How to measure the Higgs Width

Evidence of off-shell Higgs boson production from *ZZ* leptonic decay channels and constraints on its total width with the ATLAS detector

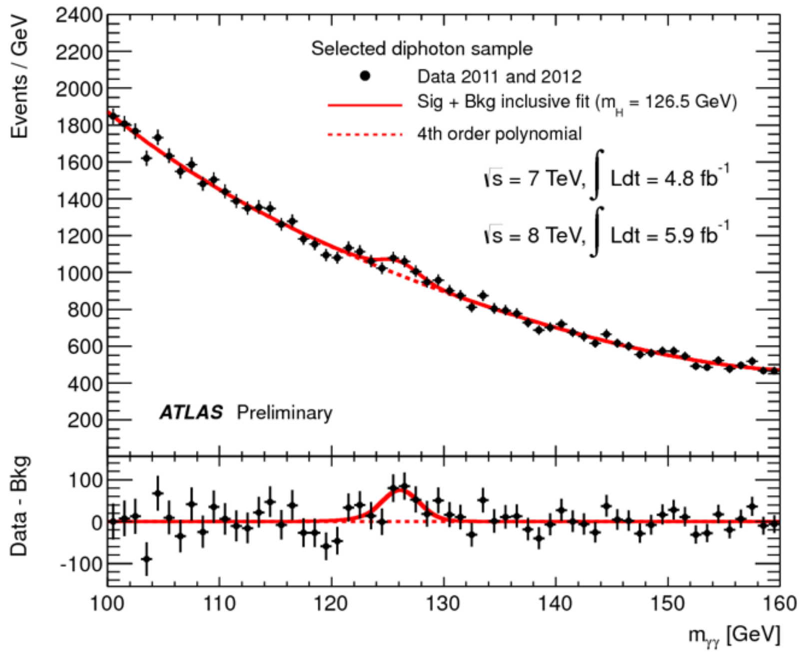
Simon Grewe

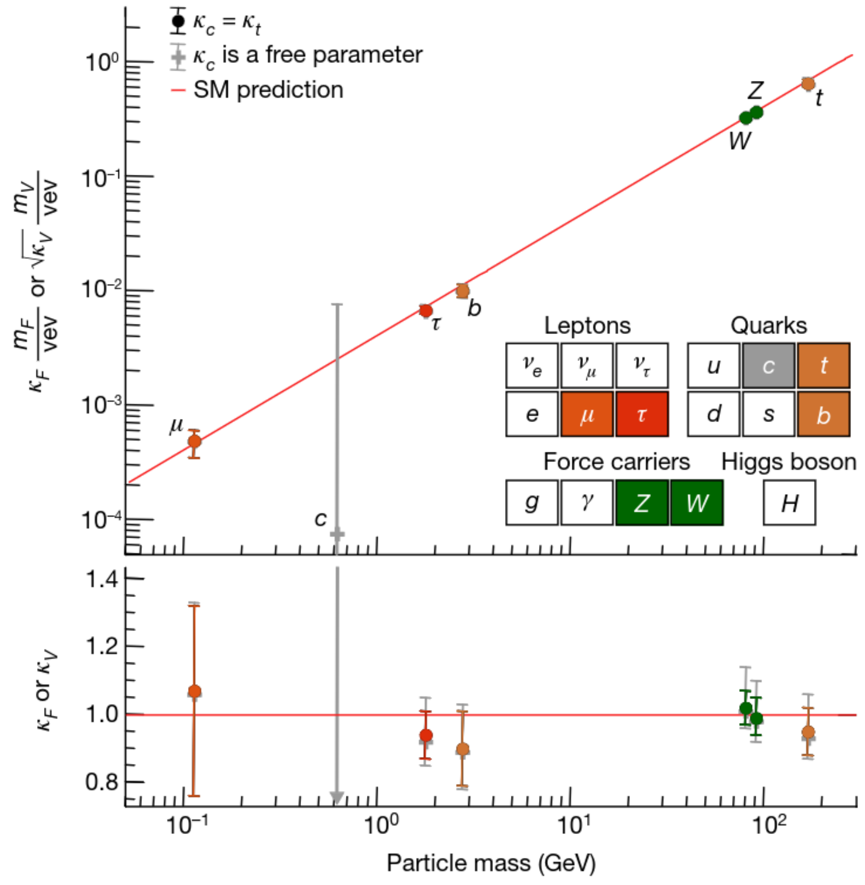
MPP LHC Seminar 2023

Based on :[2304.01532]
Talk inspired by: LHC talk by Rafael Coelho Lopes De Sa [link]

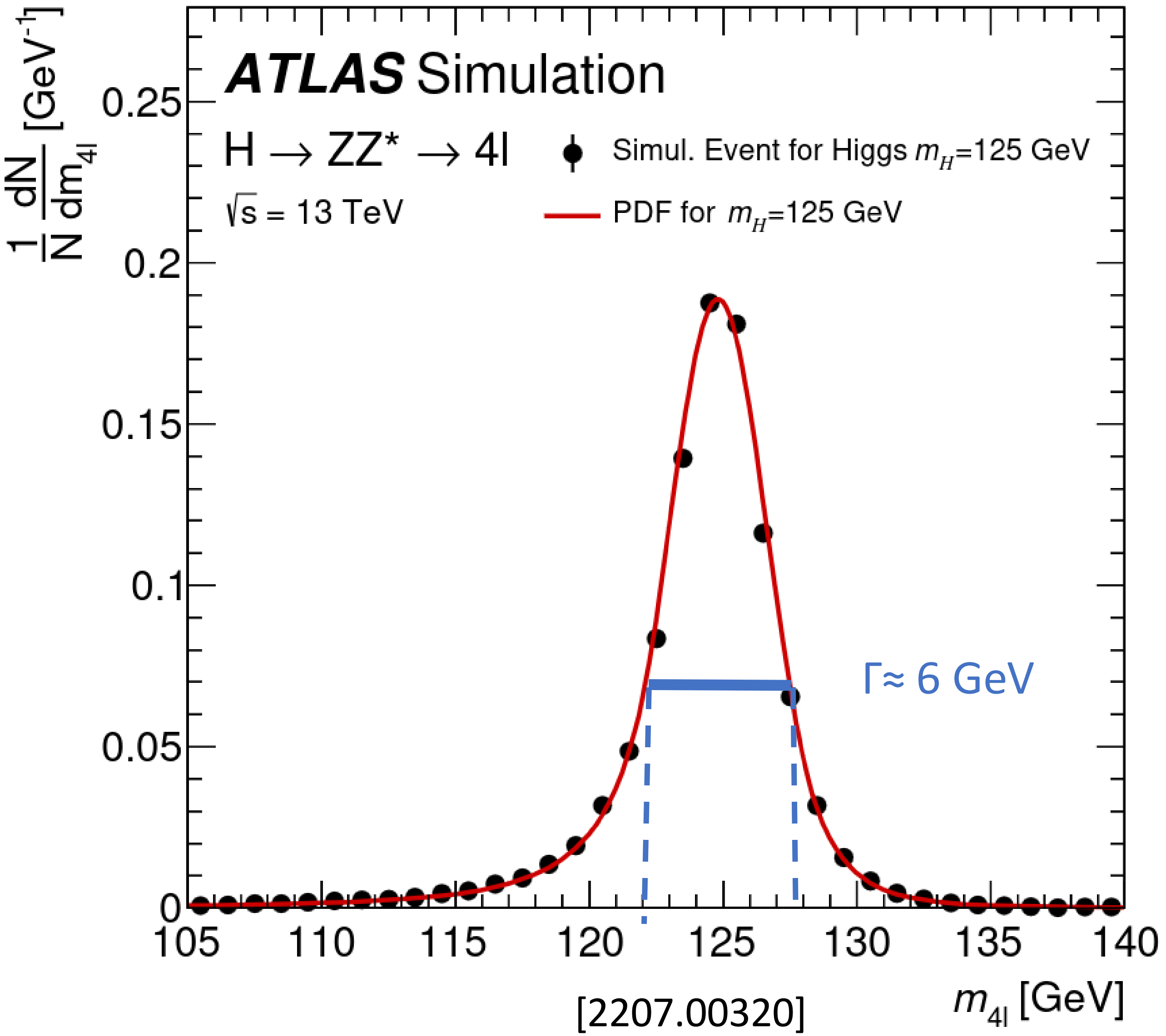
Higgs Boson

- Discovered in 2012 by the ATLAS and CMS collaborations
- "Newest" Particle in the Standard model
- Study its property
  - Mass ✓
  - Spin & CP ✓
  - Couplings ✓
  - Width ?





How to measure the Higgs width ?



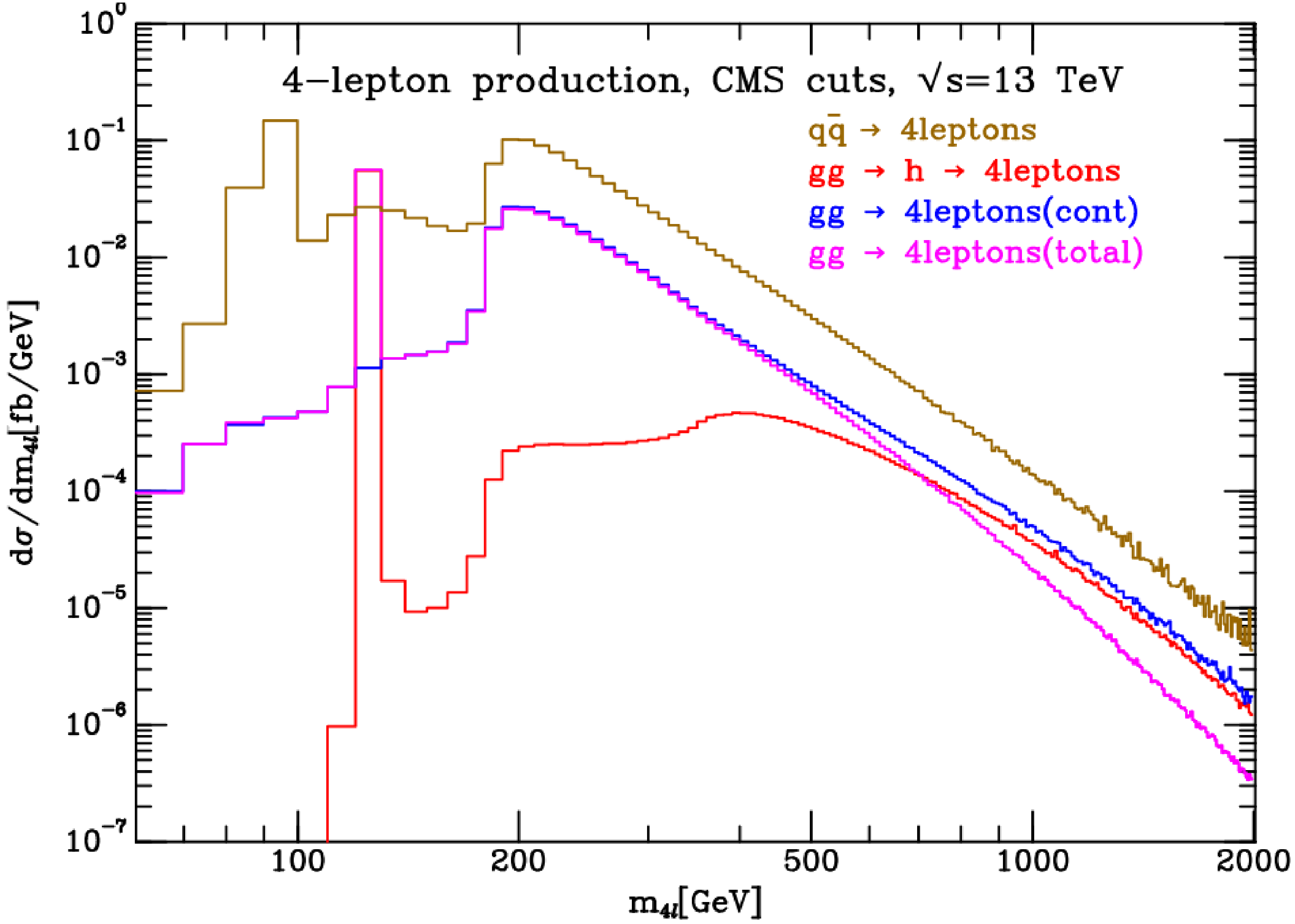
[2207.00320]

- The decay width of a particle can be extracted by measuring the line-shape of the invariant mass distribution e.g m_{4l} or $m_{\gamma\gamma}$
- But the predicted SM value for the Higgs boson width is : 4.07 MeV

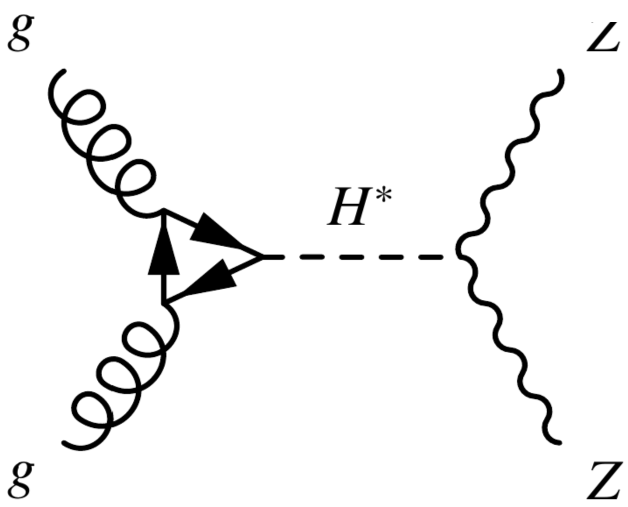
Higgs boson width is 3 orders of magnitude smaller than the experimental resolution & is thus not directly measurable !

- Still this can be done yielding limits of the Higgs mass Γ<2.6 GeV [1406.3827]
- Measurment of the Higgs lifetime Γ>3.5 e-9 MeV [1507.06656]

Off-shell production of the Higgs boson



- The Higgs boson has a sizable off-shell cross-section
- The on-shell Higgs boson production is proportional to : $\sigma^{pp\to H\to ZZ}_{\text{on-shell}} \propto \frac{g^2_{Hgg}g^2_{HZZ}}{m_H\Gamma_H}$
- While the off-shell Higgs boson production scales as: $\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggH}}g^2_{\text{HZZ}}}{m^2_{ZZ}}$



How to actually measure the Higgs width

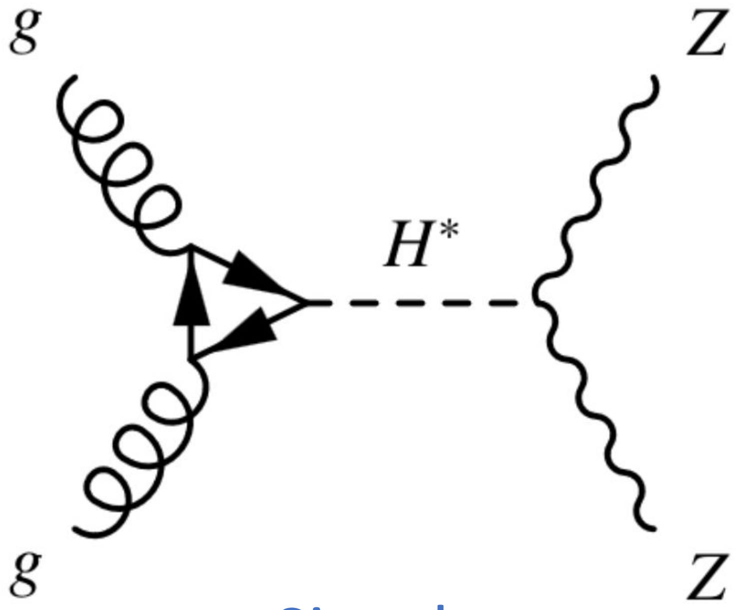
- The Higgs boson with can be calculated measuring the ratio of off-shell and on-shell Higgs production
  - Assuming that the on and off-shell coupling evolve like predicted by the SM
  - No additional new particles enter the Higgs production/decay

$$\mu_{\mathrm{on-shell}} = \frac{\sigma^{pp\to H\to ZZ}_{\mathrm{on-shell}}}{\sigma^{pp\to H\to ZZ}_{\mathrm{on-shell,SM}}} = \frac{\kappa^2_{g,\mathrm{on-shell}}\kappa^2_{V,\mathrm{on-shell}}}{\Gamma_H/\Gamma_H^{\mathrm{SM}}}$$

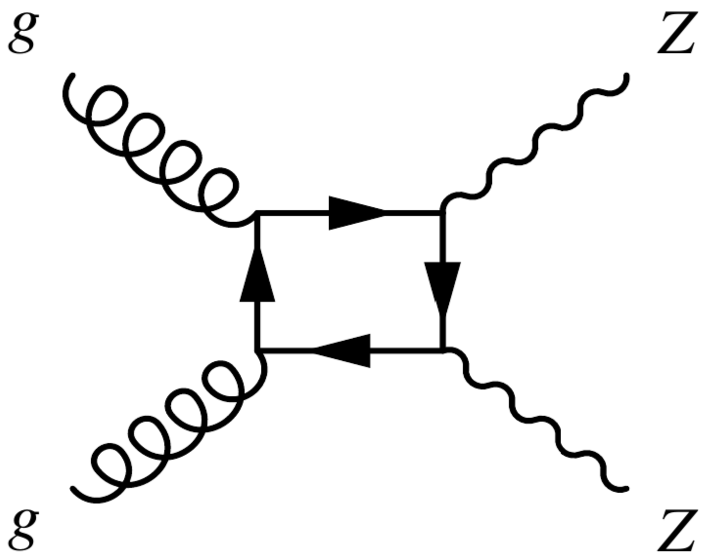
$$\mu_{\mathrm{off-shell}} = \frac{\sigma^{pp\to H\to ZZ}_{\mathrm{off-shell}}}{\sigma^{pp\to H\to ZZ}_{\mathrm{off-shell,SM}}} = \kappa^2_{g,\mathrm{off-shell}}\kappa^2_{V,\mathrm{off-shell}}$$

Measurment of the off-Shell Higgs production

- Target the Higgs to four lepton final state h→ ZZ→ 4l/2l2v
- Consider both vector-boson-fusion and gluon-fusion-production
- Large interference between the Signal and Background

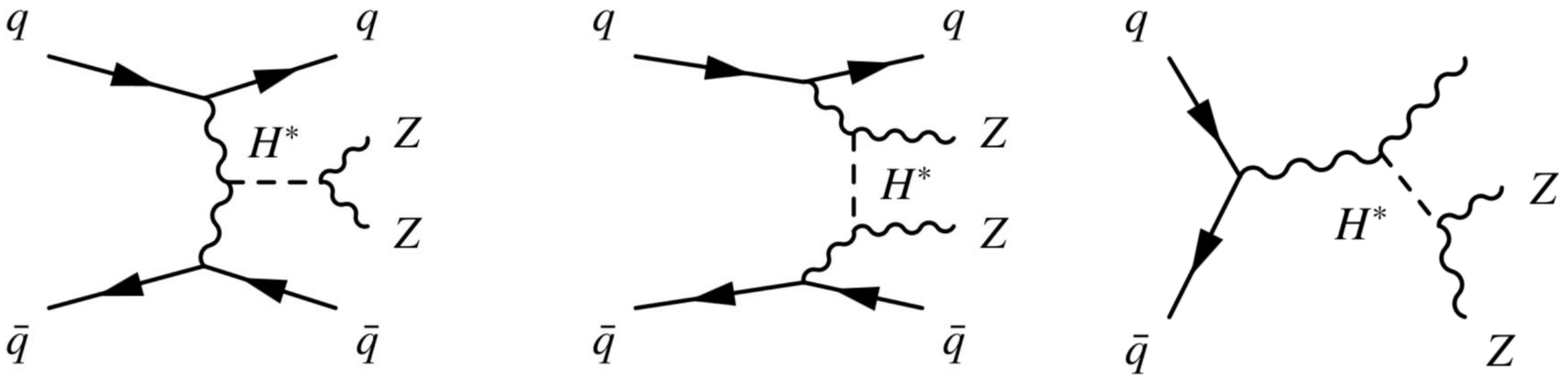


Signal



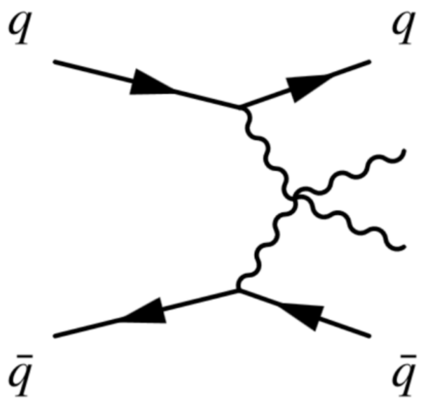
Background

VBF production

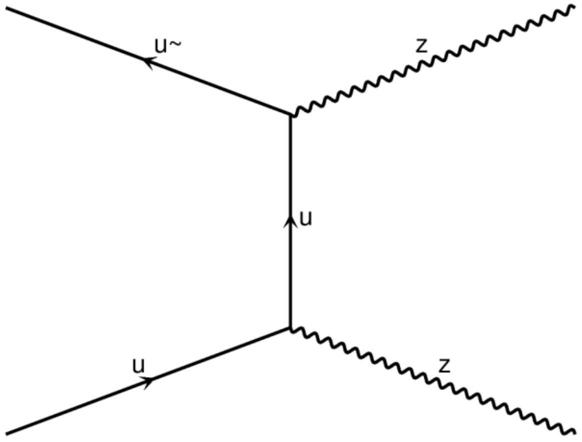


Signal

Interfering Background



Non-Interfering Background



Event Selection

ZZ →4l

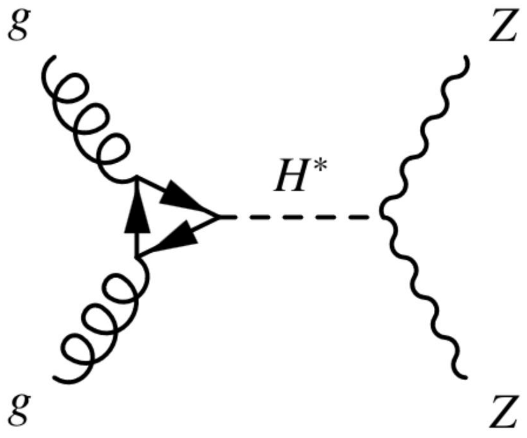
- 4 leptons
  - 2 opposite singe same flavor pairs
- Leading lepton p_T> 20,15,10 GeV
- m_{4l}> 180 GeV
- 50 GeV< m12<106 GeV
- 50-(190-m_{4l}/2)<m34<115 GeV

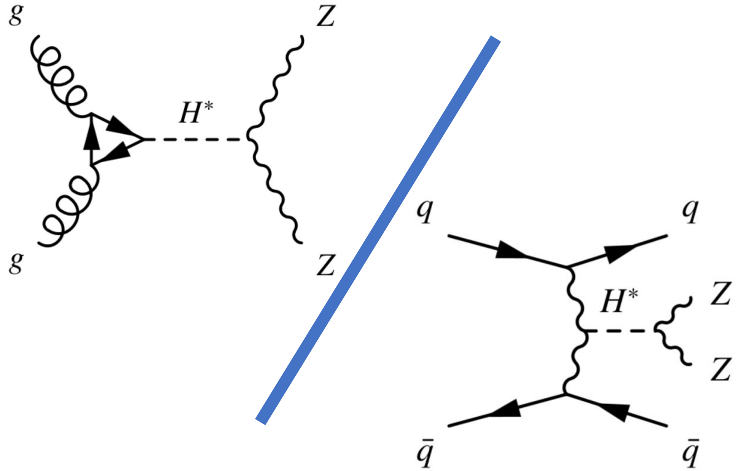
ZZ →2l2v

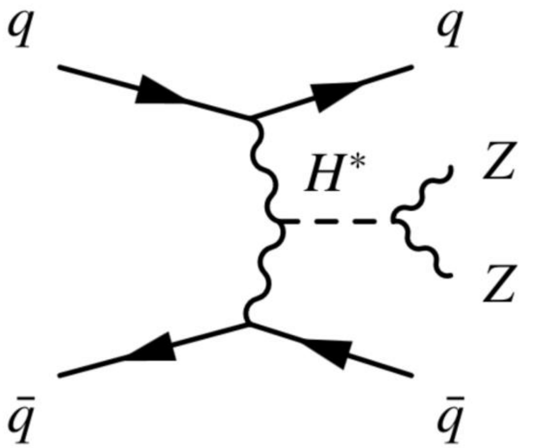
- 2 leptons
  - Same flavor opposite charged
  - Leading lepton p_T > 30,20 GeV
  - 76>m_{ll}<106 GeV
  - E_T^{miss} > 120 GeV
  - ΔR_{ll} <1.8
  - b-jet veto
  - E_T^{miss} significance >10
  - $\Delta\phi(Z,E_T^{miss})$>2.5

Analysis Strategy-Signal Regions

- Goal: be sensitive to VBF production and ggF production







ggF Signal regions

m_{4ll}>220 GeV
Failing Mixed or EW SR requirements

mixed Signal regions

m_{4ll}>220 GeV
Exactly forward1 jet
p_T jet > 30 GeV
$\eta(j)$>2.2

EW-Signal regions

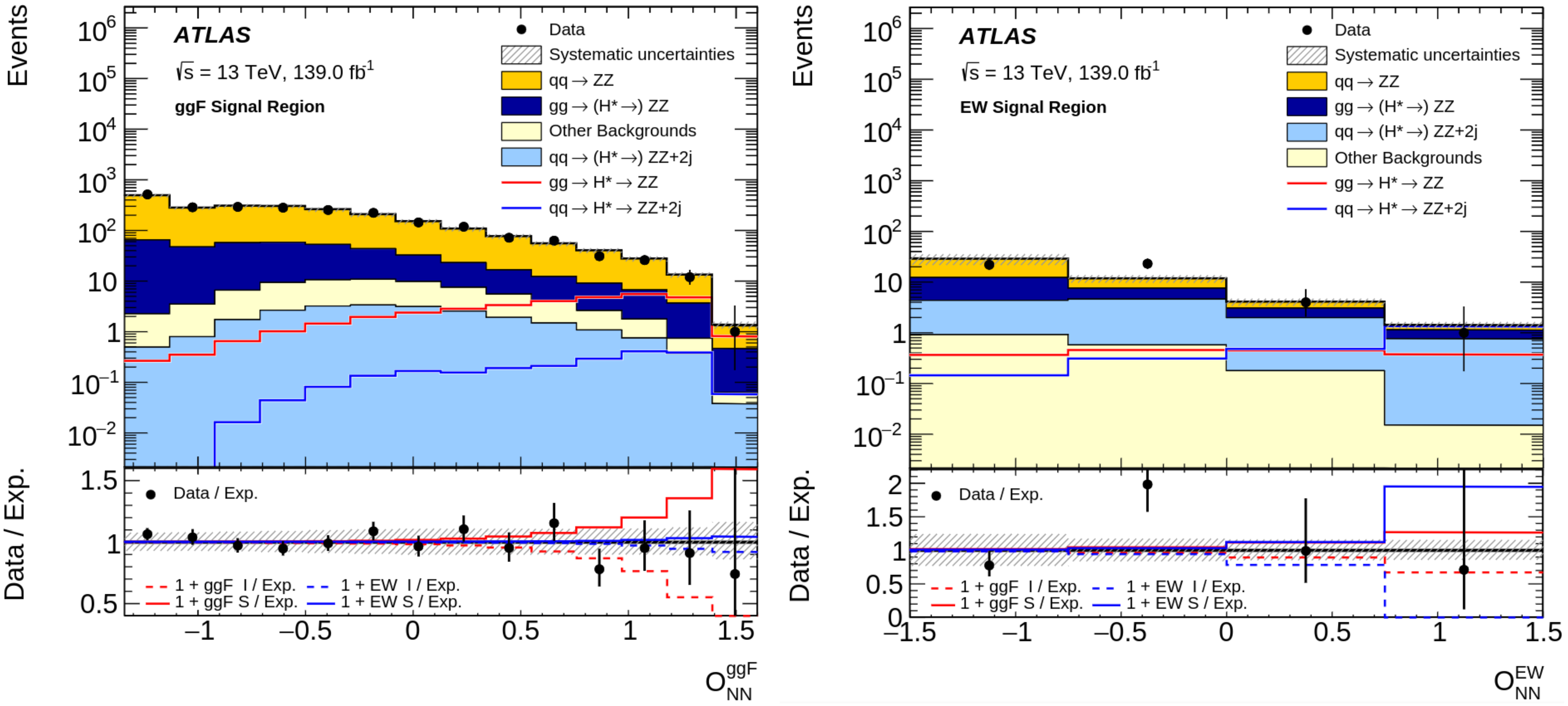
m_{4l}>220 GeV
N_{Jets} ≥2
p_T jet > 30 GeV
$\Delta\eta(jj)$>4

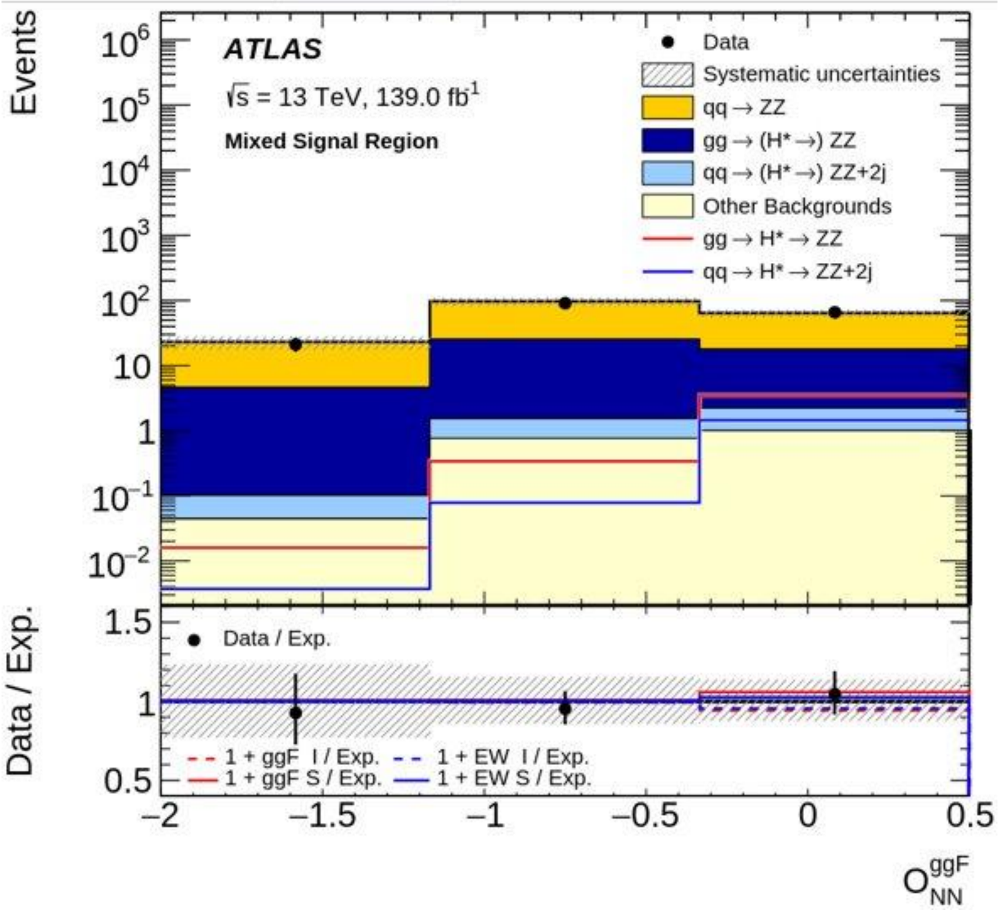
Analysis strategy in the 4l channel

- Train a Neural Network to differentiate between signal(s), interfering(B) background and non-interfering background(NI)
- Have separate NNs for ggF production (also used in the mixed SRs) and VBF production
  - Trained on the full 4-lepton kinematic +(2 jet kinematic)& the LO ME
- NN mainly focuses on the spin-parity nature of the Higgs Boson
- Construct the final discriminant:

$$O_{\mathrm{NN}} = \log_{10}\left(\frac{P_{\mathrm{S}}}{P_{\mathrm{B}} + P_{\mathrm{NI}}}\right)$$

Distributions in the 4l SRs




ATLAS
√s = 13 TeV, 139.0 fb-1
Mixed Signal Region
Data
Systematic uncertainties
qq → ZZ
gg → (H* →) ZZ
qq → (H* →) ZZ+2j
Other Backgrounds
gg → H* → ZZ
qq → H* → ZZ+2j
Data / Exp.
1 + ggF I / Exp.
1 + ggF S / Exp.
1 + EW I / Exp.
1 + EW S / Exp.
Events
Data / Exp.
O_NN^ggF

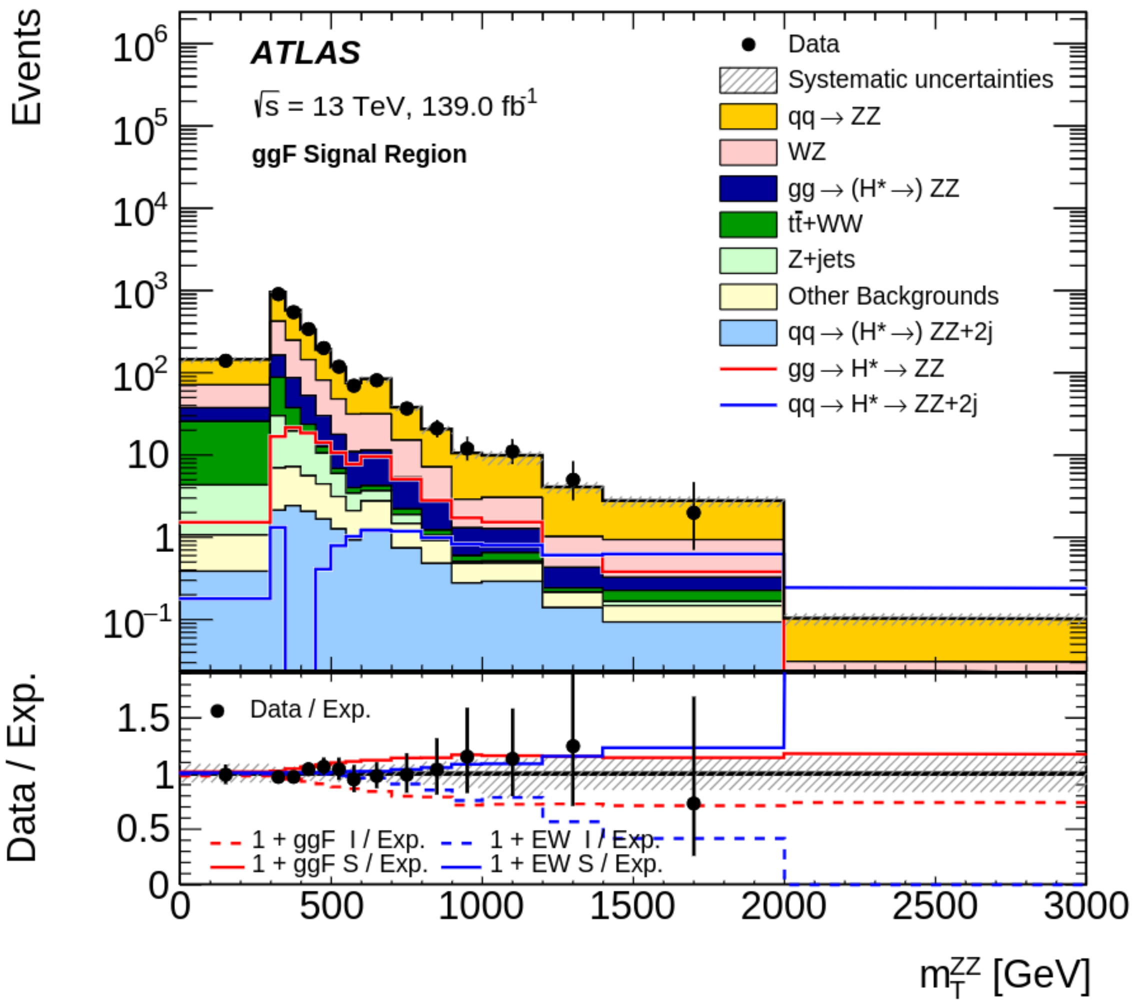
Analysis Strategy in the 2l2v channel

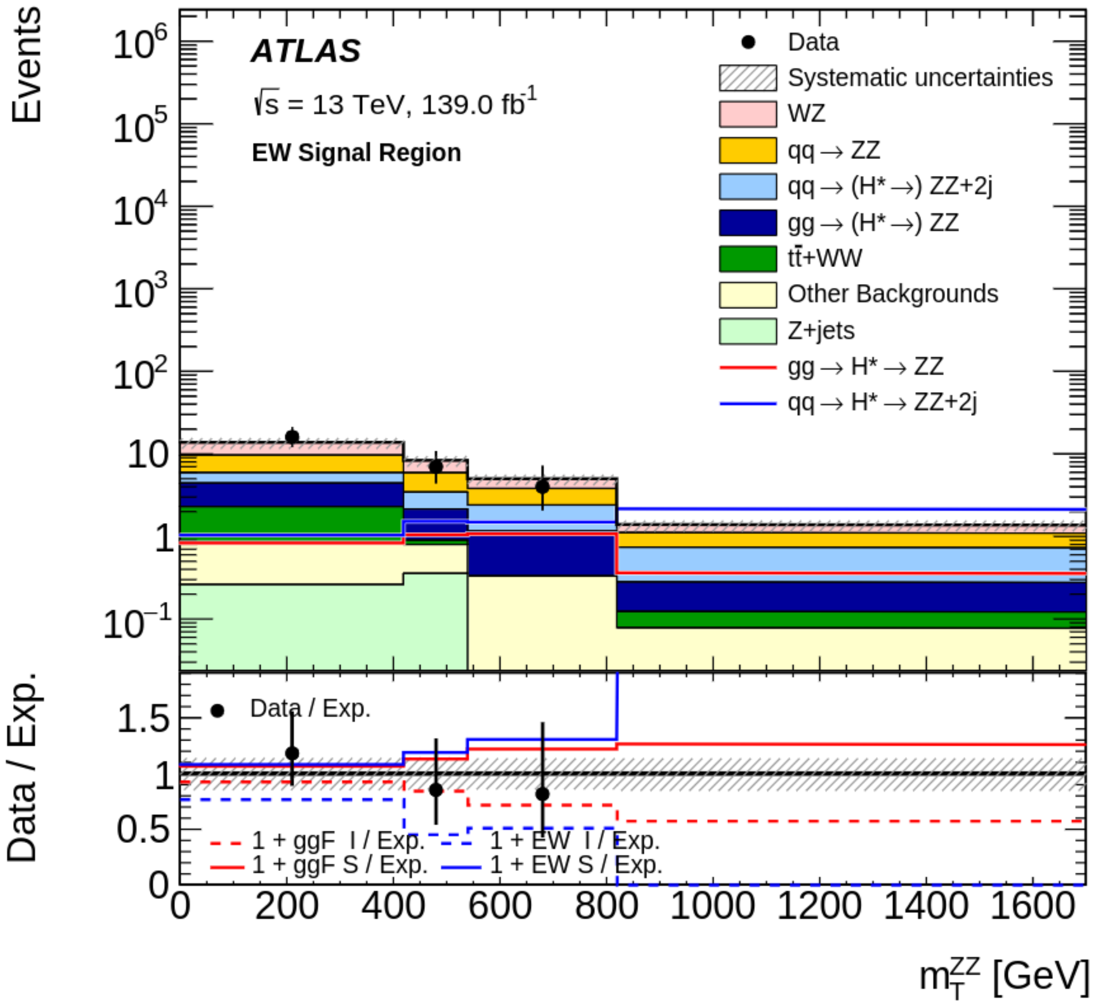
- Use the transverse mass as the discriminating variable:

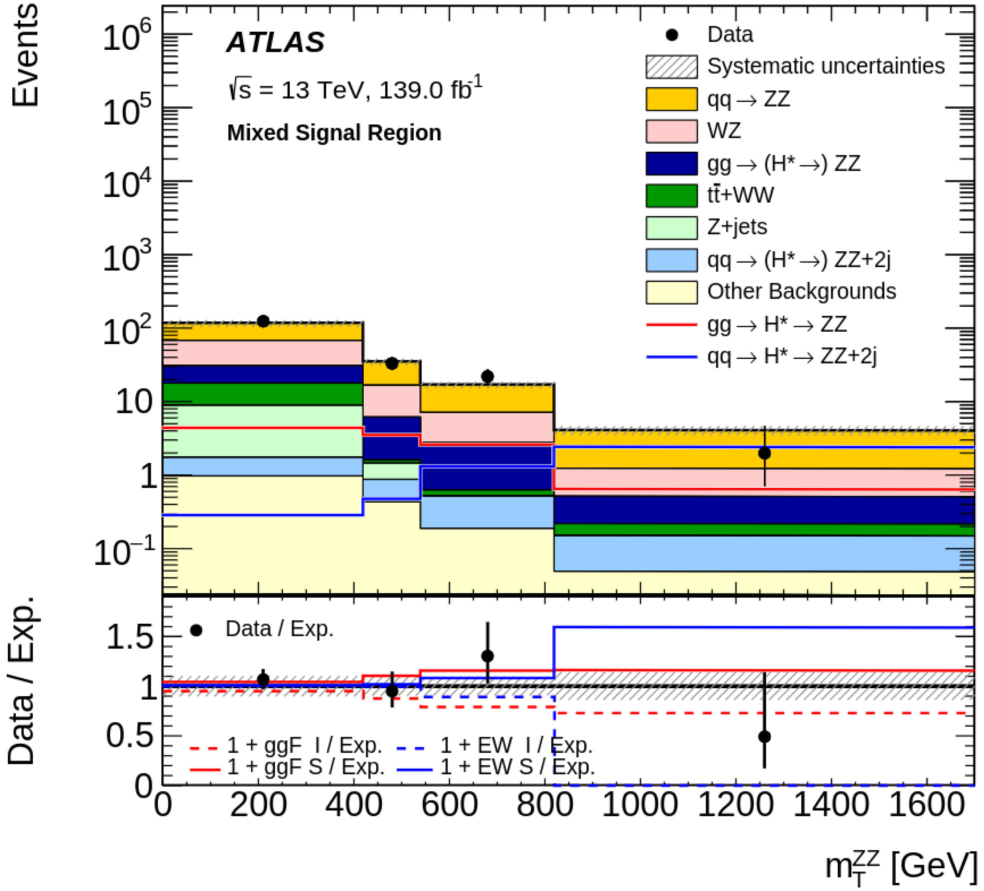
$$(m_T^{ZZ})^2 = \left[\sqrt{m_Z^2 + \left(p_T^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_T^{\text{miss}}\right)^2}\right]^2 - \left|p_T^{\ell\ell} + \overrightarrow{E_T^{\text{miss}}}\right|^2$$

- The signal is enhanced wrt. the background for high values of m_T^{ZZ}

Distributions in the 2 lepton SRs







ATLAS
√s = 13 TeV, 139.0 fb-1
Mixed Signal Region
Data
Systematic uncertainties
qq → ZZ
WZ
gg → (H* →) ZZ
tt̄+WW
Z+jets
qq → (H* →) ZZ+2j
Other Backgrounds
gg → H* → ZZ
qq → H* → ZZ+2j
Events
Data / Exp.
1 + ggF I / Exp.
1 + ggF S / Exp.
1 + EW I / Exp.
1 + EW S / Exp.
m_T^ZZ [GeV]

Background normalization and Control regions

- The normalization of the dominant background are determined from data while the shape is determined from MC (free floating)
- Have dedicated Control regions for each background
- CRs targeting qq → ZZ are defined in the 4l final state by 180 $<m_{4l}<220$
  - Further split by jet multiplicity: 0,1 2+ jets
- Further CRs are defined in the 2l2v final state
  - WZ CR: require a third lepton with $p_T>20$ GeV

Systematic uncertainties

- Measurment is dominated by modeling uncertainties

Impact of the systematic uncertainties:

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 $qq \to ZZ$	2.27
NLO QCD uncertainty for $gg \to ZZ$	2.29
Parton shower uncertainty for $qq \to ZZ$ (shape)	2.29
Jet energy scale and resolution uncertainty	2.26
None	2.30

Dominant uncertainties on the individual backgrounds

Process	Uncertainty	Final State	Value (%)
ggF Signal Region			
$qq \to ZZ$	QCD Scale	$2\ell 2\nu$	4–40
$qq \to ZZ + 2j$	QCD Scale	4ℓ	21–28
$qq \to ZZ + 2j$	QCD Scale	$2\ell 2\nu$	22–37
$qq \to ZZ + 2j$	Parton Shower	$2\ell 2\nu$	1–67
$gg \to H^* \to ZZ$	Parton Shower	4ℓ	27
$gg \to H^* \to ZZ$	Parton Shower	$2\ell 2\nu$	8–45
$gg \to ZZ$	Parton Shower	4ℓ	38
$gg \to ZZ$	Parton Shower	$2\ell 2\nu$	6–43
$WZ + 0j$	QCD Scale	$2\ell 2\nu$	1–54
1-jet Signal Region			
$gg \to H^* \to ZZ$	Parton Shower	4ℓ	27
$gg \to H^* \to ZZ$	QCD Scale	$2\ell 2\nu$	13–18
$gg \to ZZ$	Parton Shower	4ℓ	38
$gg \to ZZ$	QCD Scale	$2\ell 2\nu$	18–20
$qq \to ZZ$ (EW)	QCD Scale	$2\ell 2\nu$	7–18
2-jet Signal Region			
$qq \to ZZ + 2j$	QCD Scale	4ℓ	18–26
$qq \to ZZ + 2j$	QCD Scale	$2\ell 2\nu$	8–32
$gg \to H^* \to ZZ$	Parton Shower	4ℓ	27
$gg \to ZZ$	Parton Shower	4ℓ	38
$gg \to ZZ$	QCD Scale	$2\ell 2\nu$	18–20
$WZ + 2j$	QCD Scale	$2\ell 2\nu$	20–22
$qq \to ZZ$ Control Regions			
$qq \to ZZ + 2j$	QCD Scale	4ℓ	26
Three-lepton Control Regions			
$WZ + 2j$	QCD Scale	$2\ell 2\nu$	28

Fit

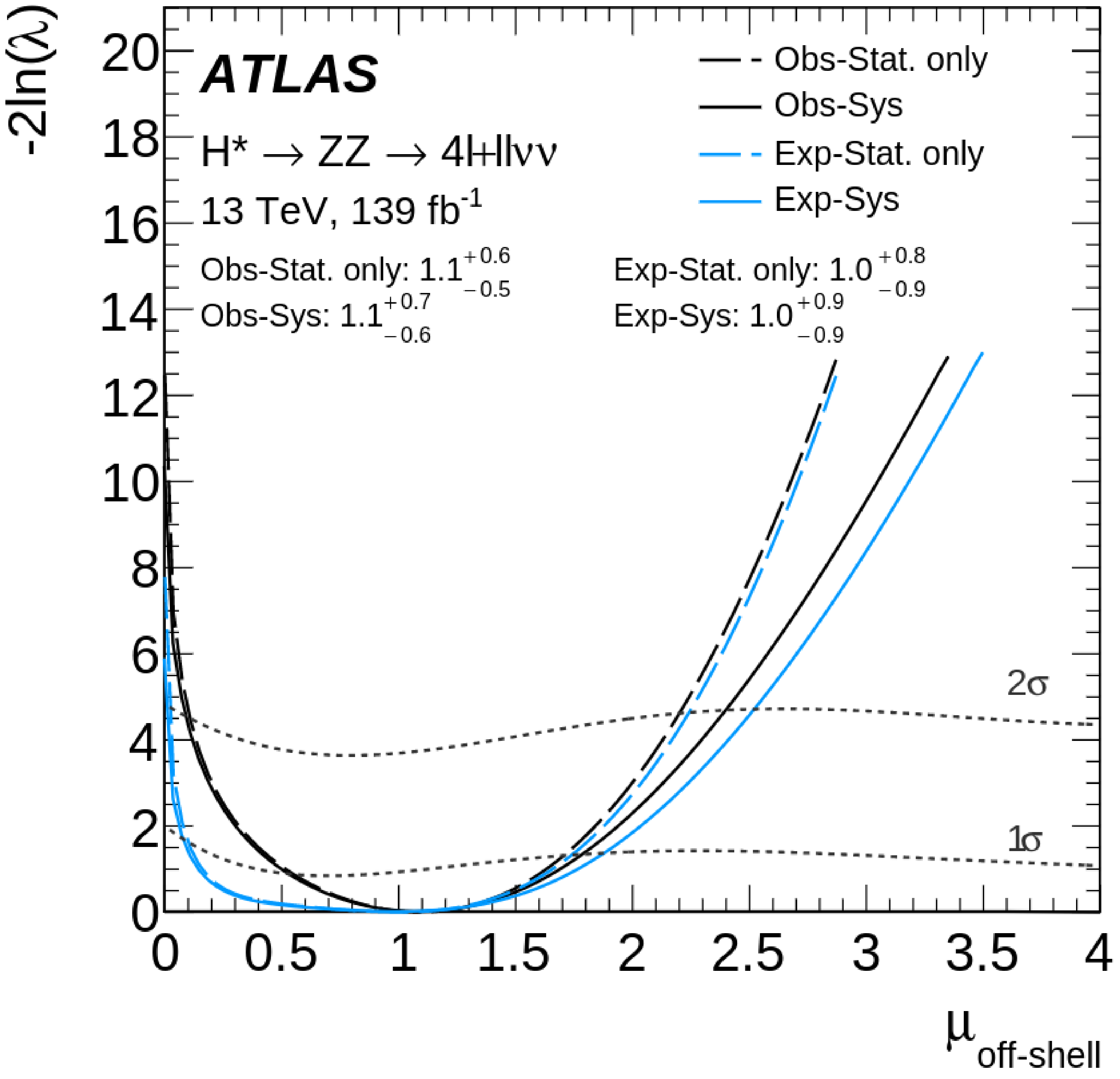
Normalization factor	Fitted value
μ_{qqZZ}	1.11 ± 0.07
μ_{qqZZ}^{1j}	0.90 ± 0.10
μ_{qqZZ}^{2j}	0.88 ± 0.26
$\mu_{3\ell}$	1.06 ± 0.03
$\mu_{3\ell}^{1j}$	0.92 ± 0.10
$\mu_{3\ell}^{2j}$	0.75 ± 0.19
μ_{Zj}	0.90 ± 0.19
$\mu_{e\mu}$	1.08 ± 0.09

- Perform a simultaneous Likelihood fit in the 6 SRs and 8 CRs
- Fit the signal strength and the normalization of the 8 backgrounds
- Because of the large interference both the signal and interfering background have to be considered
- N(gg→ZZ): $= (\mu^{\mathrm{ggF}}_{\text{off-shell}} - \sqrt{\mu^{\mathrm{ggF}}_{\text{off-shell}}}) \cdot n^{\mathrm{ggF}}_{\mathrm{S}}(\boldsymbol{\theta}) + \sqrt{\mu^{\mathrm{ggF}}_{\text{off-shell}}} \cdot n^{\mathrm{ggF}}_{\mathrm{SBI}}(\boldsymbol{\theta}) + (1 - \sqrt{\mu^{\mathrm{ggF}}_{\text{off-shell}}}) \cdot n^{\mathrm{ggF}}_{\mathrm{B}}(\boldsymbol{\theta})$

Results

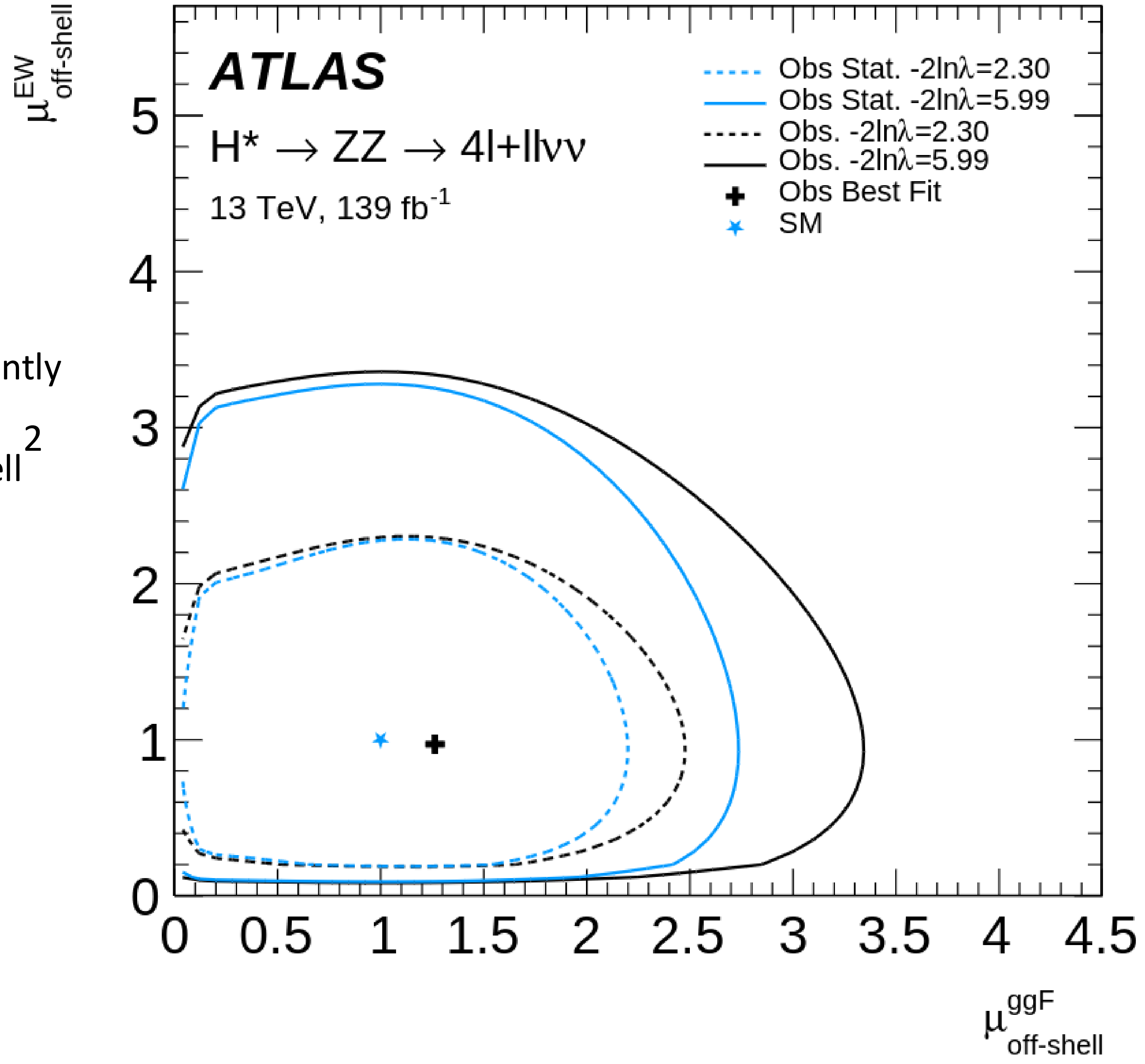
- The observed signal strength is 1.09 +- 0.6
- The background only hypothesis is rejected at 3.2 sigma
- Assuming:

$$\mu_{\text{off-shell}} = \kappa_{g,\text{off-shell}}^2 \, \kappa_{V,\text{off-shell}}^2 = \kappa_V^4$$



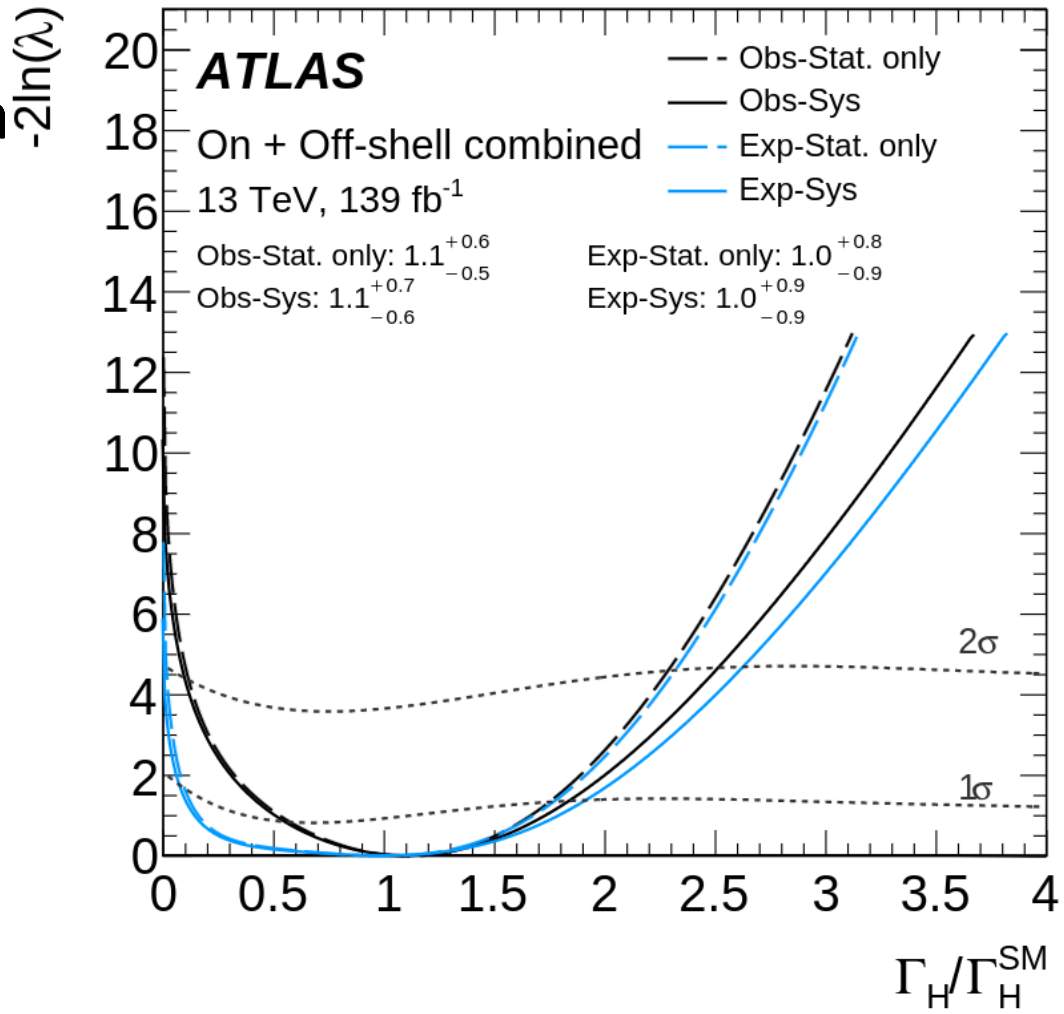
The two channels can also be fitted independently

- $\mu_{\text{off-shell}}^{\text{gFF}} = K_{\text{g,off-shell}}^{2} K_{\text{V,off-shell}}^{2}$
- $\mu_{\text{off-shell}}^{\text{VBF}} = K_{\text{V,off-shell}}^{4}$



Determination of the Higgs width

- To determine the Higgs width the off-shell production has to be combined with the on-shell production i.e [2004.03447]
- A combined Likelihood is built from the 2 analysis
- Measured ration Γ/Γ_{SM}=1.11±0.7=4.5MeV(±3.3,2.5)



Summary

- While directly not measurable the Higgs boson width can be measured from the off-shell production
- The off-shell Higgs production is measured in H→ ZZ→4l and H→ ZZ→2l2v events with the Full Run 2 dataset by ATLAS
- There is evidence for off-shell Higgs boson production. The no-offshell hypothesis is rejected with a observed significance of 3.2σ
- Trough combination with the on-shell Higgs boson measurement the width can be determined: $\Gamma_{Higgs}=4.6^{+2.6}_{-2.5}$ MeV