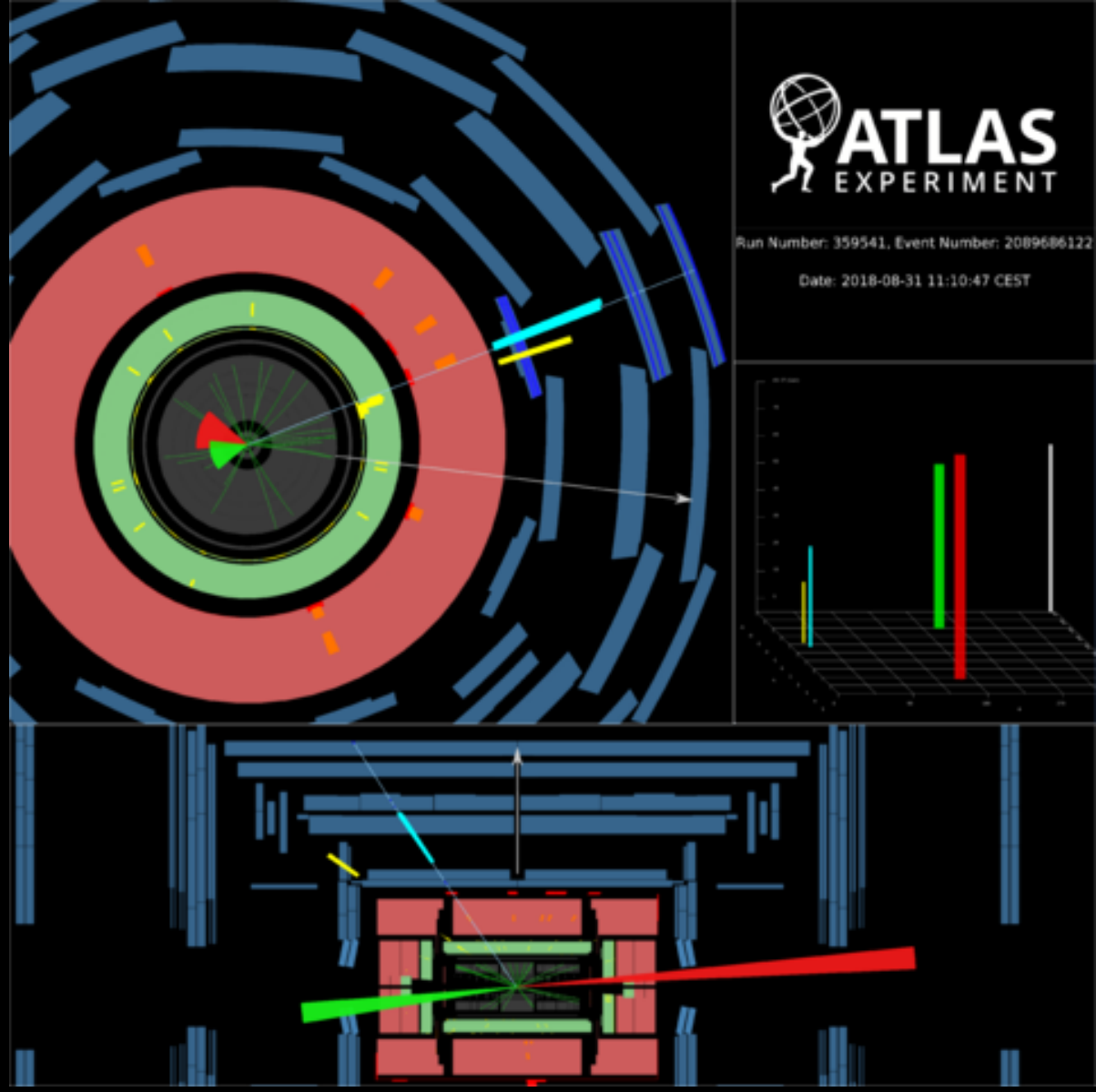
Measurements of gluon fusion and vector-boson-fusion production of the Higgs boson in $H \to WW^* \to e\nu\mu\nu$ decays using 13 TeV pp collisions with the ATLAS detector



Robin Hayes

Higgs Hunting 2021

ATLAS EXPERIMENT

UBC

TRIUMF

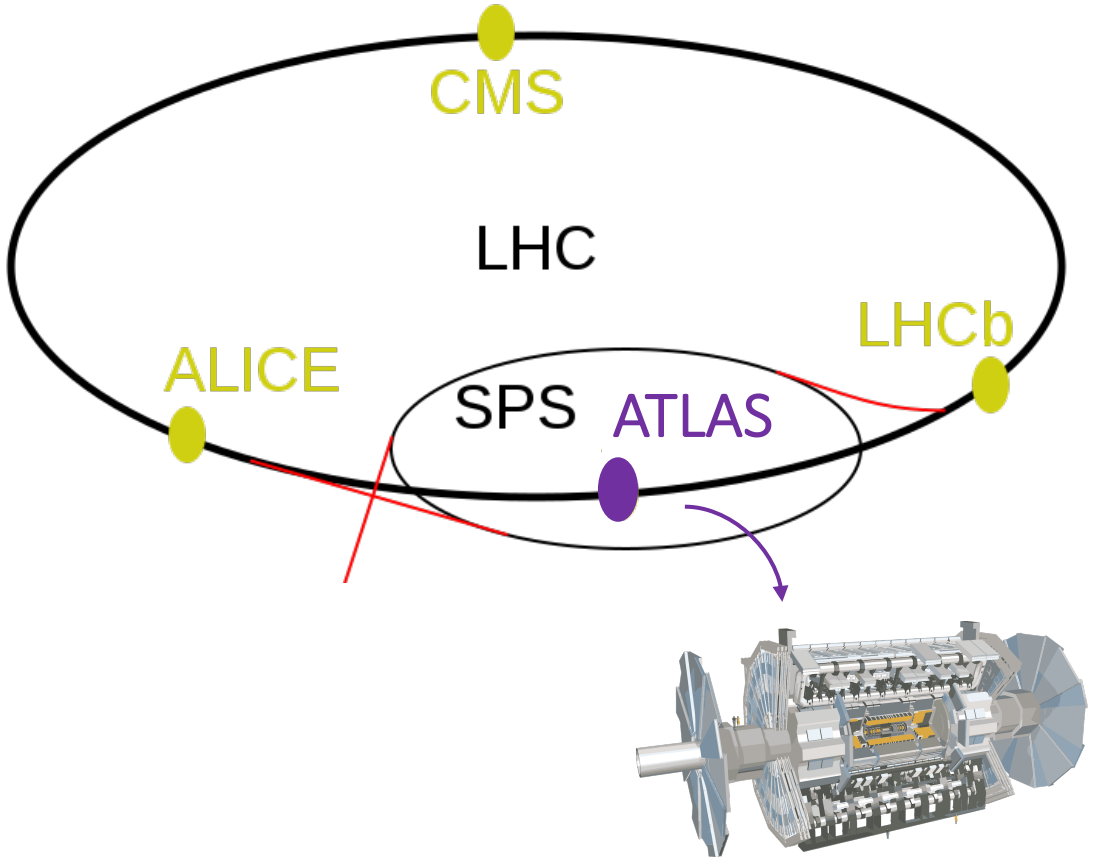
Analysis Overview

Analysis Scope: ATLAS-CONF-2021-014

- ggF and VBF production of Higgs bosons in the $H \to WW^* \to e\nu\mu\nu$ decay channel.
- Aim to measure cross-sections times branching fractions ($\sigma^{\text{obs}} \cdot BR_{H\to WW^*}$) and signal strengths ($\mu = \sigma^{\text{obs}}/\sigma^{\text{SM}}$)

Full Run-2 Result

- Data for this result comes from *pp* collisions at $\sqrt{s}$ = 13 TeV at CERN's Large Hadron Collider (LHC).
  - Collected between 2015-2018 ("Run 2") with the ATLAS detector.
- This analysis makes several changes with respect to the previous (36 fb^{-1}) ATLAS measurement [1]:
  - ✓ Addition of ggF ≥ 2-jet channel
  - ✓ Use of deep neural network (DNN) in VBF channel
  - ✓ Measurement of cross-sections in kinematic bins ("STXS").

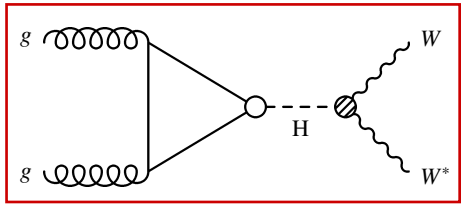


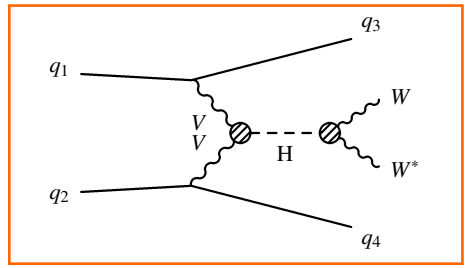
1. arXiv: 1808.09054 [hep-ex]

Analysis Strategy

Common Preselection:

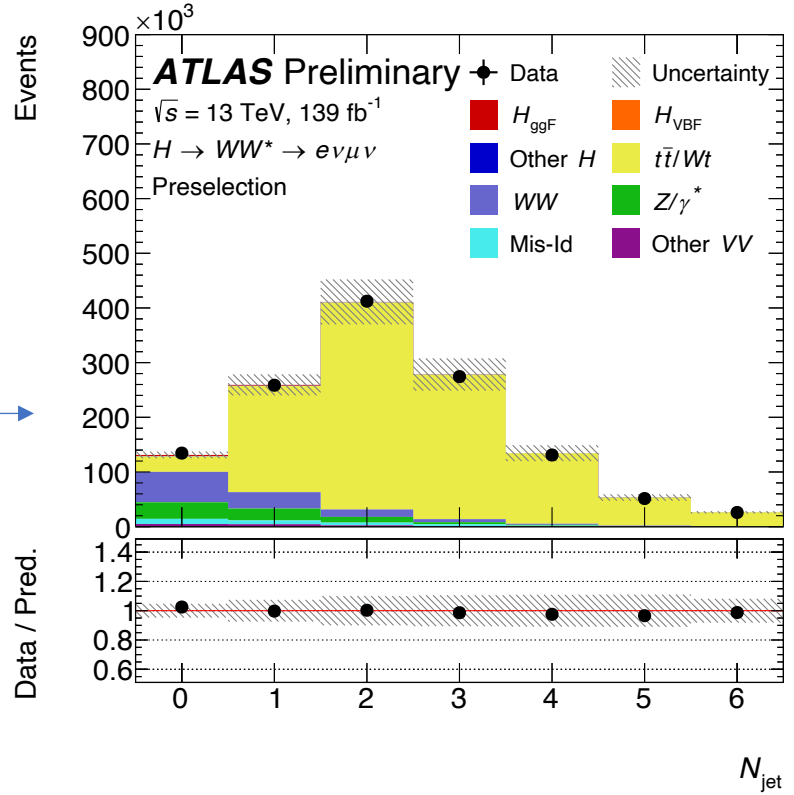
- Cuts target features of $\mathrm{H} \to WW^* \to e\nu\mu\nu$ decay and reduce some common backgrounds:
  - ✓ Single-lepton and dilepton triggers used
  - ✓ 2 different-flavour, opposite-charge leptons
  - ✓ $p_{\mathrm{T}}^{\mathrm{lead}} > 22$ GeV, $p_{\mathrm{T}}^{\mathrm{sublead}} > 15$ GeV
  - ✓ $m_{ll} > 10$ GeV
  - ✓ $p_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV (ggF channels only)





Defining Analysis Channels:

- Channels split by number of jets with $p_{\mathrm{T}} > 30$ GeV after preselection:
  - ➢ $N_{\mathrm{jets}} = 0$ and $N_{\mathrm{jets}} = 1$ channels to target ggF
  - ➢ $N_{\mathrm{jets}} \geq 2$ channels to target ggF and VBF
- Motivated by differing background compositions in each region.
- Remaining cuts are targeted to each analysis category.



ggF 0-jet and 1-jet Channels

Background rejection

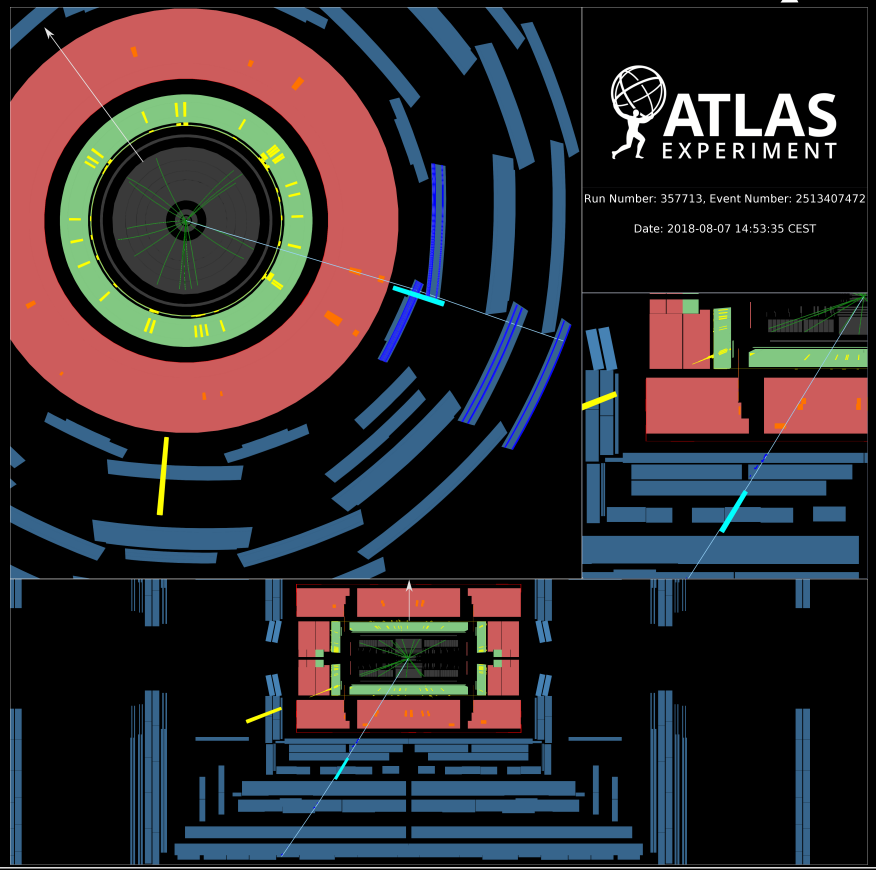
- ✓ $N_{b-jet}^{p_T>20\ \text{GeV}} = 0$ } 0 & 1-jet
- ✓ $\Delta\phi_{ll,E_T^{miss}} > \pi/2$
- ✓ $p_T^{ll} > 30$ GeV } 0-jet
- ✓ $m_{\tau\tau} < m_Z - 25$ GeV
- ✓ $\max(m_T^l) > 50$ GeV } 1-jet

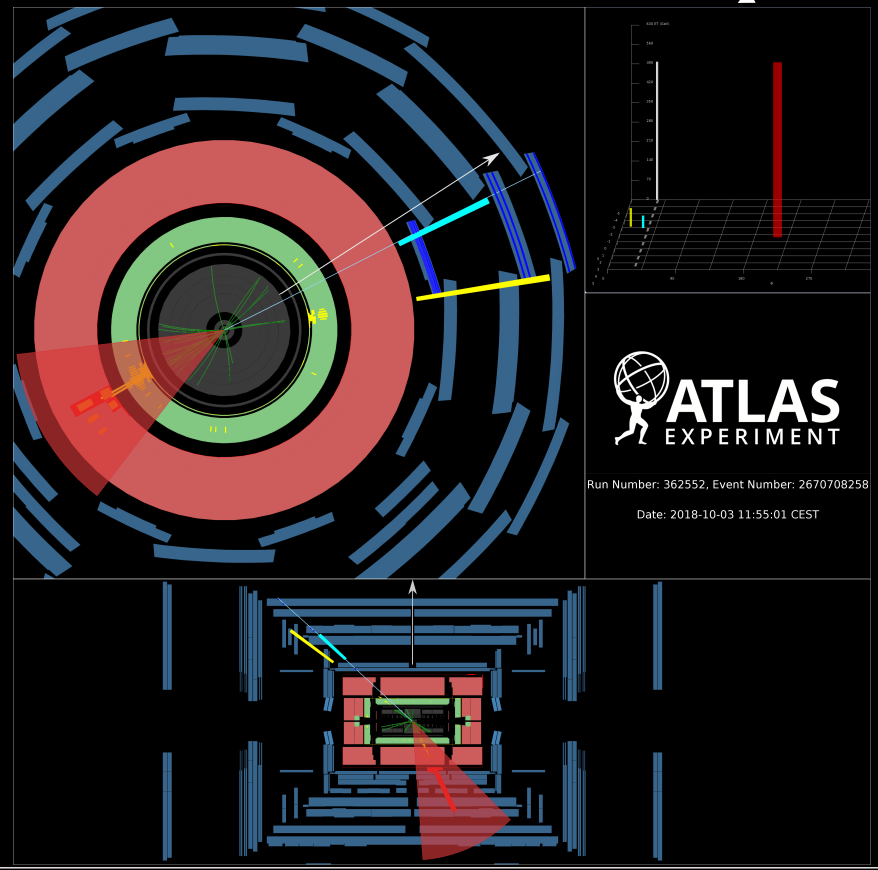
$H \to WW^* \to e\nu\mu\nu$ topology

- ✓ $m_{ll} < 55$ GeV
- ✓ $\Delta\phi_{ll} < 1.8$

Control regions for top, $qqWW$, Z/γ^* backgrounds.

Four signal regions each, split at $m_{ll} = 30$ GeV and $p_T^{sublead} = 20$ GeV





ggF ≥2-jet Channel

Background rejection

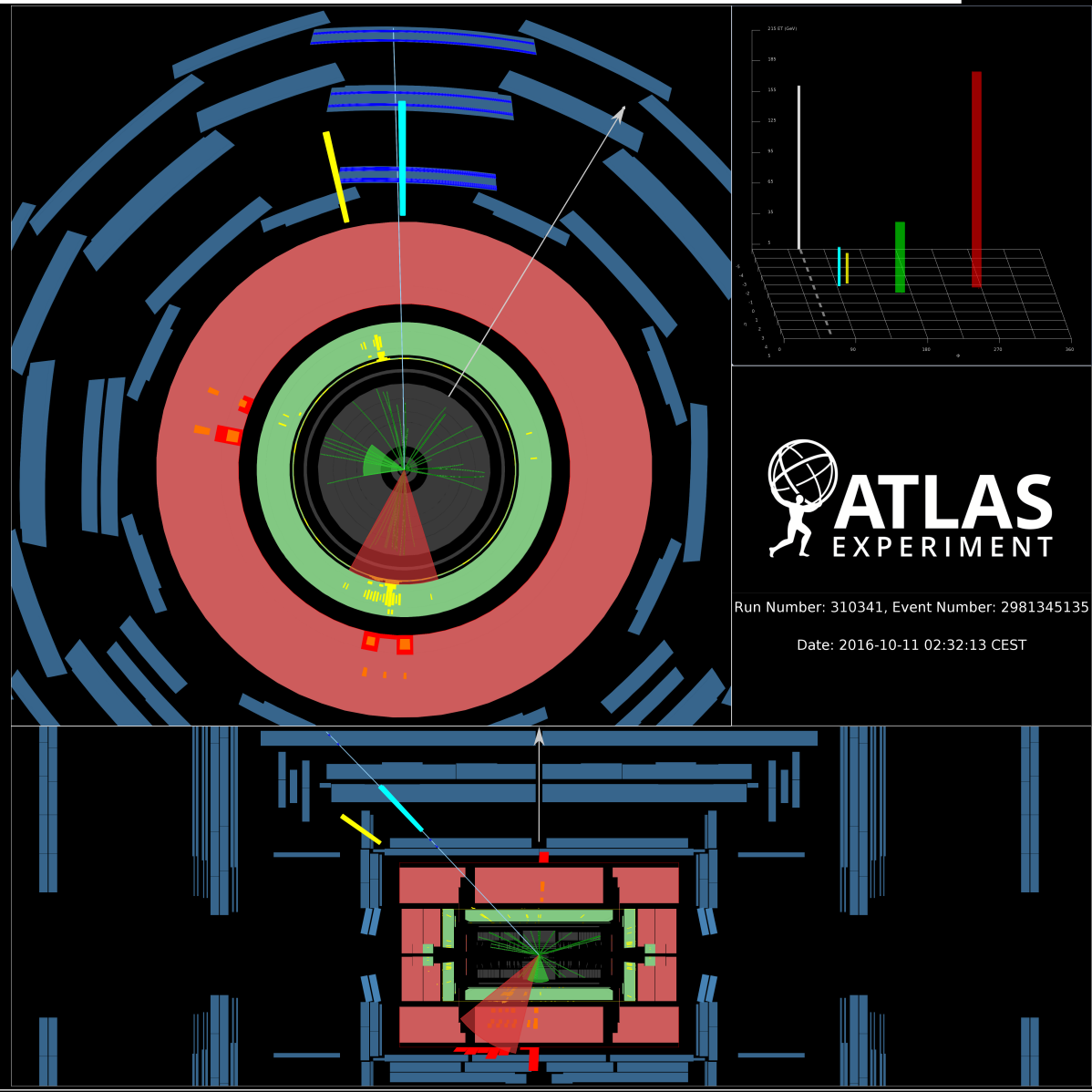
- ✓ $N_{b-jet}^{p_T>20\ \mathrm{GeV}} = 0$
- ✓ $m_{\tau\tau} < m_Z - 25\ \mathrm{GeV}$

$H \to WW^* \to e\nu\mu\nu$ topology

- ✓ $m_{ll} < 55\ \mathrm{GeV}$
- ✓ $\Delta\phi_{ll} < 1.8$
- ✓ $|m_{jj} - 85| \leq 15\ \mathrm{GeV}$ or $\Delta y_{jj} > 1.2$
- ✓ Orthogonality with VBF analysis (fail central jet veto or outside lepton veto)

Control regions for top, *qqWW*, Z/γ^* backgrounds.

Two signal regions split at $m_{ll} = 30\ \mathrm{GeV}$.



VBF ≥2-jet Channel

Background rejection

- ✓ $N_{b-jet}^{p_T>20\ \mathrm{GeV}} = 0$
- ✓ $m_{\tau\tau} < m_Z - 25\ \mathrm{GeV}$

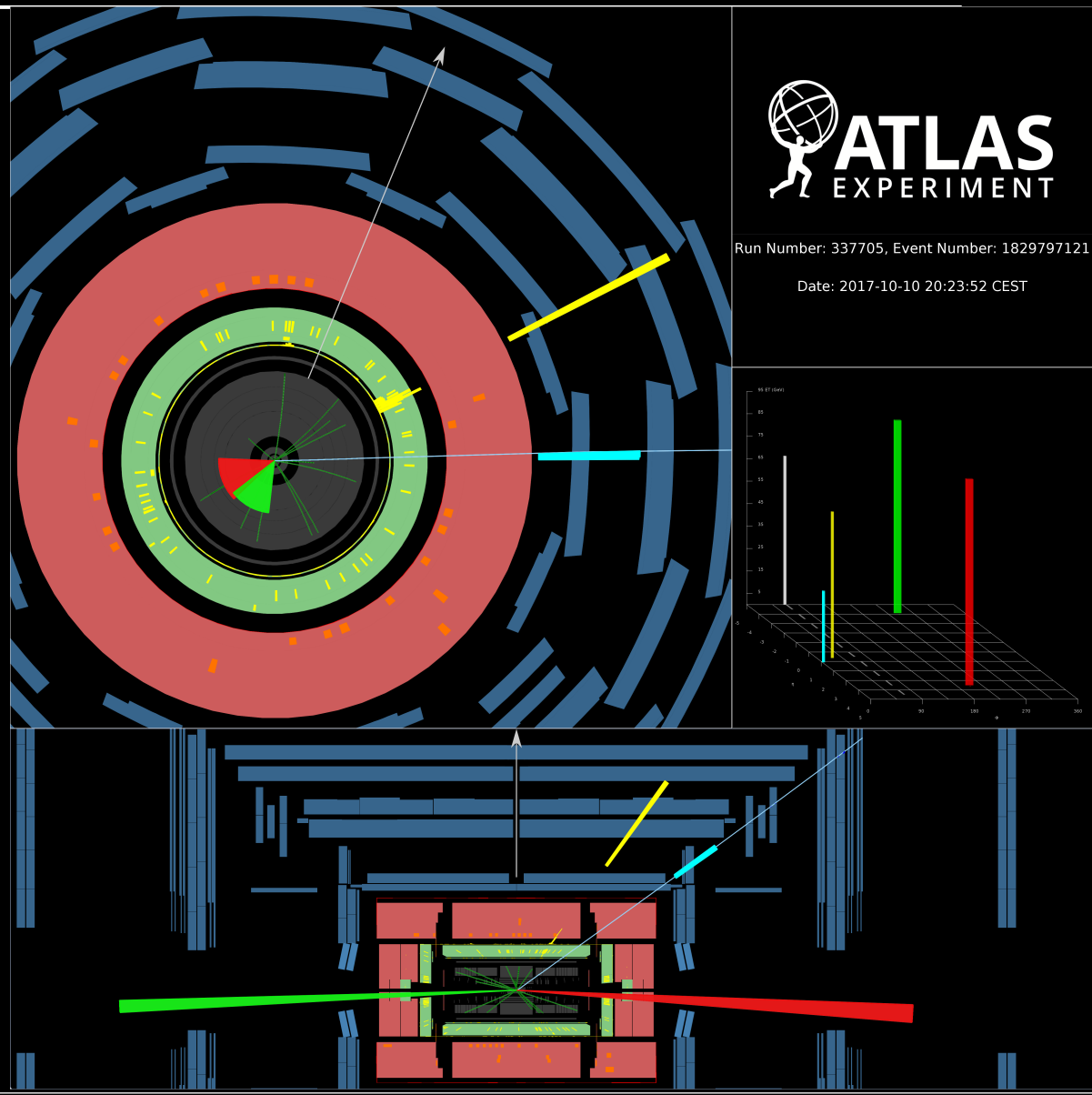
$H \to WW^* \to e\nu\mu\nu$ topology

- ✓ Central jet veto
- ✓ Outside lepton veto
- ✓ $m_{jj} > 120$ GeV (Orthogonality with VH analysis)

Control regions for top, Z/γ^* backgrounds.

Events categorized by DNN score based on 15 variables:

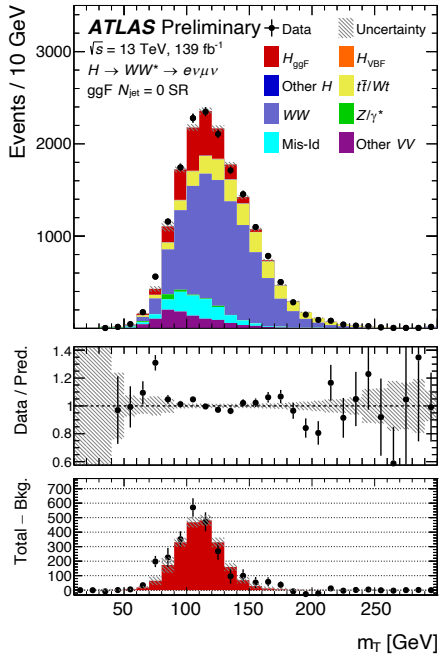
$$\Delta y_{jj}, m_{jj}, \eta_\ell^{\mathrm{centrality}}, m_{\ell 1 j1}, m_{\ell 1 j2}, m_{\ell 2 j1}, m_{\ell 2 j2},$$
$$p_{\mathrm{T}}^{\mathrm{jet}_1}, p_{\mathrm{T}}^{\mathrm{jet}_2}, p_{\mathrm{T}}^{\mathrm{jet}_3}, \Delta\phi_{\ell\ell}, m_{\ell\ell}, m_{\mathrm{T}}, p_{\mathrm{T}}^{\mathrm{tot}}, \mathrm{MET\ sig}$$



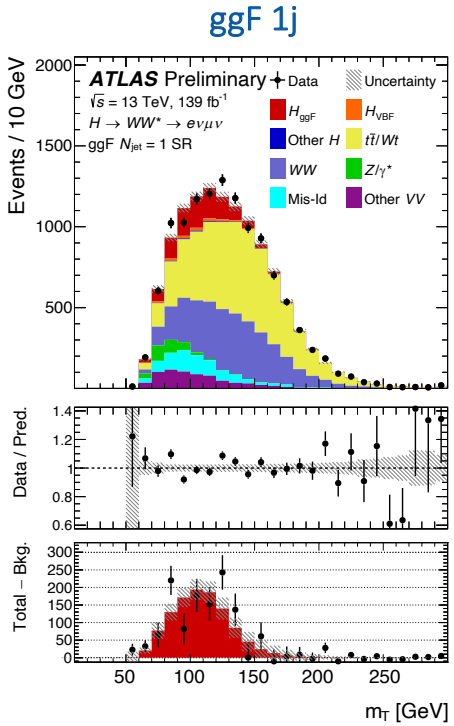
Results: Inclusive ggF and VBF Cross-Sections

- Final discriminant: m_{T} (ggF analyses) or DNN output (VBF analysis).
- Extract signal strengths using a **profile likelihood fit** to data in the signal and control regions.

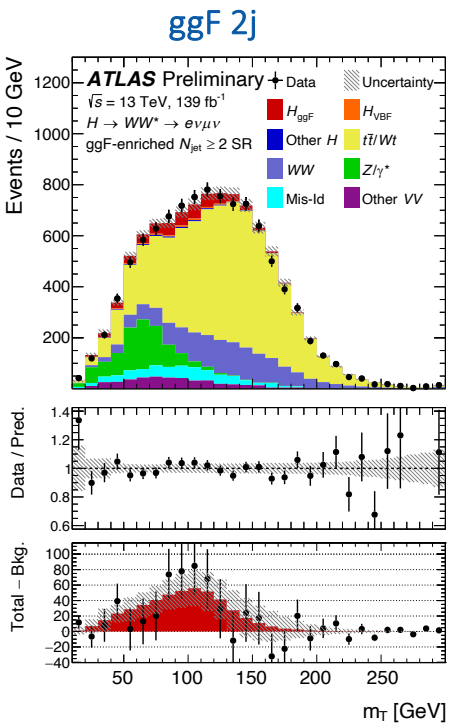
ggF 0j



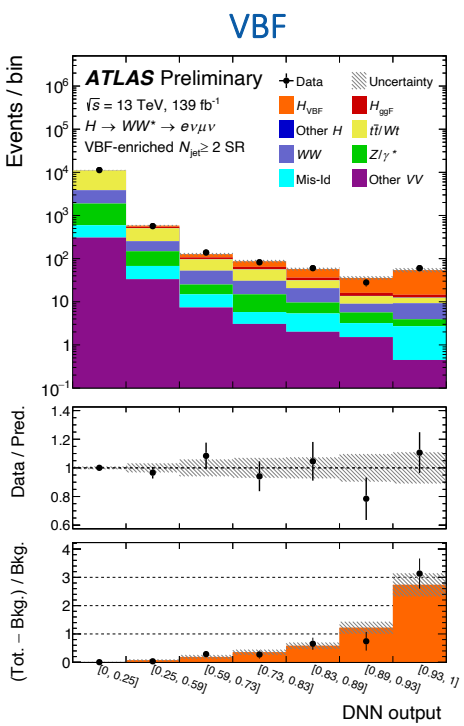
ggF 1j



ggF 2j



VBF



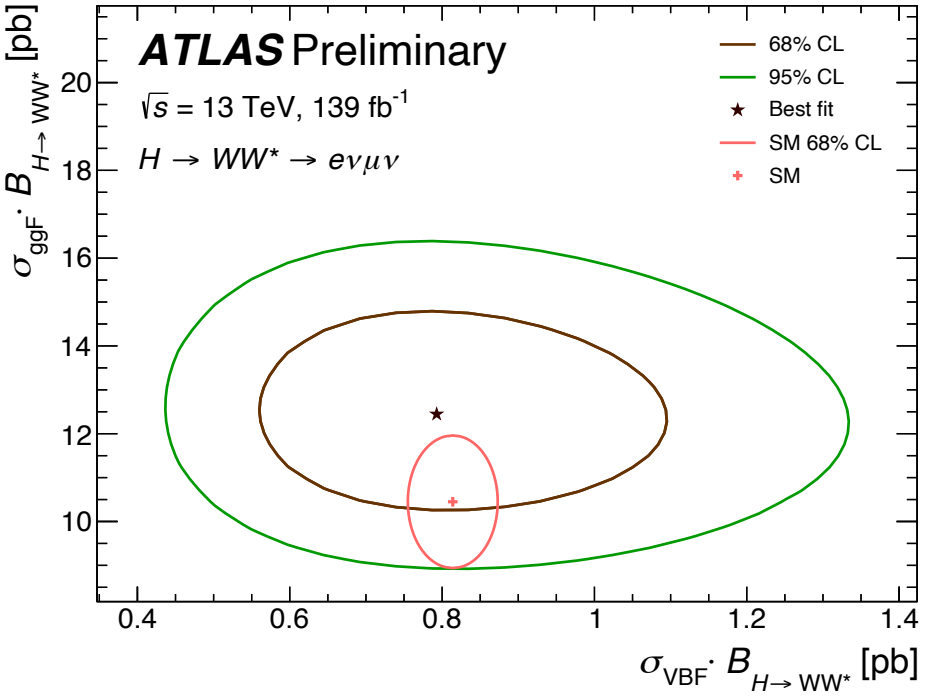
Simultaneous measurement of ggF and VBF signal strengths shows good consistency with the SM:

$$\mu_{\mathrm{ggF}} = 1.20\,^{+0.16}_{-0.15}$$
$$= 1.20 \pm 0.05\ (\mathrm{stat.})\,^{+0.09}_{-0.08}\ (\mathrm{exp\ syst.})\,^{+0.10}_{-0.08}\ (\mathrm{sig\ theo.})\,^{+0.12}_{-0.11}\ (\mathrm{bkg\ theo.})$$

$$\mu_{\mathrm{VBF}} = 0.99\,^{+0.24}_{-0.20}$$
$$= 0.99\,^{+0.13}_{-0.12}\ (\mathrm{stat.})\,^{+0.07}_{-0.06}\ (\mathrm{exp\ syst.})\,^{+0.17}_{-0.12}\ (\mathrm{sig\ theo.})\,^{+0.10}_{-0.08}\ (\mathrm{bkg\ theo.}).$$

Results: Inclusive ggF and VBF Cross-Sections

Also measure cross-sections times branching fractions for both production modes:



$$\sigma_{\mathrm{ggF}} \cdot \mathcal{B}_{H\to WW^*} = 12.4 \pm 1.5 \text{ pb}$$
$$= 12.4 \pm 0.6 \text{ (stat.)} \pm 0.9 \text{ (exp syst.)} \,^{+0.7}_{-0.6} \text{ (sig theo.)} \pm 1.0 \text{ (bkg theo.) pb}$$
$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}_{H\to WW^*} = 0.79 \,^{+0.19}_{-0.16} \text{ pb}$$
$$= 0.79 \,^{+0.11}_{-0.10} \text{ (stat.)} \,^{+0.06}_{-0.05} \text{ (exp syst.)} \,^{+0.13}_{-0.09} \text{ (sig theo.)} \,^{+0.08}_{-0.06} \text{ (bkg theo.) pb,}$$

Source	$\frac{\Delta\sigma_{\mathrm{ggF}}\cdot\mathcal{B}_{H\to WW^*}}{\sigma_{\mathrm{ggF}}\cdot\mathcal{B}_{H\to WW^*}}$ [%]	$\frac{\Delta\sigma_{\mathrm{VBF}}\cdot\mathcal{B}_{H\to WW^*}}{\sigma_{\mathrm{VBF}}\cdot\mathcal{B}_{H\to WW^*}}$ [%]
Data statistical uncertainties	5	13
Total systematic uncertainties	11	18
MC statistical uncertainties	4	3.2
Experimental uncertainties	6	7
Flavour Tagging	2.4	0.9
Jet energy scale	1.4	3.3
Jet energy resolution	2.3	1.9
$E_{\mathrm{T}}^{\mathrm{miss}}$	1.9	5
Muons	2.1	0.7
Electrons	1.5	0.3
Fake factors	2.4	1.0
Pile-up	2.4	1.3
Luminosity	2.0	2.1
Theoretical uncertainties	8	16
ggF	5	4
VBF	0.7	13
Top	4	5
$Z\tau\tau$	2.0	2.1
WW	4	5
Other VV	3	1.2
Background normalisations	5	5
WW	3.1	0.5
Top	2.4	2.2
$Z\tau\tau$	3.1	4
TOTAL	12	22

Largest contribution to measurement uncertainty comes from theory uncertainty on the **signal** (for σ_{VBF}) and **background** (for σ_{ggF}).

Simplified Template Cross-Sections

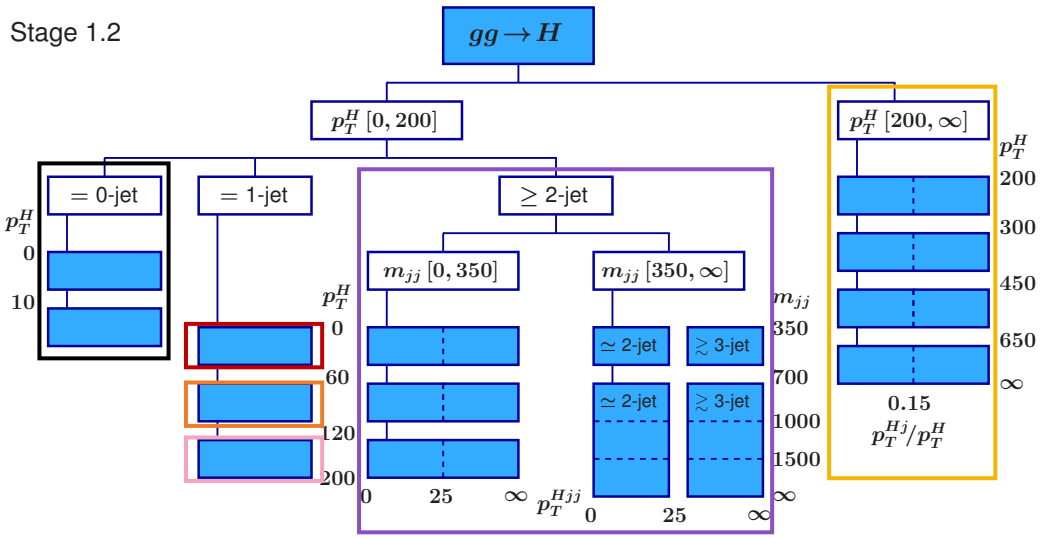
- Results are extended with measurement of cross-sections in kinematic bins prescribed by the **Simplified Template Cross-Section (STXS) framework.**
- Cross-section measured are defined by STXS Stage 1.2 splitting, with bins merged according to analysis sensitivity.

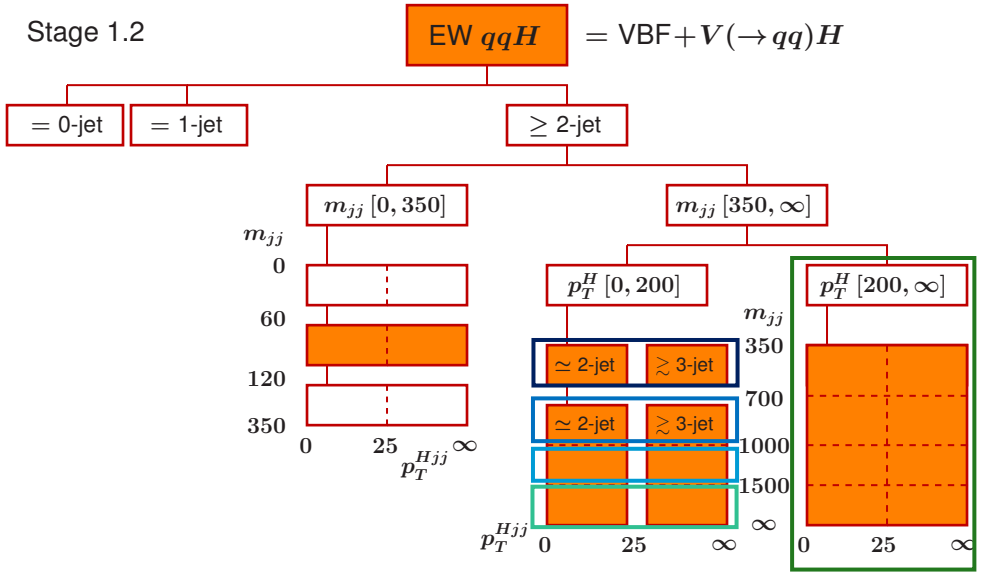
ggH production:

- Measure 6 POIs
- Targeted by 0, 1 and ≥ 2-jet ggF signal regions further split by p_{T}^{H}.

EW qqH production:

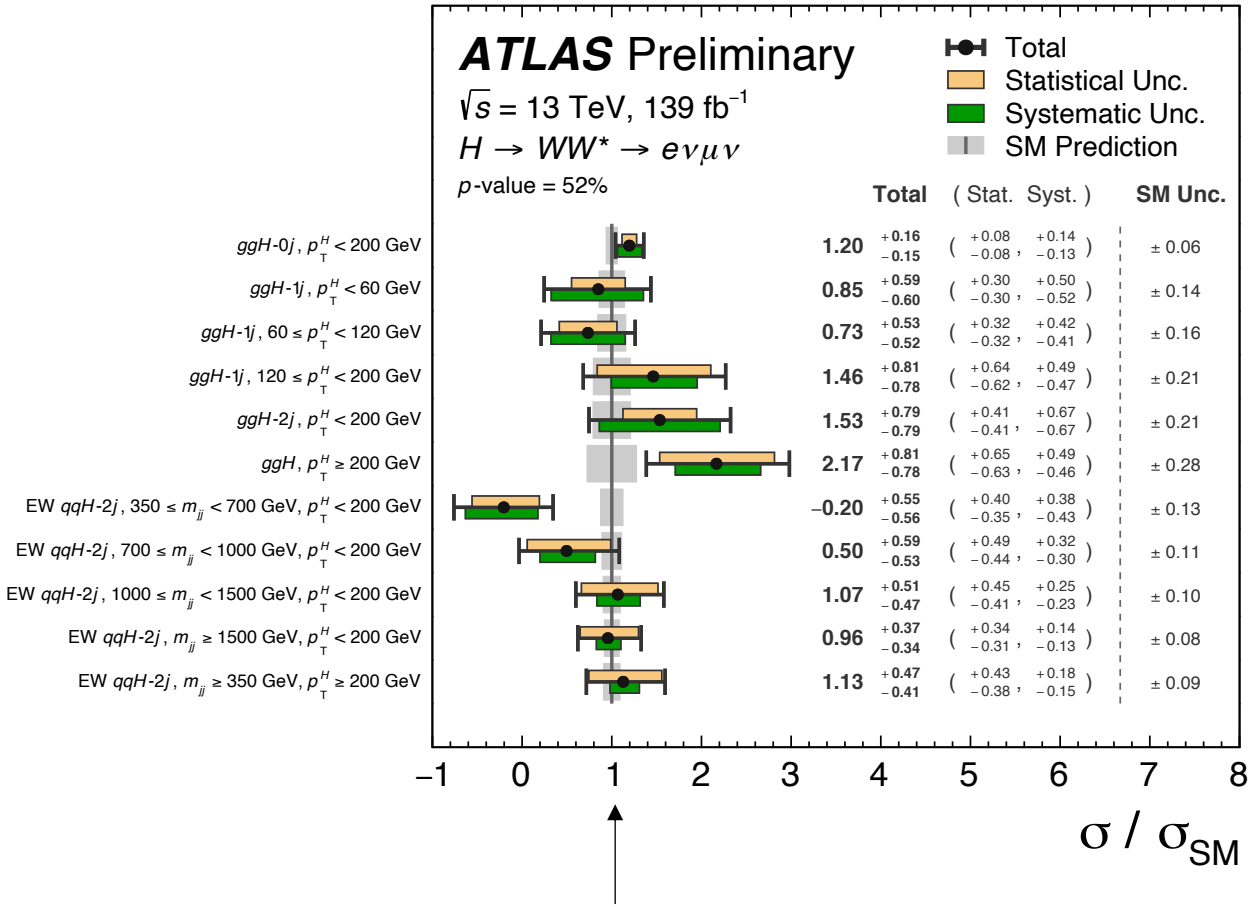
- Measure 5 POIs
- Targeted by ≥ 2-jet VBF signal region split by m_{jj}, p_{T}^{H}.



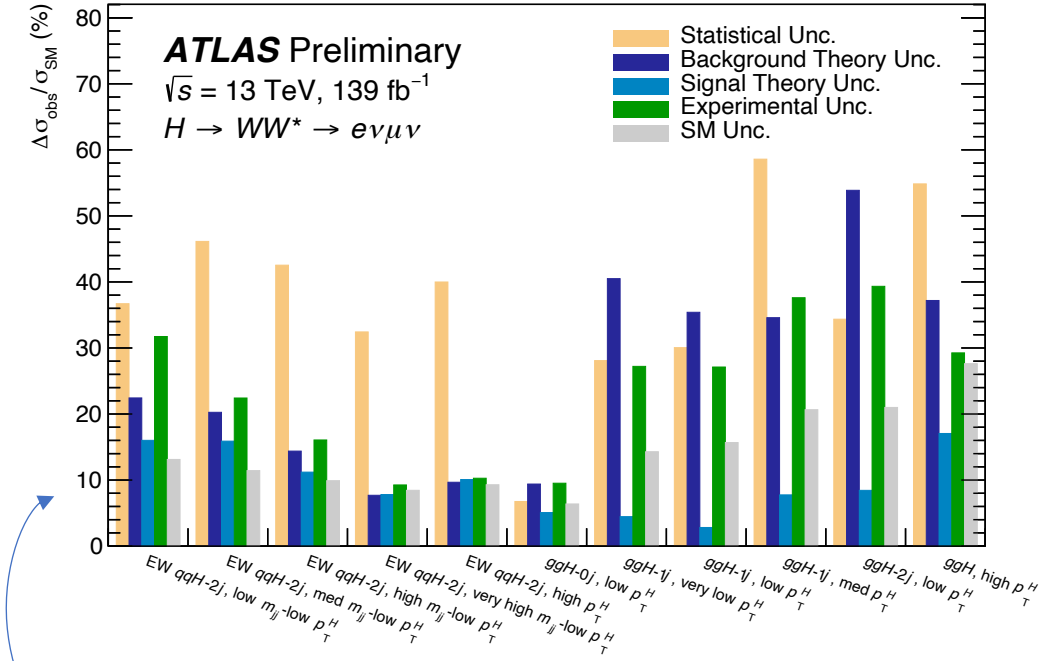


Results: Simplified Template Cross-Sections

Ratio of measured cross-section to SM prediction shown for all 11 cross-sections:



Results are **compatible with the SM**.

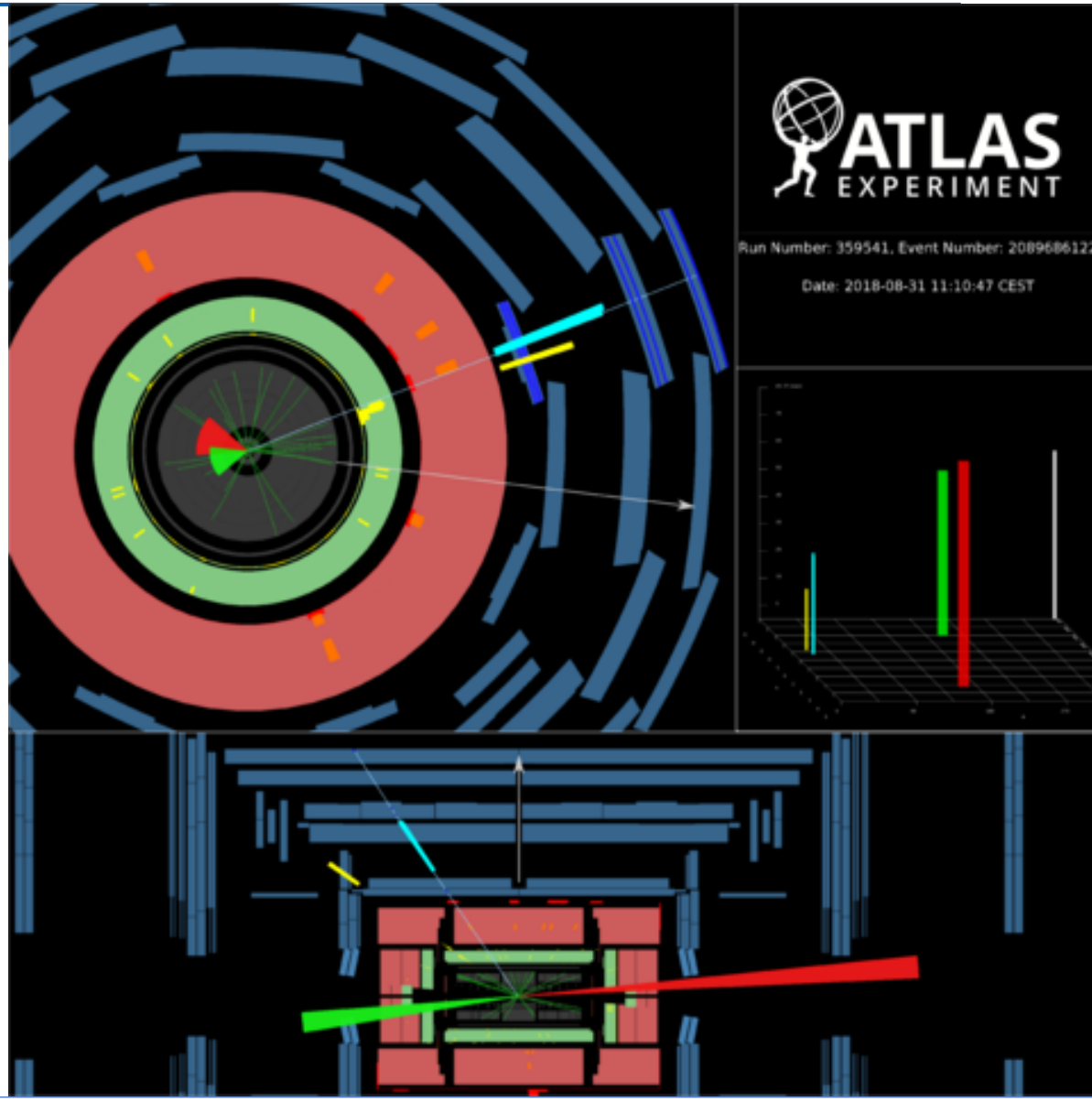


Signal theory uncertainties no longer dominate.

Most analysis categories are statistically-limited, with some ggH modes affected predominantly by background theory uncertainties.

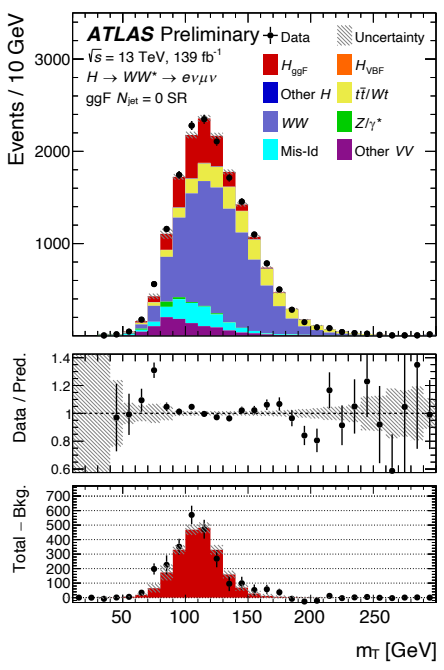
Conclusions

- This measurement of inclusive VBF and ggF $H \rightarrow WW^*$ cross-sections is the most precise to-date, and so far shows consistency with the SM.
- Measurements in STXS bins also agree with the SM, and (for EW qqH) have a precision competitive with the latest combination of all Higgs results measured with the ATLAS detector [ATLAS-CONF-2020-027].
- Future measurements will benefit from a larger dataset and improving understanding of measurement uncertainties to further test the limits of the SM.

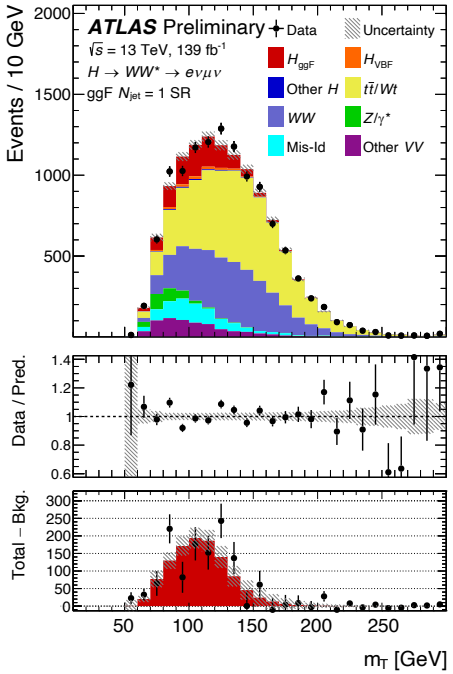


Backgrounds

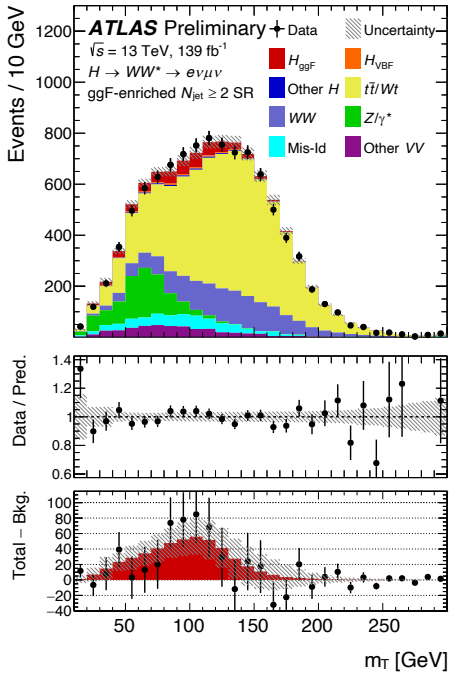
ggF 0j



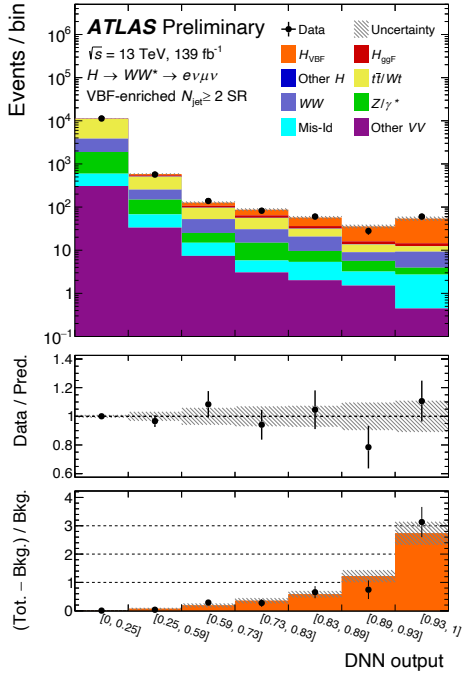
ggF 1j



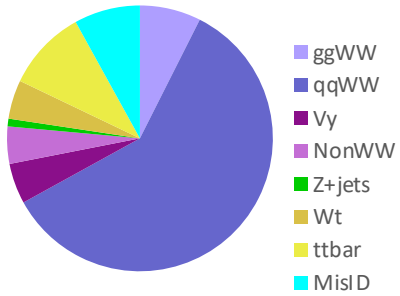
ggF 2j



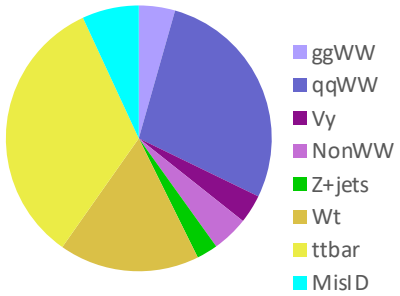
VBF



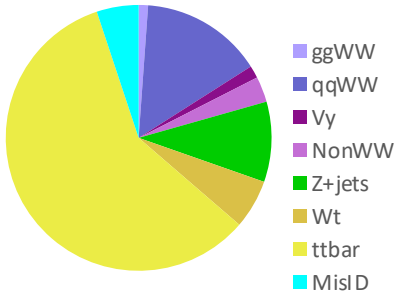
ggF 0j



ggF 1j

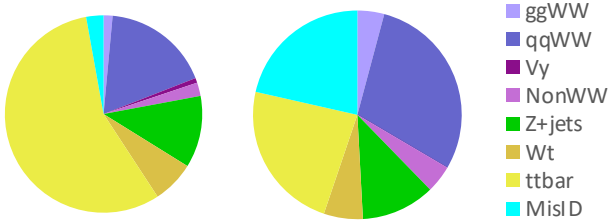


ggF 2j



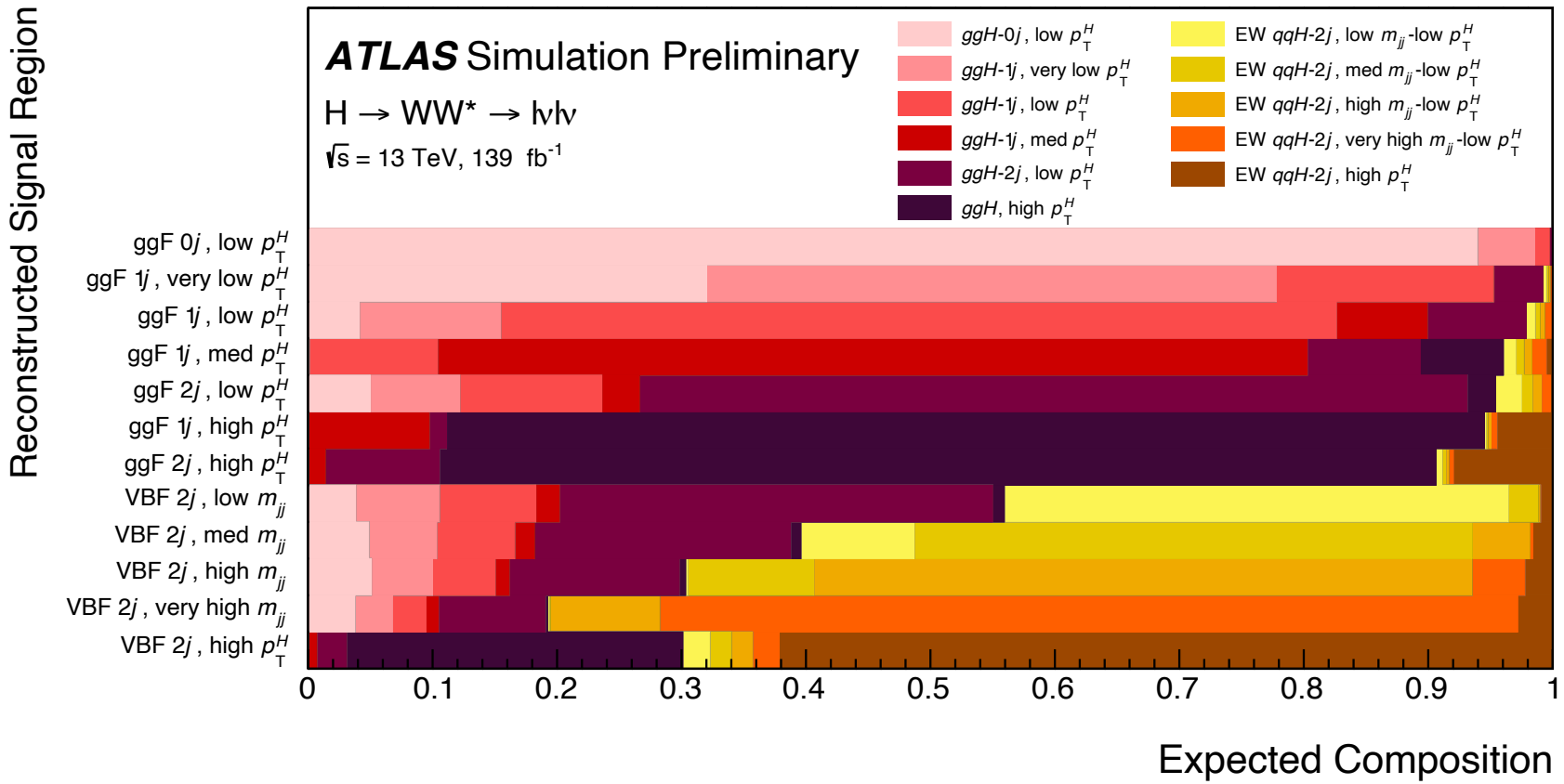
VBF

VBF, last DNN bin

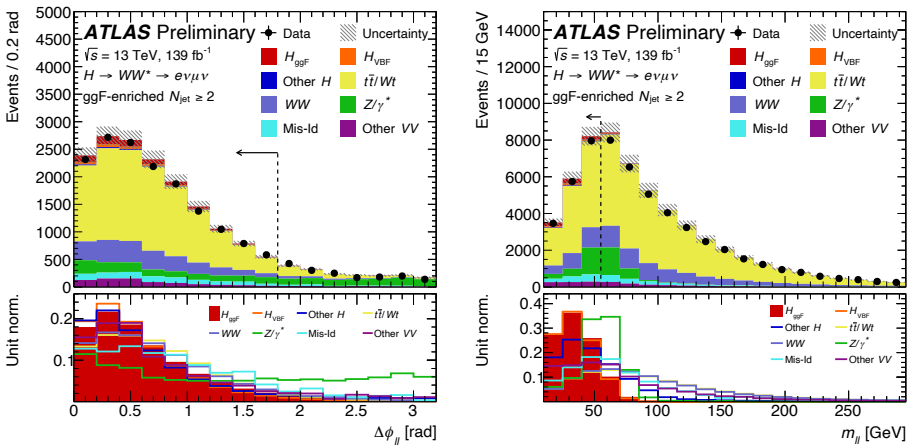


Simplified Template Cross-Sections

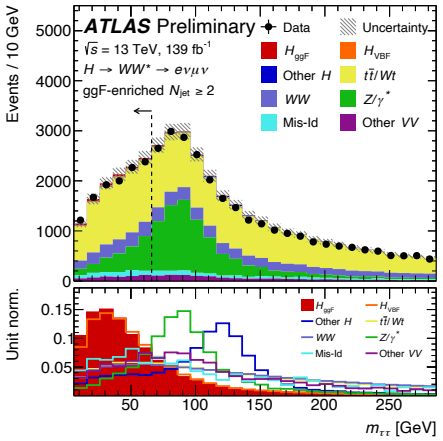
✓ Largest contribution to each reconstructed signal region come from the truth category it targets.



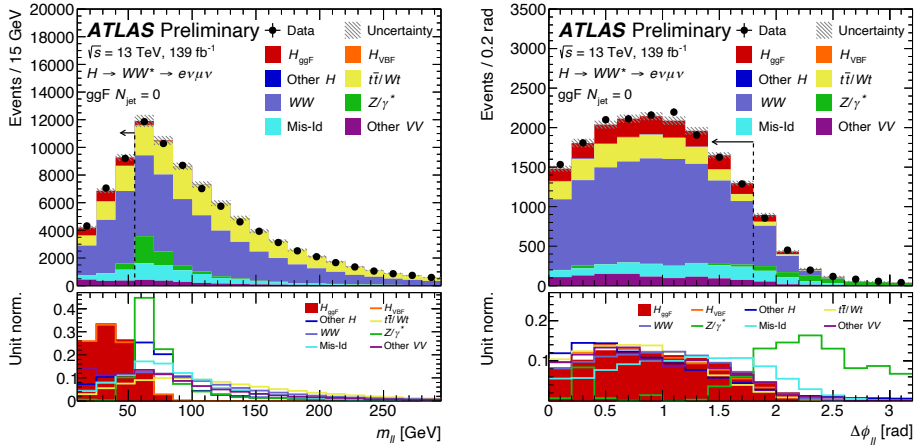
Selections



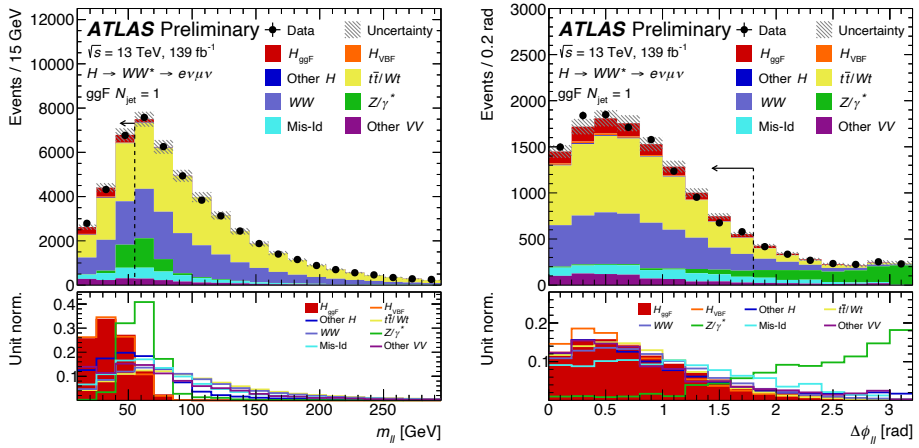
(a) (b)



(c)



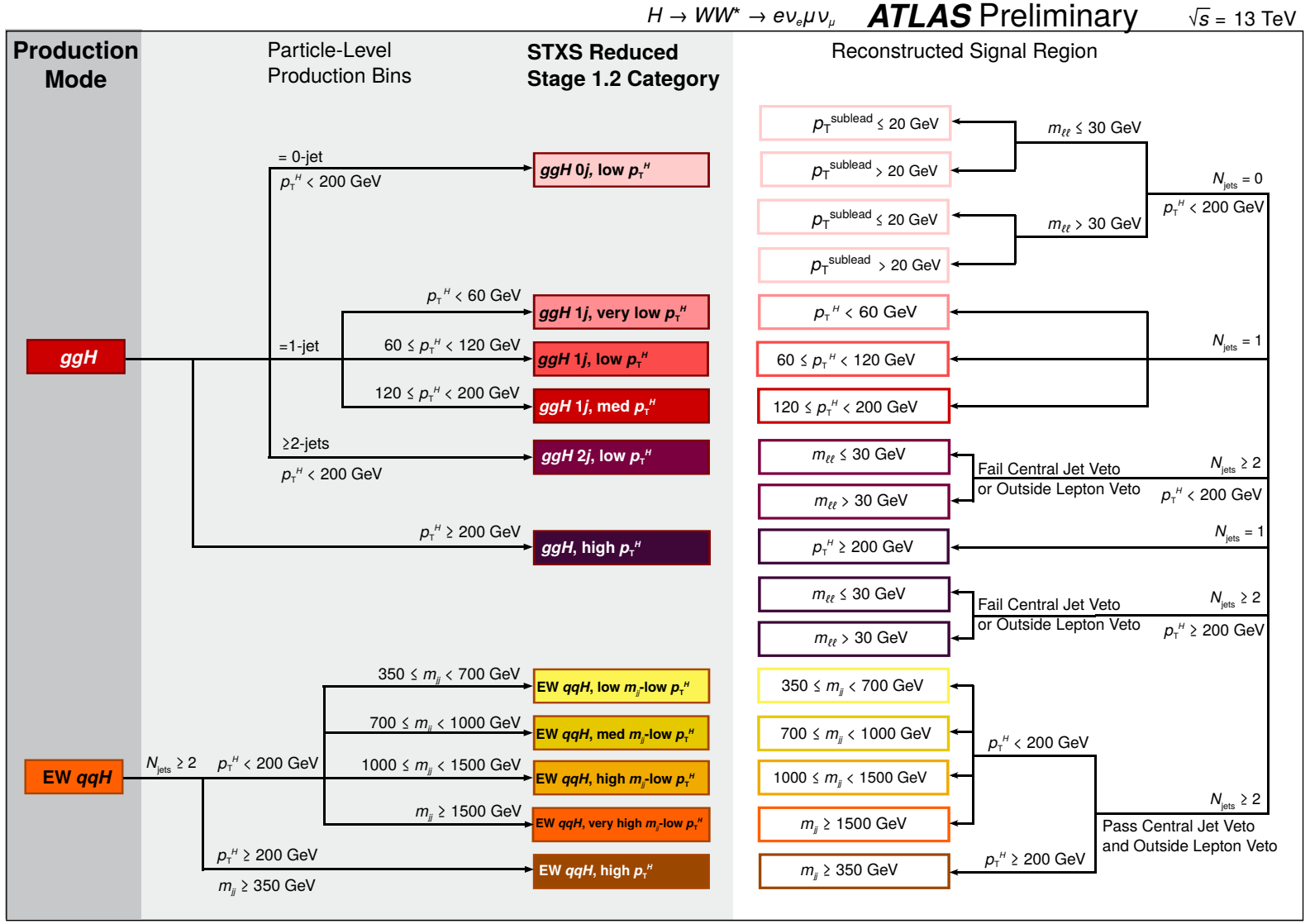
(a) (b)



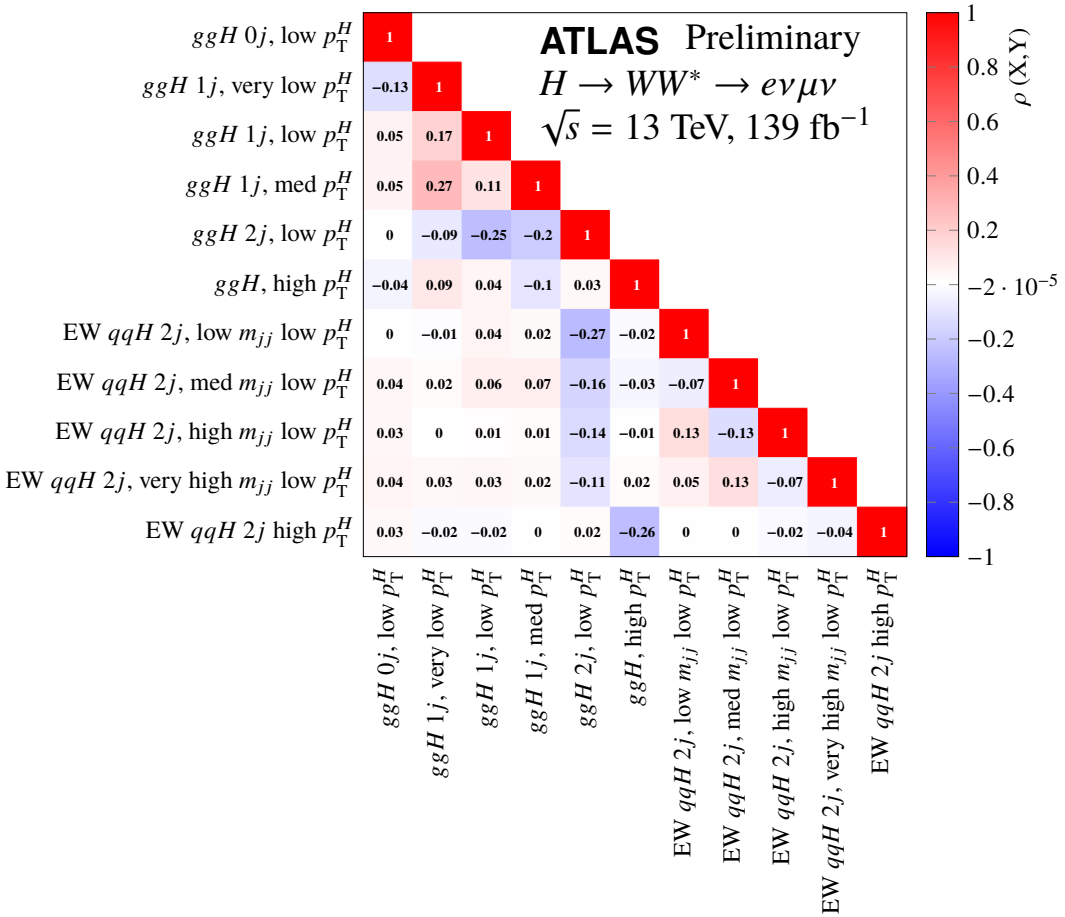
(c) (d)

$$m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left|\boldsymbol{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$$

Selections


$H \to WW^* \to e\nu_e\mu\nu_\mu$
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV
Production Mode
Particle-Level Production Bins
STXS Reduced Stage 1.2 Category
Reconstructed Signal Region
ggH
= 0-jet
p_T^H < 200 GeV
ggH 0j, low p_T^H
=1-jet
p_T^H < 60 GeV
ggH 1j, very low p_T^H
60 ≤ p_T^H < 120 GeV
ggH 1j, low p_T^H
120 ≤ p_T^H < 200 GeV
ggH 1j, med p_T^H
≥2-jets
p_T^H < 200 GeV
ggH 2j, low p_T^H
p_T^H ≥ 200 GeV
ggH, high p_T^H
EW qqH
N_{jets} ≥ 2
p_T^H < 200 GeV
350 ≤ m_{jj} < 700 GeV
EW qqH, low m_{jj}-low p_T^H
700 ≤ m_{jj} < 1000 GeV
EW qqH, med m_{jj}-low p_T^H
1000 ≤ m_{jj} < 1500 GeV
EW qqH, high m_{jj}-low p_T^H
m_{jj} ≥ 1500 GeV
EW qqH, very high m_{jj}-low p_T^H
p_T^H ≥ 200 GeV
m_{jj} ≥ 350 GeV
EW qqH, high p_T^H
$p_T^{sublead}$ ≤ 20 GeV
$m_{\ell\ell}$ ≤ 30 GeV
$p_T^{sublead}$ > 20 GeV
$p_T^{sublead}$ ≤ 20 GeV
$m_{\ell\ell}$ > 30 GeV
$p_T^{sublead}$ > 20 GeV
N_{jets} = 0
p_T^H < 200 GeV
p_T^H < 60 GeV
60 ≤ p_T^H < 120 GeV
120 ≤ p_T^H < 200 GeV
N_{jets} = 1
$m_{\ell\ell}$ ≤ 30 GeV
Fail Central Jet Veto or Outside Lepton Veto
N_{jets} ≥ 2
p_T^H < 200 GeV
$m_{\ell\ell}$ > 30 GeV
p_T^H ≥ 200 GeV
N_{jets} = 1
$m_{\ell\ell}$ ≤ 30 GeV
Fail Central Jet Veto or Outside Lepton Veto
N_{jets} ≥ 2
p_T^H ≥ 200 GeV
$m_{\ell\ell}$ > 30 GeV
350 ≤ m_{jj} < 700 GeV
700 ≤ m_{jj} < 1000 GeV
p_T^H < 200 GeV
1000 ≤ m_{jj} < 1500 GeV
N_{jets} ≥ 2
Pass Central Jet Veto and Outside Lepton Veto
m_{jj} ≥ 1500 GeV
p_T^H ≥ 200 GeV
m_{jj} ≥ 350 GeV

Results



Category	WW	$t\bar{t}/Wt$	Z/γ^*
$N_{\text{jet},(p_T>30\text{ GeV})} = 0$ ggF	$1.03^{+0.07}_{-0.07}$	$0.96^{+0.23}_{-0.18}$	$0.96^{+0.07}_{-0.06}$
$N_{\text{jet},(p_T>30\text{ GeV})} = 1$ ggF	$0.82^{+0.15}_{-0.14}$	$1.07^{+0.19}_{-0.16}$	$0.97^{+0.10}_{-0.09}$
$N_{\text{jet},(p_T>30\text{ GeV})} \geq 2$ ggF	$0.80^{+0.35}_{-0.34}$	$0.94^{+0.23}_{-0.18}$	$0.97^{+0.18}_{-0.16}$
$N_{\text{jet},(p_T>30\text{ GeV})} \geq 2$ VBF	–	$1.00^{+0.37}_{-0.22}$	$0.96^{+0.25}_{-0.20}$