Observation of the H -> WW* production by Vector Boson Fusion in 13 TeV *pp* collisions with the ATLAS detector at the LHC

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Higgs 2020
27/10/2020

ATLAS-CONF-2020-045
Analysis first presented at ICHEP 2020

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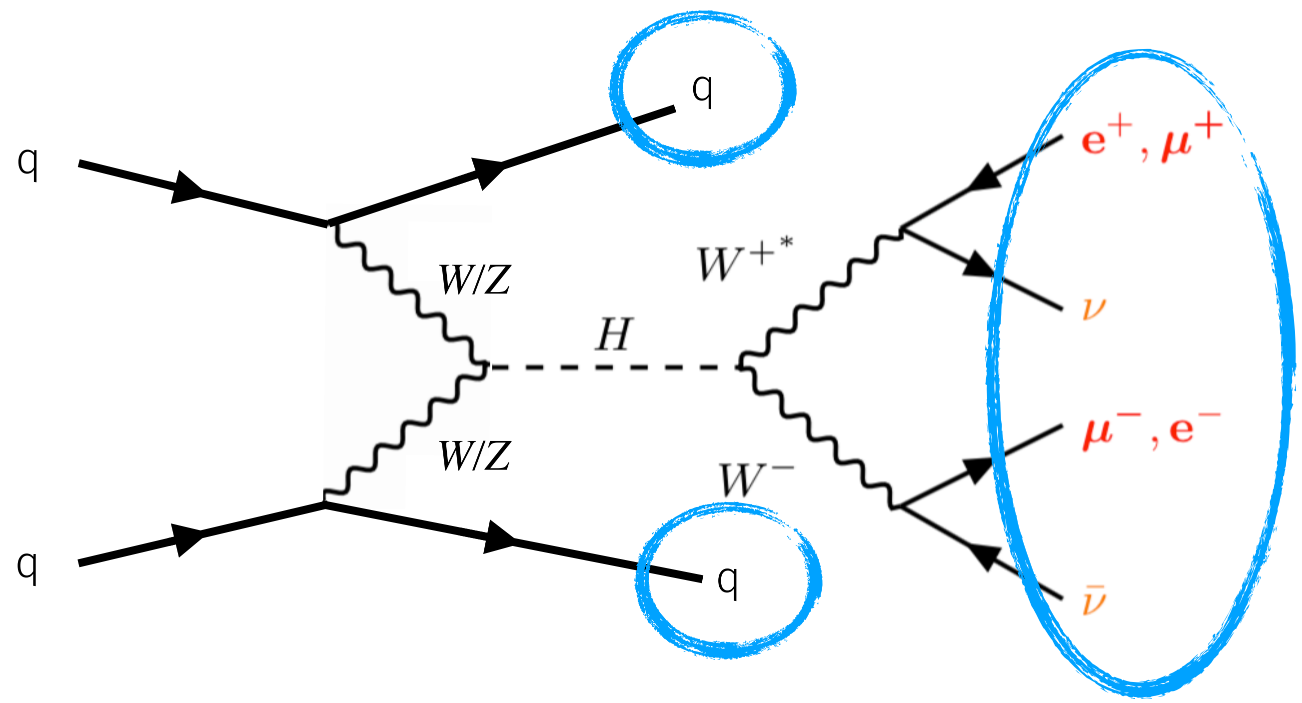
The VBF H -> WW* Final State

Motivation

- H -> WW* has 2nd highest Higgs branching ratio (~22%)
- Most sensitive channel to measure Higgs to vector-boson couplings

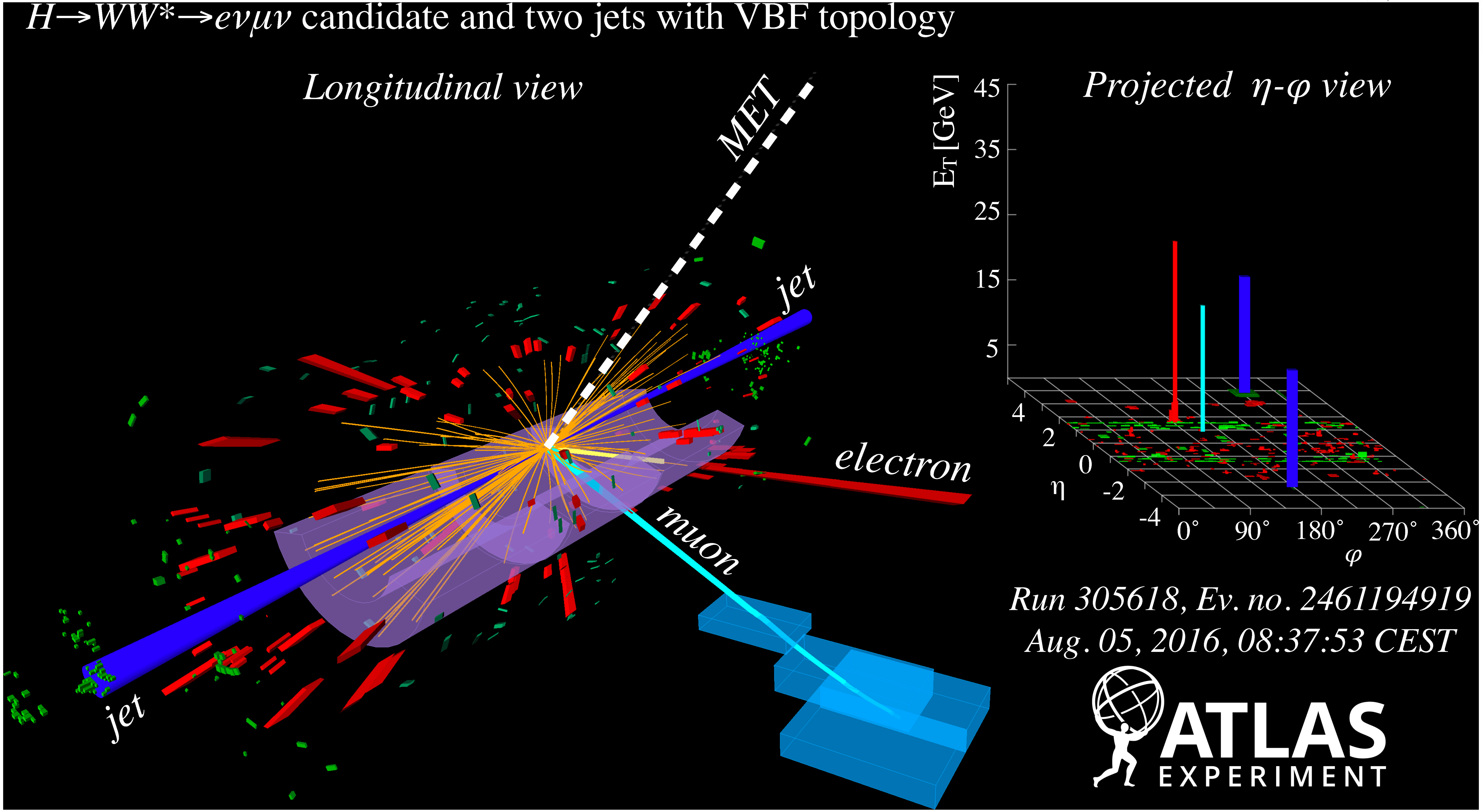


Target final state with...

- ... 2 forward jets
- ... 2 isolated, oppositely charged, different flavour* leptons
- ... 2 neutrinos

*Drop same flavour channel due to overwhelming background

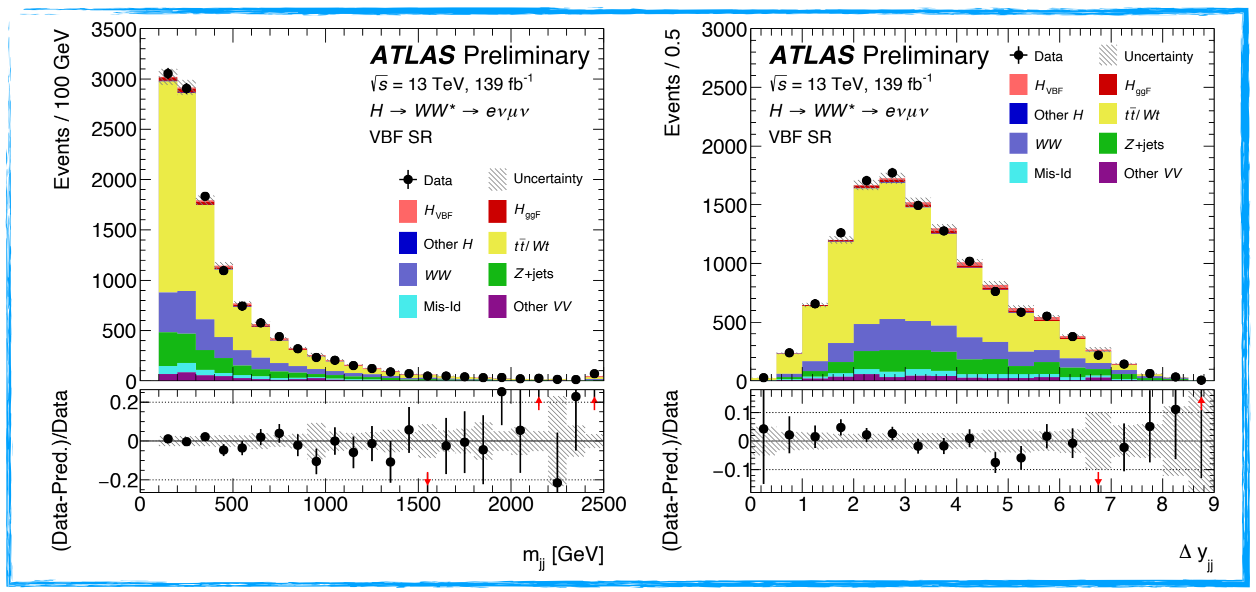
The VBF H -> WW* Signature

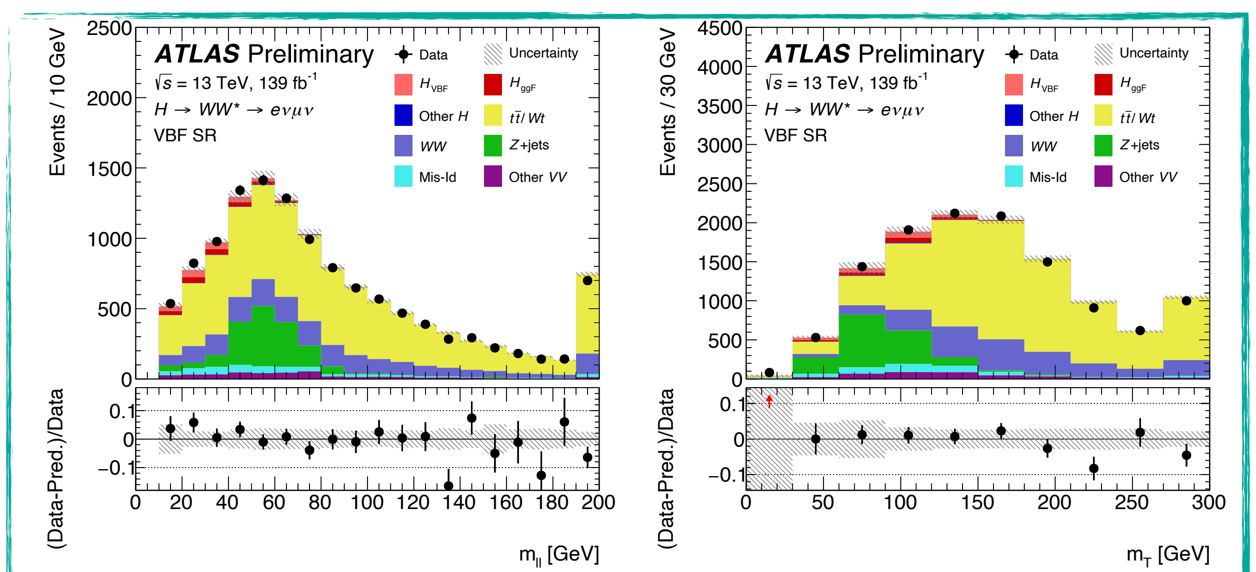


The Analysis Strategy

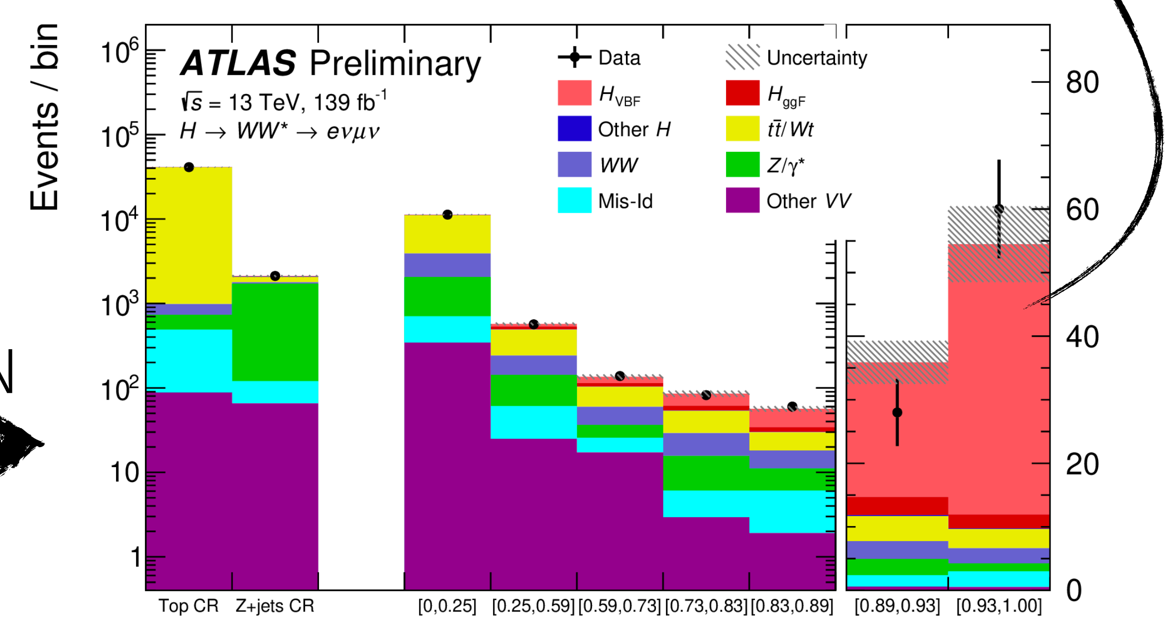
- Train deep neural network with **15 input variables** to classify VBF signal and background events
  - VBF topology: $\Delta y_{jj}, m_{jj}, \eta_{\ell}^{\text{centrality}}, m_{\ell 1 j1}, m_{\ell 1 j2}, m_{\ell 2 j1}, m_{\ell 2 j2}, p_T^{\text{jet}_1}, p_T^{\text{jet}_2}, p_T^{\text{jet}_3}$
  - H->WW decay: $m_{\ell\ell}, m_{T}, \Delta\phi_{\ell\ell}$
  - Top suppression: p_T^{tot}, **MET significance**

Signal / Background ~ 3.5





DNN



- 7 DNN bins chosen by requiring each bin to have...

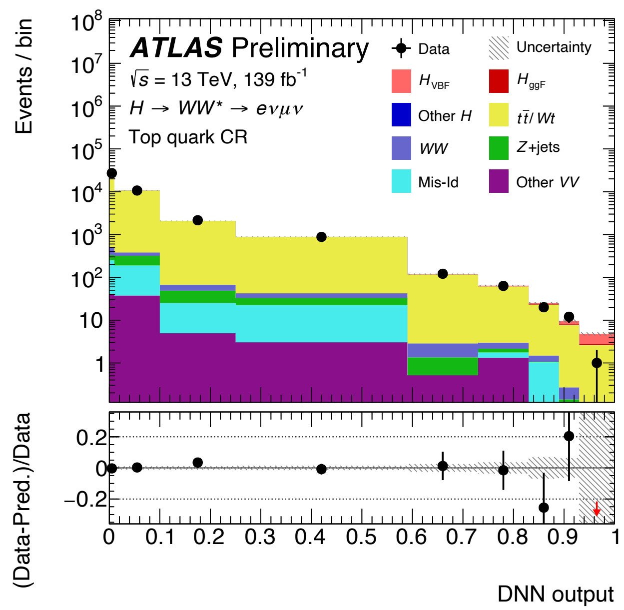
  ... > 10 VBF signal & Bkg events

  ... $\sigma_{\text{stat}}(\text{Bkg}) < 20\%$

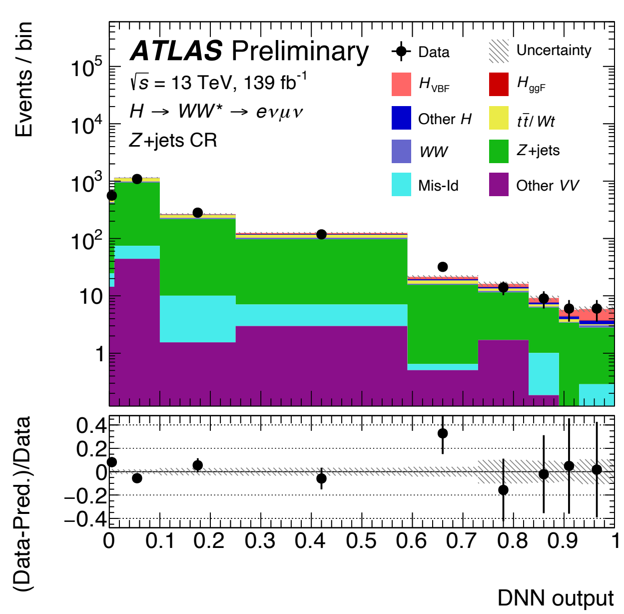
The Background Estimation

From Data in Control Regions

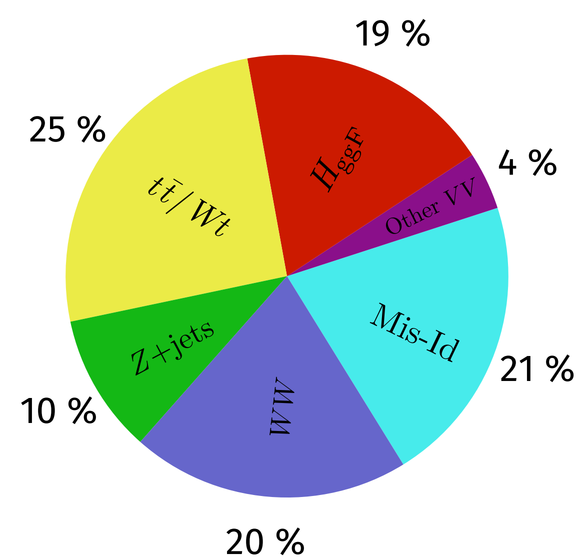
- Top (25%), *b*-tag selection



- Z+jets (10%), select m_Z window



Post-fit fraction of total background in highest DNN bin



From Monte Carlo

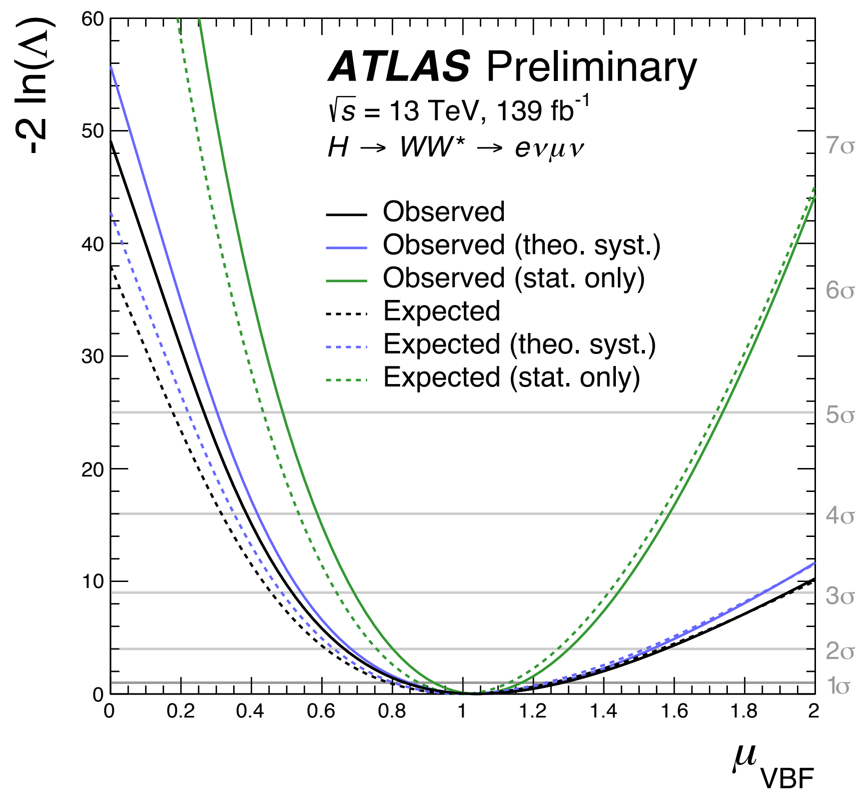
- ggF Higgs (19%)
- WW (20%)
  - Check modelling in validation region
- Other VV (4%)

Data-driven

- Mis-ID (21%)
  - Processes with mis-identified leptons
  - Mostly from *W*+jets
  - Use “fake-factor" to extrapolate from orthogonal region enriched in mis-identified leptons to signal region

The Results

- Binned profile likelihood fit to extract VBF signal in ATLAS full Run 2 dataset: 139 fb^{-1} @ 13 TeV
- **Observation** of VBF signal with observed (expected) significance: **7.0** (6.2) **σ**
- Measurements dominated by theoretical uncertainties, with largest contribution from Higgs modelling uncertainties



Measured signal strength and VBF cross-section x BR(H->WW)

$$\mu_{\mathrm{VBF}} = 1.04\,^{+0.24}_{-0.20}$$
$$= 1.04\,^{+0.13}_{-0.12}\,(\mathrm{stat.})\,^{+0.09}_{-0.08}\,(\mathrm{exp\ syst.})\,^{+0.17}_{-0.12}\,(\mathrm{sig.\ theo.})\,^{+0.08}_{-0.07}\,(\mathrm{bkg.\ theo.})$$

$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}_{H\to WW^*} = 0.85\,^{+0.20}_{-0.17}\,\mathrm{pb}$$
$$= 0.85 \pm 0.10\,(\mathrm{stat.})\,^{+0.08}_{-0.07}\,(\mathrm{exp\ syst.})\,^{+0.13}_{-0.10}\,(\mathrm{sig.\ theo.})\,^{+0.07}_{-0.06}\,(\mathrm{bkg.\ theo.})\,\mathrm{pb}$$

- This measurement provides a baseline for further ATLAS analyses: E.g. Higgs combinations, STXS measurements, EFT interpretations

Thanks for the attention!

Questions?

ATLAS Run 1 Results

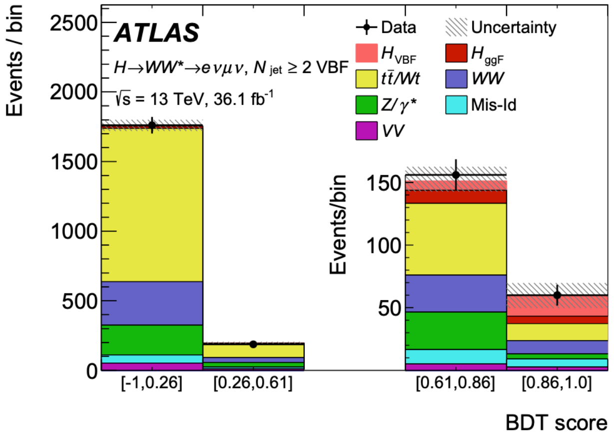
Previous results from 36fb-1 paper

$$\mu_{\mathrm{ggF}} = 1.10^{+0.10}_{-0.09}(\mathrm{stat.})^{+0.13}_{-0.11}(\mathrm{theo\ syst.})^{+0.14}_{-0.13}(\mathrm{exp\ syst.}) = 1.10^{+0.21}_{-0.20}$$

$$\mu_{\mathrm{VBF}} = 0.62^{+0.29}_{-0.27}(\mathrm{stat.})^{+0.12}_{-0.13}(\mathrm{theo\ syst.}) \pm 0.15(\mathrm{exp\ syst.}) = 0.62^{+0.36}_{-0.35}$$

Significances

σ	Z_0^{obs}	Z_0^{exp}
ggF	6.0	5.3
VBF	1.8	2.6



The Event Selection

Table 01:
Event selection criteria used to define the signal and control regions in the analysis. Definitions including the p_T thresholds for jet counting are given in the text. For leptons that are matched to the trigger, the lepton p_T requirements are applied in addition to the trigger matching scheme, which requires the p_T of the lepton to be at least 1 GeV above the trigger level threshold.

	Signal region	Z+jets CR	Top quark CR
Pre-selection	Two isolated, different-flavour leptons ($\ell = e, \mu$) with opposite charge		
	$p_{\mathrm{T}}^{\mathrm{lead}} > 22GeV$, $p_{\mathrm{T}}^{\mathrm{sublead}} > 15\,GeV$		
	$m_{\ell\ell} > 10\,GeV$, $N_{\mathrm{jet}} \geq 2$		
	$N_{b\text{-jet},(p_{\mathrm{T}}>20\ \mathrm{GeV})} = 0$	$N_{b\text{-jet},(p_{\mathrm{T}}>20\ \mathrm{GeV})} = 0$	$N_{b\text{-jet},(p_{\mathrm{T}}>20\ \mathrm{GeV})} = 1$
Selection	$m_{\tau\tau} < m_Z - 25\,GeV$	$\lvert m_{\tau\tau} - m_Z \rvert < 25\,GeV$	$m_{\tau\tau} < m_Z - 25\,GeV$
	$m_{jj} > 120\,GeV$	–	–
	–	$m_{\ell\ell} < 70\,GeV$	–
	central jet veto		
	outside lepton veto		
A DNN is applied in the SR that uses 15 discriminant variables: $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, m_{T}, Δy_{jj}, m_{jj}, $p_{\mathrm{T}}^{\mathrm{tot}}$, $\sum_\ell C_\ell$, $m_{\ell_1 j_1}$, $m_{\ell_1 j_2}$, $m_{\ell_2 j_1}$,$m_{\ell_2 j_2}$, $p_{\mathrm{T}}^{\mathrm{jet}_1}$, $p_{\mathrm{T}}^{\mathrm{jet}_2}$, $p_{\mathrm{T}}^{\mathrm{jet}_3}$, and $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$ significance			

The Event Yields

Table 02:

Post-fit MC and data yields in the VBF SRs. Yields in the highest DNN output bin are also presented. The quoted uncertainties correspond to the statistical uncertainties, together with the experimental and theory modeling systematics. The sum of all the contributions may differ from the total value due to rounding. Moreover, the total uncertainty differs from the sum in quadrature of the single-process uncertainties due to anti-correlation effects in their systematic sources which dominate over their MC statistical uncertainties.

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

The Uncertainties

Table 03:
Breakdown of impacts on the signal strength μ_{VBF}. The uncertainties are estimated by the breakdown method, in which nuisance parameters associated with the uncertainty group in question are first fixed to their best fit value and the uncertainty on the measured signal strength is recomputed. The quadrature difference between the original and recomputed uncertainties present the impact of the uncertainty group. The uncertainties of the main components were calculated by iteratively fixing the respective sets of nuisance parameters and calculating the quadrature difference to the previous step, in reverse order of display.

Source	$\Delta\mu_{\mathrm{VBF}}/\mu_{\mathrm{VBF}}$ [%]
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
b-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