Measurements of the Higgs Boson Mass and Width with the ATLAS detector

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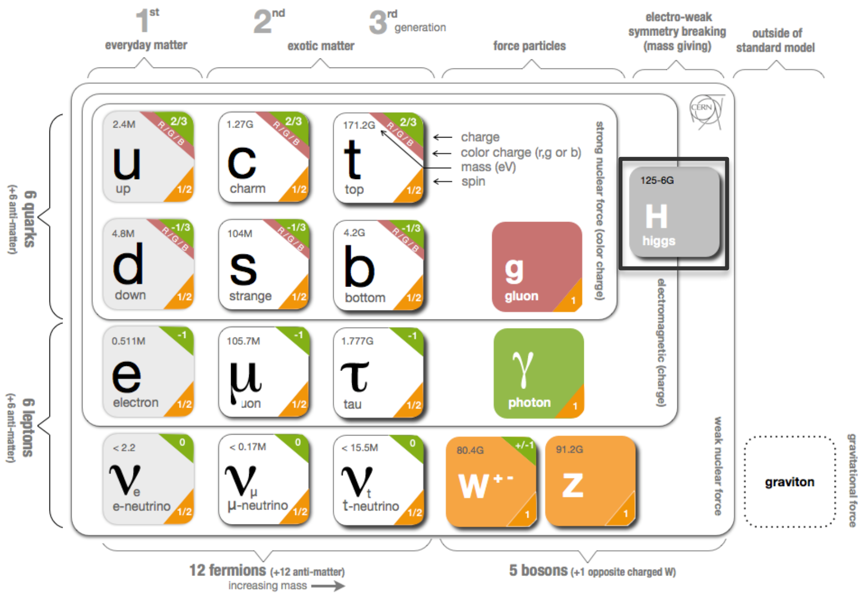
University of Massachusetts Amherst

42nd International Conference on High Energy Physics
July 18th, 2024

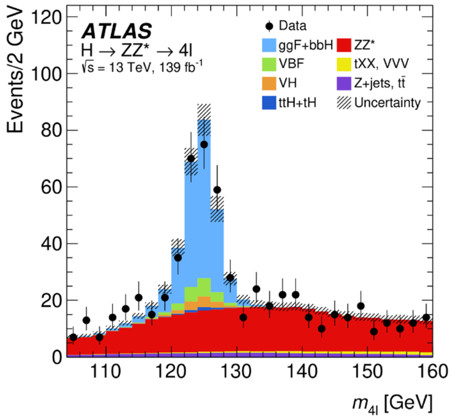
The Higgs boson

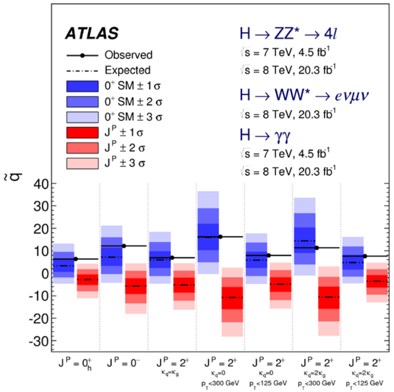
The Higgs Boson was discovered in 2012 by ATLAS and CMS



Characterization of the Higgs boson properties

- Mass
- Width
- Spin/Parity
- Couplings





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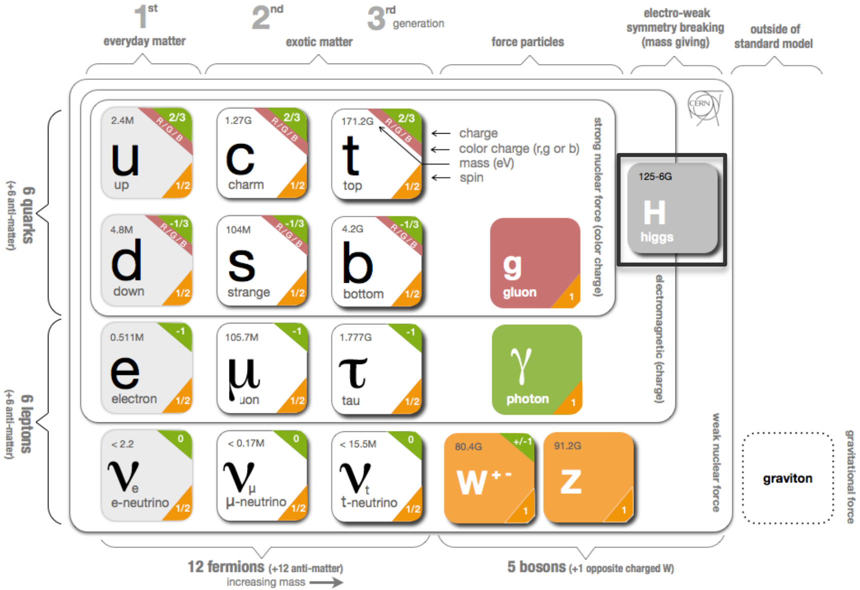
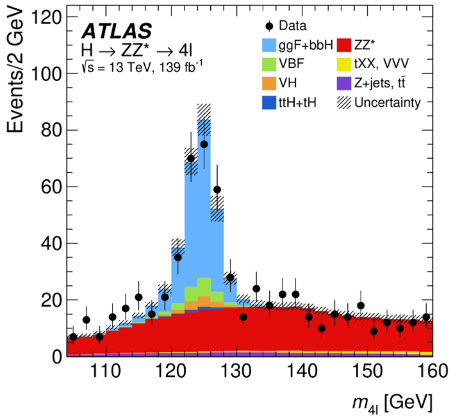
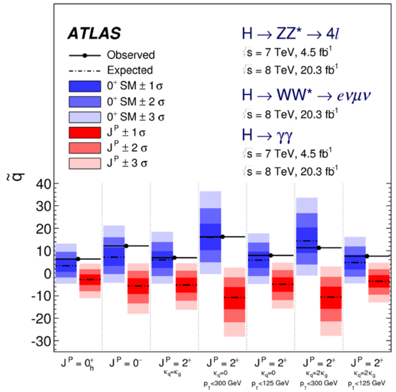


Characterization of the Higgs boson properties

- **Mass**
- **Width (with a new result!)**
- **Spin/Parity**
- **Couplings**

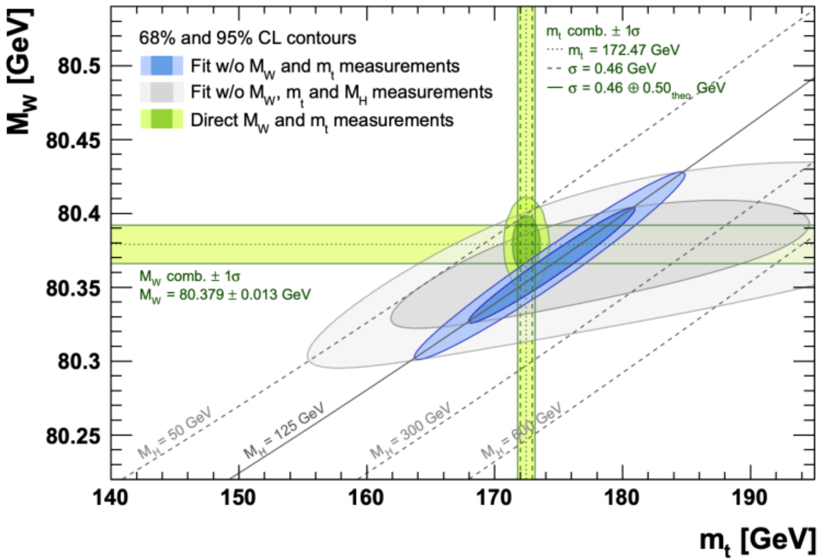


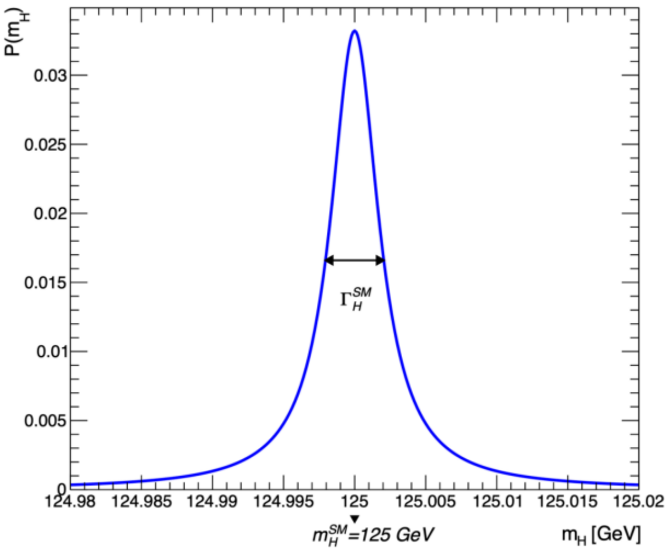


Higgs mass and width

The Higgs mass is a fundamental parameter of the SM → needs to be measured

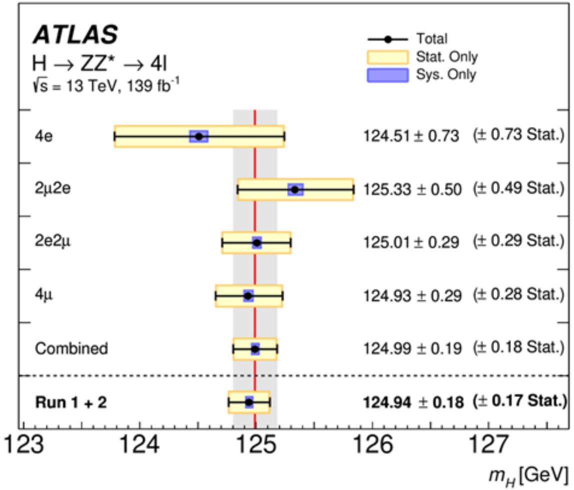
The Higgs total width in the SM is calculated to be 4.07 MeV

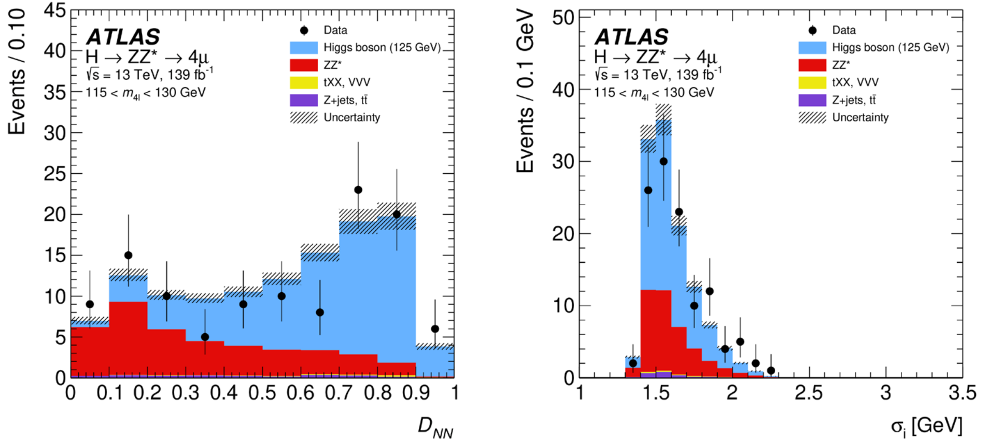




m_H measurement in $H \to ZZ \to 4\ell$

- Analysis in 4 exclusive regions
- D_{NN} neural network to discriminate signal from background
- σ_i NN to regress per-event $m_{4\ell}$ resolution
- PDFs modelled as a function of $p(\sigma_i, m_{4\ell}, D_{NN}|m_H)$





- Improved muon momentum-scale calibration
  - 20% better with respect to previous Run 2 results [MUON-2022-01]
- Results statistically limited ⇒ room for improvement in Run 3

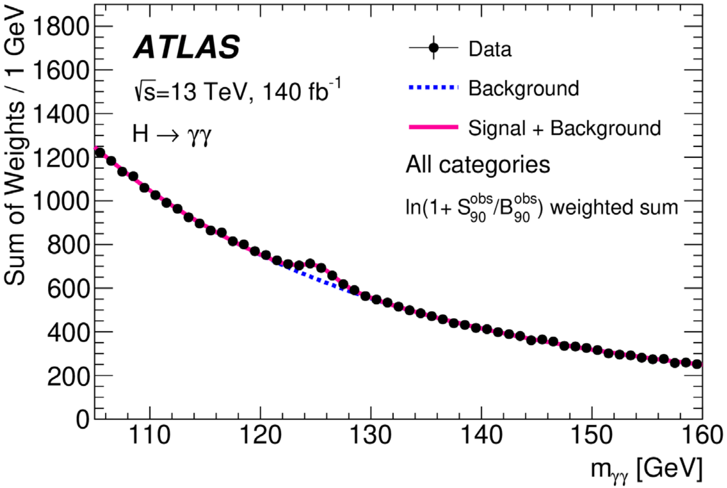
Combined Run 1 + Run 2 result:

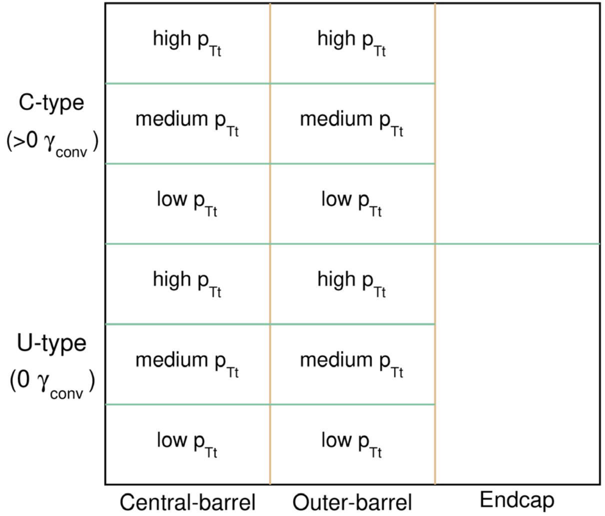
$$m_H = 124.94 \pm 0.18 \text{ GeV}$$
$$= 124.94 \pm 0.17\,(\text{stat.}) \pm 0.03\,(\text{syst.}) \text{ GeV}$$

Phys. Lett. B 843 (2023) 137880

m_H measurement in $H \to \gamma\gamma$

- 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 ⇒ 6% improvement with respect to partial Run 2 categorization.
- m_H from a maximum likelihood fit on the $m_{\gamma\gamma}$ distributions simultaneously in all categories

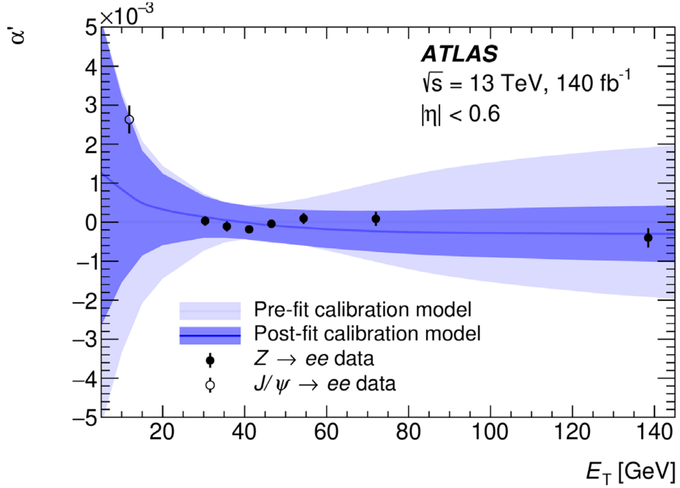


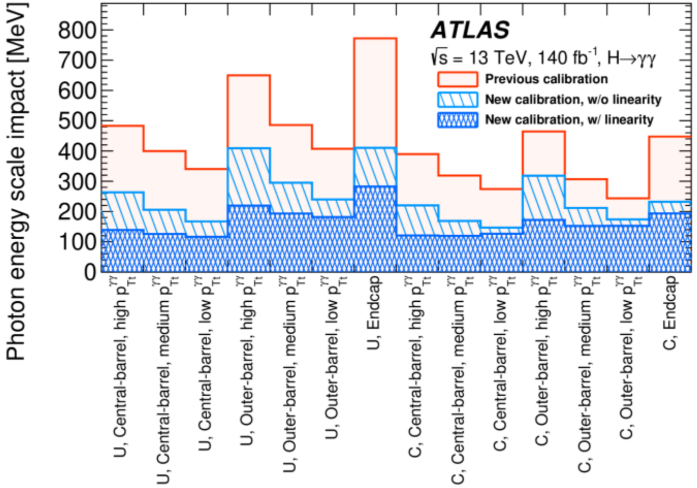


Phys. Lett. B 847 (2023) 138315

Photon energy scale improvement

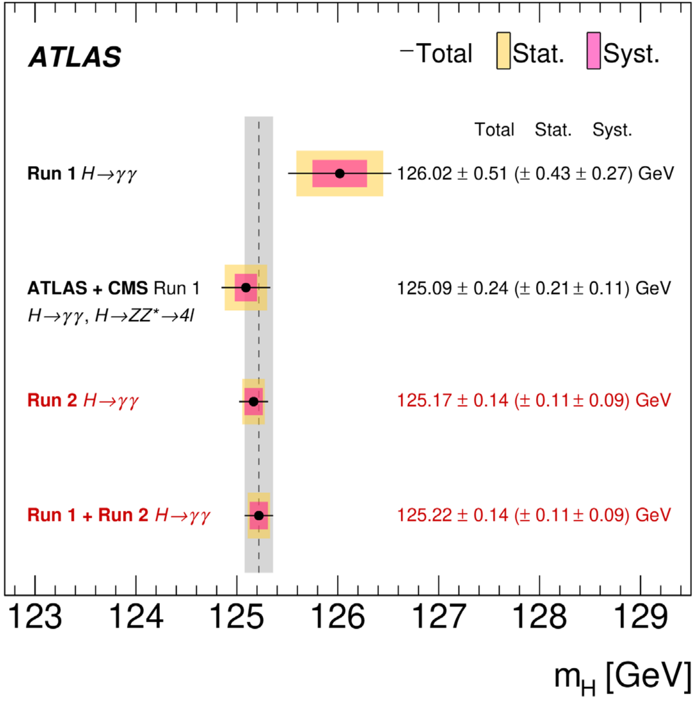
- Improved material modelling in front of calorimeter (x3 better)
- Improved description of on-detector electronics non-linearity (x2 better)
- Improved electron-to-photon scale extrapolation (x3 better)
- Improved layer intercalibration (x2 better)
- $Z \rightarrow ee$ scale factors measured as a function of p_{T} and η (linearity)





JINST 19 (2024) P02009

m_H measurement in $H \to \gamma\gamma$



Phys. Lett. B 847 (2023) 138315

Uncertainty due to photon energy scale decreased by a factor of 4 (320 MeV → 90 MeV)

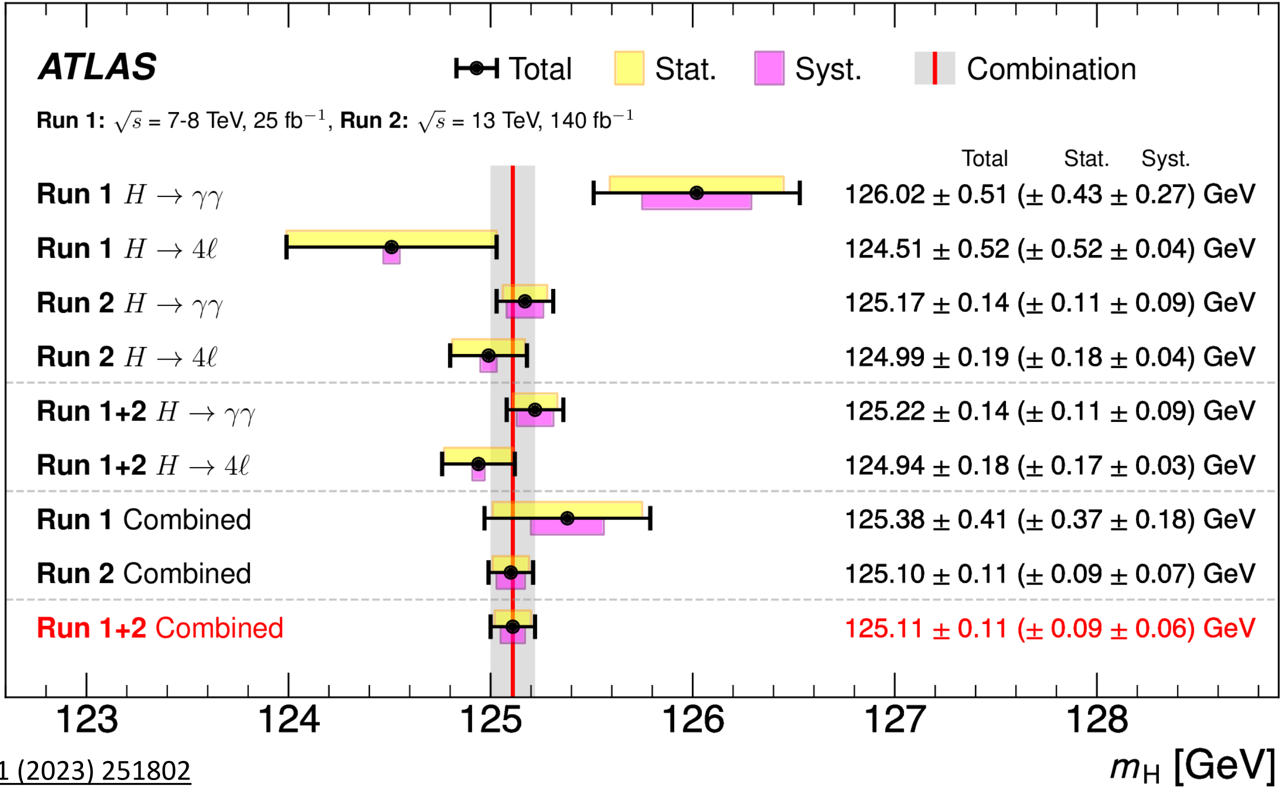
Currently below statistical uncertainty

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

Combined Run 1 + Run 2 result:

$$m_H = 125.22 \pm 0.14 \text{ GeV}$$
$$= 125.22 \pm 0.11\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \text{ GeV}$$

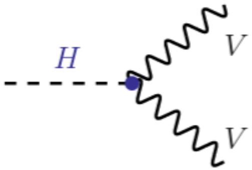
ATLAS Higgs mass combination



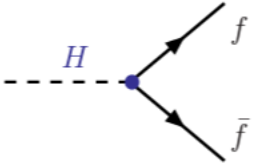
Phys. Rev. Lett. 131 (2023) 251802

Higgs total width

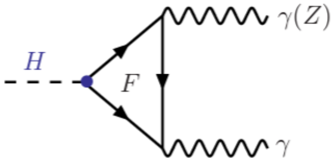
The decay widths of the Higgs boson in the Standard Model are small compared to its mass



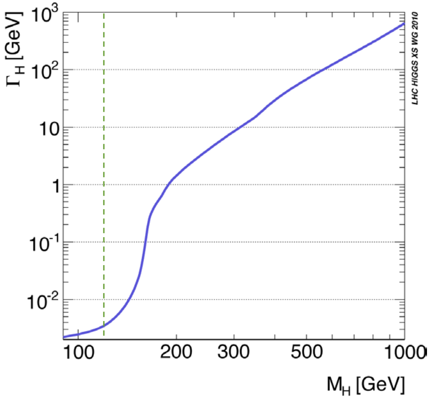
decay to off-shell weak bosons
$H \to VV^*$



small Yukawa coupling
$H \to ff$ (not the top quark)



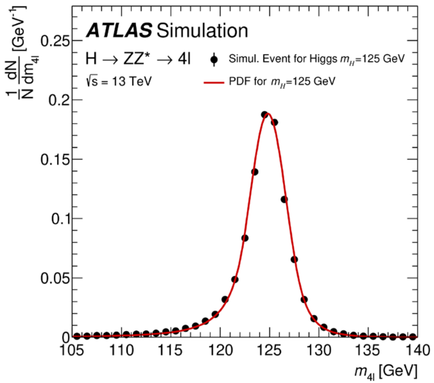
loop-suppressed
$H \to \gamma\gamma$ and $H \to Z\gamma$

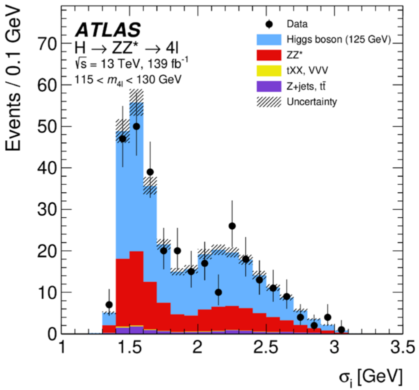


The best estimate of the Higgs boson total width is:

$$\Gamma_H^{SM} = 4.07 \text{ MeV}$$

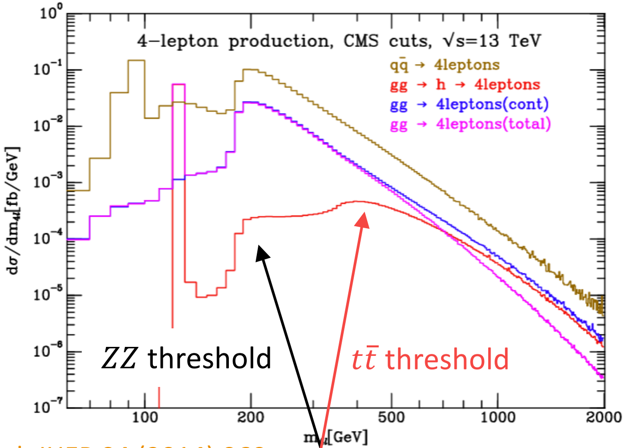
3 orders of magnitude smaller than our mass resolution



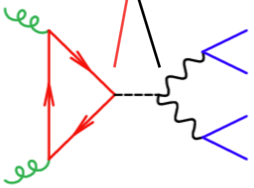


UMassAmherst ATLAS EXPERIMENT

Width via off-shell Higgs production



J. Campbell et al. JHEP 04 (2014) 060



- On-shell production analyses are measurements of Higgs couplings divided by the total width.
- Off-shell production analyses are measurements of Higgs couplings without the influence of the total width.
- A comparison of the two results yields an indirect measurement of the Higgs width

$$\frac{d\sigma^{pp\to H\to ZZ}}{dm_{ZZ}} \propto \frac{g_{Hgg}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

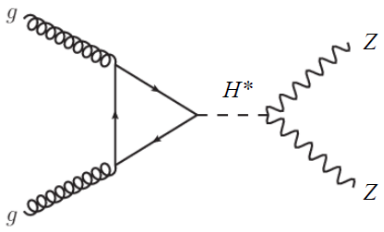
on-shell

$$\sigma_{\text{on-shell}}^{pp\to H\to ZZ} \propto \frac{g_{Hgg}^2 g_{HZZ}^2}{m_H \Gamma_H}$$

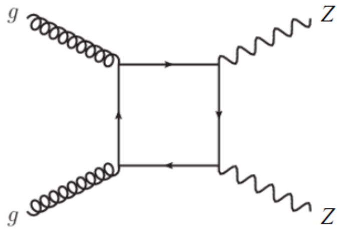
off-shell

$$\frac{d\sigma_{\text{off-shell}}^{pp\to H\to ZZ}}{dm_{ZZ}} \propto \frac{g_{Hgg}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2}$$

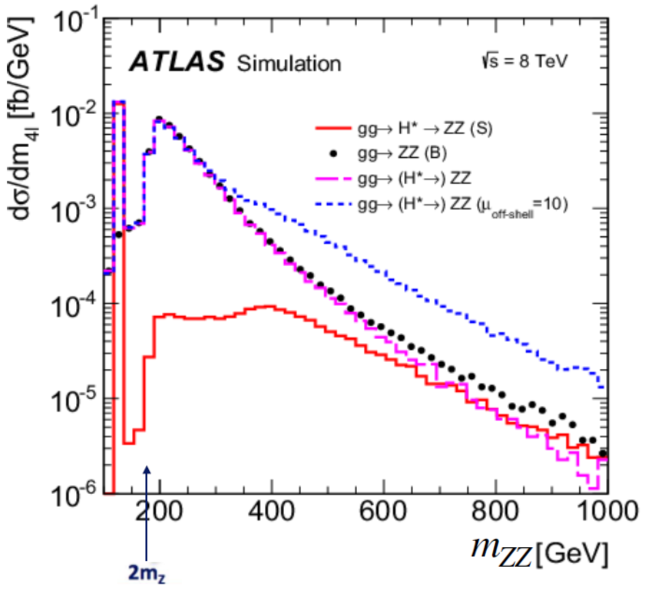
Off-shell $H \to ZZ$ production



signal (S)
$gg \to H^* \to ZZ$



background (B)
$gg \to ZZ$

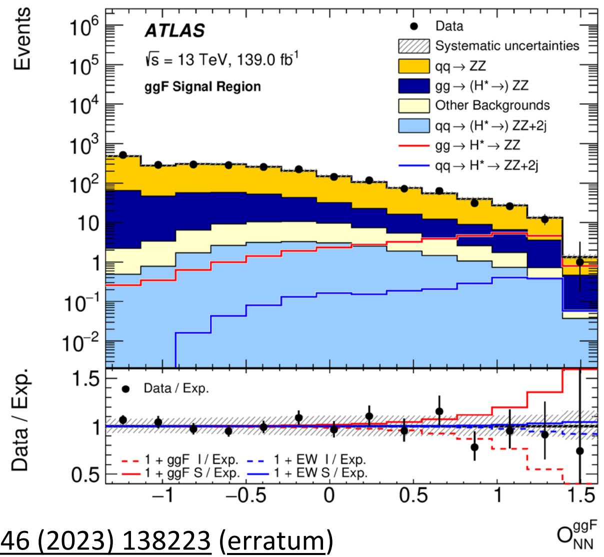


In the off-shell region, the interference (I) between the two components S and B is large and destructive (to preserve unitarity at high energies).

Off-shell $H \rightarrow ZZ$ production

4ℓ channel

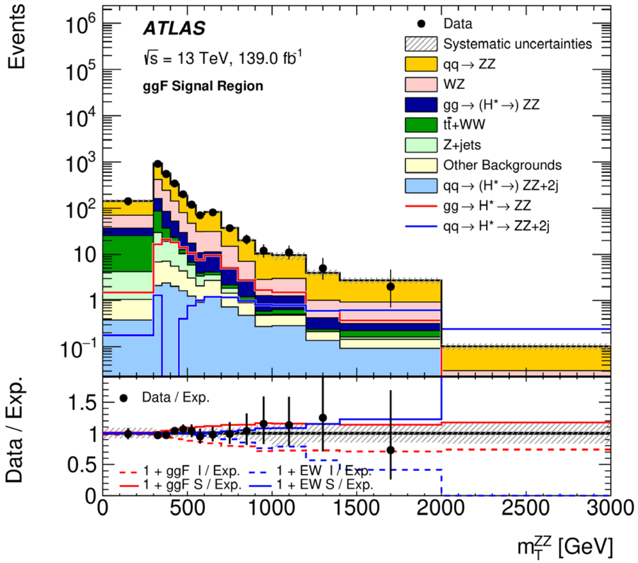
- 4ℓ events with $m_{4\ell} > 180$ GeV
- Use multi-class NN to enhance signal sensitivity (S vs B vs $q\bar{q} \rightarrow ZZ$)
- 3 SR: EW SR, one jet SR, and inclusive



Phys. Lett. B 846 (2023) 138223 (erratum)

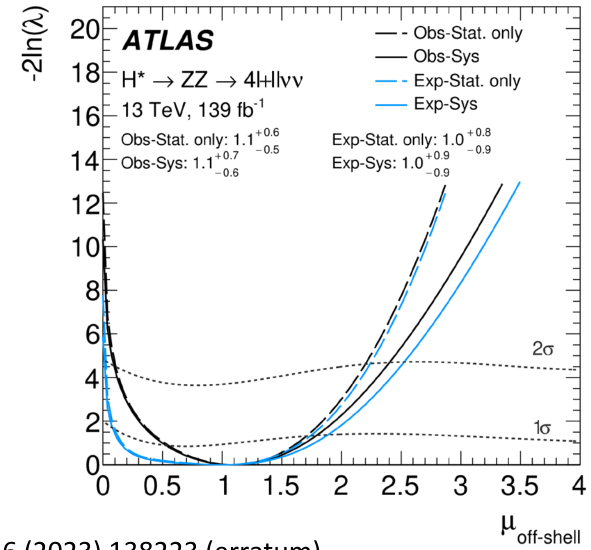
$2\ell 2\nu$ channel

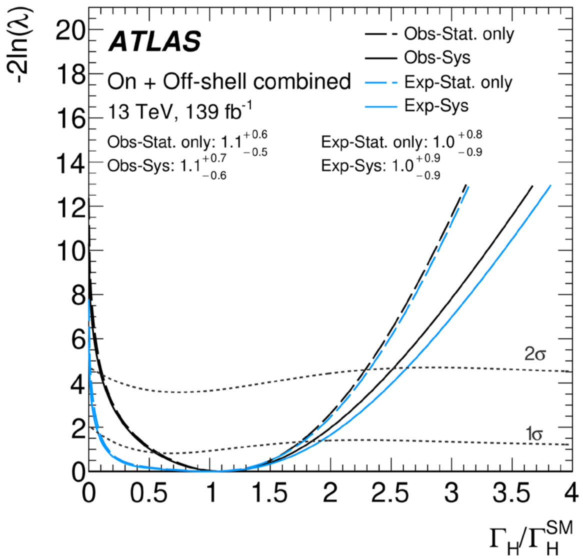
- $2\ell 2\nu$ events with large E_T^{miss} and E_T^{miss} significance
- m_T^{ZZ} as discriminating variable
- 3 SRs similar to 4ℓ analysis



Higgs width from $H \to ZZ$

- Simultaneously fit signal strength and background normalization factors in all signal regions and control regions
- Direct measurement of off-shell signal strength $\mu_{\text{off-shell}} = 1.1^{+0.7}_{-0.6}$ with significance off-shell production 3.3 (2.2)σ
- Combination with on-shell STXS $H \to ZZ \to 4\ell$ measurement [Eur. Phys. J. C 80 (2020) 957] yields $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV and $0.5\ (0.1) < \Gamma_H < 10.5\ (10.9)$ MeV @ 95% C.L.





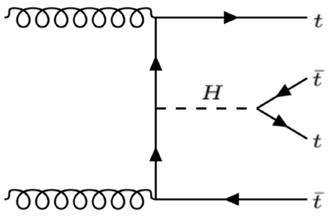
Run 2 $H \to ZZ$ result:

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

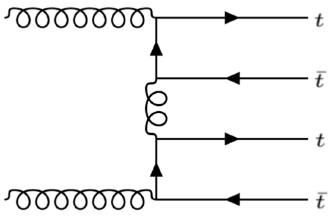
Phys. Lett. B 846 (2023) 138223 (erratum)

Off-shell $H \to t\bar{t}$ production

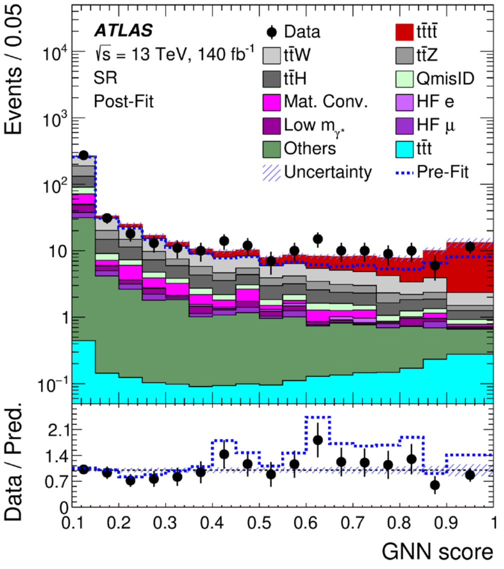
- Four-top production measured with $2\ell SS$ and multi-lepton ($> 3\ell$) events
- GNN discriminator trained with all events to discriminate $t\bar{t}t\bar{t}$ events from other sources of background.
- Interpretation of $t\bar{t}t\bar{t}$ measurement. No attempt to discriminate (Higgs) S and B.



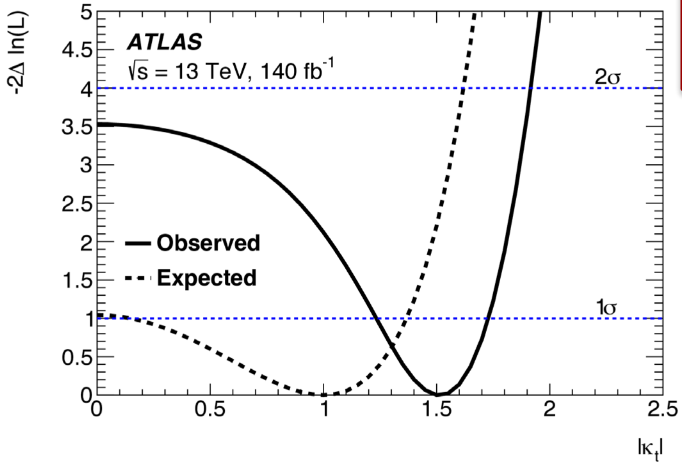
signal (S)



background (B)



$\mu_{\text{off-shell}} = |\kappa_t|^4$



With the assumption that the **Higgs contribution to the $t\bar{t}t\bar{t}$ event selection is mostly off-shell**, and if we consider **a pure CP-even κ_t**, then the observed (expected) limits are:

$$\kappa_t < 1.9\ (1.6) \text{ @ 95\% C.L.}$$

Eur. Phys. J. C 83 (2023) 496 (erratum)

Higgs width from $H \rightarrow t\bar{t}$

NEW!

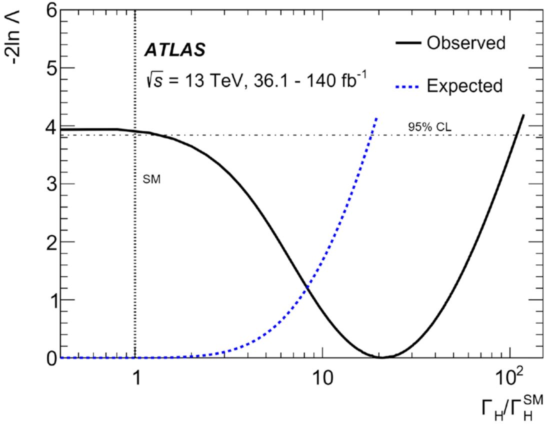
On-shell $t\bar{t}H$ measurements can be used to extract κ_t/Γ_H.

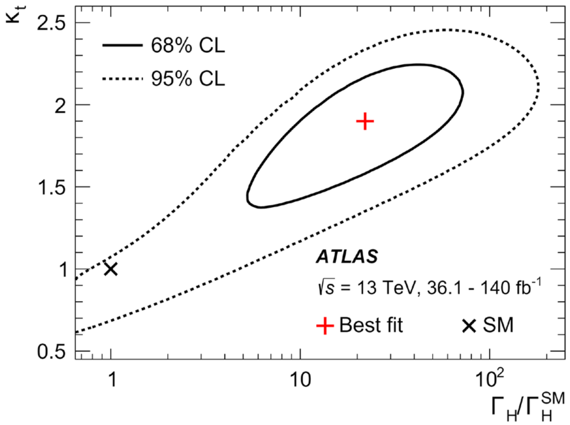
Additional processes are included to constrain the Higgs coupling to other SM particles.

Fit can be performed assuming that only SM particles contribute to the loop production of $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$

Target processes	
Off-shell measurements	
$pp \rightarrow t\bar{t}t\bar{t}$	
On-shell measurements	
Production	Decay
ggF, VBF, WH, ZH, $t\bar{t}H$, tH	$H \rightarrow \gamma\gamma$
$t\bar{t}H + tH$	$H \rightarrow b\bar{b}$
WH, ZH	$H \rightarrow b\bar{b}$
VBF	$H \rightarrow b\bar{b}$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \rightarrow ZZ$
ggF, VBF	$H \rightarrow WW$
WH, ZH	$H \rightarrow WW$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \rightarrow \tau\tau$
ggF+ $t\bar{t}H + tH$, VBF+ $WH + ZH$	$H \rightarrow \mu\mu$
Inclusive	$H \rightarrow Z\gamma$

Results **not** resolving $H \rightarrow Z\gamma$ and $H \rightarrow \gamma\gamma$





First Γ_H result with off-shell $H \rightarrow t\bar{t}$ production:

$$\Gamma_H < 445\ (75)\ \text{MeV @ 95\% C.L.}$$

Assuming only SM particles in $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$ loop-induced production:

$$\Gamma_H < 157\ (55)\ \text{MeV @ 95\% C.L.}$$

arXiv:2407.10631, submitted to PLB

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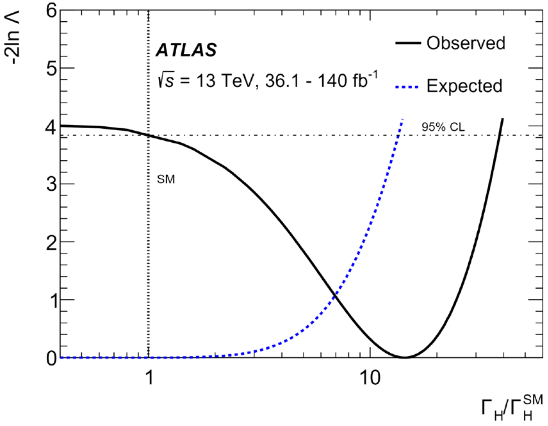
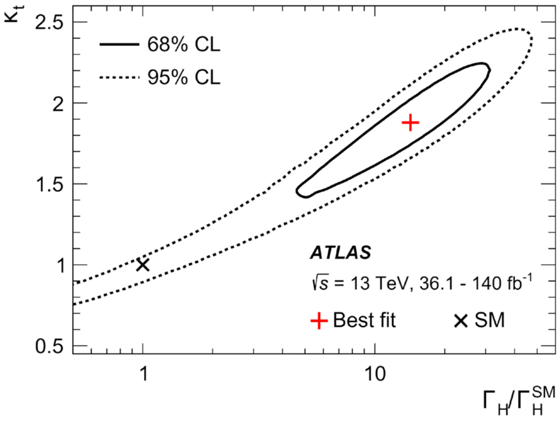
$t\bar{t}H + tH$	$H \to b\bar{b}$
WH, ZH	$H \to b\bar{b}$
VBF	$H \to b\bar{b}$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to ZZ$
ggF, VBF	$H \to WW$
WH, ZH	$H \to WW$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to \tau\tau$
ggF+ $t\bar{t}H + tH$, VBF+ $WH + ZH$	$H \to \mu\mu$
Inclusive	$H \to Z\gamma$

Results resolving $H \to Z\gamma$ and $H \to \gamma\gamma$





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arXiv:2407.10631, submitted to PLB

More details in P. Jackson's talk later today!

Conclusion

- The measurement of the Higgs boson properties is an important part of the ATLAS program at the LHC
- The mass is an independent parameter of the SM.
- The most recent ATLAS measurements of the Higgs boson mass in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ channels were presented.
  - Recent improvements in the photon energy scale calibration were essential for improvement of the measurement. The Run 1 + Run 2 combined measurement is $\mathrm{m}_H = 125.11 \pm 0.11$ GeV
- The Higgs boson width can be inferred by combining on-shell and off-shell Higgs production measurements.
- The most recent ATLAS measurement of the Higgs boson width using $H \rightarrow ZZ$ off-shell events was presented.
  - First evidence of off-shell Higgs boson production in ATLAS. Combination of the 4ℓ and $2\ell 2\nu$ decay channels yields $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV
- A new measurement of the Higgs boson width using off-shell $H \rightarrow t\bar{t}$ events was presented.
  - The analysis is a re-interpretation of the $t\bar{t}t\bar{t}$ measurement and it is the first Higgs boson width measurement using the $t\bar{t}$ threshold explicitly.
  - When combining the $t\bar{t}t\bar{t}$ with several on-shell measurements, we obtain the limit $\Gamma_H < 445$ MeV at 95% @ C.L.