Measurements of the Higgs boson mass, width, CP and anomalous couplings with the ATLAS detector

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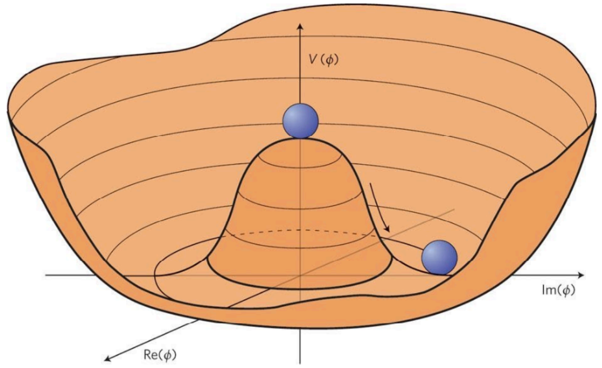
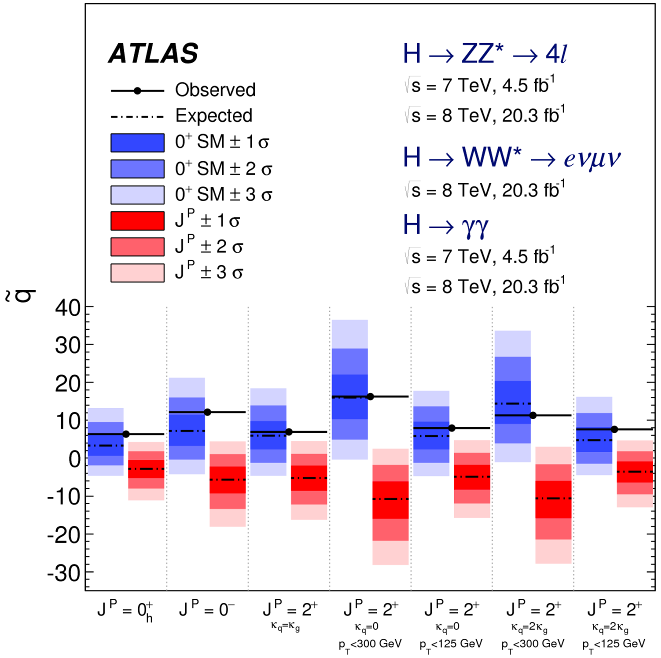
ATLAS
EXPERIMENT

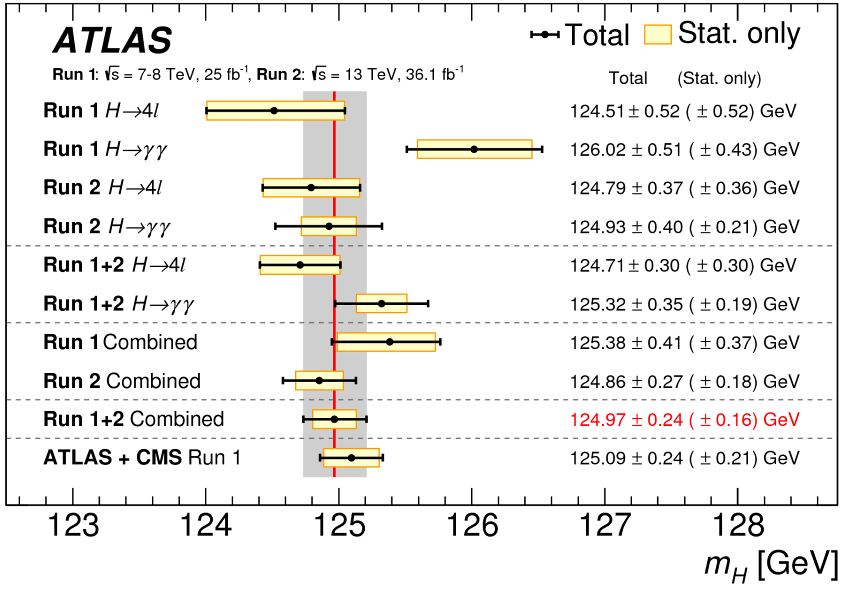
Introduction

- The Higgs boson plays a unique role in the SM of giving masses to other particles via the EW SSB
- The discovery of the Higgs boson was announced in July 4th, 2012 by ATLAS and CMS
- Precisely determining its properties is essential to test the SM.
- Latest measurements of its mass, width and CP structure and search for anomalous couplings will be presented

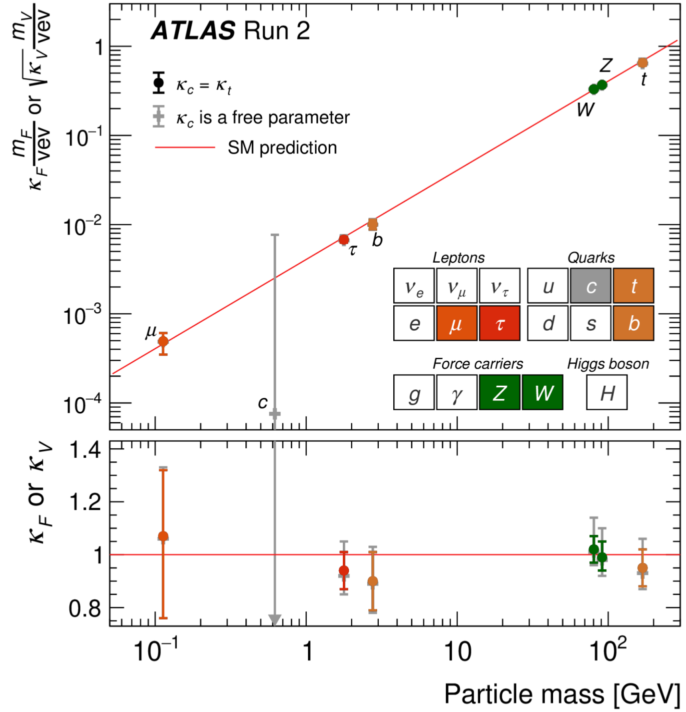




Eur. Phys. J. C75 (2015) 476



Phys. Lett. B 784 (2018) 345



Nature 607, pages 52-59 (2022)

Higgs boson mass measurement

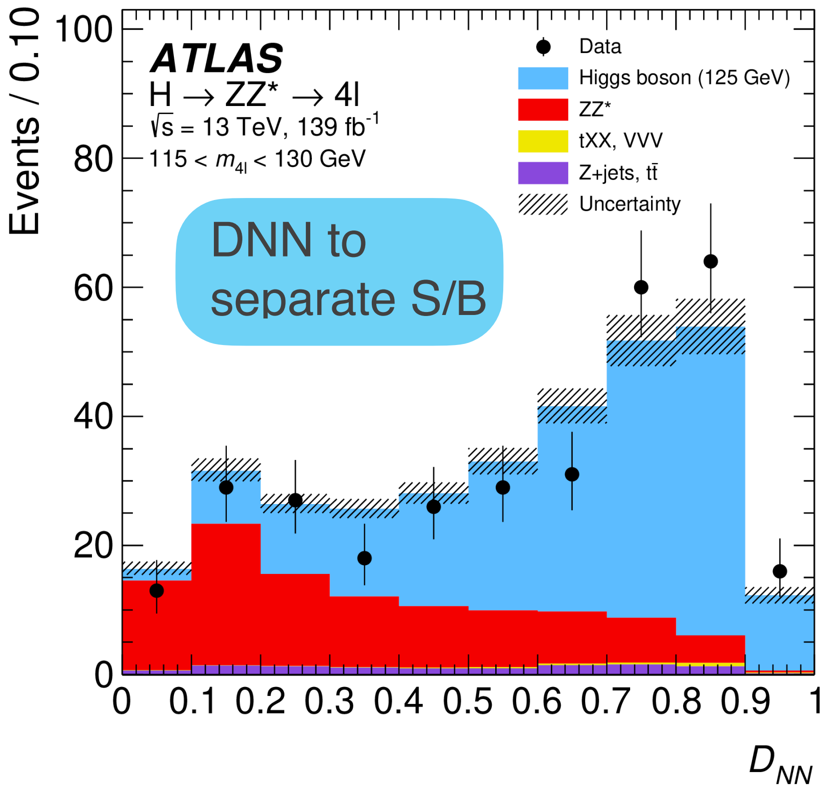
arXiv:2207.00320

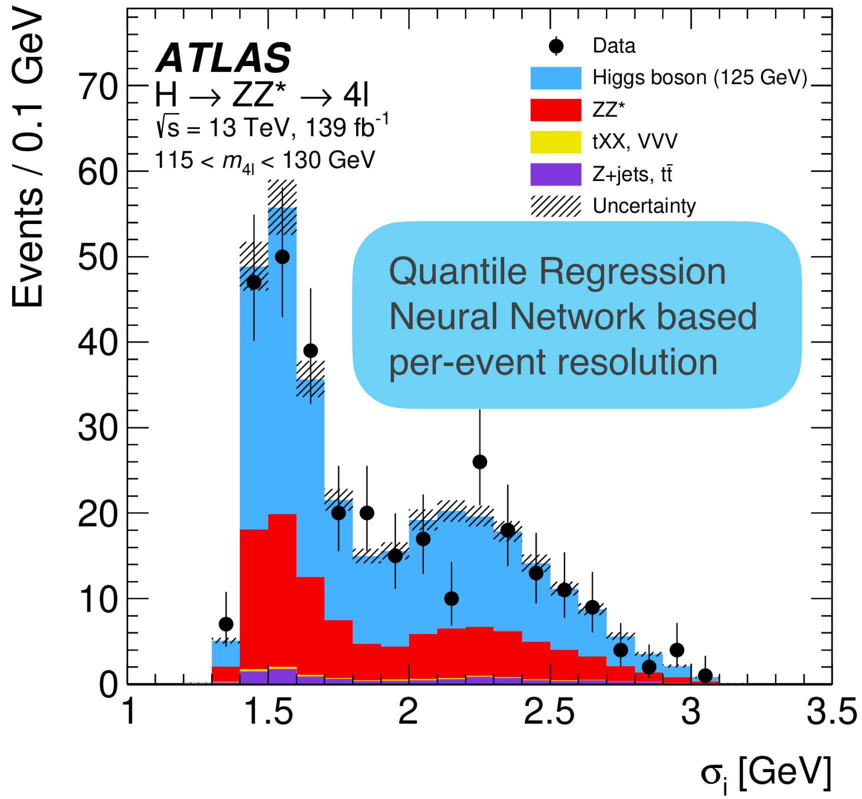
- The Higgs boson mass is a free parameter in the SM but is crucial for determining other properties
- The combined measurement from ATLAS and CMS with Run-I dataset is

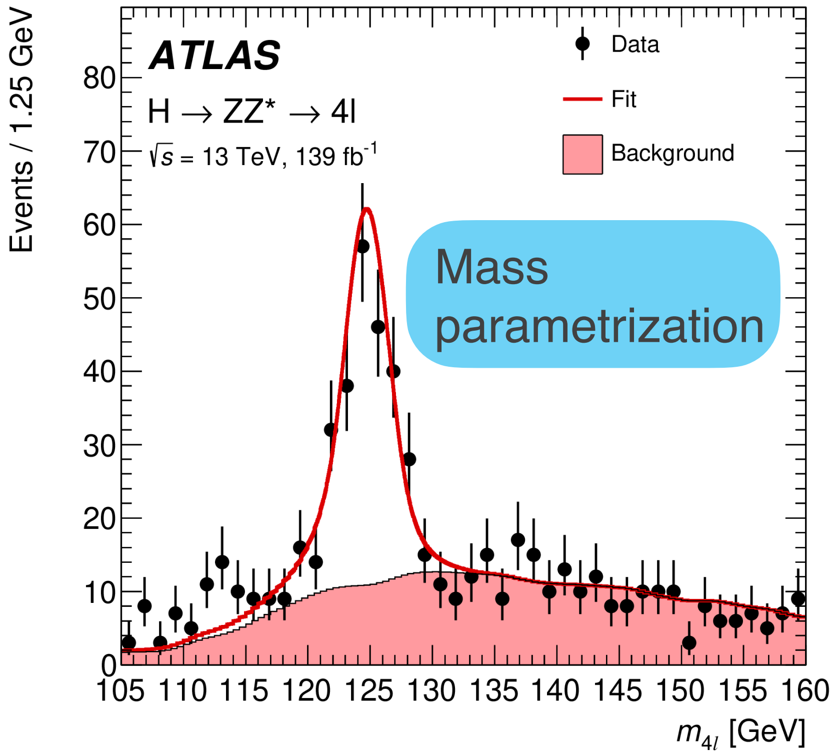
$m_H = 125.09 \pm 0.24\ [\pm 0.21\ \text{(stat.)} \pm 0.11\ \text{(syst.)}]$ GeV Phys. Rev. Lett. 114 (2015)

✓ Statistical uncertainty dominant

- Run-II measurement in H→ZZ*→4ℓ channel has been released



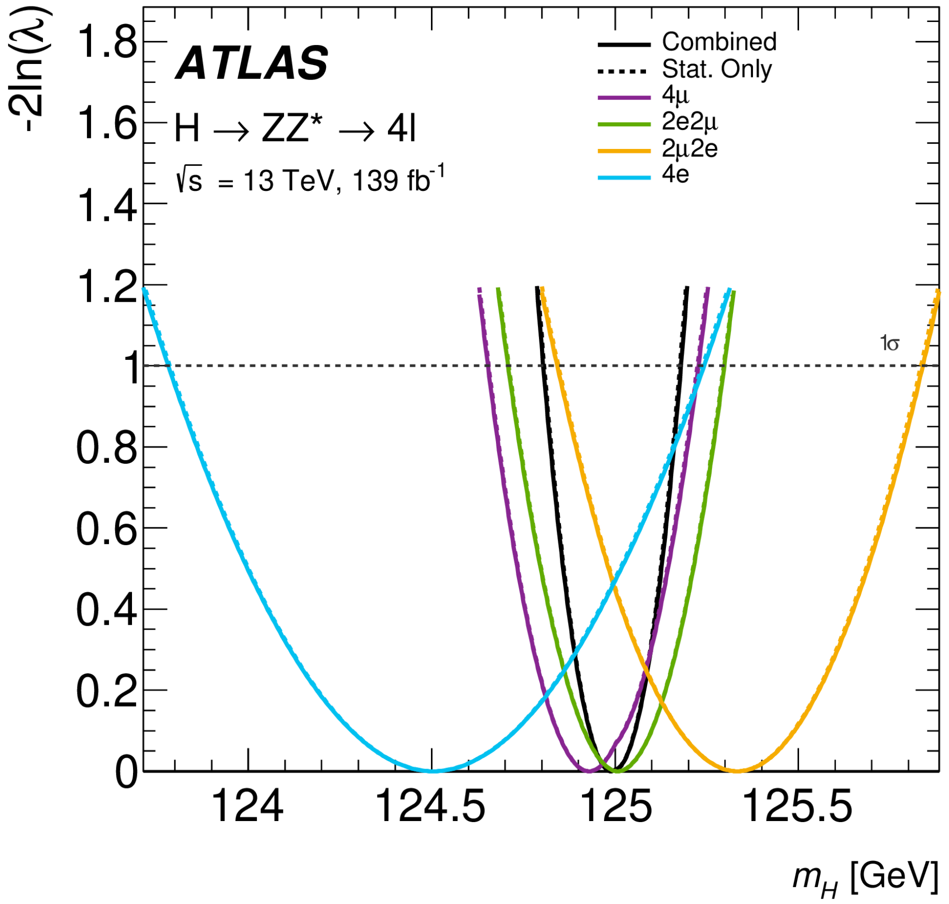


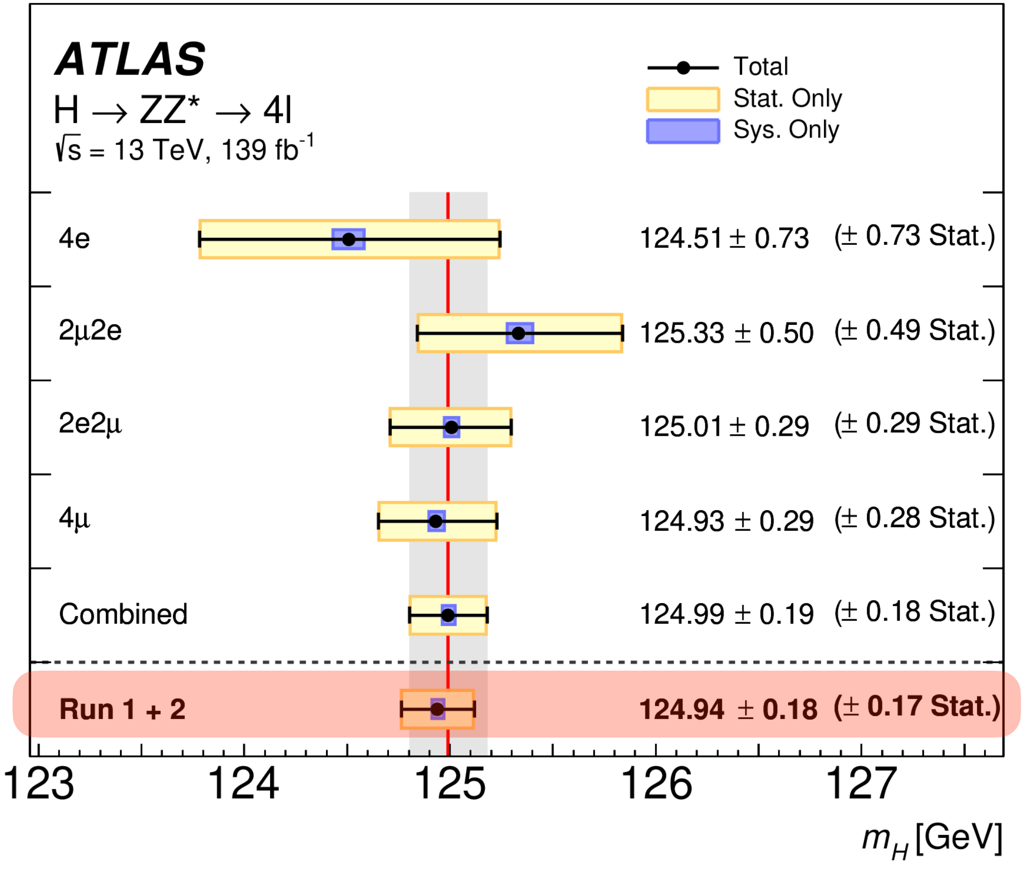


3 dimensional fit exploring DNN, σ_i, $m_{4\ell}$ to extract m_H

Higgs boson mass measurement

arXiv:2207.00320





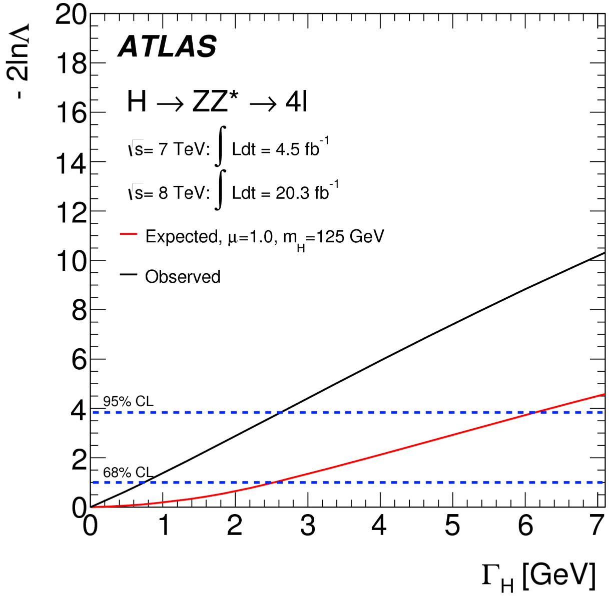
$$m_H = 124.99 \pm 0.19 \,[\pm 0.18\ (\text{stat.}) \pm 0.04\ (\text{syst.})]\ \text{GeV}$$

Still statistical uncertainty dominant

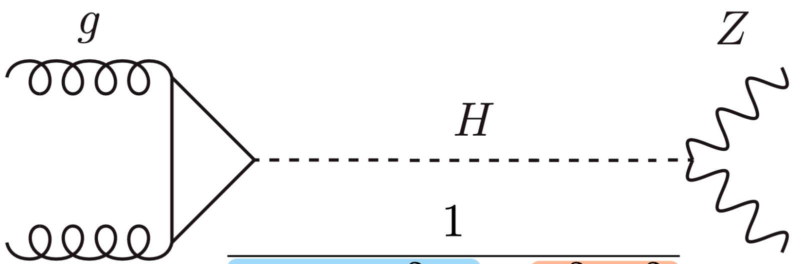
Systematic Uncertainty	Contribution [MeV]
Muon momentum scale	±28
Electron energy scale	±19
Signal-process theory	±14

Higgs boson width measurement

- The width of the Higgs boson is very small (~4.1 MeV @ m_H = 125 GeV) as predicted by the SM
  - ✓ Much smaller than experimental resolution (~1-2 GeV)
    → Unable to be directly measured from signal shape
- Could be extracted from the ratio of on-shell and off-shell signal strengths
  - ✓ Assume equal couplings for on-shell and off-shell
  - ✓ Interference with continuum gg/VV→VV production is important for off-shell → *a negative impact for total yield*



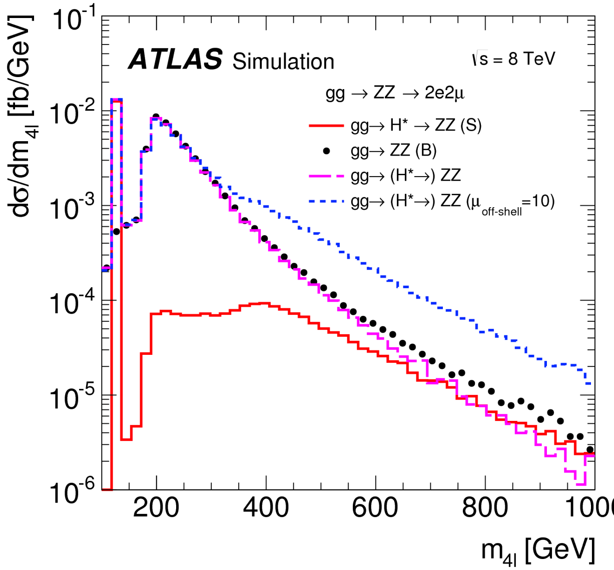
Phys. Rev. D. 90 (2014) 052004



$$\frac{1}{(m^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}$$

$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma}{\Gamma_{\text{SM}}}$$

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



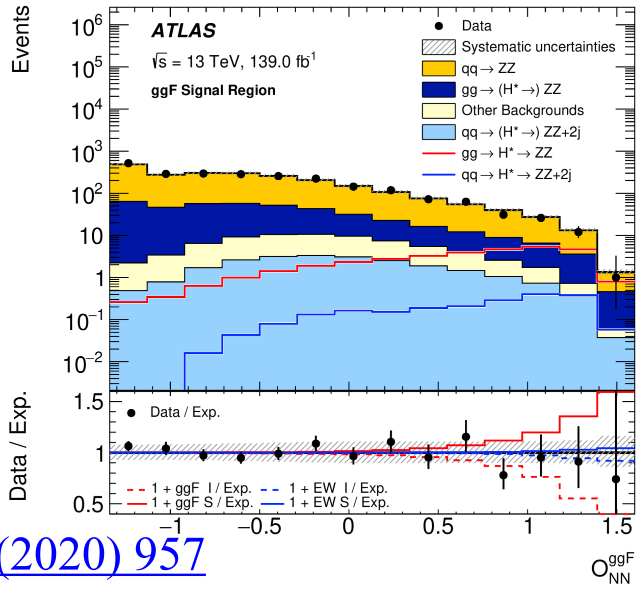
Eur. Phys. J. C (2015) 75:335

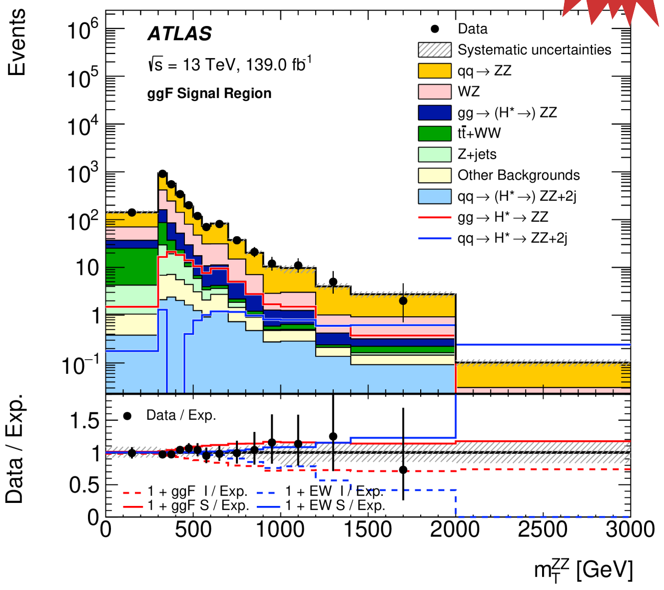
- Several analyses performed since Run-I
  - ✓ H→ZZ/WW [Run-I, Eur. Phys. J. C (2015) 75:335]
  - ✓ H→ZZ [36 fb^{-1}, Phys. Lett. B 786 (2018) 223]
  - ✓ H→ZZ [139 fb^{-1}, arXiv:2304.01532] NEW

Higgs boson width measurement

[arXiv:2304.01532](https://arxiv.org/abs/2304.01532)

- Performed in H→ZZ→4ℓ/2ℓ2ν channels
  - ✓ 4ℓ performs neural network to separate signal and backgrounds, O_{NN} as the discriminator
  - ✓ 2ℓ2ν uses m_T^{ZZ} as the discriminator
- Three SR regions defined for each channel
  - ✓ ggF, Mixed, EW (VBF)
- $\mu_{on-shell} = 1.01 \pm 0.11$ from Eur. Phys. J. C 80 (2020) 957



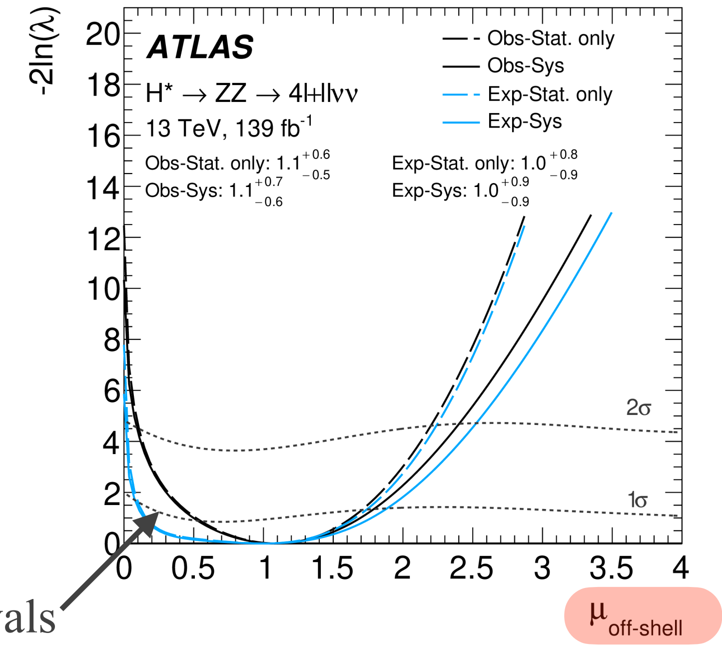


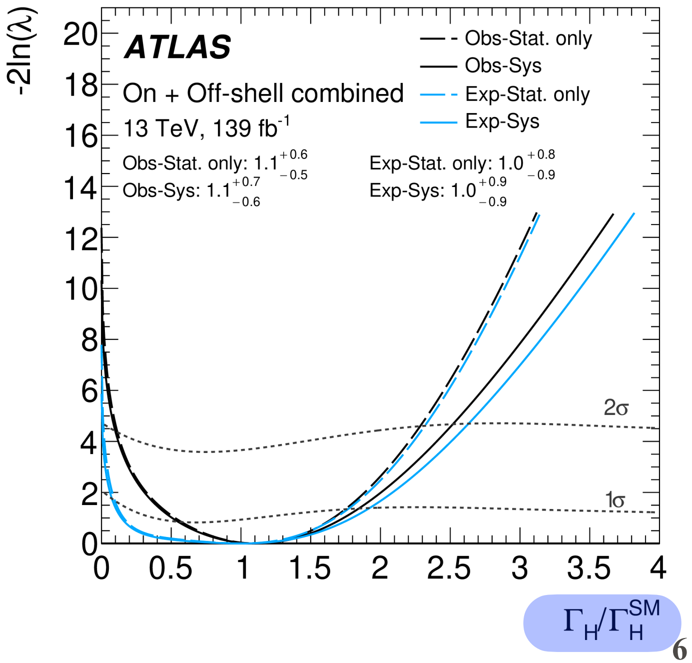
$$\mu_{off-shell} = 1.1^{+0.7}_{-0.6}$$

3.3σ (2.2σ) obs (exp.)

for off-shell Higgs boson

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



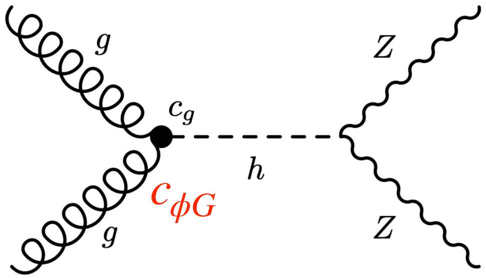


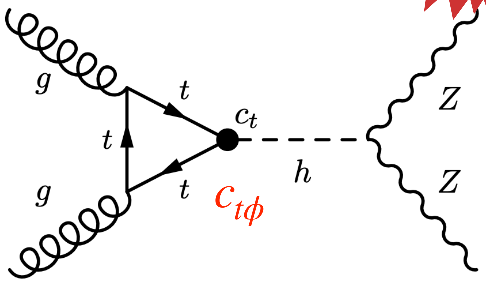
* Neyman construction to derive the confidence intervals

Off-shell measurement EFT interpretation

ATL-PHYS-PUB-2023-012

- Results interpreted with SMEFT in terms of H-top and H-gluon couplings
  - ✓ Test with $c_g - c_t$ framework (c_g, c_t)
  - ✓ Test with Warsaw basis ($c_{\phi G}$, $c_{t\phi}$)





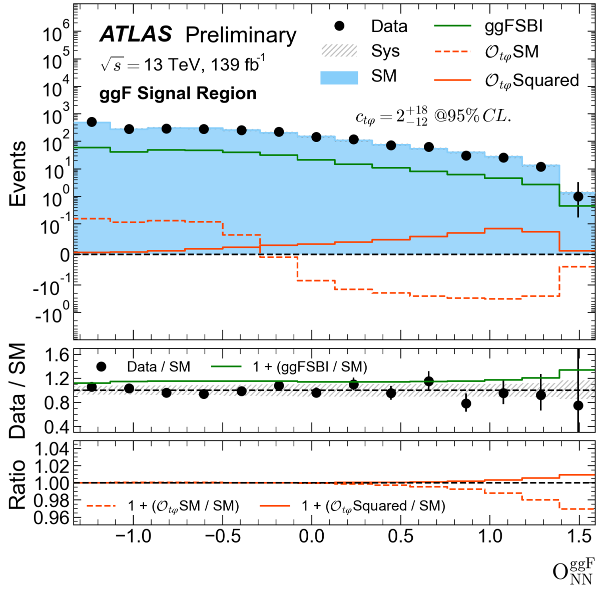
$$\frac{\sigma^{\mathrm{SMEFT}}(c_t, c_g)}{\sigma^{\mathrm{SM}}} \simeq (c_t + c_g)^2 \left(1 - \frac{7}{15}\frac{c_g}{c_t + c_g}\frac{m_h^2}{4m_t^2}\right)$$

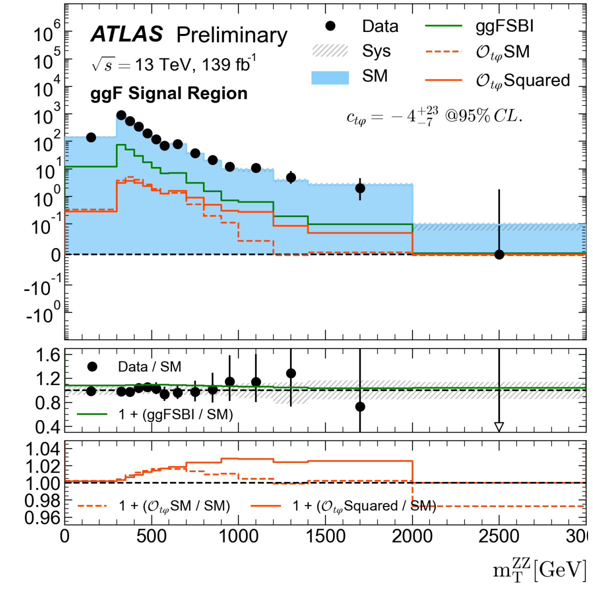
$$c_{\varphi G} = \frac{g_s^2 \Lambda^2}{48\pi^2 v^2} c_g$$

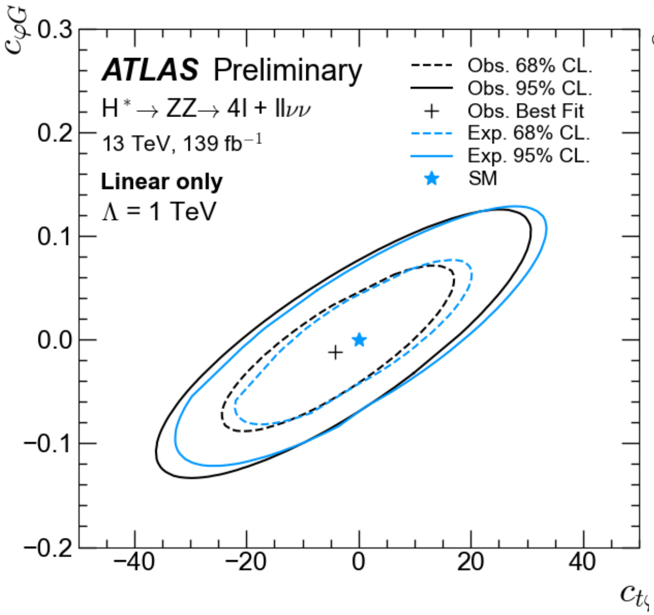
$$c_{t\varphi} = -\frac{y_t \Lambda^2}{v^2}(c_t - 1)$$

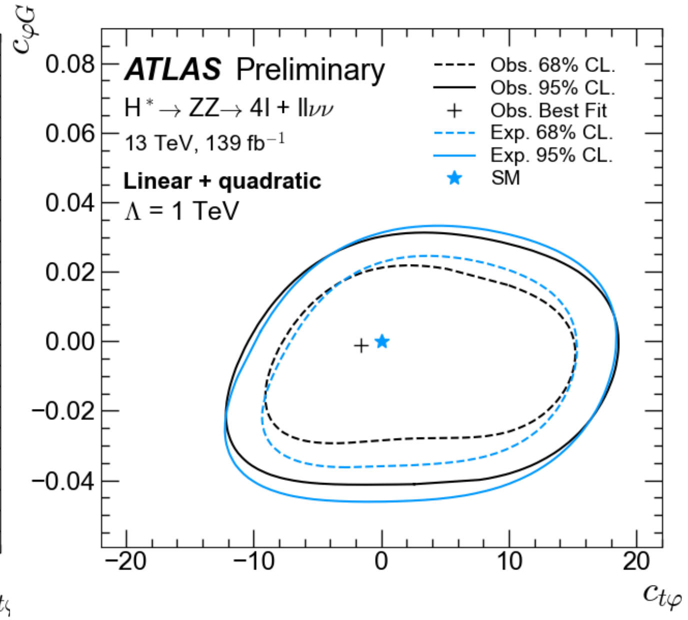
Mass term can not be neglected for off-shell Higgs boson production

↳ Separately probe c_g and c_t



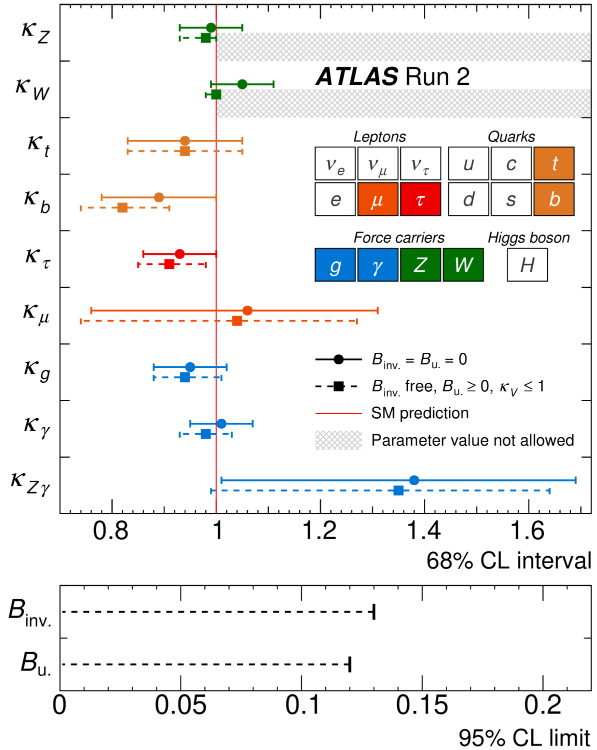






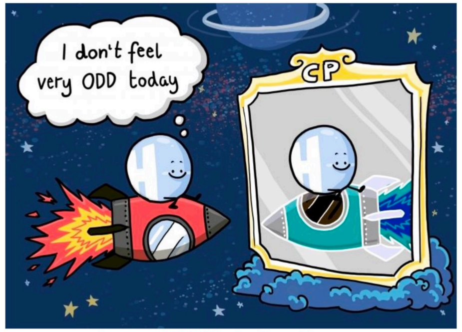
Higgs boson CP and anomalous coupling

- The Higgs boson couplings are measured by ATLAS(see Luca's talk)
  - ✓ Generally agree with the SM predictions
  - ✓ Still room for new physics (e.g. rare production/decay see Rocky's talk)
- Measuring the anomalous coupling of the Higgs boson could also probe the new physics
  - ✓ Test with the Effective Field Theory (EFT) approach
  - ✓ Could include both CP-even and CP-odd contributions
    - ↳Test with differential results presented in Roberto’s talk

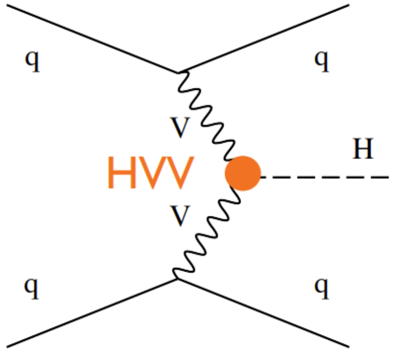


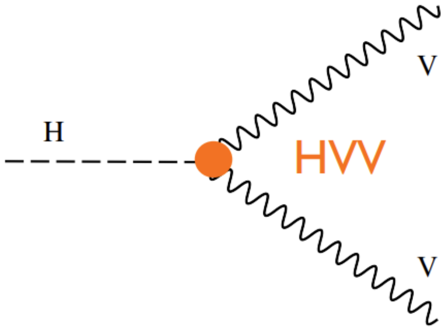
Nature 607, pages 52-59 (2022)

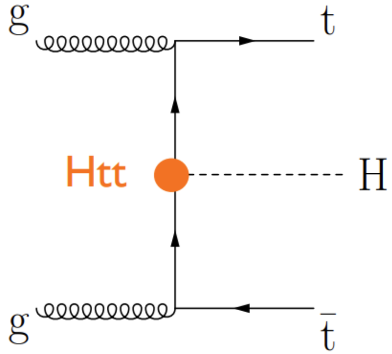
- In the SM, the Higgs boson is predicted as CP-even
- Explore CP-odd contribution in Higgs sector
  - ✓ Mixture of CP-even and CP-odd still allows
  - ✓ New source of CP violation

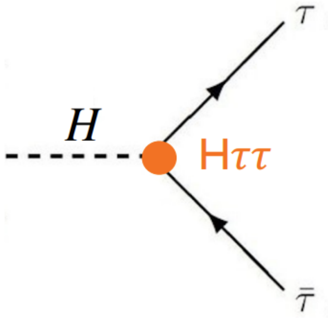


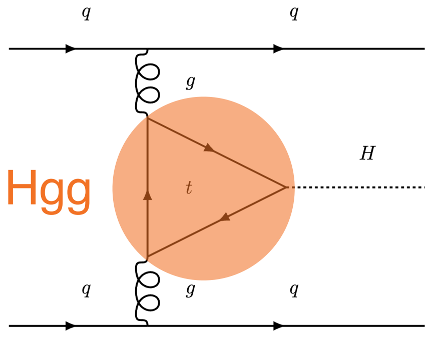
(image: DESY/designdoppel)











HVV anomalous coupling and CP structure

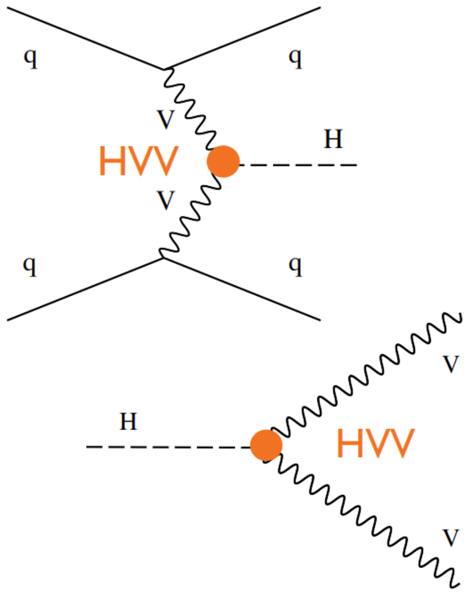
- Based on the Effective Field Theory
- Explore the **Optimal Observable (*OO*)**
  - ✓ A CP-odd variable
  - ✓ Fairly a model independent definition
- VBF $H\rightarrow\tau\tau$ [36 fb^{-1}] Phys. Lett. B 805 (2020) 135426
- VBF $H\rightarrow\gamma\gamma$ [139 fb^{-1}] arXiv:2208.02338
- $H\rightarrow ZZ$ arXiv:2304.09612
  - ✓ $H\rightarrow ZZ$ also explore decay vertex

NEW

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$

Dim-6 operators, 3 independent ones for CP-odd in SMEFT

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

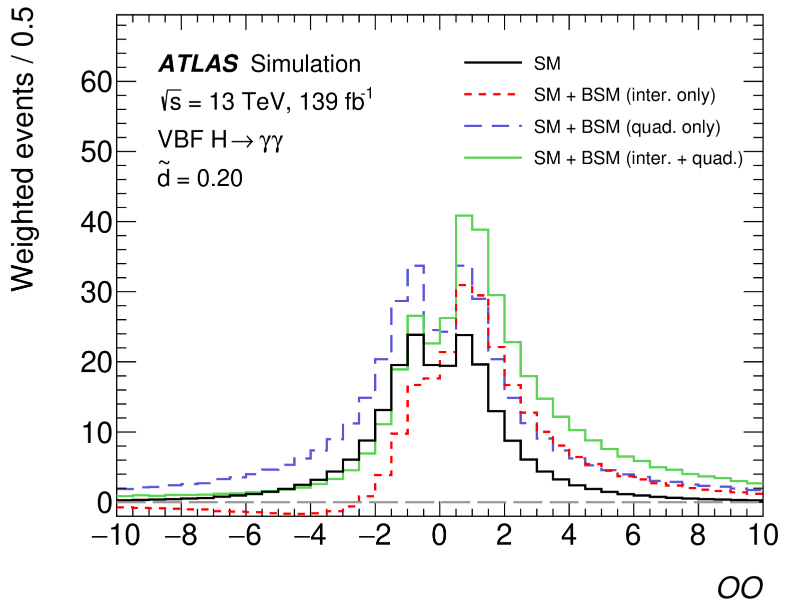


- Two parametrization sets used: **Warsaw basis** and **Higgs basis**

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

- Also explored an even simpler parametrization as defined as

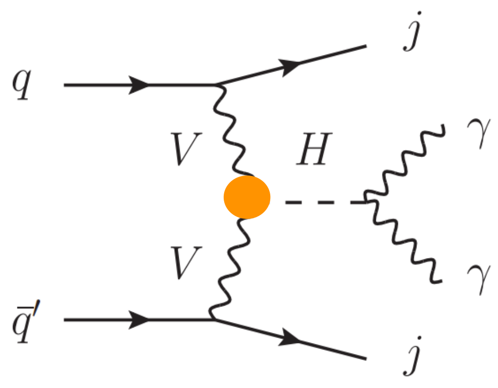
$$\tilde{d}: \begin{array}{l} c_{H\widetilde{W}B} = 0,\, c_{H\widetilde{W}} = c_{H\tilde{B}} = \frac{\Lambda^2}{v^2}\tilde{d}, \\ \tilde{c}_{z\gamma} = 0,\quad \tilde{c}_{\gamma\gamma} = \sin^2\theta_W \cos^2\theta_W \tilde{c}_{zz} \propto \tilde{d} \end{array}$$

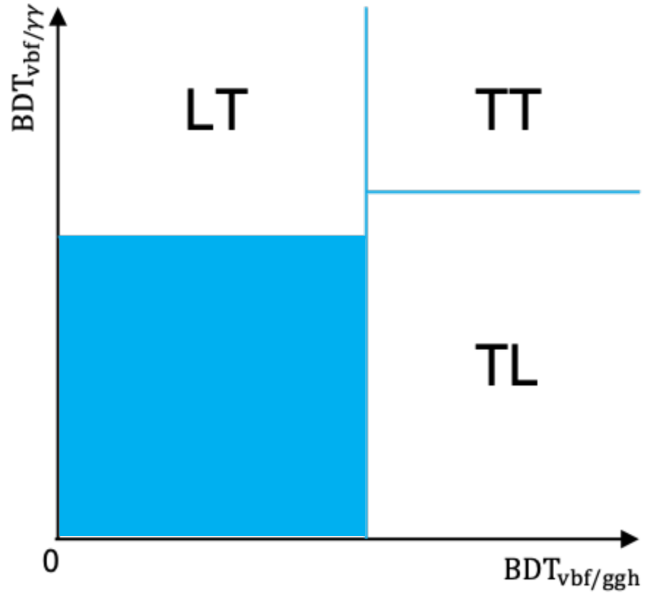


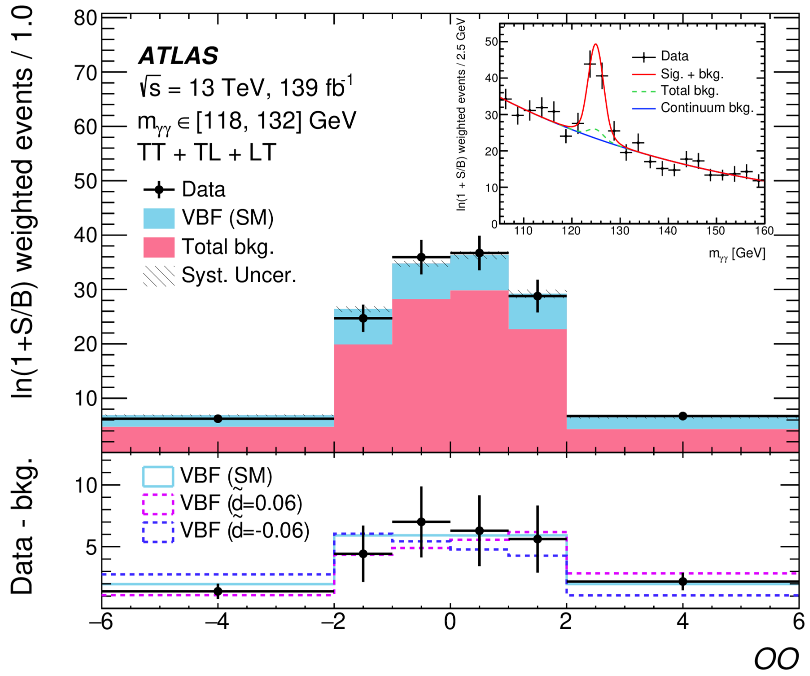
HVV anomalous coupling: VBF $H\rightarrow\gamma\gamma$

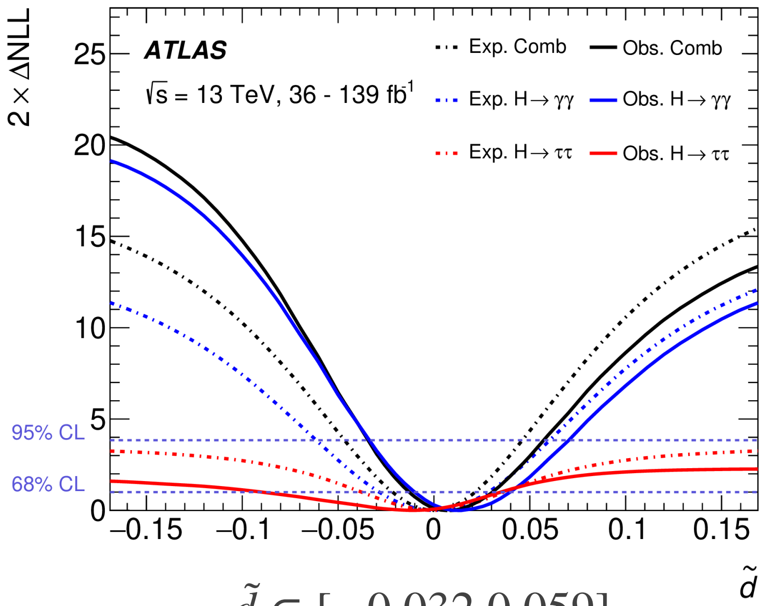
arXiv:2208.02338

- Perform two BDTs to separate VBF/ggF and VBF/continuum background
- Define three SRs with two BDT scores
- Fit on $m_{\gamma\gamma}$ distributions on 6 *OO* bins for each SR (in total 18 regions) to extract signal contribution
- Derived constraints for $\tilde{d}$ and $c_{H\tilde{W}}$

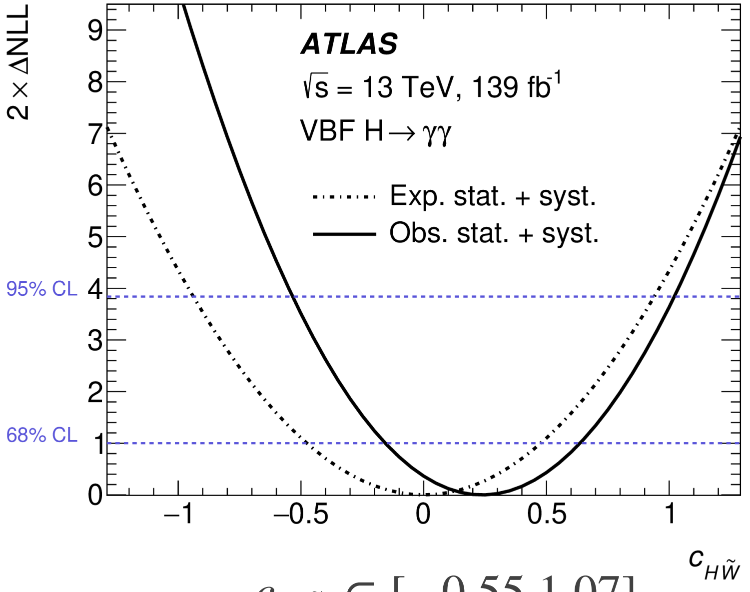








$\tilde{d} \in [-0.032, 0.059]$



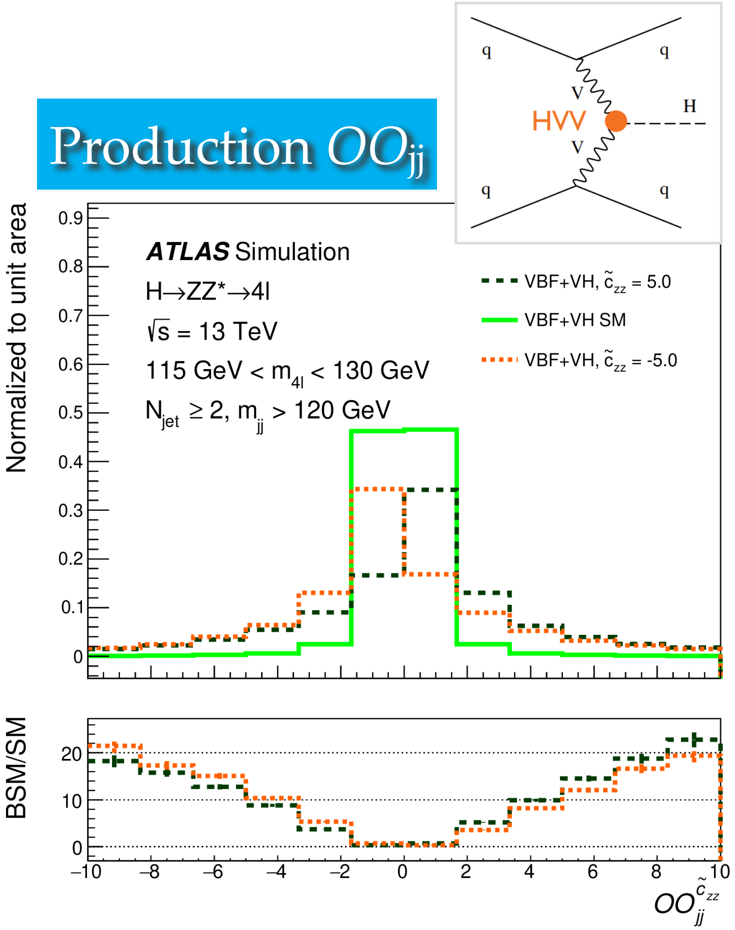
$c_{H\tilde{W}} \in [-0.55, 1.07]$

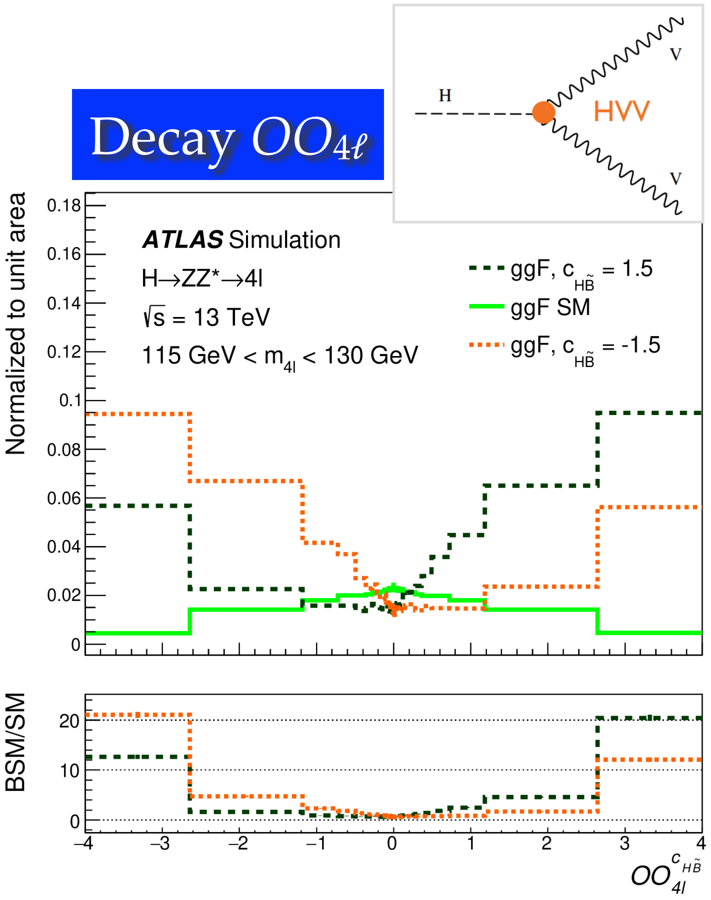
HVV anomalous coupling: $H \to ZZ \to \ell\ell\ell\ell$

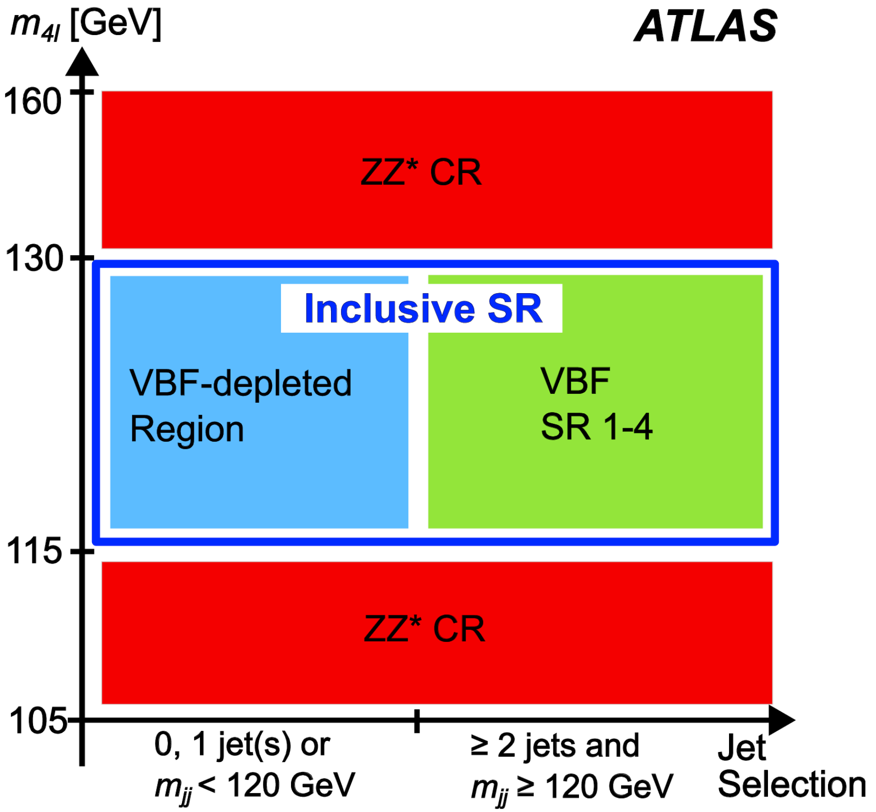
arXiv:2304.09612

NEW

- Based on the Effective Field Theory approach, using **Optimal Observable (*OO*)** to probe CP-odd component
- Define two *OOs*: for **production** (VBF enriched) and for **decay** (inclusive)





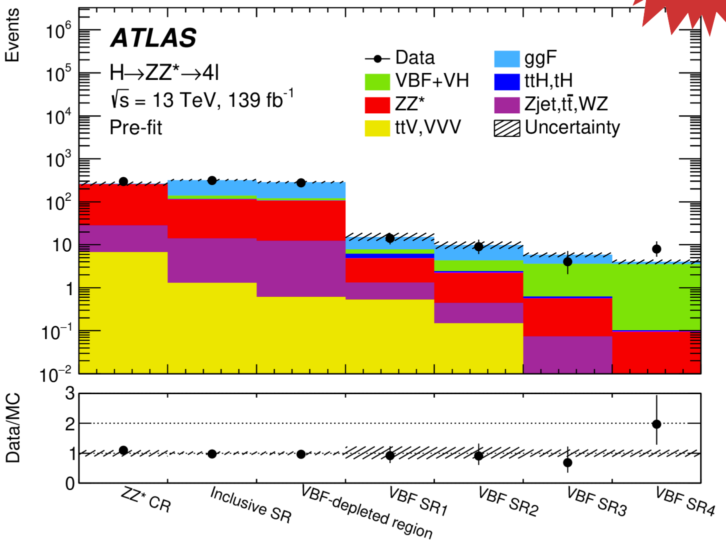


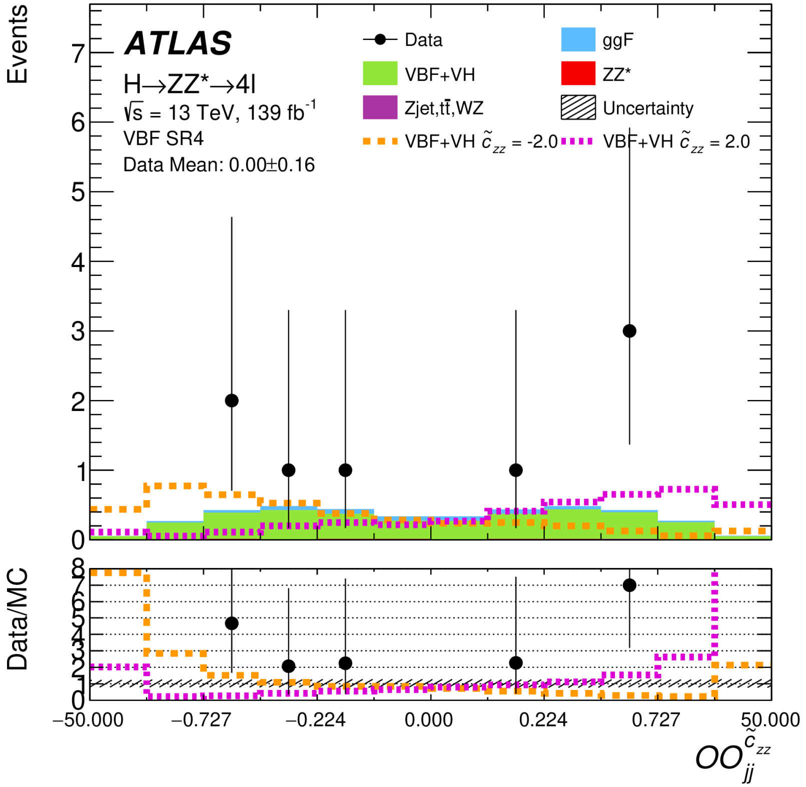
Total 7 coefficients (3 for **Warsaw basis**, 3 for **Higgs basis**, 1 for simple parametrization) are constrained

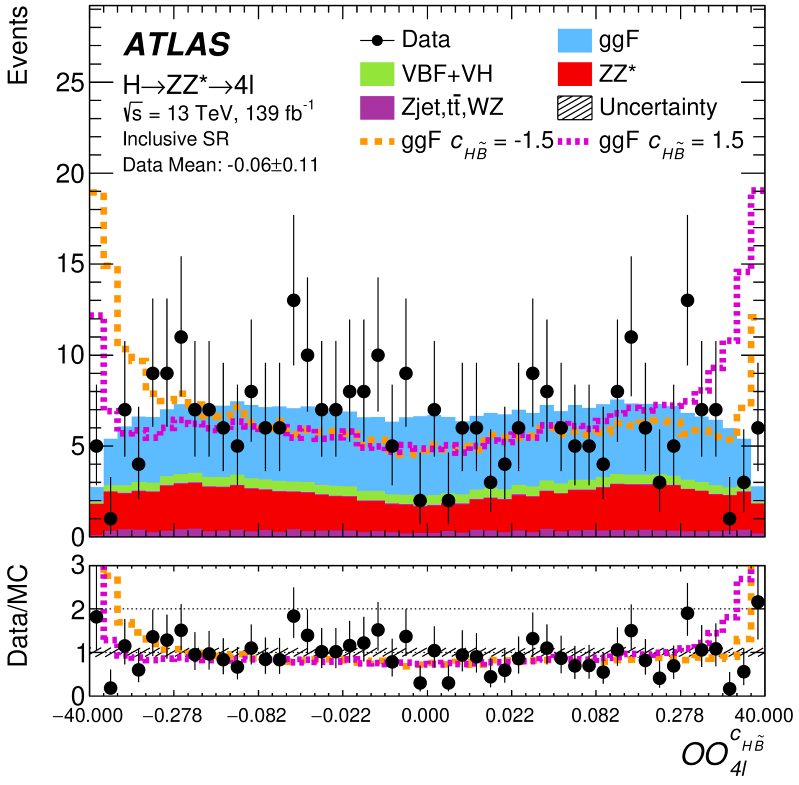
HVV anomalous coupling: H→ZZ→ℓℓℓℓ

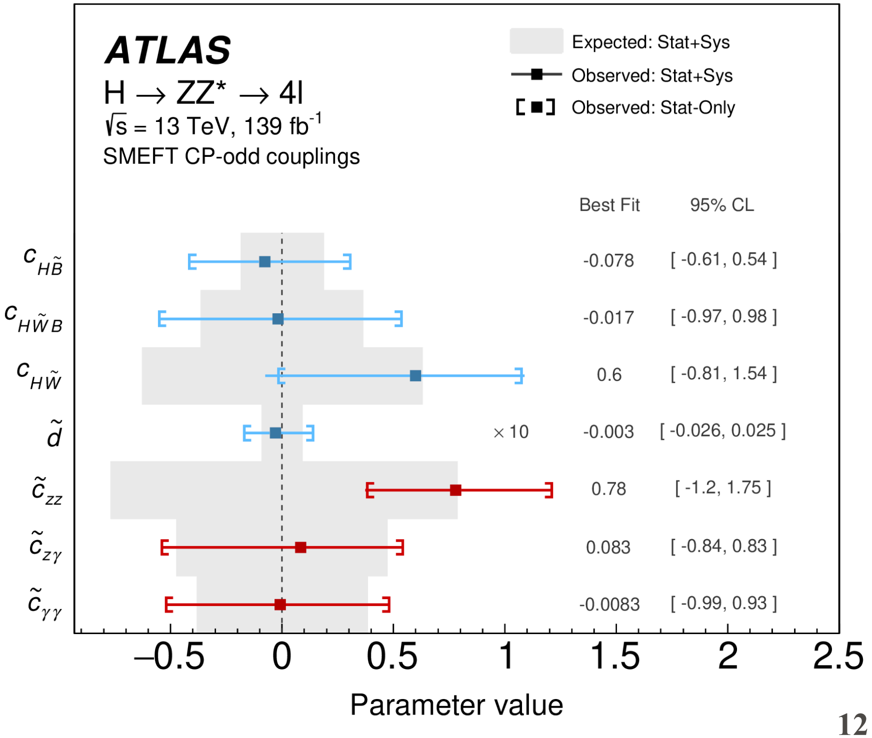
arXiv:2304.09612

- A neural-network trainning performed to enhance the VBF purity
  - ✓ 4 VBF SRs defined with NN output
- Three types of fit perform
  - ✓ Production → CR(ZZ, VBF-dep)+SR(VBF1-4)
  - ✓ Decay → CR(ZZ)+SR(inclusive)
  - ✓ Combined → CR(ZZ)+SR(VBF-dep, VBF1-4)



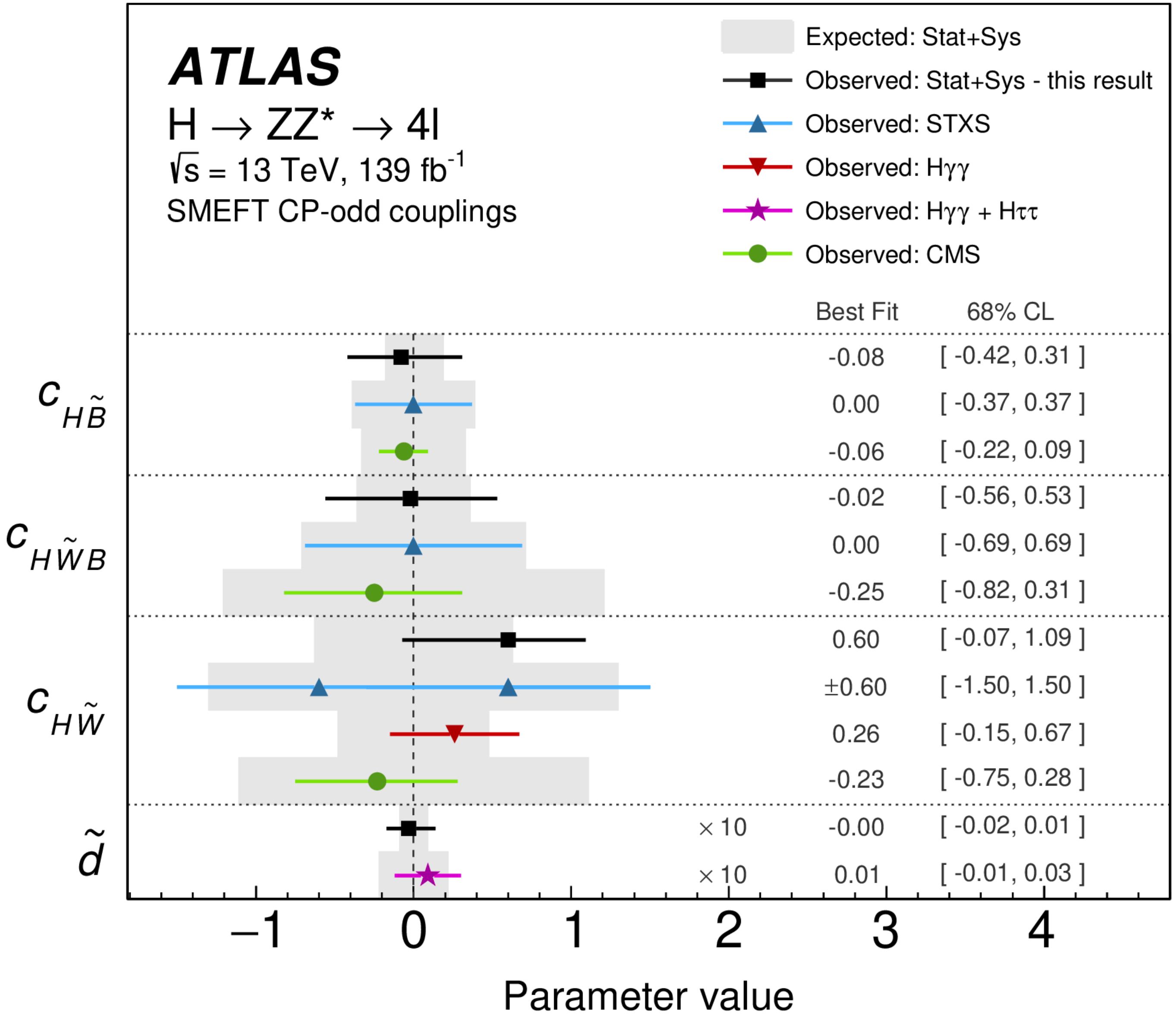


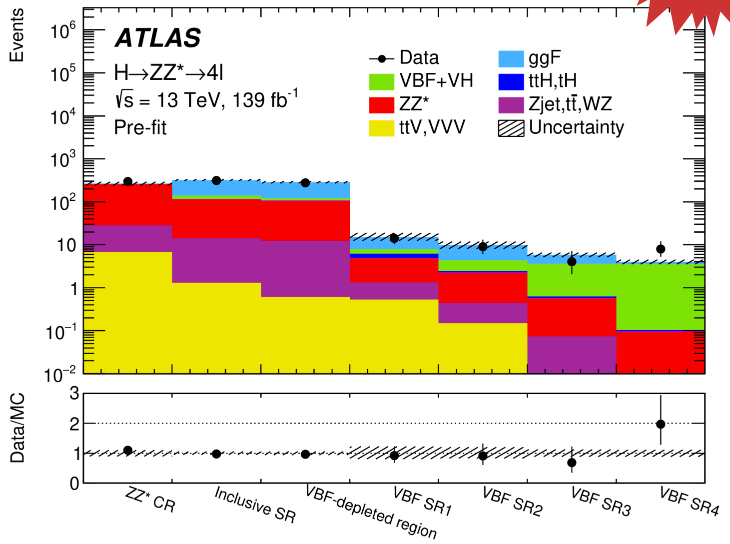


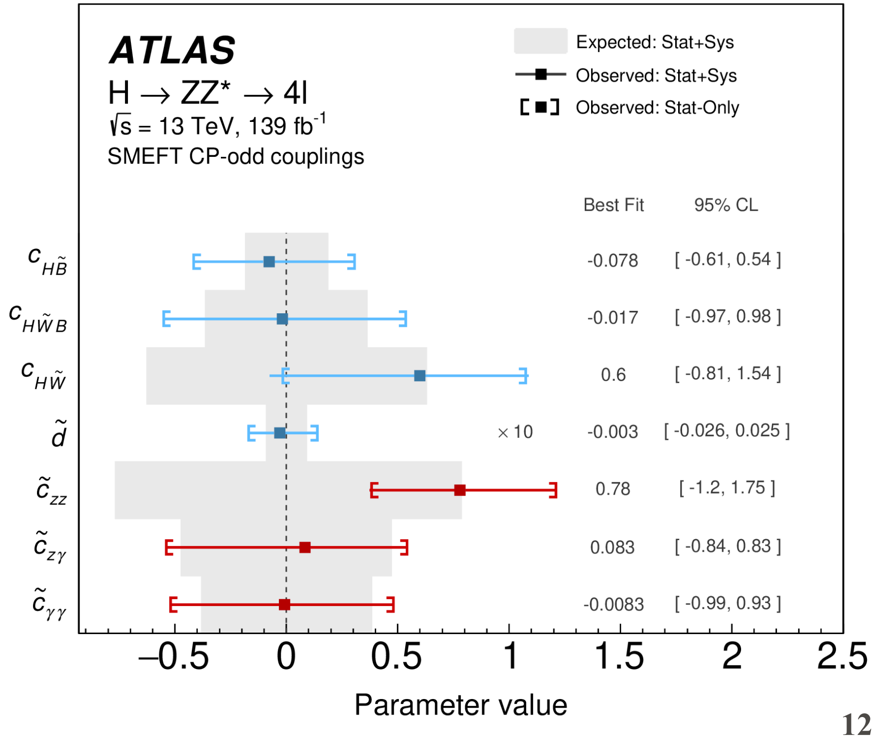


HVV anomalous coupling: H→ZZ→ℓℓℓℓ

arXiv:2304.09612







H→ττ CP structure

arXiv:2212.05833

The CP-mixing is parametrized to be sensitive to the angular of two tau planes from the Higgs boson in the Higgs boson center-of-mass frame

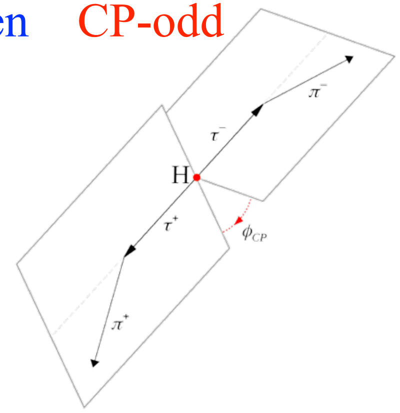
$$\mathcal{L}_{Y} = -\frac{m_\tau}{v} H(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau)$$

CP-even CP-odd

$$d\Gamma_{H\to\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_\tau)$$

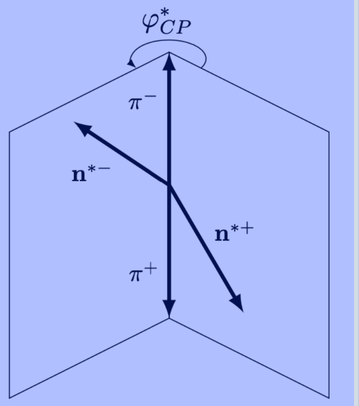
CP-mixing

$$\tan(\phi_\tau) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$



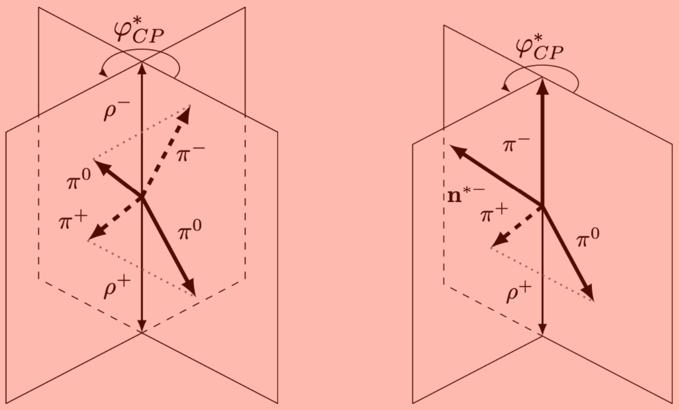
Depending on tau decays: several methods developed to reconstruct ϕ_{CP}

Impact parameter method

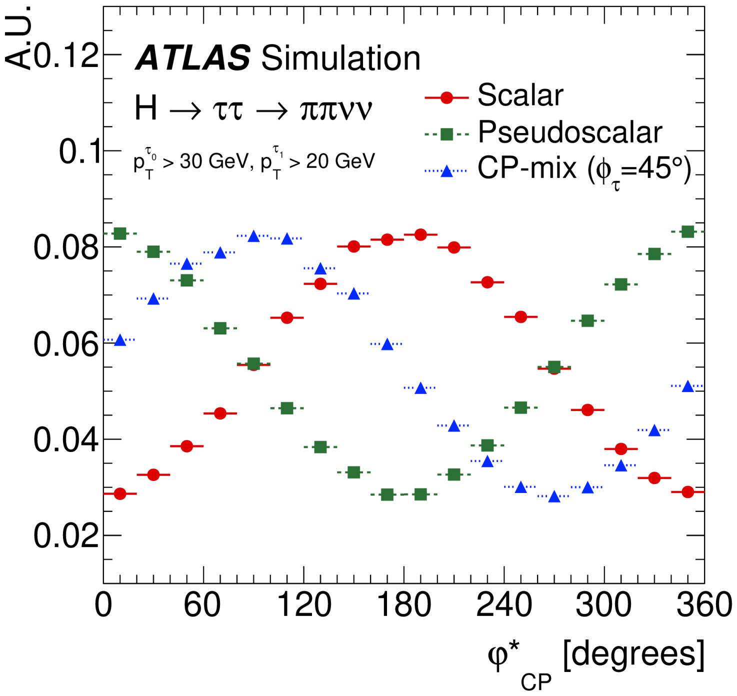


$H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$

Neutral pion method (+IP method)



$H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\pi^0\nu$ $H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\nu$



H→ττ CP structure

arXiv:2212.05833

The CP-mixing is parametrized to be sensitive to the angular of two tau planes from the Higgs boson in the Higgs boson center-of-mass frame

$$\mathcal{L}_Y = -\frac{m_\tau}{v} H(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau)$$

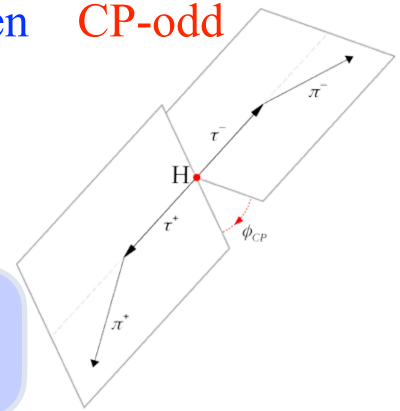
CP-even CP-odd

$$d\Gamma_{H\to\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_\tau)$$

CP-mixing

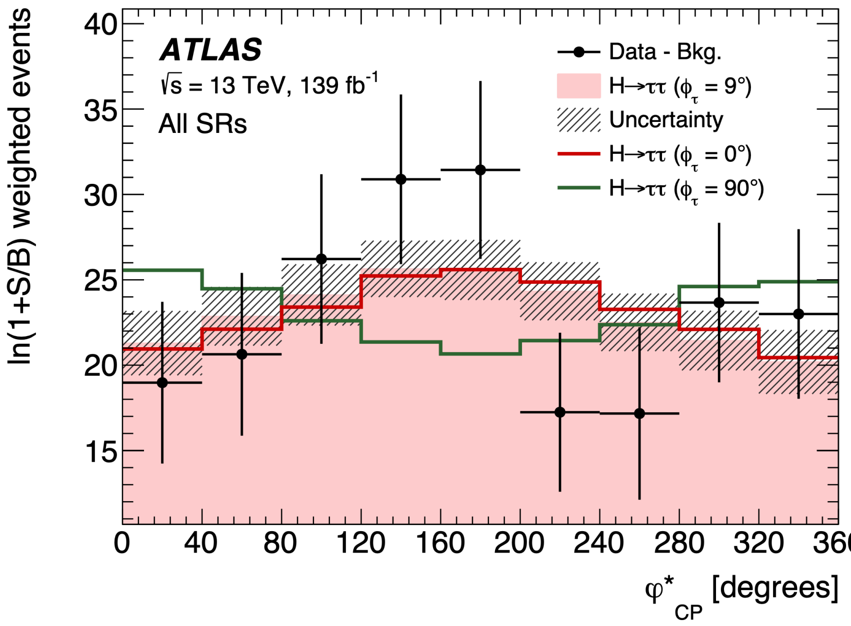
$$\tan(\phi_\tau) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

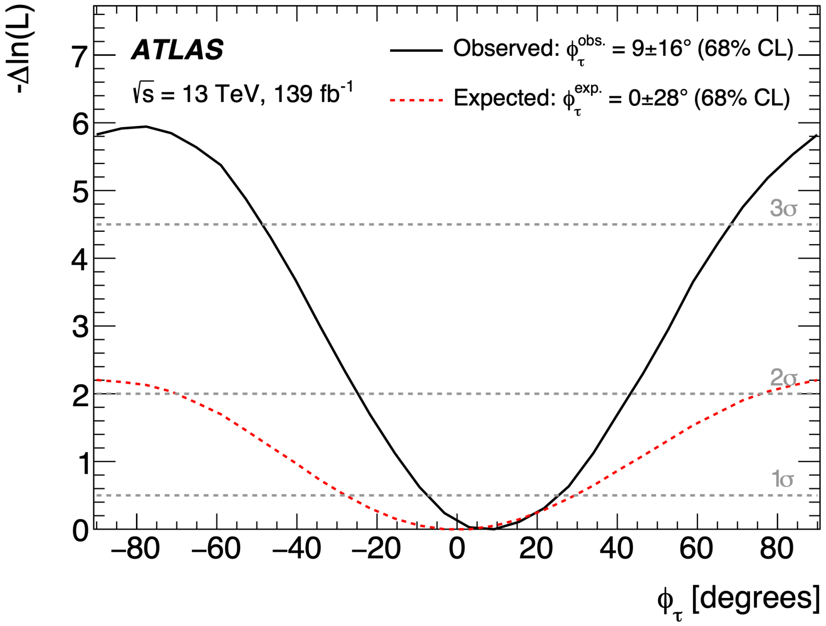
Depending on tau decays: several methods developed to reconstruct ϕ_{CP}

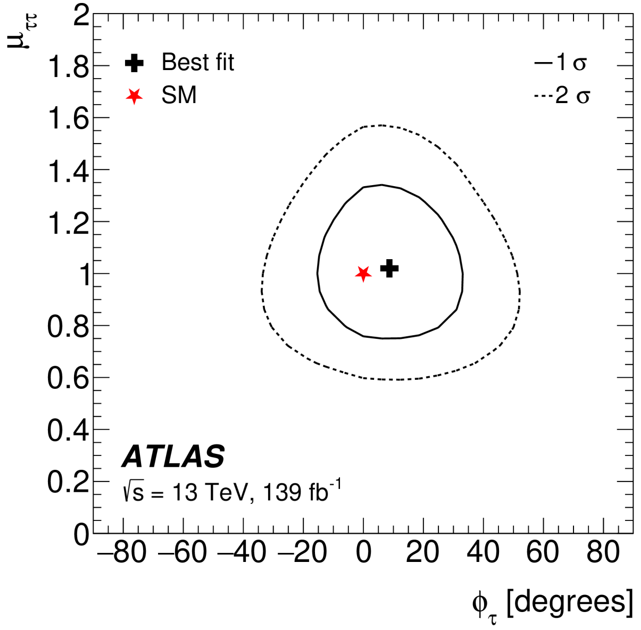


ϕ_τ = 9±16 deg. (±28 deg.)

Pure CP-odd excluded @ 3.4σ



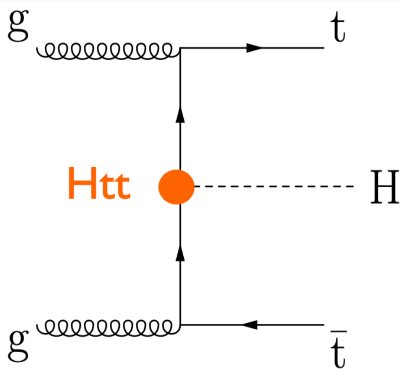




CP structure in Higgs-Top interaction

[Phys. Rev. Lett. 125 (2020) 061802]

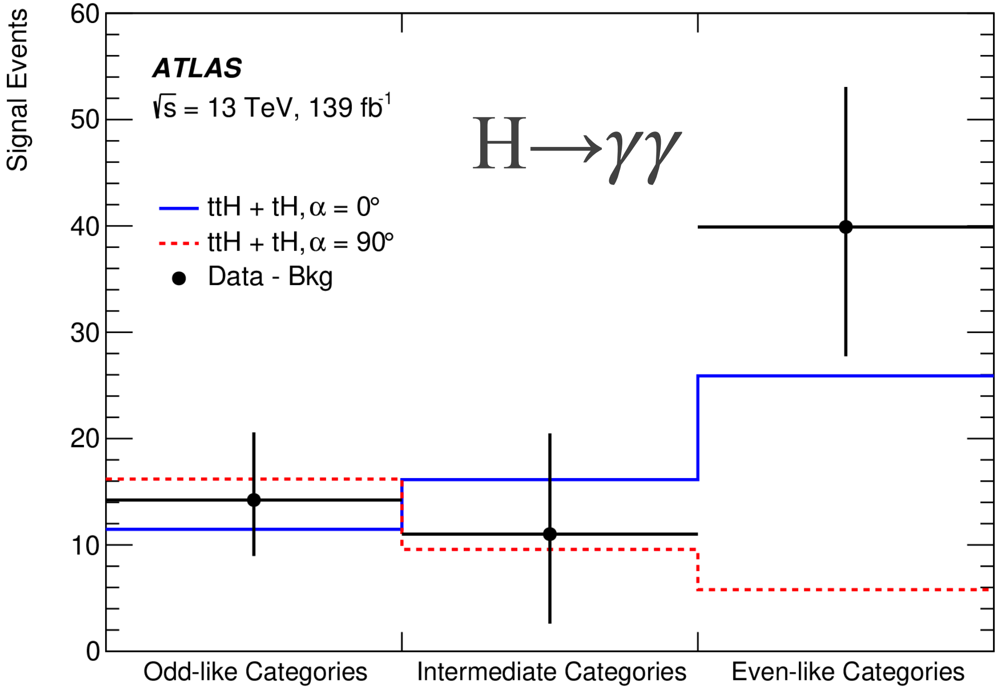
- Measure the CP structure of H-top interaction in ttH production and search for anomalous coupling



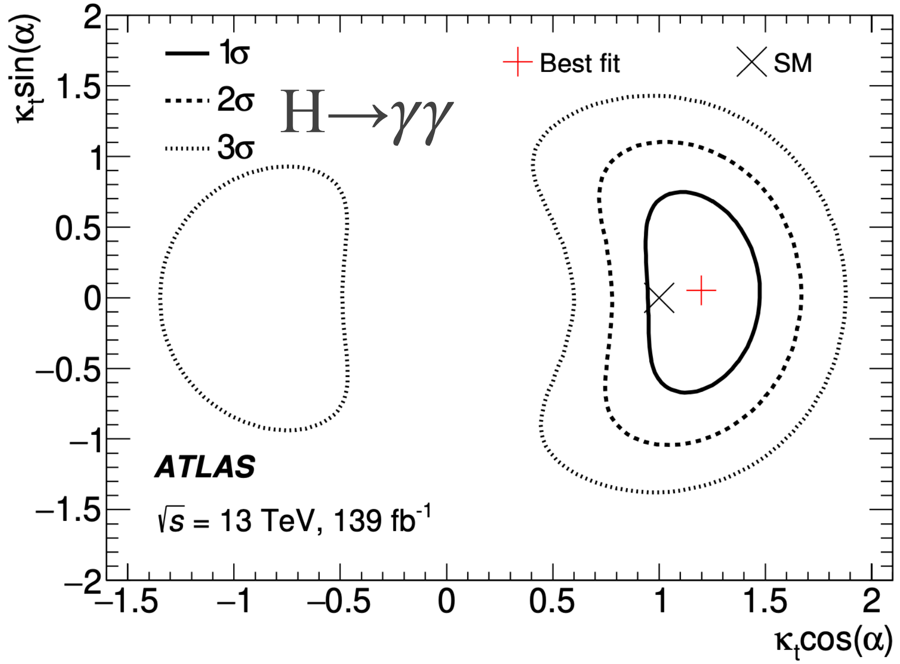
$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t\kappa_t[\cos(\alpha) + i\sin(\alpha)\gamma_5]\psi_t\}H$$

CP-even ($\cos(\alpha)$) CP-odd ($i\sin(\alpha)\gamma_5$)

- Studied in two decay channels
  - ✓ $H\to\gamma\gamma$ [Phys. Rev. Lett. 125 (2020) 061802]
  - ✓ $H\to bb$ [arXiv:2303.05974]



BDT for Higgs/Bkg, CP-even/odd separation and categorization



Mixing angle $|\alpha|<43°$ @95% CL

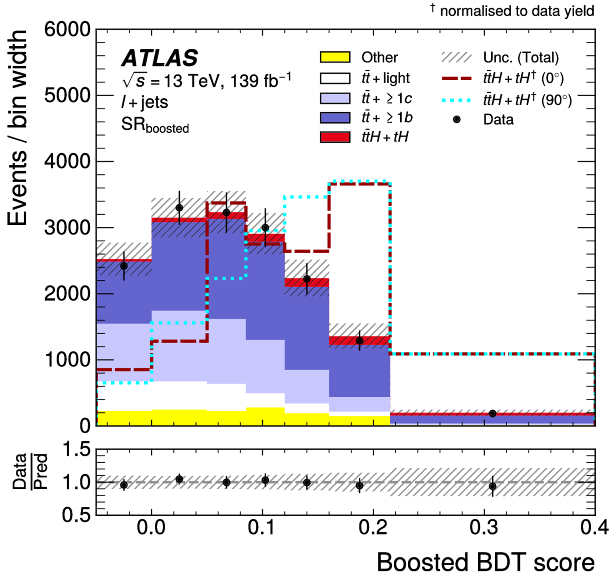
Pure CP-odd excluded @3.9σ

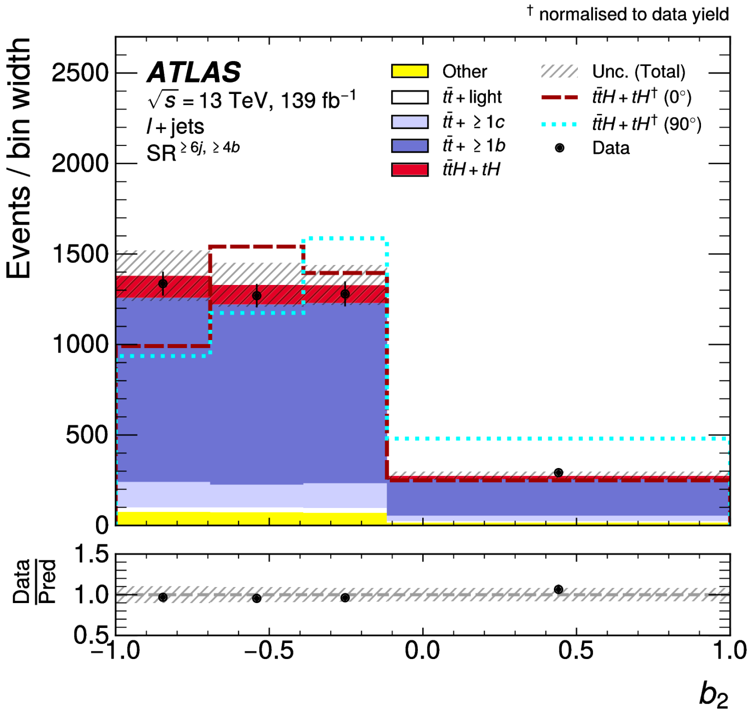
CP structure in Higgs-Top interaction

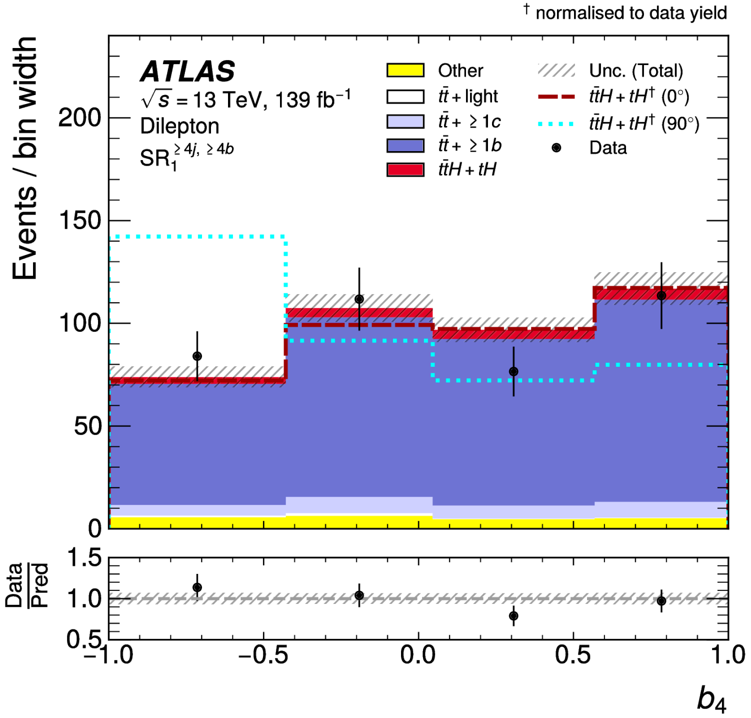
arXiv:2303.05974

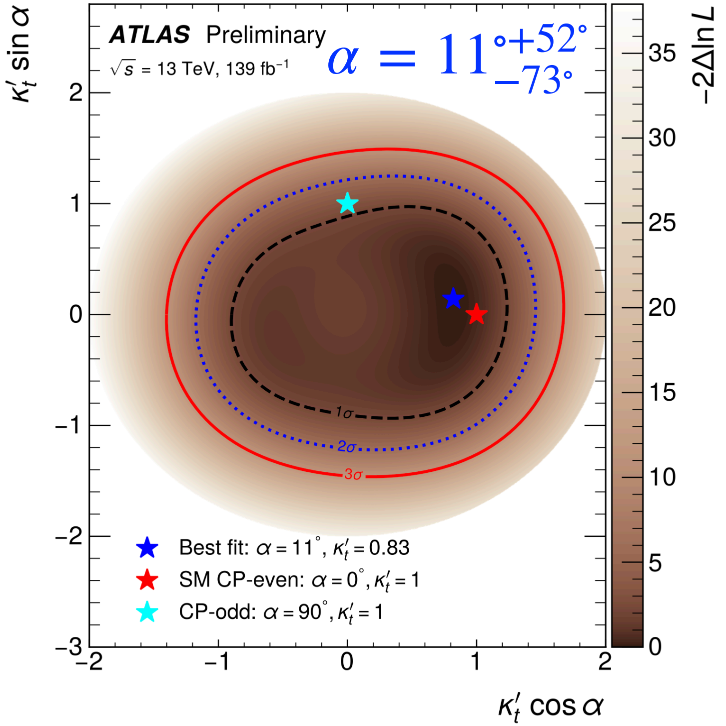
- Explore 1ℓ+jets (include boosted region) and 2ℓ channels
- Train BDT to categorize events
- Two dedicated CP sensitive variables defined with top quark kinematic information
- Use BDT for boosted region CP-even/odd separation

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









Summary

- Measurements of the Higgs boson properties in terms of mass, width, CP and anomalous couplings with the ATLAS detector are presented
- The latest Higgs boson mass is determined as $m_H = 124.99 \pm 0.19$ GeV from H→ZZ*→4ℓ channel with full Run-II dataset
- Evidence of the off-shell Higgs boson is found with an observed significance of 3.3σ in H→ZZ*→4ℓ/2ℓ2ν channel
  - ✓ Higgs boson width is measured as $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV
- The CP property of the Higgs boson is studied in various channels
  - ✓ Pure CP-odd contribution is excluded for $H\tau\tau$ and H-top interaction
  - ✓ Still room for CP-mixture
- No significant derivation from the SM prediction observed in anomalous coupling measurements

Backup

Higgs mass measurement

The signal probability density function is modelled as

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

where the following approximations are used:

- $\mathcal{P}(D_{NN}|\sigma_i, m_H) \simeq \mathcal{P}(D_{NN}|m_H)$ because the neural network discriminant does not directly depend on the per-event $m_{4\ell}$ resolution,
- $\mathcal{P}(\sigma_i|m_H) \simeq \mathcal{P}(\sigma_i)$ since the averaged per-event resolution does not depend on m_H within the range of 105 to 160 GeV used in this measurement, and
- $\mathcal{P}(\sigma_i)$ is omitted from the probability density function because it was observed that it has approximately the same distribution for signal and background events in the Higgs boson peak region. Dedicated checks of the assumption that $\mathcal{P}(\sigma_i)$ can be omitted have shown that this has negligible impact on the measurement.

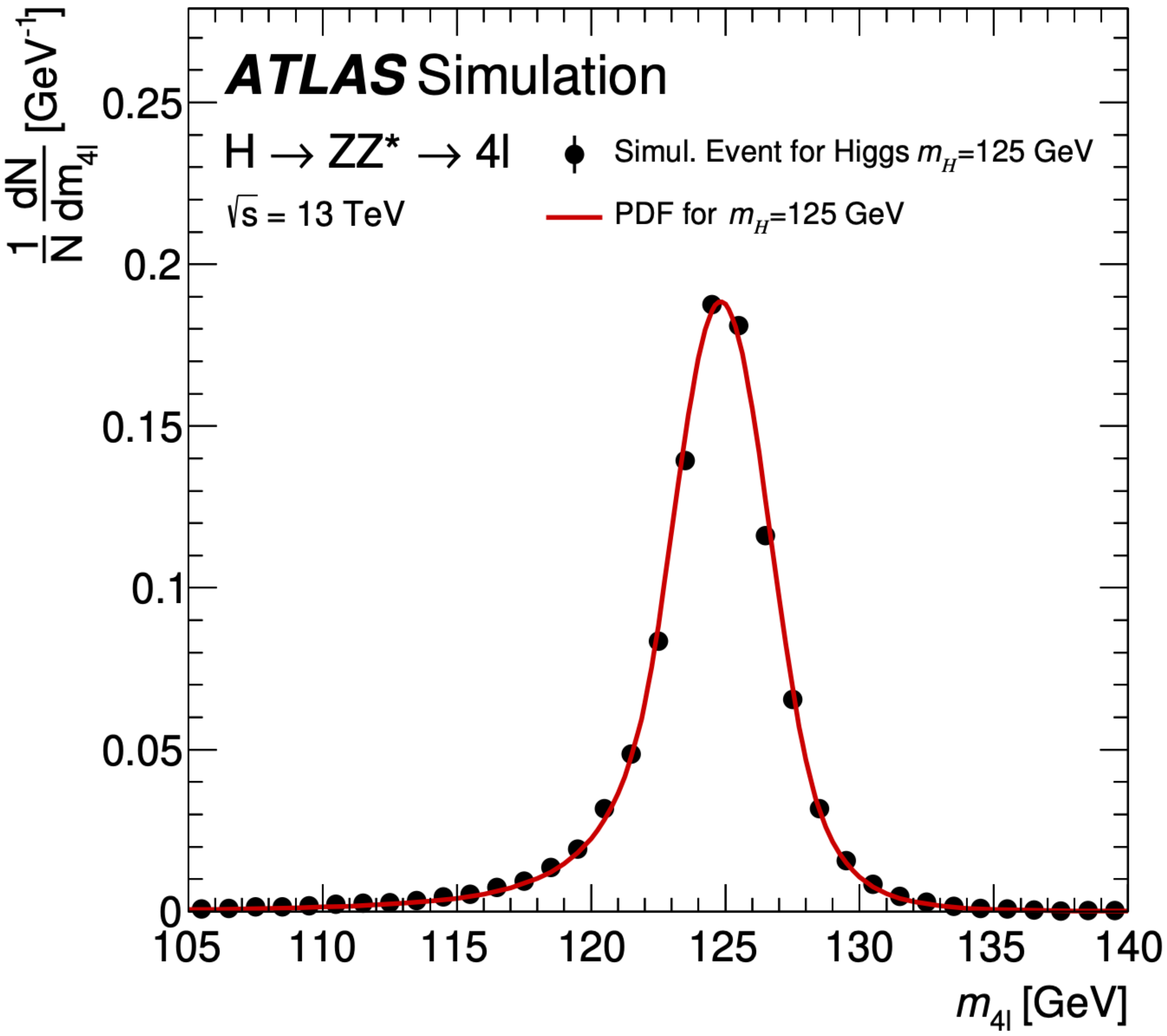
The probability density function $\mathcal{P}(m_{4\ell}|D_{NN}, \sigma_i, m_H)$ in each subchannel is described by a double-sided Crystal Ball [57] probability density function that consists of a Gaussian core and two power-law tails.

Higgs mass measurement

Signal parametrized with Double-sided Crystal ball function

Mean of Gaussian parametrized as

$$a^{\lambda} \cdot (m_H - 125\text{ GeV}) + b^{\lambda}(D_{NN})$$



Off-shell Higgs boson to measure width

Limit width through off-shell production

- Higgs boson width could be constrained using off-shell production to 2 Z bosons away from the resonance peak. Gluon fusion is dominant.

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H}$$

- Integrating around m_H or above $2m_Z$ (where m_{ZZ}-m_H>>Γ_H);

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \quad \text{and} \quad \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}.$$

- Taking signal strengths in terms of coupling scale factors;

$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma^{SM}_H} \qquad \mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

  - On-shell (NWA) depends on total width Off-shell does not!

- Assumption of **independence of scale factors from s** (energy scale) in high mass region considered in the analysis.
- A measurement of the relative on-shell and off-shell production provides direct information on Higgs width, assuming **coupling ratios unchanged** (no new physics).
- **NNLO K-factor for the gg → VV process unknown**. CMS assumes same NNLO K factor with the signal and adds **10% uncertainty**. ATLAS provides the result as a **function of the ratio** of these two.

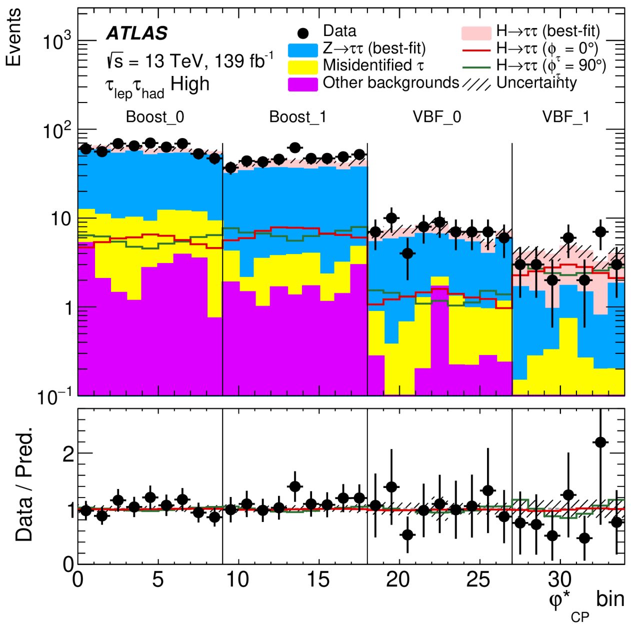
H→ττ coupling structure

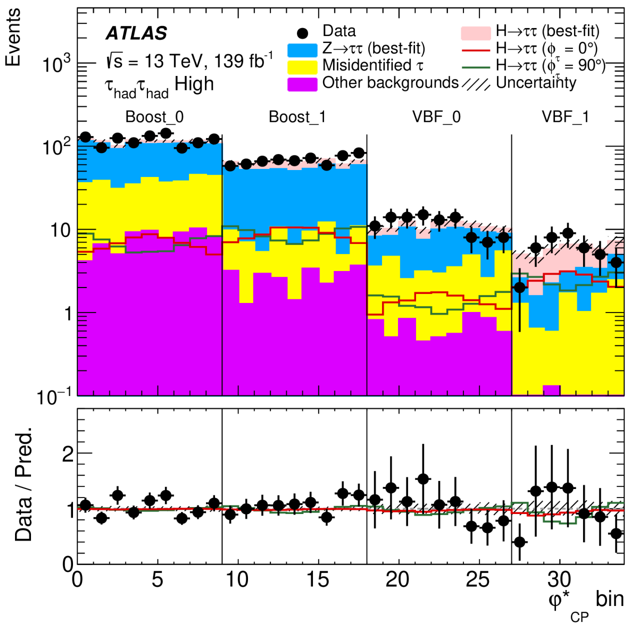
arXiv:2212.05833

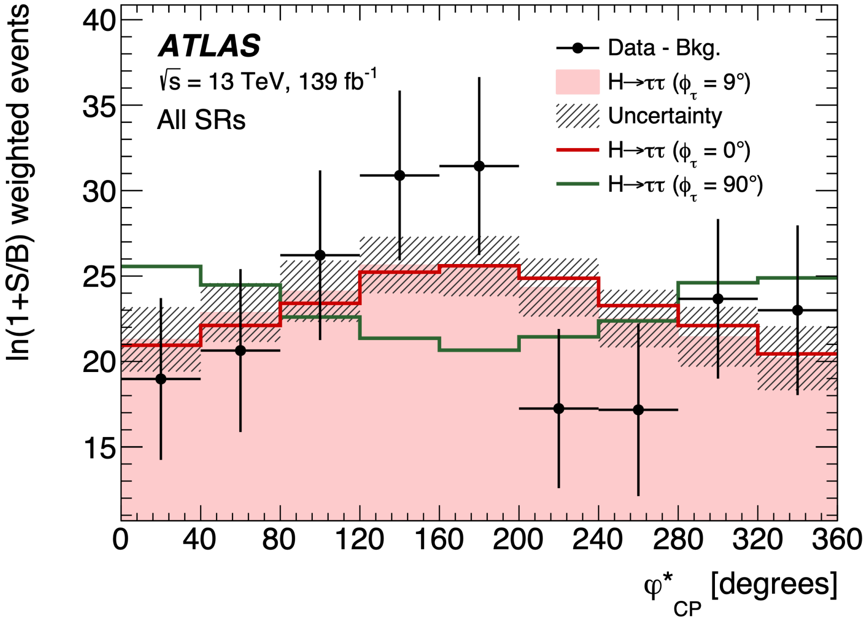
Measured results by ATLAS

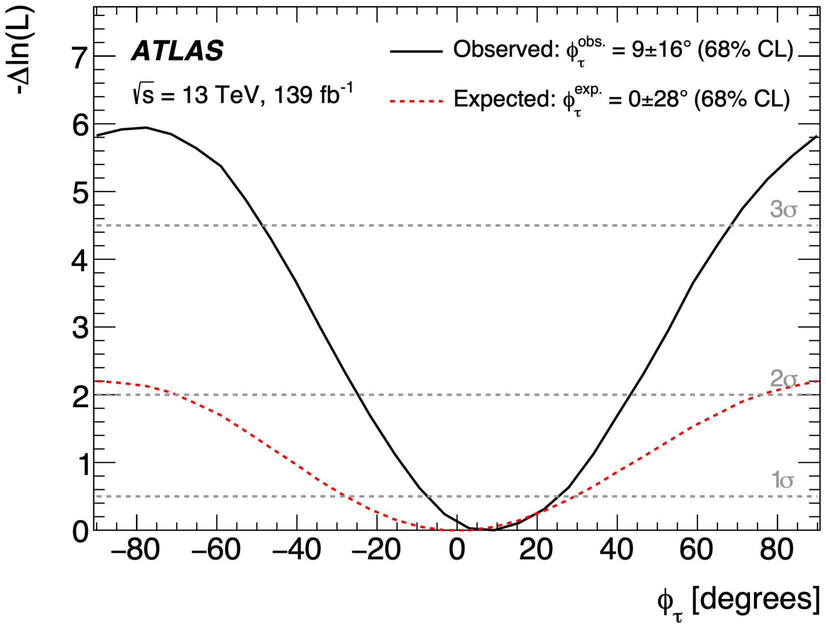
ϕ_τ = 9±16 deg. (±28 deg.)

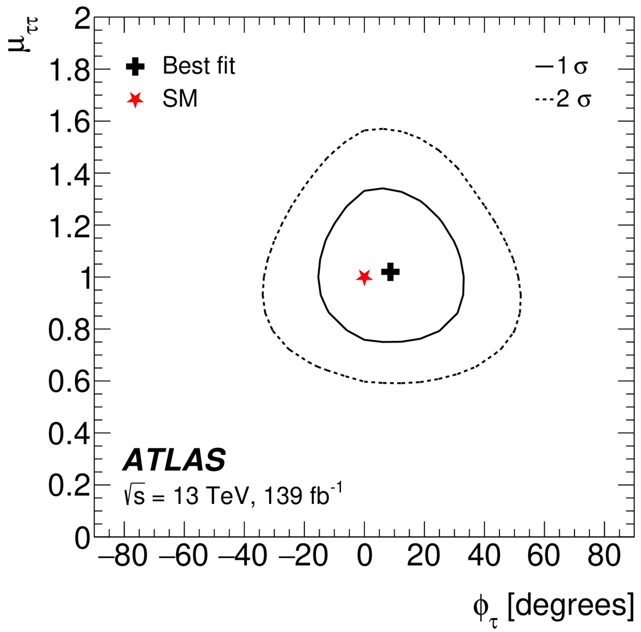
Pure CP-odd excluded @ 3.4σ









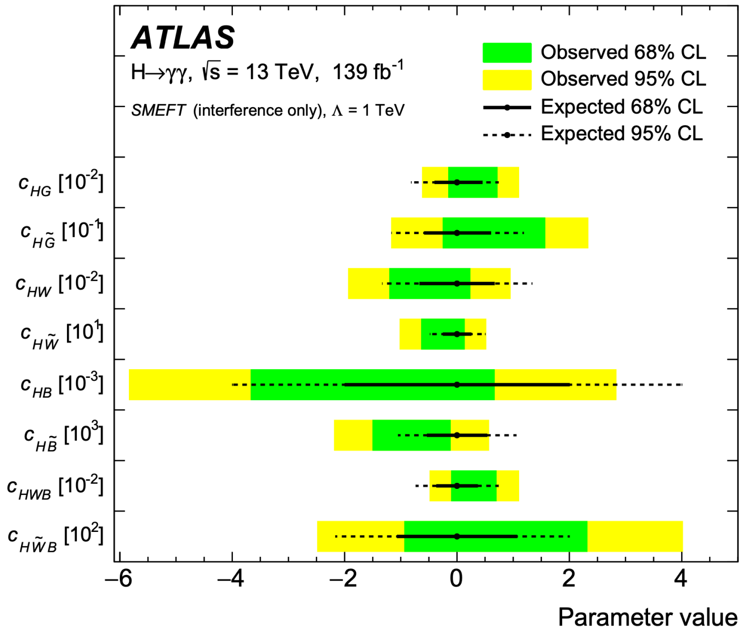


Constrain anomalous coupling with differential measurements

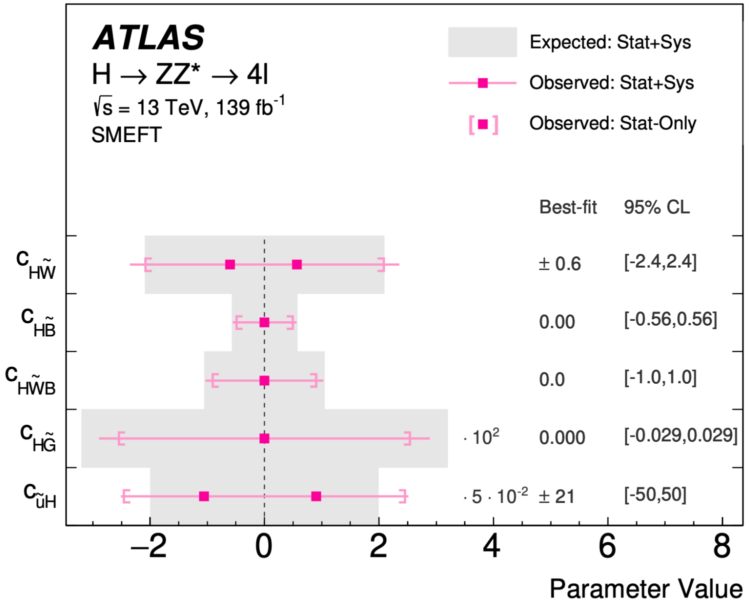
- Differential/STXS cross-section measurements could be interpreted to measure the anomalous coupling
- SMEFT approach used for H→$\gamma\gamma$, H→ZZ and H→WW results

$$\mathcal{L}_{\text{eff}}^{\text{SMEFT}} \supset c_{HG}O'_g + c_{HW}O'_{HW} + c_{HB}O'_{HB} + c_{HWB}O'_{HWB}$$ **CP-even**

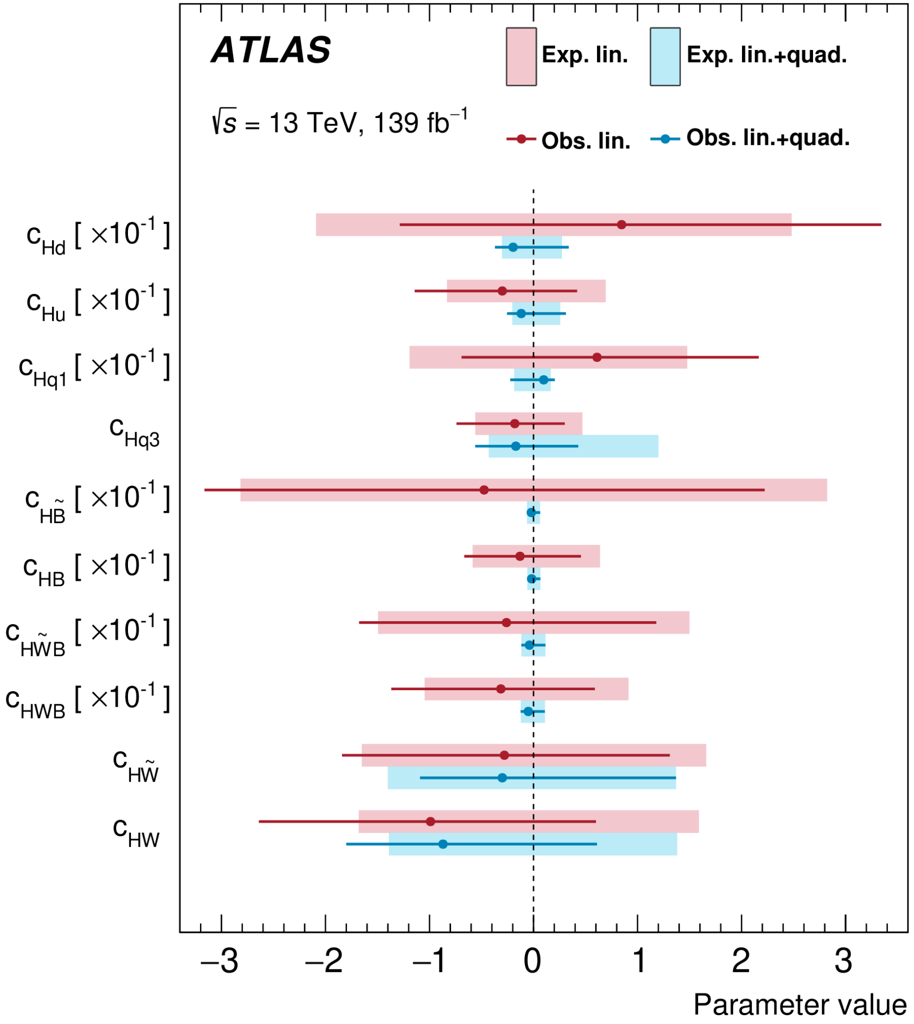
CP-odd $$+c_{H\widetilde{G}}\widetilde{O}'_g + c_{H\widetilde{W}}\widetilde{O}'_{HW} + c_{H\widetilde{B}}\widetilde{O}'_{HB} + c_{H\widetilde{W}B}\widetilde{O}'_{HWB}$$



H→$\gamma\gamma$ JHEP 08 (2022) 027

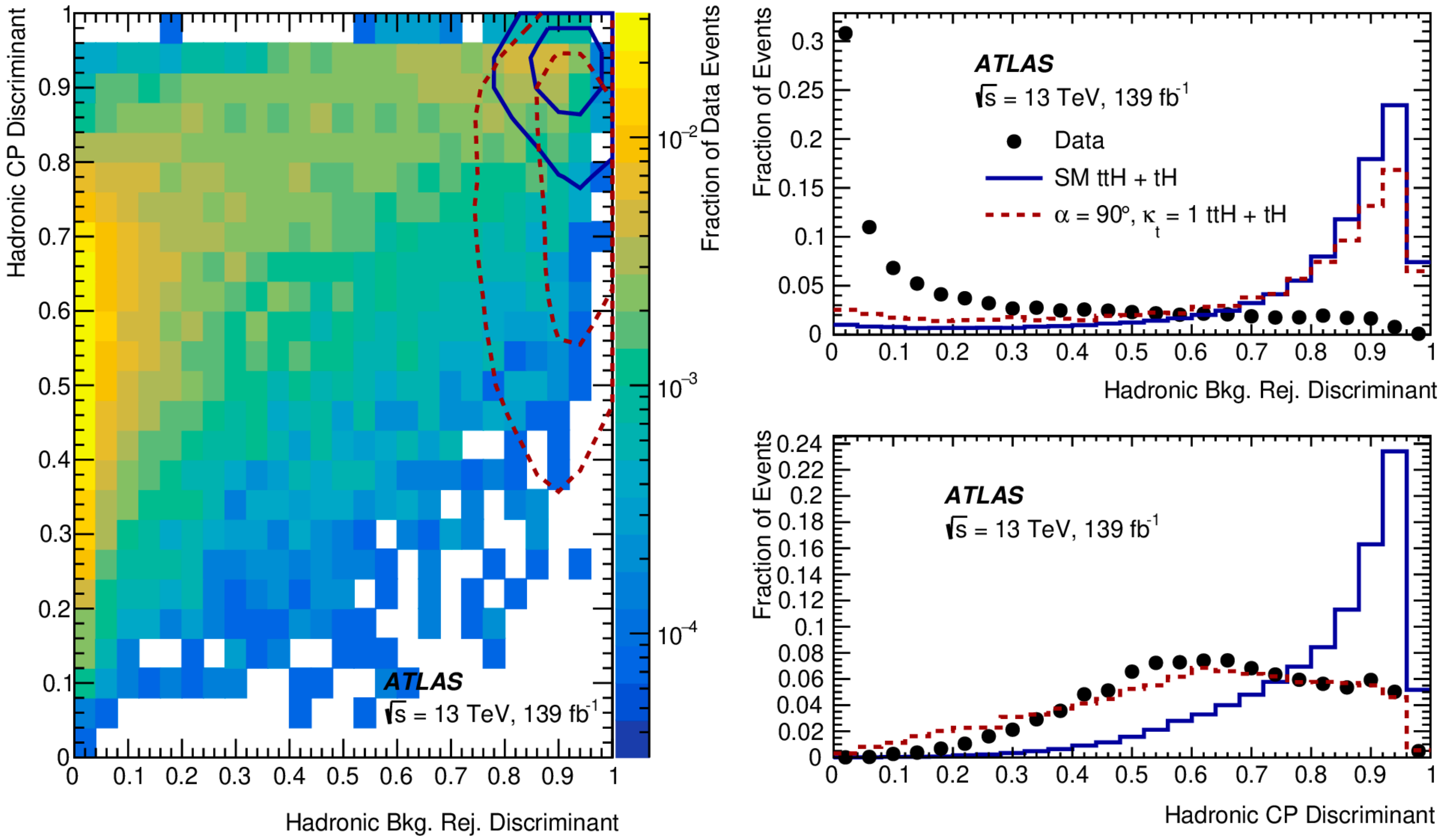


H→ZZ Eur. Phys. J. C 80 (2020) 957

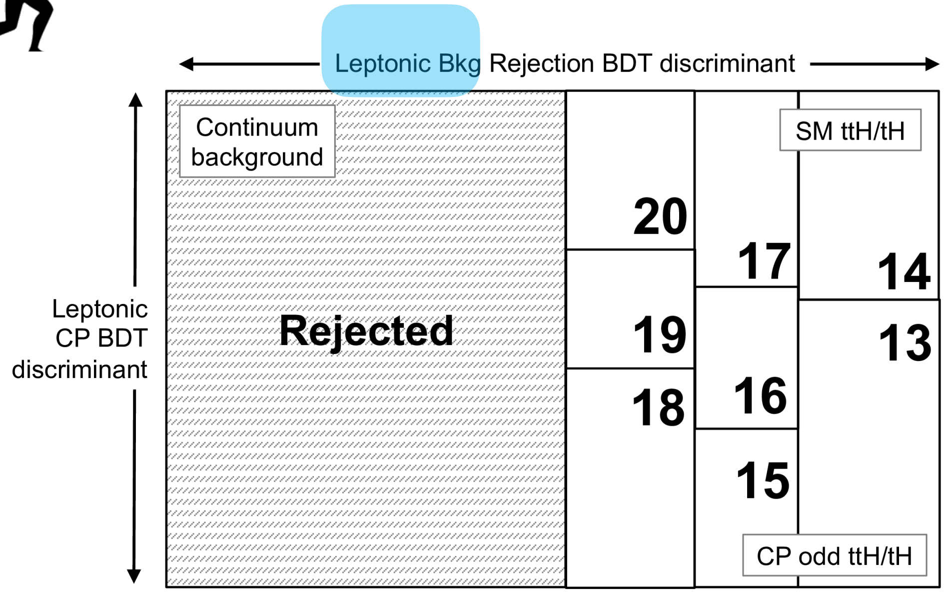


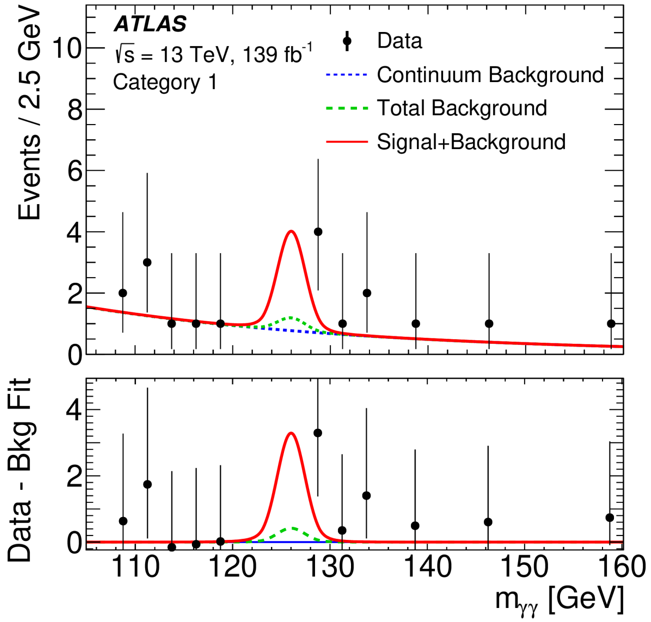
H→WW arXiv:2304.03053

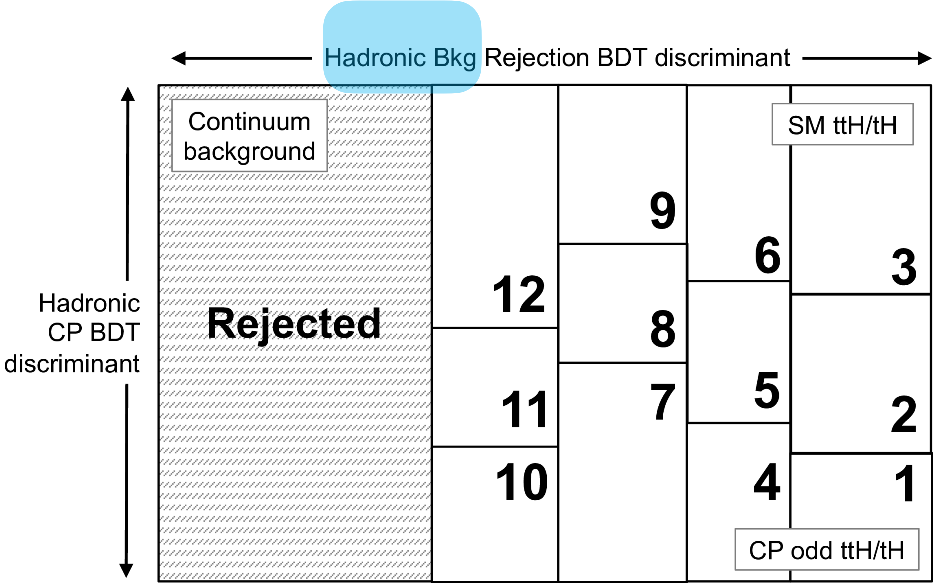
Higgs-Top CP structure: H→γγ

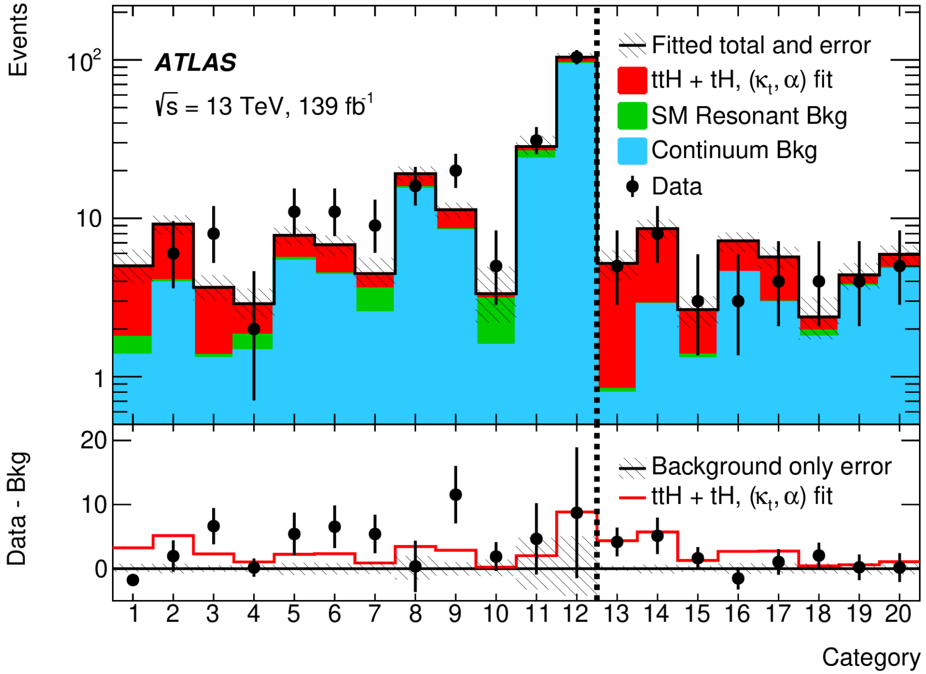


Higgs-Top CP structure: $H \rightarrow \gamma\gamma$









ttH/tH Hbb CP measurement

Region		Dilepton $\mathrm{TR}^{\geq 4j,\geq 4b}$	Dilepton $\mathrm{CR}^{\geq 4j,3b}_{\mathrm{hi}}$	Dilepton $\mathrm{CR}^{\geq 4j,3b}_{\mathrm{lo}}$	Dilepton $\mathrm{CR}^{3j,3b}_{\mathrm{hi}}$	ℓ+jets $\mathrm{TR}^{\geq 6j,\geq 4b}$	ℓ+jets $\mathrm{CR}^{5j,\geq 4b}_{\mathrm{hi}}$	ℓ+jets $\mathrm{CR}^{5j,\geq 4b}_{\mathrm{lo}}$	ℓ+jets $\mathrm{TR}_{\mathrm{boosted}}$
N_{jets}		≥ 4			$= 3$	≥ 6	$= 5$		≥ 4
$N_{b\text{-tag}}$	@85%	–				≥ 4			
	@77%	–				–			$\geq 2^{\dagger}$
	@70%	≥ 4	$= 3$			≥ 4			–
	@60%	–	$= 3$	< 3	$= 3$	–	≥ 4	< 4	–
$N_{\mathrm{boosted\ cand.}}$		–				0			≥ 1
Fit observable		–	Yield			–	$\Delta R^{\mathrm{avg}}_{bb}$		–

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

ttH/tH Hbb CP measurement