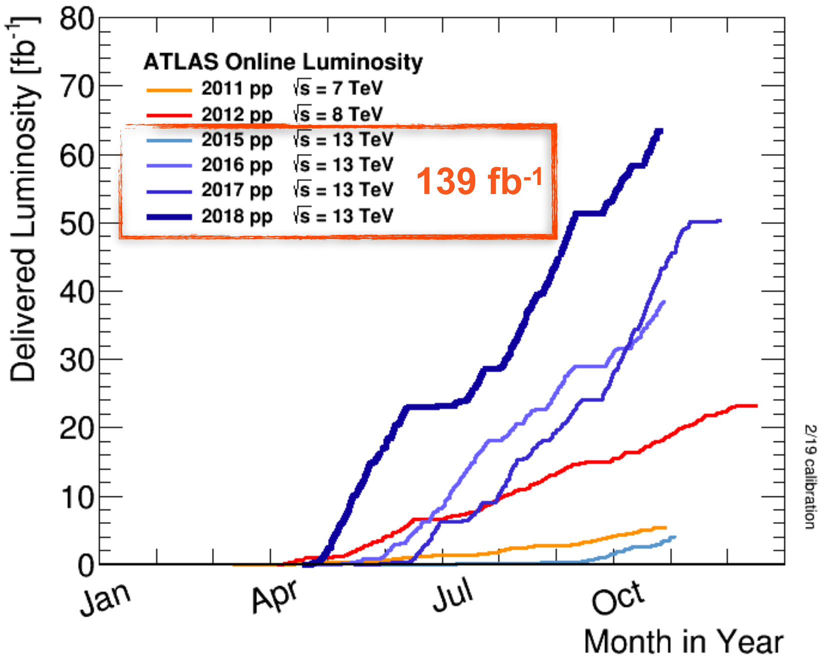
c ≡ Wilson coefficient

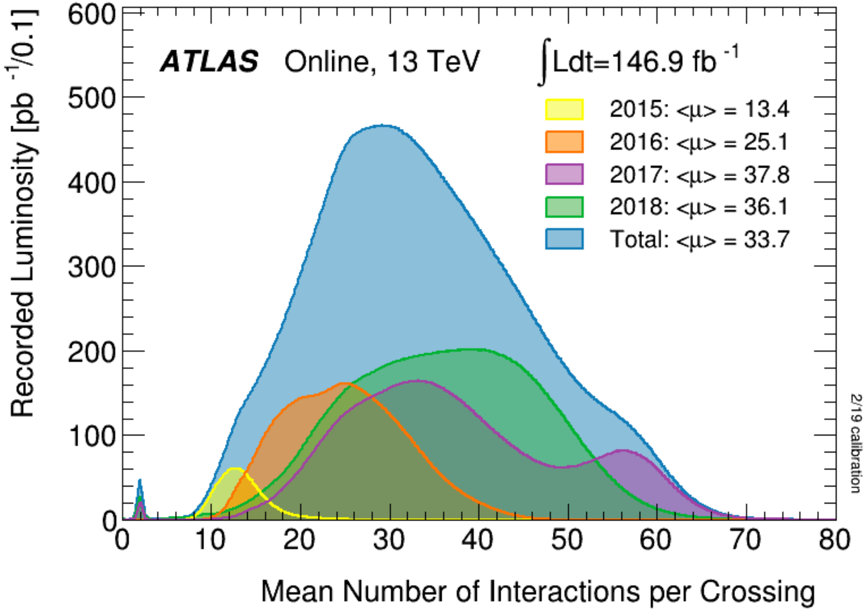
Fermionic couplings:

- More democratic test of CP nature since CP even and CP odd components can have same magnitude.
- Mixing angle α between CP-even and CP-odd components, which can occur at tree-level.

$$\mathscr{L}_{ffH} = \kappa_f' y_f \phi \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha)\psi_f$$

ATLAS Run 2 data





Bosonic Couplings

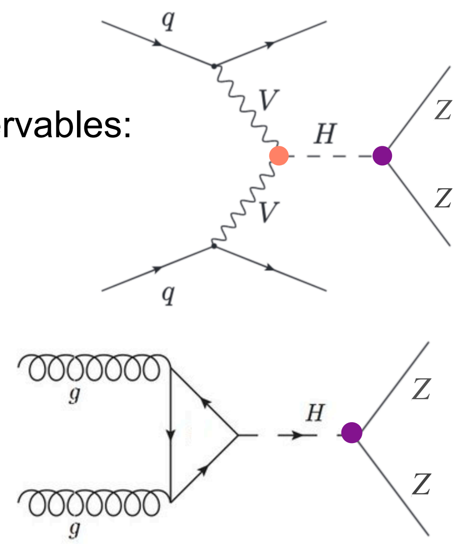
$H \to ZZ^* \to 4\ell$: 2304.09612 (submitted to JHEP)

VBF $H \to \gamma\gamma$: 2208.02338 (submitted to PRL)

2304.09612 (submitted to JHEP)

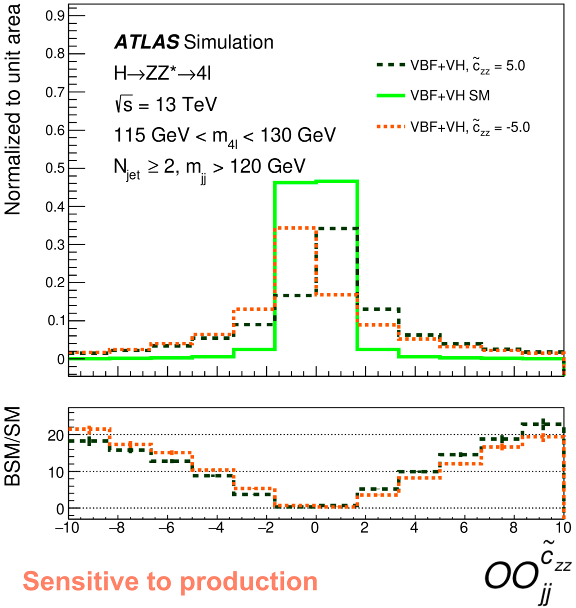
H→ZZ*→4ℓ

- Searching for CP-odd effects in **production** and **decay** via Optimal Observables:

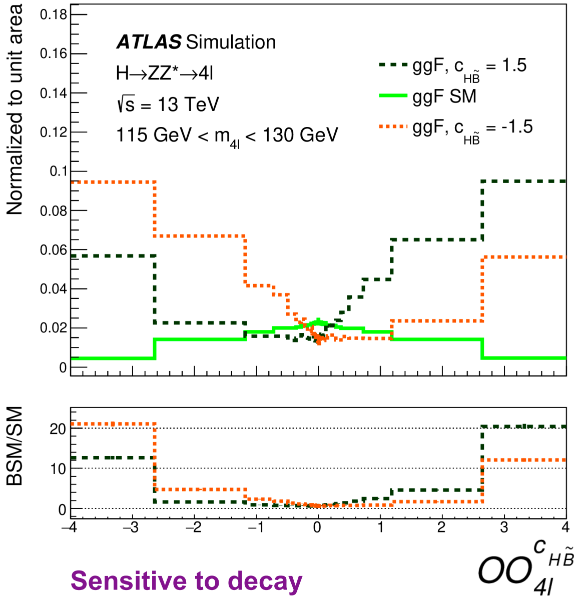


$$|M|^2 = |M_{SM}|^2 + 2\Re(M_{SM}^* M_{BSM}) + |M_{BSM}|^2$$

CP-even CP-odd CP-even



Sensitive to production



Sensitive to decay

$$OO = \frac{2\Re(M_{SM}^* M_{BSM})}{|M_{SM}|^2}$$

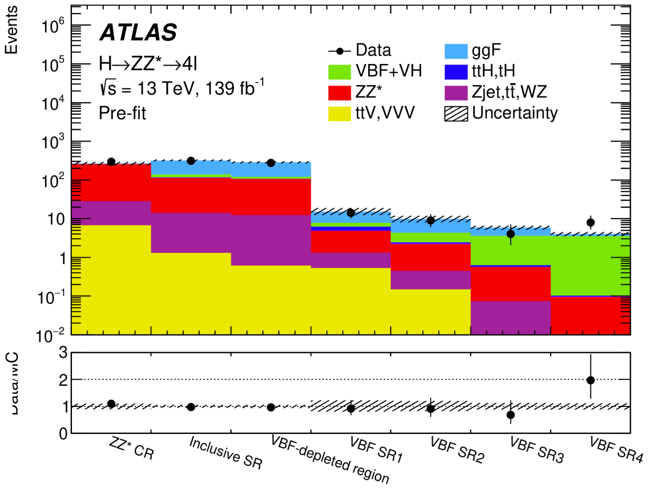
Optimal Observable

- ✓ Warsaw basis
- ✓ Higgs basis
- ✓ $\tilde{d}$ in HISZ basis

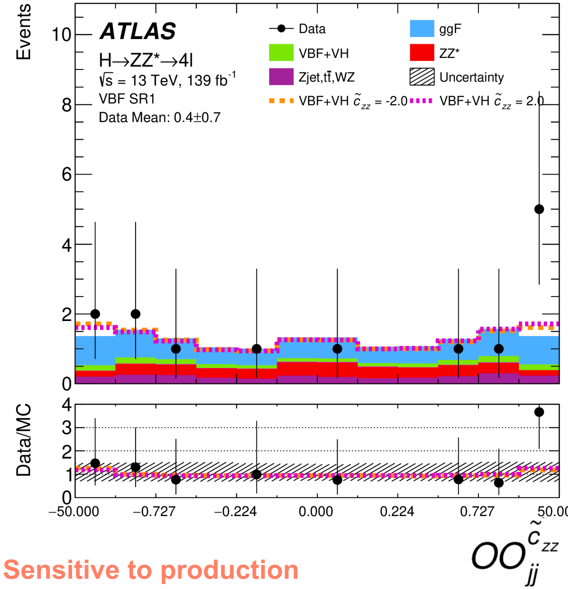
2304.09612 (submitted to JHEP)

H→ZZ*→4ℓ

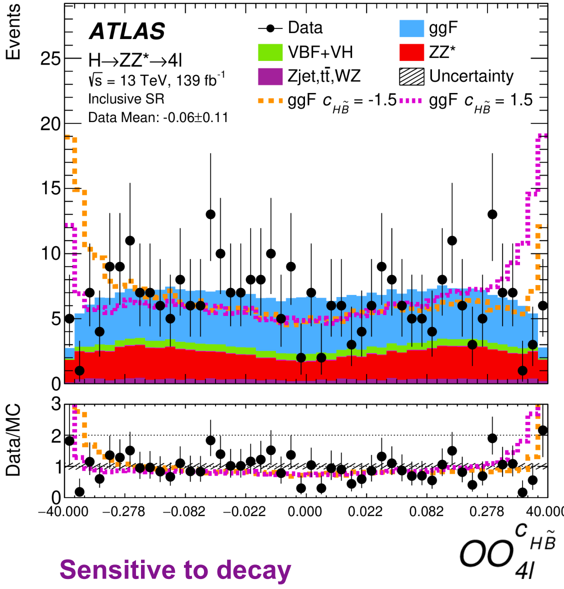
- *Production-level* fit uses VBF enriched signal-regions.
- *Decay-level* fit is dominated by ggF signal events.
- Mass sidebands for constraining ZZ* normalisation.
- Measurement insensitive to CP-even signatures of BSM physics.



Rates of **SM signal** and **background** as free parameters in the fit.



Sensitive to production



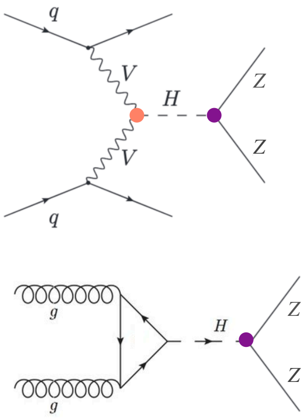
Sensitive to decay

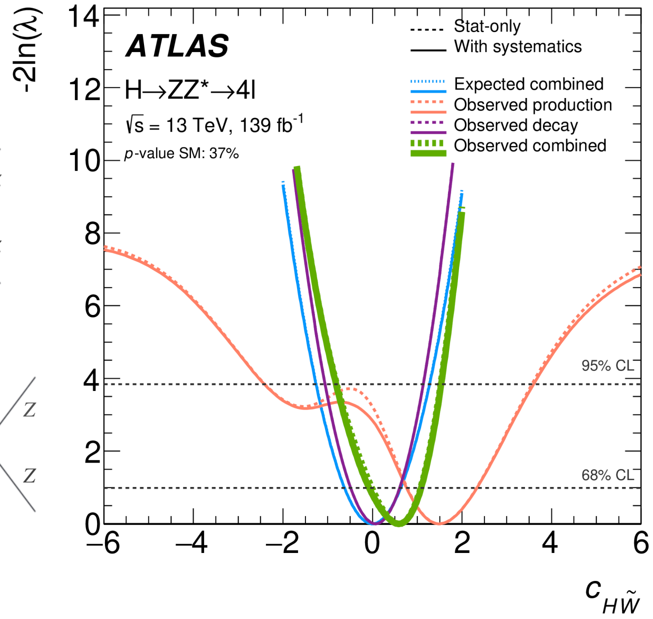
Very small excess of VBF candidates at positive $OO_{jj}^{\tilde{c}_{zz}}$

H→ZZ*→4ℓ

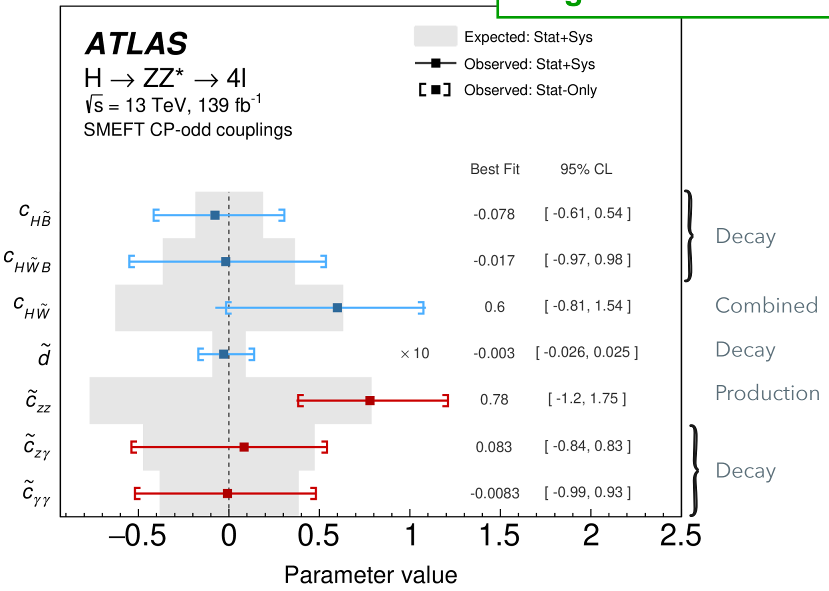
2304.09612 (submitted to JHEP)

- Slight preference for a non-zero BSM coupling in production-level analysis:
  - Compatible with SM at 2σ and not confirmed by decay analysis.
- Precision limited by statistical uncertainty of the data.
  - Production-level fits impacted by systematic uncertainties that lead to event migration.



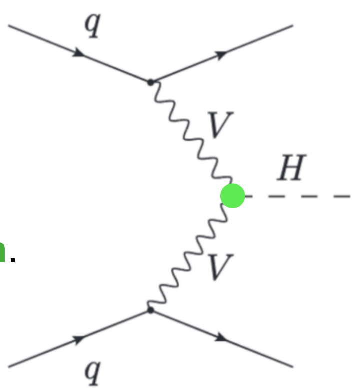


In agreement with SM

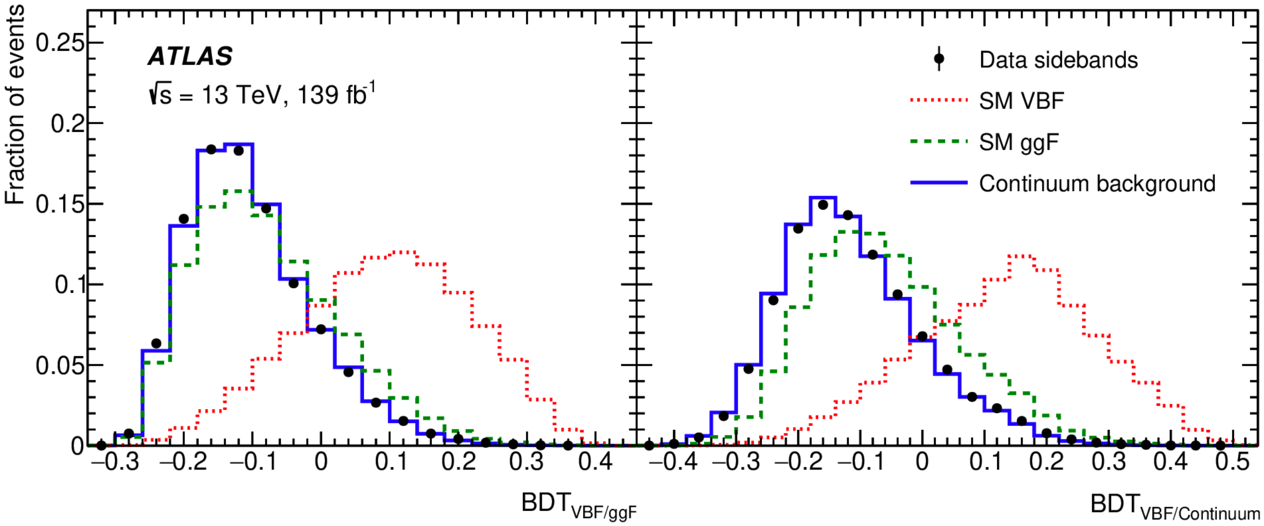


VBF H→γγ

- Once again, CP-odd component can be described using effective field theory and adding a dimension-6 operator to the SM Lagrangian.
  - Optimal Observables employed to study CP structure in the **VBF production**.



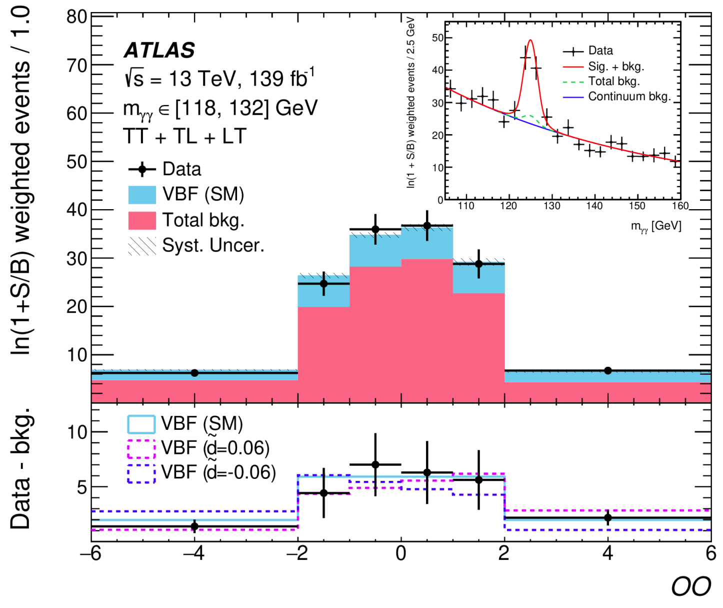
- ✓ $c_{H\tilde{W}}$ in Warsaw basis
- ✓ $\tilde{d} = \tilde{d}_B$ in HISZ basis

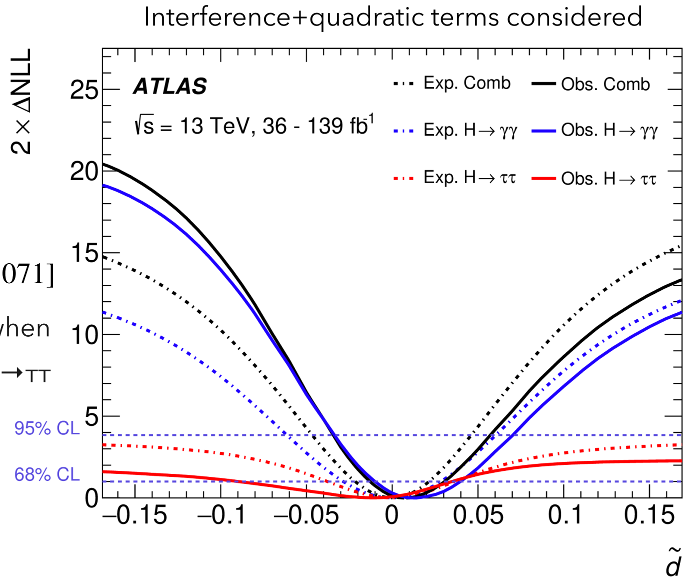


BDTs trained to increase VBF signal purity against ggF and continuum background ($\gamma\gamma, \gamma j, jj$), using features insensitive to CP properties of VBF

VBF H→γγ

- Unbinned likelihood fit with $m_{\gamma\gamma}$ spectra in bins of OO.
  - Results compatible with SM with precision limited by statistical uncertainty of the data.





$\tilde{d}$@95 % CL : [−0.034,0.071]

$\tilde{d}$@95 % CL : [−0.034,0.057] when combining with H→ττ

$c_{H\tilde{W}}$@95 % CL : [−0.55,1.07]

Together with VBF H→4ℓ, these are some of the most stringent constraints to date on CP violation in the coupling between Higgs and weak bosons.

Fermionic Couplings

$H \to \tau^+\tau^-$: Eur. Phys. J. C 83 (2023) 563

$tH, t\bar{t}H$ **with** $H \to b\bar{b}$: 2303.05974 (submitted to PLB)

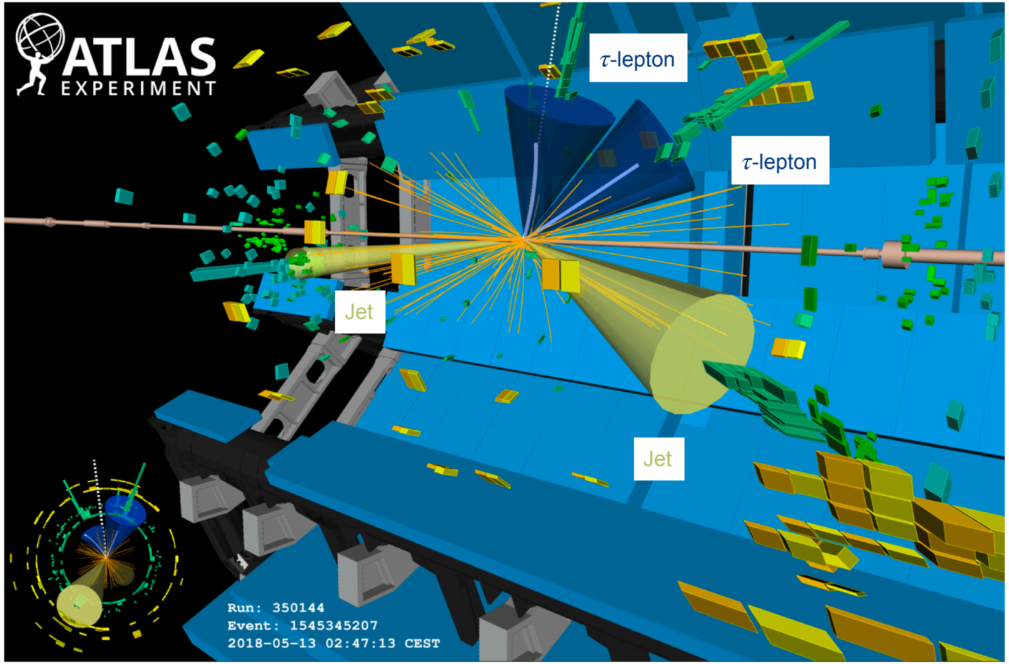
Eur. Phys. J. C 83 (2023) 563

$H \to \tau^+\tau^-$ via CP-sensitive angular observables

- Study of CP properties of the interaction between the Higgs boson and τ-leptons via angular observables defined by visible decay products of the τ.
- Effective interaction parameterised as:

$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{\nu}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

κ_τ: reduced Yukawa coupling strength
ϕ_τ: CP-mixing angle
SM: $\phi_\tau = 0°$



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$$\mathscr{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

Related to $\varphi^*_{CP} \equiv$ signed acoplanarity angle between τ-lepton decay planes

κ_τ: reduced Yukawa coupling strength
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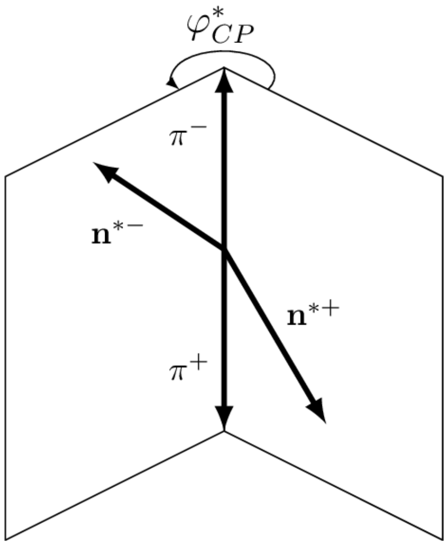
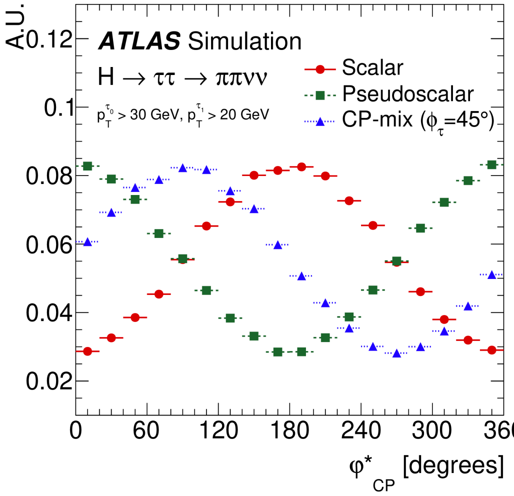


$H \to \tau\bar{\tau} \to \pi^+\pi^- + 2\nu$

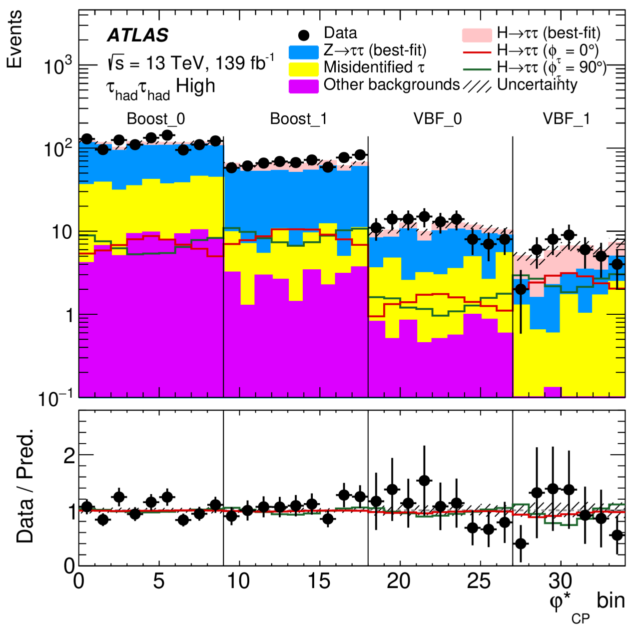


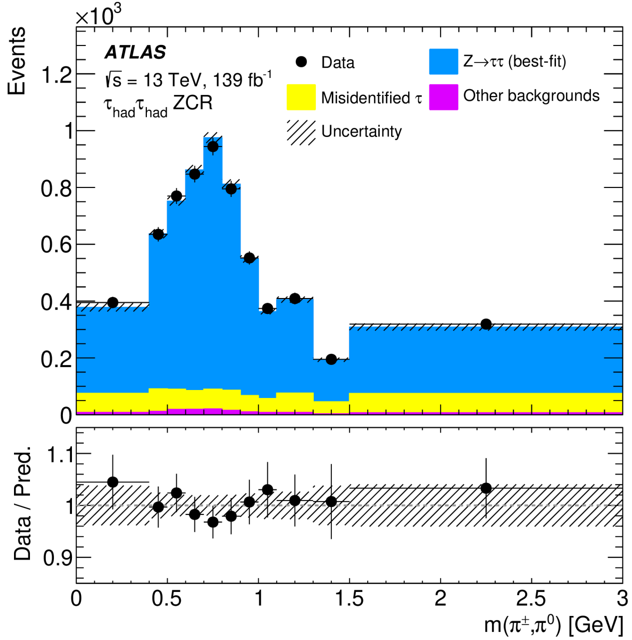
$H \to \tau^+\tau^-$ via CP-sensitive angular observables

- **Production channels:** vector-boson-fusion (VBF) and boosted gluon-gluon fusion (ggF).
- **Decay channels:** $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$. τ_{had} decay mode classification via BDT using number of tracks, single-π_0 and multi-π_0 clusters.

Fit performed to φ^*_{CP} distribution.

Z+jets normalisation extracted from data CR.

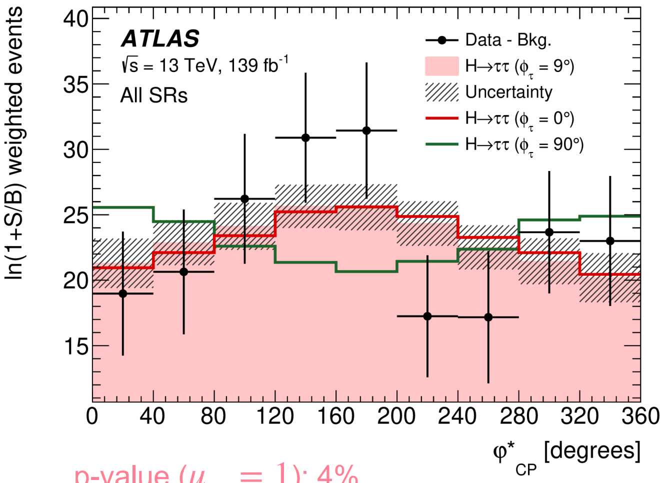


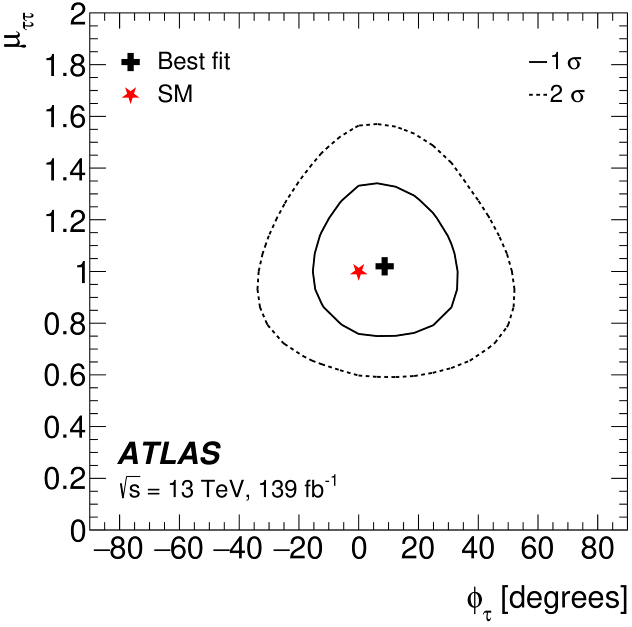


Eur. Phys. J. C 83 (2023) 563

$H \to \tau^+\tau^-$ via CP-sensitive angular observables

- Observed (expected) value of ϕ_τ is $9^\circ \pm 16^\circ (0^\circ \pm 28^\circ)$ at 68% CL and $\pm 34^\circ (^{+75^\circ}_{-70^\circ})$ at 95% CL.
  - Data disfavours pure CP-odd hypothesis at 3.4σ level.
  - Results compatible with SM expectation.
- Total uncertainty dominated by statistical uncertainties.
  - Dominant systematics from jet energy scale and resolution.





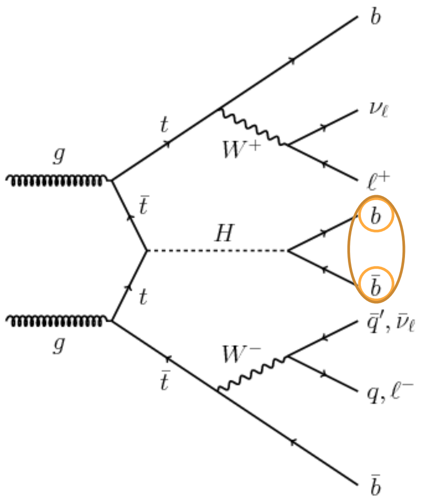
p-value ($\mu_{\tau\tau} = 1$): 4%

$tH, t\bar{t}H$ with $H \rightarrow b\bar{b}$

- Studying the CP properties of the top-Yukawa coupling for the first time in this final state.
- BSM top-Higgs interactions parameterised as:

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

κ'_t: coupling modifier
α: CP-mixing angle
SM: $\alpha = 0, \kappa'_t = 1$



Analysis strategy:

- Target **high jet multiplicities**, including b-quarks.
- Exploit collimated decay topology of the Higgs boson using **reclustered** jets.
- BDTs/DNN for Higgs and top reconstruction and for signal classification.
- Dedicated CP-sensitive observables are used in the fit to the resolved signal regions:

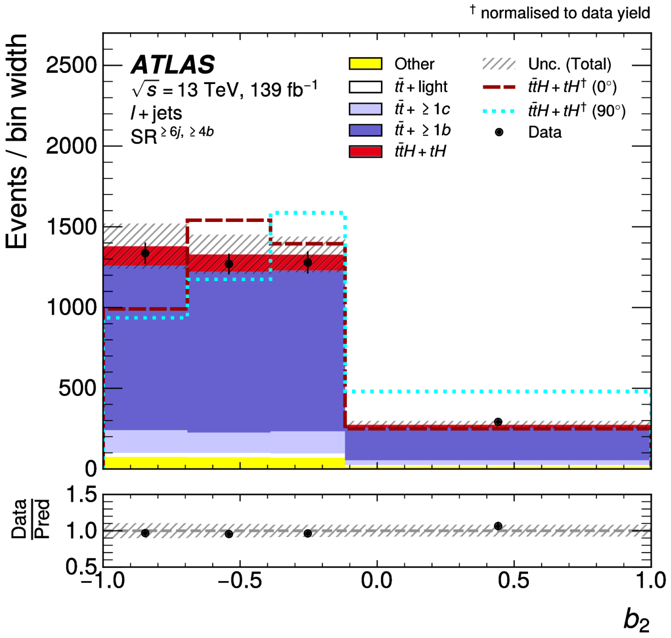
$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|} \qquad b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

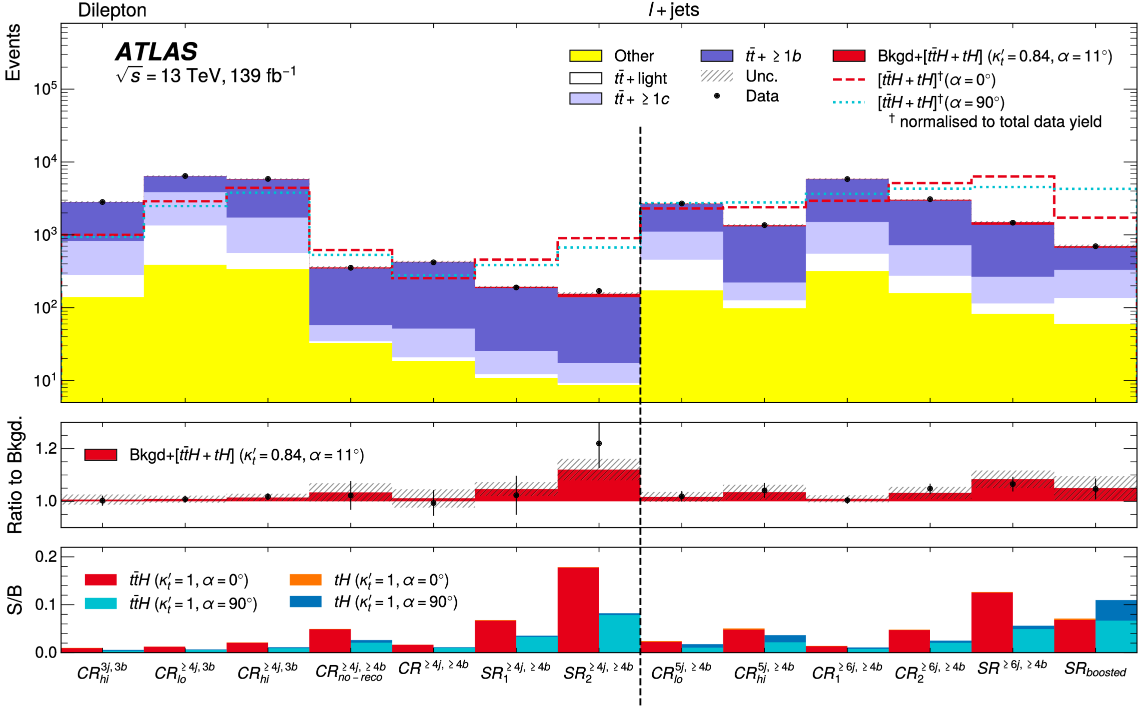
l+jets channel — Dilepton channel

2303.05974 (submitted to PLB)

$tH, t\bar{t}H$ with $H \rightarrow b\bar{b}$

- Simultaneous binned profile likelihood fit performed to all analysis regions.





$t\bar{t} + \geq 1b$ scale factor at $1.30^{+0.09}_{-0.08}$

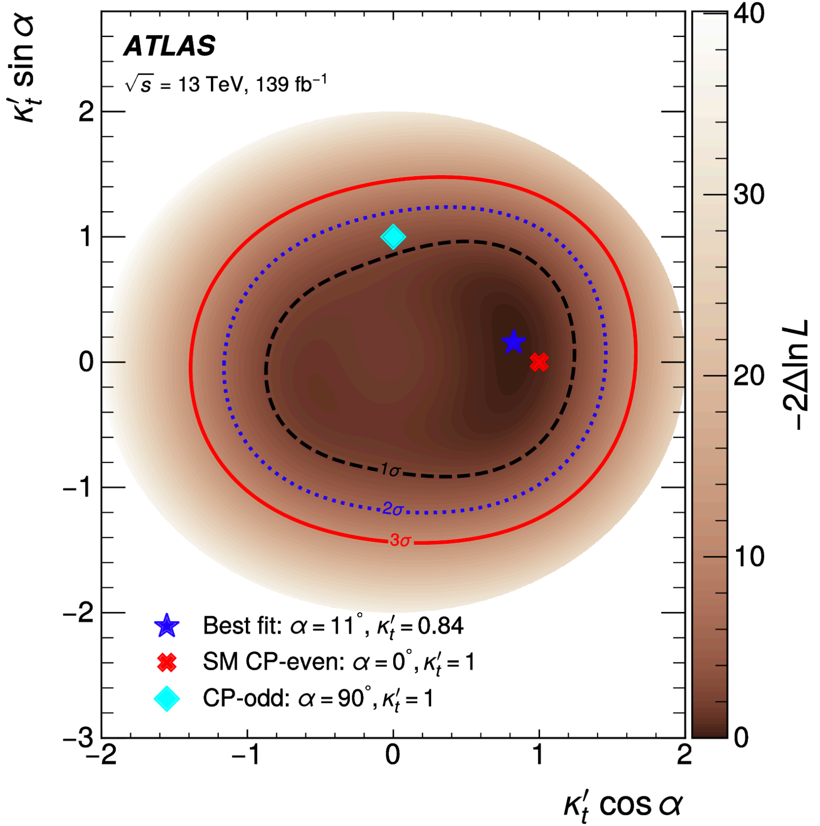
$tH, t\bar{t}H$ with $H \rightarrow b\bar{b}$

- Best-fit values in agreement with SM expectation:

$$\alpha = 11^{\circ}{}^{+56^{\circ}}_{-77^{\circ}}$$

$$\kappa_t' = 0.84^{+0.30}_{-0.46}$$

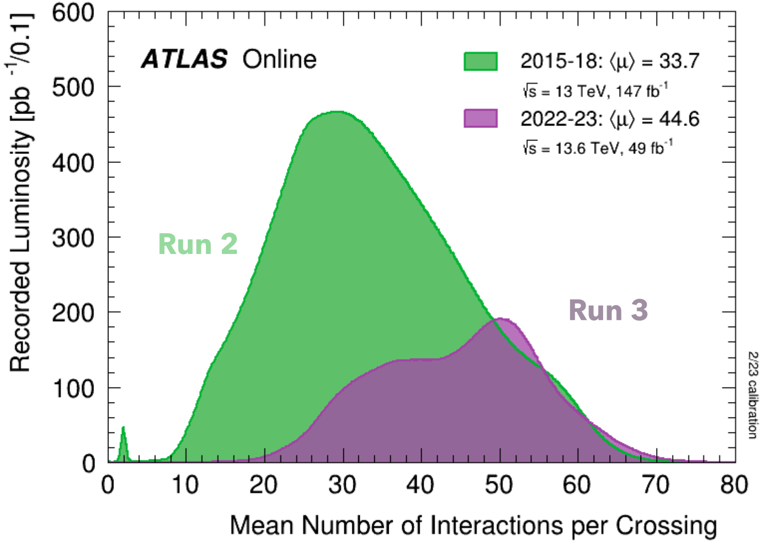
- Uncertainties in measured values dominated by $t\bar{t} + \geq 1b$ modelling uncertainties:
  - NLO matching procedure, parton shower and hadronisation models, flavour scheme.
- This is the first probe of the CP properties in top-quark's Yukawa coupling to the Higgs boson in $tH, t\bar{t}H$ with $H \rightarrow b\bar{b}$.
  - A better theoretical understanding of this background (along with additional LHC data) will greatly benefit future measurements.

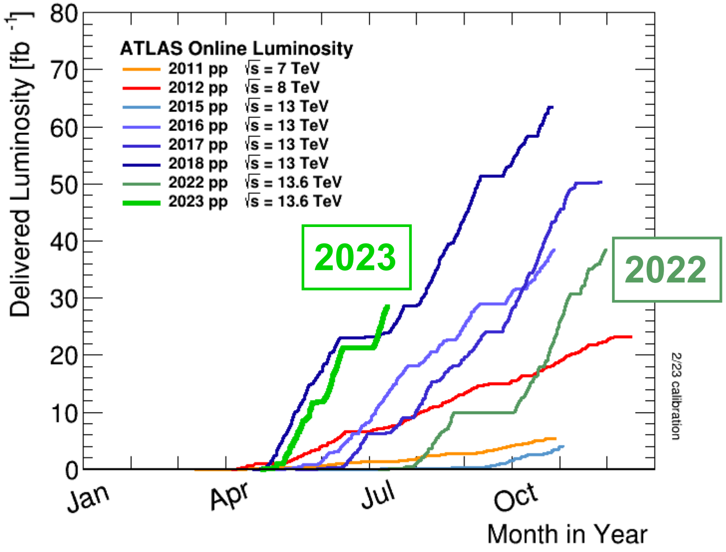


Summary

Summary

- **All measurements consistent with the SM expectation of a CP-even Higgs boson.**
- We continue to develop new analysis ideas and methods to **fully explore the Run 2 data**, as we prepare to analyse the **Run 3 data at √s=13.6 TeV**.





Thank you for your attention!