Evidence of off-shell Higgs boson production to *ZZ* leptonic decay channels & measurement of its total width by the ATLAS experiment

CERN-EP-2023-03

arXiv:2304.01532 [hep-ex]

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Why look for off-shell Higgs production

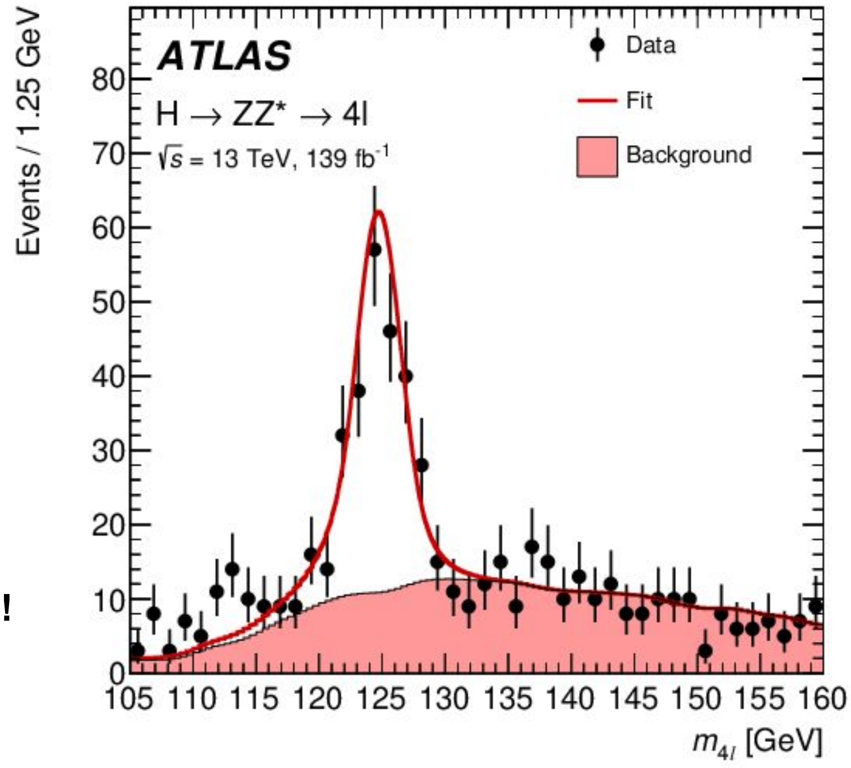
- Higgs peak in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel

- Predicted width by the SM: $\mathbf{\Gamma_H = 4.1}$ **MeV**

- Experimental resolution at ATLAS for $m_{4\ell}$:
  - ➢ **1.5 GeV** for 4μ and $2e2\mu$
  - ➢ **2.1 GeV** for $2\mu2e$ and $4e$

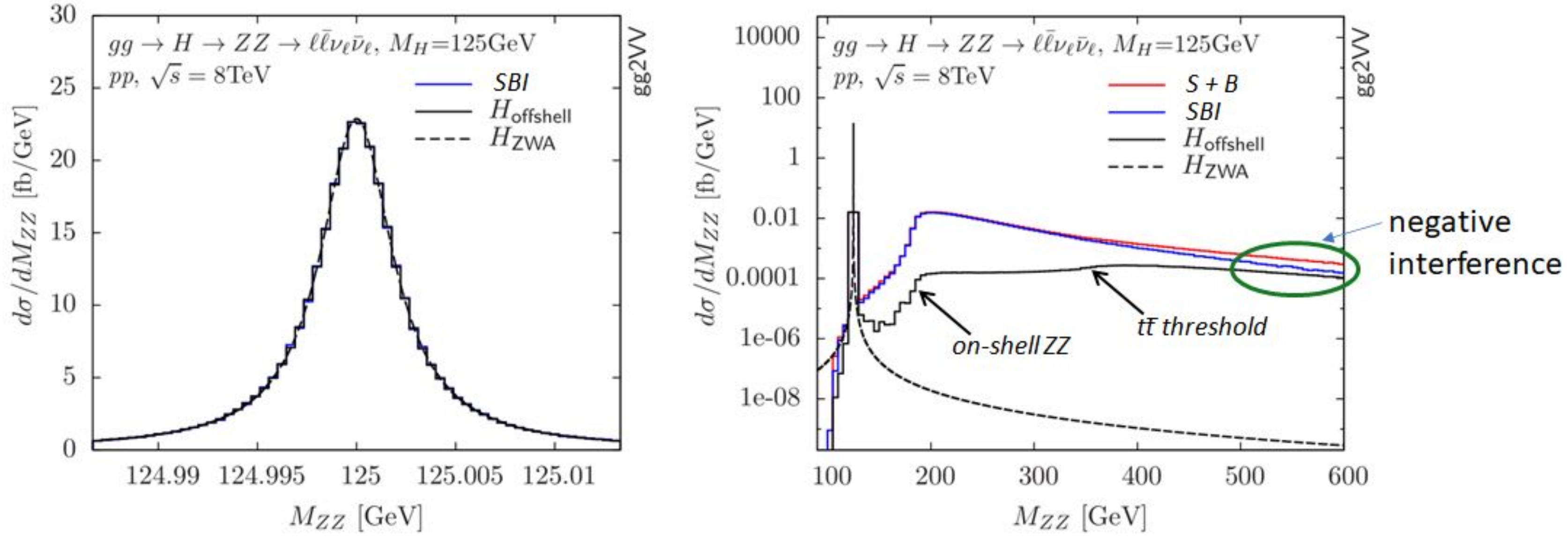
↪ **cannot directly measure Γ_H from the peak width!**

arXiv:2207.00320



Why look for off-shell Higgs production

- But m_H = 125 GeV while Γ_H = 4.1 MeV…
- Off-shell Higgs production is not negligible (15% of Higgs production) ⟵ **larger phase space**
  - ➢ on-shell ZZ at 180 GeV
  - ➢ *tt* threshold at ~350 GeV



(a) Near the Higgs resonance (b) In the high-mass region

Inadequacy of zero-width approximation for a light Higgs boson signal, N. Kauer, G. Passarino, arXiv:1206.4803 **[hep-ph]**

Accessing the Higgs' width

$$\sigma_{i\to H\to f} \sim \int \frac{\mathrm{d}s \quad g_i^2 g_f^2}{(s-m_h)^2 + m_h^2\Gamma_h^2}$$

so

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

and

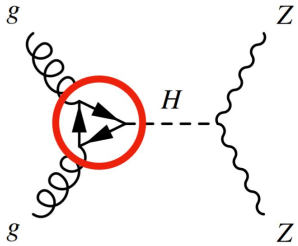
$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{m^2_{ZZ}}$$

- **On-shell** Higgs boson production (in the ggH production channel) is inversely proportional to Γ_H
- **Off-shell** Higgs boson production (in the same production channel) has no width dependence.

⇒ **Ratio of off-shell and on-shell gives Γ_H**

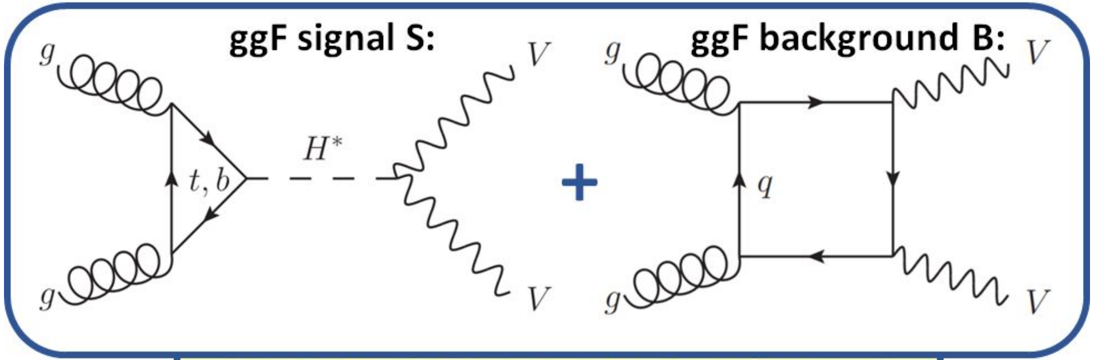
⇒ **Solution: move away from the mass peak, in the "high-mass region" ($m_{4\ell}$>220 GeV)**

/!\ Important assumption: ggH follows the SM prediction with no new particles entering the quark loop, so that on-shell and off-shell production are the same.



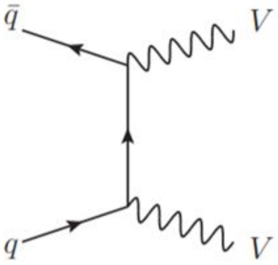
SBI: Signal, Interference and Background(s)

Example diagrams for gluon-gluon fusion (ggF)



Total signal SBI (negative interference)

+ Background qqZZ:



Destructive interference ⇒ deficit

Note that not all backgrounds are interfering, such as the qqZZ background.

SBI: Signal, Interference and Background(s)

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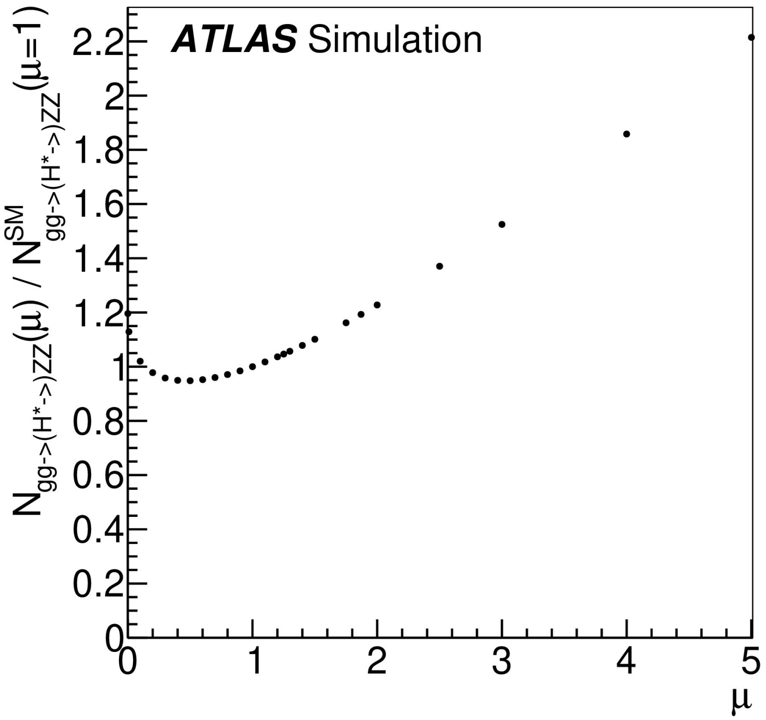


Yield not linear in $\mu_{\text{off-shell}}$!

- ➢ Distribution of the test statistic not exactly the asymptotic χ^2 distribution.
- ➢ Confidence intervals on $\mu_{\text{off-shell}}$ must be built based on the Neyman construction (making toys).

J. Neyman,
Outline of a Theory of Statistical Estimation Based on the Classical Theory of Probability, Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences 236 (1937) 333, issn: 00804614.

4ℓ final state

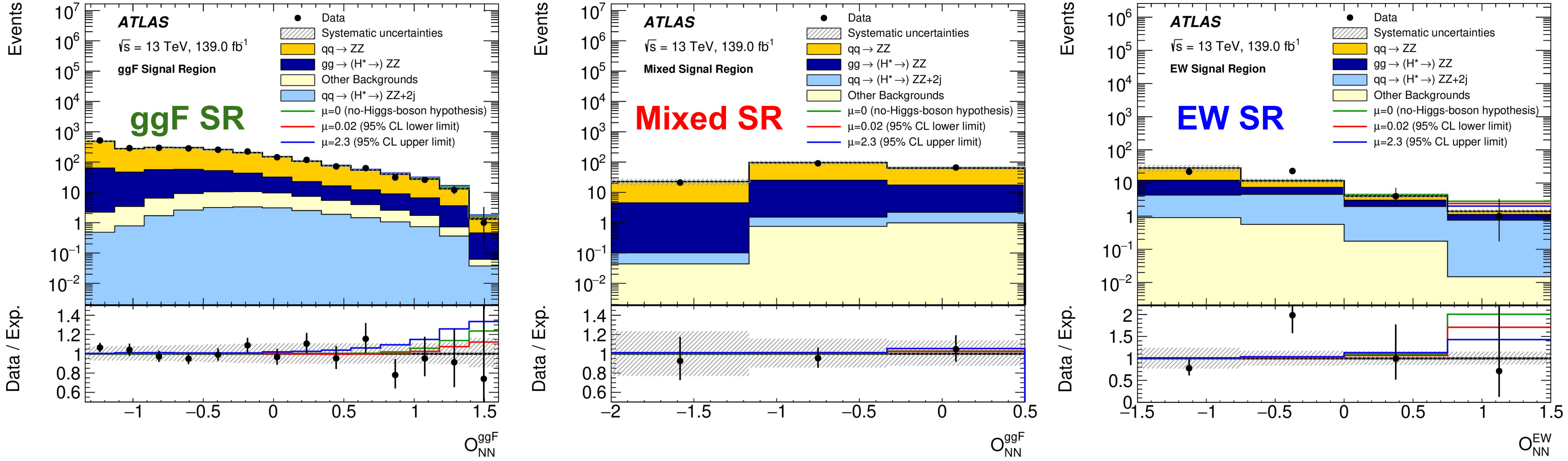
Signal Region (SR) is defined as $m_{4\ell} \geq 220$ GeV, separated in 3 regions:

- **Mixed** (1-jet) and **electroweak (EW)** (2-jet) SRs are defined targeting EW (**VBF+VH**) production.
- Remaining events from the **ggF Signal Region (SR)**.

qqZZ production is the dominant background.

- Constrained using data Control Regions (CR): $180 < m_{4\ell} < 220$ GeV ; Njets = 0, 1, ≥2.
- Other backgrounds are mainly ttV and VVV, fakes from Z+jet and ttbar are negligible.

Dense NNs were trained in the SRs to enhance events with Higgs boson candidate, to better separate ggF and EW signal from interfering gg background and non-interfering qqZZ background.



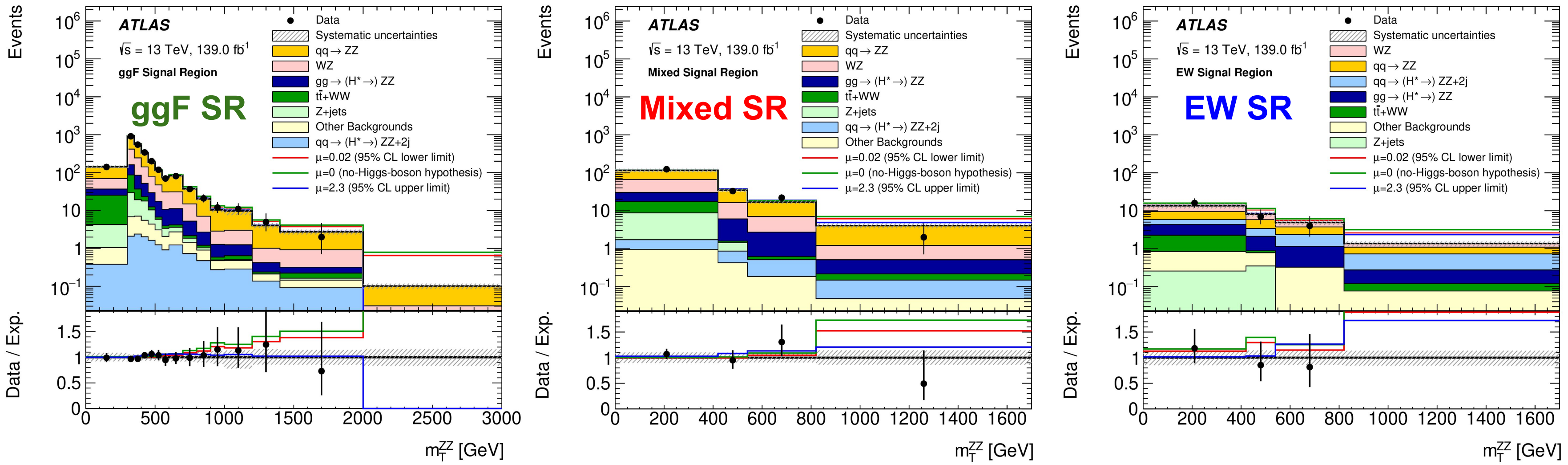
$2\ell 2\nu$ final state

Same SRs (Signal Region) as for the 4ℓ final state: **ggF SR**, **mixed SR** and **EW SR**, with $E_{\mathrm{T}}^{\mathrm{miss}} > 120$ GeV

qqZZ production is still the dominant background.

- Constrained using 4ℓ CRs (Control Region).
- Separate CRs constructed to constrain WZ, Z+jets and non-resonant backgrounds

The $2\ell 2\nu$ channel uses the transverse mass of the ZZ system $m_{\mathrm{T}}^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_{\mathrm{T}}^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_{\mathrm{T}}^{\mathrm{miss}}\right)^2}\right]^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$



Measurement of off-shell Higgs production

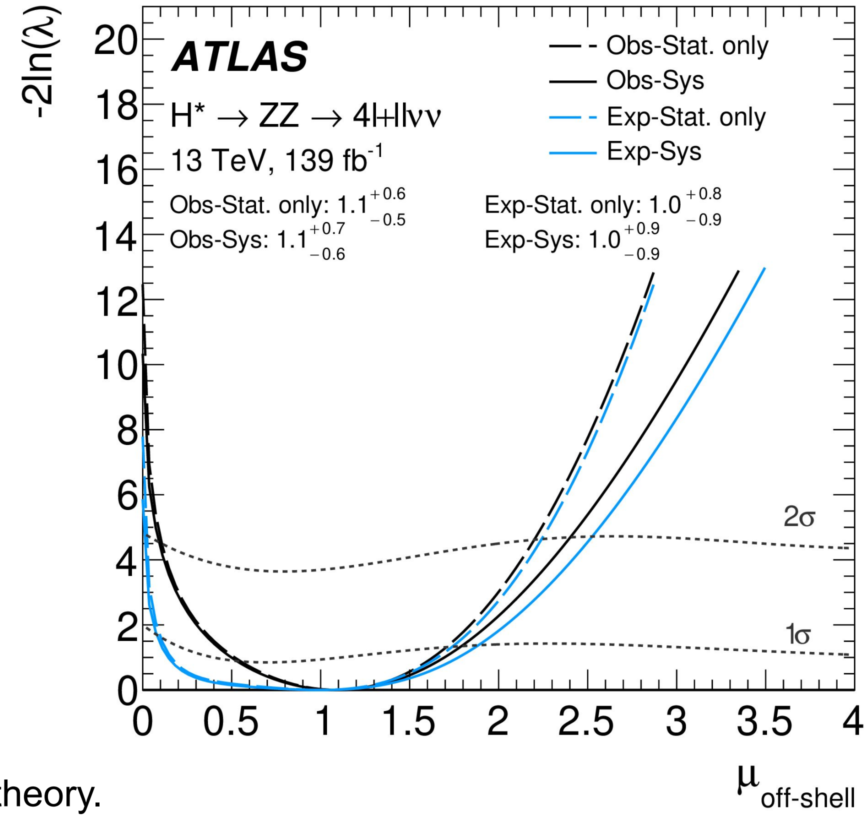
- Both channels combined in the final result.
- Asymptotic limit assumption is not valid here
  ↪ **Confidence Intervals constructed from toys using Neyman construction.**

➤ Measured value of $\mu_{\text{off-shell}} = 1.1^{+0.7}_{-0.6}$

- 95% CL upper limit of $\mu_{\text{off-shell}}$ is 2.4
- 3.3 σ evidence for off-shell production
  (i.e. rejection of background-only hypothesis).

Uncertainties:

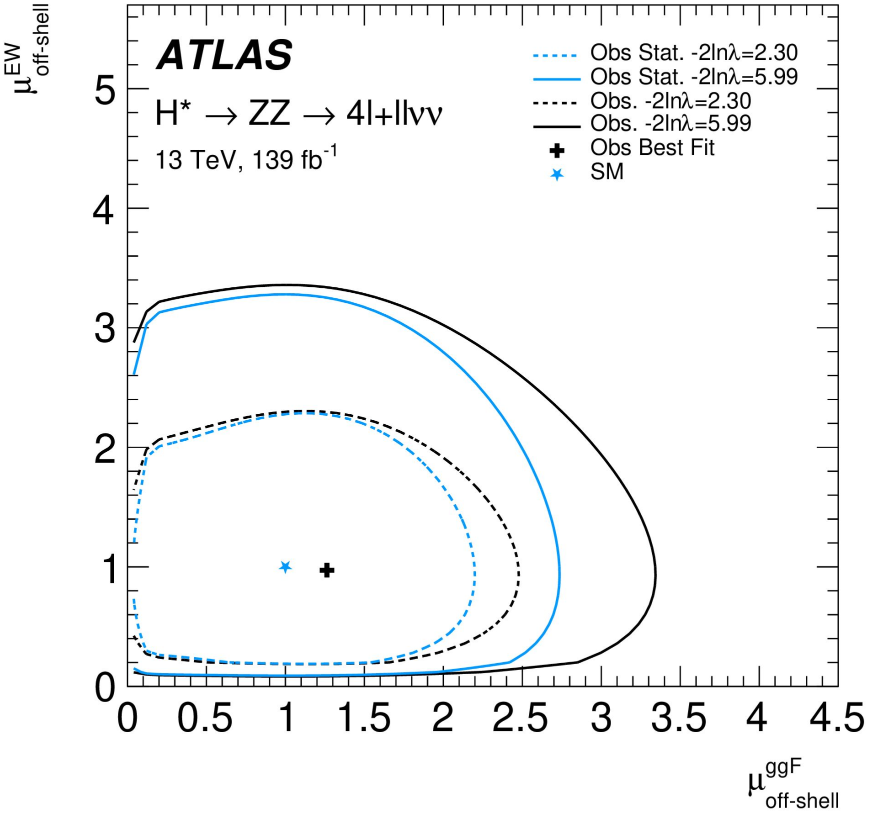
- Stat-limited measurement.
- Main systematics come from jets and background theory.



Measurement of off-shell Higgs production

Simultaneous constraint of off-shell EW and ggF production

↪ **Good agreement observed with the SM**



Measurement of Higgs width

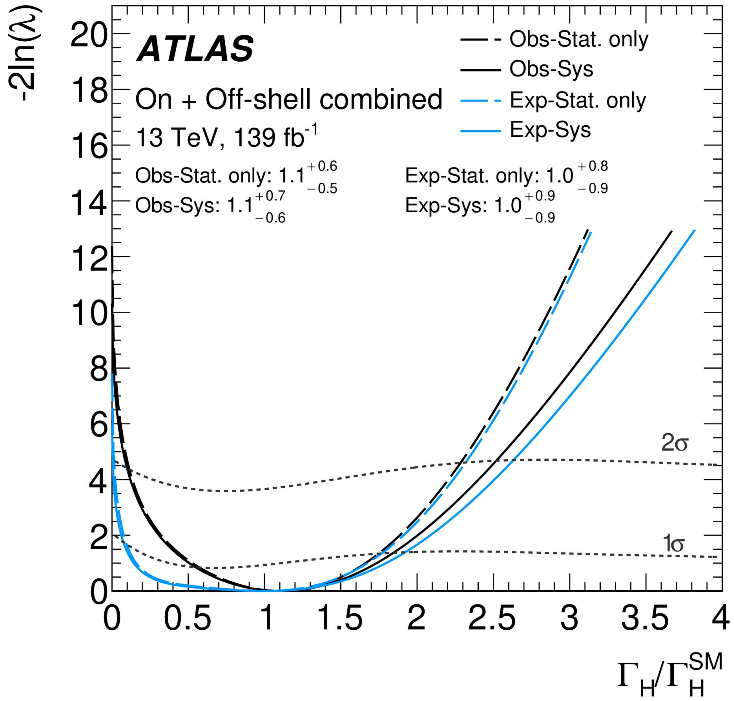
We measure the ratio Γ_H/Γ_H^{SM} then multiply by the width of the SM Higgs boson, obtaining the following result:

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

At 95% CL, $0.5 < \Gamma_H < 10.5$ MeV using the Neyman construction (see below).

↪ **Good agreement observed with the SM**

(Γ_H = 4.1 MeV for SM)



Measurement of effective couplings

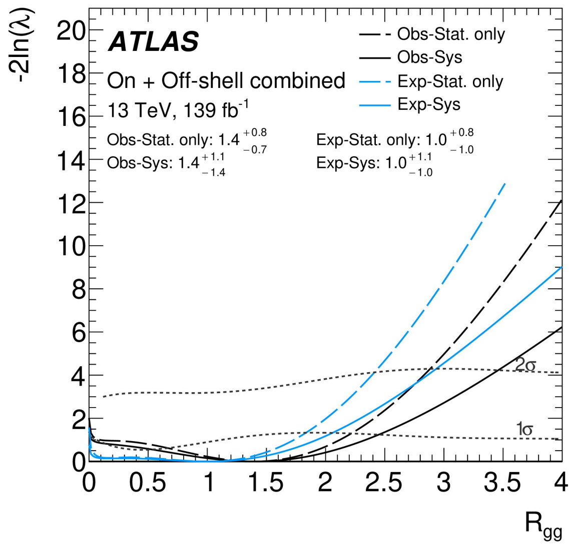
We also measure the ratio of effective Higgs boson-gluon couplings (R_{gg}) and the ratio of Higgs boson to vector-boson couplings (R_{VV}) between the off-shell and on-shell regions, assuming the SM value of Γ_H .

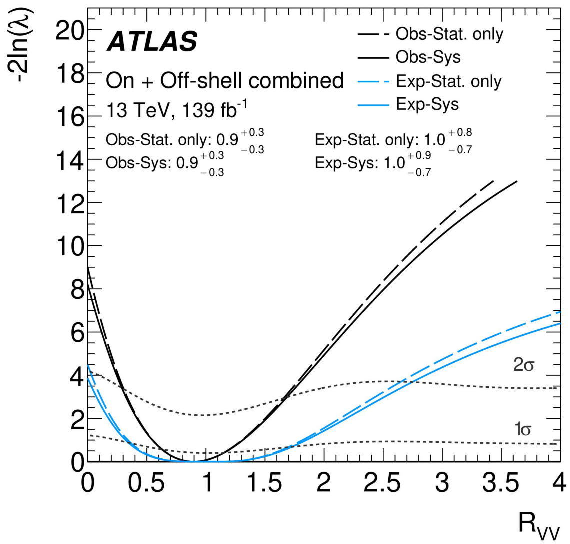
Combining with the on-shell HZZ analysis gives us the ratio of off-shell to on-shell coupling:

- for ggF production $R_{gg} \equiv \kappa^2_{g,\text{ off-shell}} / \kappa^2_{g,\text{ on-shell}}$
- and EW production $R_{VV} \equiv \kappa^2_{V,\text{ off-shell}} / \kappa^2_{V,\text{ on-shell}}$

The measured values are the following:

- $R_{gg} = 1.4^{+1.1}_{-1.4}$
- $R_{VV} = 0.9^{+0.3}_{-0.3}$





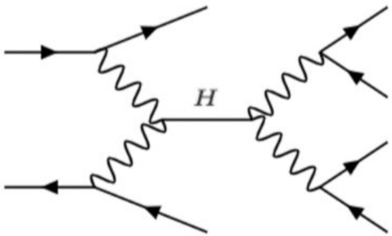
Summary & outlook

- Evidence of off-shell production in the H → ZZ decay channel
- $\mu_{\text{off-shell}} = 1.1^{+0.7}_{-0.6}$
- Measured total Higgs width: $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV
  - *Assumption that on-shell and off-shell ggF Higgs production are the same*
- **Stat-limited measurement ⇒ looking forward to Run-3 data!**

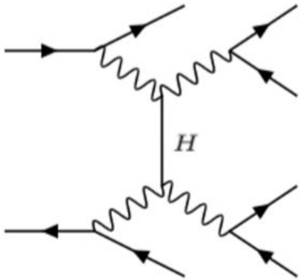
Backup

Signal Interference Background (EW)

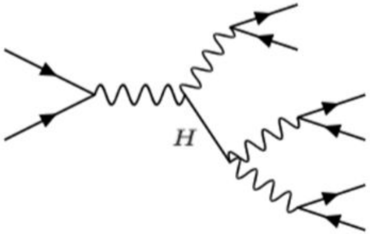
Diagrams for ElectroWeak production (EW)



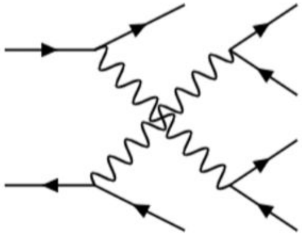
Resonant
s-channel VBF*
signal



Non-resonant
t-channel VBF*
signal



Higgsstrahlung
(VH) signal



Vector
Boson
Scattering
background

*VBF: Vector Boson Fusion

Expected and observed yields

Expected and observed yield (in the 4ℓ final state):

Process	ggF SR	Mixed SR	EW SR
$gg \to (H^* \to) ZZ$	341 ± 117	42.5 ± 14.9	11.8 ± 4.3
$gg \to H^* \to ZZ$	32.6 ± 9.07	3.68 ± 1.03	1.58 ± 0.47
$gg \to ZZ$	345 ± 119	43.0 ± 15.2	11.9 ± 4.4
$qq \to (H^* \to) ZZ + 2j$	23.2 ± 1.0	2.03 ± 0.16	9.89 ± 0.96
$qq \to ZZ$	1878 ± 151	135 ± 23	22.0 ± 8.3
Other backgrounds	50.6 ± 2.5	1.79 ± 0.16	1.65 ± 0.16
Total expected (SM)	2293 ± 209	181 ± 29	45.3 ± 10.0
Observed	2327	178	50

Neyman construction

For an Asimov MC dataset created for a given μ_{truth} (multiplying S, SBI, B etc events by the appropriate coefficient):

- throw toys / create pseudo-experiments;
- for each toy, compute the value of the test statistic at $\mu = \mu_{\text{truth}}$;
- plot an histogram of this value for all toys;
- asymptotically, one would expect 68% of toys to have the above value less than 1 (1σ), 95% to be less than 2^2 (2σ);
- in reality, this is not exactly the case:
    - integrate the above histogram until 68% of toys are taken: this gives the Confidence Level at 1σ for this value of μ_{truth}
    - do the same to integrate 95% of toys: this gives the CL at 2σ at $\mu = \mu_{\text{truth}}$.

↪ Do this for several values of μ_{truth} : we have constructed Neyman CL at 1σ and 2σ.