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20TH WORKSHOP OF THE LHC HIGGS WORKING GROUP, NOV 13 – 15, 2023

MEASUREMENT OF HIGGS BOSON OFF-SHELL PRODUCTION AND TOTAL WIDTH USING THE $H \rightarrow ZZ \rightarrow 4L$ AND 2L2V CHANNELS AT THE ATLAS EXPERIMENT

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MEASURING THE HIGGS BOSON WIDTH

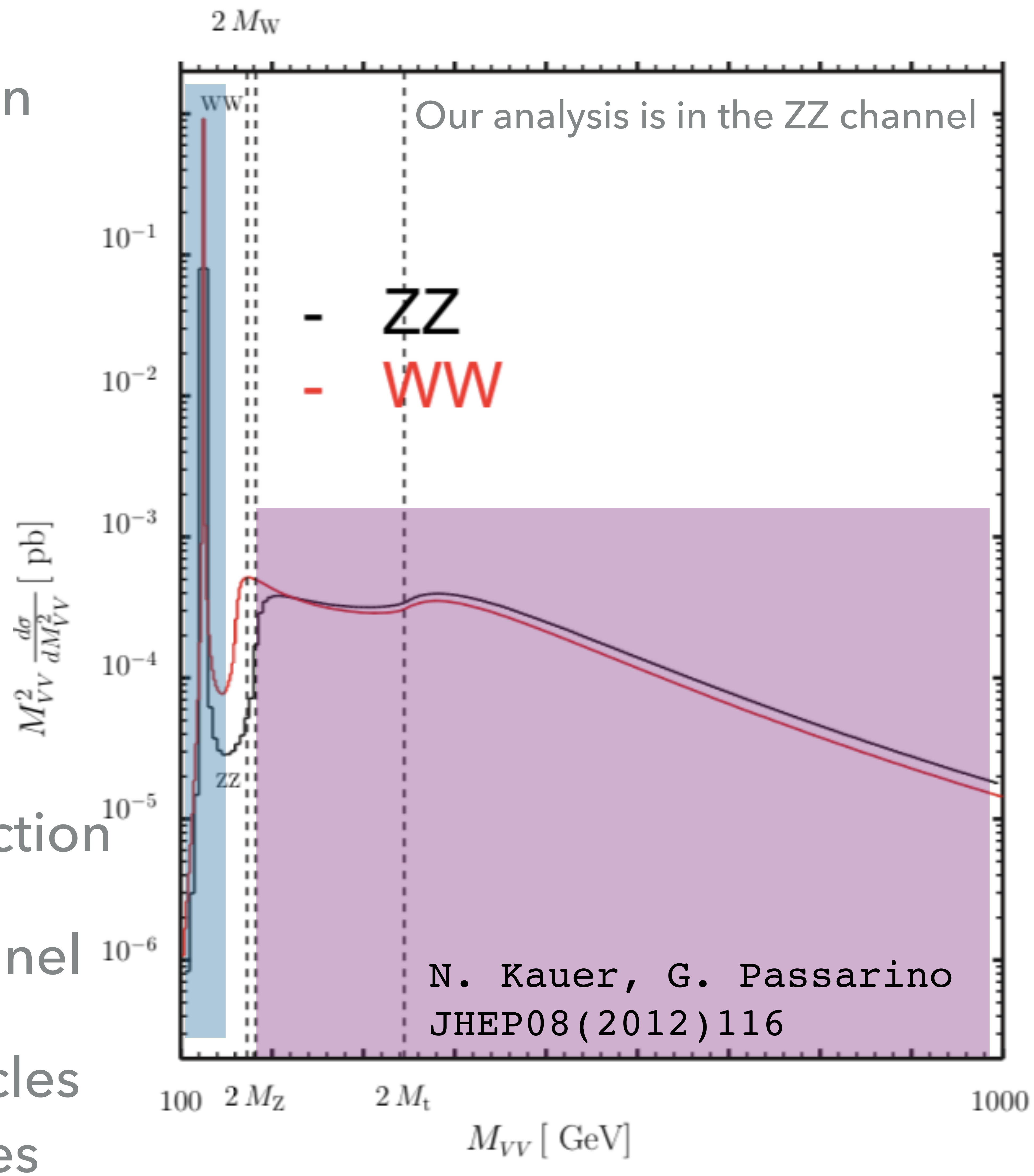
- Theory prediction: 4.1 MeV → Too small for detector resolution of the LHC experiments
- Instead, use the ratio of on-shell and off-shell Higgs production

$$\sigma^{pp\to H\to ZZ}_{onshell} \sim \frac{g^2_{Hgg}\, g^2_{HZZ}}{m_H \Gamma_H}$$

$$\sigma^{pp\to H\to ZZ}_{offshell} \sim \frac{g^2_{Hgg}\, g^2_{HZZ}}{{M_{ZZ}}^2}$$

$$\frac{\sigma_{offshell}}{\sigma_{onshell}} \propto \Gamma_H$$

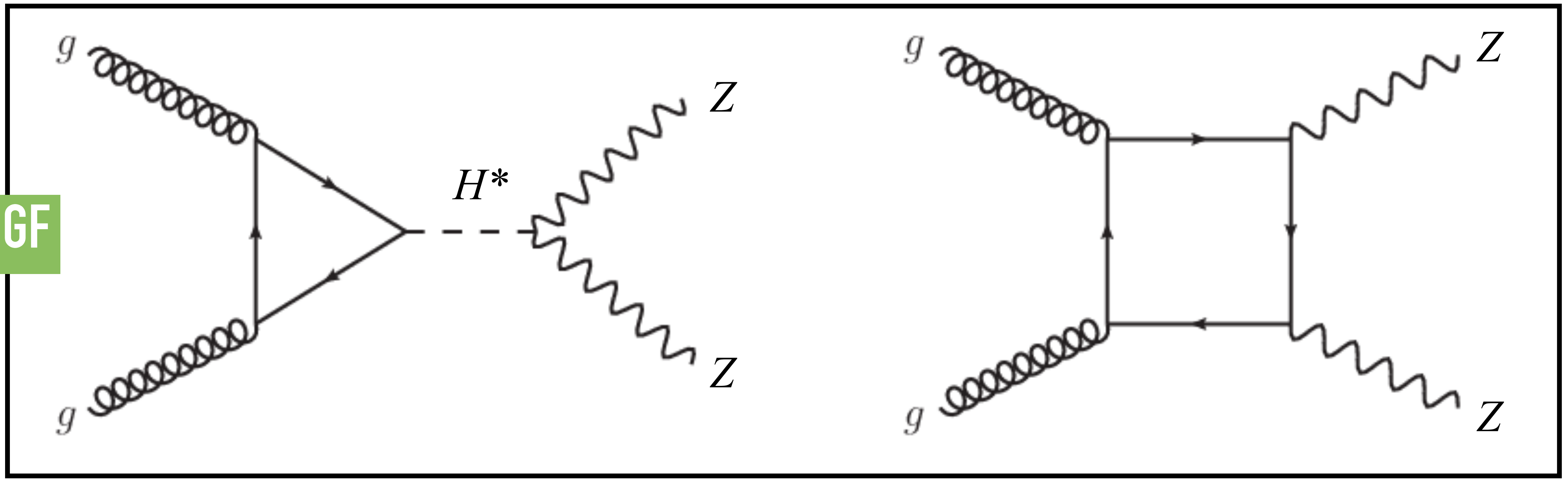
- Exploits enhanced off-shell production for H → VV
- Assume equal coupling ratios for o-nshell and off-shell production
- This talk focusses on the off-shell measurement in the ZZ channel
- We assume no significant contributions from new heavy particles below ~2 TeV, as confirmed by searches in the same final states



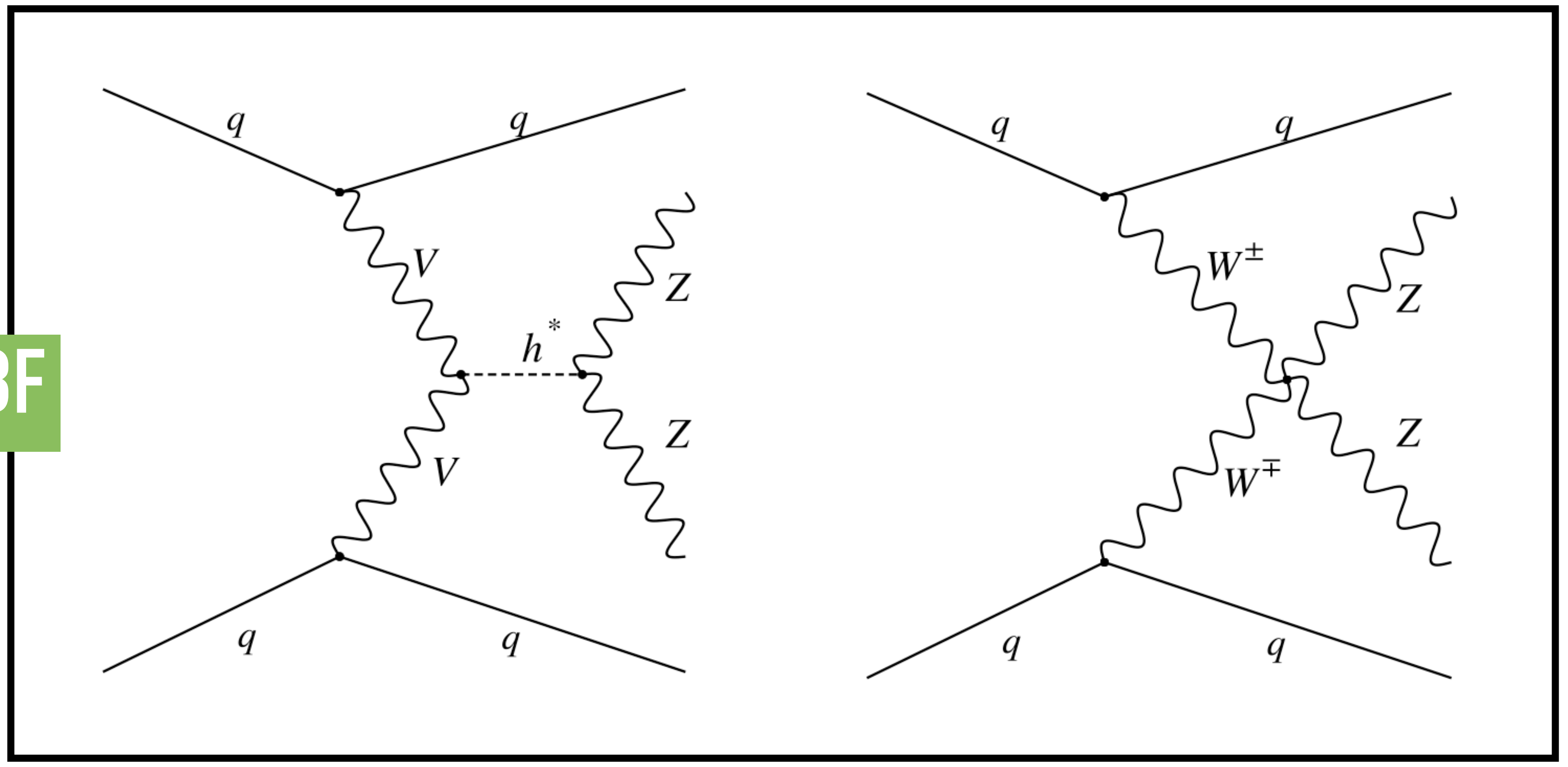
ZZ INTERFERENCE FOR GGF

- The Higgs signal and ZZ background cannot be distinguished, there is an interference effect

GGF



VBF



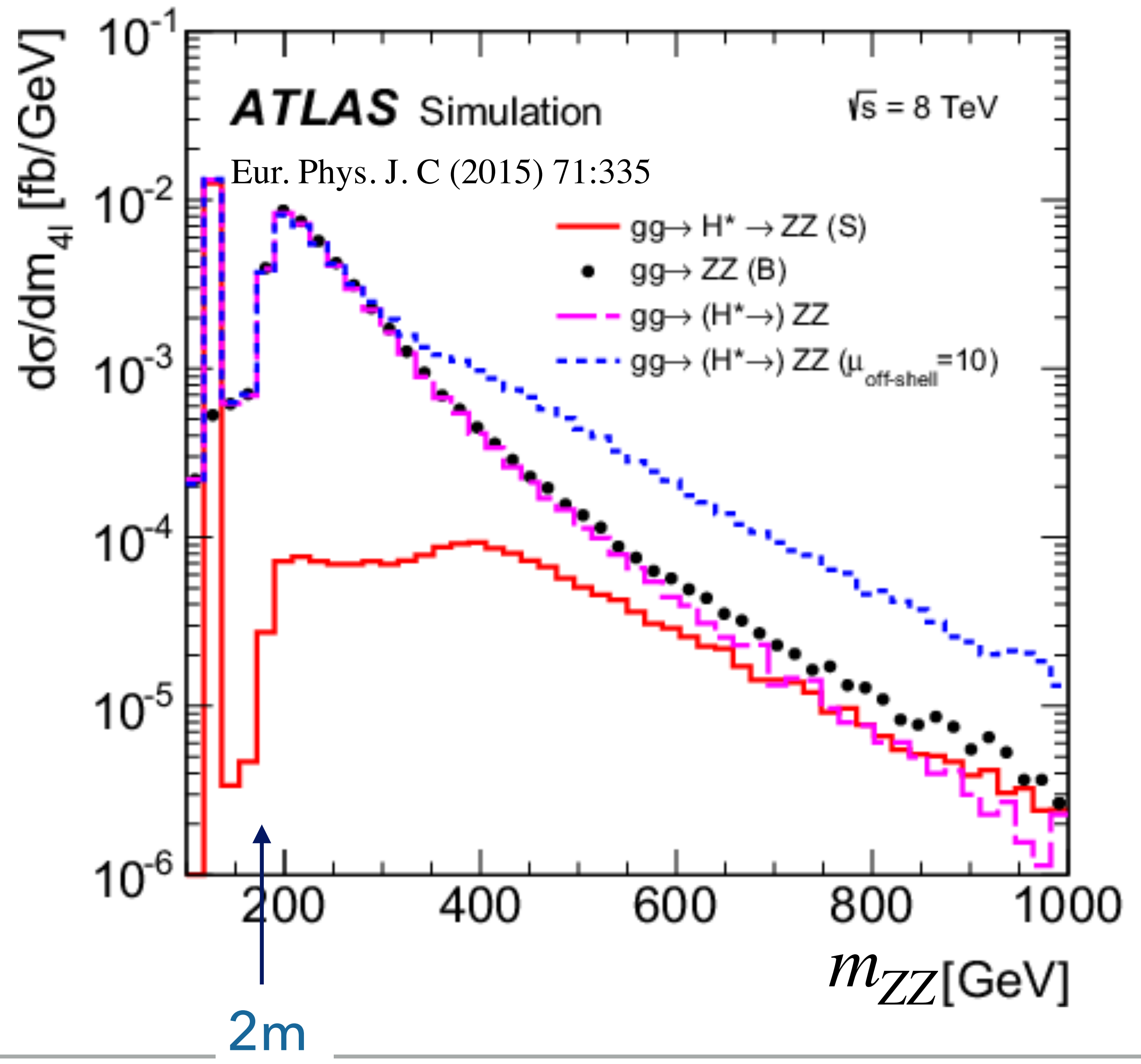
- At the SM width, we measure a deficit in ZZ events, the size of the deficit depends on the off-shell signal strength (μ).

- Total number of events is given by:

$$N = \mu S + \sqrt{\mu} I + B$$

- Interference is parametrised as:

$$I = SBI - S - B < 0$$

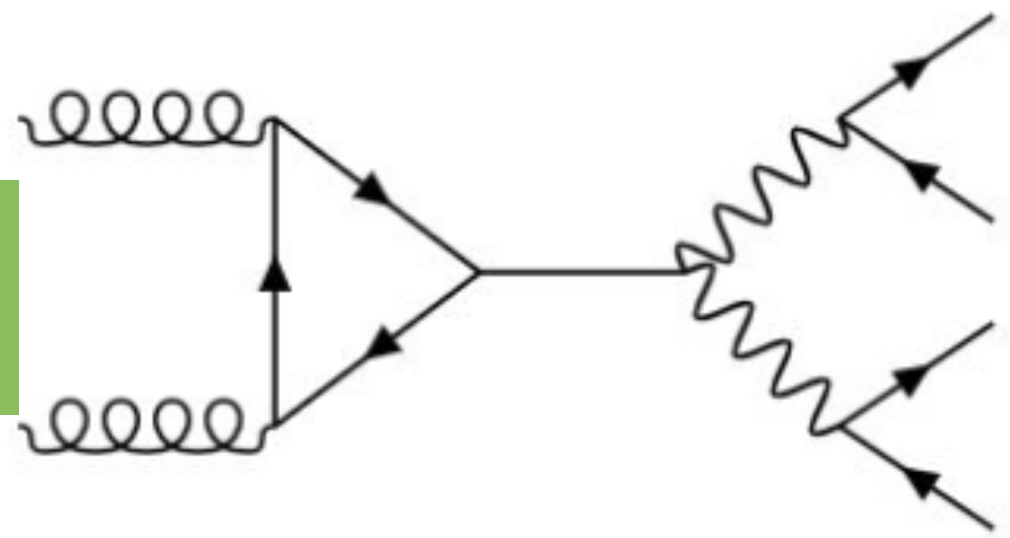


SIGNAL REGIONS

- There are three signal regions in the analysis, targeting both ggF and EW production, while we use two complementary final states

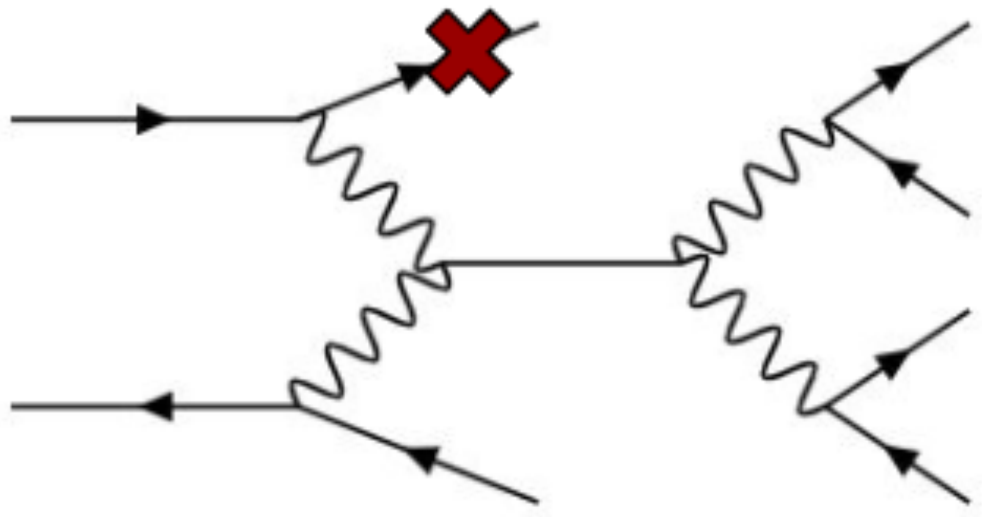
PRODUCTION MODES

ggF Signal region



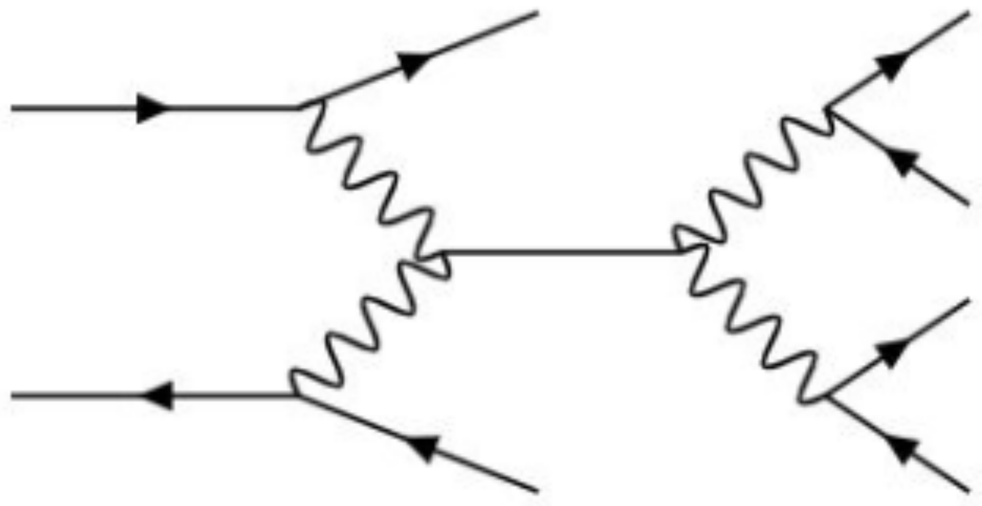
Rest of the events

1 jet mixed signal region



$n_{jets} = 1$ and $|\eta_j| > 2.2$

EW signal region



$n_{jets} \geq 2$ and $|\Delta\eta_{jj}| > 4.0$

FINAL STATES

ZZ → 4l

- Advantage:
  - Clean signal
  - Fully reconstructible
- Observable:
  - Neural net discriminants

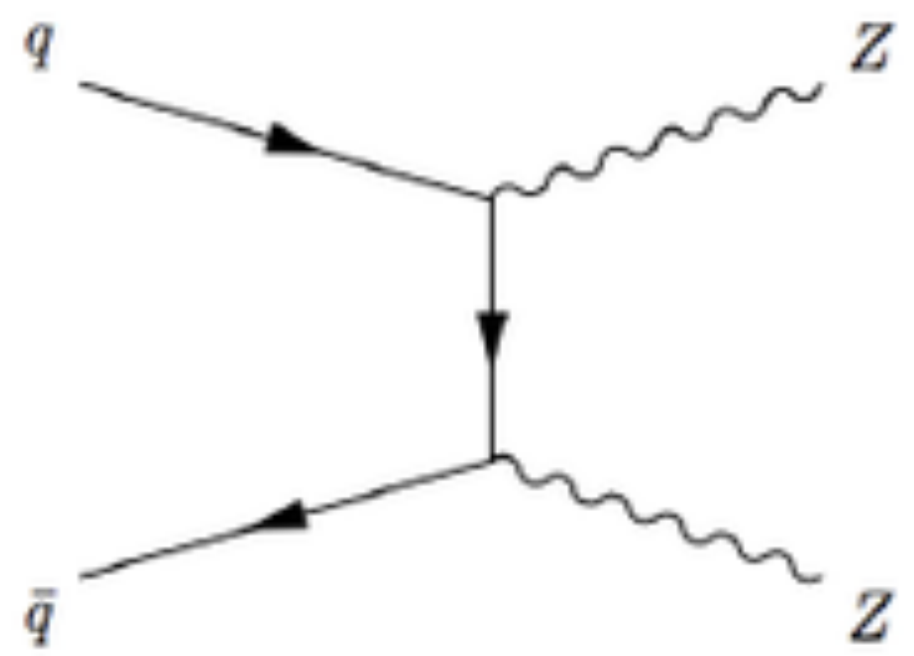
ZZ → 2l2v

- Advantage:
  - Six times higher branching ratio
- Observable
  - Transverse ZZ mass

- In the final measurement, a simultaneous fit is performed in all channels

4-LEPTON CHANNEL BACKGROUNDS

- The dominant non-interfering background in the 4-lepton channel is qq → ZZ
  - Contribution from other non-interfering background is ~2%



- A control region rich in qq → ZZ is defined to constrain the background

qqZZ CR: 180 GeV < $m_{4\ell}$ < 220 GeV

- The normalisation is left as a free parameter in the profile likelihood fit, separately for each jet multiplicity to reflect the signal regions
  - Three qq → ZZ regions: With no jets, one jet and two or more jets

4-LEPTON CHANNEL SIGNAL REGIONS

- To maximise the signal sensitivity, multi-class dense neural networks are employed to enhance the contribution of events with off-shell Higgs boson production
- Different observables are used in different jet categories
- Observable defined using the probability of an event classified as off-shell Higgs signal, interfering background or non-interfering background

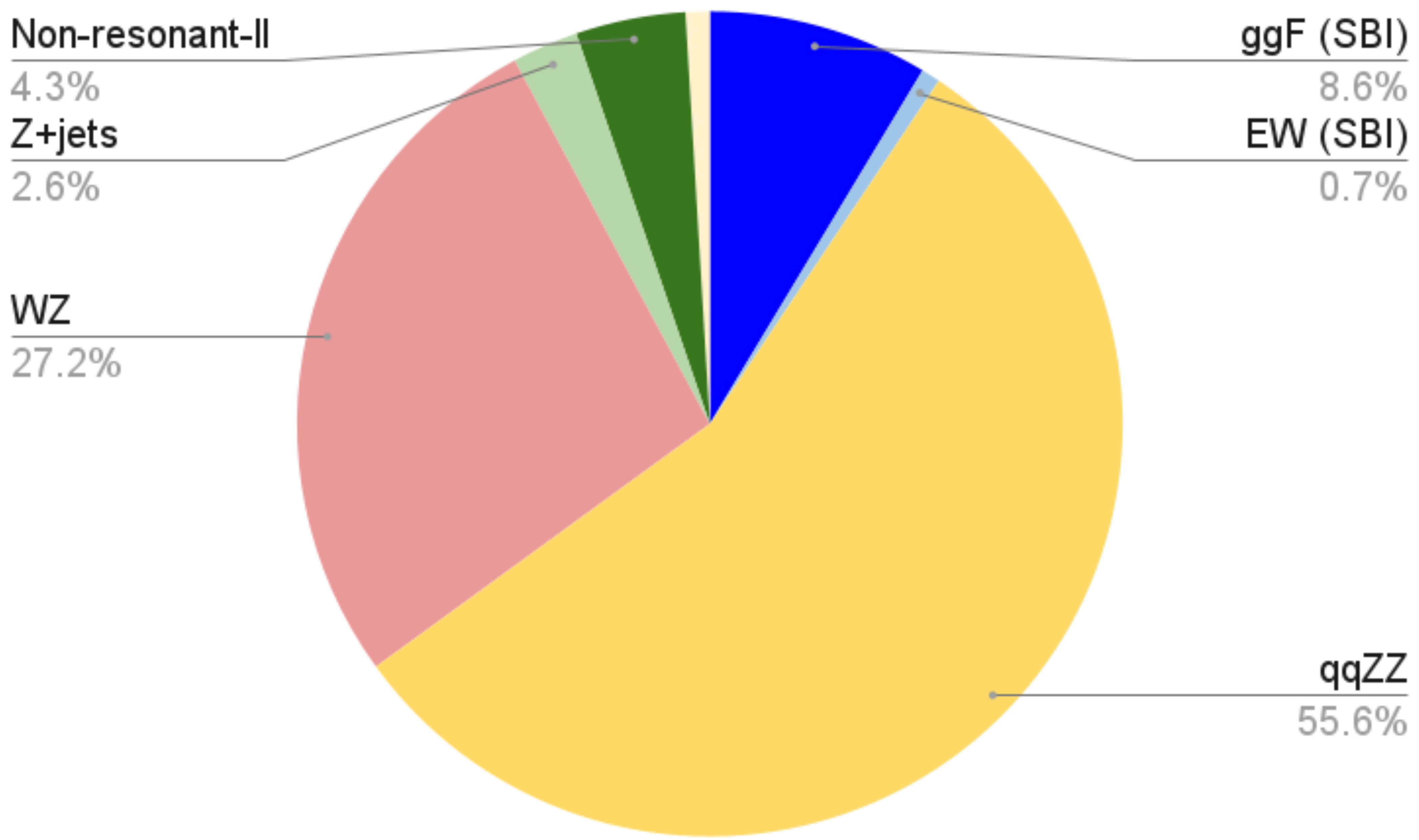
$$NN_{ggF} = \log_{10}\left(\frac{P_{ggHZZ}}{P_{ggZZ} + P_{qqZZ}}\right)$$

$$NN_{EW} = \log_{10}\left(\frac{P_{VBFH}}{P_{VBS} + P_{qqZZ}}\right)$$

2L2V CHANNEL BACKGROUNDS

- The 2l2v channel has more backgrounds in addition to qq → ZZ, as WZ, WW/top and Z+jets processes are relevant
- Each background has an associated control region, and a floating normalisation in the fit
  - Like the qq →ZZ control region, the WZ control region is split by jet multiplicity to reflect the signal region
- In the combined simultaneous fit, the 4-lepton qq →ZZ control regions are also used for the normalisation of the 2l2v qq →ZZ background

Relative expected yields in the llvv channel



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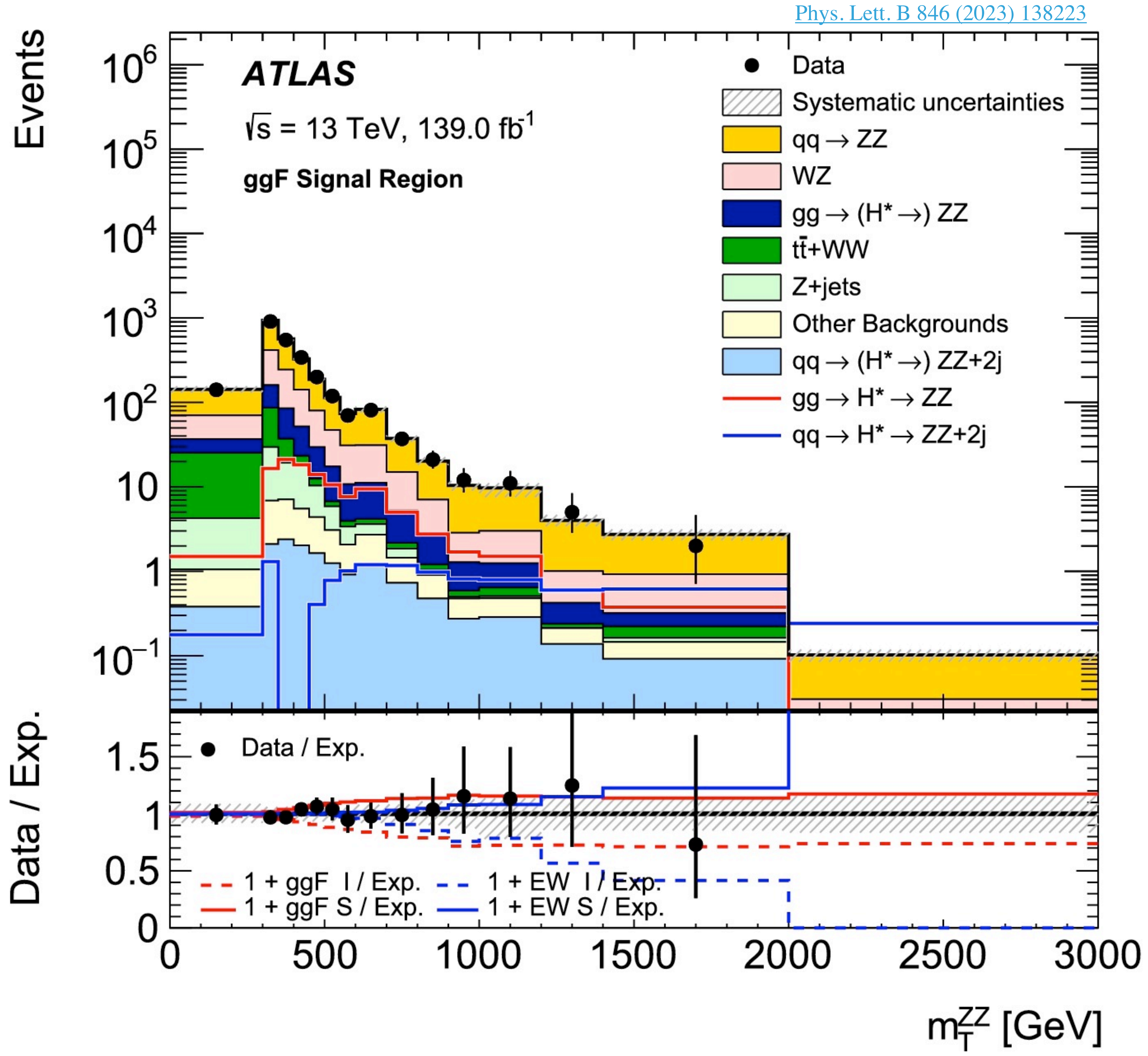
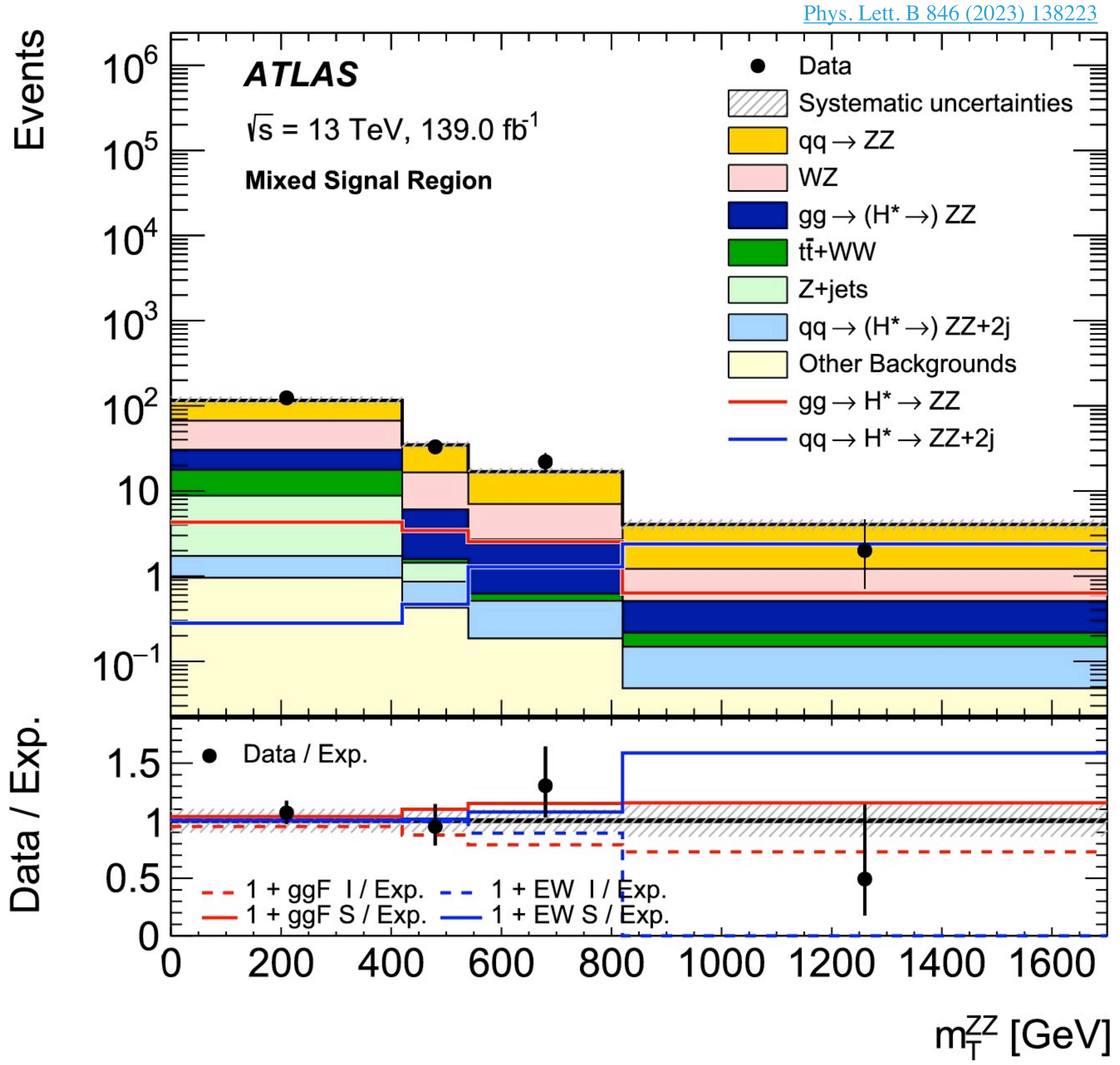
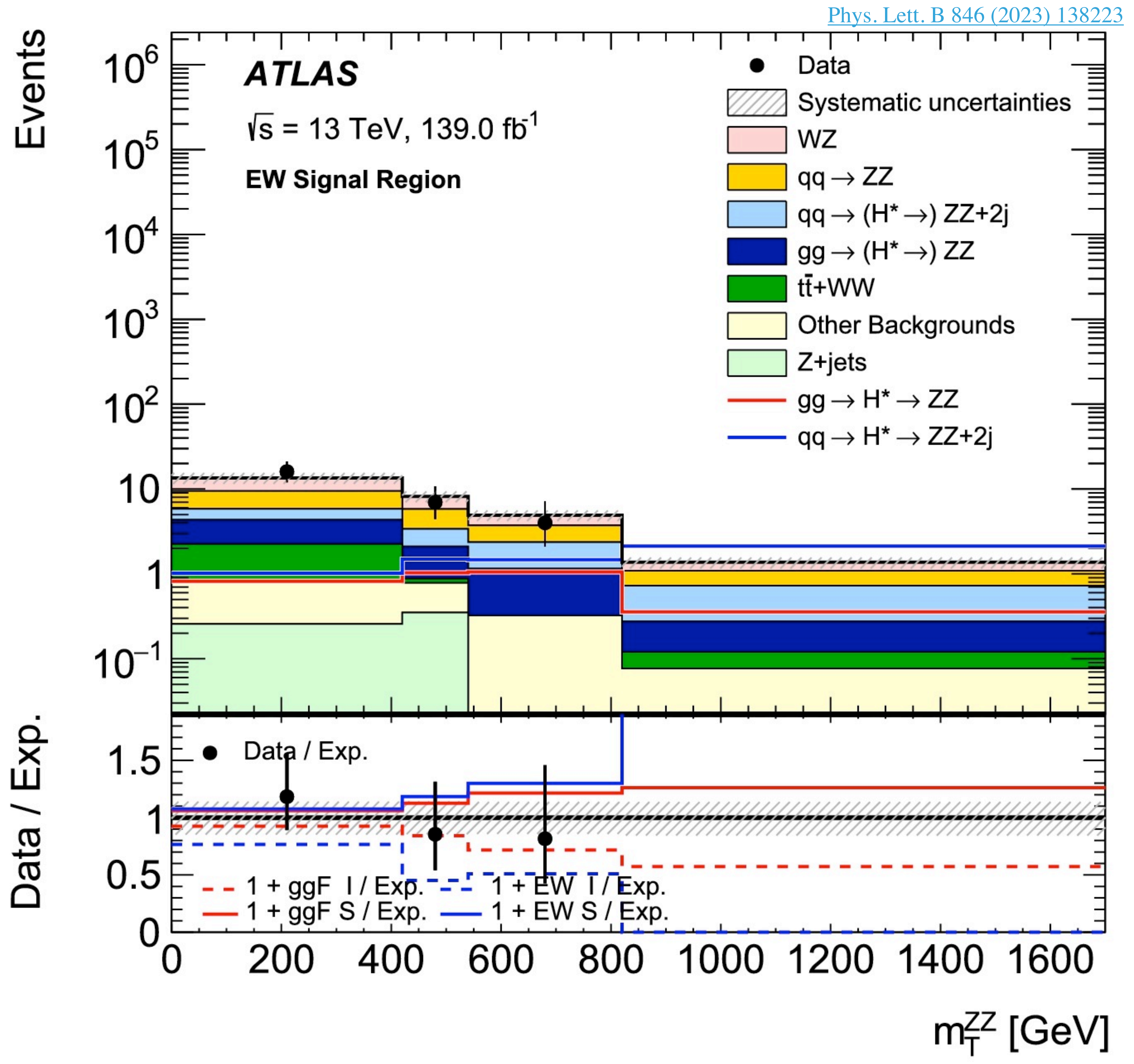
2L2V SIGNAL REGIONS

- The transverse ZZ mass is used as an observable, since the final state is not fully reconstructable

$$m_T^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_T^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_T^{\text{miss}}\right)^2}\right]^2 - \left|\vec{p_T}^{\ell\ell} + \vec{E}_T^{\text{miss}}\right|^2},$$







COMBINED RESULTS

- Simultaneous fit in the six signal regions and eight control regions for the off-shell signal strength

Normalisation factor	Fitted value
μ_{qqZZ}	1.11 ± 0.07
μ_{qqZZ}^{1j}	0.90 ± 0.10
μ_{qqZZ}^{2j}	0.88 ± 0.26
$\mu_{3\ell}$	1.06 ± 0.03
$\mu_{3\ell}^{1j}$	0.92 ± 0.10
$\mu_{3\ell}^{2j}$	0.75 ± 0.19
μ_{Zj}	0.90 ± 0.19
$\mu_{e\mu}$	1.08 ± 0.09

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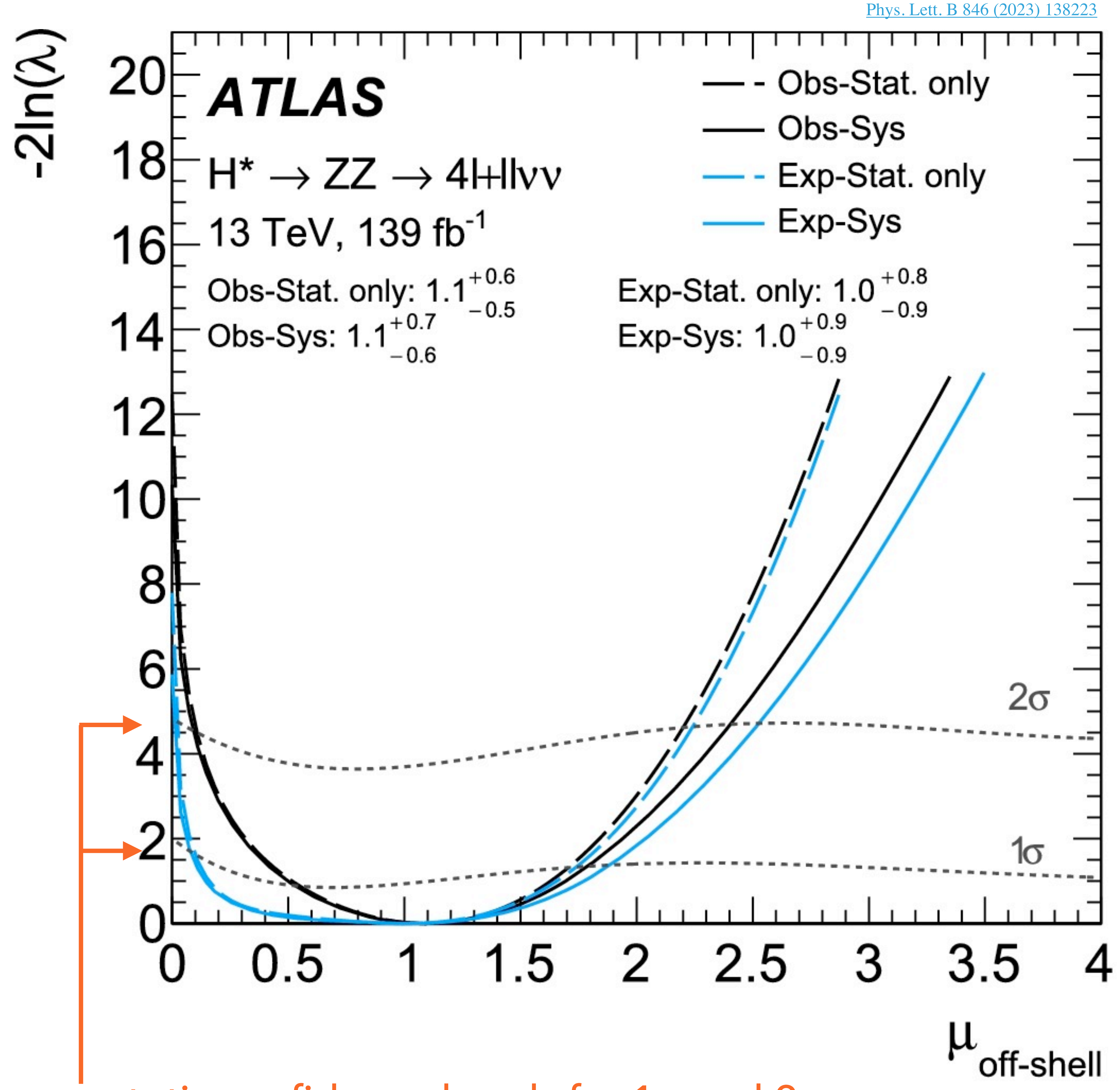

non-asymptotic confidence bands for 1σ and 2 σ

- The background-only hypothesis is rejected at an observed significance of 3.3σ (2.2σ expected)
- The observed value of μ with the 1σ confidence intervals is μ = $1.1^{+0.7}_{-0.6}$

OFF-SHELL SIGNAL STRENGTH FOR GGF AND EW

- 2D contours for the off-shell signal strength for ggF and EW

- The separate signal strength can be expressed in the couplings

$$\mu_{ggF} = \kappa_g^2 \cdot \kappa_V^2 \qquad \mu_{EW} = \kappa_V^4$$

- Where

$$\kappa_g = \frac{g_{Hgg}}{g_{Hgg}^{SM}} \qquad \kappa_V = \frac{g_{HVV}}{g_{HVV}^{SM}}$$

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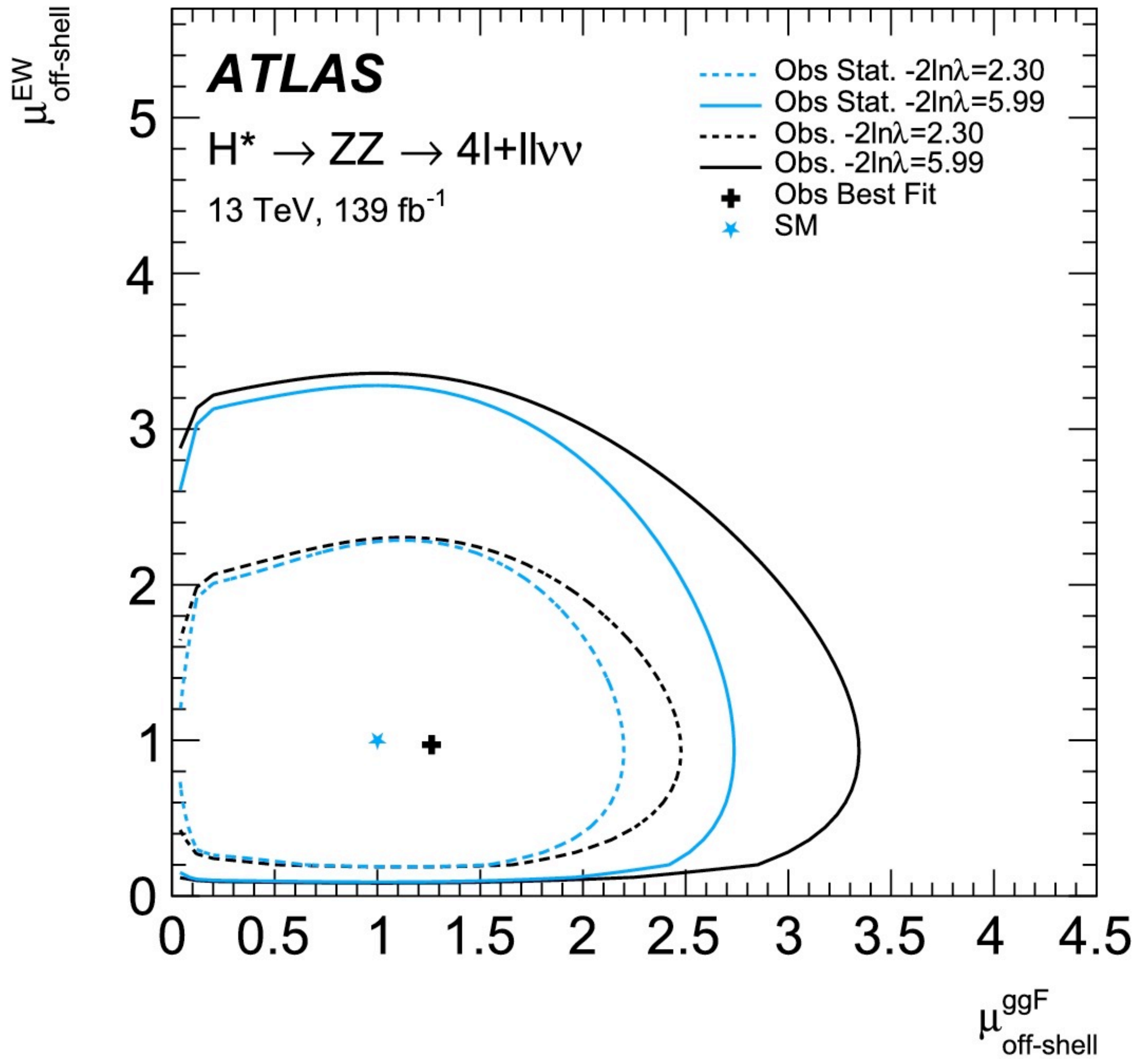

MEASUREMENT OF COUPLING TO THE HIGGS BOSONS

- Combine the off-shell with the 4l measurement of the on-shell signal strength (Eur. Phys. J. C 80 (2020) 957)
- Interpret the measurement as a measurement of the ratio of off-shell to on-shell Higgs couplings

$R_{gg} = \kappa^2_{g,off-shell} / \kappa^2_{g,on-shell}$

$R_{VV} = \kappa^2_{V,off-shell} / \kappa^2_{V,on-shell}$

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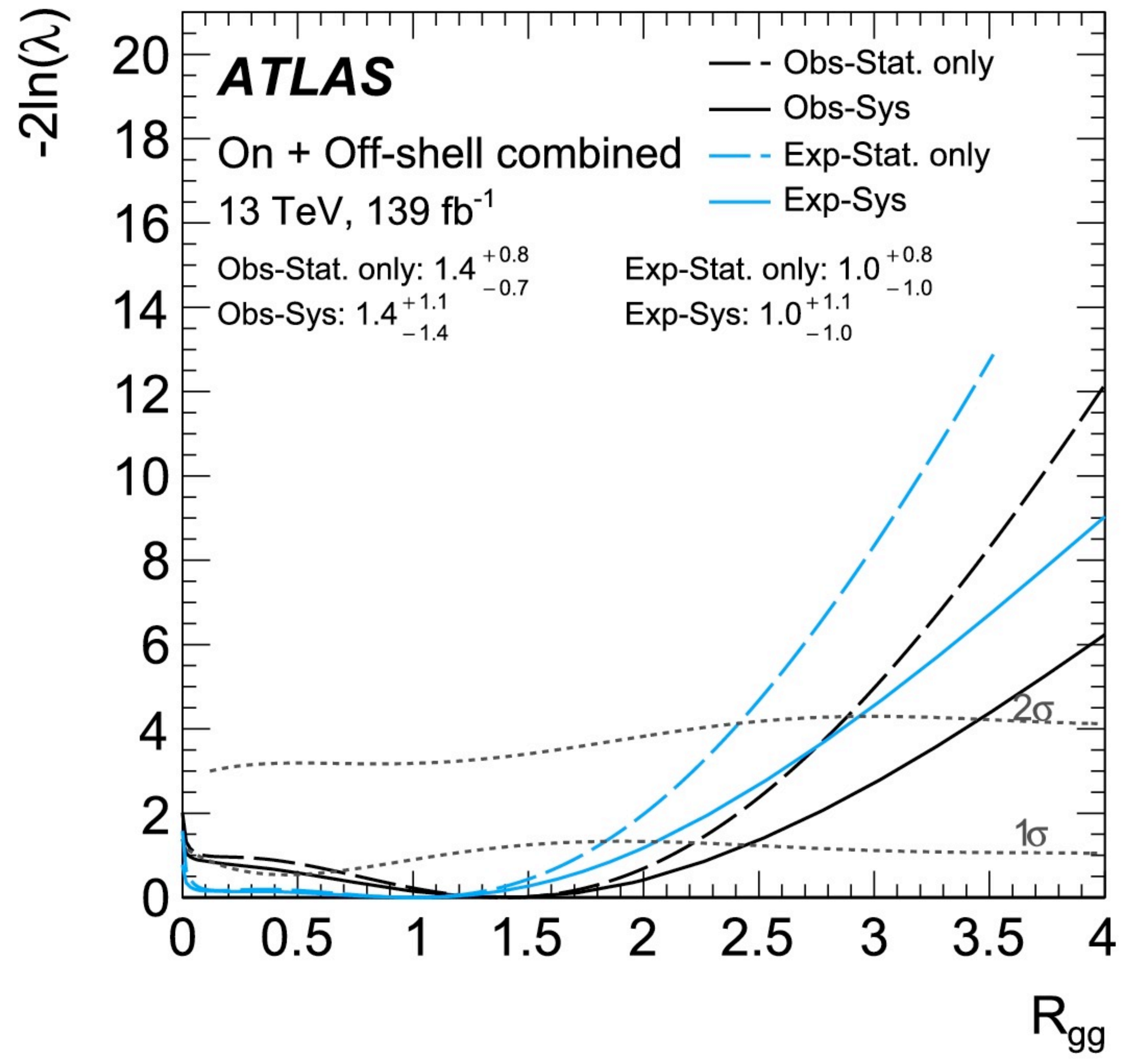

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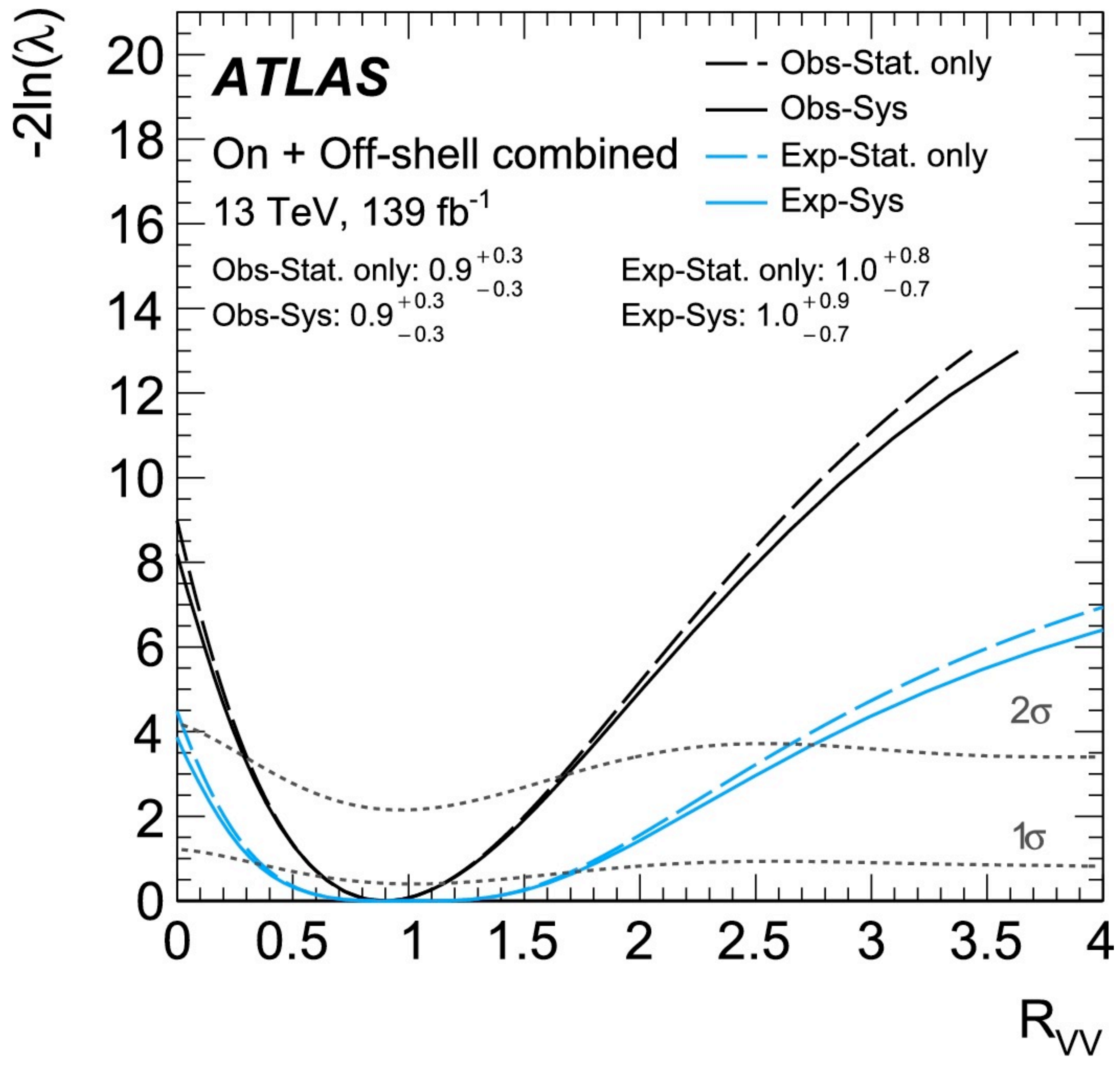

MEASUREMENT OF THE HIGGS BOSON TOTAL WIDTH

- Combine the off-shell analysis with the 4l measurement of the on-shell signal strength (Eur. Phys. J. C 80 (2020) 957) to find the Higgs boson total width
- The corresponding measured values are the following: $\Gamma_H/\Gamma_H^{SM} = 1.1^{+0.7}_{-0.6}$
- This corresponds to a measurement of the total Higgs boson width of

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

- Uncertainty is the 1σ uncertainty in the asymptotic approximation.

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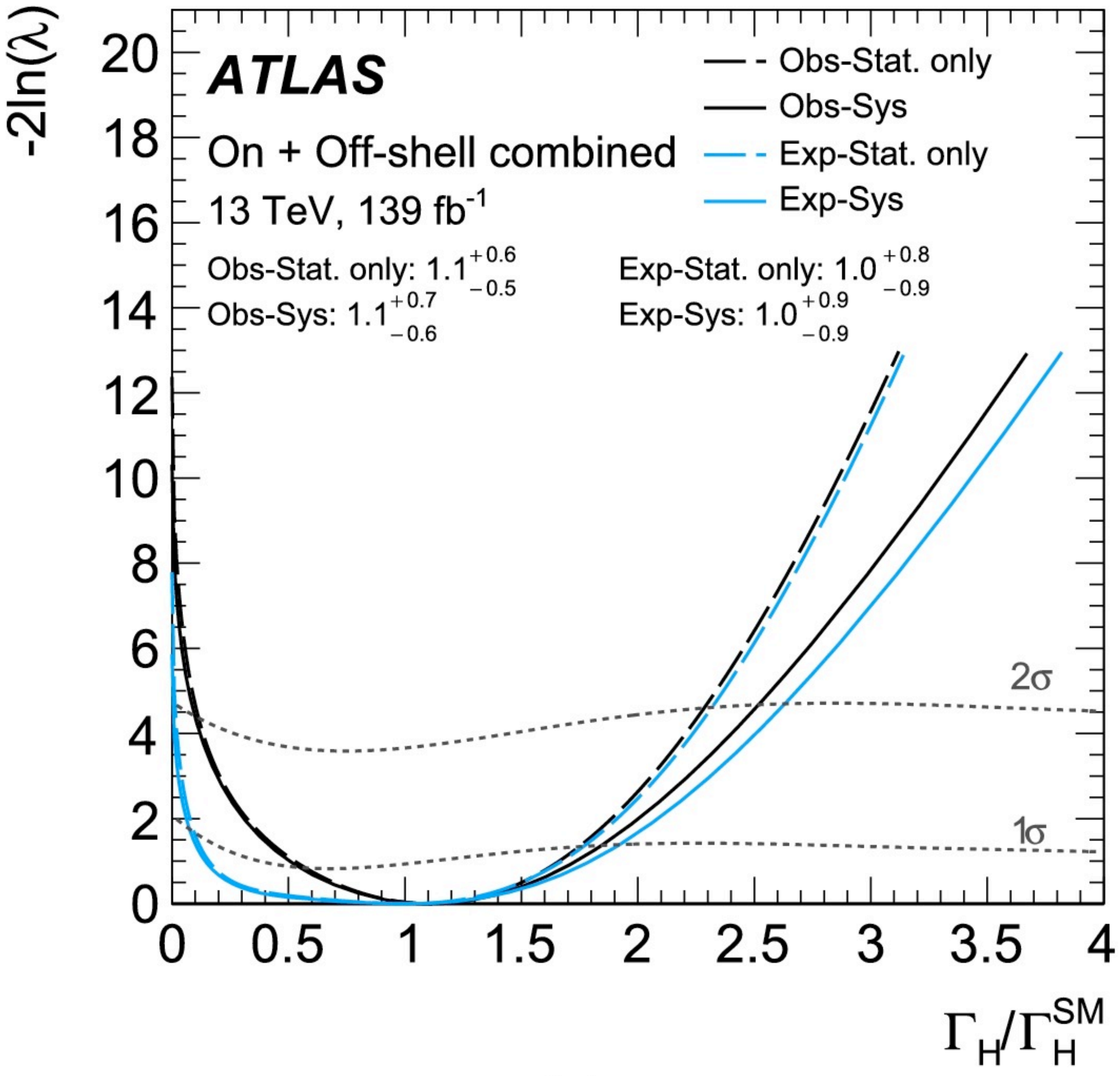


CONCLUSION

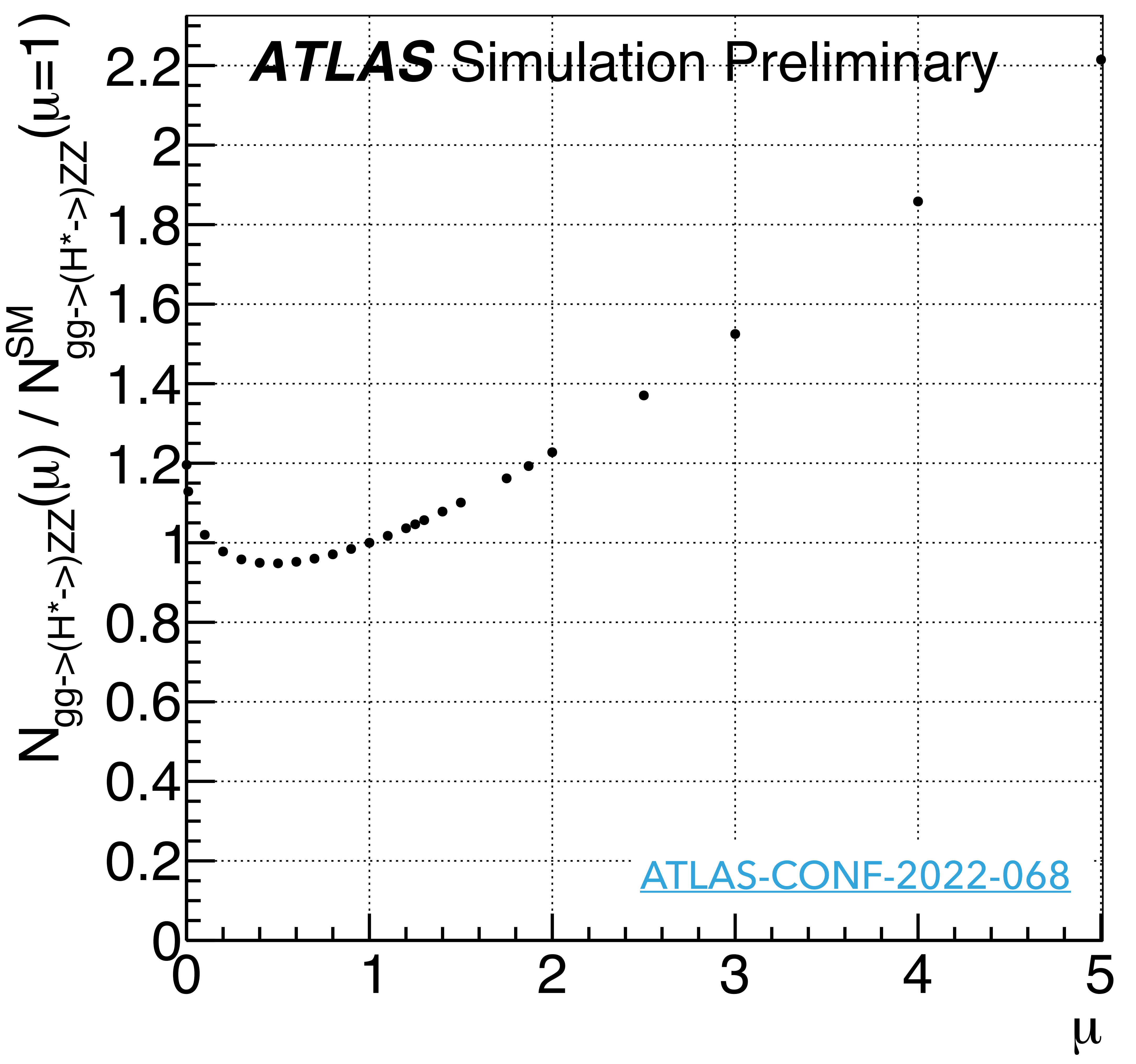
- Idea: measure the Higgs boson total width by exploiting the ratio between on-shell and off-shell production
- We measured the off-shell Higgs boson production in the ggF and EW production mades and in the ZZ to 4l and ZZ to 2l2v final states
- The background-only hypothesis is rejected at an observed significance of 3.3σ (2.2σ expected)
- We find a measured total Higgs width of

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

BACKUP

FEATURES OF THE OFF-SHELL PARAMETERISATION

- There is a parabolic dependence of the number of events on the off-shell signal strength μ
  - Due to the quadratic nature of the parameterisation
- Two interesting features:
  - Minimum occurs around μ=0.4
  - At μ =1.8, the yield is equal to the yield at μ =0
- This is a complication when determining the confidence interval on the measurement, as the confidence bands are non-asymptotic
- There is a dependence in the EW production, where the minimum is closer to 1



SYSTEMATIC UNCERTAINTIES

Table 5. The impact of most important systematic uncertainties on the observed upper value of $\mu_{\text{off-shell}}$ for which $-2\ln\lambda = 4$, obtained by the combined fit. This value corresponds to the two standard deviation upper limit of $\mu_{\text{off-shell}}$ with the asymptotic method. The first column denotes the systematic uncertainty that was excluded from the fit. The last row gives the nominal upper limit, where all uncertainties are included. The further the upper limit is deviating from the last row value, the more important that uncertainty is.

Systematic Uncertainty Fixed	$\mu_{\text{off-shell}}$ **value at which** $-2\ln\lambda(\mu_{\text{off-shell}}) = 4$
Parton shower uncertainty for $gg \to ZZ$ (normalisation)	2.26
Parton shower uncertainty for $gg \to ZZ$ (shape)	2.29
NLO EW uncertainty for $q\bar{q} \to ZZ$	2.27
NLO QCD uncertainty for $gg \to ZZ$	2.29
Parton shower uncertainty for $q\bar{q} \to ZZ$ (shape)	2.29
Jet energy scale and resolution uncertainty	2.26
None	2.30

YIELDS

Table 2. The observed and expected yields together with their uncertainties, for the ggF- and EW-enriched categories in the 4ℓ channel. The results are obtained after the simultaneous fit to both the 4ℓ and $2\ell 2\nu$ channels with $\mu_{\text{off-shell}} = 1$. The first row represents the inclusive *ZZ* process from *gg* production, including the signal, background, and interference components. The signal and background components are shown separately in rows 2–3: they do not add up to match the inclusive yield due to the presence of negative interference. The other backgrounds include contributions from $t\bar{t}V$ and *VVV* processes. The uncertainties in the expected number of events include the statistical and systematic uncertainties. The uncertainties in the $qq \rightarrow ZZ$ background are quoted as the sum in quadrature of all three jet multiplicity contributions for purposes of illustration.

Process	ggF SR	Mixed SR	EW SR
$gg \rightarrow (H^* \rightarrow) ZZ$	341 + 117	42.5 + 14.9	11.8 + 4.3
$gg \rightarrow H^* \rightarrow ZZ$	32.6 + 9.07	3.68 + 1.03	1.58 + 0.47
$gg \rightarrow ZZ$	345 + 119	43.0 + 15.2	11.9 + 4.4
$q\bar{q} \rightarrow (H^* \rightarrow) ZZ + 2j$	23.2 + 1.0	2.03 + 0.16	9.89 + 0.96
$q\bar{q} \rightarrow ZZ$	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