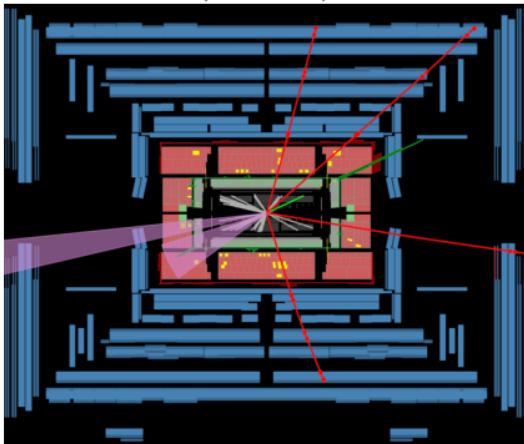


# Measurement of cross sections and properties of the Higgs boson in decays to four leptons using the ATLAS detector

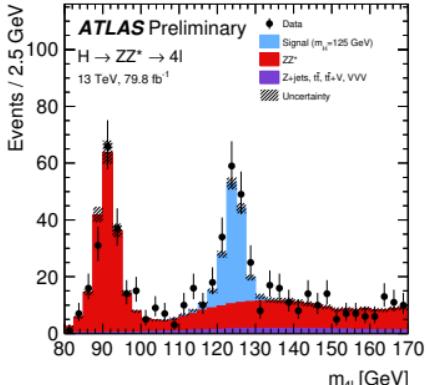
O. Kortner on behalf of the ATLAS collaboration

Max-Planck-Institut für Physik, München

ICHEP 2018, Seoul, 06.07.2018



# $H \rightarrow ZZ^* \rightarrow 4\ell$ channel



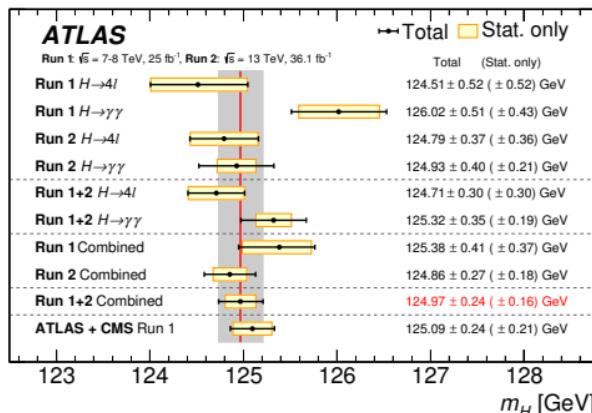
## Higgs boson decay under consideration

- $H \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell'^+\ell'^-$  ( $\ell, \ell' = e, \mu$ ).
- $\sigma(pp \rightarrow H \rightarrow ZZ^* \rightarrow 4\ell) = 1.33 \text{ pb}$ .

## Experimental signature

- Two pairs of oppositely charged isolated electrons or muons from a common vertex.
- Mass of one lepton pair close to  $m_Z$ .

## Measurement of the Higgs boson mass



- Most precise Higgs boson mass measurement from  $H \rightarrow 4\ell$  channel.
- Small error on  $m_H$  totally dominated thanks to excellent lepton energy and momentum calibration.

# Quantities for the study of Higgs boson properties

## Higgs boson production modes

Gluon gluon fusion “ggF” (49 pb)	Vector boson fusion “VBF” (3.8 pb)	W/Z associate production “VH” (2.2 pb)	ttH production “ttH” (0.5 pb)

## Transverse momentum of the Higgs boson $p_{T,4\ell}$

- Test perturbative QCD calculations like ISR in ggF.
- Sensitivity to Lagrangian structure of the Higgs boson interactions.

Number of jets in the final state  $N_{jets}$  provide sensitivity to

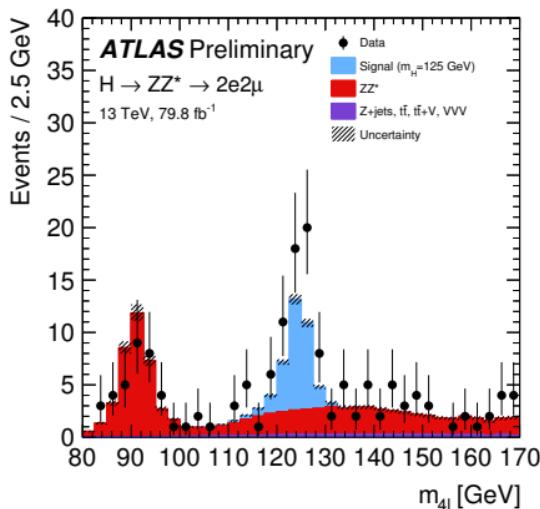
- theoretical modelling of gluon emission,
- the fractions of the different production modes.

Analysis based on LHC run-II data from 2015-2017: (ATLAS-CONF-2018-018)

$$\int \mathcal{L} dt = 79.8 \text{ fb}^{-1}, \sqrt{s} = 13 \text{ TeV}.$$

# Number of observed events grouped by final state

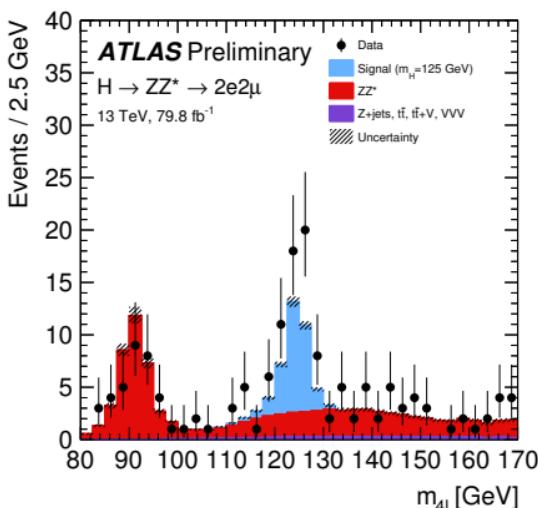
Final state	Signal	$ZZ^*$ background	Other backgrounds	Total expected	Observed
$4\mu$	$40.5 \pm 1.7$	$19.0 \pm 1.1$	$1.71 \pm 0.10$	$61.2 \pm 2.0$	64
$2e2\mu$	$28.2 \pm 1.2$	$13.3 \pm 0.8$	$1.38 \pm 0.10$	$42.8 \pm 1.4$	64
$2\mu2e$	$22.1 \pm 1.4$	$9.2 \pm 0.9$	$2.99 \pm 0.09$	$34.3 \pm 1.7$	39
$4e$	$21.1 \pm 1.4$	$8.6 \pm 0.8$	$2.90 \pm 0.09$	$32.5 \pm 1.6$	28
Total	$112 \pm 5$	$50 \pm 4$	$8.96 \pm 0.12$	$171 \pm 6$	195



- Good agreement between the number of expected and observed events.
- Overall 14% excess of observed events due to an upward fluctuations of  $H \rightarrow 2e2\mu$  events.

# Fiducial cross sections

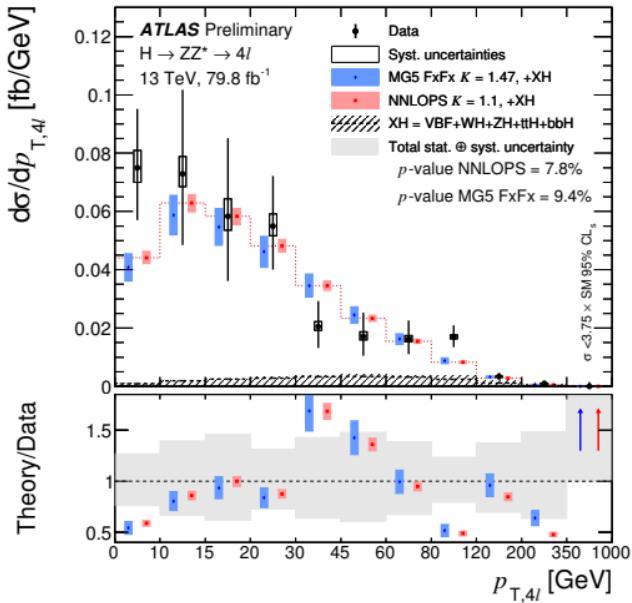
Cross section [fb]	Data ( $\pm$ (stat.)	$\pm$ (syst.)	)	Standard Model prediction
$\sigma_{4\mu}$	0.97	$\pm 0.17$	$\pm 0.05$	$0.886 \pm 0.039$
$\sigma_{4e}$	0.61	$\pm 0.21$	$\pm 0.07$	$0.886 \pm 0.039$
$\sigma_{2\mu 2e}$	0.88	$\pm 0.21$	$\pm 0.08$	$0.786 \pm 0.035$
$\sigma_{2e 2\mu}$	1.37	$\pm 0.22$	$\pm 0.07$	$0.786 \pm 0.035$
$\sigma_{\text{tot}} [\text{pb}]$	67.2	$\pm 6.8$	$\pm 4.1$	$55.7 \pm 2.5$



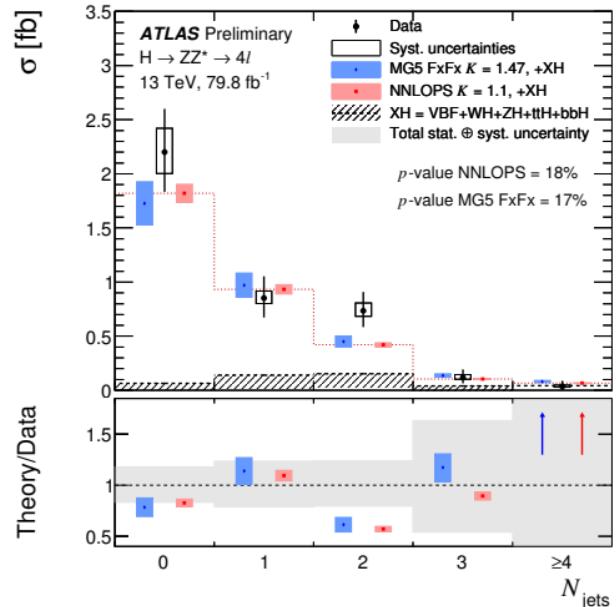
- Good agreement between the number of expected and observed events.
- Overall 14% excess of observed events due to an upward fluctuations of  $H \rightarrow 2e2\mu$  events.
- Dominant systematic uncertainty from 3% luminosity and  $\sim 4\text{-}8\%$  uncertainties from pile-up (mainly affecting lepton isolation).

# Differential fiducial cross sections

## Transverse Higgs boson momentum

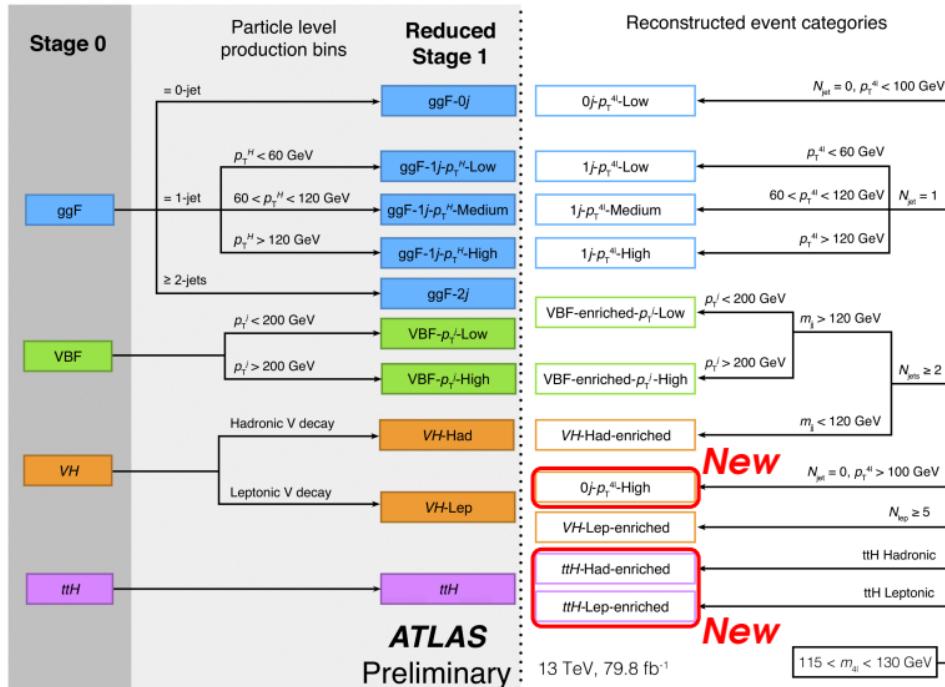


## Jet multiplicity



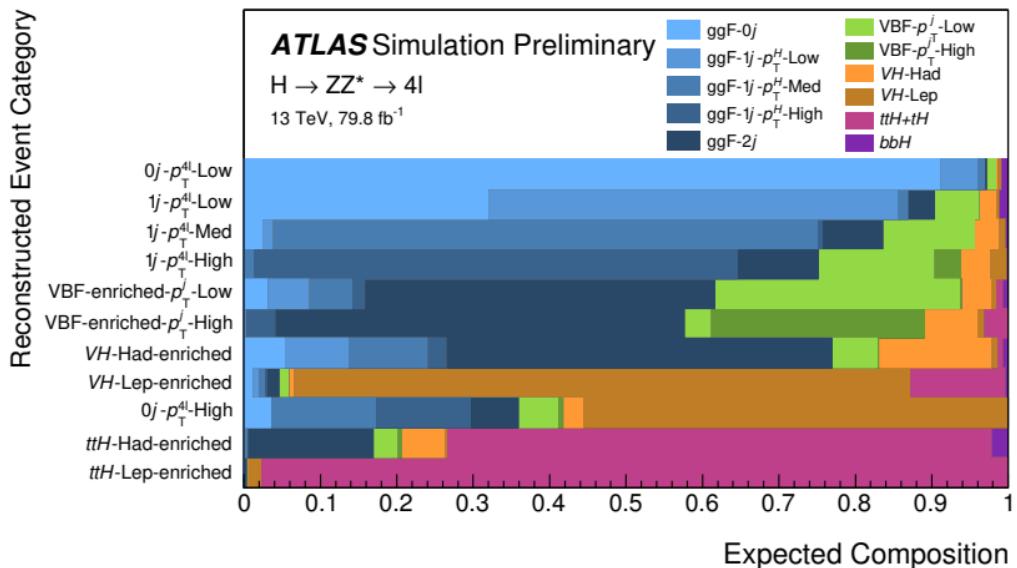
No statistically significant deviations of the differential distribution from the Standard Model predictions!

# Event categories



- Cross sections measured in selected particle-level production bins (simplified template cross section framework).
- Bins are chosen to minimize theoretical uncertainty of the measurement and provide sensitivity to BSM effects.

# Purities of the event categories at reconstruction level

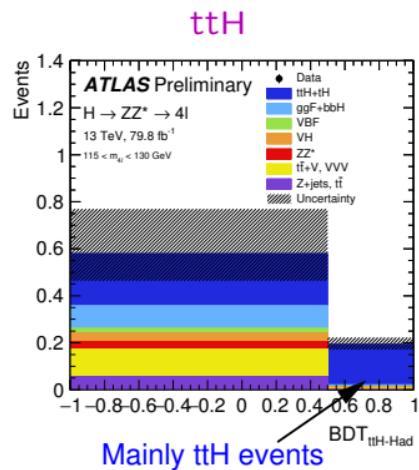
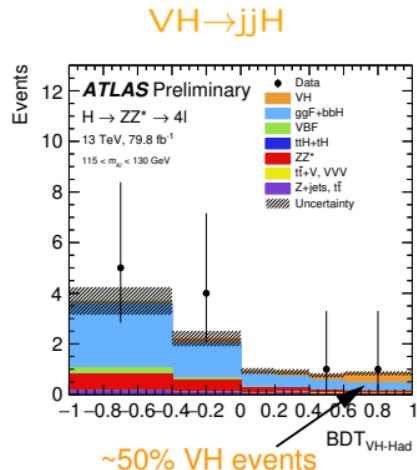
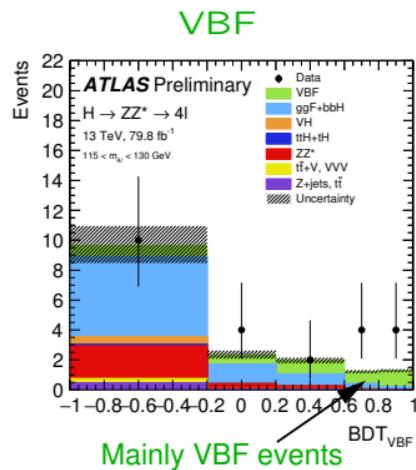


- Event categories not purely from a given production mode, e.g. only ~30% of the events in the VBF enriched category from **VBF** events, dominant contribution from **ggF** events.
- Boosted decision trees used to improve the discrimination between the categories.

# Input variables to the boosted decisions trees

Reconstructed event category	BDT discriminant	Input variables
$0j-p_T^{4\ell}$ -Low	$BDT_{ggF}$	$p_T^{4\ell}, \eta_{4\ell}, D_{ZZ^*}$
$1j-p_T^{4\ell}$ -Low	$BDT_{VBF}^{1j-p_T^{4\ell}\text{-Low}}$	$p_T^j, \eta_j, \Delta R(j, 4\ell)$
$1j-p_T^{4\ell}$ -Med	$BDT_{VBF}^{1j-p_T^{4\ell}\text{-Med}}$	$p_T^j, \eta_j, \Delta R(j, 4\ell)$
VBF-enriched- $p_T^j$ -Low	$BDT_{VBF}$	$m_{jj}, \Delta\eta_{jj}, p_T^{j1}, p_T^{j2}, \eta_{4\ell}^*, \Delta R_{jZ}^{\min}, p_T^{4\ell jj}$
$VH$ -Had-enriched	$BDT_{VH\text{-Had}}$	$m_{jj}, \Delta\eta_{jj}, p_T^{j1}, p_T^{j2}, \eta_{4\ell}^*, \Delta R_{jZ}^{\min}, \eta_{j1}$
$t\bar{t}H$ -Had-enriched	$BDT_{t\bar{t}H\text{-Had}}$	$m_{jj}, \Delta\eta_{jj}, \Delta R_{jZ}^{\min}, \Delta R(j, 4\ell), \eta_{4\ell}^*, E_T^{\text{miss}}, p_T^{jj}, N_{\text{jets}}, N_{b\text{-jets}}, H_T, \mathcal{M}_{sig}$

# Examples of distributions of BDT scores



# Systematic uncertainties on the cross sections

Measurement [-0.5ex]	Experimental uncertainties [%]				Theory uncertainties [%]				
	Lum.	$e, \mu,$ pile-up	Jets, flavour tagging	Reducible backgr.	$ZZ^*$ backgr.	PDF	QCD scale	Signal Parton Shower	Composition
Fiducial cross section									
	2.8	4.3	< 0.1	0.3	1.6	0.6	0.5	0.4	0.1
Per decay channel fiducial cross sections									
$4\mu$	2.8	3.9	< 0.1	0.3	1.6	0.6	0.4	0.6	0.2
$4e$	2.8	9.0	< 0.1	1.0	1.6	0.6	0.8	0.5	0.1
$2\mu 2e$	2.7	8.6	< 0.1	0.9	1.5	0.6	0.7	0.5	0.1
$2e 2\mu$	2.8	3.6	< 0.1	0.4	1.8	0.6	0.7	0.5	0.2
Stage-0 production bin cross sections									
ggF	2.9	3.9	1.3	0.7	2.3	0.4	2.1	0.7	-
VBF	1.7	1.5	10.5	0.5	2.3	2.3	9.5	5.1	-
$VH$	2.0	1.7	7.8	1.8	5.6	2.1	14.9	3.1	-
$t\bar{t}H$	2.5	1.9	3.9	1.5	1.9	0.3	8.8	9.6	-

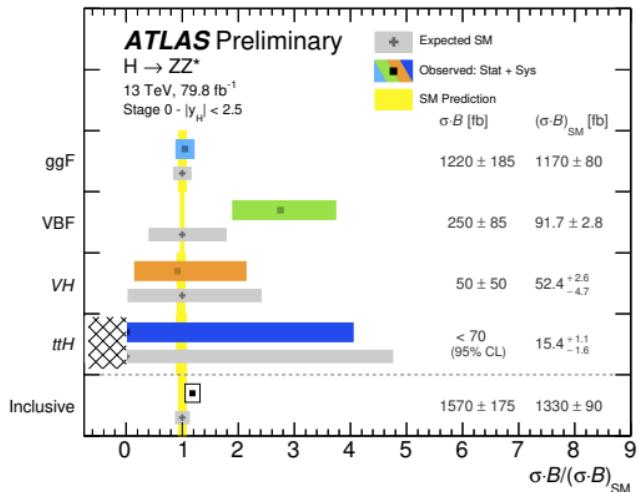
## Dominant experimental uncertainties

- Luminosity uncertainty  $\sim 3\%$ .
- Uncertainties from pile-up (mainly affecting lepton isolation)  $\sim 4\text{-}8\%$ .
- Jet reconstruction and flavour tagging  $\sim 5\text{-}10\%$  for VBF, VH, ttH.

## Dominant theoretical uncertainties

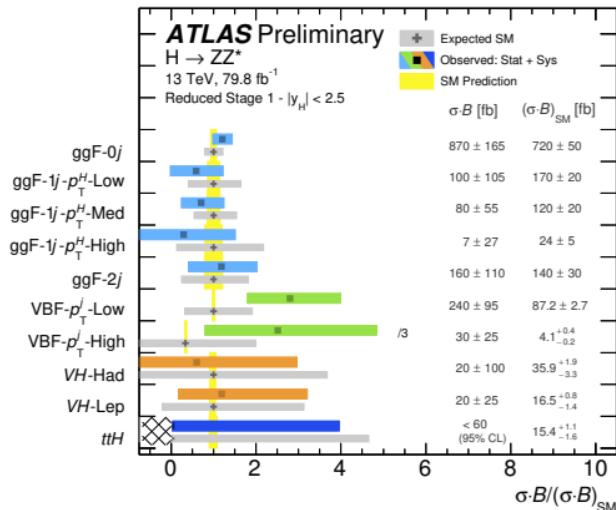
- $ZZ^*$  cross section  $\sim 2\%$ .
- QCD scale  $\sim 10\%$  for VBF, VH, ttH.

# Measured production cross sections



- Excellent agreement of the measured cross sections for **ggF** and **VH** production.
- Almost 3 times larger measured **VBF** cross section than predicted, but only  $1.8\sigma$  deviation.
- No observed **ttH** event in the  $4\ell$  final state, but 95% CL limits in agreement with the SM prediction.

# A more detailed look at the measured cross sections

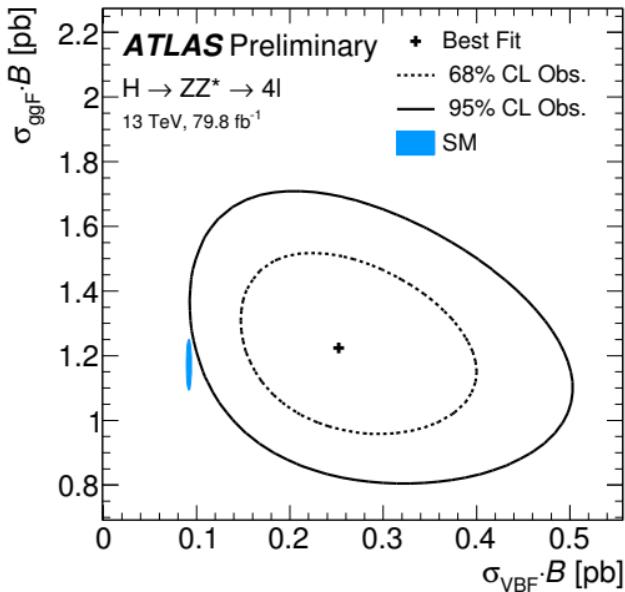


- Excellent agreement of the measured cross sections in all **ggF** and **VH** categories.
- Deviation of the measured **VBF** cross sections from the SM prediction
  - at  $1.6\sigma$  level for the low jet  $p_T$  category,
  - $< 1\sigma$  level for the high jet  $p_T$  category.

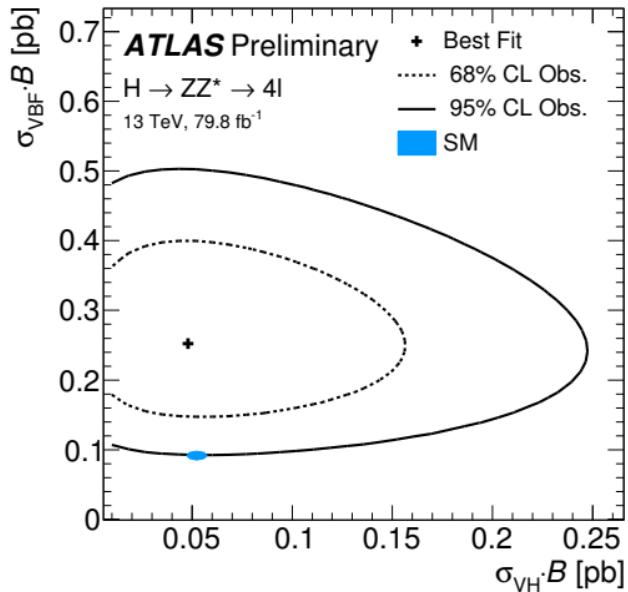
No statistically significant deviations from the Standard Model predictions!

# Likelihood contours

ggF vs VBF



VBF vs VH



Agreement between the measured and predicted cross sections at a level of  $<2\sigma$  due to the observed excess of VBF events.

# Off-shell Higgs boson production

- On-shell Higgs boson production:  $118 \text{ GeV} < m_{4\ell} < 129 \text{ GeV}$ .
- Off-shell Higgs boson production:  $220 \text{ GeV} < m_{4\ell} < 2000 \text{ GeV}$ .

## Motivation for studying off-shell production

$$\bullet \quad \mu_{\text{off-shell}} = \frac{\sigma_{\text{off-shell}}^{gg \rightarrow H^* \rightarrow ZZ}}{\sigma_{\text{off-shell,SM}}^{gg \rightarrow H^* \rightarrow ZZ}} = \kappa_{g,\text{off-shell}}^2 \cdot \kappa_{Z,\text{off-shell}}^2 \quad \mu_{\text{on-shell}} = \frac{\sigma_{\text{on-shell}}^{gg \rightarrow H \rightarrow ZZ}}{\sigma_{\text{on-shell,SM}}^{gg \rightarrow H \rightarrow ZZ}} = \frac{\kappa_{g,\text{on-shell}}^2 \cdot \kappa_{Z,\text{on-shell}}^2}{\Gamma_H / \Gamma_H^{\text{SM}}}$$

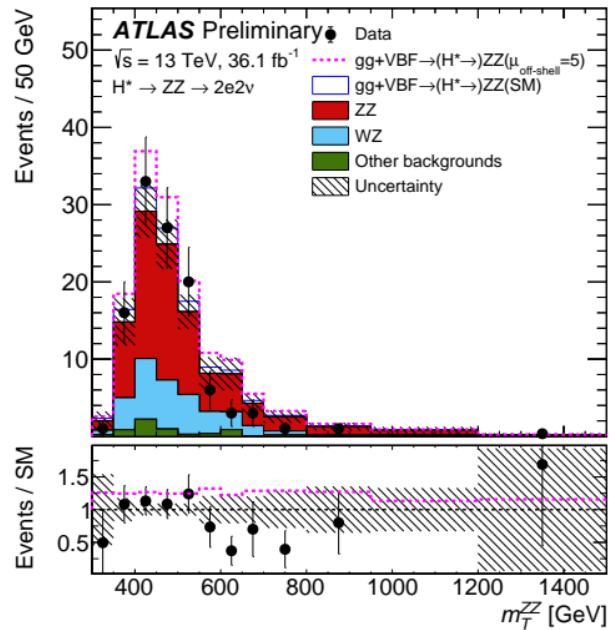
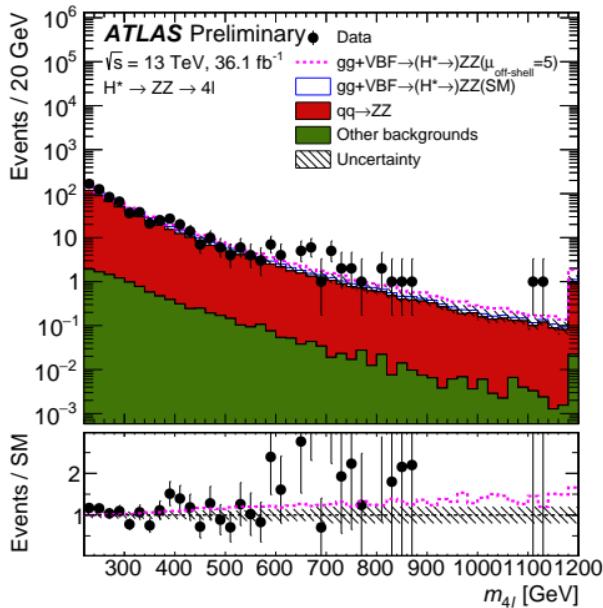
⇒ If  $\kappa_{\text{off-shell}} = \kappa_{\text{on-shell}}$  then

$$\frac{\mu_{\text{on-shell}}}{\mu_{\text{off-shell}}} = \frac{\Gamma_H}{\Gamma_H^{\text{SM}}}.$$

⇒ Provides sensitivity to  $\Gamma_H$  which is only 4.2 MeV in the SM and inaccessible through the width of the Higgs peak in the  $m_{4\ell}$  distribution.

# Limits on the Higgs boson's width $\Gamma_H$

NEW!



- No significant excess over the  $ZZ$  and  $WZ$  background.
- ⇒ 95% CL limits on signal strength and  $\Gamma_H$ :
  - $\mu_{\text{off-shell}} < 3.8$  (3.4 expected),
  - $\Gamma_H < 14.4 \text{ MeV}$  (15.2 MeV expected).

- The properties of the Higgs boson have been studied with  $H \rightarrow ZZ^* \rightarrow 4\ell$  events of the run-II ATLAS data.
- Accurate measurement of the Higgs boson mass with  $H \rightarrow 4\ell$  events with negligible systematic error:  $m_H = (124.71 \pm 0.30) \text{ GeV}$ .
- No deviations from the Standard Model have been found in the differential cross sections  $d\sigma/dp_{T,4\ell}$  and  $d\sigma/dN_{jets}$ .
- The measured cross sections for the dominant Higgs boson production cross section are found to be in agreement with the Standard Model prediction at a level of better than  $2\sigma$ .  
Maximum deviation:  $1.9\sigma$  excess of VBF events.
- ⇒ Excellent overall agreement with the Standard Model predictions.
- Constraint from off-shell Higgs boson production:  $\Gamma_H < 14.4 \text{ MeV}$ .