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

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Is the observed Higgs boson the one predicted by the SM?

- To find the answer, we need to measure its properties.
- The **mass of the Higgs boson** m_H has to be measured accurately because:
  - its value is not predicted by the Standard Model (SM) and it determines the Higgs boson production and decay rates,
  - it is input for global fits that measure electroweak observables,
  - it determines the stability of the electroweak vacuum.
- Why do we need to measure the **width of the Higgs boson**?
  - Because it is sensitive to the potential presence of BSM Higgs boson decays that are not covered by dedicated experimental searches.
- Why shall we search for **CP violation (CPV) in the Higgs sector**?
  - To find an additional source of CPV that can contribute to explain the matter-antimatter asymmetry observed in the Universe.

- This presentation will show the most recent ATLAS analyses targeting the understanding of these three Higgs boson properties.
- All the analyses presented here were performed using the full Run-2 dataset recorded by the ATLAS detector during the years 2015-2018 (unless the opposite is specified).

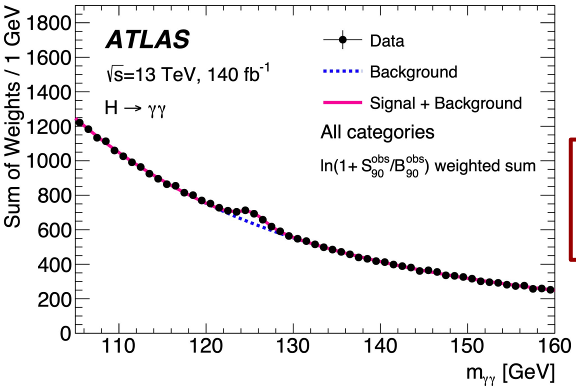
Higgs boson mass measurements

Higgs mass measurements

- The Higgs boson mass is measured via $H\to\gamma\gamma$ and $H\to ZZ^*\to 4\ell$ decay channels as the Higgs can be fully reconstructed with high resolution.

$H\to\gamma\gamma$ analysis
(Phys.Lett.B 847 (2023) 138315)

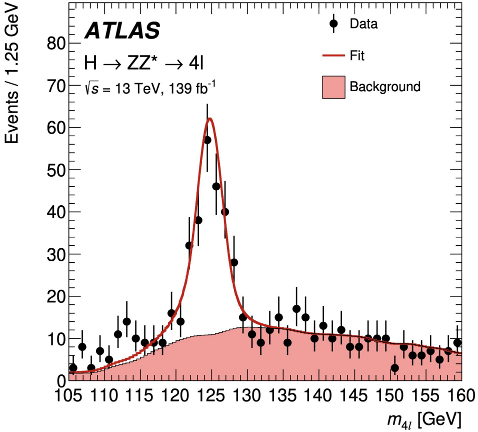
- m_H determined from the position of the peak in the diphoton invariant mass distribution $m_{\gamma\gamma}$.
- Perform profile likelihood fit over 14 analysis categories with different S/B ratios, $m_{\gamma\gamma}$ resolution and photon energy-scale uncertainties.
- Main improvements with respect to previous measurement:
  - Reduced the impact of photon energy-scale uncertainties by four times → JINST 19 (2024) P02009.
  - Larger data sample
  - Improved $e\to\gamma$ extrapolation.
  - More optimised event categorisation strategy.



$m_H = 125.17 \pm 0.14\ (0.11\ \text{stat})$ GeV

$H\to ZZ^*\to 4\ell$ analysis
(Phys. Lett. B 843 (2023) 137880)

- m_H determined from the position of the peak in the four-lepton invariant mass distribution $m_{4\ell}$.
- Perform profile likelihood fit over four analysis categories (4μ, $4e$, $2\mu 2e$, $2e2\mu$).
- Main improvements with respect to previous measurements:
  - Improved momentum-scale calibration of the muons.
  - DNN for signal vs. bckg discrimination.
  - $m_{4\ell}$ resolution estimated for each event → Output for quantile-regression NN.

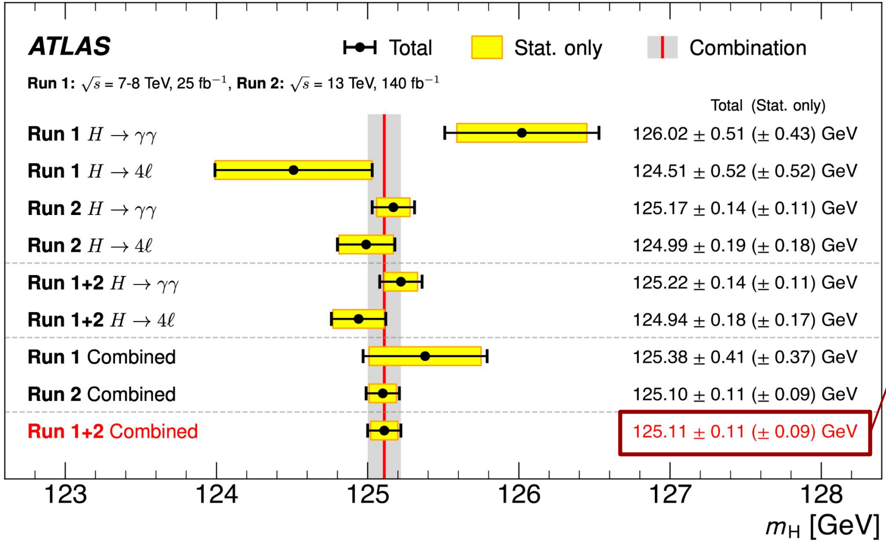


$m_H = 124.99 \pm 0.19\ (0.18\ \text{stat})$ GeV

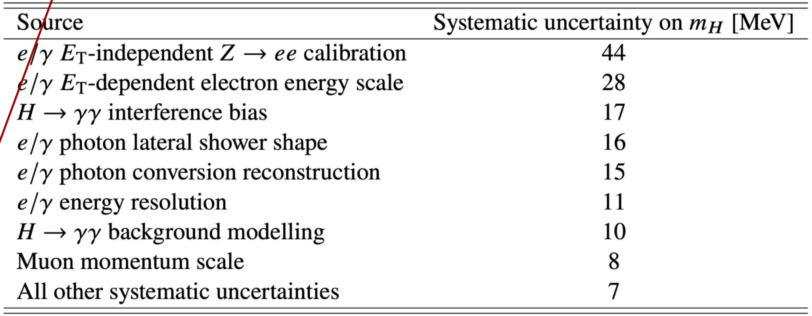
Higgs mass combination

Phys. Rev. Lett. 131 (2023) 251802

- The two previous Higgs mass measurements were combined together, and also with the corresponding Run 1 measurements.
- Combination scheme:
  - m_H correlated.
  - Signal strengths in each decay channel and run period uncorrelated.
  - Nuisance parameters (NPs) correlated following Combined Performance (CP) groups recommendations.



The most precise measurement of the Higgs mass at the LHC!!



Source	Systematic uncertainty on m_H [MeV]
e/γ E_T-independent $Z \to ee$ calibration	44
e/γ E_T-dependent electron energy scale	28
$H \to \gamma\gamma$ interference bias	17
e/γ photon lateral shower shape	16
e/γ photon conversion reconstruction	15
e/γ energy resolution	11
$H \to \gamma\gamma$ background modelling	10
Muon momentum scale	8
All other systematic uncertainties	7

Higgs boson width measurements

Higgs boson width determination

- The SM predicts the Higgs boson total width, Γ_H, to be only 4.1 MeV (for m_H ~125 GeV).
- Due to limited detector resolution, Γ_H cannot be constrained via direct measurement of the Higgs boson line shape or flight distance.
- However, the combination of on-shell and off-shell Higgs production measurements can probe Γ_H.
- The differential XS for Higgs production as a function of the invariant mass of its final state is given by the Breit-Wigner function:

$$\frac{d\sigma}{dm^2} = \frac{g_{i,SM}^2 g_{f,SM}^2 \kappa_i^2 \kappa_f^2}{(m^2 - m_H^2)^2 + \boxed{m_H^2 \Gamma_H^2}}$$

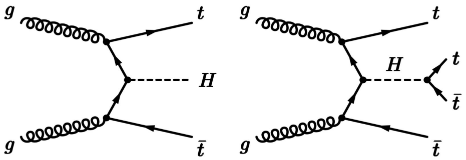
This term becomes negligible in the off-shell regime. Thus, **the off-shell XS does not depend on Γ_H**.

where *i* represents the Higgs production mode, *f* the Higgs decay mode, g_{SM} the (effective) SM coupling and *k* the corresponding coupling modifier (*k*=1 for SM). Signal strengths are then easily expressed as:

$$\mu_{\text{off-shell}} = \kappa_i^2 \kappa_f^2, \qquad \mu_{\text{on-shell}} = \frac{\kappa_i^2 \kappa_f^2}{\Gamma_H / \Gamma_H^{\text{SM}}}, \qquad \boxed{\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma_H}{\Gamma_H^{\text{SM}}}.}$$

This expression assumes that the couplings are the same at different energy scales.

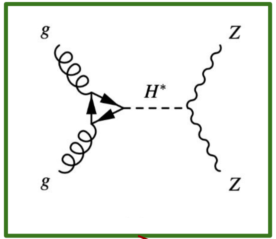
- The ATLAS collaboration probed Γ_H in two independent channels (details in next slides):
  - Combining the on-shell H→ZZ* and the off-shell H*→ZZ productions. The ggF, VBF and VH production mechanisms are considered. One needs to assume that the ggH effective coupling and the VVH coupling are the same in the on-shell and off-shell regimes.
  - Combining on-shell-Higgs ttH production and the off-shell-Higgs four-top-quark production. One needs to assume that the Higgs-top Yukawa coupling is the same in the on-shell and off-shell regimes.

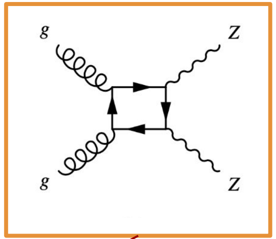


Higgs width constrains via H(*)→ZZ(*) production

Phys. Lett. B 846 (2023) 138223

- This analysis (apart from probing Γ_H) targets the observation of off-shell Higgs production.
- Signal and main background Feynman diagrams for ggF production are (also VBF/VH production is targetted):





ZZ→4ℓ

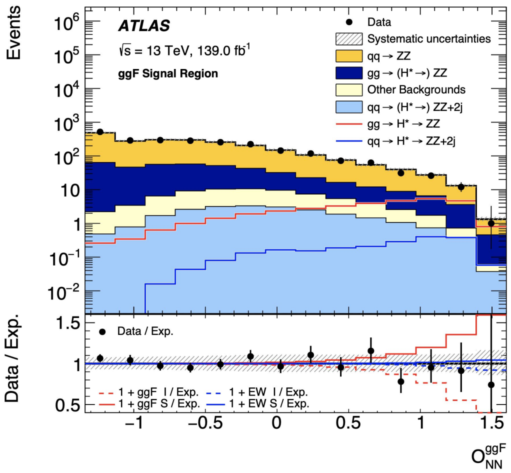
- Cleaner backgrounds (signal has no neutrinos).
- Use two Neural Network (NN) observables: one for ggF signal and one for EW signal.

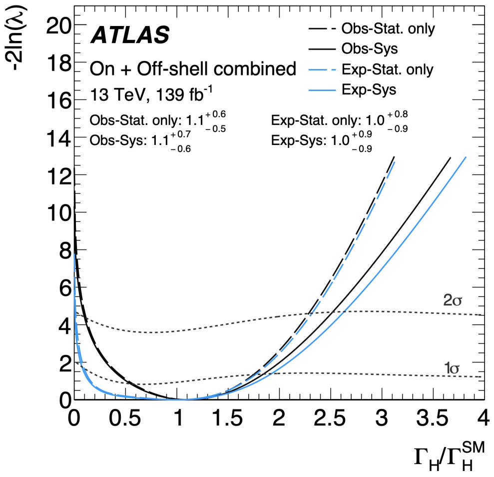
ZZ→2ℓ2ν

- Larger branching ratio.
- Backgrounds: WZ, eμ, Z+jets, etc
- Use transverse mass of ZZ as observable.

Notice that the interference between signal and background diagrams must be taken into account.

- Find evidence of off-shell Higgs boson production (3.3σ) and, after combining with on-shell Higgs measurements, a total width **Γ_H = 4.5 +3.3 -2.5 MeV** is observed, in agreement with SM.
- The observed (expected) upper limit on the total width is found to be 10.5 (10.9) MeV at 95% CL.
- Results are consistent with the analogous CMS analysis (arXiv:2409.13663).



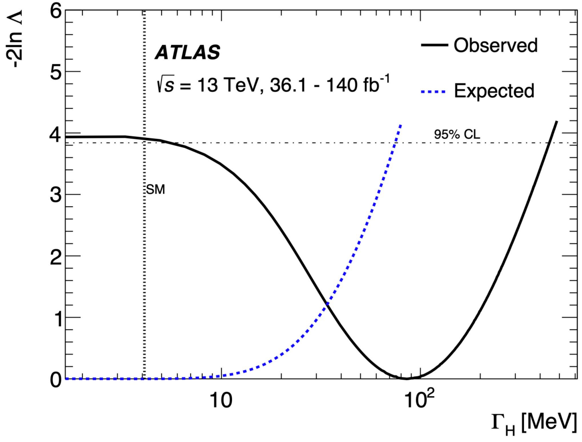


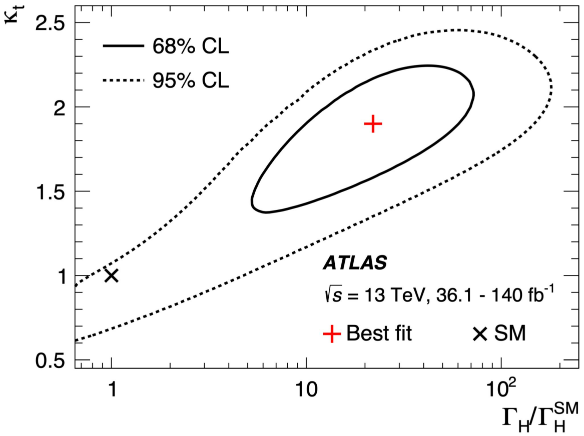
Higgs width constrains via four-top-quark production

https://arxiv.org/abs/2407.10631

New

- This analysis combines the observation of four-top-quark production (Eur. Phys. J. C 83 (2023) 496), as off-shell Higgs production, and the measurements of on-shell Higgs production published in Nature in 2022 (Nature 607, pages 52-59 (2022)).
- All measurements are parametrised in the *k* framework with Γ_H left as a free parameter.
- Full statistical combination of the input analyses with the appropriate correlation of systematic uncertainties.
- The observed (expected) 95% CL upper limit on Γ_H is found to be 450 (75) MeV i.e. 110 (18) times the SM prediction.
- Assuming that only SM particles contribute to the loop-induced ggF, $H\to\gamma\gamma$, $H\to Z\gamma$ processes, the observed (expected) upper limit decreases to 39 (13) times the SM prediction.
- The tension between the data and the SM prediction is 2.0σ in both scenarios and it is driven by the 1.8σ difference between data and SM in the four-top measurement.



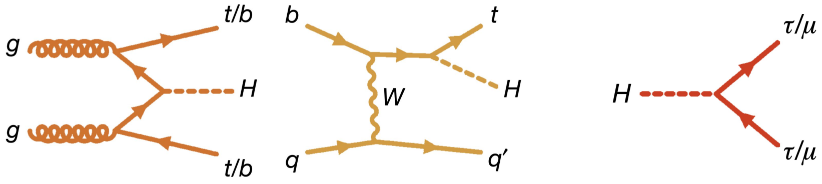


CP violation in the Higgs sector

CP violation in the Higgs sector

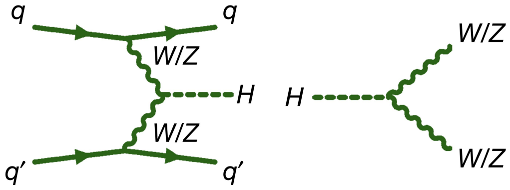
- The SM predicts the Higgs boson to have $J^{CP} = 0^{++}$ i.e. SM Higgs interaction terms are invariant under CP transformation.
- How do we look for CP violation? → Look for CP-odd interaction terms in addition to the CP-even SM-like terms.
- Pure CP-odd scenario has been thoroughly excluded. However a mixture of CP-odd and CP-even states could indicate CPV in the Higgs sector.
- The most recent ATLAS measurements look for CPV in:
  - Higgs to vector bosons (VVH) and
  - Higgs to fermions (ffH) couplings.

ttH and $\tau\tau$H coupling



$$\mathcal{L}_{t\bar{t}H} = -\underbrace{\boxed{\kappa_t'}}_{\text{Coupling modifier}} y_t \phi \bar{\psi}_t \big(\overbrace{\cos \underbrace{\boxed{\alpha}}_{\text{CP-phase}}}^{\text{Scalar (SM-like)}} + \overbrace{i\gamma_5 \sin\alpha}^{\text{Pseudoscalar (BSM-like)}}\big)\psi_t$$

VVH coupling



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

VVH CP-odd-sensitive operators

Operator	Structure	Coupling
	Warsaw Basis	
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\tilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\tilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\tilde{B}}$

CP violation in the Higgs Yukawa sector

ttH(H→bb) CP analysis
(Phys. Lett. B. 849 (2024) 138469)

- Benefits from large H→bb branching ratio.
- Large tt + ≥ 1b bckg → its modeling is the main unc. in the analysis.
- Single-lepton (6 jets, 4 b-tagged) and dilepton (4 jets, 4 b-tagged) channels are defined.
- In each channel, two BDTs are trained: one for reconstruction of the ttH system and one for signal vs. bckg separation.
- Fit CP-sensitive observables:

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

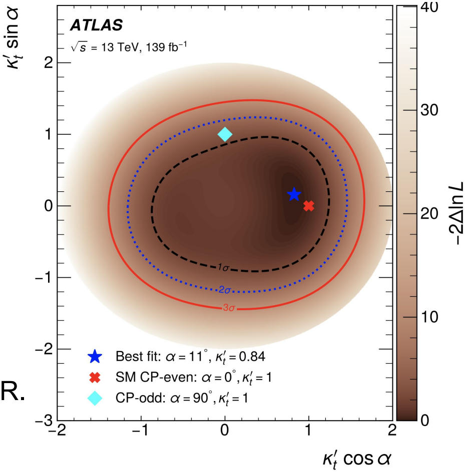
$$b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|} \quad \text{Dilepton}$$

where p_1 and p_2 represent the momentum of top and antitop.

- In the single-lepton channel, an additional boosted SR is defined by requiring a high-p_T Higgs candidate (identified by a DNN). New BDT score is fitted in this SR.
- **Results agree with the SM**:

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

and are consistent with the previous ttH(H→$\gamma\gamma$) CP analysis (Phys. Rev. Lett. 125, 061802 (2020)) → |α| > 45º was excluded at 95% CL.

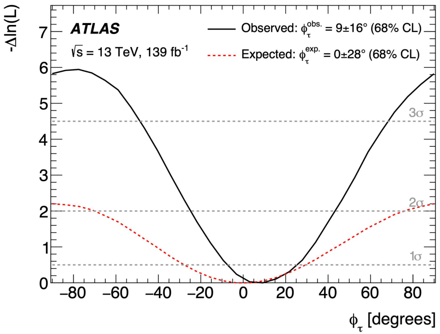


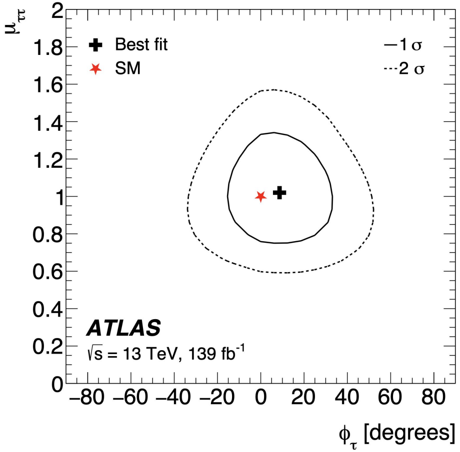
H→$\tau\tau$ CP analysis
(Eur. Phys. J. C 83 (2023) 563)

- Fit CP-sensitive observable φ_{CP}^*, which is the signed acoplanarity between the τ decay planes.
- There is a direct relationship between φ_{CP}^* and the CP-mixing angle

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

- Perform profile likelihood fit over different categories based on $\tau\tau$ decay mode, VBF/ggF production mode and Higgs mass estimator.
- No strong correlation observed between signal strength $\mu_{\tau\tau}$ and ϕ.
- **CP angle** is found to be 9º ± 16º, **in agreement with the SM**.





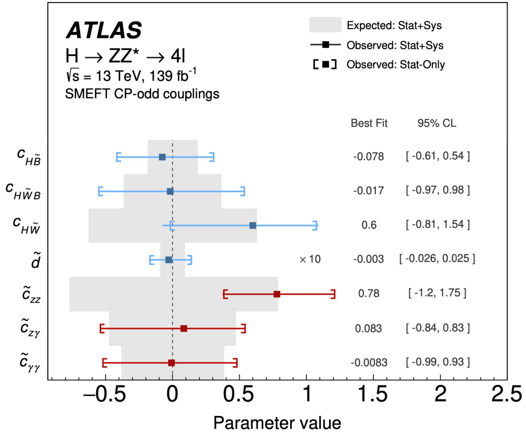
CP violation in the VVH interaction

VBF, H→4ℓ CP analysis
(JHEP 05 (2024) 105)

- Clean experimental signature.
- VVH coupling present in production and decay.
- Use CP-sensitive Optimal Observable (*OO*):

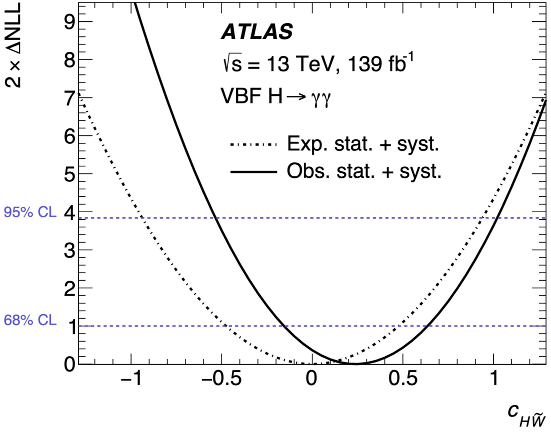
$$\mathcal{OO} = \frac{2\Re\left(\mathcal{M}^{*}_{\mathrm{SM}}\mathcal{M}_{\mathrm{BSM}}\right)}{|\mathcal{M}_{\mathrm{SM}}|^{2}}$$

- *OO* is symmetric in the absence of CPV.
- NN to separate VBF from ggF events.
- **Constrains on CP-odd couplings agree with the SM.**



VBF, H→γγ CP analysis
(Phys. Rev. Lett. 131 (2023) 061802)

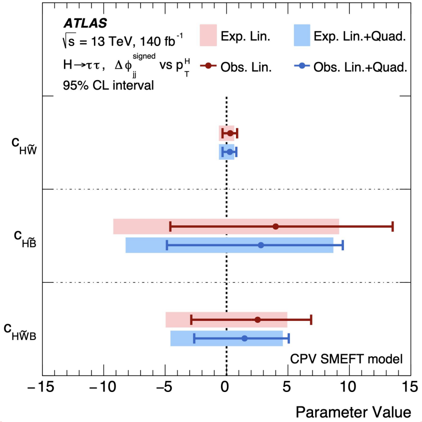
- Clean experimental signature.
- Mainly constrains $c_{HW\sim}$ as HWW dominates VBF production.
- Uses the same CP-sensitive *OO* as H→4ℓ.
- Two BDTs are used: VBF vs. ggF and VBF vs. continuum background.
- Fit $m_{\gamma\gamma}$ distribution in six *OO* bins.
- **Constrain on the CP-odd coupling $c_{HW\sim}$ agrees with the SM.**



H→ττ XS analysis
(arXiv:2407.16320)

New

- Differential cross-section measurement in a VBF-enhanced phase space (also CP).
- BDT to separate VBF from ggH/Z→ττ.
- $p_T(H)$ reconstruction using a NN that exploits E_T^{miss} and ττ variables.
- Fit $\Delta\phi_{jj}^{signed}$ observable in two $p_T(H)$ bins (below and above 200 GeV).
- **Constrains on CP-odd couplings agree with SM.**
- **$c_{HW\sim}$ constrain is the most stringent to date from any channel.**



Summary: is the observed Higgs boson the one predicted by the SM?

- It definitely looks very much like it!
- Higgs mass measurements → Reached 0.09% precision!
- Higgs width determination → Γ_H = 4.5 +3.3 -2.5 MeV. However, current measurements rely on off-shell to on-shell cross-section ratios i.e. model-dependent measurements.
- Search for CPV in the Higgs sector → Currently no signs of CPV in Higgs-boson interactions.

- What about the future? → We need more data from the LHC and future machines: HL-LHC and e^+e^- collider mainly.
  - Need to fully map the Higgs potential and understand stability of the electroweak vacuum.
  - Need to measure Higgs boson width using complementary methods (maybe more model-independent than the comparison of the on-shell vs. of-shell Higgs production).
  - We need to keep looking for CPV in the Higgs sector: cannot leave any stone unturned!

Thanks for your attention!

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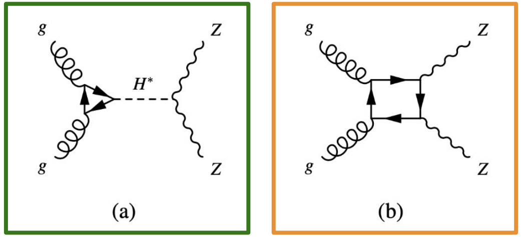
BACKUP

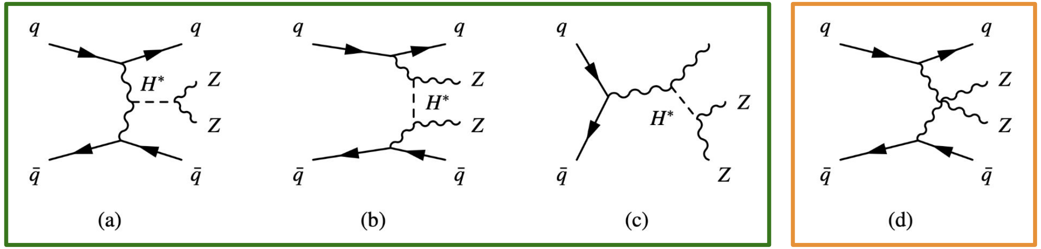
Higgs width constrains via off-shell H→ZZ production

- Signal and background Feynman diagrams:



(a) (b)

Figure 1: The leading-order Feynman diagrams for the (a) ggZZ signal and (b) background processes. In the signal process the quark loop is dominated by top and bottom, while for the continuum background it is mainly light quarks.



(a) (b) (c) (d)

Figure 2: The leading-order Feynman diagrams for (a) the *s*-channel vector-boson fusion signal, (b) the *t*-channel vector-boson fusion signal, (c) the vector-boson associated production signal, and (d) the vector-boson scattering background.