



THE UNIVERSITY of EDINBURGH
School of Physics
and Astronomy



Measurement of production mode cross sections of the Higgs boson in decays to bosons using the ATLAS detector

Liza Mijović on behalf of the ATLAS Collaboration

ICHEP2020, Prague, 30th of July



Outline

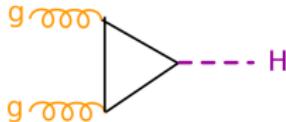
Production mode cross sections of the Higgs for:

- $H \rightarrow \gamma\gamma$
 - New result with full Run2 dataset (139 fb^{-1}):
ATLAS-CONF-2020-026
- $H \rightarrow WW^* \rightarrow e\nu\mu\nu$
 - New result with full Run2 dataset for VBF mode:
ATLAS-CONF-2020-045
 - Other modes with partial dataset (36.1 fb^{-1}):
Phys. Lett. B 789 (2019)
- $H \rightarrow ZZ^* \rightarrow 4\ell$
 - Paper with full Run2 dataset released in April:
arXiv:2004.03447

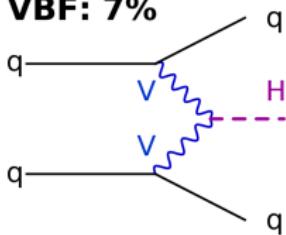
Related results: $t\bar{t}H$ production in Jelena Jovićević's talk,
Higgs combination ATLAS-CONF-2020-027 in Matt Klein's talk.

Higgs Production and Decay

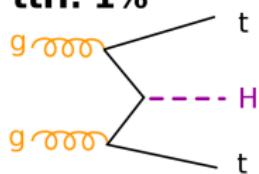
ggF: 87%



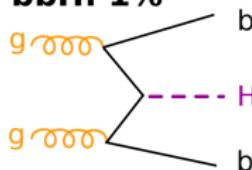
VBF: 7%



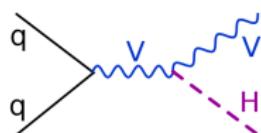
ttH: 1%



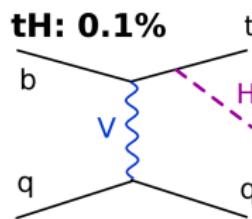
bbH: 1%



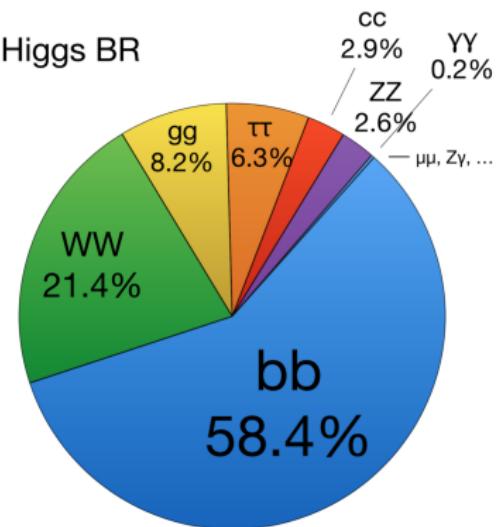
VH: 4%



tH: 0.1%

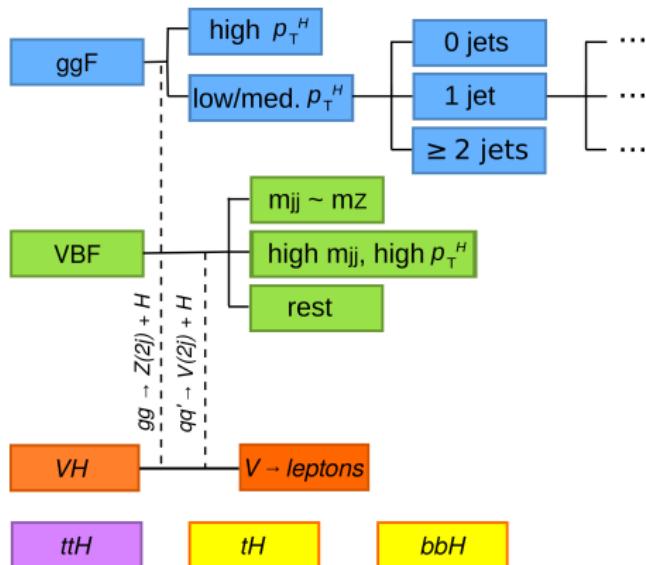


Higgs BR



Simplified Template X-Sections

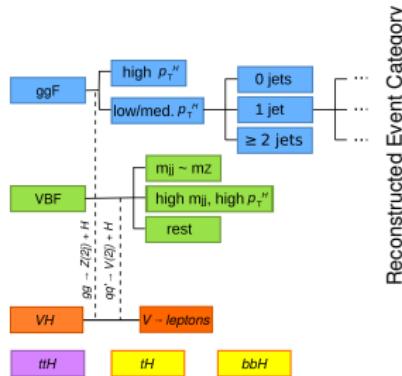
STXS targets phase space regions within production modes, using Standard Model kinematics as a template.



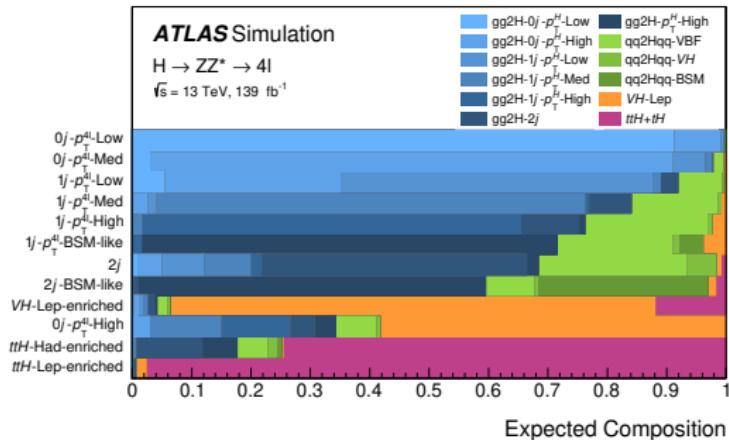
Compromise: maximise experimental sensitivity vs minimise dependence on theory assumptions.

Simplified Template X-Sections

- Design reconstructed categories to target STXS bins
- Extract cross-sections in each STXS bin from category yields



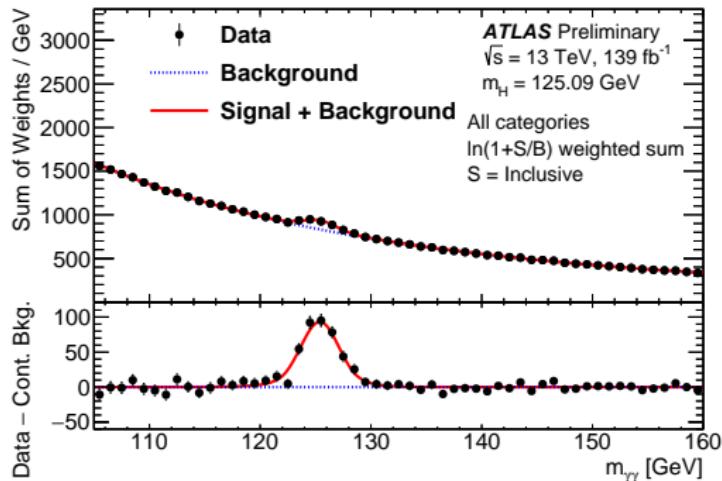
Reconstructed Event Category



Run2 sensitivity: $H \rightarrow WW$: stage 0 (production modes),
 $H \rightarrow ZZ$ stage 1.1 granularity, $H \rightarrow \gamma\gamma$: stage 1.2 granularity.

$H \rightarrow \gamma\gamma$

New result with full Run2 data-set: [ATLAS-CONF-2020-026](#)



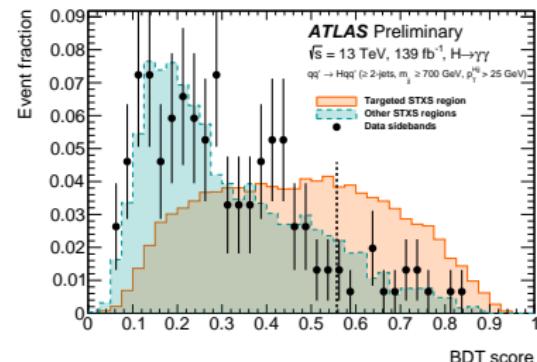
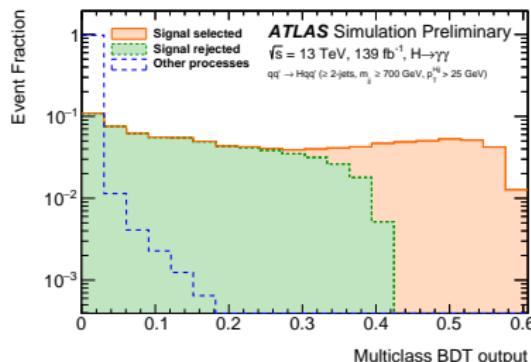
Largest updates in analysis strategy:

- New categorization; reduces uncertainties and correlations.
- Increased granularity; 27 STXS categories from 88 reconstruction categories.

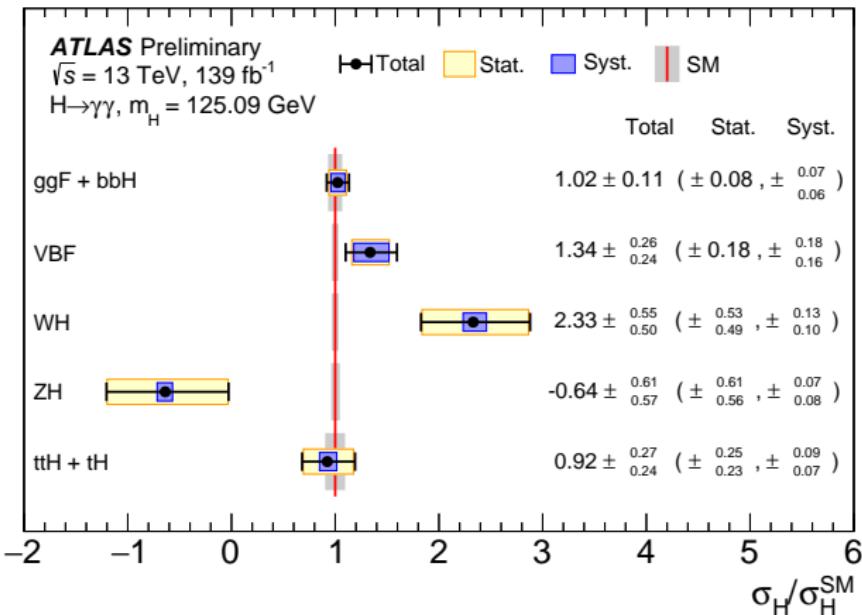
$H \rightarrow \gamma\gamma$: Categorization

All processes considered simultaneously, maximising global STXS sensitivity. Replaces sequential categorization.

- Step1: **signal**: **Multi-class BDT** with output discriminant for each STXS bin splits signal into classes, aiming to **minimise determinant of the covariance matrix**.
- Step2: **signal vs continuum background**: binary BDT in each class.



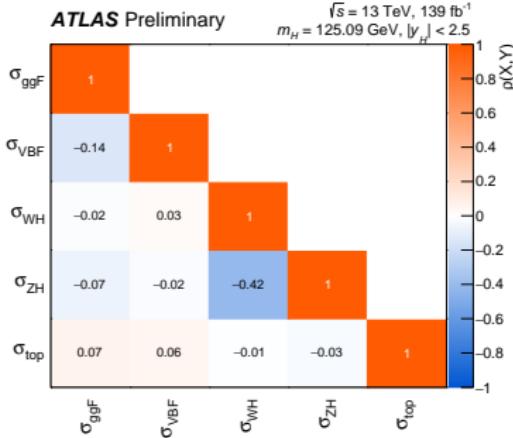
$H \rightarrow \gamma\gamma$: Production Modes



- ggF and VBF: stat. \approx syst. uncertainty; largest syst.: ggF:background modelling(4.1%), VBF:signal modelling(10%)
- SM compatibility of 5-POI fit: p-value = 3% (1.9 σ deviation)

$H \rightarrow \gamma\gamma : VH$

WH and ZH anti-correlated
main source: WH events
populating 0 charged lepton
category (targeting ZH).

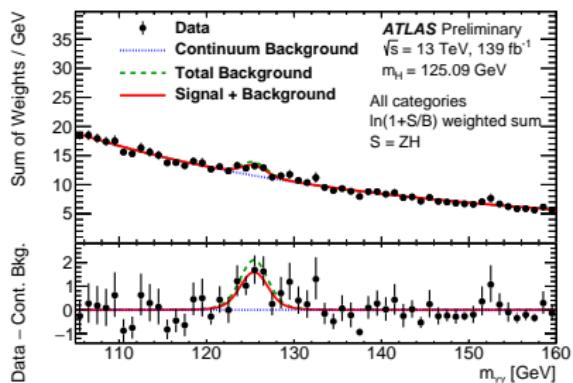
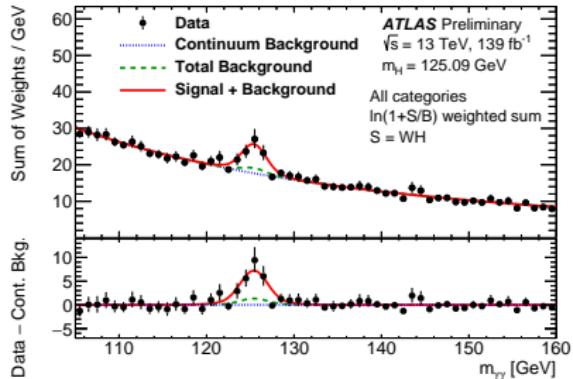


Measured $WH+ZH$ cross-section:

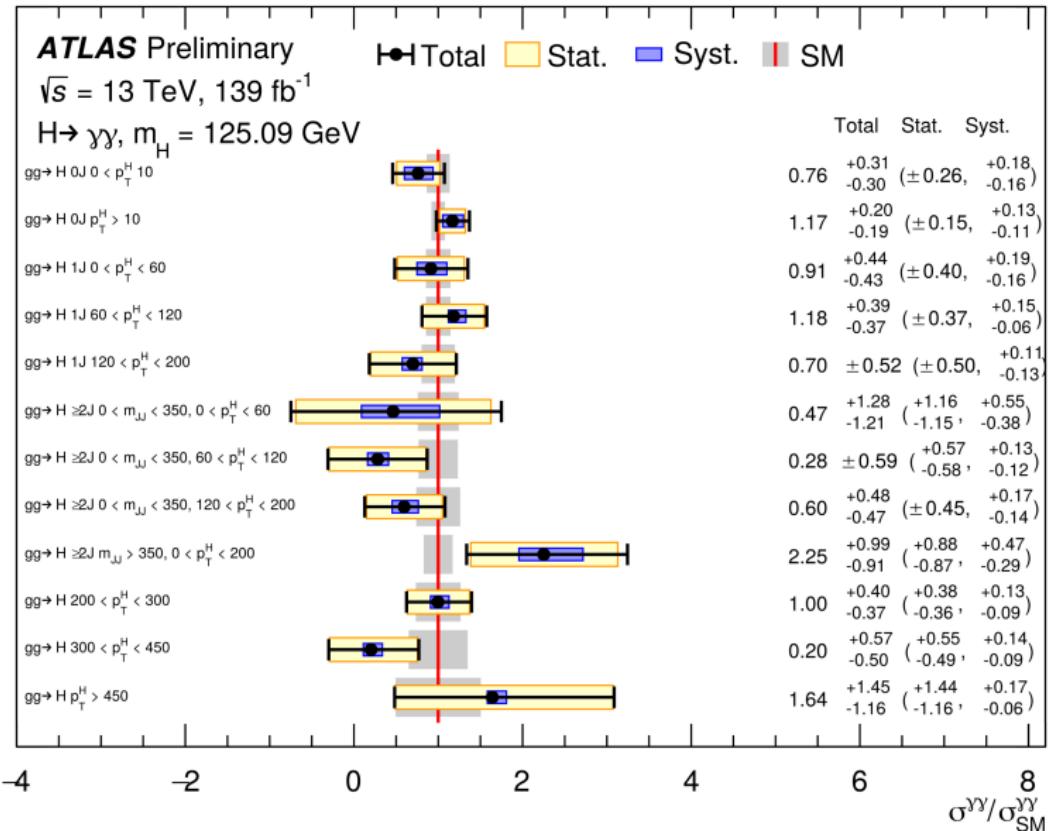
$$\sigma_{VH} = 5.9 \pm 1.4 \text{ fb}$$

$$\sigma_{VH,\text{expected}} = 4.53 \pm 0.12 \text{ fb}$$

(p-value: 50%)



$H \rightarrow \gamma\gamma$: STXS ggF Bins



-4

-2

0

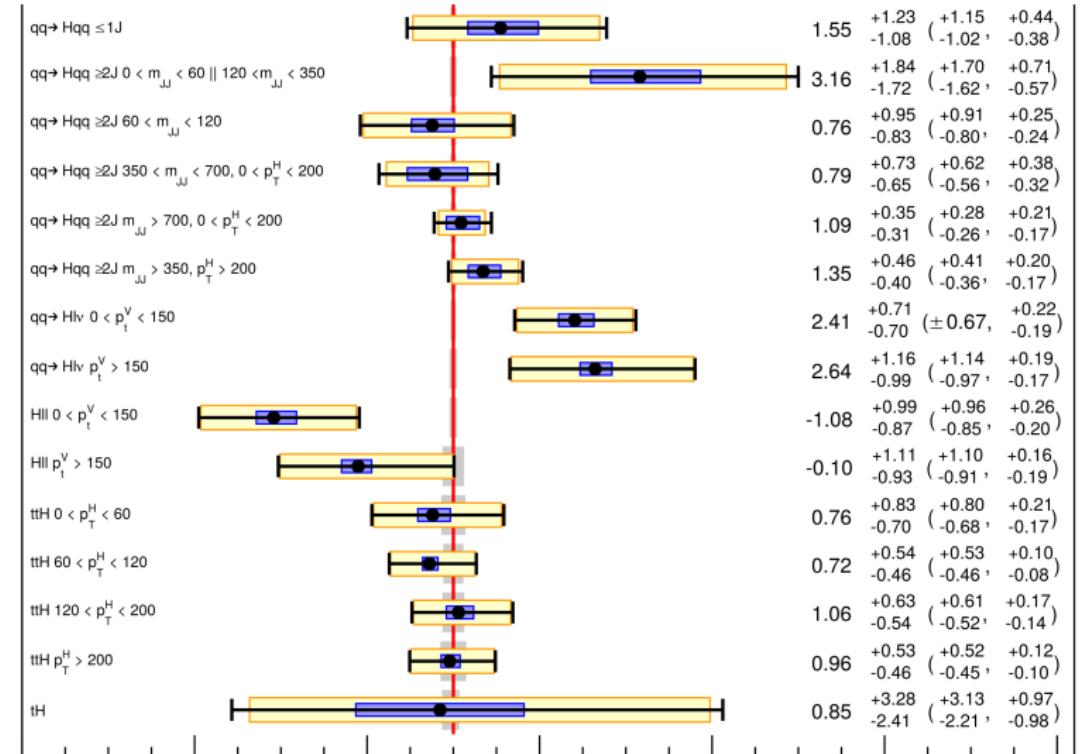
2

4

6

8

$H \rightarrow \gamma\gamma$: STXS VBF, VH, top



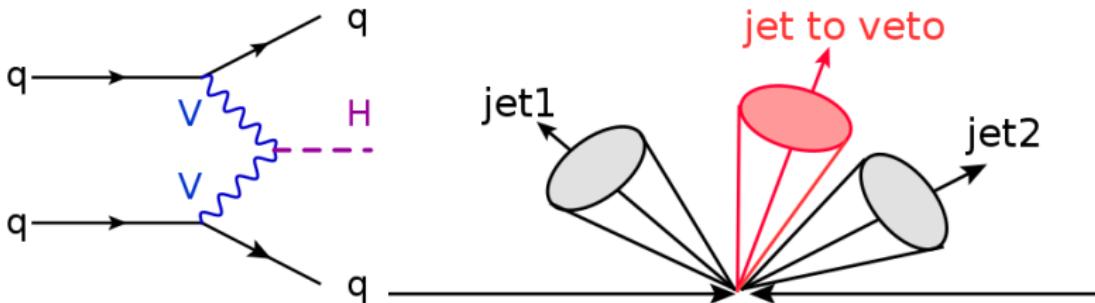
$$H \rightarrow WW^* \rightarrow e\nu\mu\nu : VBF$$

New result with full Run2 dataset (139 fb^{-1}):

ATLAS-CONF-2020-045.

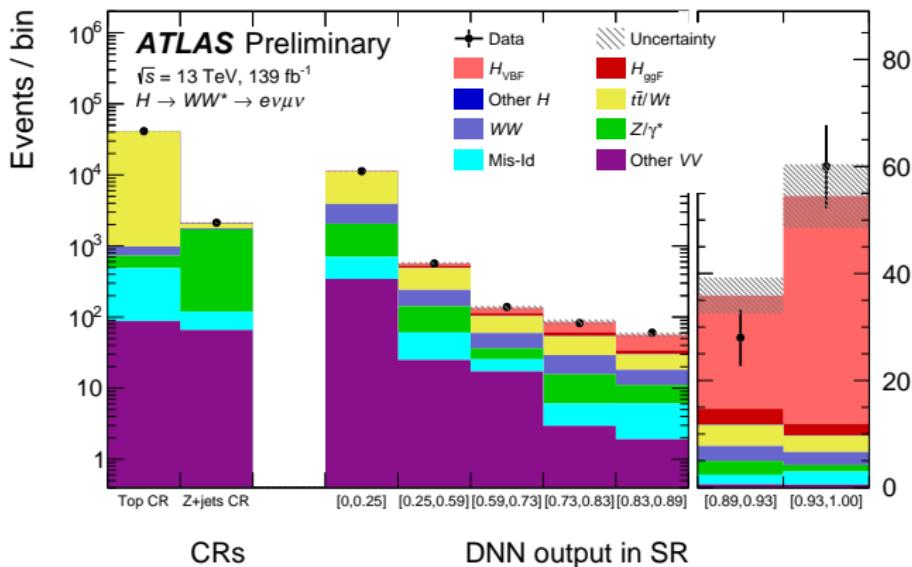
Higher sensitivity compared to previous (36 fb^{-1} publication) strategy, predominantly from:

- optimisation of **central jet veto**; $p_T > 20 \text{ GeV} \rightarrow p_T > 30 \text{ GeV}$
- New multi-variate discriminant for categorization; BDT replaced with DNN, input variables optimised and extended.



$H \rightarrow WW^* \rightarrow e\nu\mu\nu$: VBF

- most backgrounds from MC, CR-s for top and Z+jets, backgrounds with lepton Mis-Id estimated from data
- Signal Region: 7 DNN output bins:
 - require ≥ 10 signal and bkg. events & $\sigma(bkg) < 20\%$
 - set bin boundary once $N_{signal} \geq 20$ in a given bin



$H \rightarrow WW^*$: VBF Observation

Measured signal strength:

$$\mu_{VBF} = 1.04^{+0.13}_{-0.12} \text{ stat. } ^{+0.09}_{-0.08} \text{ exp. } ^{+0.17}_{-0.12} \text{ sig. theo. } ^{+0.08}_{-0.07} \text{ bkg. theo.}$$

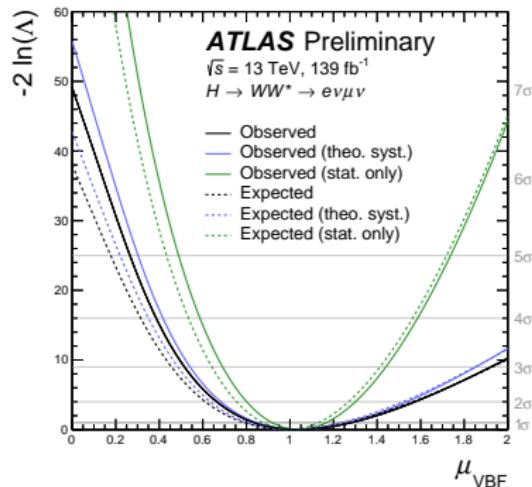
Observed (expected) significance over bkg: $7.0(6.2)\sigma$

Measured:

$$\sigma_{VBF} BR(WW^*) = 0.85^{+0.20}_{-0.17} \text{ pb}$$

SM prediction:

$$\sigma_{VBF} BR(WW^*) = 0.81 \pm 0.02 \text{ pb}$$

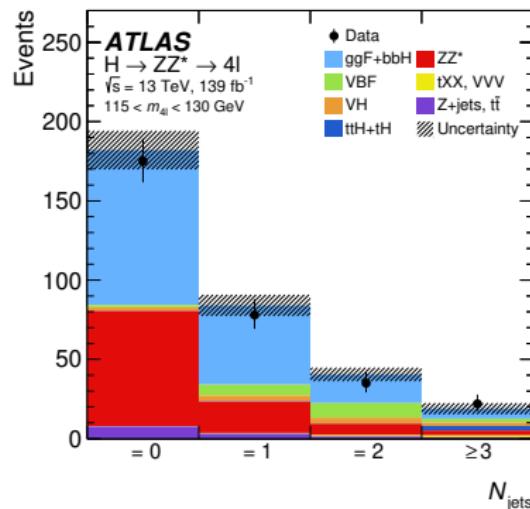
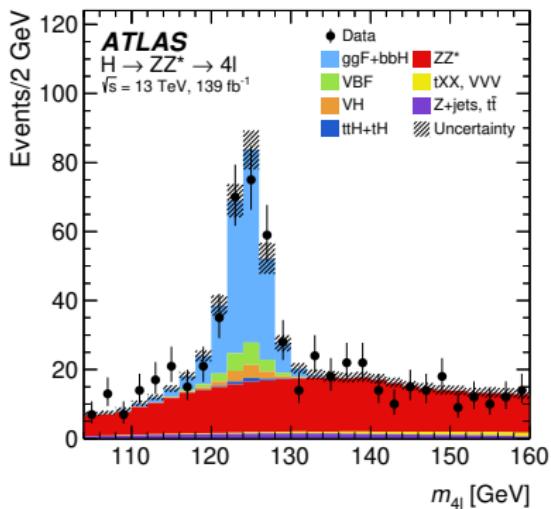


Measurement uncertainty is systematics dominated, largest contribution is from VBF signal modelling (14.4%)

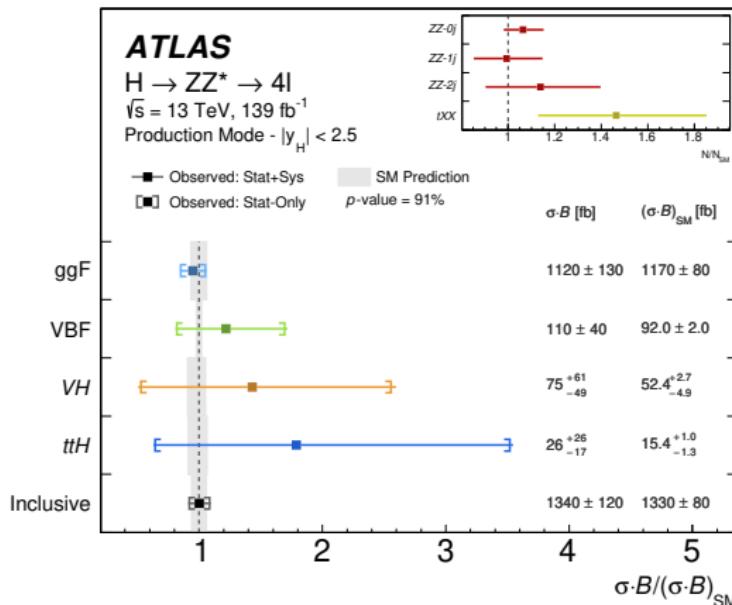
⇒ strong potential for further improvement.

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

- High purity; S/B ~ 2 in the mass peak
- About 200 events observed (& expected), good modelling of all kinematic observables used to measure STXS bins



$H \rightarrow ZZ^*$: Production Modes



Measured $(\sigma BR) / (\sigma BR)_{\text{SM}}$ and stat., exp., and theory uncertainty:

$$\text{ggF: } 0.96 \pm 0.10 \pm 0.03 \quad {}^{+0.03}_{-0.03}$$

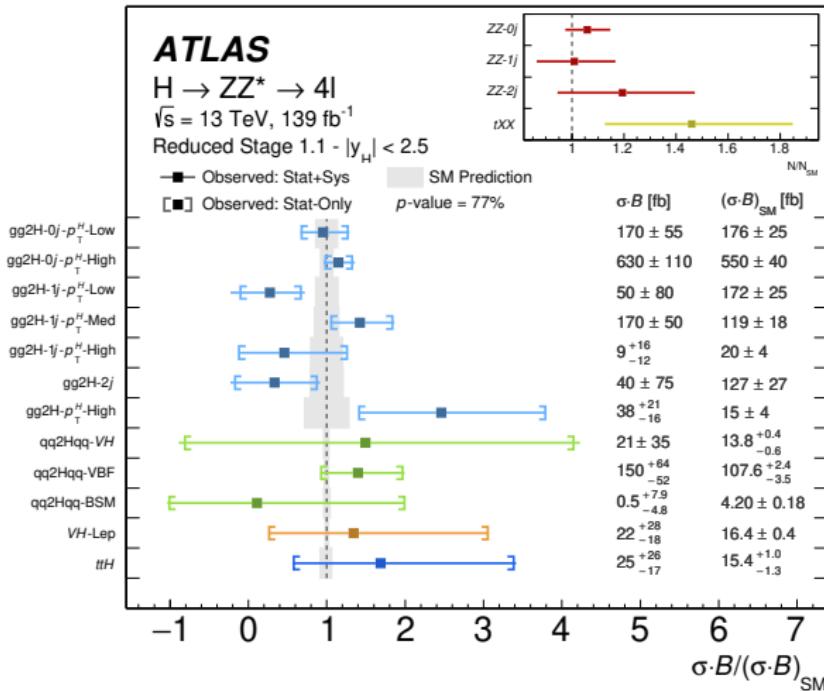
$$\text{VH: } 1.44 \quad {}^{+1.13}_{-0.90} \quad {}^{+0.21}_{-0.14} \quad {}^{+0.24}_{-0.17}$$

$$\text{VBF: } 1.21 \pm 0.44 \quad {}^{+0.13}_{-0.08} \quad {}^{+0.07}_{-0.05}$$

$$\text{ttH: } 1.7 \quad {}^{+1.7}_{-1.2} \quad \pm 0.2 \pm 0.2$$

$H \rightarrow ZZ^* \rightarrow 4\ell$: STXS Bins

Results for (Reduced) STXS stage 1.1 granularity



All results consistent with SM, uncertainty stat.-dominated.

Summary

**Production mode cross sections of Higgs → bosons:
two new preliminary results with the full Run2 dataset.**

- $H \rightarrow \gamma\gamma$: detailed characterization of Higgs boson in 27 STXS bins. Compatible with SM (p-value: 60%).
- $H \rightarrow WW^*$: observation of VBF production with $7.0(6.2)\sigma$
(Other production modes not yet updated.)

Beyond larger stats., **increase in sensitivity** wrt. previous results from improvements in **ML discriminants and event selection**.

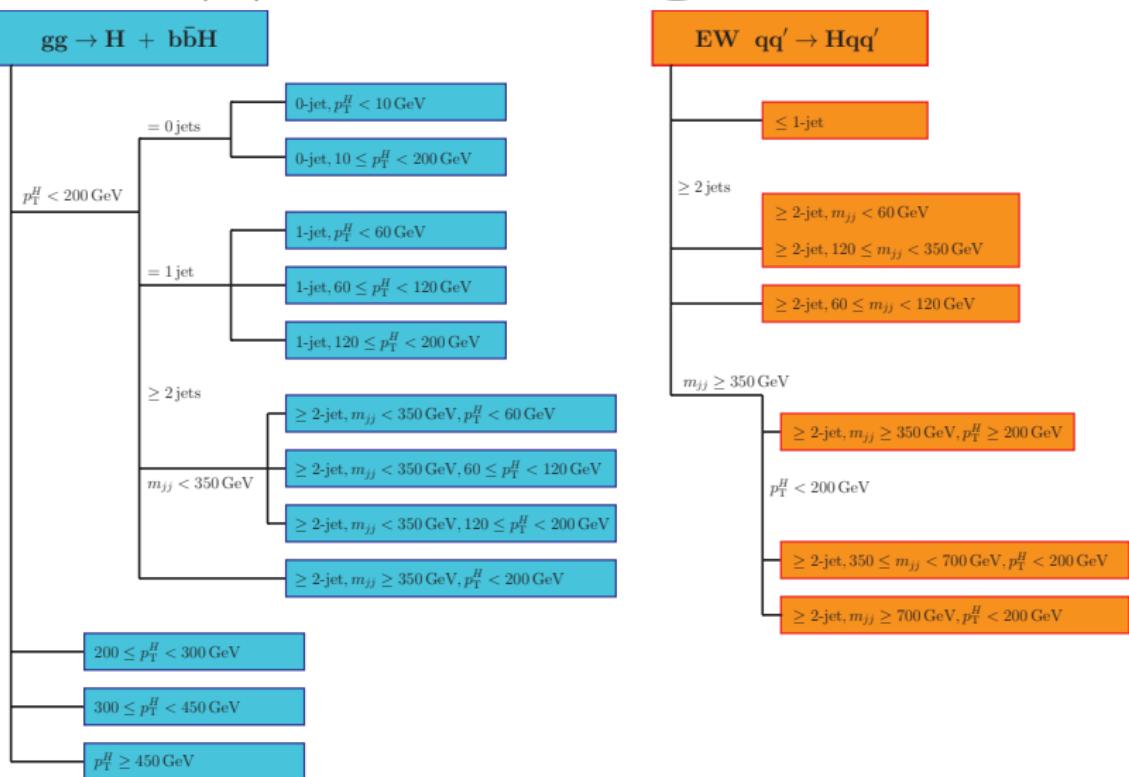
Outlook:

- The measurements in $H \rightarrow ZZ^*$ decays and $VH, t\bar{t}H, tH$ production cross-section measurements in $H \rightarrow \gamma\gamma$ and STXS granularity remain limited by stat. uncertainty in Run2.
- VBF production mode measurements in $H \rightarrow \gamma\gamma, H \rightarrow WW^*$ are limited by signal modelling uncertainty ⇒ strong potential for improvement.

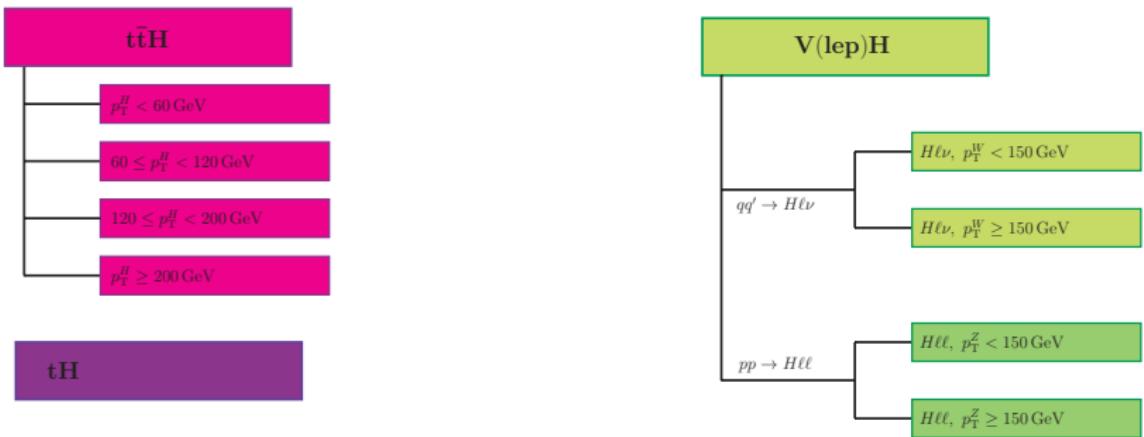
Extra



$H \rightarrow \gamma\gamma$: STXS regions

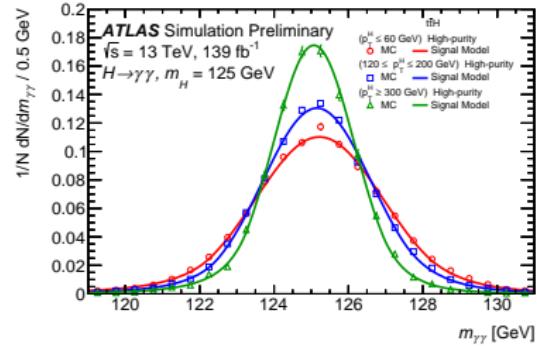
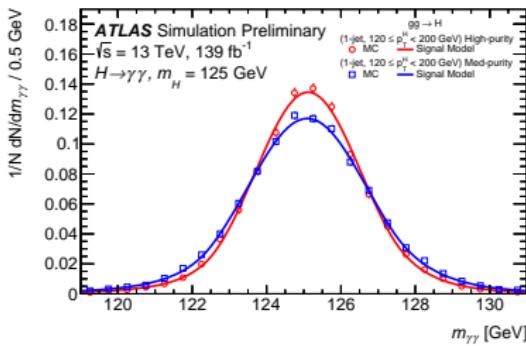


$H \rightarrow \gamma\gamma$: STXS regions Cont'd

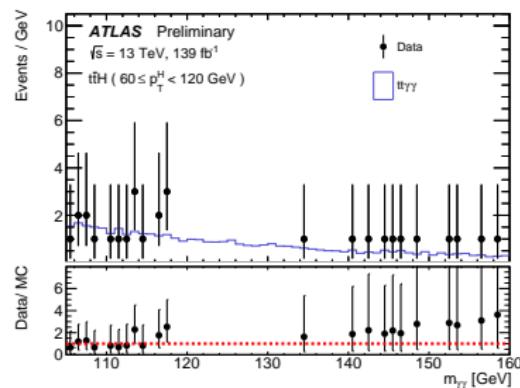
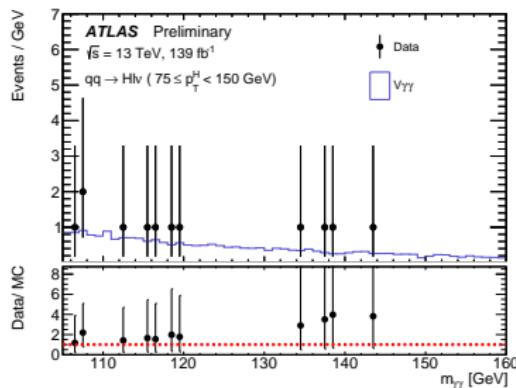
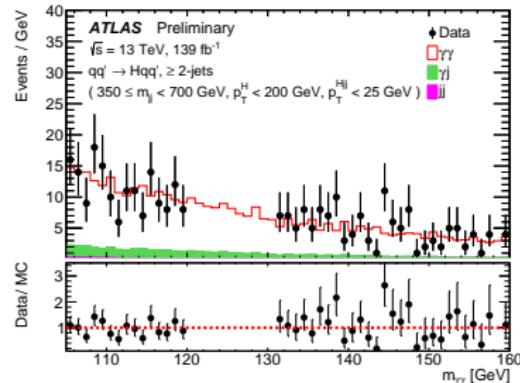
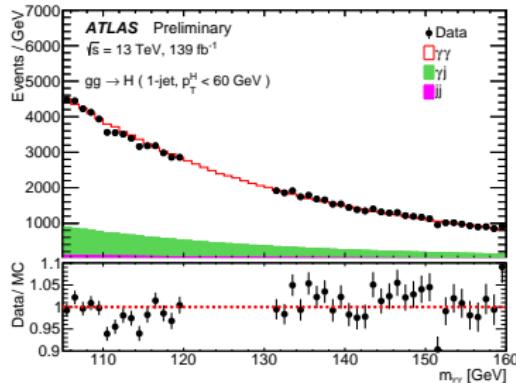


$H \rightarrow \gamma\gamma$: Signal Modelling

- Signal shape is described using a double-sided Crystal Ball function
- left: $gg \rightarrow H$ (1-jet, $120 \leq p_T^H < 200$ GeV) bin, different purities
- right: categories targeting different p_T^H regions of the $t\bar{t}H$ mode



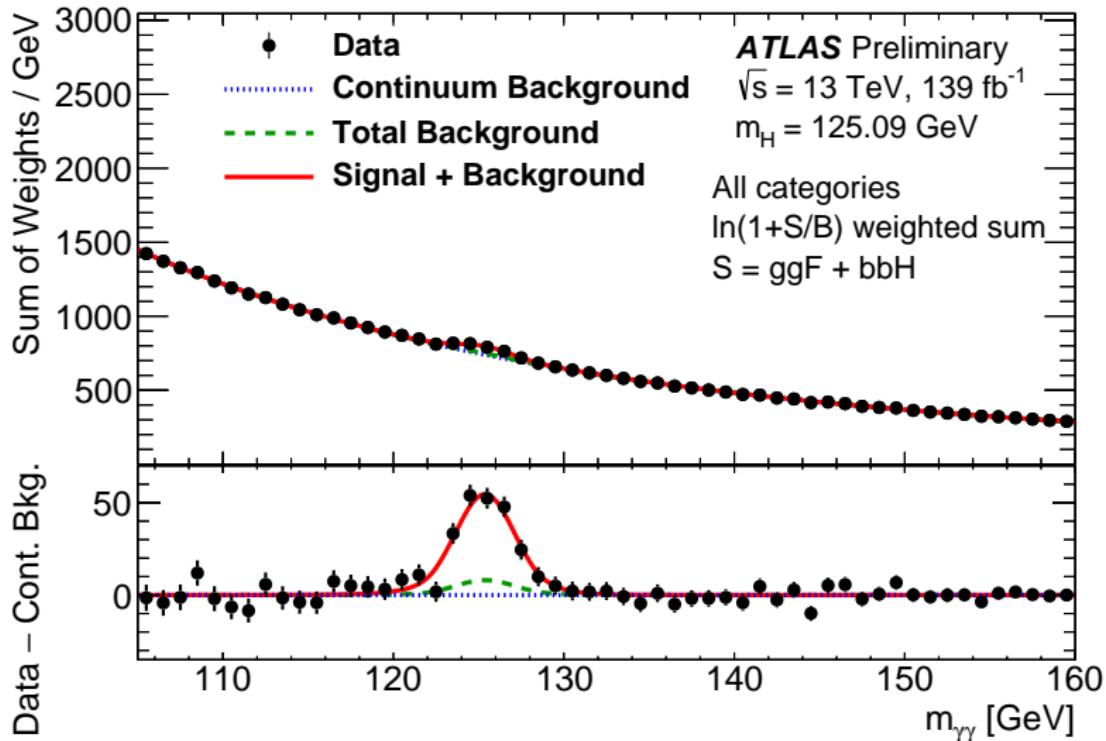
$H \rightarrow \gamma\gamma$: Backgrounds



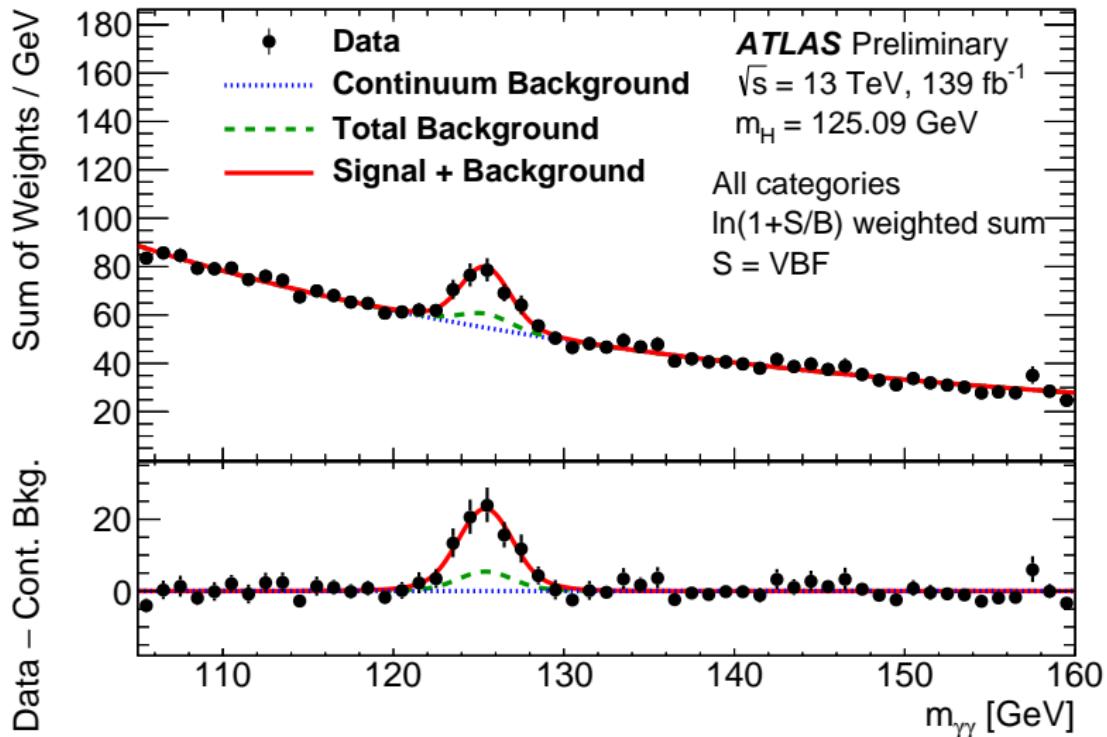
$H \rightarrow \gamma\gamma$: Uncertainties

Uncertainty source	ggF+ bbH	VBF	WH	ZH	$t\bar{t}H + tH$
	$\Delta\sigma[\%]$	$\Delta\sigma[\%]$	$\Delta\sigma[\%]$	$\Delta\sigma[\%]$	$\Delta\sigma[\%]$
Underlying Event and Parton Shower (UEPS)	± 2.3	± 10	$< \pm 1$	± 9.6	± 3.5
Modeling of Heavy Flavor Jets in non- $t\bar{t}H$ Processes	$< \pm 1$	$< \pm 1$	$< \pm 1$	$< \pm 1$	± 1.3
Higher-Order QCD Terms (QCD)	± 1.6	$< \pm 1$	$< \pm 1$	± 1.9	$< \pm 1$
Parton Distribution Function and α_S Scale (PDF+ α_S)	$< \pm 1$	± 1.1	$< \pm 1$	± 1.9	$< \pm 1$
Photon Energy Resolution (PER)	± 2.9	± 2.4	± 2.0	± 1.3	± 4.9
Photon Energy Scale (PES)	$< \pm 1$	$< \pm 1$	$< \pm 1$	± 3.4	± 2.2
Jet/ E_T^{miss}	± 1.6	± 5.5	± 1.2	± 4.0	± 3.0
Photon Efficiency	± 2.5	± 2.3	± 2.4	± 1.4	± 2.4
Background Modeling	± 4.1	± 4.7	± 2.8	± 18	± 2.4
Flavor Tagging	$< \pm 1$				
Leptons	$< \pm 1$				
Pileup	± 1.8	± 2.7	± 2.1	± 3.8	± 1.1
Luminosity and Trigger	± 2.1	± 2.1	± 2.3	± 1.1	± 2.3
Higgs Boson Mass	$< \pm 1$	$< \pm 1$	$< \pm 1$	± 3.7	± 1.9

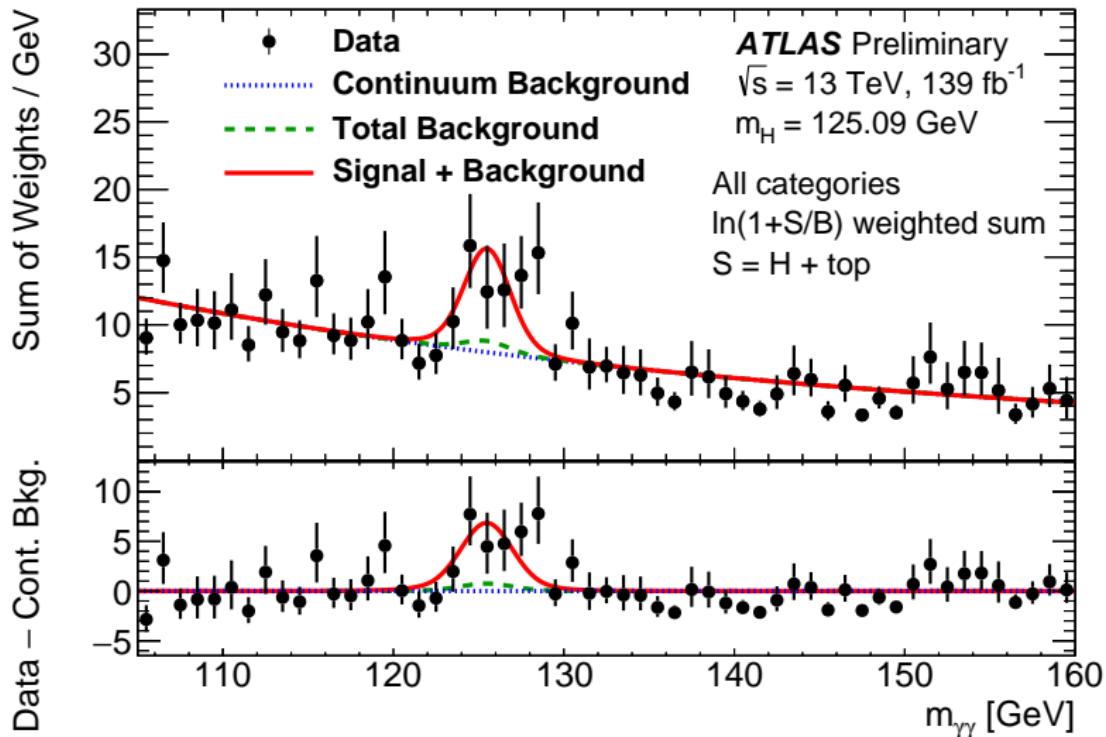
$H \rightarrow \gamma\gamma : ggF$



$H \rightarrow \gamma\gamma : \text{VBF}$



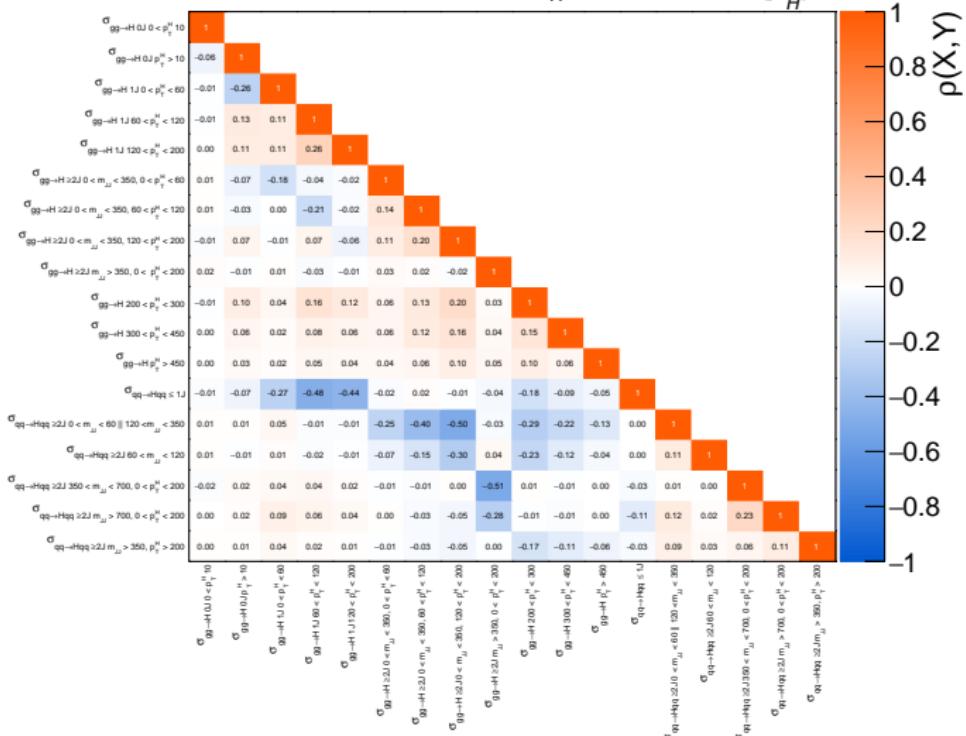
$H \rightarrow \gamma\gamma : ttH + tH$



H → γγ : ggF/VBF Correl.

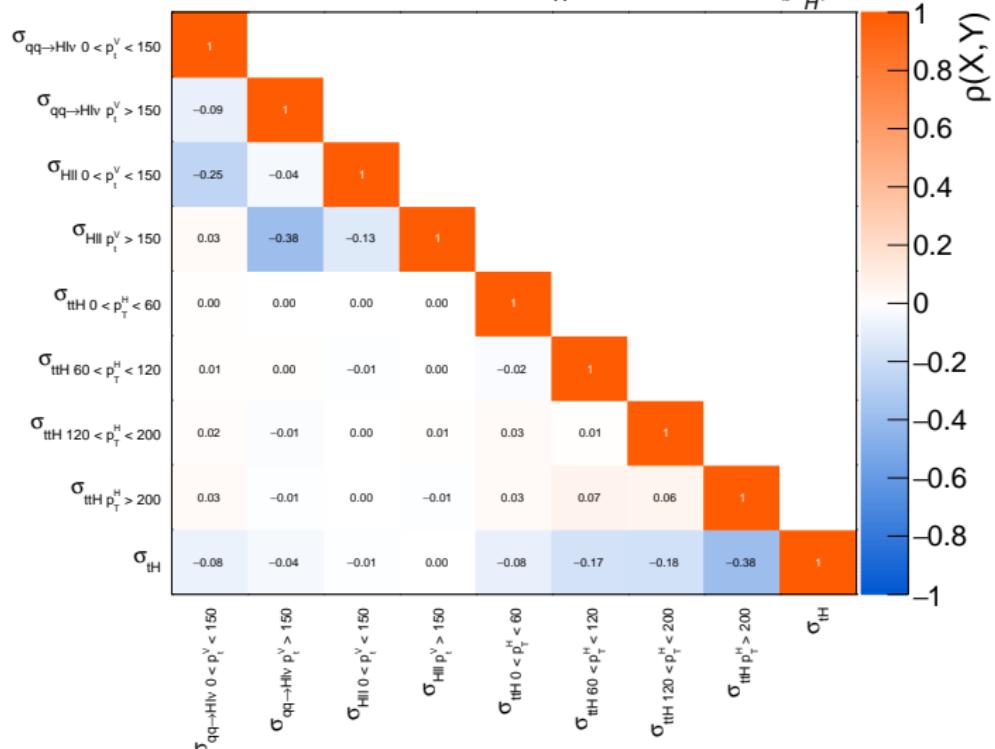
ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$
 $m_H = 125.09 \text{ GeV}, |y_H| < 2.5$

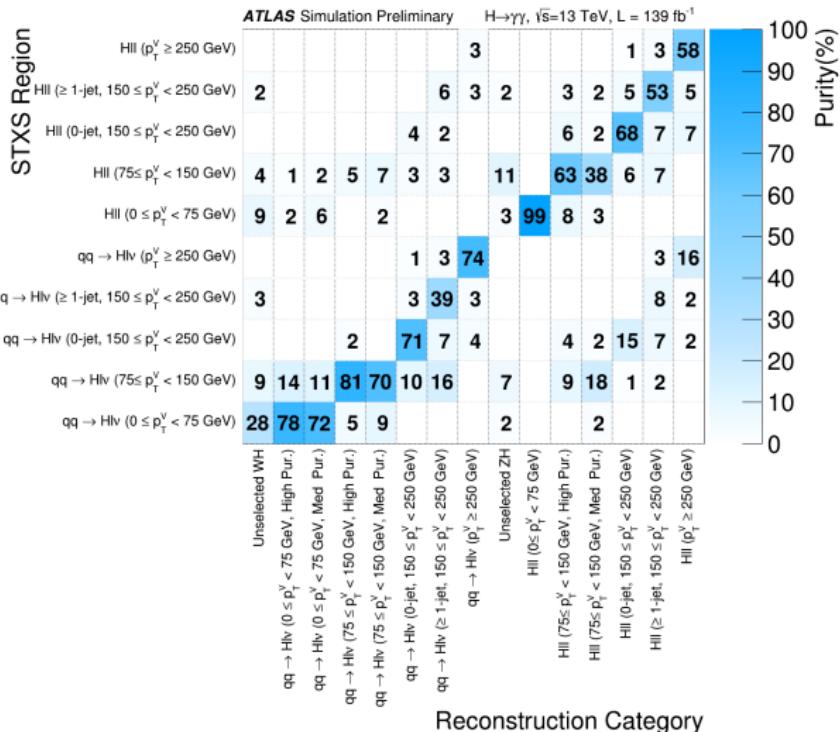


$H \rightarrow \gamma\gamma$: VH, top Correlations

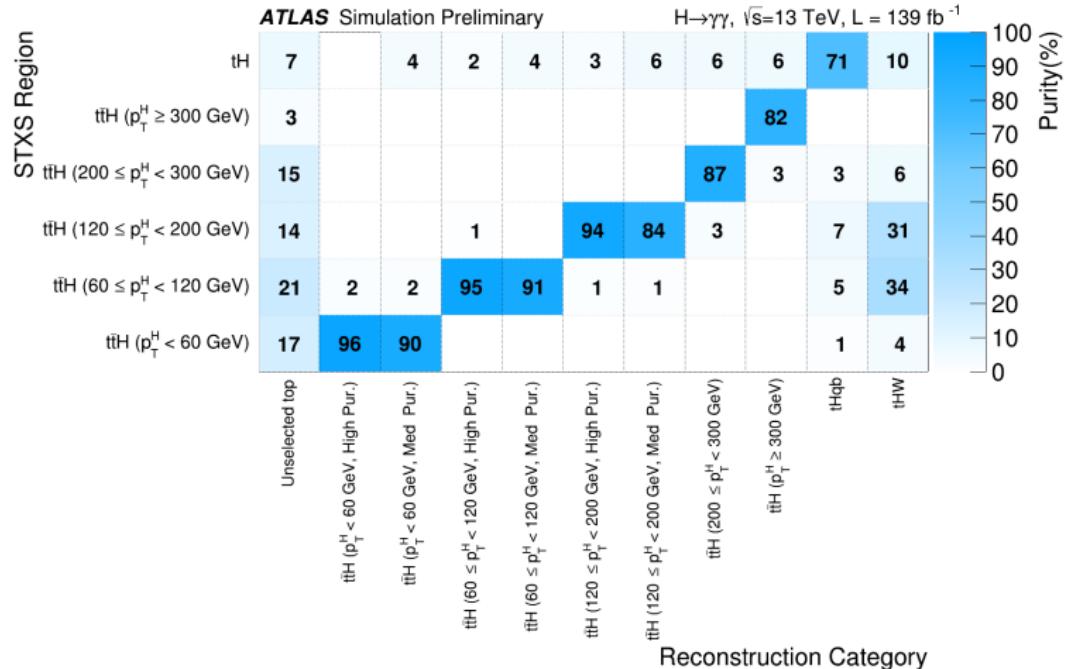
ATLAS Preliminary $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$
 $m_H = 125.09 \text{ GeV}, |y_H| < 2.5$



$H \rightarrow \gamma\gamma$: STXS

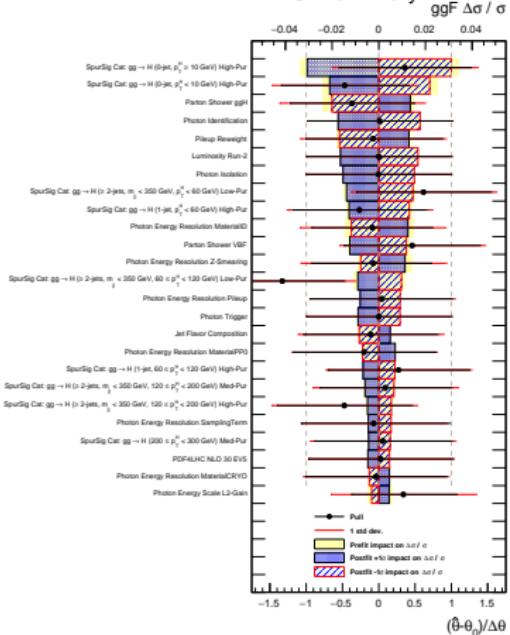


$H \rightarrow \gamma\gamma$: STXS

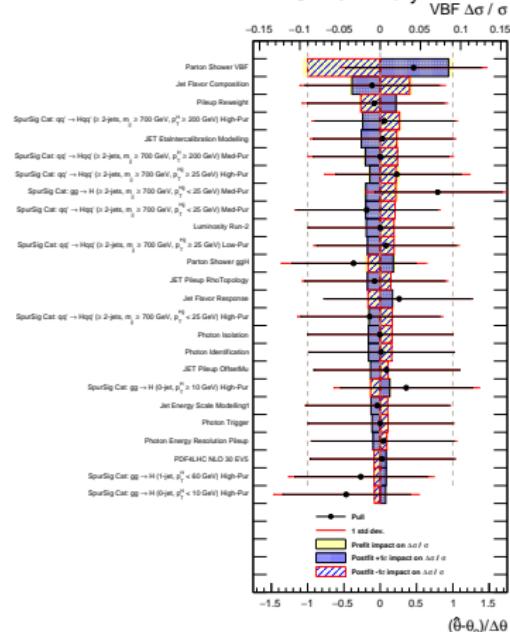


H → γγ : Fit

ATLAS Preliminary



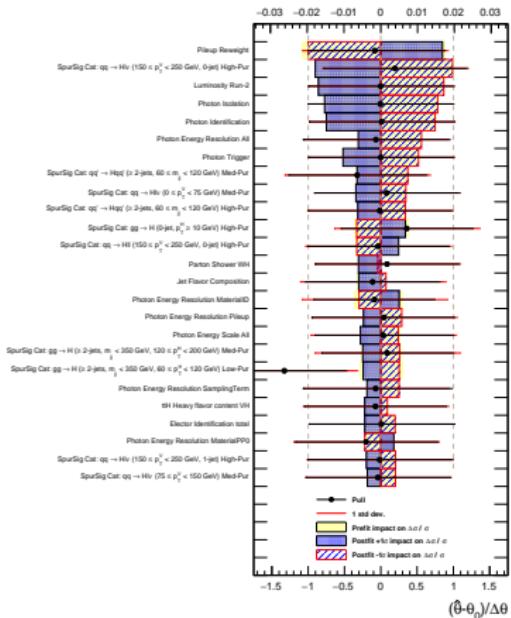
ATLAS Preliminary



$H \rightarrow \gamma\gamma$: Fit

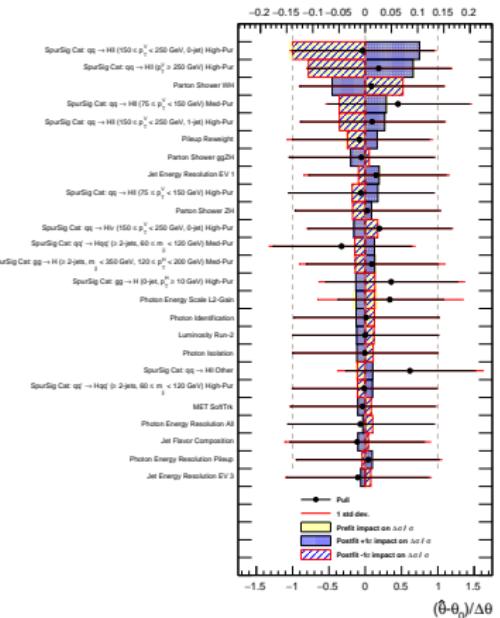
ATLAS Preliminary

WH $\Delta\sigma / \sigma$



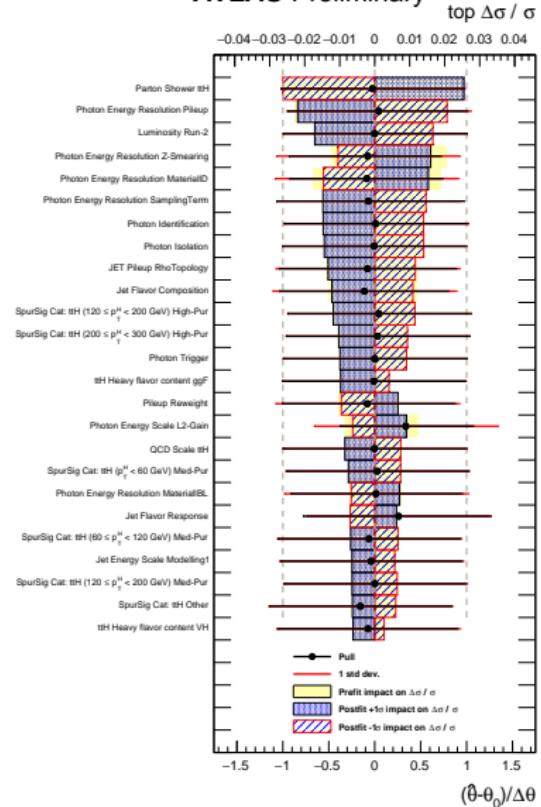
ATLAS Preliminary

ZH $\Delta\sigma / \sigma$



$H \rightarrow \gamma\gamma$: Fit

ATLAS Preliminary



$H \rightarrow WW^* \rightarrow e\nu\mu\nu : \text{VBF}$

Event selection

	Signal region	$Z + \text{jets CR}$	Top quark CR
Pre-selection	<p>Two isolated, different-flavour leptons ($\ell = e, \mu$) with opposite charge</p> <p>$p_T^{\text{lead}} > 22 \text{ GeV}$, $p_T^{\text{sublead}} > 15 \text{ GeV}$</p> <p>$m_{\ell\ell} > 10 \text{ GeV}$, $N_{\text{jet}} \geq 2$</p> <p>$N_{b\text{-jet},(p_T > 20 \text{ GeV})} = 0$</p>	<p>$N_{b\text{-jet},(p_T > 20 \text{ GeV})} = 0$</p>	<p>$N_{b\text{-jet},(p_T > 20 \text{ GeV})} = 1$</p>
Selection	<p>$m_{\tau\tau} < m_Z - 25 \text{ GeV}$</p> <p>$m_{jj} > 120 \text{ GeV}$</p> <p>–</p>	<p>$m_{\tau\tau} - m_Z < 25 \text{ GeV}$</p> <p>–</p> <p>$m_{\ell\ell} < 70 \text{ GeV}$</p> <p>central jet veto</p> <p>outside lepton veto</p>	<p>$m_{\tau\tau} < m_Z - 25 \text{ GeV}$</p> <p>–</p> <p>–</p>

A DNN is applied in the SR that uses 15 discriminant variables:

$$\Delta\phi_{\ell\ell}, m_{\ell\ell}, m_T, \Delta y_{jj}, m_{jj}, p_T^{\text{tot}}, \sum_\ell C_\ell, m_{\ell_1 j_1}, m_{\ell_1 j_2}, m_{\ell_2 j_1}, m_{\ell_2 j_2}, p_T^{\text{jet}_1}, p_T^{\text{jet}_2}, p_T^{\text{jet}_3}, \text{and } E_T^{\text{miss}}$$

$H \rightarrow WW^*$: VBF Discriminant

Deep Neural Network with keras TensorFlow used to separate signal from background. Inputs (**extended** and refined):

- **VBF topology:**

- m_{jj} , Δy_{jj}
- $\sum_\ell C_\ell$, where $C_\ell = |2\eta_\ell - \sum \eta_j|/\Delta\eta_{jj}$ (lepton η -centrality)
- $p_T^{jet_1}$, $p_T^{jet_2}$, $p_T^{jet_3}$, $m_{\ell_1 j_1}$, $m_{\ell_1 j_2}$, $m_{\ell_2 j_1}$, $m_{\ell_2 j_2}$

- **$H \rightarrow WW$ decay topology**

- $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$
- m_t (dilepton+ E_T transverse mass)

- **$t\bar{t}$ background suppression**

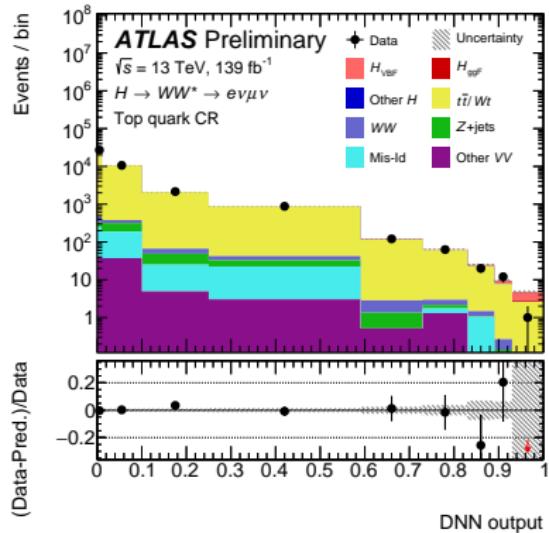
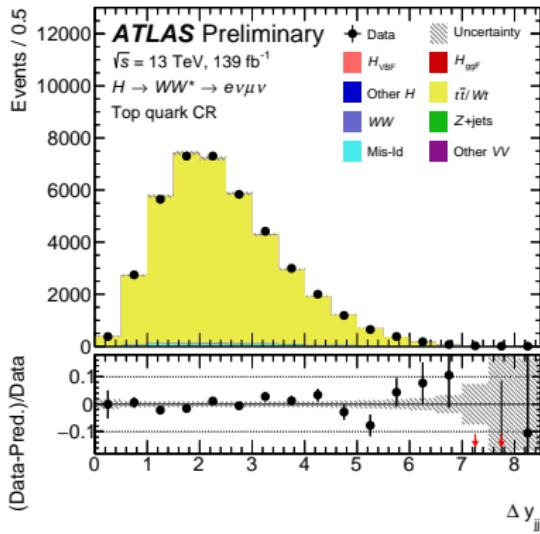
- p_T^{tot} (magnitude of vectorial sum of p_T of all selected objects)
- E_T^{miss} significance

Previous analysis BDT inputs were:

m_{jj} , Δy_{jj} , $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_t , $\sum_\ell C_\ell$, p_T^{tot} , $\sum_{\ell,j} m_{\ell j}$

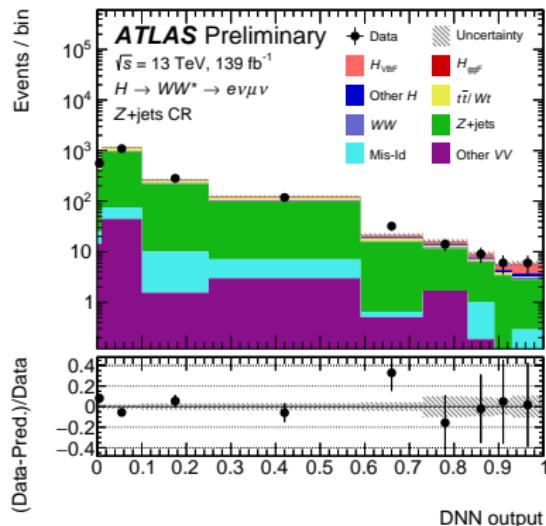
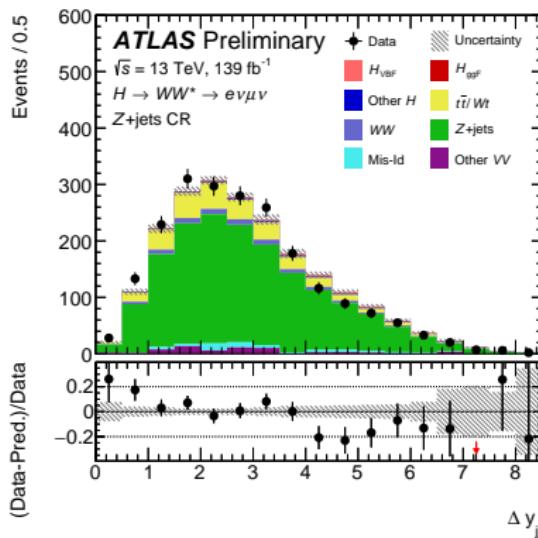
$H \rightarrow WW^* : \text{VBF, Top CR}$

- CR definition requires exactly one b-jet instead of b-jet veto
- CR is 98% pure in top quark backgrounds
- post-fit normalization factor: $1.02^{+0.17}_{-0.13}$



$H \rightarrow WW^* : \text{VBF, Z CR}$

- CR definition inverts $Z \rightarrow \tau\tau$ mass veto
- CR is 78% pure in $Z+\text{jets}$ backgrounds
- post-fit normalization factor: $0.94^{+0.25}_{-0.20}$



$H \rightarrow WW^* : \text{VBF SR Yields}$

Process	Total	Highest DNN bin
H_{VBF}	209 ± 37	42.5 ± 6.5
H_{ggF}	169 ± 62	2.2 ± 1.5
Other Higgs	28 ± 2.0	0.1 ± 0.3
$t\bar{t}/Wt$	7520 ± 830	3.0 ± 1.7
Z/γ^*	1460 ± 370	1.2 ± 1.1
WW	2000 ± 350	2.4 ± 1.6
Mis-Id	416 ± 58	2.5 ± 1.6
Other VV	392 ± 64	0.5 ± 0.7
Total	12200 ± 120	54.5 ± 6.0
Observed	12189	60

$H \rightarrow WW^* : VBF$ Uncertainty

Source	$\Delta\mu_{VBF}/\mu_{VBF}$ [%]
Data statistics	12.5
Total systematics	17.8
Experimental uncertainties	8.8
Missing ET	4.7
MC statistics	3.1
Jet energy scale	2.2
Luminosity	1.9
Modelling of pile-up	1.7
<i>b</i> -tagging	1.6
Jet energy resolution	1.4
Misidentified leptons	0.9
VBF signal theory uncertainties	14.4
Background theory uncertainties	7.7
ggF Higgs	5.2
Top-quark	3.3
WW	2.5
Z+jets	1.9
Total	22

$H \rightarrow ZZ^*$: Categories

ATLAS $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$

