HIGGS 2022 PISA, 9TH OF NOVEMBER

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

Michiel Veen
on behalf of the ATLAS Collaboration

MEASURING THE HIGGS BOSON WIDTH

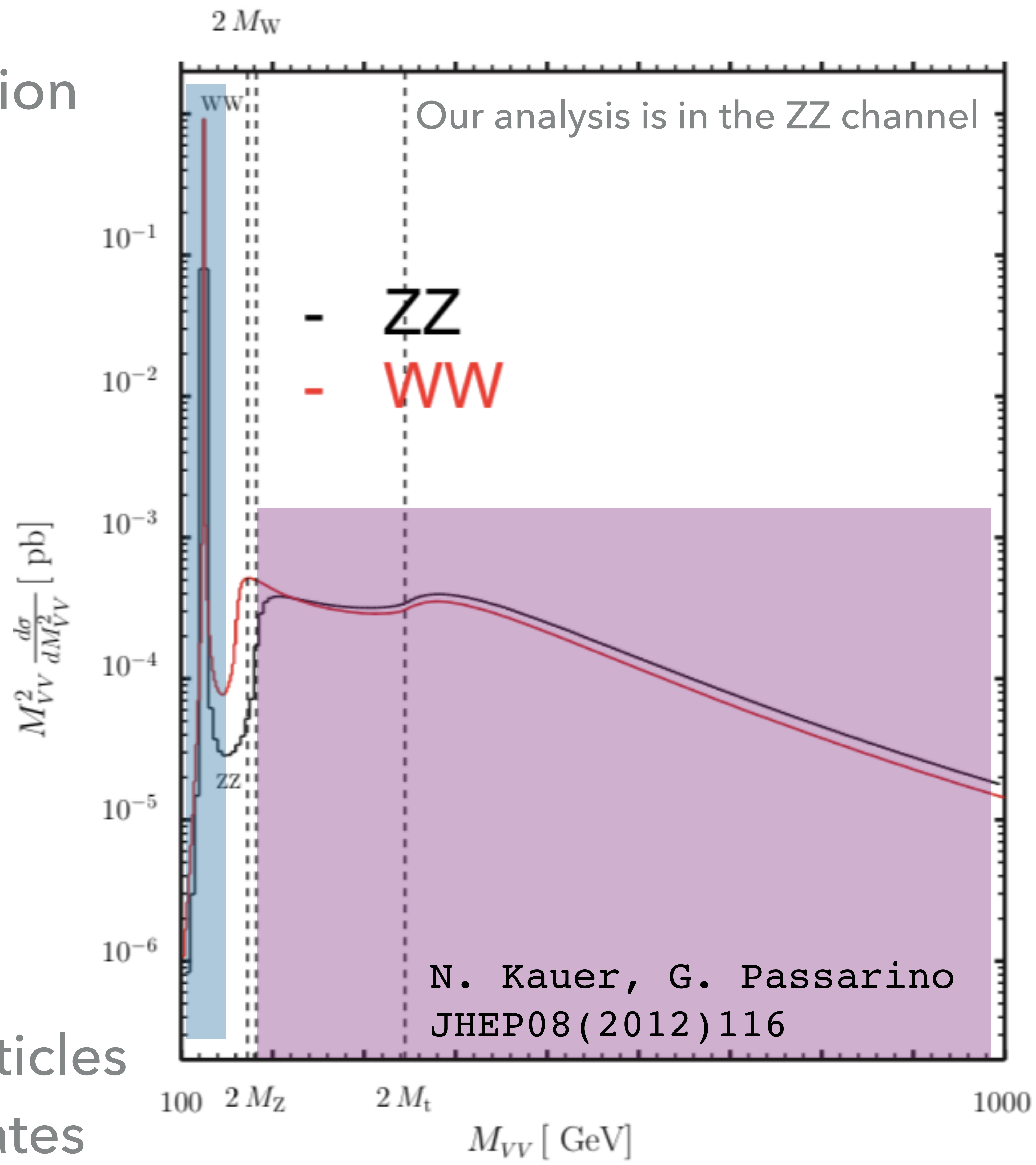
- Theory prediction: 4.1 MeV → Too small for detector resolution of the LHC experiments
- Instead, use the ratio of on-shell and off-shell Higgs production

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

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

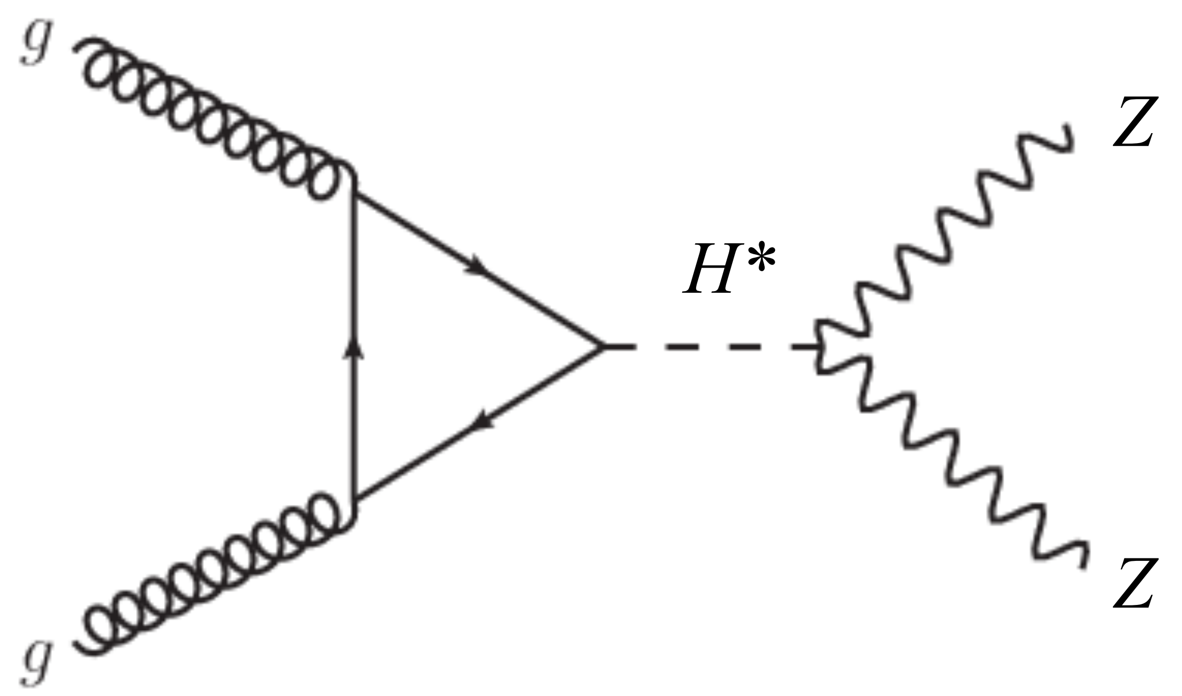
$$\frac{\sigma_{offshell}}{\sigma_{onshell}} \propto \Gamma_H$$

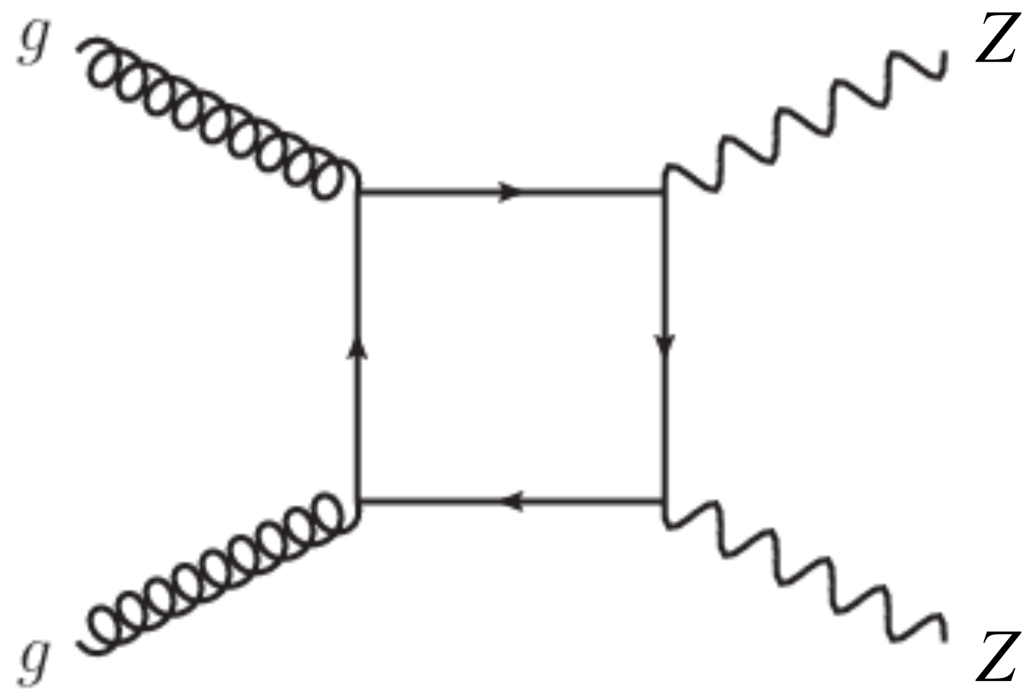
- Exploits enhanced off-shell production, unique to H → VV
- This talk focusses on the off-shell measurement in the ZZ channel
- We assume no significant contributions from new heavy particles below ~2 TeV, as confirmed by searches in the same final states



ZZ INTERFERENCE FOR GGF

- Because the Higgs signal and gg → ZZ background cannot be distinguished, there is an interference effect





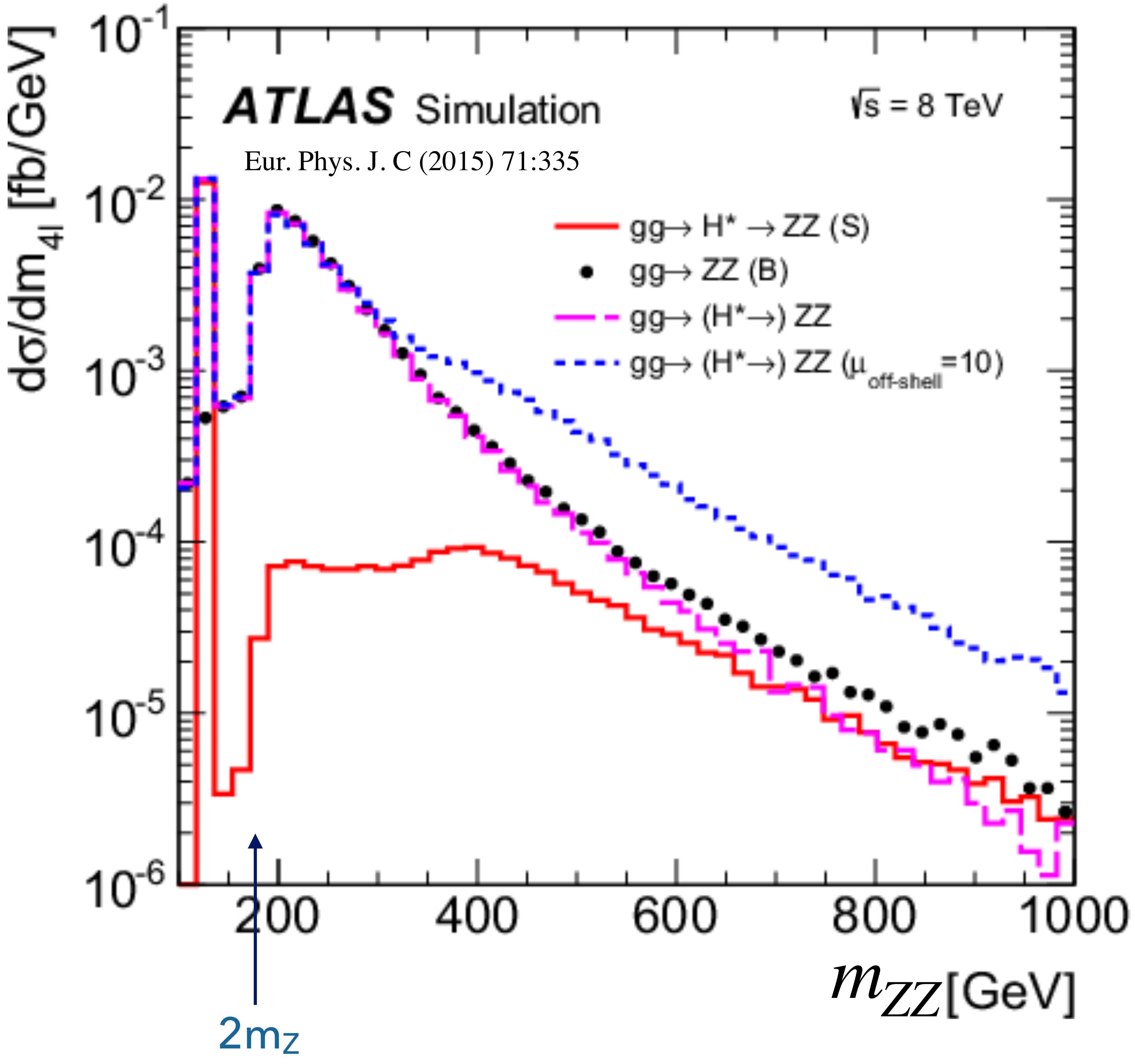
- At the SM width, we measure a deficit in gg → ZZ events, the size of the deficit depends on the off-shell signal strength (μ).

- Total number of events is given by:

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

- Interference is parametrised as:

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



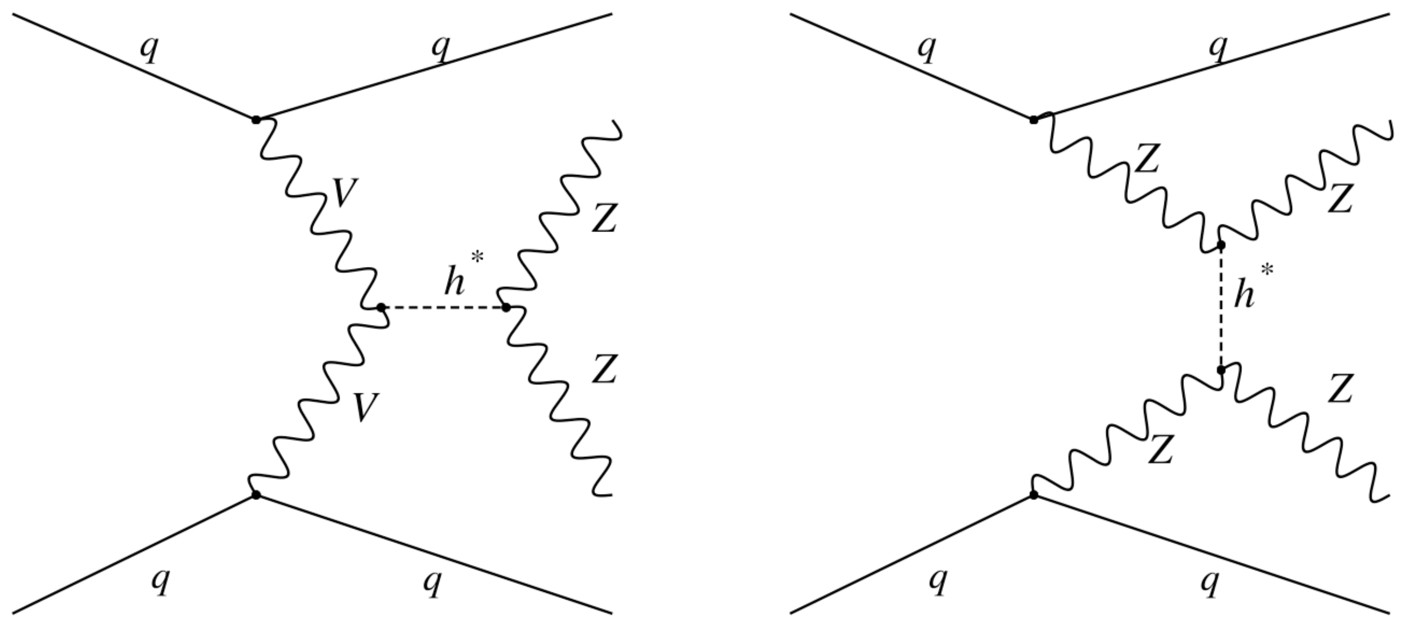
ZZ INTERFERENCE FOR VBF

- There is a similar interference effect in the EW production (mainly VBF, with some VH)

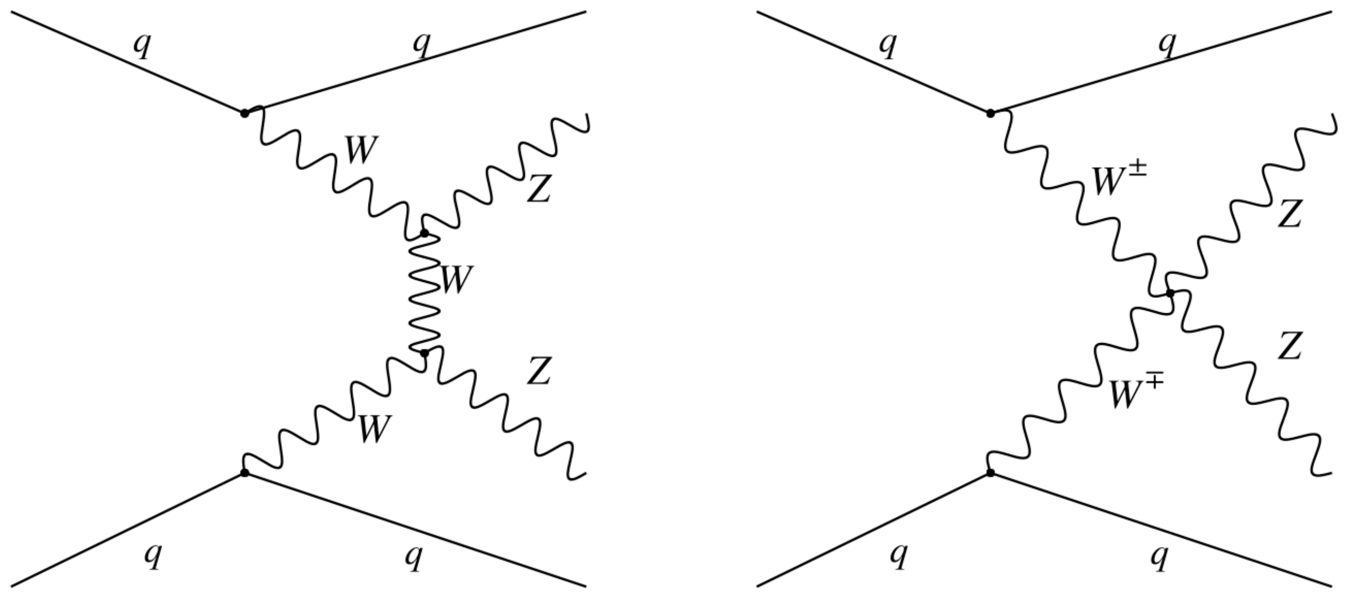
- Signal consists of a s-channel and t-channel
- Interference with vector boson scattering processes
- A description in terms of a single signal component as done for ggF production is not possible in the VBF case because of the t-channel

- Instead, the parametrisation is done using three simulation samples: the background-only (μ=0), the SM sample (μ=1) and a sample of the SBI with μ=10

S:

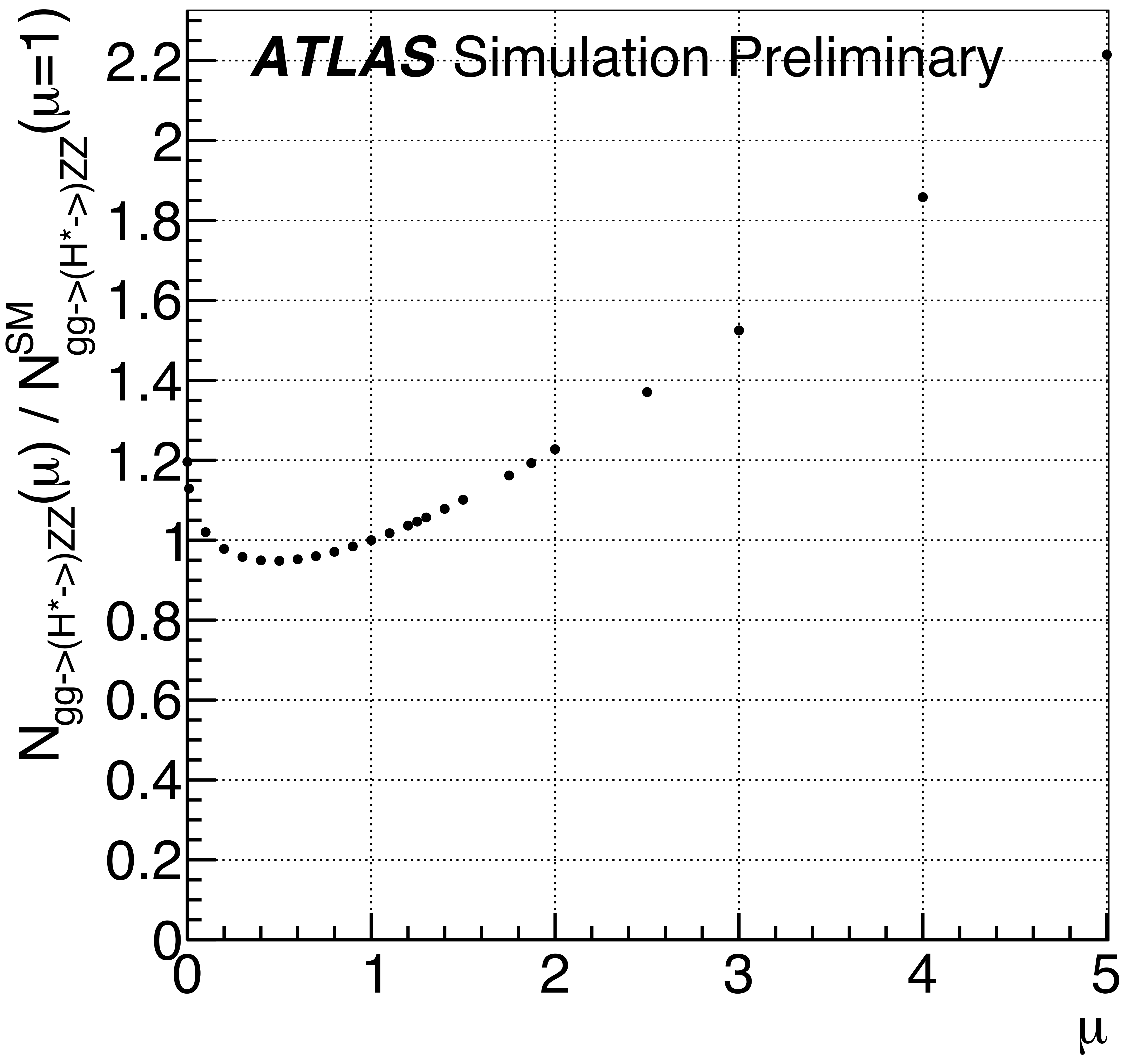


B:



FEATURES OF THE OFF-SHELL PARAMETERISATION

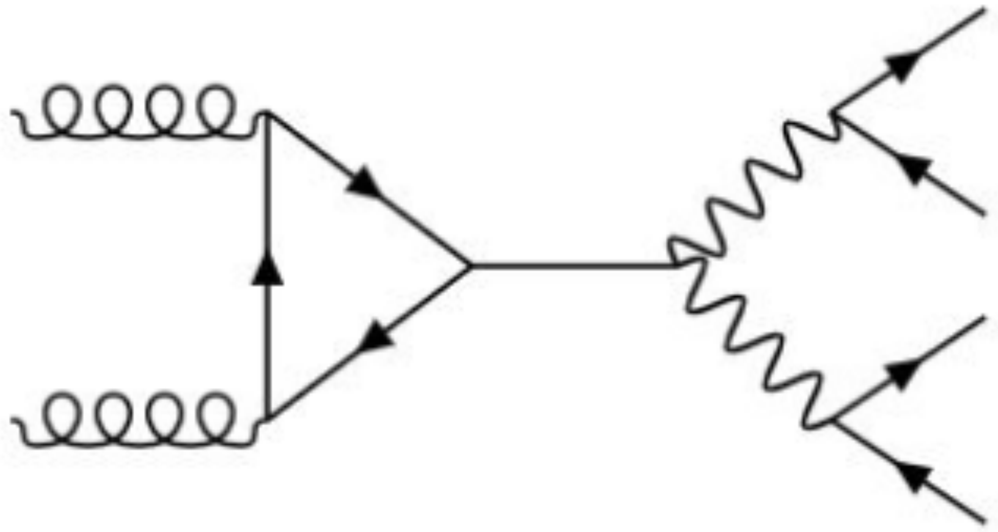
- There is a parabolic dependence of the number of events on the off-shell signal strength μ
  - Due to the quadratic nature of the parameterisation
- Two interesting features:
  - Minimum occurs around μ=0.4
  - At μ =1.8, the yield is equal to the yield at μ =0
- This is a complication when determining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



SIGNAL REGIONS

- There are three signal regions in the analysis, targeting both ggF and VBF production

ggF Signal region

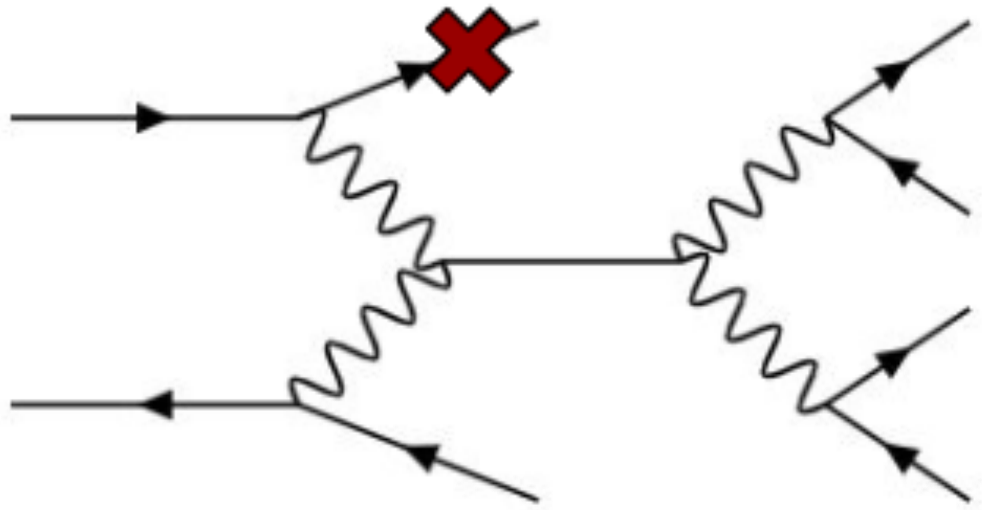


$n_{\text{jets}} = 0$

$n_{\text{jets}} = 1$ and $\eta_j < 2.2$

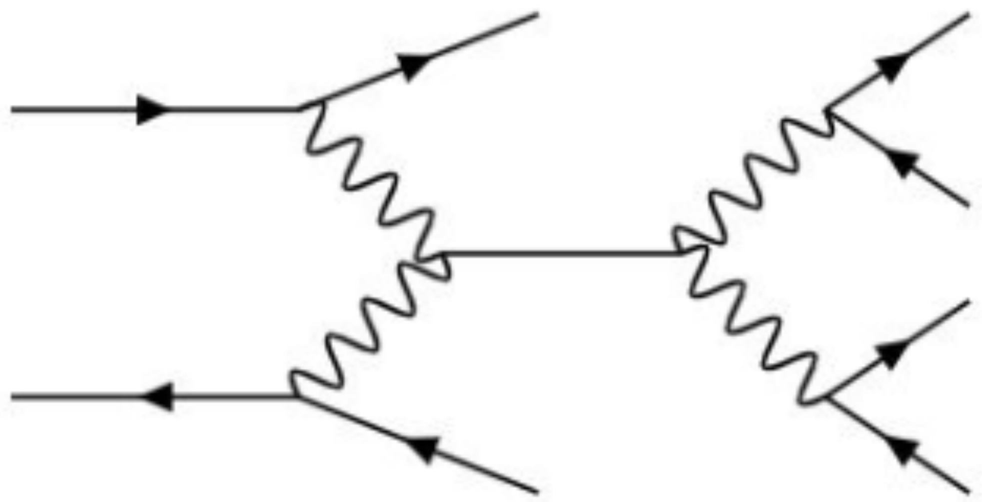
$n_{\text{jets}} \geq 2$ and $\Delta\eta_{jj} < 4.0$

1 jet mixed signal region



$n_{\text{jets}} = 1$ and $\eta_j \geq 2.2$

EW signal region



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

Yields in 4l final state

Process	ggF	Mixed	EW
$gg \to (H^* \to)ZZ$	341 ± 162	42.5 ± 20.3	11.8 ± 5.8
$gg \to H^* \to ZZ$	32.6 ± 9.06	3.68 ± 1.03	1.58 ± 0.47
$gg \to ZZ$	345 ± 117	43.0 ± 14.9	11.9 ± 4.3
$qq \to (H^* \to)ZZ + 2j$	23.2 ± 6.4	2.03 ± 1.09	9.89 ± 3.32

OFF-SHELL ANALYSIS FINAL STATES

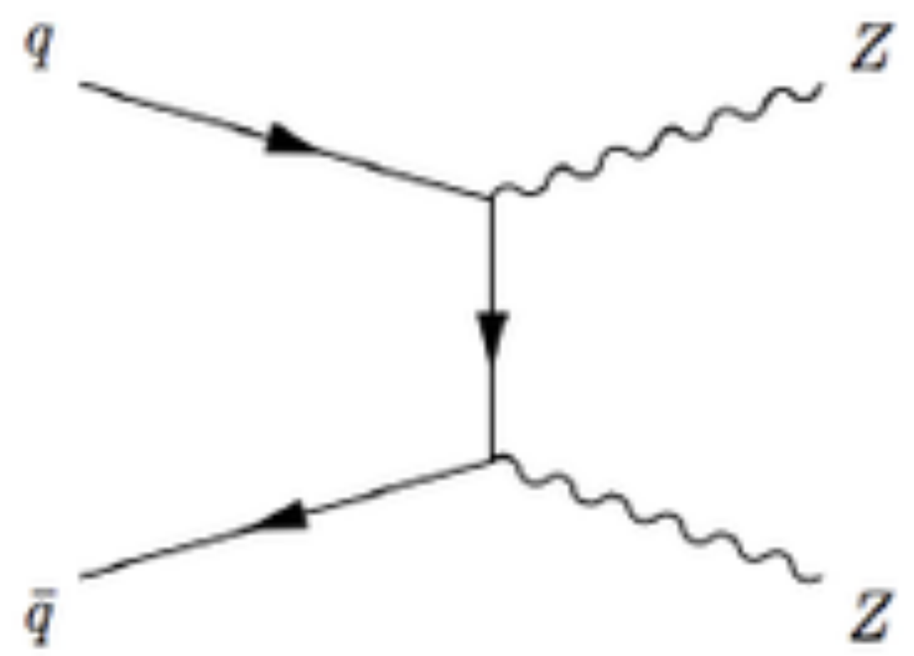
- The measurement is performed in two complementary channels
  - ZZ → 4l
  - Advantage:
    - Clean signal
    - Fully reconstructible
  - Observable:
    - Neural net discriminants
  - ZZ → 2l2v
  - Advantage:
    - Six times higher branching ratio
  - Observable:
    - Transverse ZZ mass

$$m_{\mathrm{T}}^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_{\mathrm{T}}^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_{\mathrm{T}}^{\mathrm{miss}}\right)^2}\,\right]^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2},$$

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

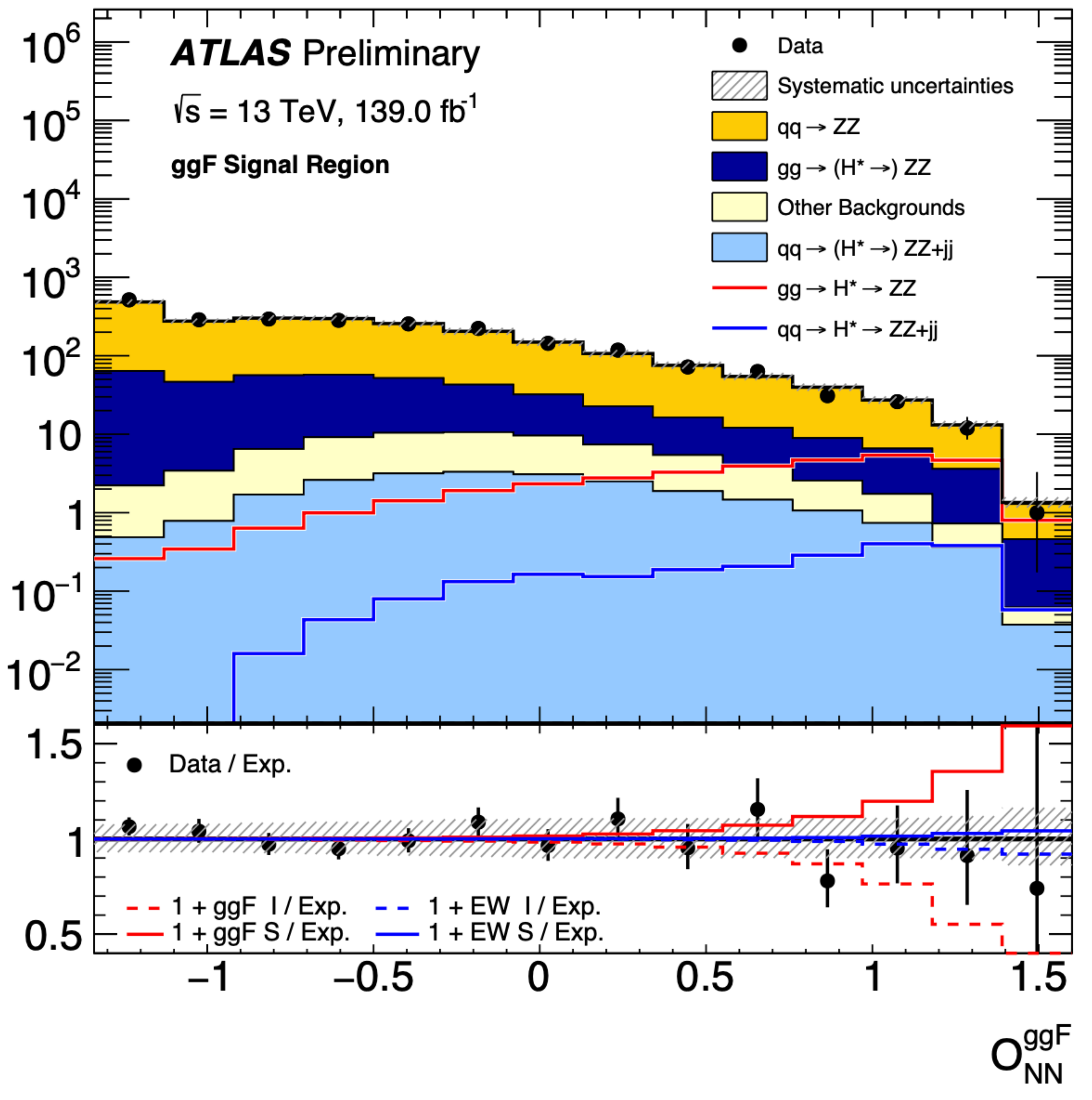
- To maximise the signal sensitivity, multi-class dense neural networks are employed to enhance the contribution of events with off-shell Higgs boson production

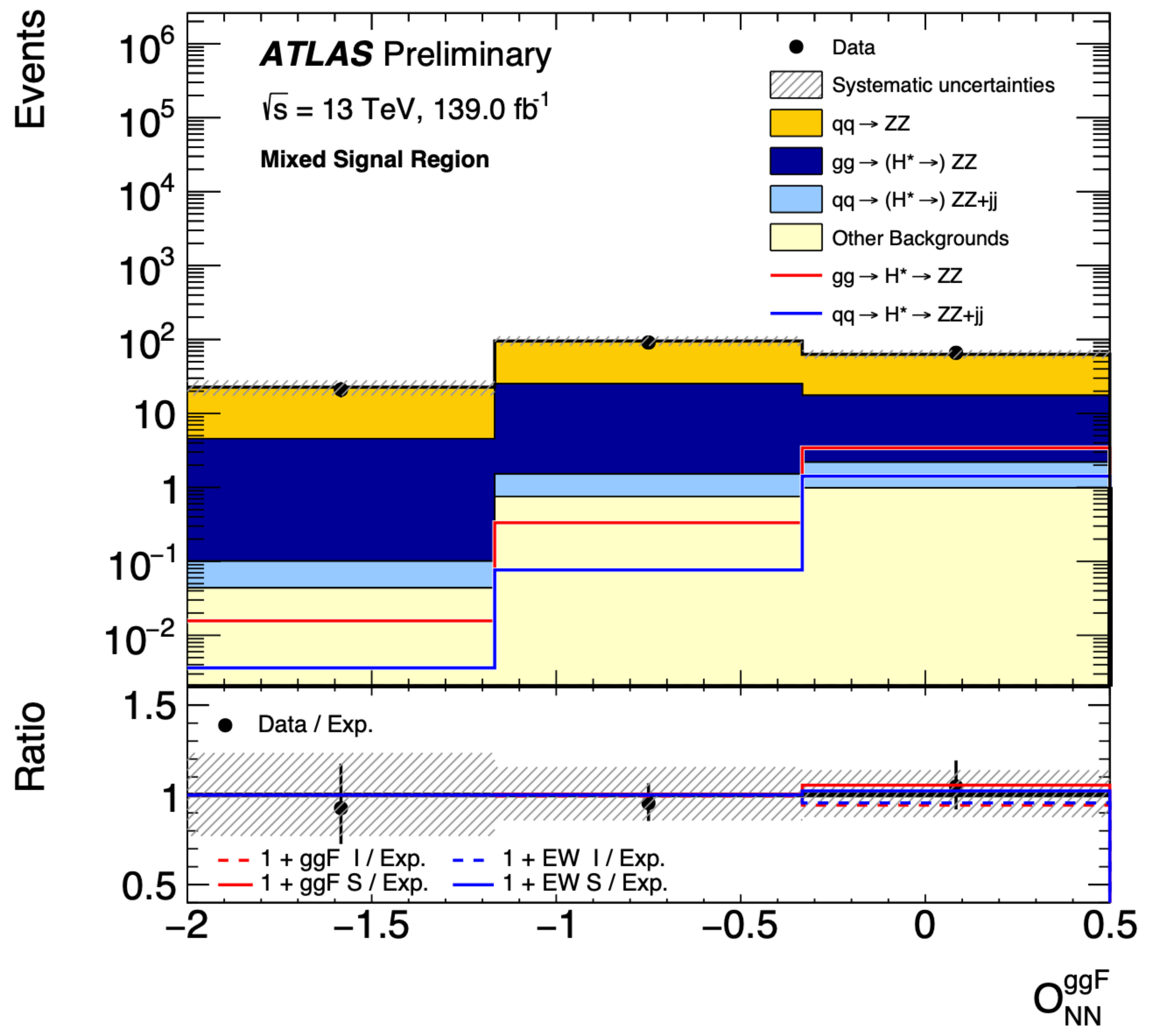
- Different observables are used in different jet categories

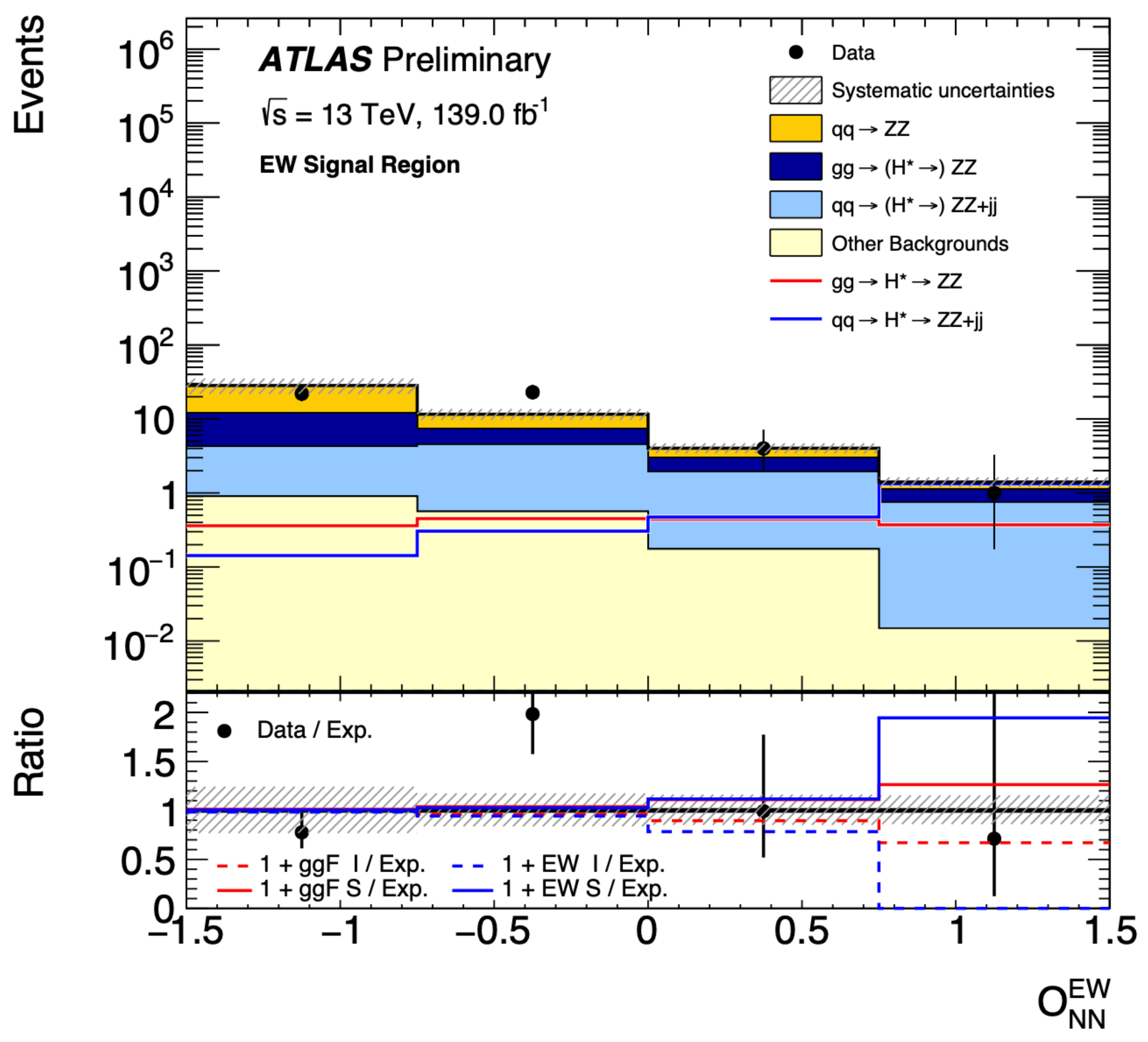
- Observable defined using the probability of an event classified as off-shell Higgs signal, interfering background or non-interfering background

$$\mathrm{NN}_{\mathrm{H+0jet}} = \log_{10}\left(\frac{P_{\mathrm{ggHZZ}}}{P_{\mathrm{ggZZ}} + P_{q\bar{q}}}\right)$$

$$\mathrm{NN}_{\mathrm{H+2jet}} = \log_{10}\left(\frac{P_{\mathrm{VBFH}}}{P_{q\bar{q}\mathrm{EW}} + P_{q\bar{q}\mathrm{QCD}}}\right)$$

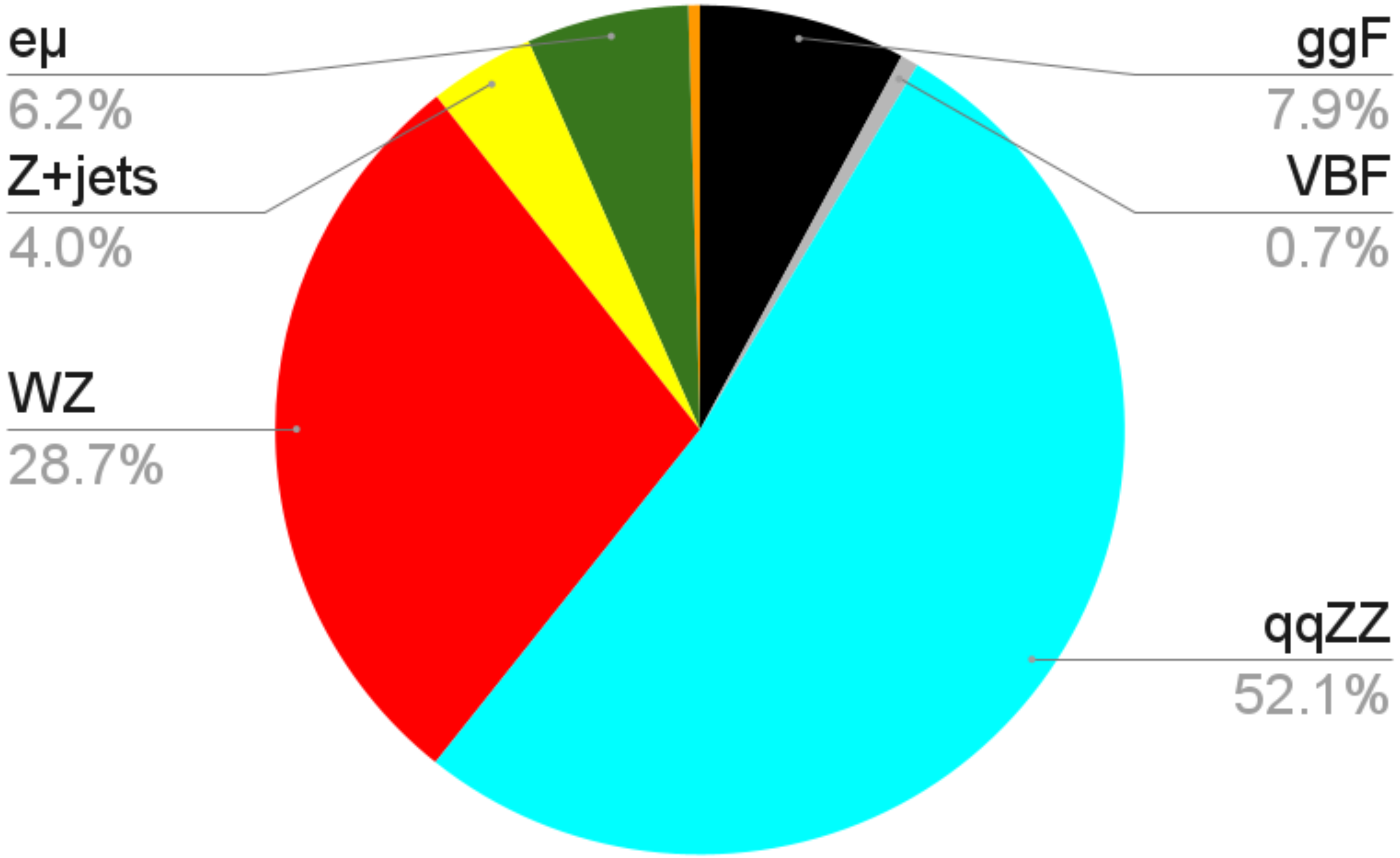






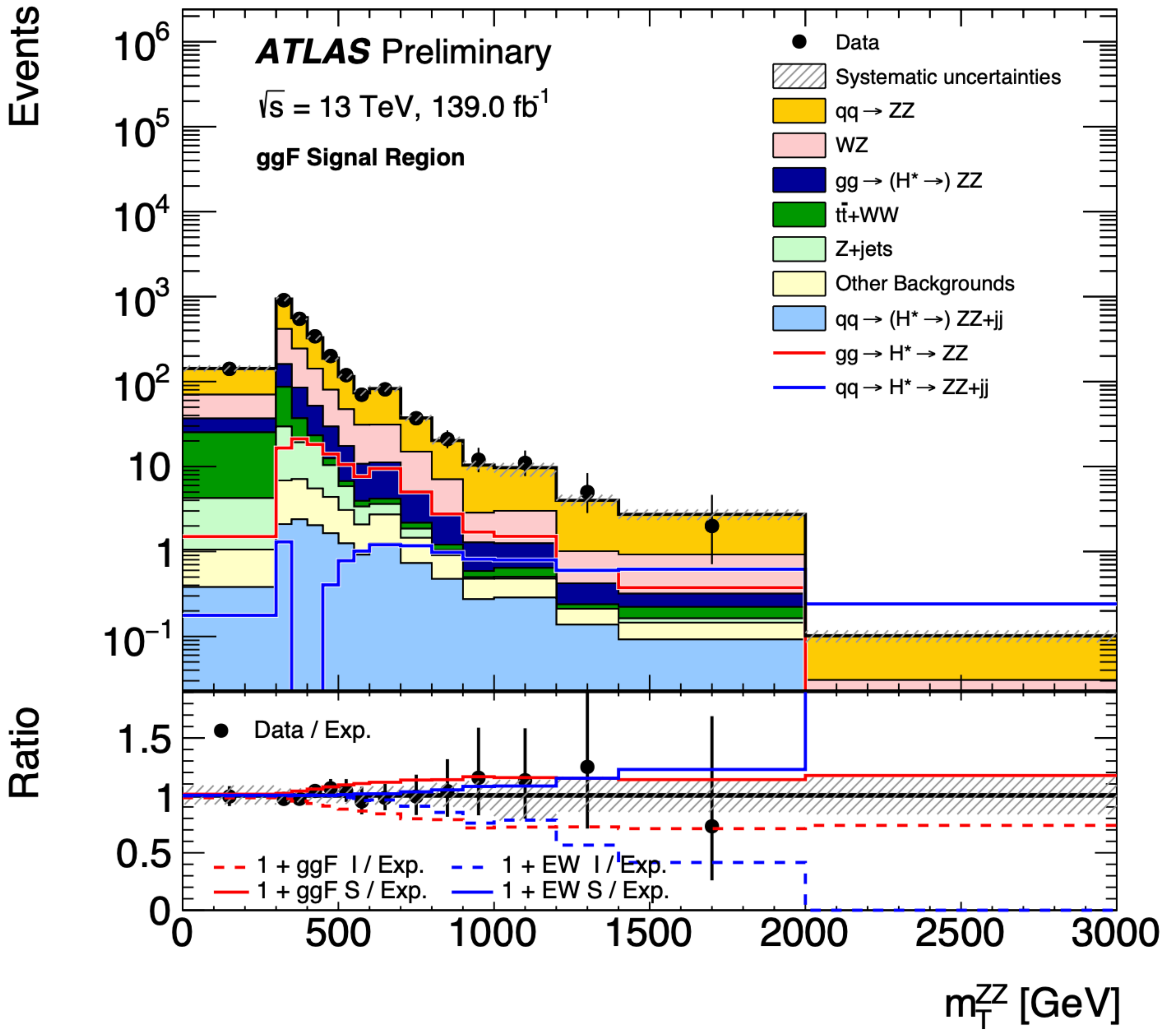
2L2V CHANNEL BACKGROUNDS

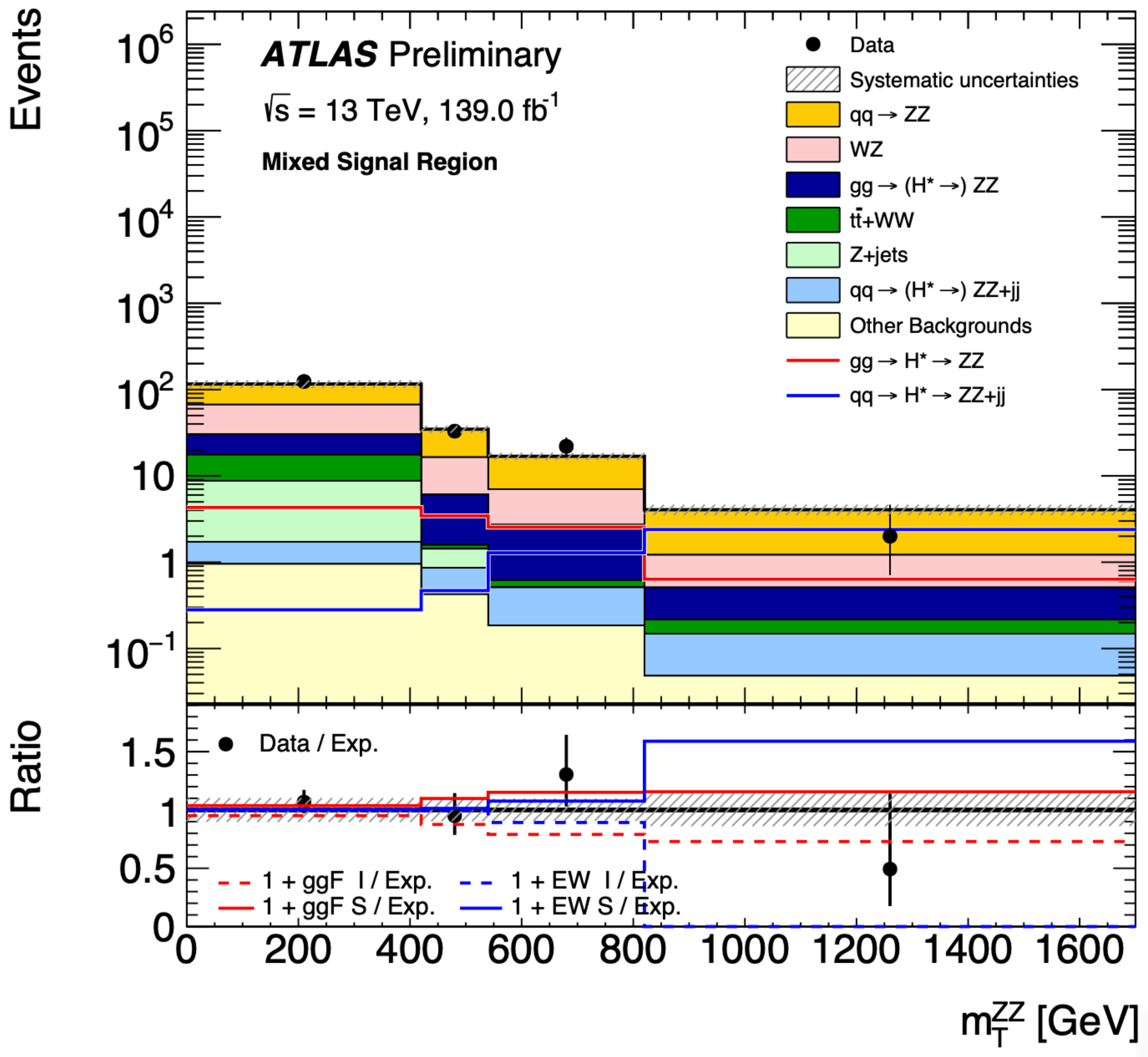
- The 2l2v channel has more backgrounds in addition to qq → ZZ, as WZ, WW/top and Z+jets processes are relevant
- Each background has an associated control region, and a floating normalisation in the fit
  - Like the qq →ZZ control region, the WZ control region is split by jet multiplicity to reflect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

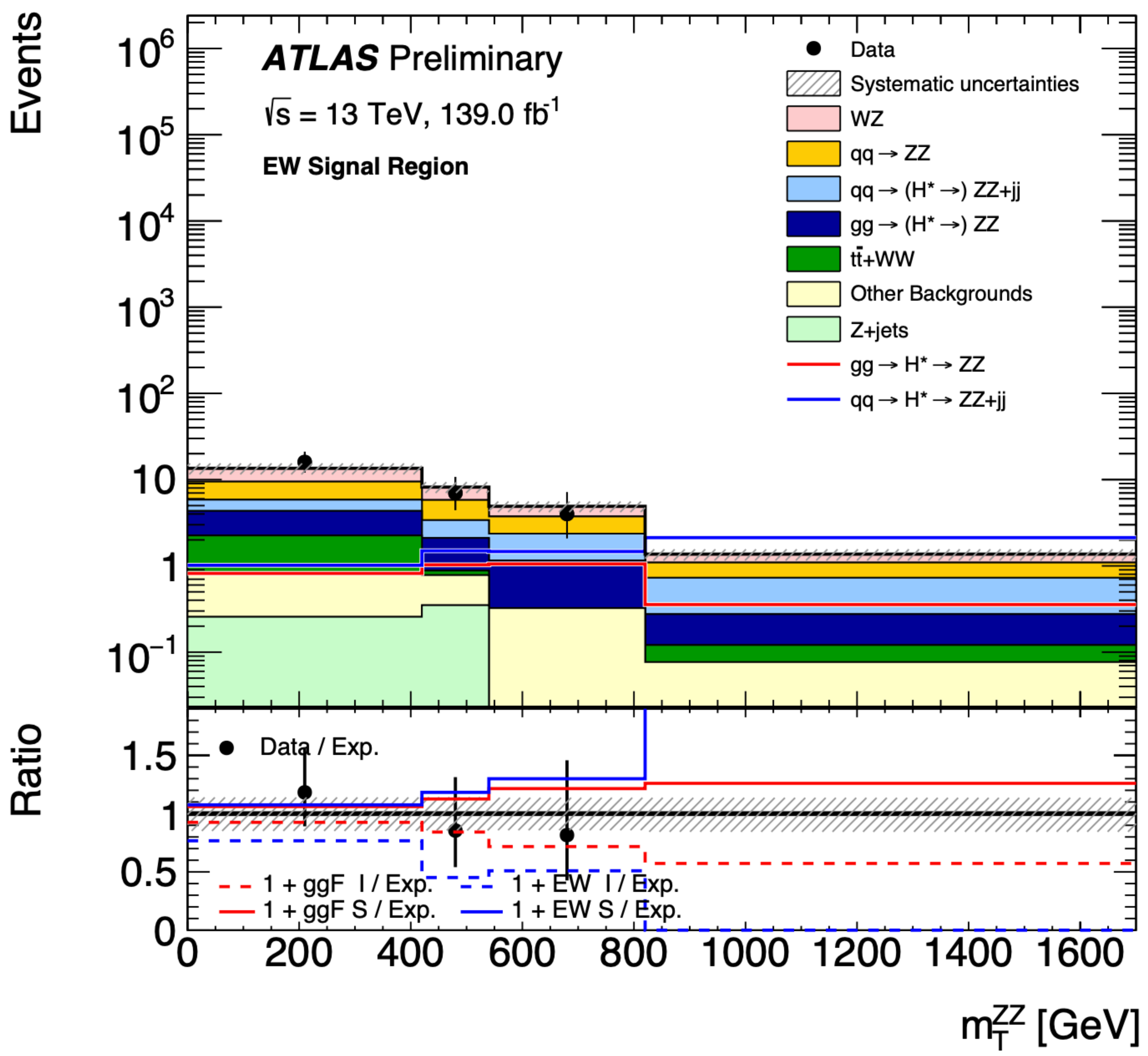


2L2V SIGNAL REGIONS

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







MAIN UNCERTAINTIES IN THE ANALYSIS

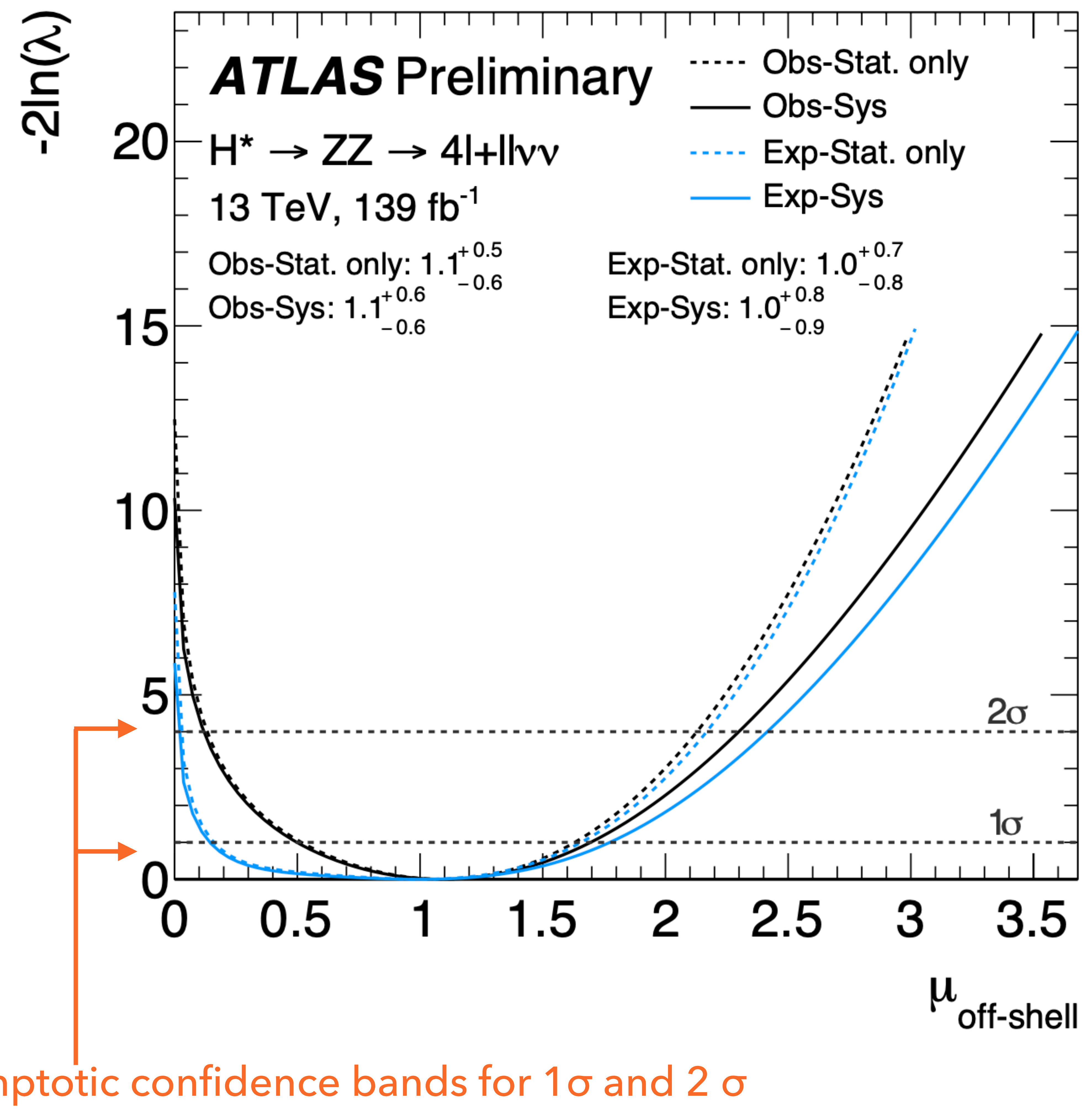
- For the ggF and VBF signal, and for the qqZZ background:
  - Uncertainties on the parton shower (PS)
  - Higher order QCD (HOQCD) uncertainties, correlated between S, B, and SBI for ggF and between B, SBI and SBI10 for VBF
- For qqZZ, in addition:
  - Uncertainties on the NLO EW corrections
- Leading systematics are the PS and HOQCD uncertainties for ggF and qqZZ and the NLO EW uncertainties for qqZZ
- Standard experimental uncertainties are also taken into account
  - Mainly jet uncertainties are important, because of the jet binning and the MET in the 2l2v channel
- In the combined 4l+2l2v fit, all shared uncertainties are correlated between the channels

COMBINED RESULTS

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

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

- The background-only hypothesis is rejected at an observed significance of 3.2σ (2.4σ expected)
- The observed value of μ with the 1σ confidence intervals is $\mu = 1.09^{+0.60}_{-0.59}$



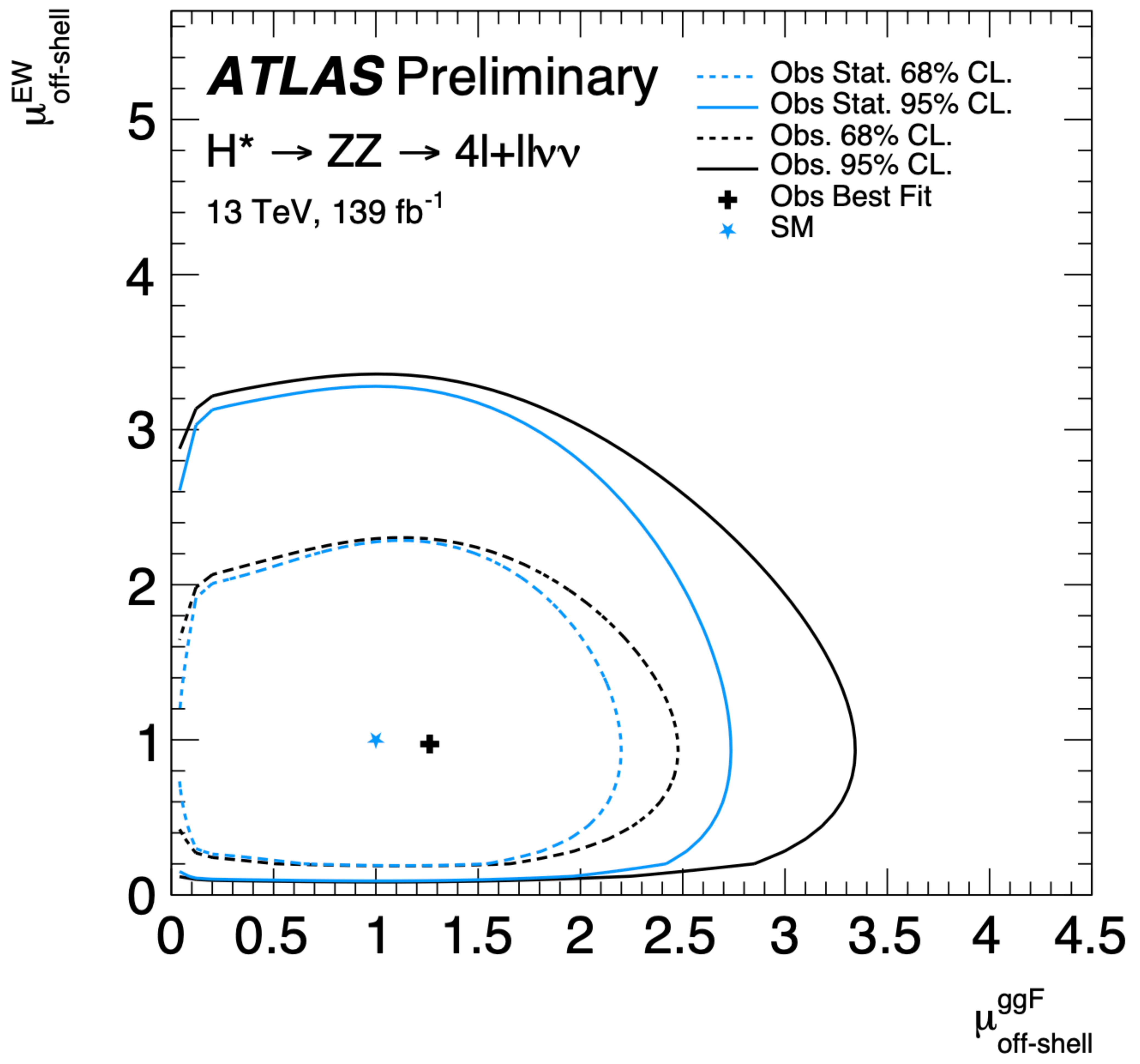
OFF-SHELL SIGNAL STRENGTH FOR GGF AND VBF

- 2D contours for the off-shell signal strength for ggF and VBF
- The separate signal strength can be expressed in the couplings

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

- Where

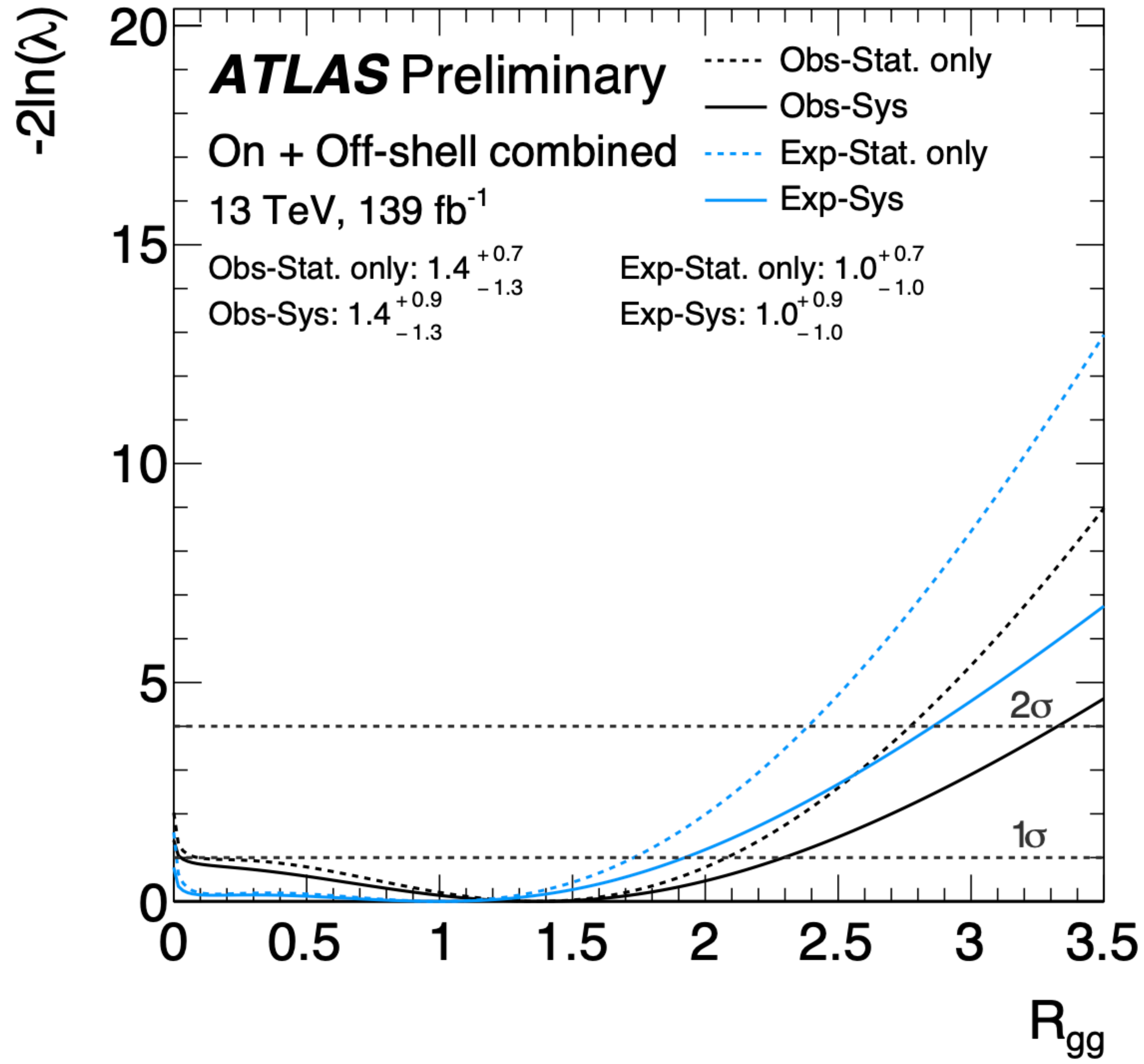
$$\kappa_g = \frac{g_{Hgg}}{g_{Hgg}^{SM}} \qquad \kappa_V = \frac{g_{HVV}}{g_{HVV}^{SM}}$$



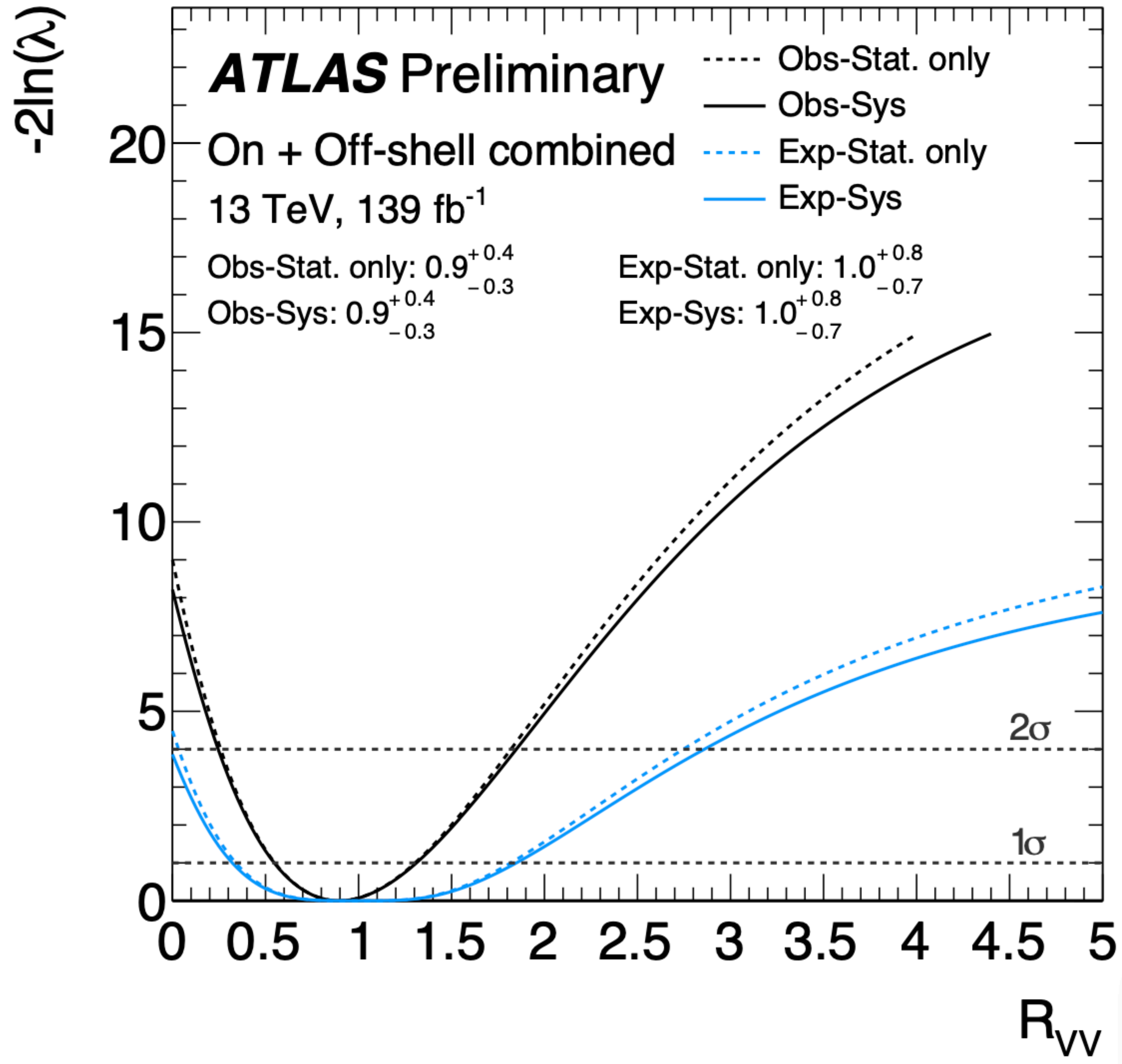
MEASUREMENT OF COUPLING TO THE HIGGS BOSONS

- Combine the off-shell analysis with the 4l measurement of the on-shell signal strength (HIGG-2018-28)
- Interpret the measurement as a measurement of the ratio of off-shell to on-shell Higgs couplings

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



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

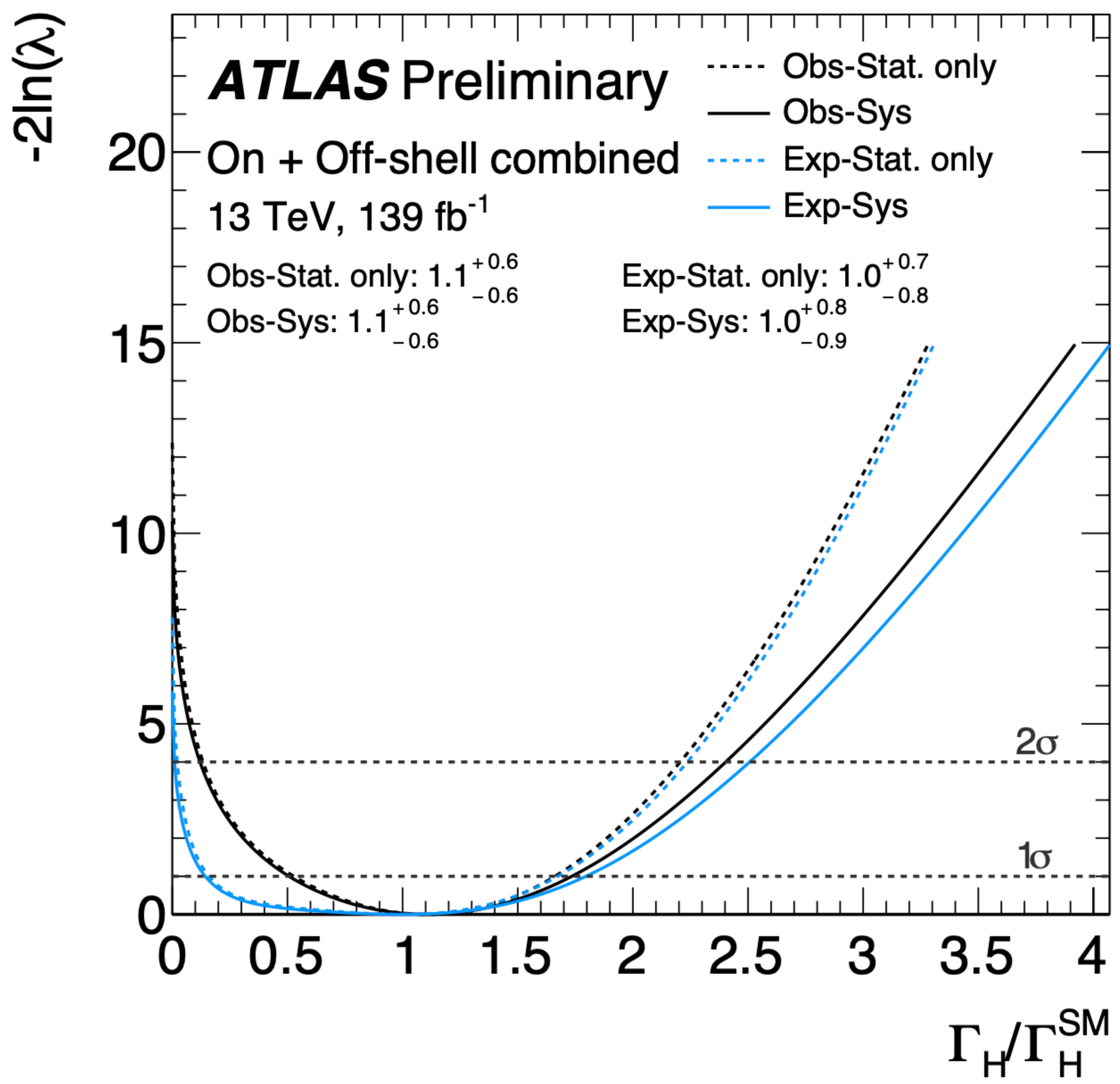


MEASUREMENT OF THE HIGGS BOSON TOTAL WIDTH

- Combine the off-shell analysis with the 4l measurement of the on-shell signal strength (HIGG-2018-28) to find the Higgs boson total width
- The corresponding measured values are the following: $\Gamma_H/\Gamma_H^{SM} = 1.11^{+0.63}_{-0.60}$
- This corresponds to a measurement of the total Higgs boson width of

$$\Gamma_H = 4.6^{+2.6}_{-2.5}\ \text{MeV}$$

- Uncertainty is the 1σ uncertainty in the asymptotic approximation.
- Result are preliminary as they use the asymptotic confidence bands, but are not expected change significantly



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 ZZ to 4l and ZZ to 2l2v final states

- We find a measured total Higgs width of

$$\Gamma_H = 4.6^{+2.6}_{-2.5}\ \text{MeV}$$