Higgs mass and width measurements at ATLAS

PASCOS2024
20th Rencontres du Vietnam

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on behalf of the ATLAS Collaboration

Motivations behind the measurements 📚

m_H

The **Higgs boson mass** m_H is a fundamental free parameter of the Standard Model:

- the Higgs boson *production cross sections* σ and *decay branching ratios*, i.e. the Higgs boson **couplings** with all other particles, are established only when m_H is fixed
- m_H plays a key role in the **global EW fit**, i.e. in the internal consistency of the SM (interplay between the m_t, m_W and m_H)
- the **stability of the EW vacuum** depends on m_H

⇒ m_H **experimental measurement** needed!

Γ_H

The **Higgs boson width** Γ_H is predicted in the SM as a function of m_H: Γ_H ~ 4.1 MeV for m_H = 125 GeV.

Measurement needed to:

- Verify the SM predictions
- Solve the degeneracy between couplings and Γ_H: Higgs *production cross sections* as measured in different production and decay gives access to this ratio:

$$\sigma_{i\to H\to f} = \frac{g_i^2 g_f^2}{\Gamma_H}$$

where g_x is the modifier to H*xx* coupling

Higgs boson mass at ATLAS

m_H

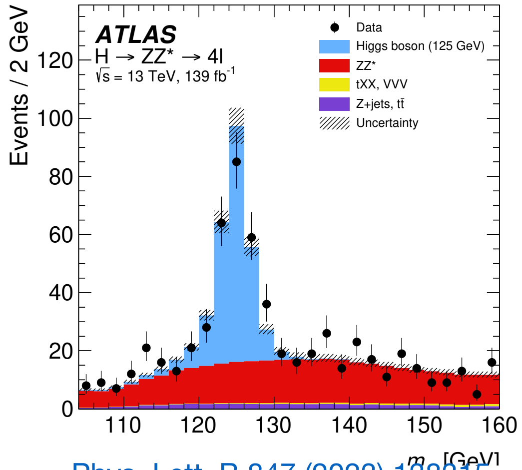
The history of the mass measurement in ATLAS 📚

Previous measurements by ATLAS (CMS) with $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$ channels:

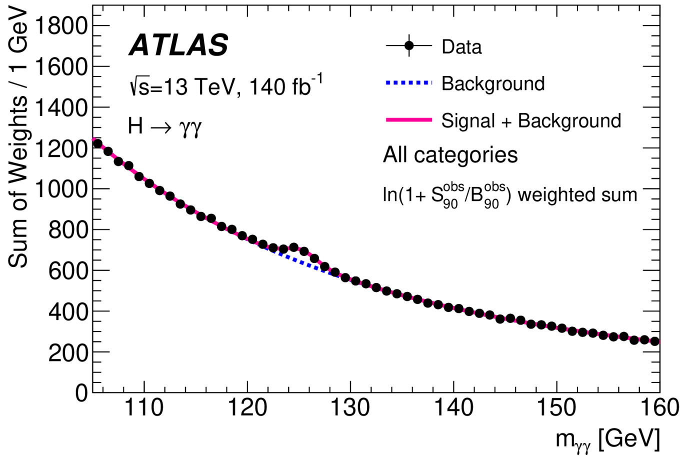
- **Full kinematic reconstruction** of the final state
- **Best invariant mass resolution** (1-2%) on the signal
- **Peak** above a continuum bkg in the $m_{\gamma\gamma}$ or m_{4l} distributions

Year	Analysis	Precision on m_H	
2012	Discovery	**0.45%**	Phys.Lett. B716 (2012) 1-29 — 126.0 ± 0.4 (stat.) ± 0.4 (syst.) GeV
2015	Run1 (25 fb[-1] @ $\sqrt{s}$ = 7/8 TeV) ATLAS $H \to \gamma\gamma$	**0.4%**	Phys. Rev. Lett. 114, 191803 (2015)
2015	Run1 (25 fb[-1] @ $\sqrt{s}$ = 7/8 TeV) ATLAS+CMS $\gamma\gamma + 4l$	**0.2%**	Phys. Lett. B 784 (2018) 345
2018	*Partial* Run2 (36 fb[-1] @ $\sqrt{s}$ = 13 TeV) ATLAS $H \to \gamma\gamma$	**0.3%**	
2018	ATLAS $H \to 4l$	**0.3%**	
2022	Run2 ATLAS $H \to 4l$	**?%**	Analyses and results reported in today's presentation!
2023	Run2 ATLAS $H \to \gamma\gamma$; Run1 + Run2 ATLAS $\gamma\gamma + 4l$	**?%**	Analyses and results reported in today's presentation!

Phys. Lett. B 843 (2023) 137880

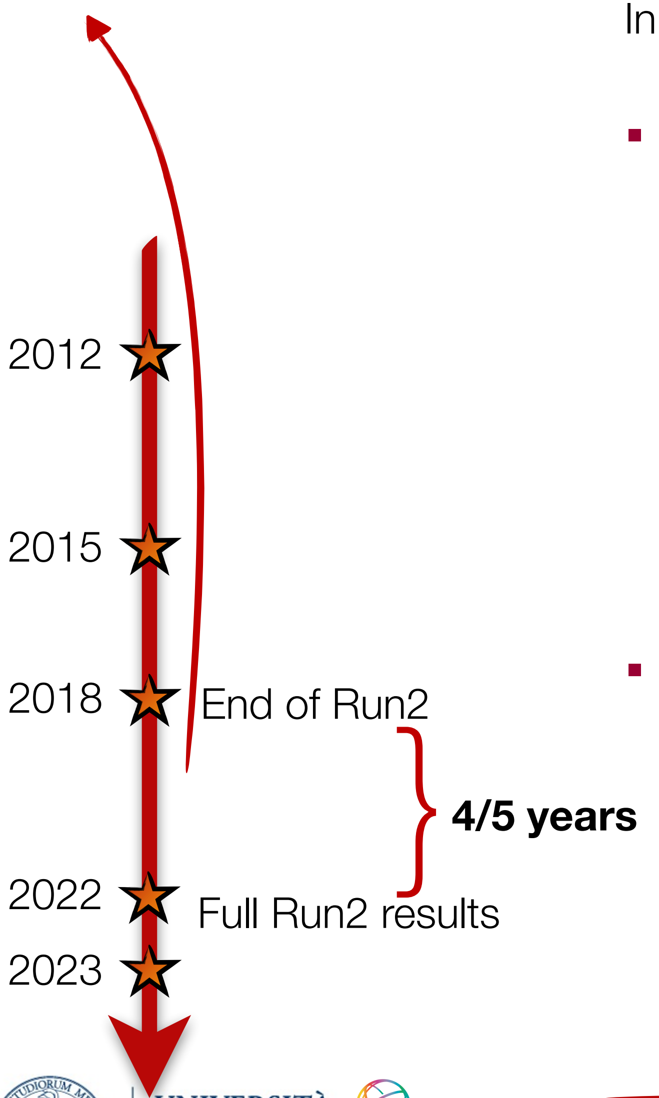


Phys. Lett. B 847 (2023) 138315



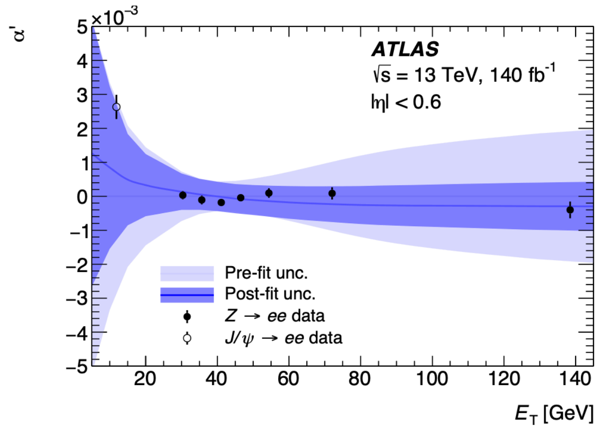
Electron, photon and muon calibration achievements 🏆

Why did it take **4/5 years** between the end of Run2 data taking (2018) and the full Run 2 mass results (2022/2023)?

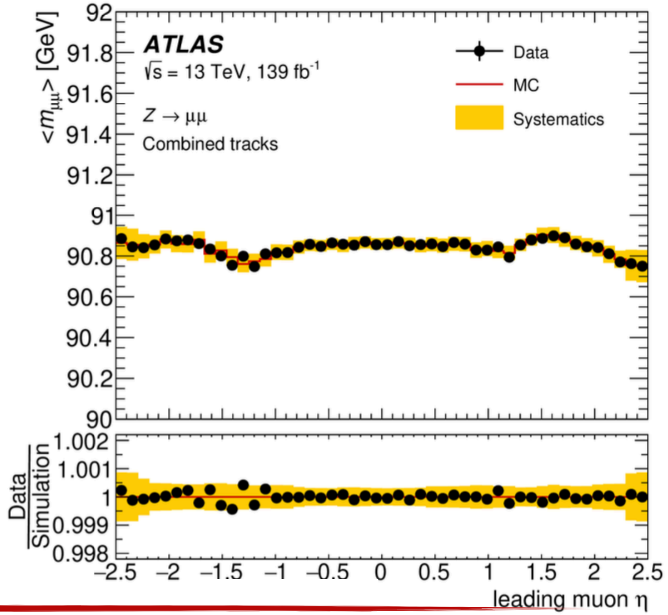


In-depth understanding of the **detector performance**, in particular regarding **e**, γ and μ

- **e/gamma:** JINST 19 (2024) P02009 backup slides 41-50
  - ✦ Larger datasets (Zee, Zlly)
  - ✦ Updated/improved methods (LAr layer inter-calibration, uniformity corrections..)
  - ✦ **New linearity fit**: E_T dependent systematics are constrained by the measurement scale factors in E_T bins
  - ✦ Overall calibration uncertainty reduced by a factor of 2–3, depending on particle type η and p_T



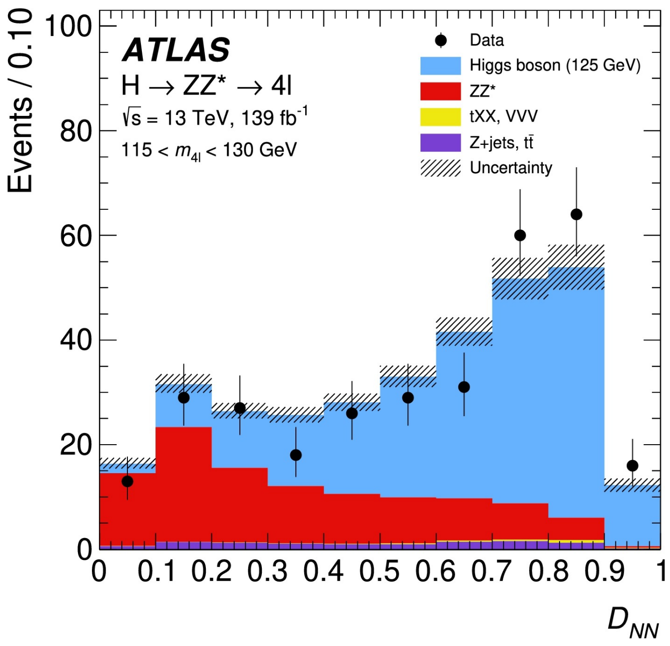
- **muon:** Eur. Phys. J. C 83 (2023) 686 backup slides 52-58
  - ✦ New methodology charge-dependent sagitta bias scale correction
  - ✦ Inclusion of $J/\psi \rightarrow \mu\mu$ data in scale/reso correction
  - ✦ New fitting techniques with better convergence
  - ✦ Momentum scale uncertainty reduced up to a factor of 2

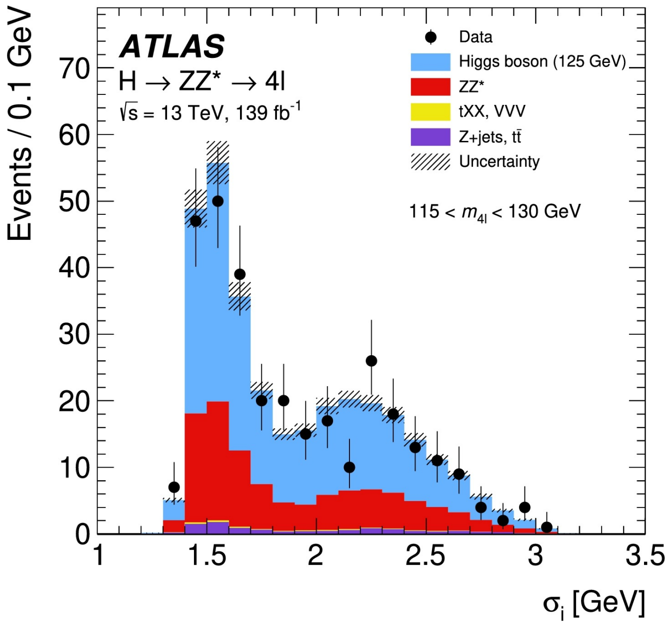


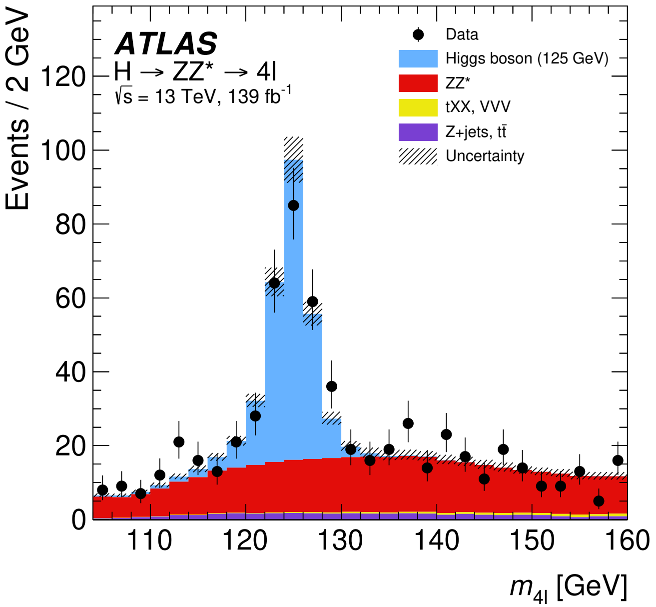
Mass measurement in the $H \rightarrow ZZ^* \rightarrow 4l$ channel

[Phys. Lett. B 843 (2023) 137880]

- Events containing at least four isolated leptons (l = *e*, μ) emerging from a common vertex, forming two pairs of oppositely charged same-flavour leptons.
- 4 channels: 4μ, 2μ2e, 2e2μ, 4e
- Dominant background = **non-resonant ZZ*** production (~90% of bkg yield)
- **Neural Network** based discriminant separating signal and background (D_{NN})
- Modelling of **per-event resolution** (σ_i)
  - The resolution ranges from 1.5 GeV (4μ and 2μ2e) to about 2.1 GeV (2e2μ and 4e)
- **Signal PDF** modelled as a function of D_{NN} , σ_i and m_{4l}



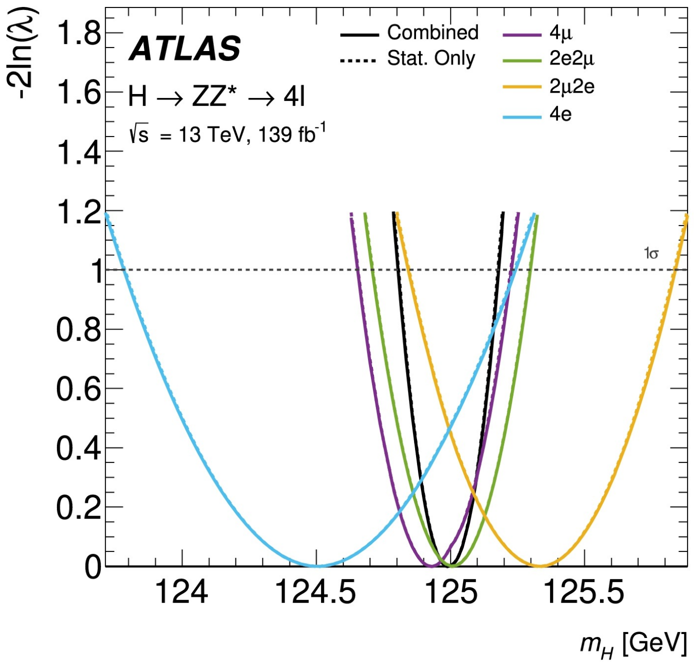


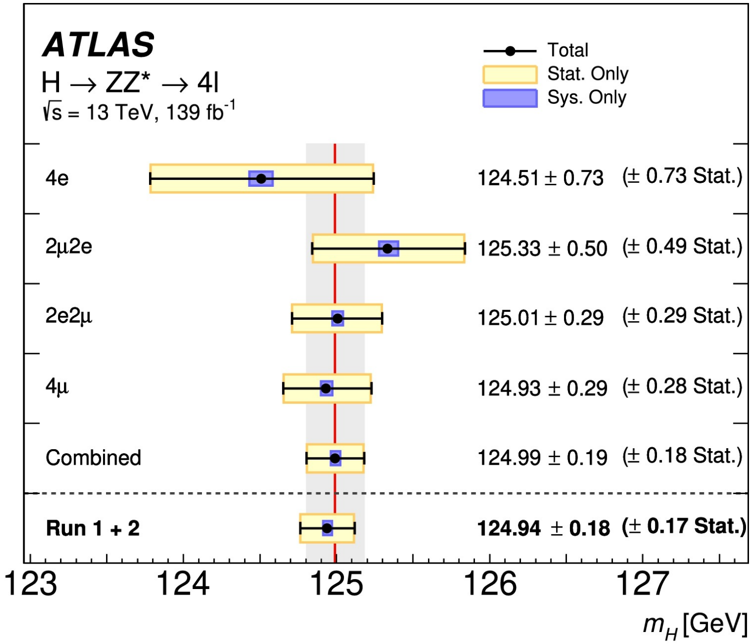


Mass measurement in the $H \to ZZ^* \to 4l$ channel

Phys. Lett. B 843 (2023) 137880

m_H from a simultaneous unbinned maximum-likelihood fit to the four channels in the mass range between 105 and 160 GeV





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

- Statistically dominated
- Main syst. uncertainties from μ and e scale

0.15% precision

Run2 H→4l: m_H = 124.99 ± 0.18 (stat.) ± 0.04 (syst.) = 124.99 ± 0.19 GeV

Also performed combination with Run1 analysis:

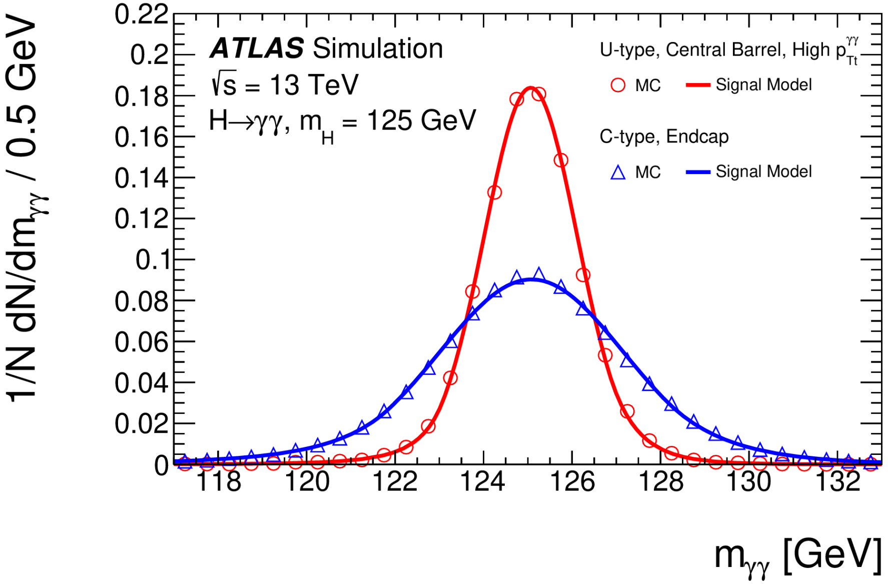
0.14% precision

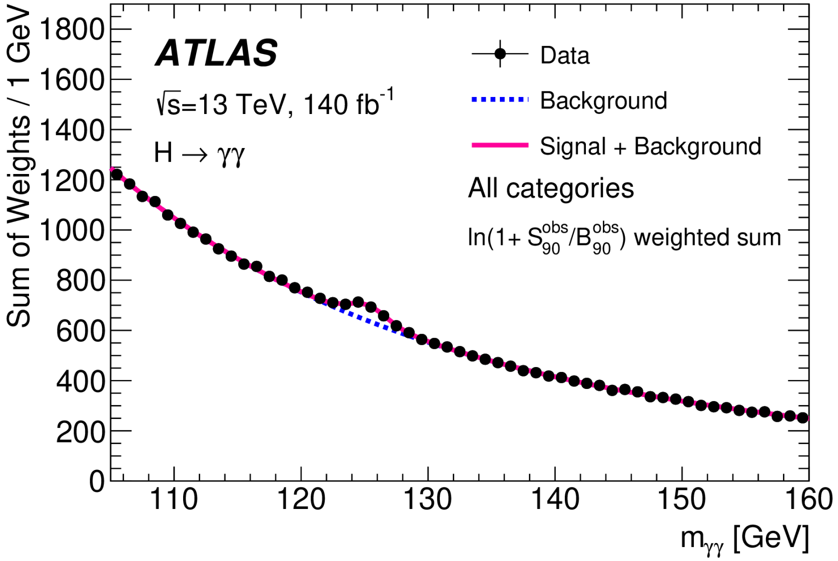
Run1+Run2 H→4l: m_H = 124.94 ± 0.17 (stat.) ± 0.03 (syst.) = 124.94 ± 0.18 GeV

Mass measurement in the $H \to \gamma\gamma$ channel

Phys. Lett. B 847 (2023) 138315

- Require two good-quality and isolated photons with $p_T/m_{\gamma\gamma}$ > 0.35 (0.25)
- Separate events into 14 mutually exclusive **categories** to minimise the total expected uncertainty on m_H
- Model the **signal** and smoothly falling **background** with analytical functions

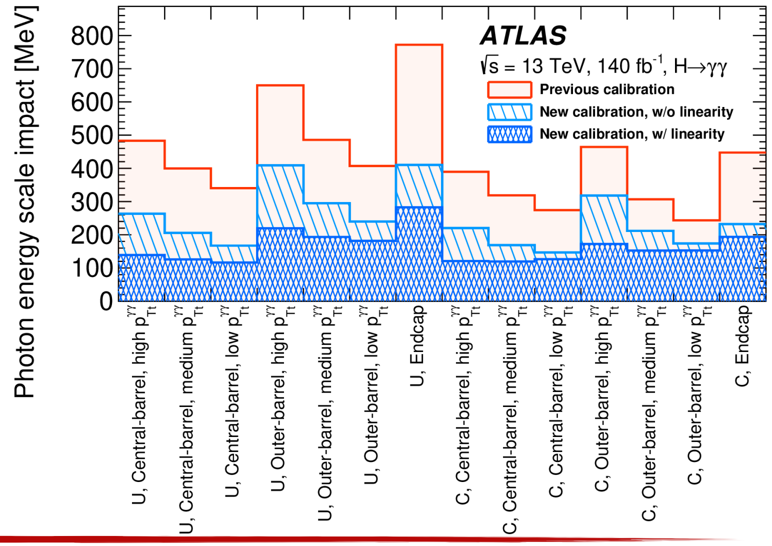




- **Systematic uncertainties** included in the model exploit new photon reconstruction with improved energy resolution and calibration
- Systematic uncertainty on m_H dominated by **photon energy scale**

Systematic uncertainty on m_H $(H \to \gamma\gamma)$		
Previous calibration	New calibration	New calibration + linearity
270 MeV	**180 MeV**	**83 MeV**

30% reduction   50% reduction



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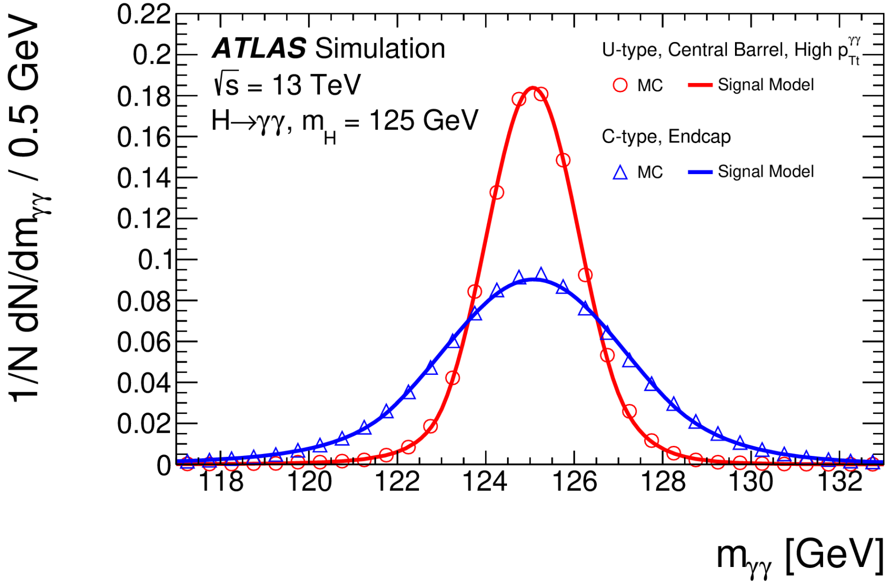
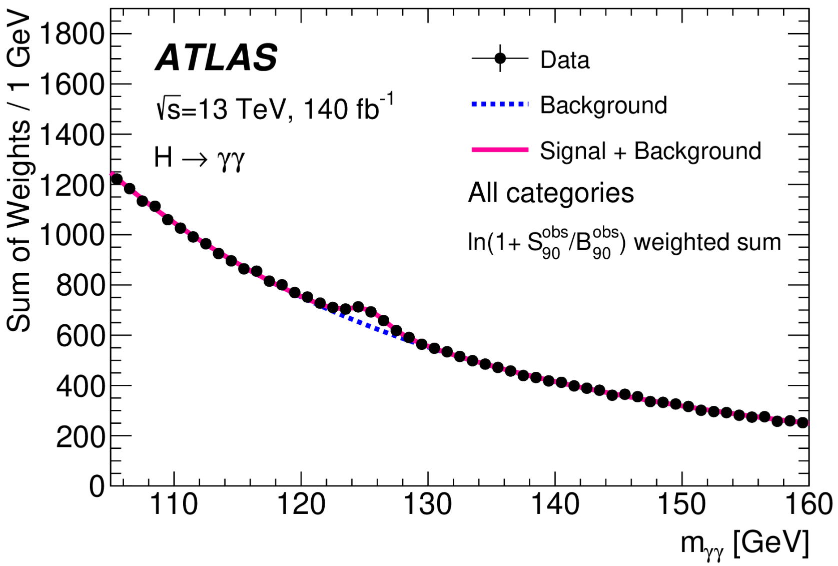




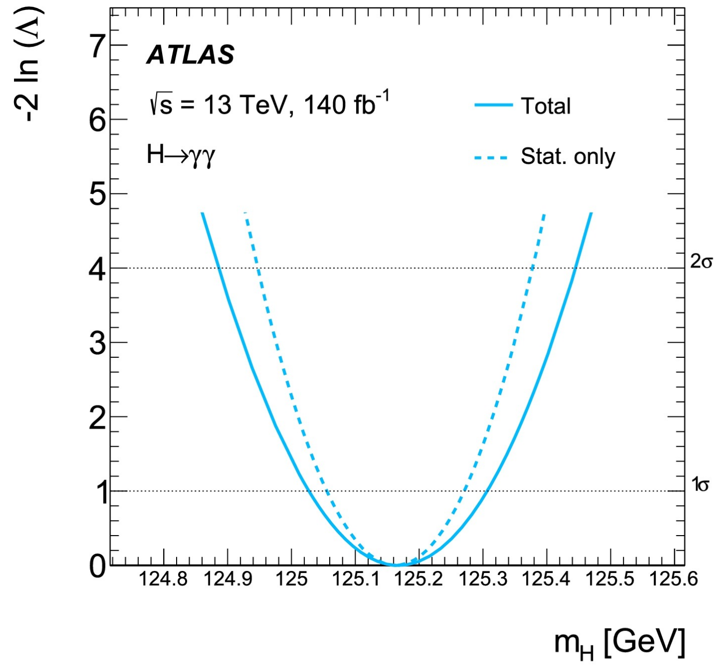
- **Systematic uncertainties** included in model as nuisance parameters, exploiting new photon reconstruction with improved energy resolution and calibration
- Systematic uncertainty on m_H dominated by **photon energy scale**
- **Interference** between the gg→H→γγ signal and the gg/qg→γγ background included as a systematic uncertainty
- Minor impact of signal and background modeling

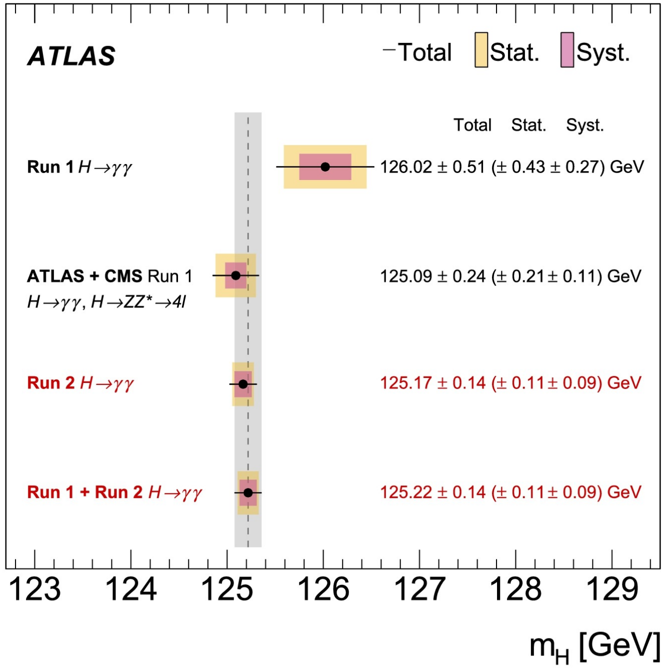
Source	Impact [MeV]
Photon energy scale	83
$Z \rightarrow e^+e^-$ calibration	59
E_T-dependent electron energy scale	44
$e^\pm \rightarrow \gamma$ extrapolation	30
Conversion modelling	24
Signal–background interference	26
Resolution	15
Background model	14
Selection of the diphoton production vertex	5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

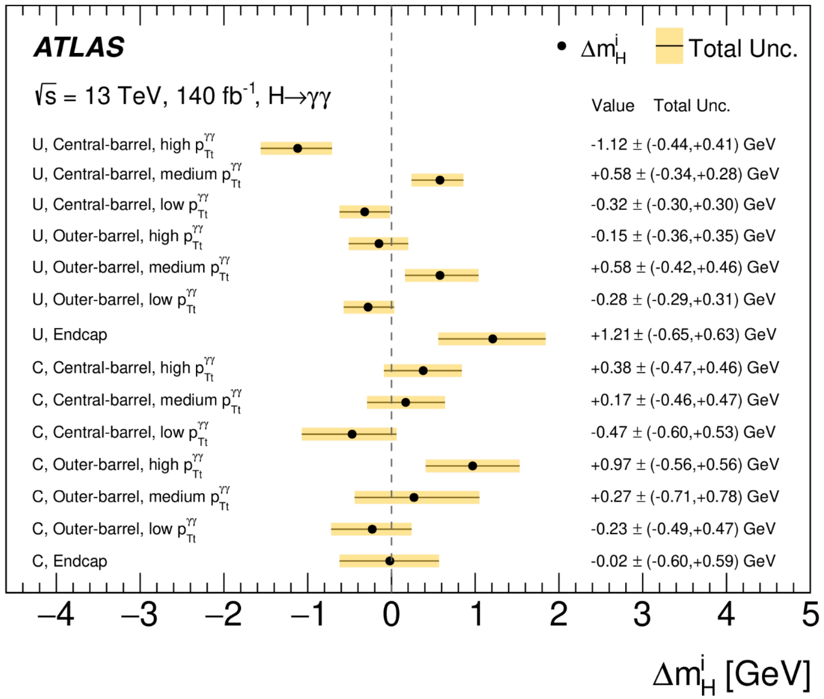
Mass measurement in the $H \to \gamma\gamma$ channel

[Phys. Lett. B 847 (2023) 138315]

m_H from a simultaneous maximum-likelihood fit to the 14 categories in the mass range between 105 and 160 GeV







Run2 $H\to\gamma\gamma$: m_H = 125.17 ± 0.11 (stat.) ± 0.09 (syst.) = 125.17 ± 0.14 GeV

Also performed combination with Run1 analysis:

0.11% precision

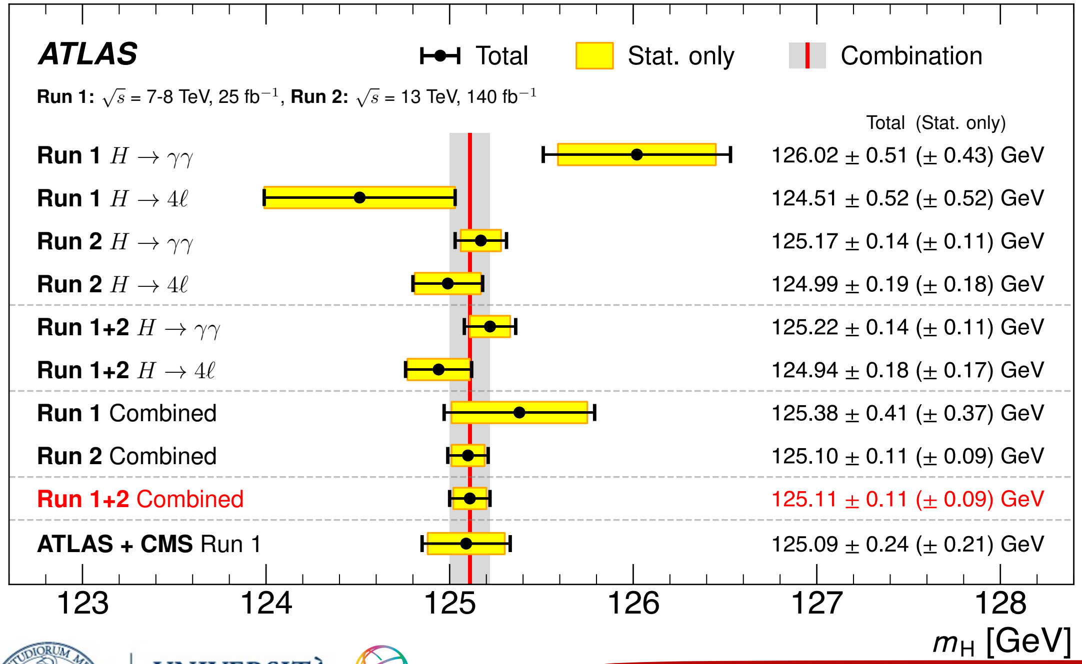
Run1+Run2 $H\to\gamma\gamma$: m_H = 125.22 ± 0.11 (stat.) ± 0.09 (syst.) = 125.22 ± 0.14 GeV

Now stat. dominated

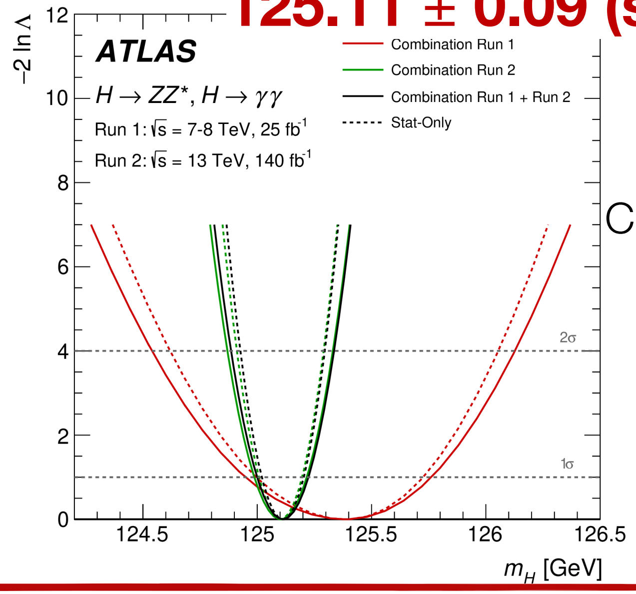
$H \to \gamma\gamma$ + $H \to 4l$ Run1-Run2 combination 🥇

Phys. Rev. Lett. 131 (2023) 251802

	Fitted m_H	Uncertainty [GeV] Total	Stat.	Syst.	Fitted m_H	Uncertainty [GeV] Total	Stat.	Syst.	Fitted m_H	Uncertainty [GeV] Total	Stat.	Syst.
	H→γγ				**H→4l**				**Combination: ≠ channel, = Run**			
Run1	126.02	0.51	0.44	0.27	124.51	0.53	0.53	0.03	125.38	0.43	0.39	0.19
Run2	125.17	0.14	0.11	0.09	124.99	0.18	0.18	0.03	125.10	0.11	0.09	0.07
Combination: = channel, ≠ Run	125.22	0.14	0.11	0.09	124.94	0.18	0.17	0.03	**125.11**	**0.11**	**0.09**	**0.06**



Run1+Run2 comb: m_H = 125.11 ± 0.11 GeV = 125.11 ± 0.09 (stat.) ± 0.06 (syst.)



Current **most precise measurement** of m_H

Total uncertainty ~ 110 MeV

< 1‰ precision!! 🥳

Higgs boson width at ATLAS

$$\boxed{\Gamma_H}$$

Measurement of the Higgs boson width

Phys. Lett. B 846 (2023) 138223

SM predicts the Higgs boson **width** of Γ_H = 4.1 MeV ⇒ too small for direct on-shell measurement!

- **gg→H→ZZ** final state: production cross-section as a function of the invariant mass of the four leptons m_{4l}

$$\frac{d\sigma_{pp\to H\to ZZ}}{dm^2_{4l}} \sim \frac{g^2_{Hgg}g^2_{HZZ}}{(m^2_{4l}-m^2_H)^2+m^2_H\Gamma^2_H}$$

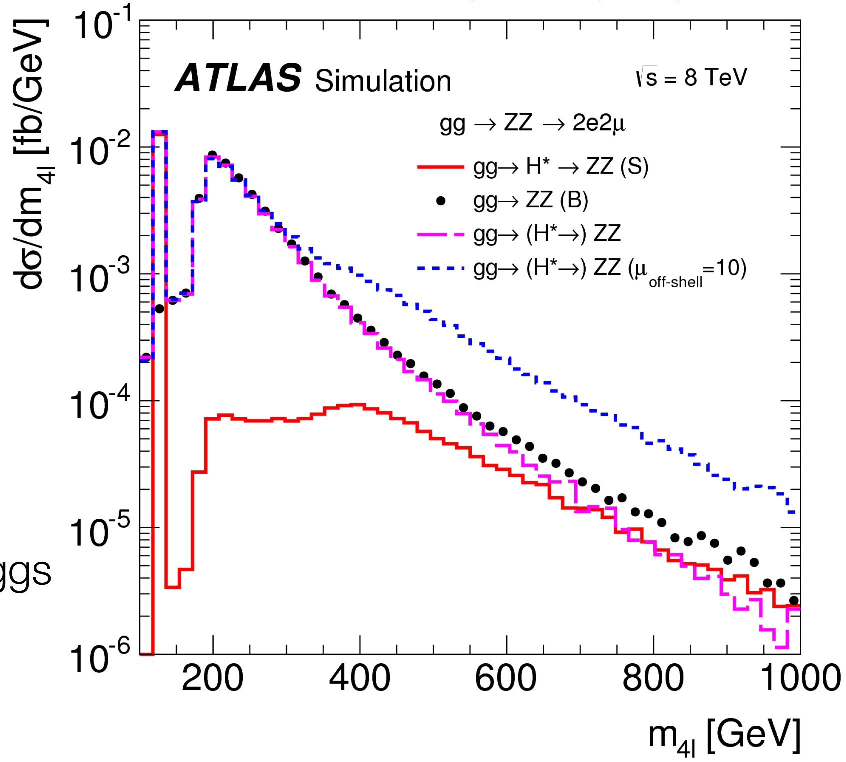
$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{Hgg}g^2_{HZZ}}{m_H\Gamma_H}$$ **on-shell**, $m_{ZZ} \sim m_H$

$$\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{Hgg}g^2_{HZZ}}{m^2_{4l}}$$ **off-shell**, $m_{ZZ} \gg m_H$

- Assuming that the on-shell and off-shell Higgs production follow SM prediction (the H_{gg} and H_{ZZ} coupling modifiers are the same on-shell and off-shell), Γ_H can be measured (indirectly) from the ratio of **off-shell/on-shell** Higgs boson cross sections

$$\Gamma_H \propto \frac{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ}}{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*}}$$

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



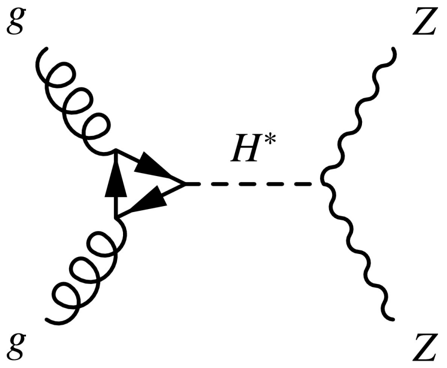
In SM the total impact of the H is negative ⇒ off-shell Higgs manifestation = deficit of events w.r.t. background only expectation

Measurement of the Higgs boson width

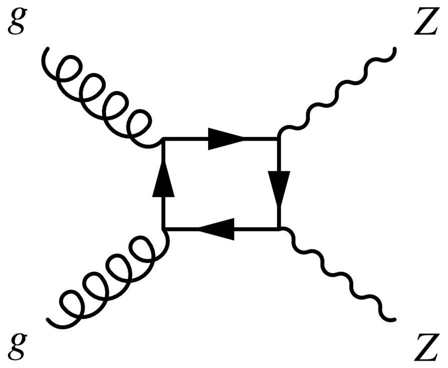
Phys. Lett. B 846 (2023) 138223

Measuring the **off-shell** contribution not straightforward: **interference** with continuum background

- **Gluon-gluon (ggF) production**



ggF signal (S)

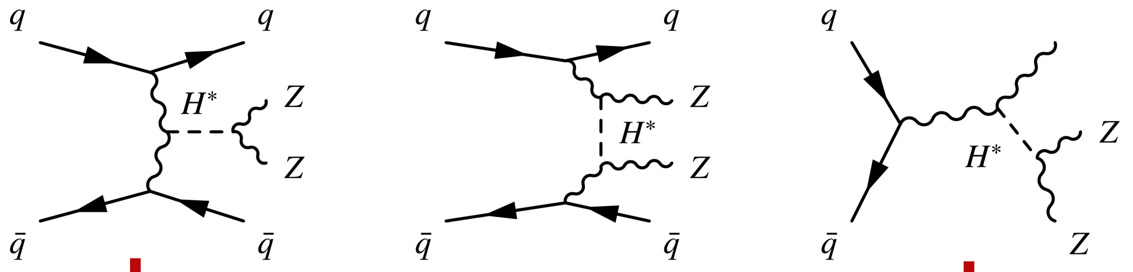


gg→ZZ background (B)

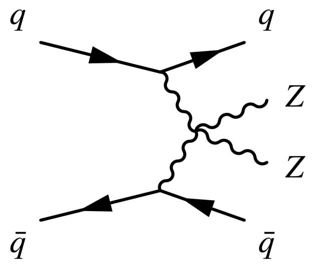
Interference (I)

$$N_{gg\to(H^*)\to ZZ} = \mu_{\text{off-shell}} N_S + \sqrt{\mu_{\text{off-shell}}}\,(N_{S+B} - N_S - N_B) + N_B$$

- **Electroweak EW (VBF+VH) production**



EW signal (S)



EW background (B)

Measurement of the Higgs boson width

Phys. Lett. B 846 (2023) 138223

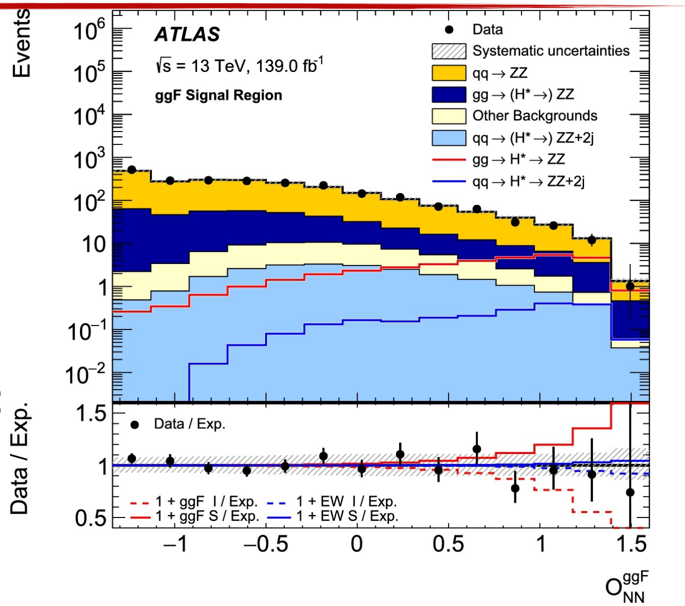
The measurement is performed considering two final states:

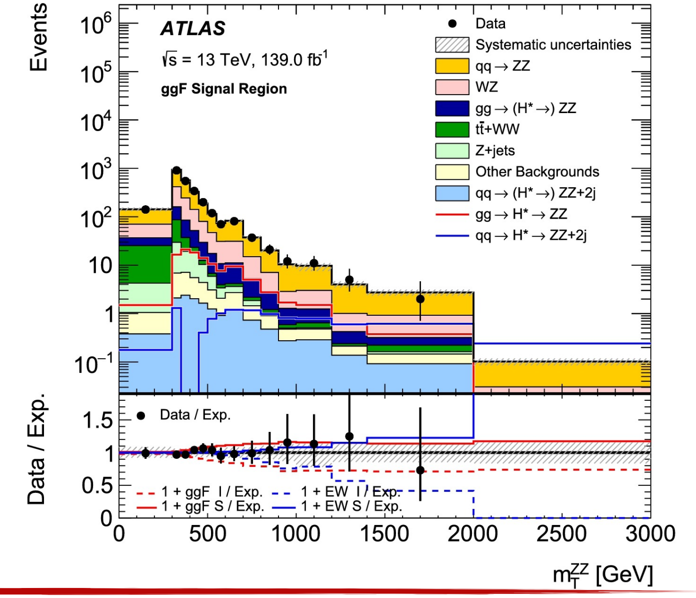
- $ZZ \rightarrow 4l$: clean and fully reconstructed final state
- $ZZ \rightarrow 2l2\nu$: six times higher branching ratio

Targeting off-shell contribution from both **ggF** and **EW** (VBF+VH) modes

- Three signal regions (SR) are defined after requiring $m_{4l} > 220$ GeV. Events separated in:
  - electroweak-like (require two or more jets with $p_T > 30$ GeV and $|\Delta\eta_{jj}| > 4$),
  - mixed categories = require exactly one jet with $|\eta_j|$>2.2
  - ggF-like = remaining events
- Normalization of non-interfering background from $qq \rightarrow ZZ$ fitted on data CR

Signal vs bkg discriminated using **NN** (*4l*) or **transverse mass** (2l2v)





Measurement of the Higgs boson width

[Phys. Lett. B 846 (2023) 138223]

- Simultaneous fit **signal strength** and **background normalization factors** in all signal regions and control regions
- Direct measurement of off-shell signal strength $\mu_{\text{off-shell}}$

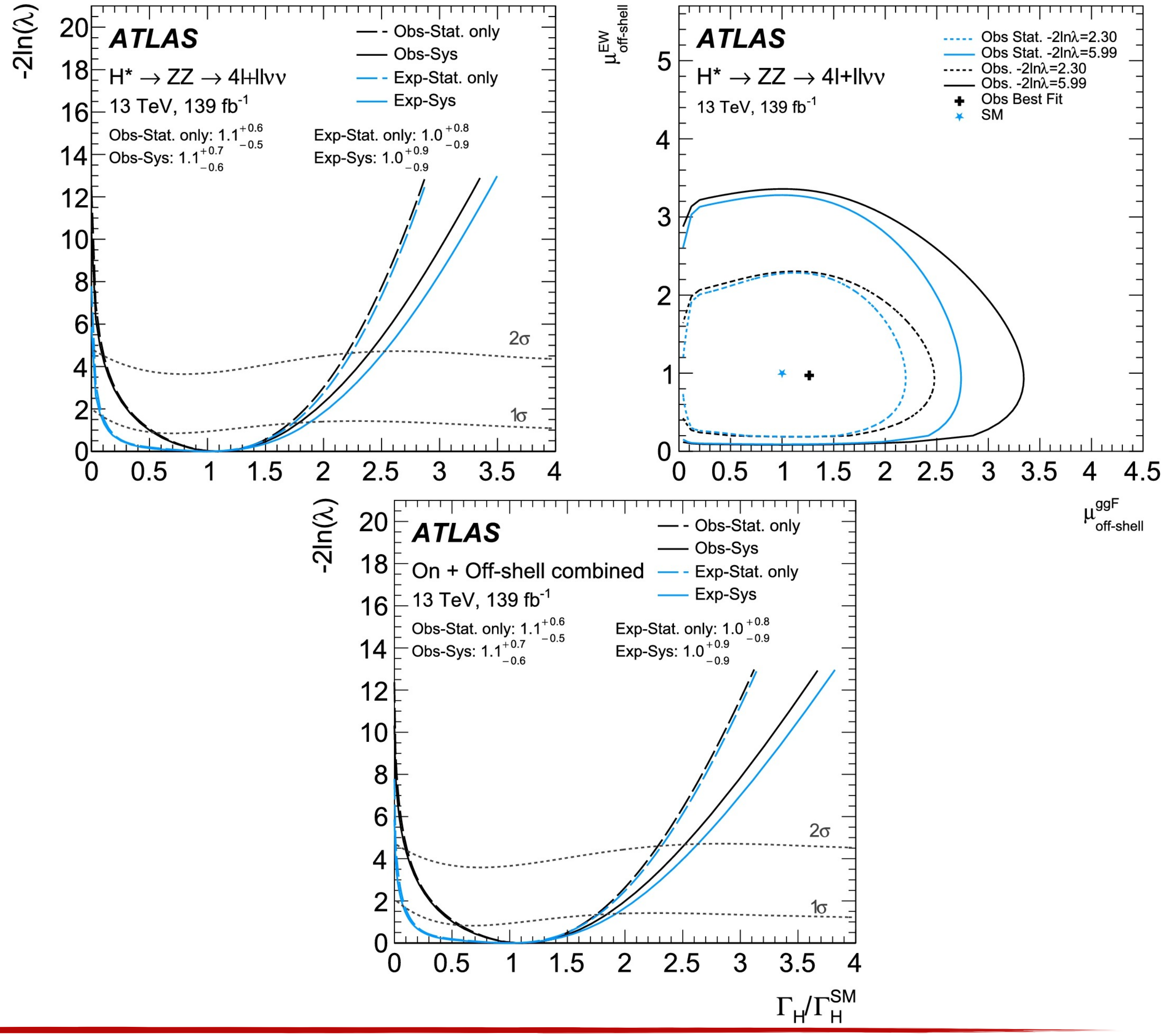
$\mu_{\text{off-shell}} = 1.1 \pm^{0.7}_{0.6}$

with a significance of off-shell production 3.3 (2.2) σ

- Combining the off-shell with on-shell $H \to ZZ^* \to 4l$ measurement to measure Γ_H with correlated (uncorrelated) experimental (theoretical) systematic uncertainties

$\Gamma_H = 4.5 \pm^{3.3}_{2.5}$ MeV

and 0.5 (0.1) < Γ_H < 10.5 (10.9) MeV at 95% CL



Conclusions

- ATLAS made huge efforts in improving the understanding of the detector's performance during Run 2 (140 fb^{-1} at 13 TeV of centre-of-mass energy) allowing improvements in m_H uncertainty

- The new ATLAS measurements of the Higgs boson mass by combining $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^*\rightarrow 4l$ final states and using $\sqrt{s}$=7,8 and 13 TeV data, resulted in the current most precise m_H measurement with an uncertainty of 0.09%:

Run1+Run2 comb: m_H = 125.11 ± 0.11 GeV = 125.11 ± 0.09 (stat.) ± 0.06 (syst.)

- The determination of the Higgs boson width Γ_H is very hard at hadron colliders: exploiting the ratio of off-shell to on-shell Higgs boson production in the ZZ decay channel with reasonable assumptions, ATLAS measured the Higgs boson width:

$\Gamma_H = 4.5 \pm^{3.3}_{2.5}$ MeV, and 0.5 (0.1) < Γ_H < 10.5 (10.9) MeV at 95% CL

Thank you for your attention!
cảm ơn!