EPS-HEP CONFERENCE
07-11 JULY, 2025
PALAIS DU PHARO
MARSEILLE, FRANCE

Measurements of the CP structure of Higgs-boson couplings with the ATLAS detector

Marina Kholodenko (LIP, Portugal)
On behalf of ATLAS collaboration

TÉCNICO LISBOA
LIP
fct Fundação para a Ciência e a Tecnologia
2024.00227.CERN
2023.00042.RESTART
Co-funded by the European Union

ATLAS EXPERIMENT

Introduction

- **Fundamental open question:** Baryon asymmetry of the universe
  - Not explained by SM
- Three Sakharov conditions (1967): to explain it
  - Baryon number violation
  - **Charge-Parity symmetry violation**
  - Thermal equilibrium

Standard Model

- CP violation: from a complex phase in the quark mixing matrix
  - Too small to explain observed value of baryon asymmetry

Motivation for searching new sources of CP violation

- SM Higgs boson - scalar particle
  - CP violation still allowed in Higgs interaction with SM particles

Search for CP violation in:

- **Higgs interaction with EW bosons**
- **Higgs interaction with Fermions**
  - The results are in backup slides

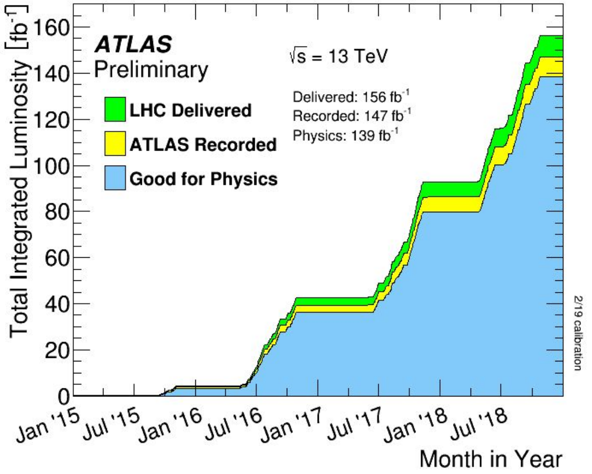
Overview

Search for CP-violation in Higgs interaction with vector bosons

- $H \to ZZ^* \to 4\ell$ (JHEP 05 (2024) 105)
- VBF $H \to \gamma\gamma$ (Phys. Rev. Lett. 131 (2023) 061802)
- $H \to WW^* \to \ell\nu\ell\nu$ (arXiv:2504.07686) - NEW results
- WH ($H \to bb$) (ATL-PHYS-PUB-2025-022) - NEW results
- VBF $H \to \tau\tau$ (arXiv:2506.19395) - NEW results

All presented analyses are based on the full Run 2 dataset (139 fb^{-1})

ATLAS RUN 2 integrated luminosity



Effective Field Theory

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_i}{\Lambda^4} O_i^{(8)} + \ldots,$$

Wilson coefficients

Scale of new physics (1 TeV)

Dimension-6 operators describing new physics

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + \frac{c_{H\widetilde{W}}}{\Lambda^2} 2\Re\left(\mathcal{M}^*_{O_{H\widetilde{W}}} \mathcal{M}_{SM}\right) + \frac{c^2_{H\widetilde{W}}}{\Lambda^4} |\mathcal{M}_{O_{H\widetilde{W}}}|^2$$

CP-odd

CP-even

All the analysis assumed Λ = 1 TeV

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

HISZ basis

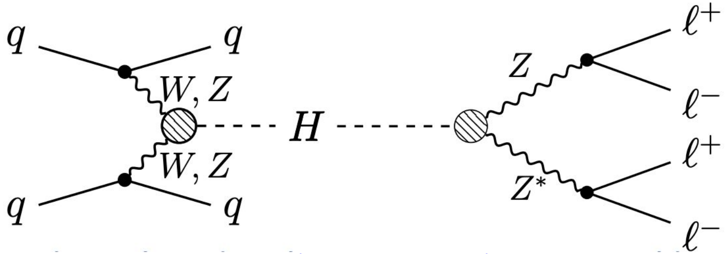
$$c_{H\widetilde{W}} = c_{H\widetilde{B}} = \frac{\Lambda^2}{v^2}\tilde{d}, \quad c_{H\widetilde{W}B} = 0$$

CP-odd contribution parameterized through **one parameter: $\tilde{d}$**

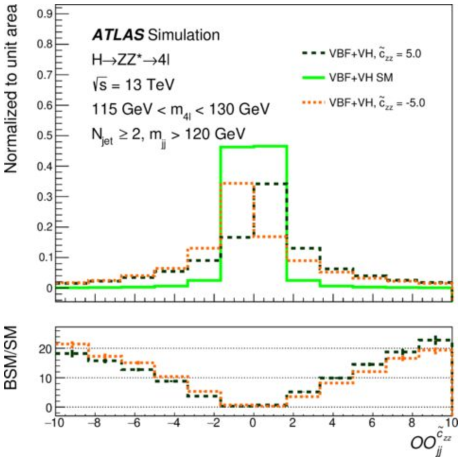
$H\to ZZ^*\to 4\ell$

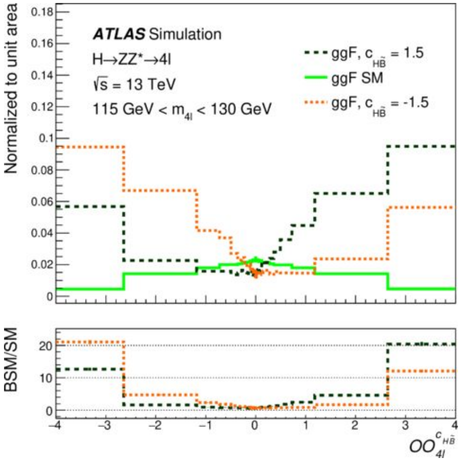
JHEP 05 (2024) 105

VBF production vertex **$H\to ZZ^*$ decay vertex**



Optimal observable distributions





EFT interpretation:

- HISZ basis and Warsaw basis

CP-odd optimal observables (OO)

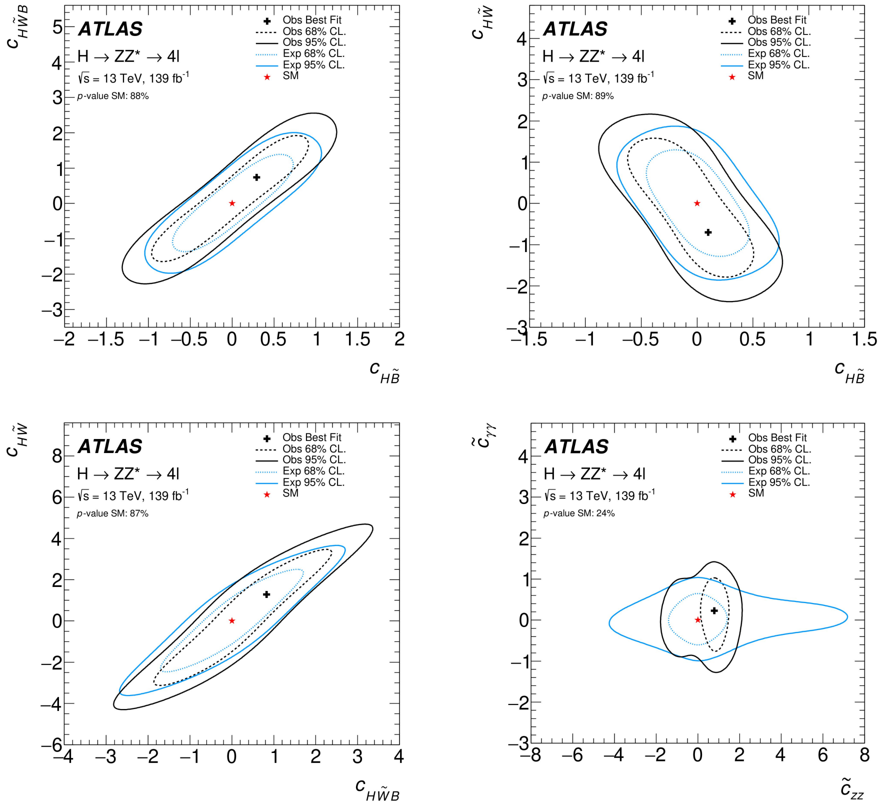
$$\mathcal{OO} = \frac{2\Re\left(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{BSM}}\right)}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

- CP-odd by construction
- Symmetric for SM
- Any asymmetry - direct sign of CP-violation
- **Two types:**
  - Production-level OO
  - Decay-level OO
- Analysis used VBF, ggF and VH productions

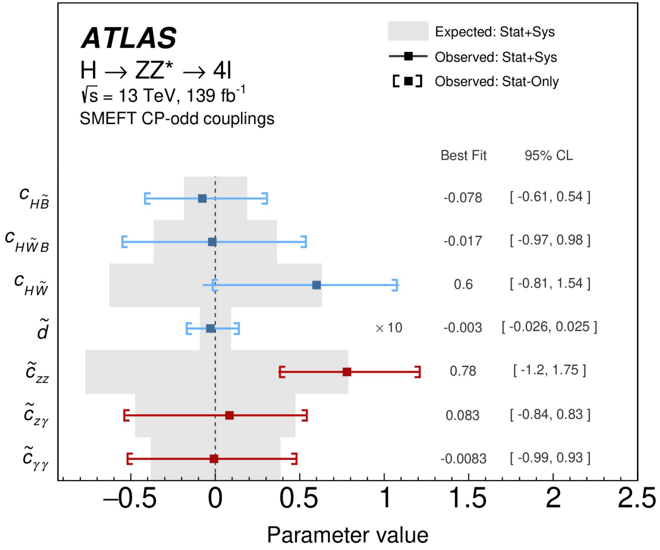
H→ZZ*→4ℓ

JHEP 05 (2024) 105

2D contours of pairing Wilson coefficients



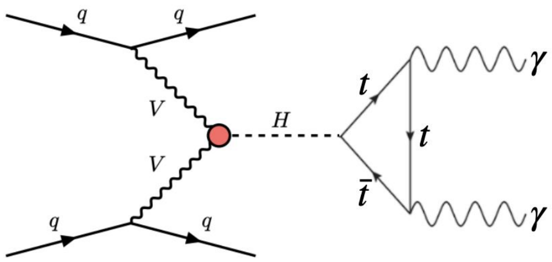
CP-odd Wilson coefficients limits 68% and 95% CLs



- Shape only fit
  - Signal normalization floated in the fit
  - CP-odd sensitivity only
- Linear + quadratic terms
- The results are consistent with SM expectations
- No sign of CP-violation

VBF H→γγ

Phys. Rev. Lett. 131 (2023) 061802



Optimal Observable

$$OO = 2\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}})/|\mathcal{M}_{\text{SM}}|^2$$

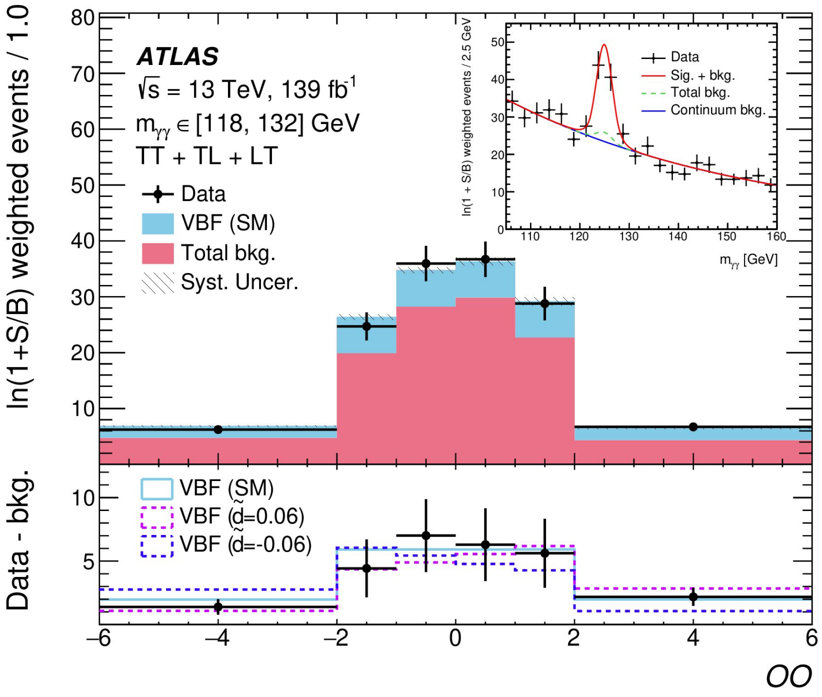
EFT bases

- Warsaw: $c_{H\tilde{W}}$
- HISZ: $\tilde{d}$

Interpretation

- Interference only term
- Interference + quadratic

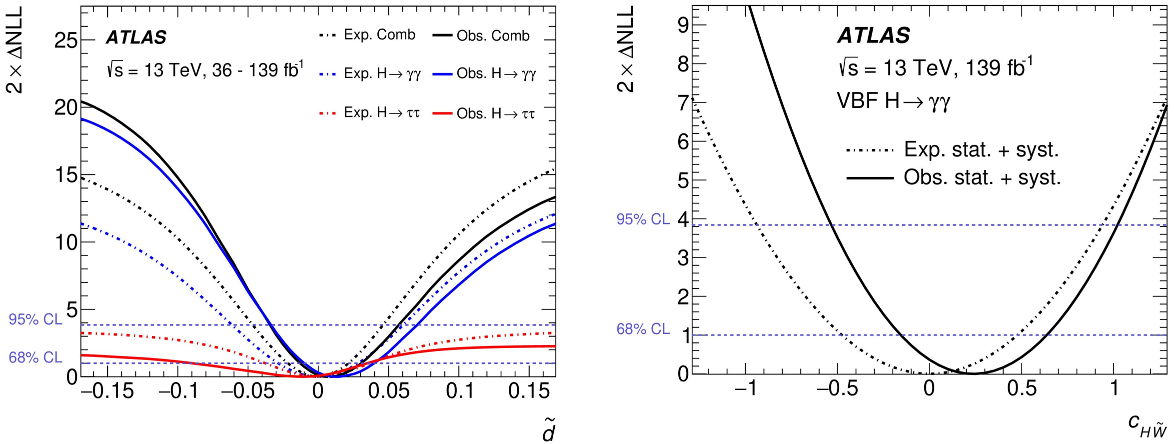
Optimal Observable distribution



VBF $H \to \gamma\gamma$

Phys. Rev. Lett. 131 (2023) 061802

Negative log-likelihood scans



- **Shape only fit**
  - Signal normalization float in the fit
- **NLL scans** for various $c_{H\tilde{W}}$ and $\tilde{d}$ hypotheses.
- **Inter only** and **Inter+quad fit**

95% CL, Interference only term

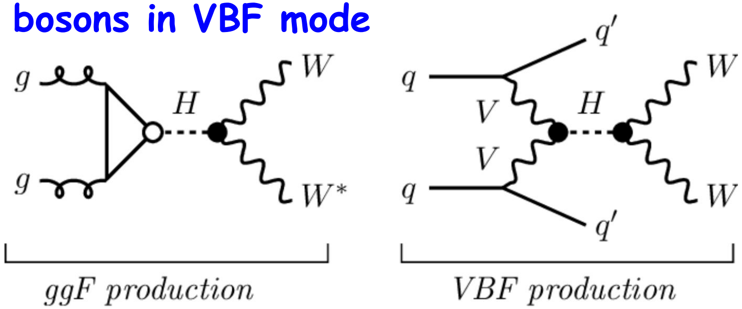
- $\tilde{d}$: [-0.032,0.059]
- $c_{H\tilde{W}}$: [-0.53,1.02]

- The results compatible with SM
- **Precision** is limited by statistical uncertainty
- No sign of CP violation
- **Small difference** between **Inter only** and **Inter+quad**

$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$

arXiv:2504.07686 **NEW**

Direct probes Higgs boson couplings to W/Z bosons in VBF mode



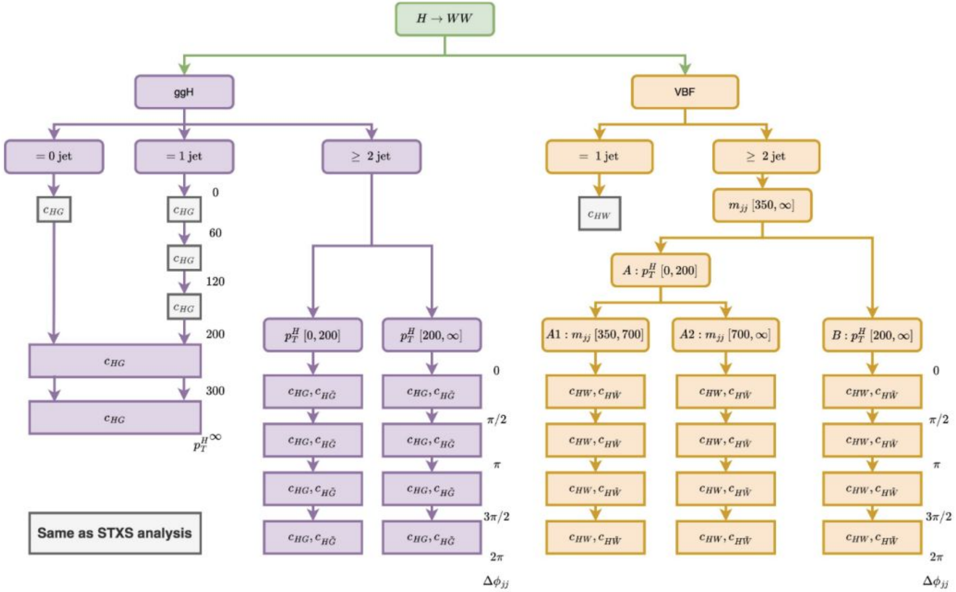
CP-sensitive angular observable: $\Delta\phi^{\pm}_{jj}$

- Signed azimuthal difference between two leading jets
- Four bins:
  - $[-\pi, -\pi/2), [-\pi/2, 0), [0, +\pi/2), [+\pi/2, \pi)$

EFT interpretation:

- Warsaw basis
  - c_{HG}, c_{HW} - CP-even
  - $c_{H\tilde{G}}$, $c_{H\tilde{W}}$ - CP-odd

Simplified Template Cross-Section (STXS) scheme



Categorization:

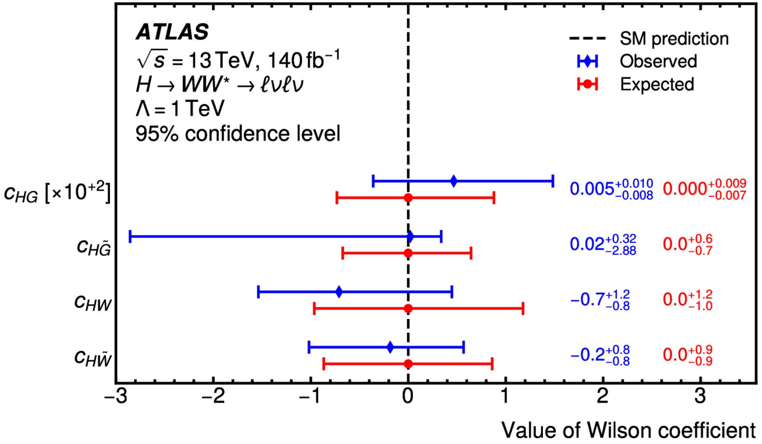
- Njets, Higgs transverse momentum p_T^H
- Di-jet invariant mass m_{jj}
- $\Delta\phi^{\pm}_{jj}$

$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$

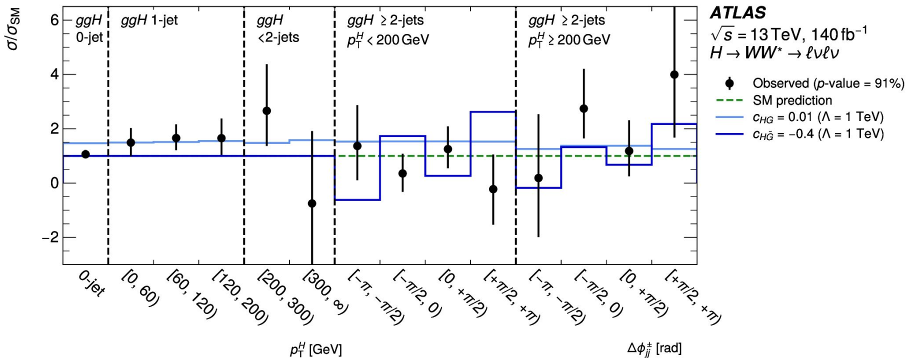
arXiv:2504.07686 NEW

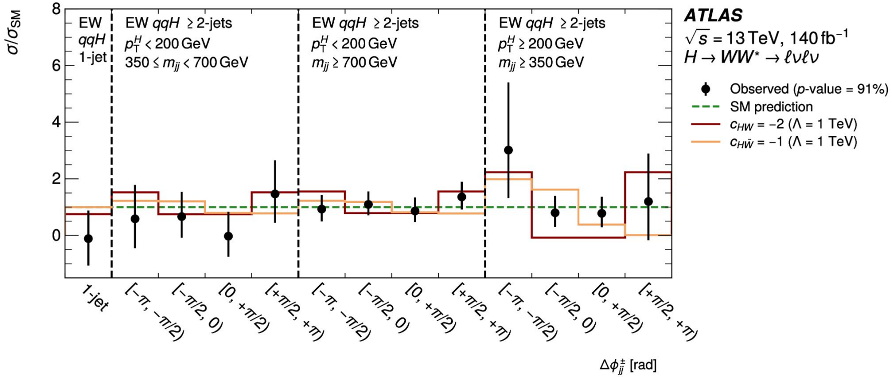
- Deep Neural Network (DNN)
  - To identify signal topology
- Shape only fit
  - Signal normalization floated in the fit
- No signs of CP violation
- The correlation between different Wilson coefficients is **less than 5%**

Wilson coefficients limits



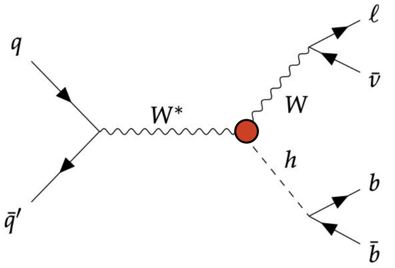
Signal strength in STXS bins normalised to SM predictions





WH ($H\to bb$)

ATL-PHYS-PUB-2025-022 NEW



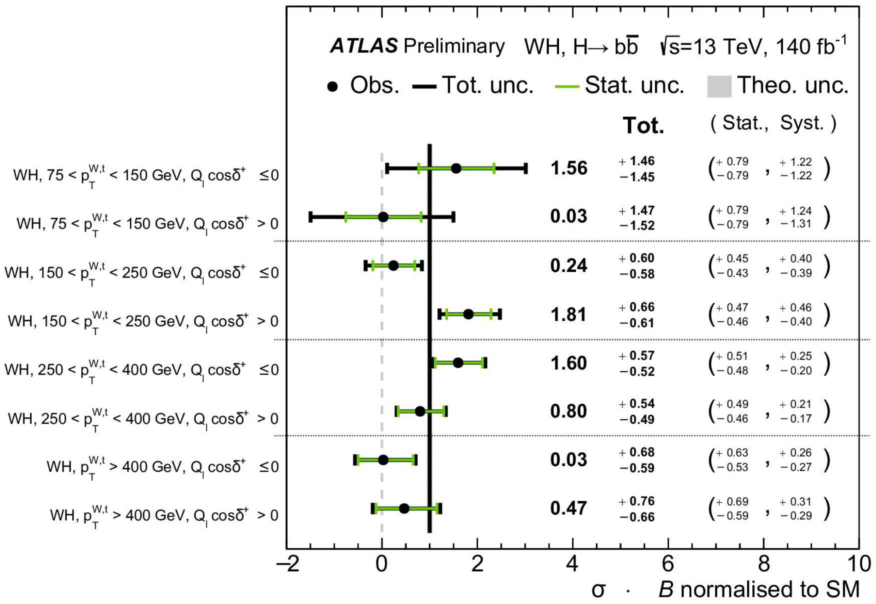
Observables:

Angular: $Q_\ell \cos\delta^+$

Energy-related: p_T^W

$$Q_\ell \cos\delta^+ = Q_\ell \frac{\vec{p_\ell}^{(W)} \cdot (\vec{p_H} \times \vec{p_W})}{\left|\vec{p_\ell}^{(W)}\right| |\vec{p_H} \times \vec{p_W}|}$$

Measured *WH* production cross sections times branching ratios



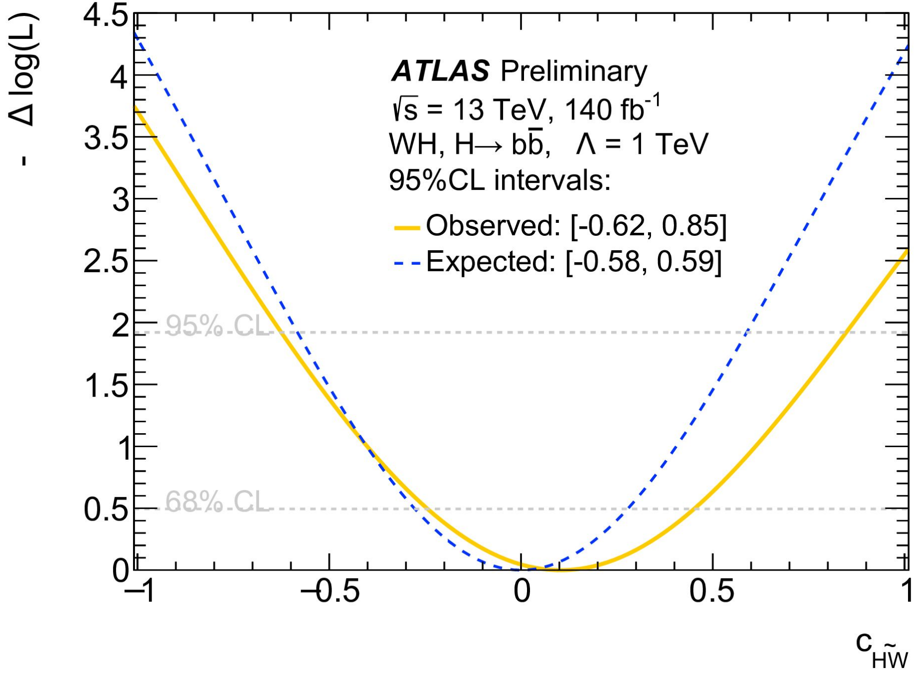
- STXS measurements
  - $p_T^W \times Q_\ell \cos\delta^+$ categorization
- EFT interpretation:
  - Warsaw basis: $c_{H\tilde{W}}$
  - **SM-SMEFT interference** term only

Analysis strategy from:
- ATLAS VH ($H\to bb/cc$) arxiv:2410.19611

- The results are in agreement with the SM expectations

WH (H→bb)

ATL-PHYS-PUB-2025-022 **NEW**



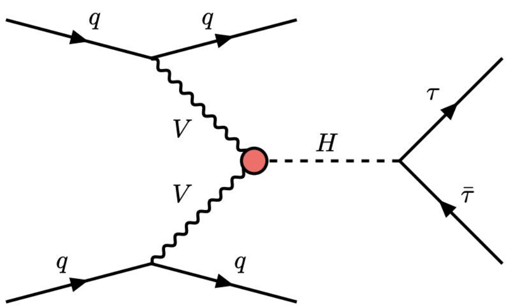
95% CL $c_{H\tilde{W}}$: [-0.62,0.85]

- Shape only fit
  - Signal normalization float in the fit
- In agreement with SM expectation
- **No CP violation observed**
- Among the most stringent results
  - Fewer assumptions on other coefficients
  - **Sensitivity only to $c_{H\tilde{W}}$**

VBF $H \to \tau\tau$

arXiv:2506.19395

NEW



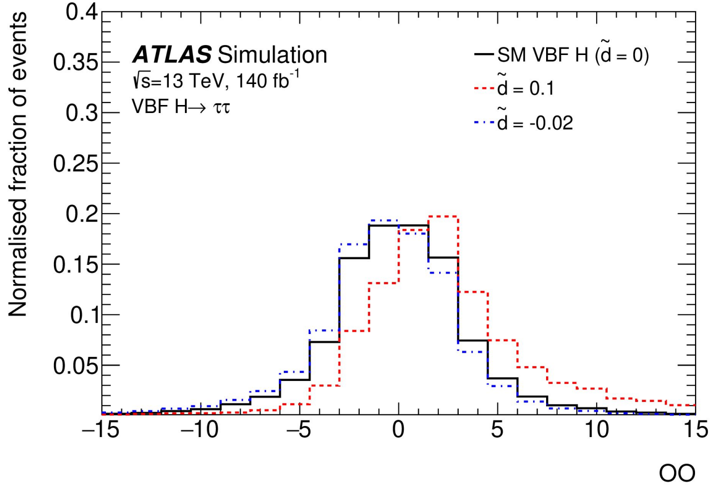
EFT interpretation:

- HISZ basis: $\tilde{d}$ ($c_{H\gamma\gamma}$, c_{HZZ}, c_{HWW}, $c_{H\gamma Z}$)
- Warsaw basis: $c_{H\tilde{W}}, c_{H\tilde{B}}, c_{H\tilde{W}B}$

CP-odd optimal observables

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

Optimal observable distribution



Three combination of τ-lepton decay:

- $\tau_{had}\tau_{had}$ - fully hadronic
- $\tau_{lep}\tau_{had}$ - semileptonic ($\tau_{lep} \to \ell\nu\nu$)
- $\tau_{lep}\tau_{lep}$ - leptonic ($e\nu\nu$, $\mu\nu\nu$)
  - Same-flavours leptonic decays rejected

VBF H→ττ

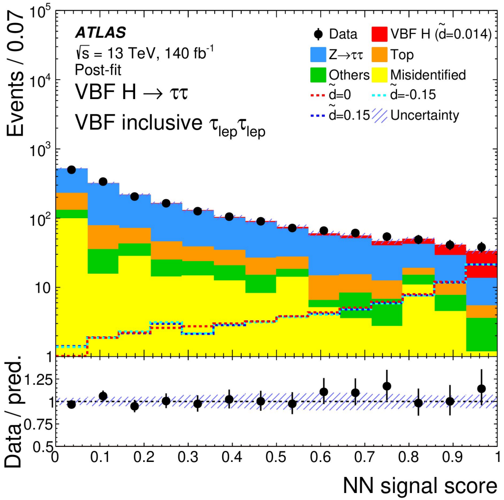
arXiv:2506.19395 **NEW**

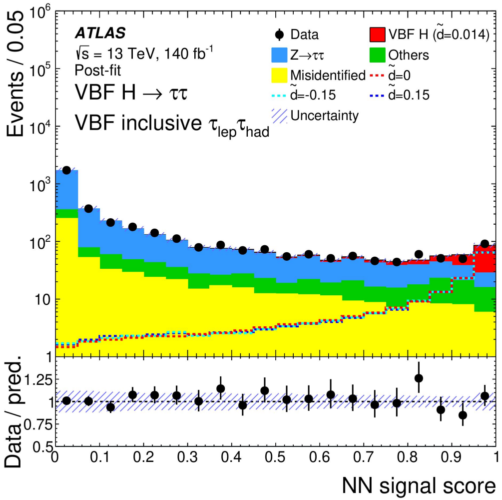
Neural Network is used to construct SR

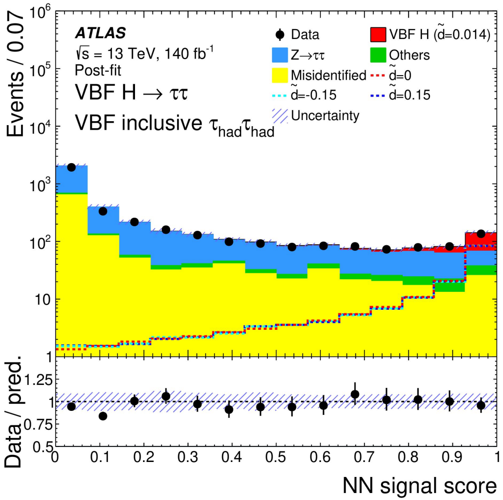
- Separate for each channel
- Trained on VBF Higgs SM
- Tested for different CP-odd hypothesis
  - Consistent with SM, no biases

Main backgrounds:

- **Z(→ττ)+jets**
  - Estimated using **object-level embedding**
- misidentified τ candidates,
- top-quark processes, multi-boson production





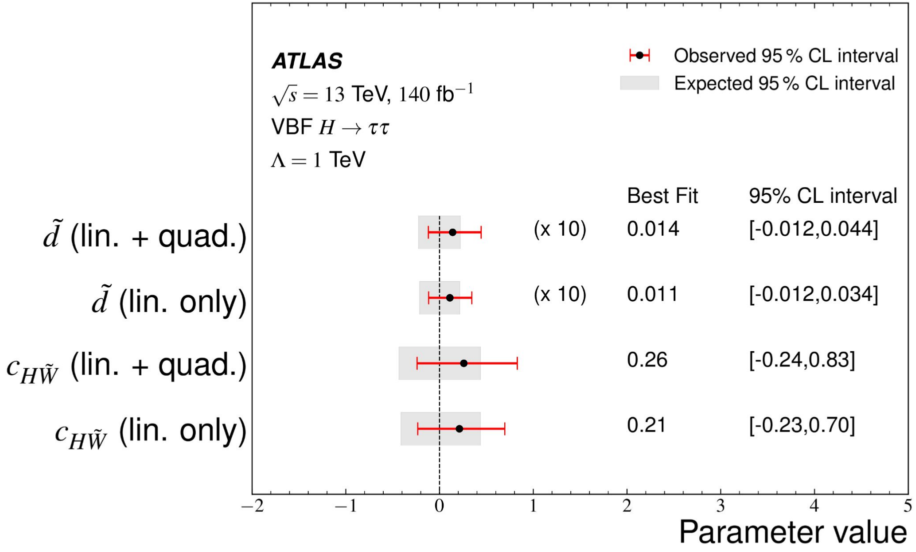


VBF $H\rightarrow\tau\tau$

arXiv:2506.19395 NEW

- Negative log likelihood scan (NLL) to get sensitivity to CP-odd coupling
- SRs are binned in OO
- Shape only fit
  - Signal normalization float in the fit
- Expected results from OO fit also compared with fits using other observables:
  - **5% stronger** than using $2p_{T+}p_{T-}\sin(\Delta\phi^{sign}_{jj})$
  - **30% stronger** than using $\Delta\phi^{sign}_{jj}$
- Adding quadratic term gives small difference
- The results are consistent with SM expectation
- No sign of CP-violation

Wilson coefficients limits



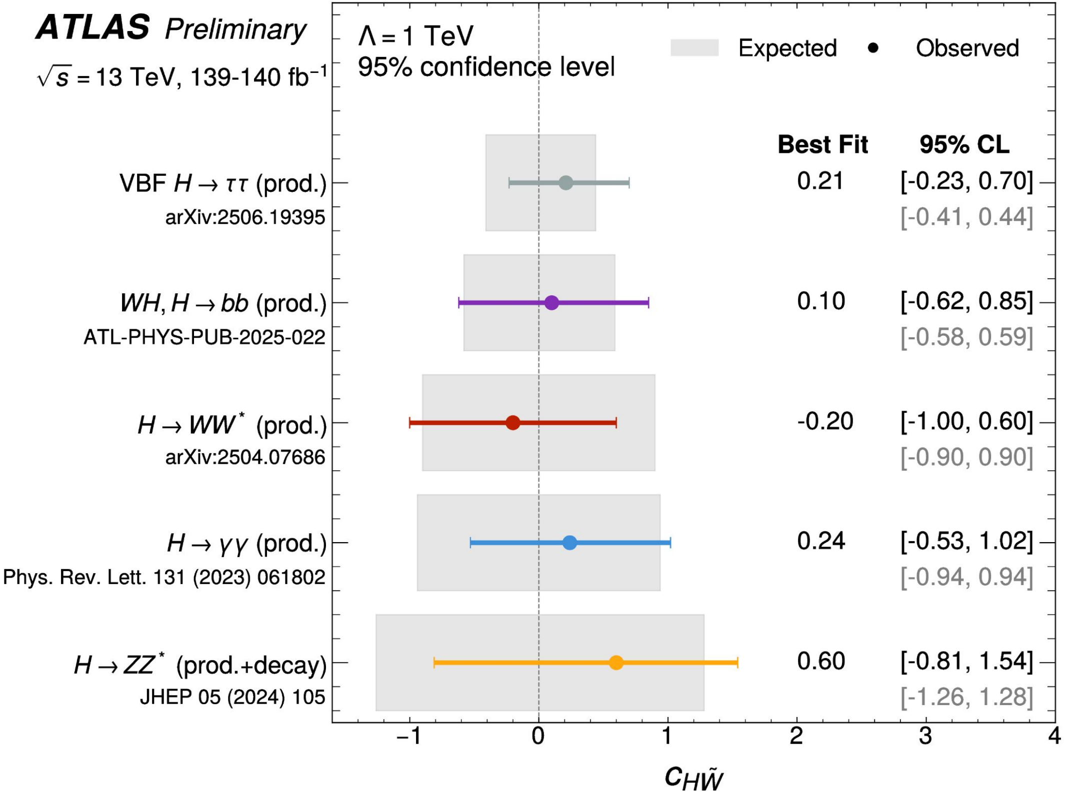
Among the most stringent limits

95% CL lin+quad:

$\tilde{d}$: [-0.012,0.044]

$c_{H\tilde{W}}$: [-0.24,0.83]

Summary plot: $c_{H\tilde{W}}$ limits



- 95% CL $c_{H\tilde{W}}$ comparison, Λ = 1 TeV
- **Linear only** interpretation
  - Except $H \to ZZ^* \to 4\ell$: negligible impact from quadratic term
- $H \to WW^*$ simultaneous fit to c_{HG}, $c_{H\tilde{G}}$, c_{HW}, $c_{H\tilde{W}}$
  - Correlations < 5%

Different measurements affected by different assumptions

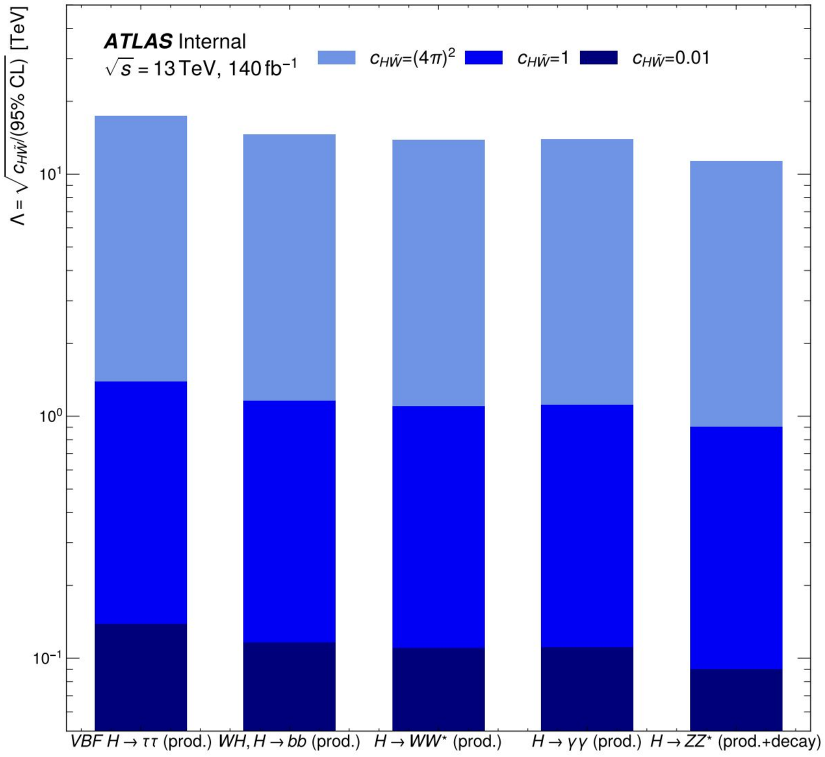
Summary

- **Five ATLAS searches for CP-violation in Higgs interactions with vector bosons** using the Run 2 dataset presented
  - **New results are reported for the channels:**
    - **VBF $H\to\tau\tau$, WH ($H\to bb$), $H\to WW^{*}\to\ell\nu\ell\nu$**
  - No evidence for CP-violation was observed in any channel
  - Limits on the relevant Wilson coefficients were set within the EFT framework
  - The combined measurements of the CP properties of Higgs boson to vector bosons are ongoing
- Extensive CP-measurements program from the ATLAS experiment in Run 2 in many different production channels and final states
- CP-measurements using Run 3 dataset are ongoing

Thank you

Back up

Summary 95% CL limits on Λ



- The limits are derived using the results from 5 analysis presented above.
- Asymmetric uncertainties are symmetrised using the root mean square.

Optimal observable

$$\mathcal{OO} = \frac{2\Re\left(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{BSM}}\right)}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

- Combines the information from different kinematic variables
- Higher sensitivity
- Defined by the ratio of the interference term in the matrix element (ME) to the SM contribution
- The mean value of the Optimal Observable can be experimentally measured
- In SM the distribution is symmetric witm mean value equal zero

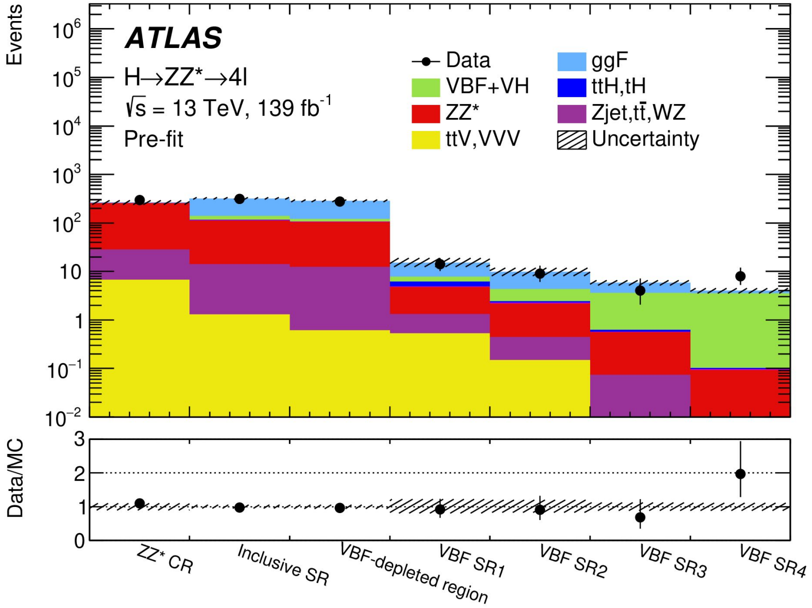
H→ZZ*→4ℓ

JHEP 05 (2024) 105

Three different fits:

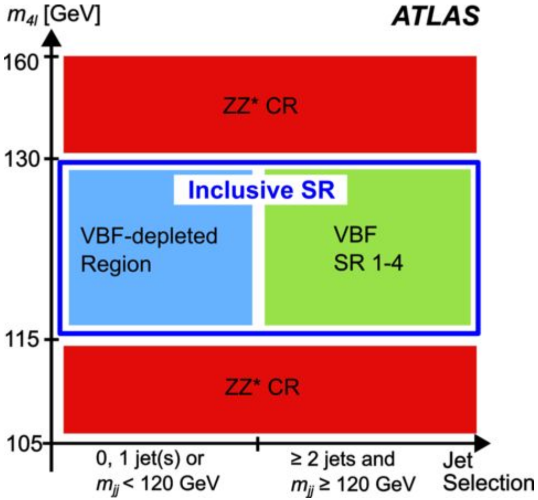
- Decay-only, production-only, combined

Dominant background: non-resonant ZZ*



Event categorization:

- Side band **ZZ* CR**
- **Inclusive SR** - for decay-only fit
- **VBF SRs** - for production-only fit
  - NN discrimination between VBF, VH, ggF
  - 2 VBF high purity SRs
  - 2 SRs with large ggF admixture



Morphing method

$$\sigma = \sum_{k=0}^{4} c^k A_k = \vec{c} \cdot \vec{A}, \quad \text{with} \quad \vec{c} = \left(1, c, c^2, c^3, c^4\right) \quad \text{and} \quad \vec{A} = (A_0, A_1, A_2, A_3, A_4)$$

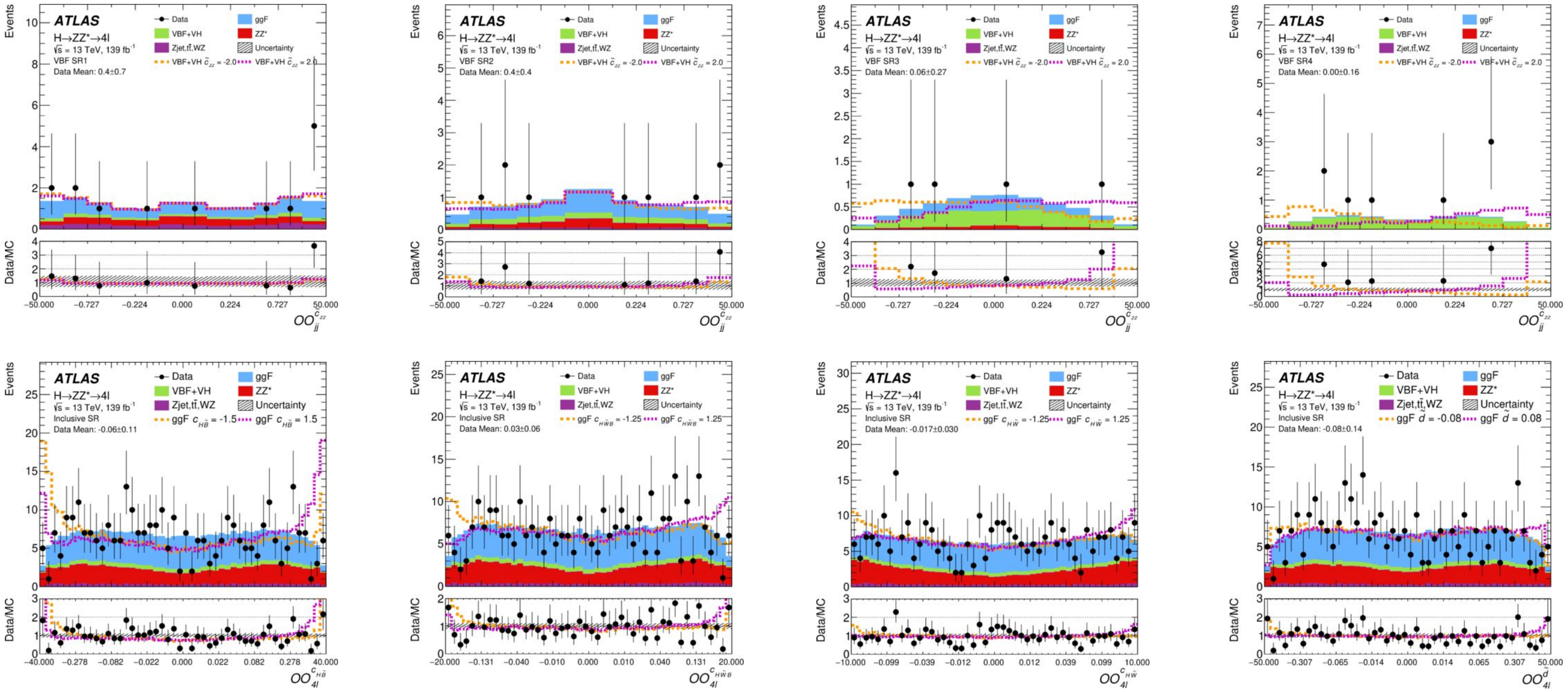
- The cross-section in each phase space bin is a polynomial function of the EFT coupling

$$\sigma = \vec{c} \cdot \vec{A} = \vec{c} \cdot \left(\vec{C}^{-1} \cdot \vec{\sigma}_{\text{simulated}}\right) = \sum_j \underbrace{\left(\vec{C}_j^{-1} \cdot \vec{c}\right)}_{w_j(\vec{c})} \sigma_j$$

- The cross-section is expressed as a linear combination of the existing, simulated cross-sections
- The weights to be applied to each of the simulated samples to obtain the signal prediction.
- The number of samples is determined by the number of unique coupling combinations for three BSM couplings and two (production and decay) HVV vertices

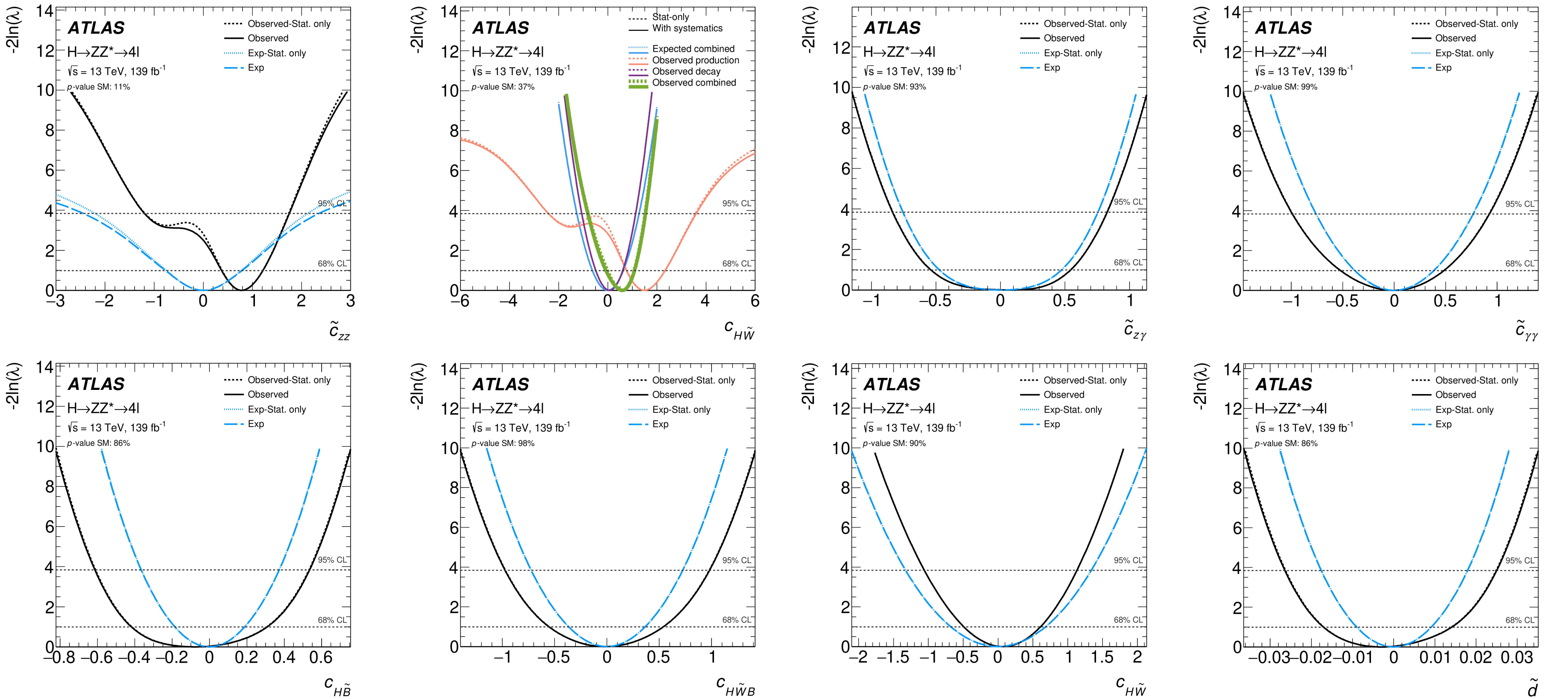
H→ZZ*→4ℓ: OO distributions

JHEP 05 (2024) 105

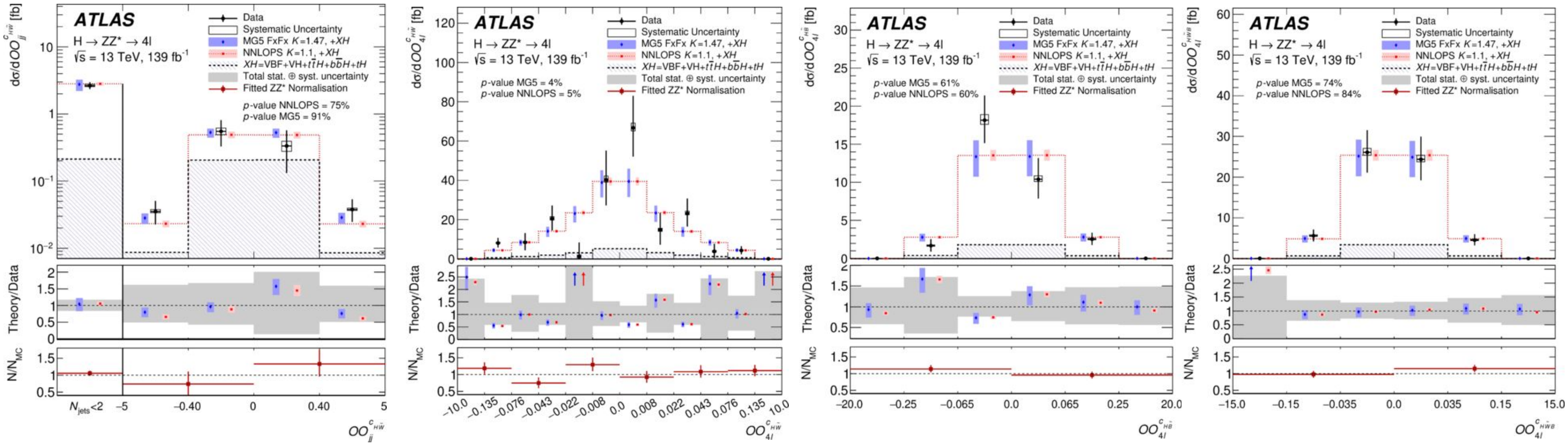


$H \to ZZ^* \to 4\ell$: NLL scans

JHEP 05 (2024) 105



Differential cross-section measurements



- Model-independent result
- Sensitive to possible BSM effects on both the yields and the shape
- Fiducial phase space unfolding

- All measurements are consistent with the SM
- No significant CP-odd component is observed

VBF $H\to\gamma\gamma$

Phys. Rev. Lett. 131 (2023) 061802

Interpretation

- Reweighting method

HISZ basis:

- 2 weights
- HAWK program

$$w_1 = 2\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}})/|\mathcal{M}_{\mathrm{SM}}|^2$$

$$w_2 = |\mathcal{M}_{\text{CP-odd}}|^2/|\mathcal{M}_{\mathrm{SM}}|^2$$

Warsaw basis:

$$\frac{d\sigma}{dOO} = \left(\frac{d\sigma}{dOO}\right)^{\mathrm{NLO}} \times \left(\frac{d\sigma}{dOO}\right)^{\mathrm{MG5}}_{c_{H\tilde{W}}} \Big/ \left(\frac{d\sigma}{dOO}\right)^{\mathrm{MG5}}_{c_{H\tilde{W}}=0}$$

- prediction from MadGraph using SMEFTSim
- NLO SM VBF signal sample

VBF $H \to \gamma\gamma$

Phys. Rev. Lett. 131 (2023) 061802

	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]

VBF H→γγ

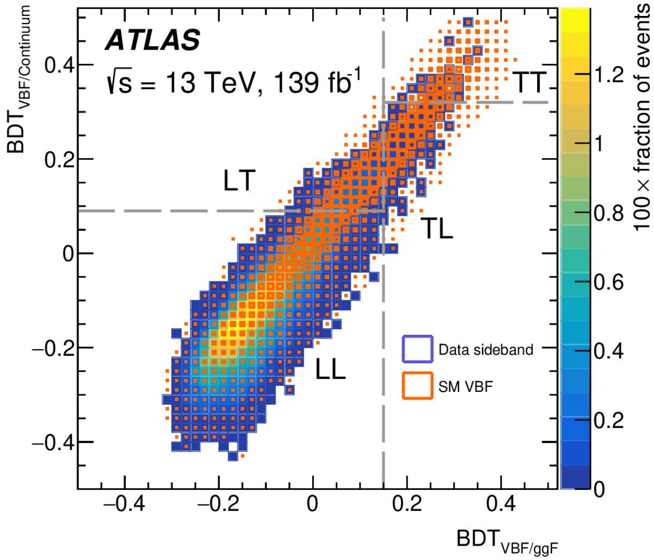
Phys. Rev. Lett. 131 (2023) 061802

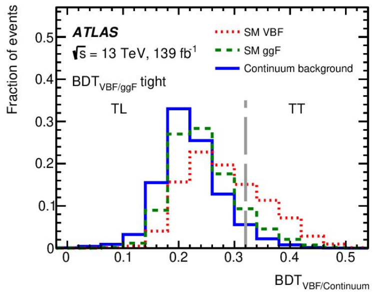
BDT trees

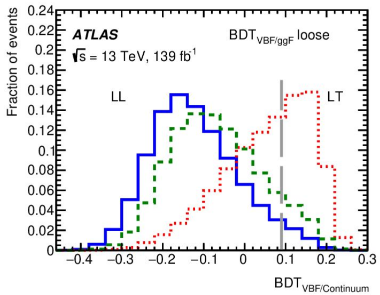
- To separate VBF signal from ggF
- To distinguish signal from continuum background
  - Prompt di-photon events
  - Misidentified jets as photons

- **T** (tight)/**L**(loose) BDT regions
- **VBF signal / ggF** about 10 for tight region

Event categorization



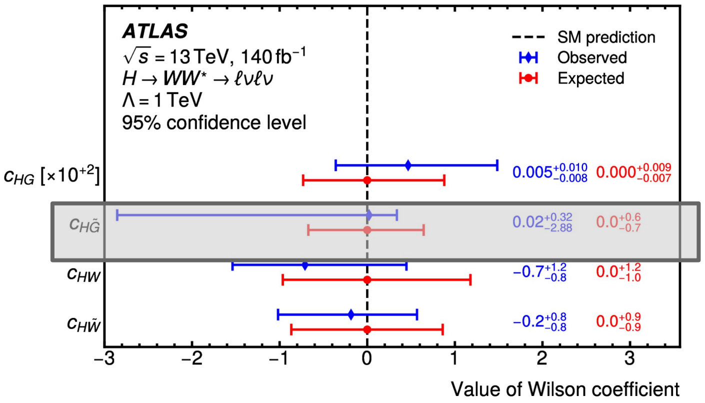




$H \to WW^* \to \ell\nu\ell\nu$

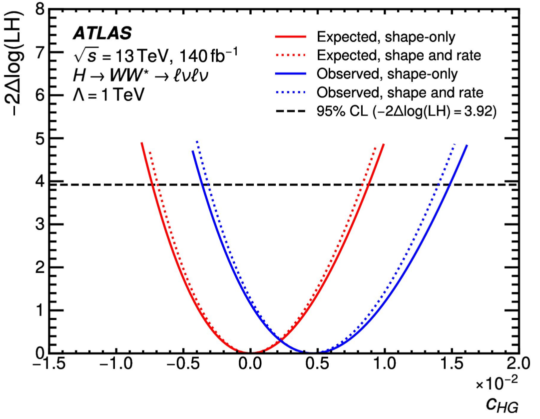
arXiv:2504.07686

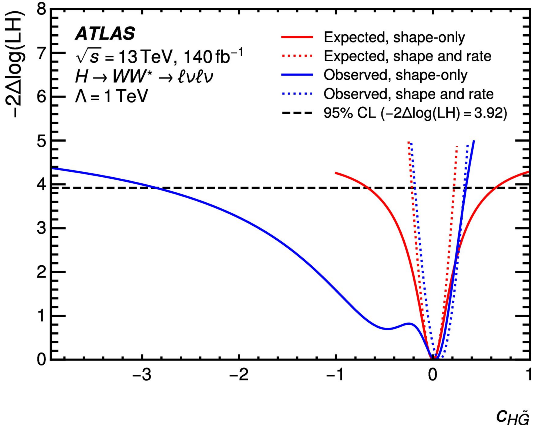
NEW

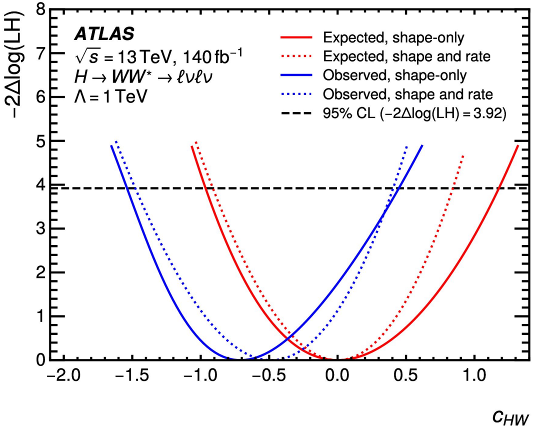


The asymmetry between the lower and upper uncertainties for the observed value of $c_{H\tilde{G}}$:

- Floating the signal NFs significantly broadens the likelihood curve
- The operator associated with $c_{H\tilde{G}}$ induces large absolute yield variations in $\Delta\phi \pm jj$ bins (i.e. 375%)
- second local minimum at $c_{H\tilde{G}}$=-0.4

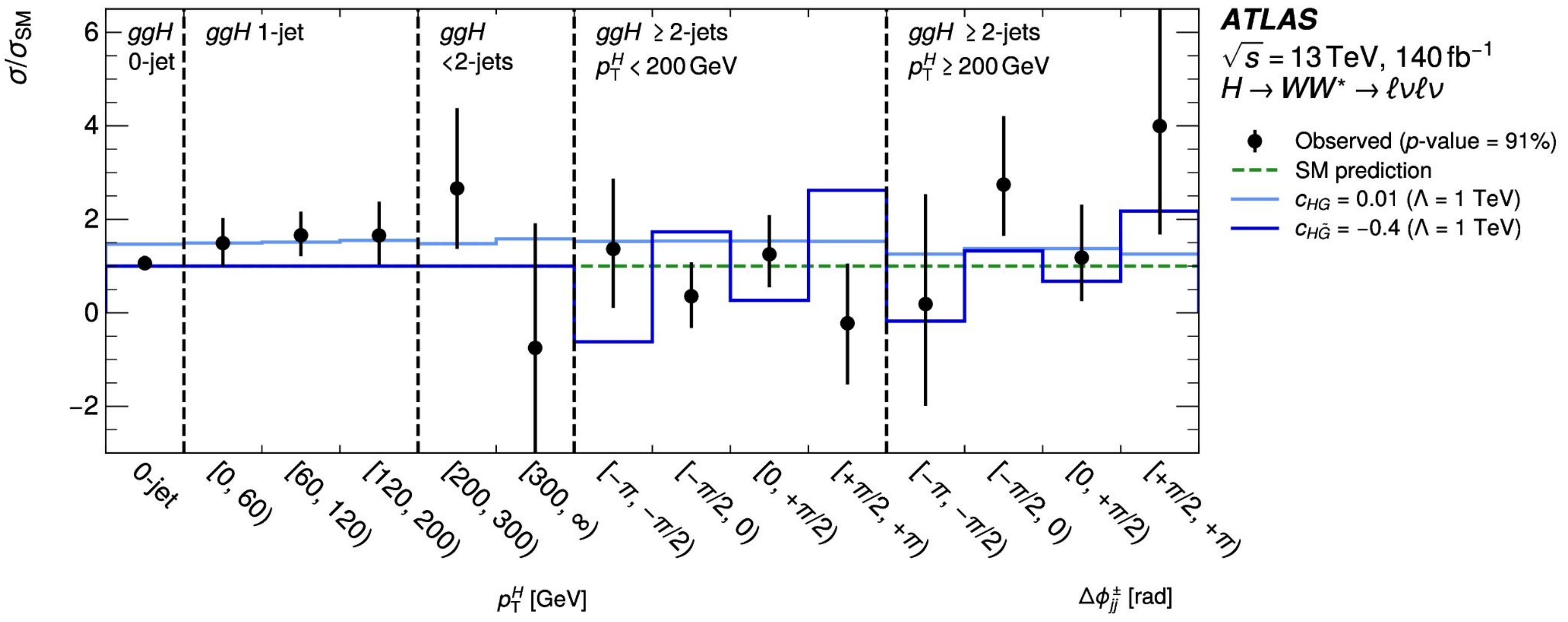






$H \to WW^* \to \ell\nu\ell\nu$

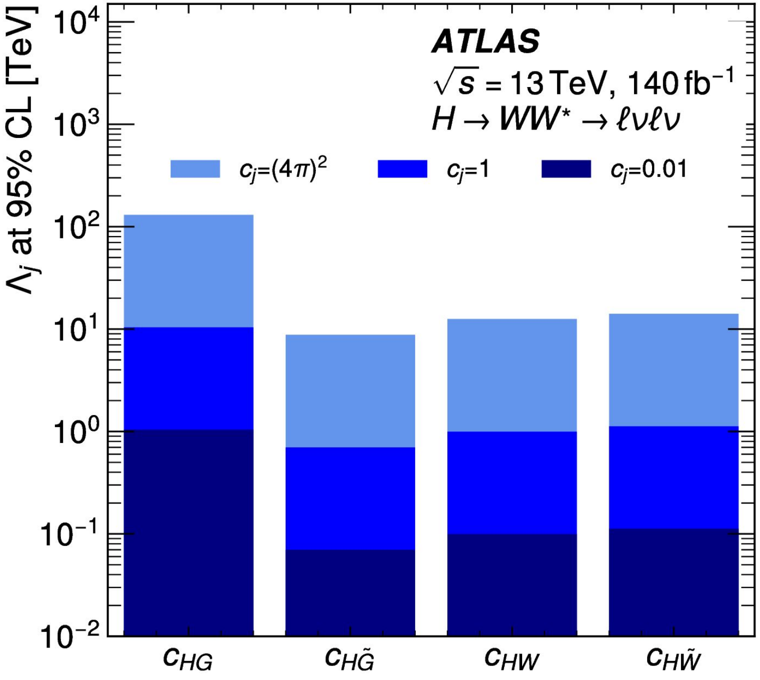
arXiv:2504.07686 **NEW**



- The measured ggH ≥2-jets STXSCP POIs exhibit opposite trends below and above pHT = 200 GeV

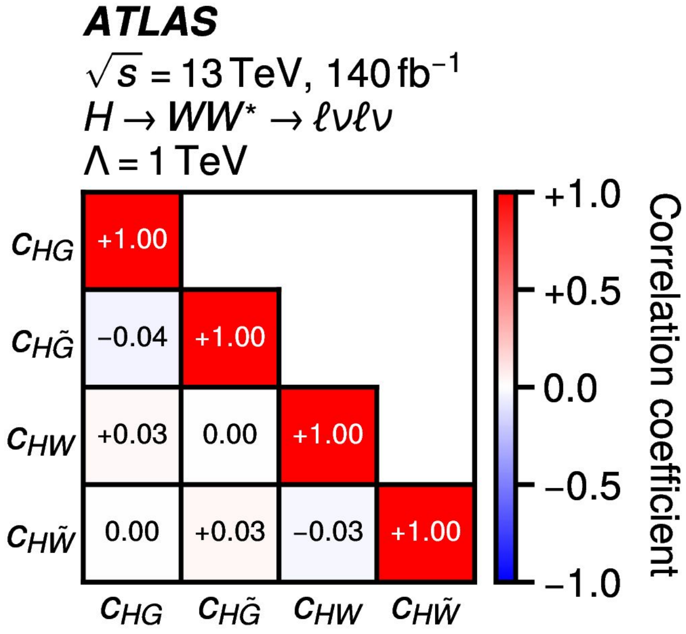
$H \to WW^* \to \ell\nu\ell\nu$

arXiv:2504.07686 NEW



Limits on energy scale Λ:

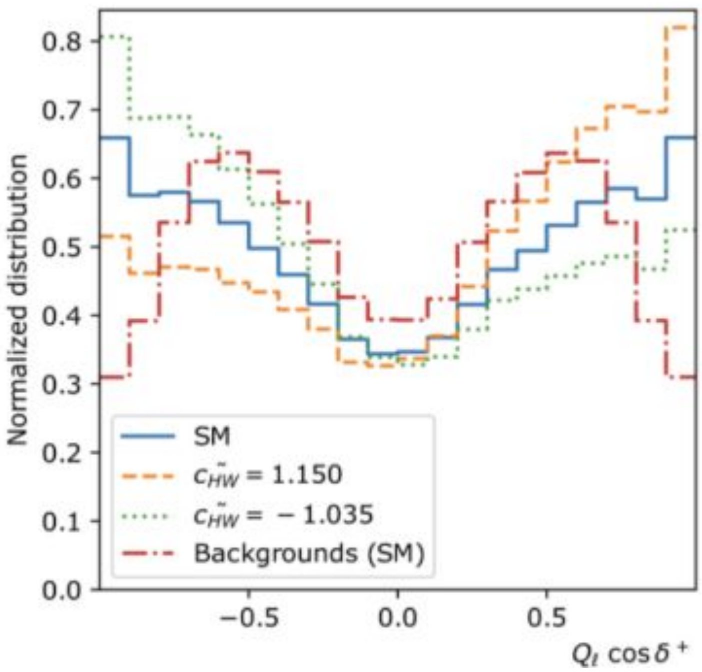
- 100 TeV - for c_{HG}
- 10 TeV - for c_{HW}, $c_{H\tilde{W}}$, $c_{H\tilde{G}}$



WH ($H \to bb$)

ATL-PHYS-PUB-2025-022 NEW

Angular observable distribution



JHEP04(2024)014

$$\cos\delta^+ = \frac{\mathbf{p}_\ell^{(W)} \cdot (\mathbf{p}_H \times \mathbf{p}_W)}{|\mathbf{p}_\ell^{(W)}| \cdot |\mathbf{p}_H \times \mathbf{p}_W|}$$

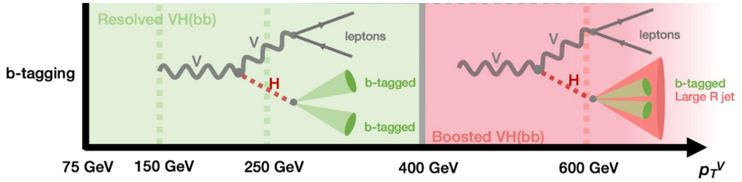
$Q_\ell \mathrm{Cos}\delta^+$

- Symmetric for SM
- asymmetric for $c_{H\tilde{W}} \neq 0$

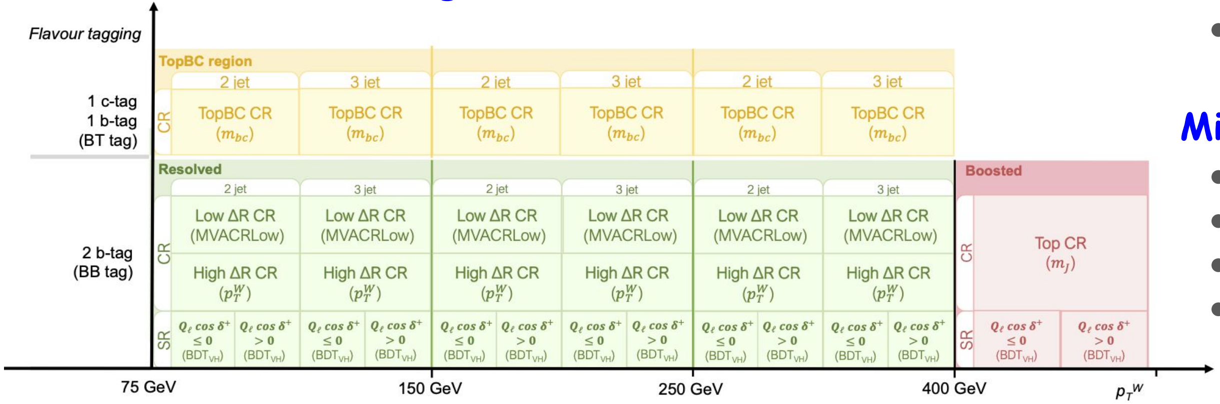
WH (H→bb)

ATL-PHYS-PUB-2025-022 **NEW**

Higgs candidate reconstruction : Resolved and boosted



Event categorization in SR and CRs



Signal WH process:

- Isolated lepton
- Missing transverse energy from the neutrino
- 2 b-jets in the final state

Dominant backgrounds:

- Top quark (ttbar, Wt)
- W+jets (mainly heavy flavoured)

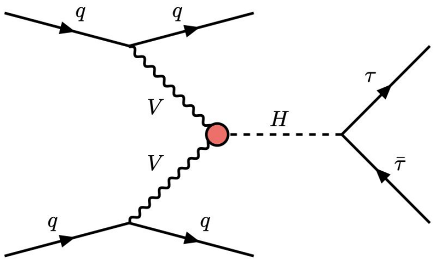
Minor backgrounds:

- Single top s/t-channels
- Diboson
- Z+jets
- Multijets

VBF H→ττ

arXiv:2506.19395

NEW



HISZ basis: CP-odd for the vertex HVV

$$\tilde{c}_{H\gamma\gamma} = \frac{g}{2m_W}(\tilde{d}\sin^2\theta_W + \tilde{d}_B\cos^2\theta_W) \qquad \tilde{c}_{H\gamma Z} = \frac{g}{2m_W}\sin 2\theta_W(\tilde{d} - \tilde{d}_B)$$

$$\tilde{c}_{HZZ} = \frac{g}{2m_W}(\tilde{d}\cos^2\theta_W + \tilde{d}_B\sin^2\theta_W) \qquad \tilde{c}_{HWW} = \frac{g}{m_W}\tilde{d},$$

Warsaw basis: CP-odd for the vertex HVV

$$\frac{c_{H\tilde{W}}}{\Lambda^2}H^\dagger H\tilde{W}^I_{\mu\nu}W^{\mu\nu I}, \frac{c_{H\tilde{B}}}{\Lambda^2}H^\dagger H\tilde{B}_{\mu\nu}B^{\mu\nu}, \frac{c_{H\tilde{W}B}}{\Lambda^2}H^\dagger H\sigma^I\tilde{W}^I_{\mu\nu}B^{\mu\nu},$$

- The two representations are not independent, and it is possible to transform one into the other

VBF H→ττ

arXiv:2506.19395

NEW

Signal sample production with non-vanishing values of CP violation in the HVV vertex

- Reweighting procedure based on EFT interpretation
- HISZ basis:
  - HAWK: the ratio of the squared ME value of the VBF process associated with a specific amount of CP mixing to that obtained from the SM
- Warsaw basis:
  - based on the OO distribution at different values of the Warsaw basis operator considered
  - MADGRAPH samples (MG5) for $c_i \neq 0$ obtained at Λ=1 TeV fixing all other Wilson coefficients to zero

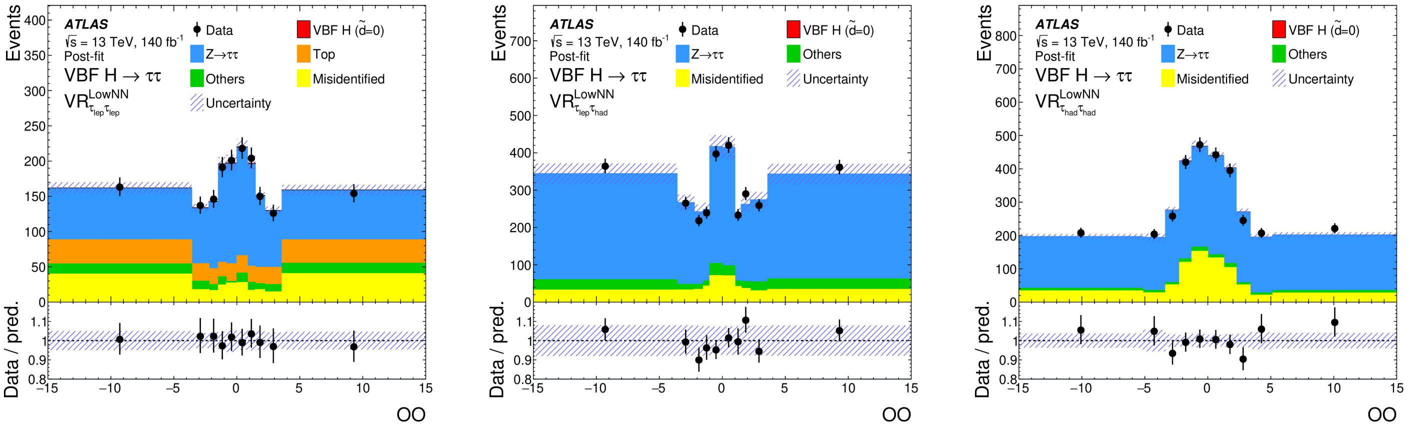
$$\frac{d\sigma}{dOO} = \left(\frac{d\sigma}{dOO}\right)^{\text{NLO}} \times \left(\frac{d\sigma}{dOO}\right)^{\text{MG5}}_{c_i} \Bigg/ \left(\frac{d\sigma}{dOO}\right)^{\text{MG5}}_{c_i=0}$$

VBF H→ττ

[arXiv:2506.19395](https://arxiv.org/abs/2506.19395) **NEW**

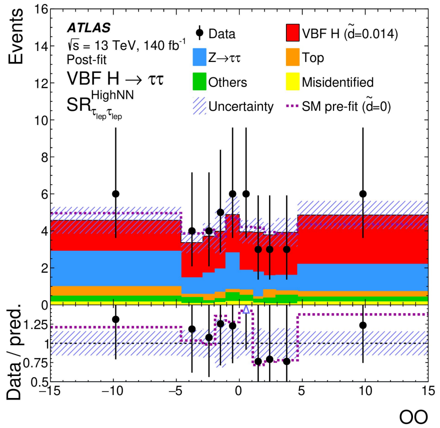
Background estimation:

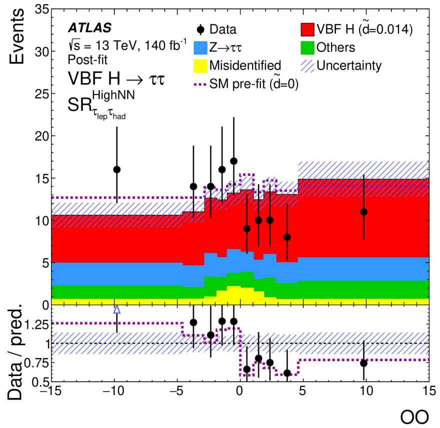
- **Z(→ττ)+jets**
  - Embedding procedure (arXiv: 1506.05623)
  - Relies on assumption that Z→ℓℓ (ℓ=e,μ) and Z→ττ kinematically identical
  - Z(→ℓℓ)+jets enriched templates
    - Momentum of reconstructed leptons scaled
- **Misidentified τ candidates**:
  - Estimated using data-driven method: Matrix method and fak-factor method (arXiv: 2211.16178)

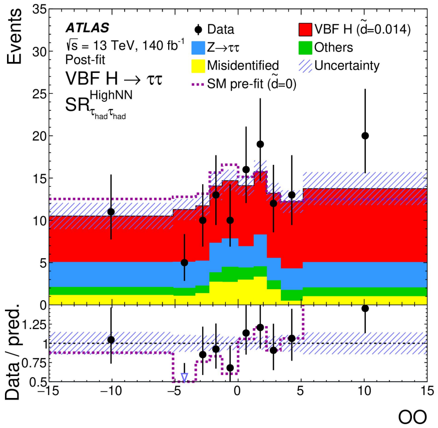


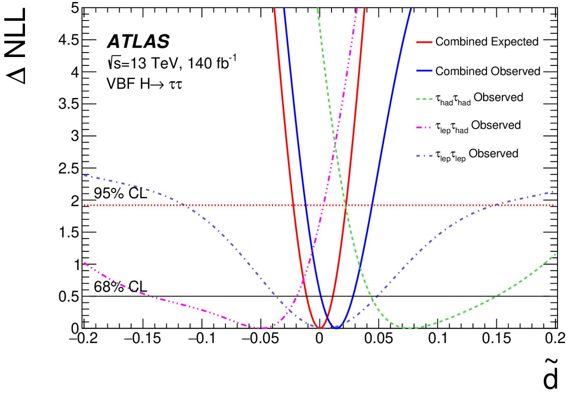
VBF H→ττ: post-fit OO, NLL scan

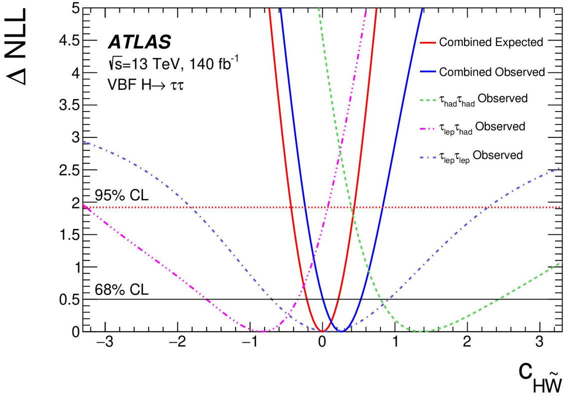
NEW











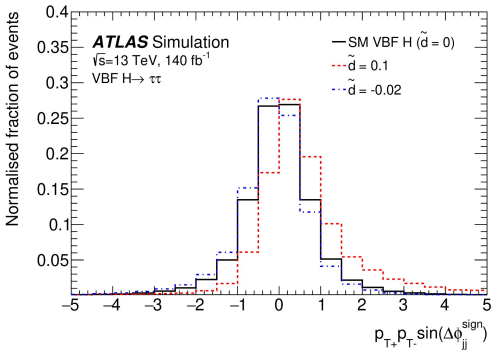
VBF $H\to\tau\tau$

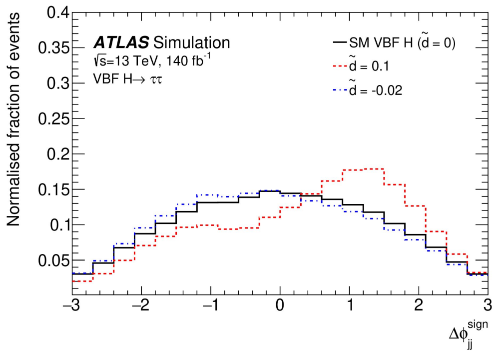
arXiv:2506.19395 **NEW**

- Expected results from OO fit also compared with fit from other observables:
  - **5% stronger** than using $2p_{T+}p_{T-}\mathrm{Sin}(\Delta\phi^{sign}_{jj})$
  - 30% stronger than using $\Delta\phi^{sign}_{jj}$

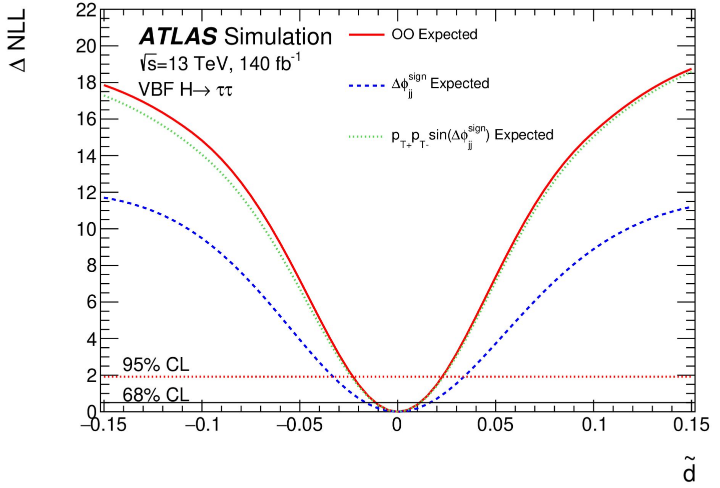
Other CP-odd observables

$2p_{T+}p_{T-}\sin(\Delta\phi^{sign}_{jj})$ $\Delta\phi^{sign}_{jj}$





NLL scans for fits with different observables

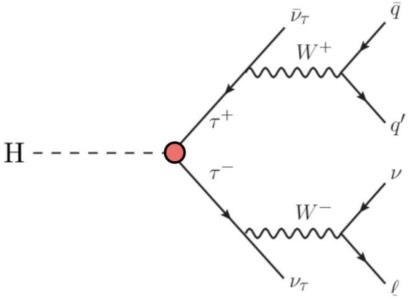


Higgs fermion couplings

Introduction

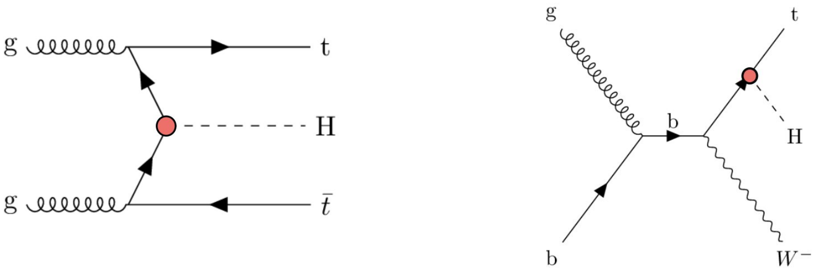
- **Higgs interactions with fermions → Yukawa couplings**
- **CP-odd contribution to Yukawa couplings**
  - Can be present at tree level
  - CP-odd component of HVV coupling suppressed by Λ

Higgs interaction with τ-leptons



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

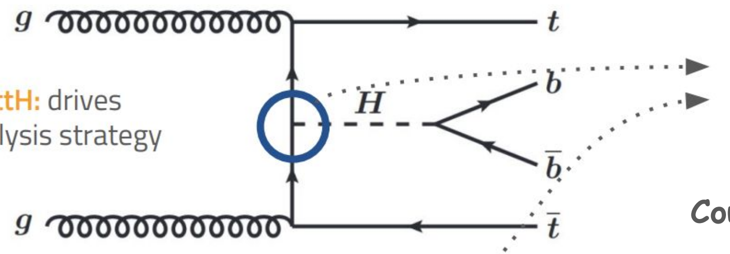
Top-Higgs Yukawa coupling in



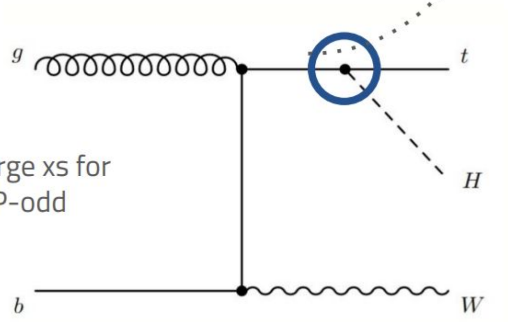
Phys. Lett. B 849 (2024) 138469

ttH/tH (H→bb)

[Phys. Lett. B 849 (2024) 138469]



ttH: drives analysis strategy



tH: large xs for CP-odd

SM extension:

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

Coupling modifier

SM Yukawa coupling strength

CP-mixing angle

SM case:

The analysis optimised for
Considered as signal

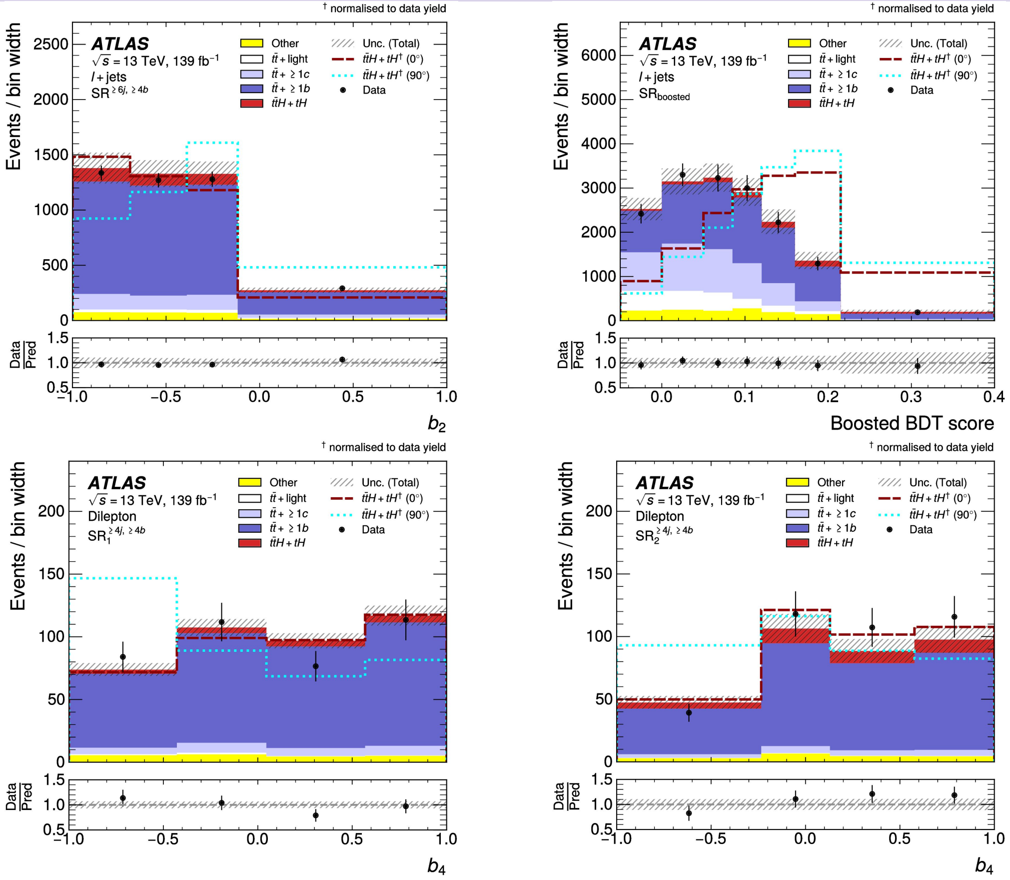
CP-sensitive observables:

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

→ **Simultaneous fit to define:**

ttH/tH (H→bb)

[Phys. Lett. B 849 (2024) 138469]

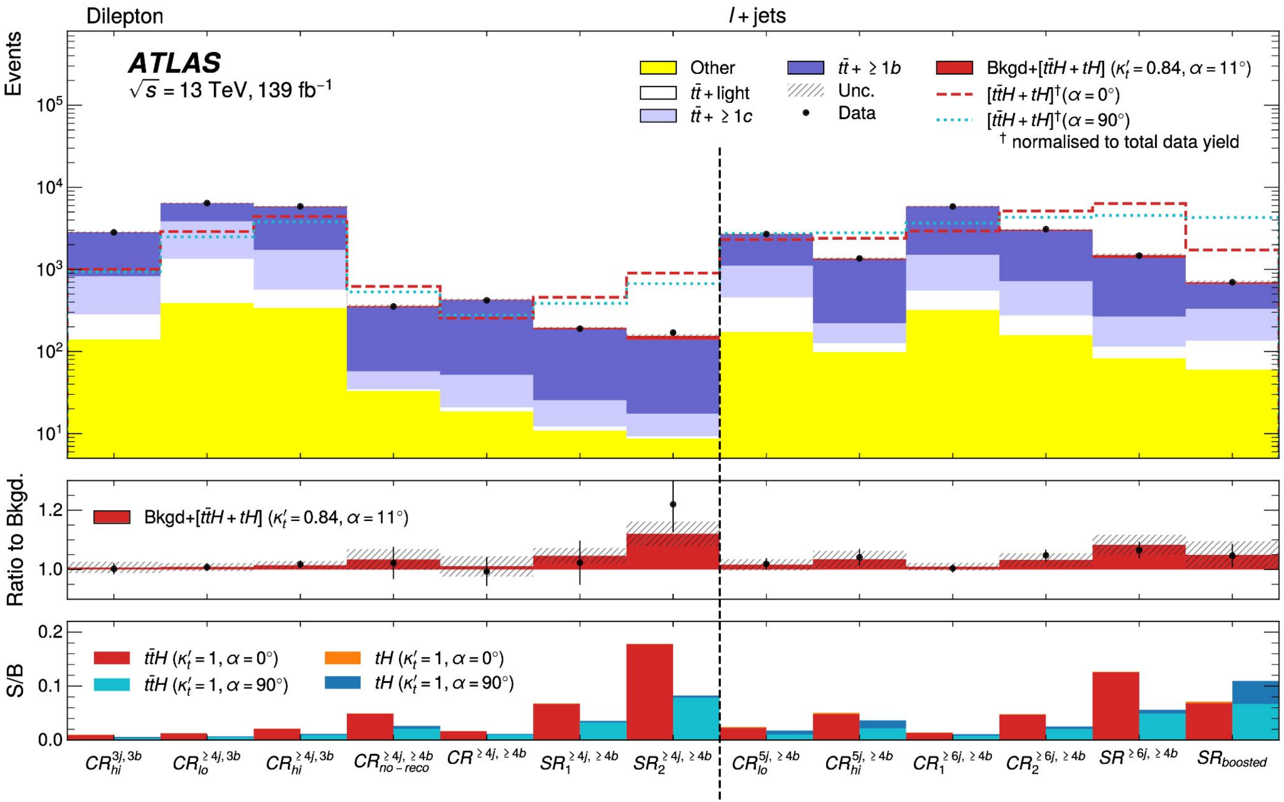


Post-fit distributions in SRs

- κ_t' - free parameters in the fit
- Red solid histogram - best fit signal with $\kappa_t' = 0.84$
- Dashed/dotted lines - predictions for pure CP-even and CP-odd hypothesis

ttH/tH (H→bb)

Phys. Lett. B 849 (2024) 138469



- Post-Fit plot
- Expected yields for pure CP-even and CP-odd signals (dashed lines)
-

ttH/tH (H→bb)

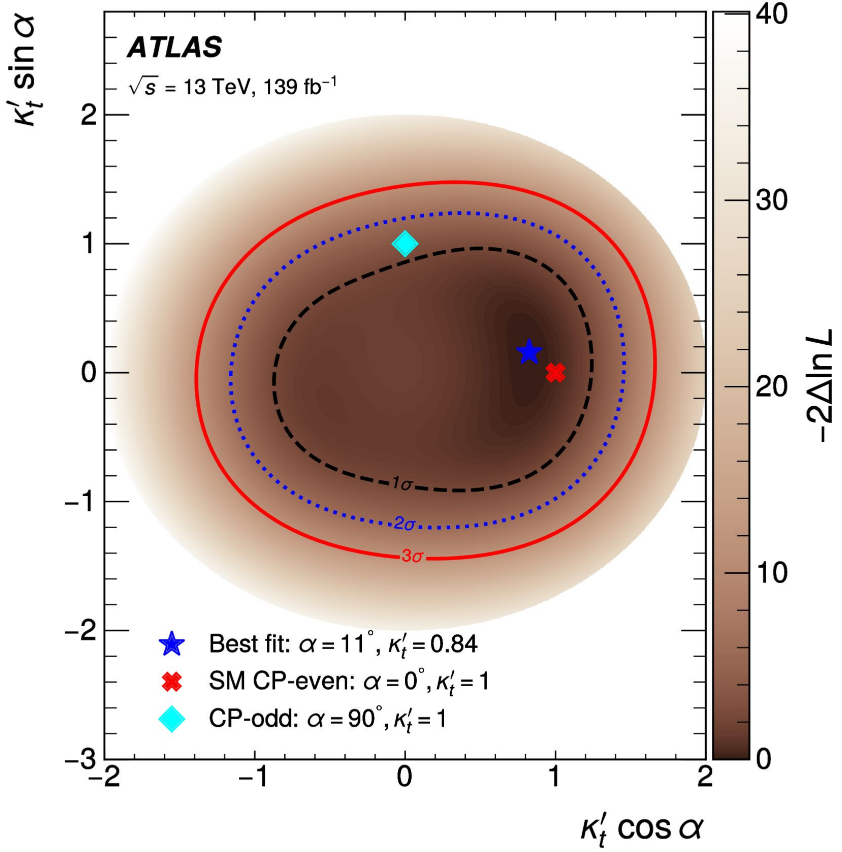
[Phys. Lett. B 849 (2024) 138469]

Event categorization

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

ttH/tH (H→bb)

Phys. Lett. B 849 (2024) 138469



$$\kappa'_t = 0.84^{+0.30}_{-0.46} \qquad \alpha = 11^{\circ}{}^{+52^\circ}_{-73^\circ}$$

- The results are consistent with SM
- First probe of the CP properties of the Higgs-top Yukawa coupling in this channel
- The pure CP-odd hypothesis disfavoured at 1.2σ

$H\rightarrow\tau\tau$

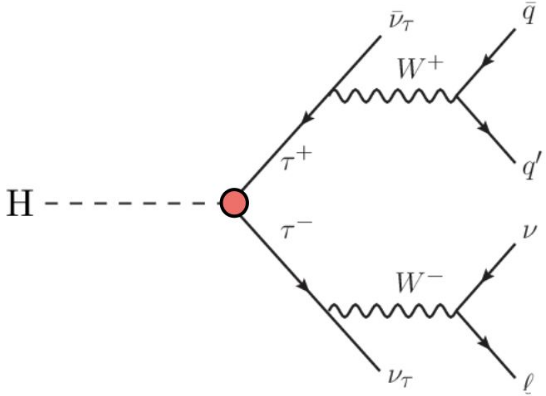
Eur. Phys. J. C 83 (2023) 563

Decay mode combinations of the τ-lepton pair and the corresponding methods to construct the φ^*_{CP} observable

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%

$H \to \tau\tau$

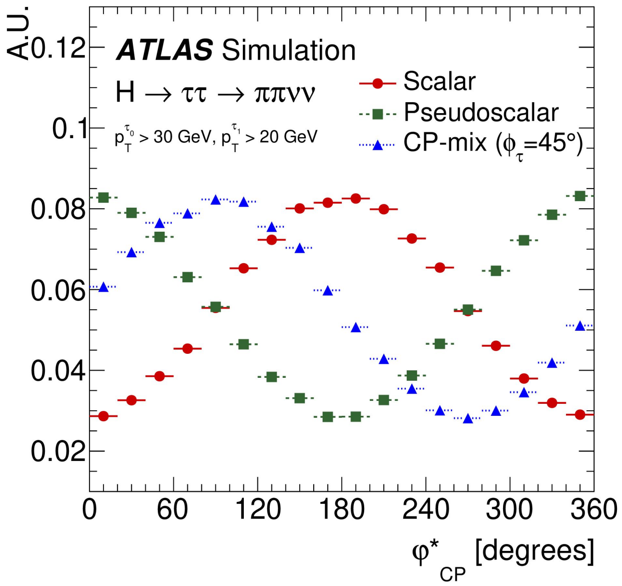
Eur. Phys. J. C 83 (2023) 563



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

Yukawa coupling strength

CP-mixing angle



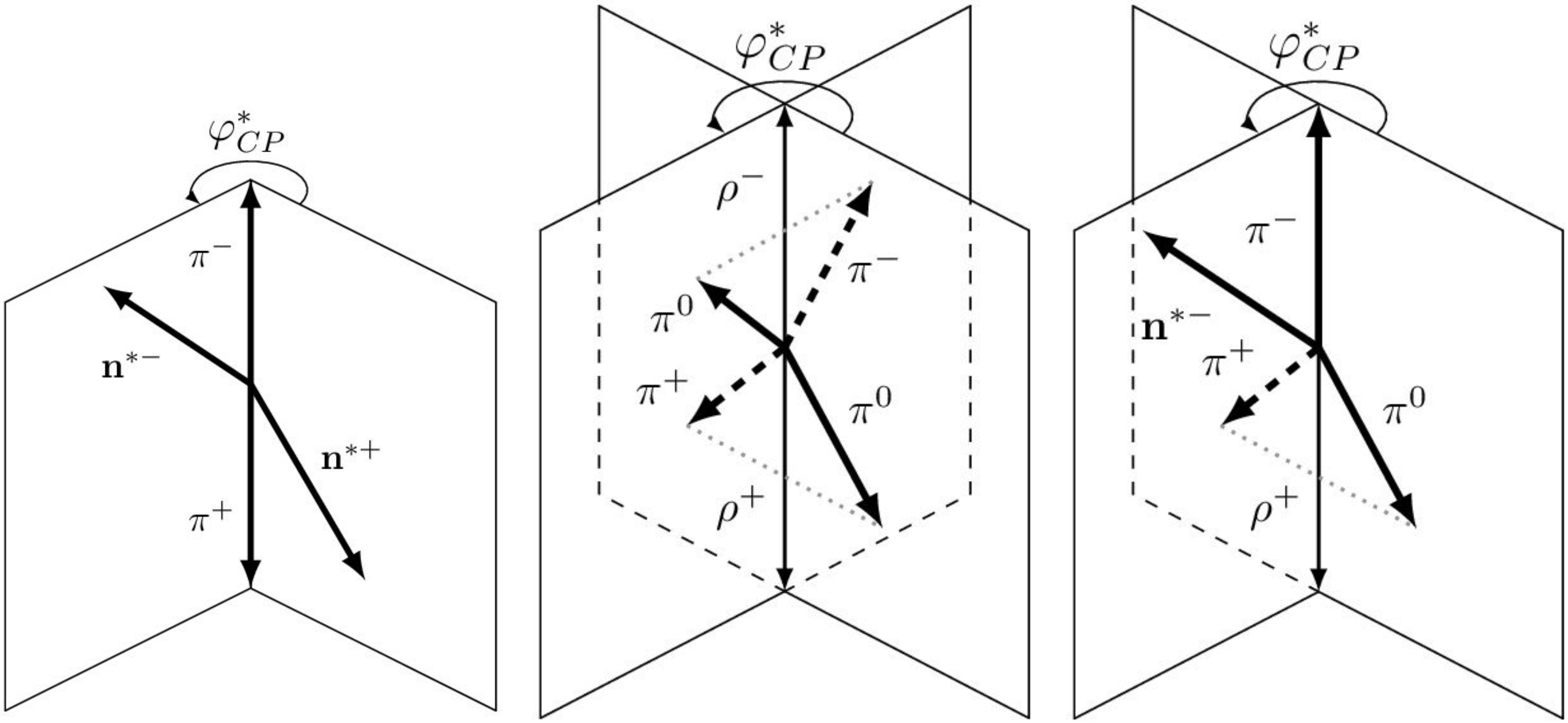
CP-sensitive angular observable φ^*_{CP}

- Signed acoplanarity angle between the τ-lepton decay planes
- Different reconstruction methods for different τ-decays

The analysis targets:

- τ_{lep}, τ_{had} - one leptonic and one hadronic τ-decays
- τ_{had}, τ_{had} - two hadronically decaying τ-leptons

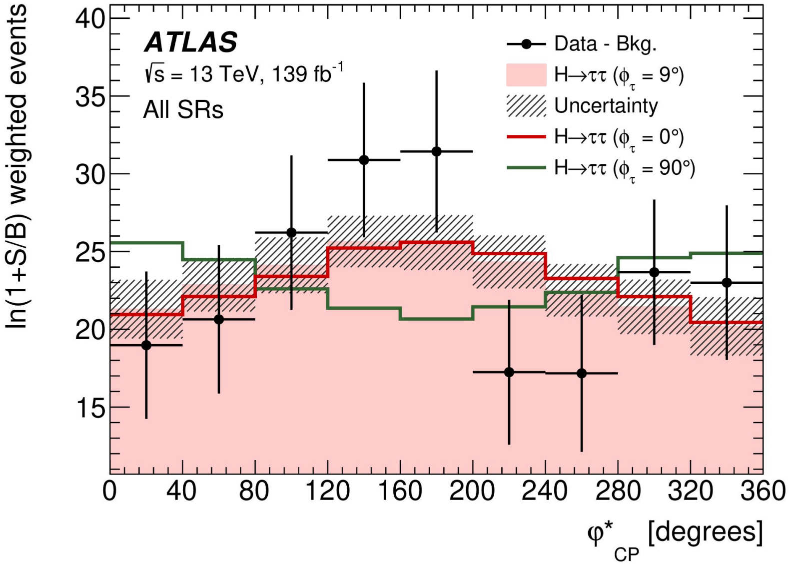
τ-lepton decay planes for constructing φ^*_{CP} observable



H→ττ

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

Combined post-fit distribution



Two VBF and two gluon-gluon Higgs production SRs

- **High, Medium, Low SRs**
  - Based on τ-decay mode
  - Different levels of sensitivity

Dominant backgrounds:

- **Z(→ττ)+jets**
  - Normalisation determined in dedicated CR
- **Jets misidentified** as hadronically decaying τ-leptons
  - Determined by data-driven approach using fake factors

Simultaneous likelihood fit as function of mixing angle ϕ_τ

- Free floating normalization on $Z\to\tau\tau$
- Higgs boson signal strength $\mu_{\tau\tau}$ left unconstrained
  - Only shape of φ^*_{CP} exploited

$H \to \tau\tau$

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

Event categorization

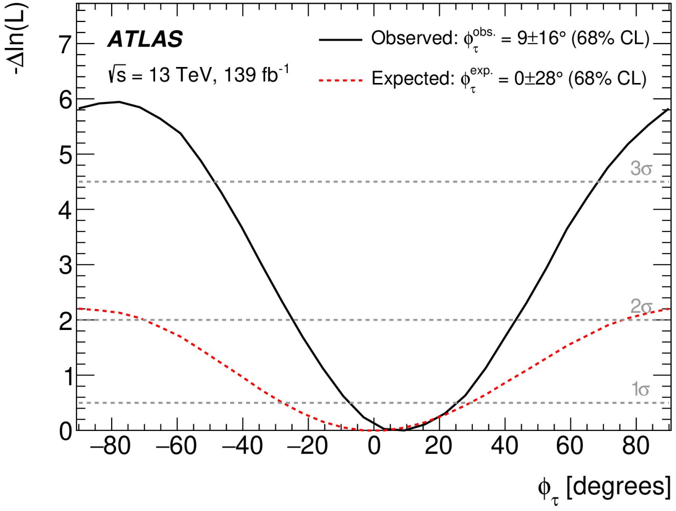
- VBF production
  - BDT based VBF tagger
- Gluon-gluon fusion

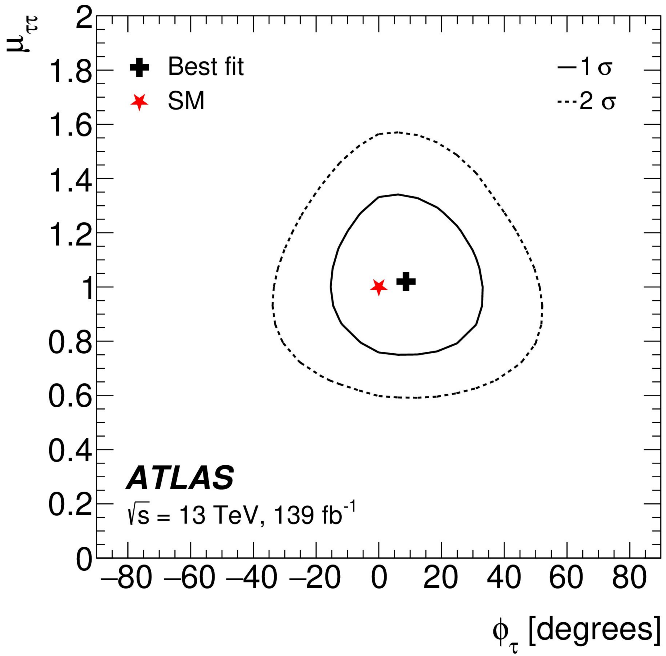
VBF		Boost	
$p_T^{j_2} > 30$ GeV $m_{jj} > 400$ GeV $\lvert\Delta\eta_{jj}\rvert > 3.0$ $\eta_{j_1} \cdot \eta_{j_2} < 0$ Central τ-leptons		Not VBF $p_T^{\tau\tau} > 100$ GeV	
Signal region ($110 < m_{\tau\tau}^{MMC} < 150$ GeV)			
VBF_1	VBF_0	Boost_1	Boost_0
BDT(VBF) > 0	BDT(VBF) < 0	$\Delta R_{\tau\tau} < 1.5$ and $p_T^{\tau\tau} > 140$ GeV	$\Delta R_{\tau\tau} > 1.5$ or $p_T^{\tau\tau} < 140$ GeV
$Z \to \tau\tau$ control region ($60 < m_{\tau\tau}^{MMC} < 110$ GeV)			
VBF_1 Z CR	VBF_0 Z CR	Boost_1 Z CR	Boost_0 Z CR

H→ττ

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

The observed and expected -Δln(L) scans in ϕ_τ 68% CL:





- **Pure CP-odd hypothesis** disfavored at **3.4σ level**
- The results are compatible with SM expectations
- **The total uncertainty** is dominated by the statistical uncertainties of the data sample

- No strong correlation between $\mu_{\tau\tau}$ and ϕ_τ observed
- The measurements are compatible with SM predictions