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

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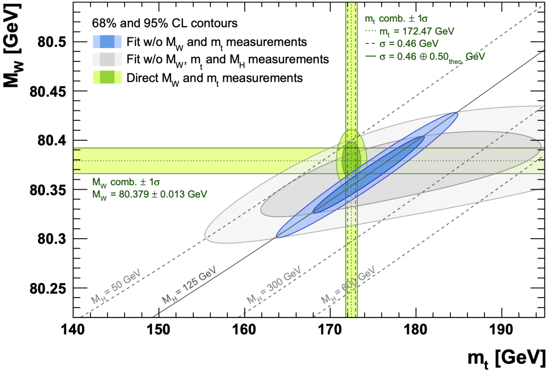
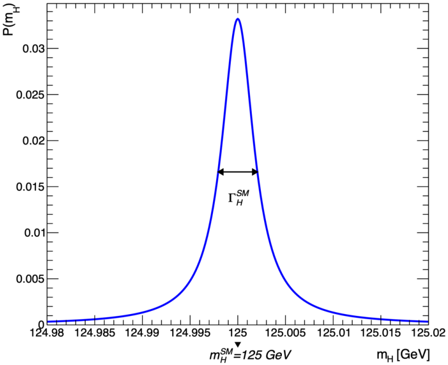
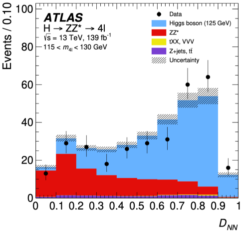
- LHC experiments discovered Higgs boson in 2012, very rich phenomenology now explored
- m_H is a **fundamental parameter** of the SM$\rightarrow$ to be measured experimentally
  - Higgs width and coupling are predicted in the SM once is known m_H
- Higgs CP-even scalar with $J^{CP} = 0^{++} \Rightarrow$ CP-odd couplings indicates BSM phenomena
- Higgs boson properties are one of our most **promising windows into new physics** $\Rightarrow$ **increase precision, perform combinations and interpretations!**

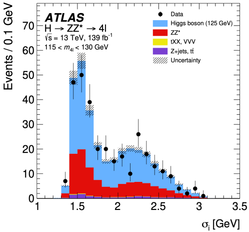


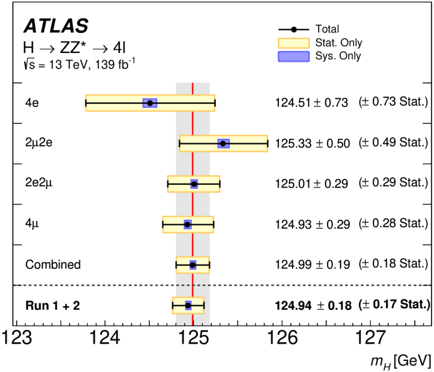


Higgs boson mass

- Analysis in 4 exclusive regions
- DNN discriminates signal from background
- **Quantile regression NN describes per-event $m_{4\ell}$ resolution**
- Signal PDF modelled as a function of σ_i, D_{NN}, $m_{4\ell}$





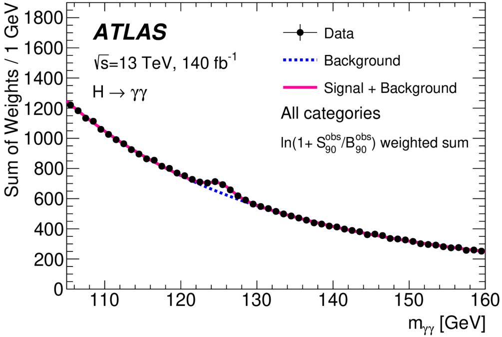


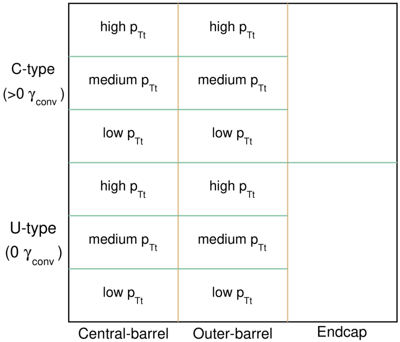
- Improved muon momentum-scale calibration
  - 20% better wrt latest Run 2 results
- Results statistically limited ⇒ **room for improvement in Run 3**

Combined **Run 1 + Run 2** result

$$m_H = 124.94 \pm 0.18\,\text{GeV}$$
$$= 124.94 \pm 0.17\,(\text{stat.}) \pm 0.03\,(\text{syst.})\,\text{GeV}$$

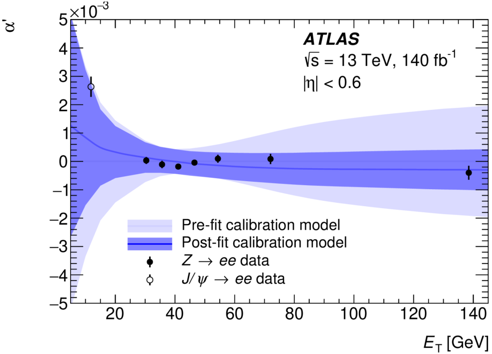
- Model the signal and smoothly falling background with analytical functions
- Separate events in **14 mutually exclusive categories based on photons kinematic**
  - Minimizing the total expected uncertainty on $m_H \Rightarrow$ 6% improvement wrt partial Run 2 results
- m_H from a maximum likelihood fit on the $m_{\gamma\gamma}$ distributions simultaneously in all categories

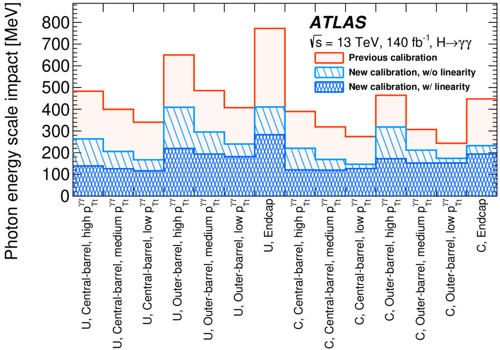




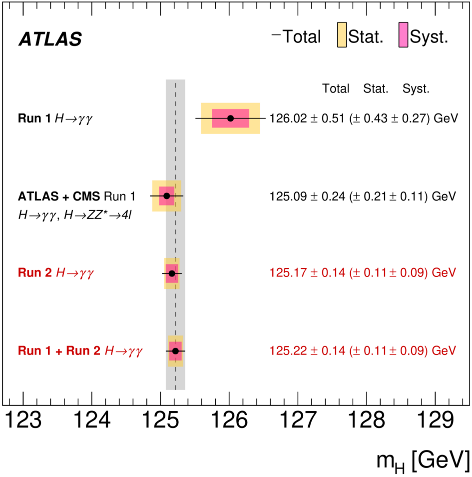
Worked hard to reduce the energy scale uncertainties and understand the detector better

- Improved material modelling in front of calorimeter (**x3 better**)
- Improved description of on-detector electronics non-linearity (**x2 better**)
- Improved electron-to-photon scale extrapolation (**x3 better**)
- Improved layer intercalibration (**50% better**)
- **E_T dependent systematics constrained by measured $Z \to ee$ scale factors** (*linearity fit*)



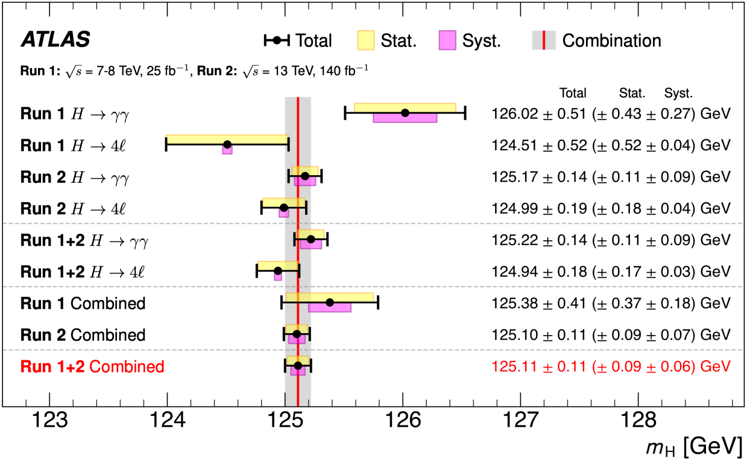


Reaching a precision of 0.11%: systematic uncertainties smaller than statistical ones!



- Inclusion of $gg \to H \to \gamma\gamma$ and $gg \to \gamma\gamma$ interference as systematic
- **Uncertainty due to PES decreased by a factor of 4 (320 MeV $\to$ 90 MeV)** $\Rightarrow$ below statistical uncertainty

Source	Impact [MeV]
Photon energy scale	83
$Z \to e^+e^-$ calibration	59
E_T-dependent electron energy scale	44
$e^\pm \to \gamma$ extrapolation	30
Conversion modelling	24
Signal–background interference	26
Resolution	15
Background model	14
Selection of the diphoton production vertex	5
Signal model	1
Total	90



- **Current most precise measurement of m_H reaching a sub-permil precision (0.09%)**
- Systematic uncertainties dominated by $H \to \gamma\gamma$ channel uncertainties, but room for improvements in Run 3

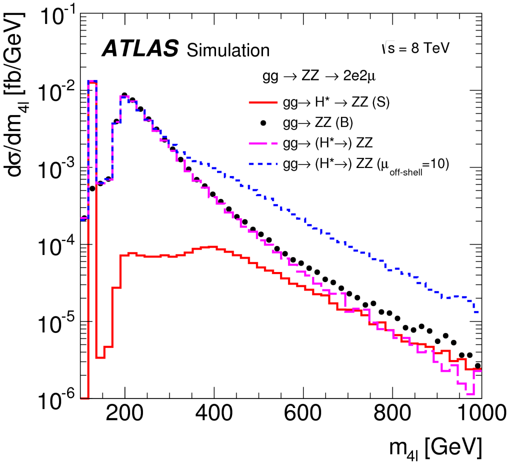
Higgs boson width

SM predicts the Higgs boson width of $\Gamma_H = 4.1$ MeV → too small for direct on-shell measurement!

- Interesting because BSM contributions could bring a huge enhancement
- Unfortunately Γ_H intrinsically interwined with couplings

Two possible solutions

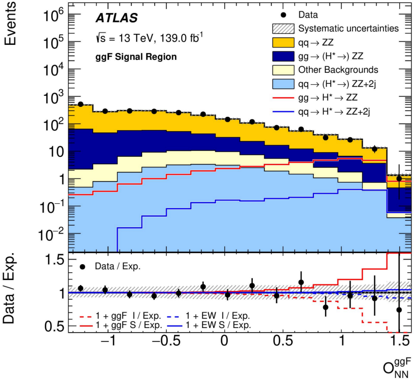
- On-shell $\sigma_{on} \sim \frac{g_i^2 g_f^2}{m_H^2 \Gamma^2}$ fully degenerate with couplings
  - needs strong assumptions on κ-modifiers to extract $\mathcal{B}_i$ (results in Rui's presentation)
- **Infer Γ_H from ratio of off-shell cross section $\sigma_{off} \sim \frac{g_i^2 g_f^2}{(\hat{s} - m_H)^2}$ to on-shell one**
  - Assuming $(g_i^2 g_f^2)_{on} = (g_i^2 g_f^2)_{off}$
  - Indirect measurement performed in the $H^* \to ZZ$ decay channel ⇒ need good understanding of interfering background



text

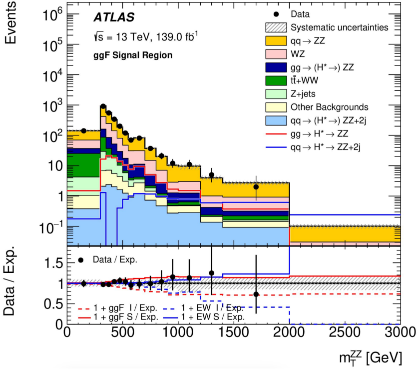
4ℓ channel

- $H \to 4\ell$ events with $m_{4\ell} > 220$ GeV
- Use **multi-class neural network (NN)** to enhance signal sensitivity (S vs B vs not-interfering B) $\Rightarrow$ 3 different SRs
  - EWK SR, one jet SR and ggF



$2\ell 2\nu$ channel

- Require 2 isolated leptons and large E_T^{miss}
- m_T^{ZZ} as discriminating variable
- 3 SRs similar to 4ℓ analysis



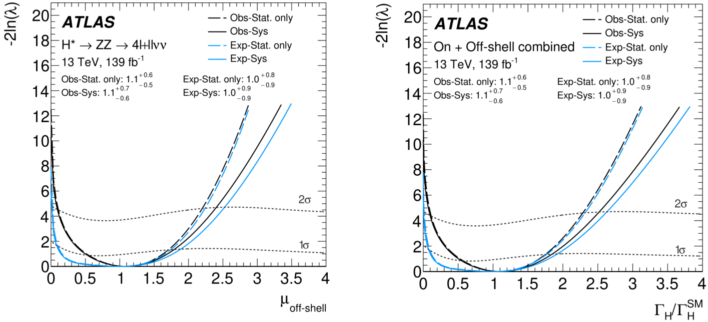
- Simultaneously fit signal strength and background normalization factors in all signal regions and control regions
- **Direct measurement of off-shell signal strength**

$$\mu_{\text{off-shell}} = 1.1\,^{+0.7}_{-0.6} \text{ with significance off-shell production } 3.3(2.2)\sigma$$

- **Combination with on-shell $H \to ZZ^* \to 4\ell$ measurement**

$$\Gamma_H = 4.5\,^{+3.3}_{-2.5} \text{ and } 0.5(0.1) < \Gamma_H < 10.5(10.9)\text{MeV @95\%}\,CL$$

- Unfortunately **all results compatible with SM**



Higgs boson spin/CP

CP-odd Higgs boson couplings to other particles can be described by adding corresponding terms to the SM Lagrangian

Coupling to Bosons

- Parametrized with SMEFT operators $c_{H\tilde{B}}, c_{H\tilde{W}B}, c_{H\tilde{W}}$

$$\mathcal{M} = \mathcal{M}_{SM} + \tilde{d} \cdot \mathcal{M}_{BSM} \quad \text{with } \tilde{d} = \tilde{d}(c_{H\tilde{B}}, c_{H\tilde{W}B}, c_{H\tilde{W}})$$

- Define **Optimal Observable**, **asymmetric if CP-odd contributions are present**

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

Coupling to Fermions

- Parametrized by a mixing angle α between CP-even and CP-odd components
  - **Pure CP-even has $\alpha = 0$, while pure CP-odd has $\alpha = 90$**

$$\mathcal{L}_{HFF} = -\frac{m_F}{v}\kappa_F(\cos\alpha\bar{\psi}\psi + \sin\alpha\bar{\psi}i\gamma_5\psi)H$$

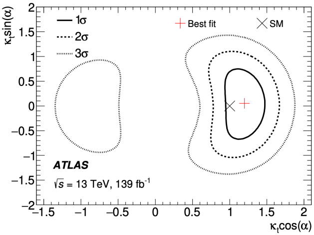
Plethora of measurements already available by ATLAS

- H-boson coupling: VBF $H \to \gamma\gamma$, VBF $H \to \tau\tau$
- H-fermion coupling: $ttH \to \gamma\gamma$, (t)tH$\to b\bar{b}$

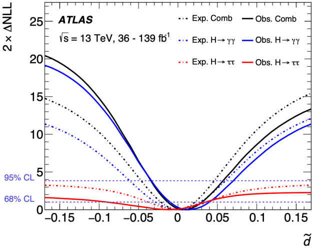
I will go through only the latest results

- H-boson: $H \to WW^*$ differential analysis and VBF $H \to 4\ell$ CP analyis

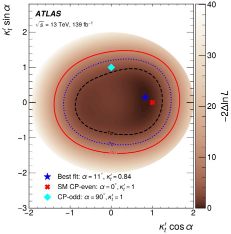
ttH$\to \gamma\gamma$ CP



VBF $H \to \gamma\gamma$ and $H \to \tau\tau$

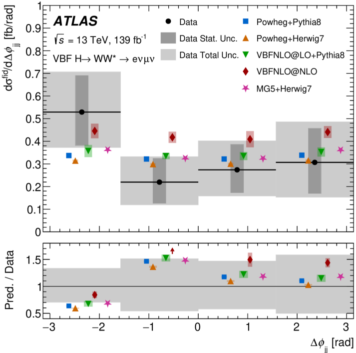


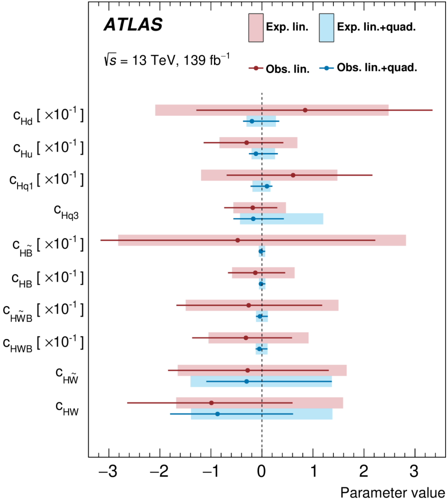
(t)tH$\to b\bar{b}$ CP analysis



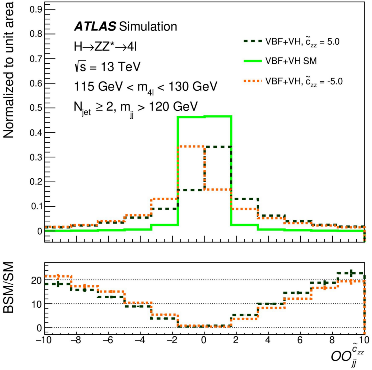
Interpret differential $H \to WW^*$ analysis for CP measurement

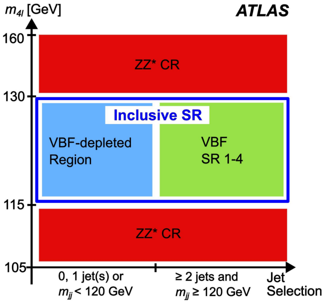
- Unfolding multiple observables simultaneously and interpret with EFT operators
- **$\Delta\Phi_{jj}$ in VBF channel being particularly sensitive to CP-odd contributions**
- Analysis designed around 2 BDTs to enhance S/B ratio: selecting VBF and reject top+VV

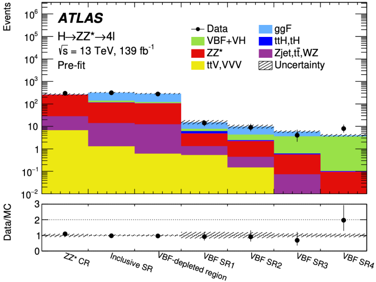




- Search for CP violation both in production and decay
- ZZ^* bkg normalized with CR outside $m_{4\ell}$ window
- 3-class NN to separate VH, VBF and ggH
  - SR 1-4: VBF sensitive can probe CP-odd in production
  - Inclusive SR sensitive to CP-odd in decay
  - SR1-4 + VBF-depleted region probe decay and production CP-odd simultaneously

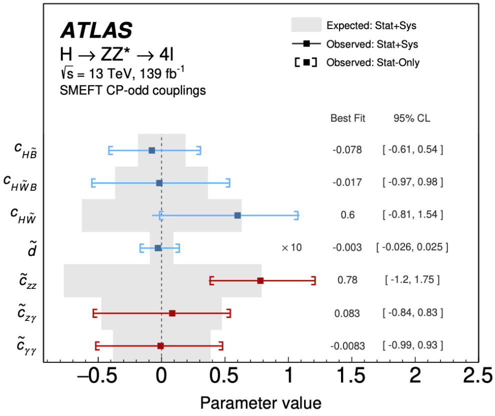






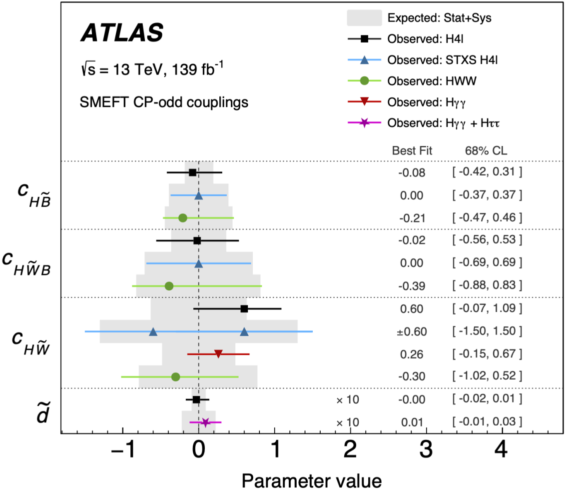
- Maximum-likelihood fit performed for CP-odd coupling parameters
- Also constrain on coupling parameters obtained scanning individually and in 2D
- **No deviation from SM expectation observed**

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



- CP coupling properties are probed both via boson and fermion interactions
- CP measurements can be performed with dedicated analysis or re-interpretation of available ones
  - EFT interpretations of differential and STXS/coupling analyses
- Unfortunately no signs of CP-odd contributions in the interaction so far

Higgs-Bosons coupling CP summary



- **Impressive progress made in measuring the Higgs boson properties with Run 2 dataset**
- Huge effort in improving detector understanding from precision analyses like m_H
  - Greatly beneficial for the whole ATLAS collaboration!
- **Higgs boson mass known with 0.09% uncertainty**, combining golden channels and Run 1 results
- **Higgs boson width measurements around SM expectation** $\Gamma_{\mathrm{H}} = 4.5\,^{+3.3}_{-2.5}$
- **No signs of Higgs CP-odd** interactions measured so far

Nonetheless, **exciting time ahead of us** with Run 3 data taking in full swing

- Already collected 100 fb^{-1} of data, expect to double the Run 2 luminosity!
- New triggers and new analysis technique will be able to boost even more our sensitivity!

Thank you