Canadian Association of Physicists
Association canadienne des physiciens et physiciennes

NSERC CRSNG

Measurement of associated production of Higgs bosons decaying to pairs of *W* bosons with the ATLAS detector at the Large Hadron Collider

Canadian Association of Physicists Congress, May 26-31, 2024

Matthew Basso (TRIUMF/SFU),
On behalf of the ATLAS Collaboration

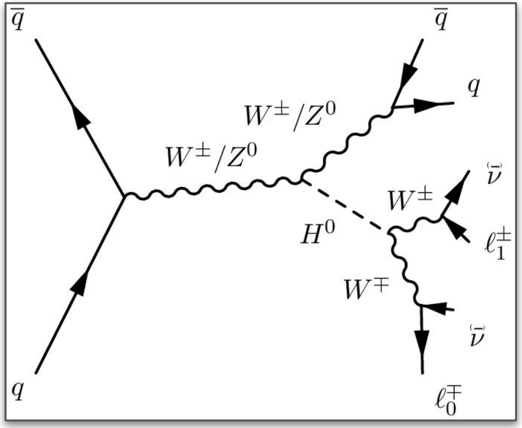
ATLAS EXPERIMENT TRIUMF SFU SIMON FRASER UNIVERSITY

https://indico.cern.ch/event/1316311/contributions/5861251/

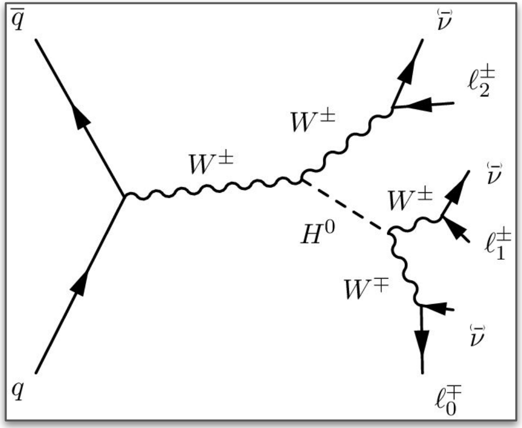
Associated production of Higgs bosons in the *WW** decay channel

- Production of Higgs bosons in association with a vector boson (*VH*): 3rd largest production mode (2.4 pb) at the Large Hadron Collider (LHC)
- Higgs decays to *WW** ($H \rightarrow WW^*$): 2nd largest branching fraction (22%)
- $VH(\rightarrow WW^*)$: provides direct access Higgs-vector couplings at both production and decay vertices, measurements of which provide **stringent tests** of the Standard Model (SM)
  - *VH* production (1808.08238) and $H \rightarrow WW^*$ decays (1412.2641) have been independently observed by ATLAS → **observation of $VH(\rightarrow WW^*)$ expected**
  - Deviations from this expectation could indicate Beyond the SM (BSM) physics (extended Higgs sectors, additional heavy vector bosons, …)

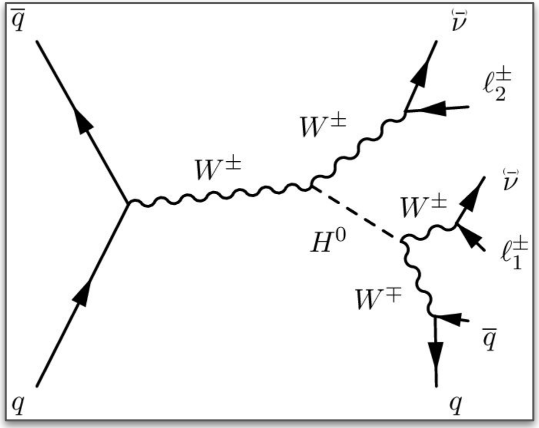
Tree-level diagrams of *VH*(→*WW**) topologies



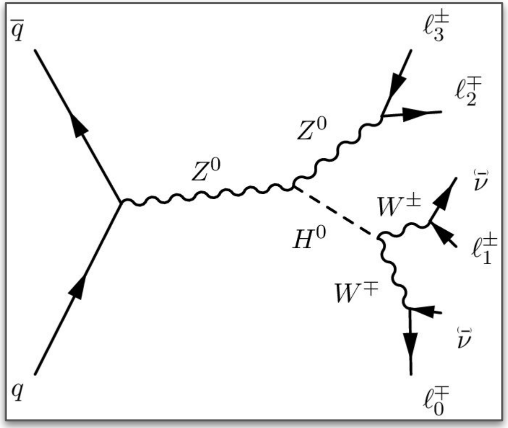
VH(→*WW**) decaying to 2 opposite-sign leptons



WH(→*WW**) decaying to 3 leptons



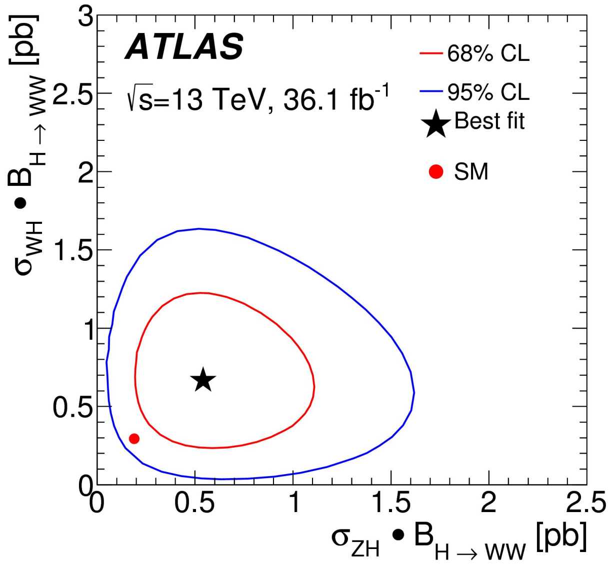
WH(→*WW**) decaying to 2 same-sign leptons



ZH(→*WW**) decaying to 4 leptons

Previous measurements by ATLAS

- Previous measurement conducted by the ATLAS experiment using 36.1 fb^{-1} of LHC data at $\sqrt{s}$ = 13 TeV
  - Considered 3- and 4-lepton final states
  - Measured inclusive *VH* production as well as resolved *WH*/*ZH* production
- Measured *VH*(→*WW**) with an observed significance of 4.1σ over the background-only hypothesis
  - Precision limited by **availability of data**



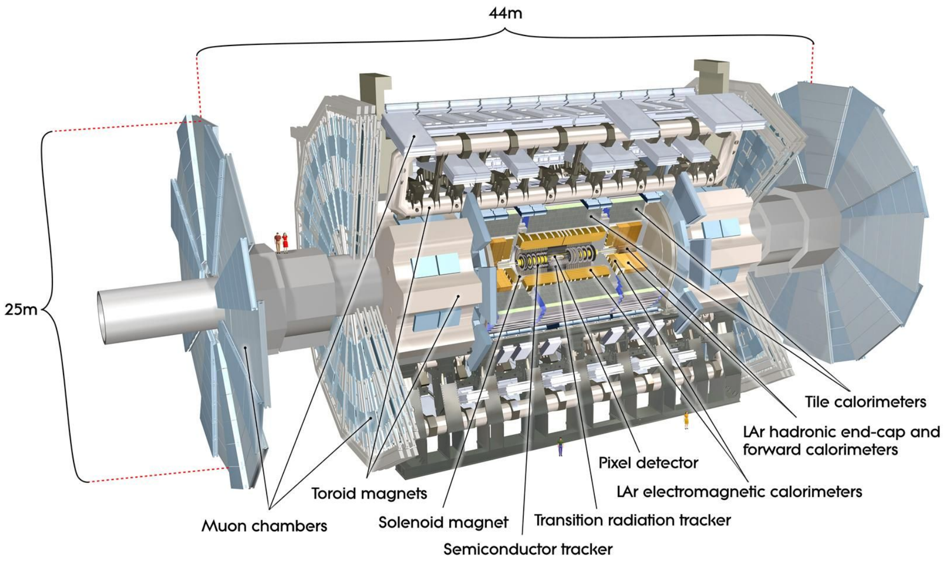
Measured *WH*/*ZH* cross sections times the *H*→*WW** branching fraction (source: 1903.10052)

Full LHC Run 2 measurement

- Full LHC Run 2 measurement: ATLAS-CONF-2022-067
  - 139 fb^{-1} of integrated luminosity collected over 2015-18
  - Corresponding CMS measurement: CMS-HIG-20-013
- Considers the 2-, 3-, and 4-lepton final states shown earlier (slide 3)
  - All channels characterized by the presence of missing transverse momentum (MET) and collimated leptons from the Higgs decay
- Analysis benefits from the use of machine learning in all channels by:
  - Multivariate (MVA) discriminants: MVAs of different architectures are trained to separate signal from background(s) (input variables in the Backup)
  - Neural-network-based lepton isolation: significantly reduces sources of misidentified leptons (from light/heavy-flavour decays or $\gamma \rightarrow e^+e^-$)

The ATLAS detector

- General purpose detector with cylindrical symmetry and near hermetic coverage
  - Tracking subsystem in 2 T magnetic field for charged particle reconstruction
  - Calorimeters for reconstruction of electrons/photons and hadrons
  - Muon spectrometer for reconstruction of muons
  - 2-stage trigger, reducing event rate to ~1 kHz

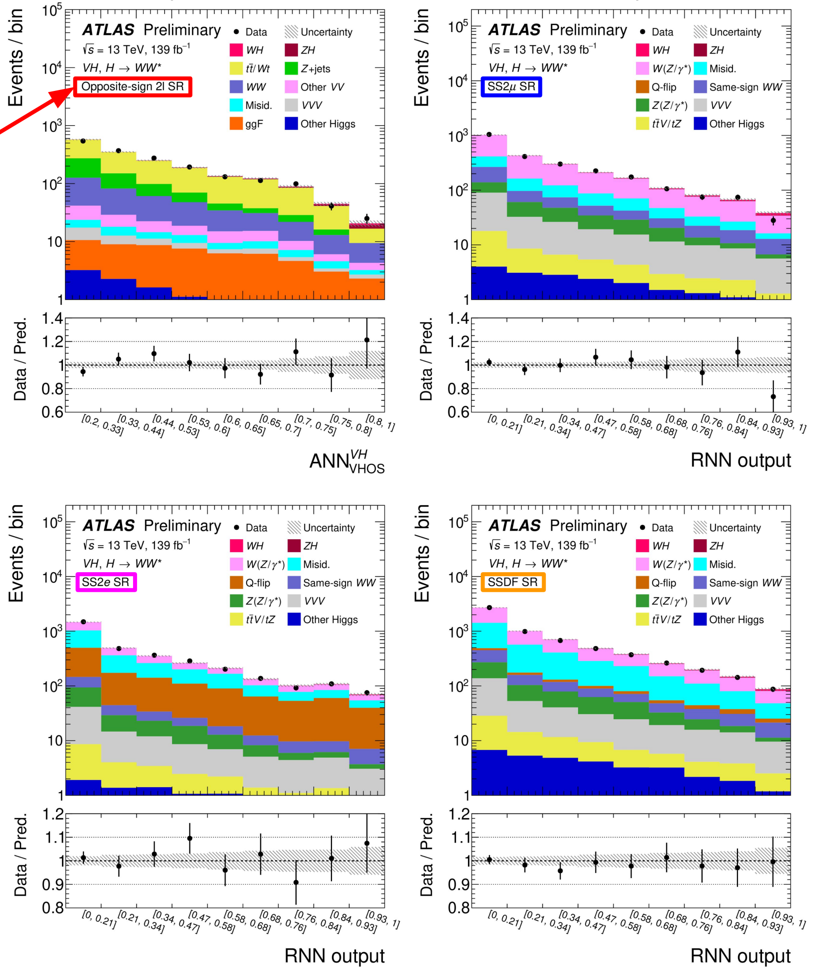


Labelled diagram of the ATLAS detector (source: https://cds.cern.ch/record/1095924)

Strategy: 2-lepton channels

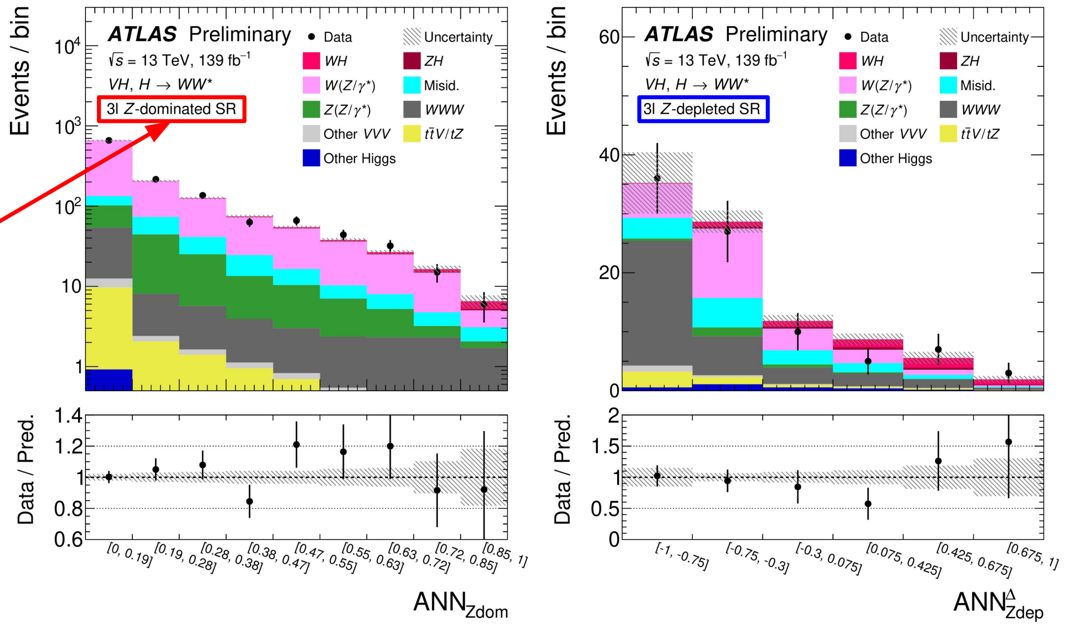
(source: [ATLAS-CONF-2022-067]())

- Different-flavour, opposite-sign (**DFOS**) channel: requires 2 DFOS leptons and ≥2 jets
  - Artificial neural network (ANN) separating *VH* from Higgs/non-Higgs backgrounds
  - Dedicated [control regions]() normalizing top quark, *WW*, and *Z*+jets backgrounds
- Same-sign (SS) channel: requires 2 SS leptons and ≥1 jets
  - Subdivided further according to lepton flavour: ***μμ***, ***ee***, and ***eμ/μe***
  - Recurrent neural network (RNN) separating *WH* and *WZ* production



Strategy: 3-lepton channels

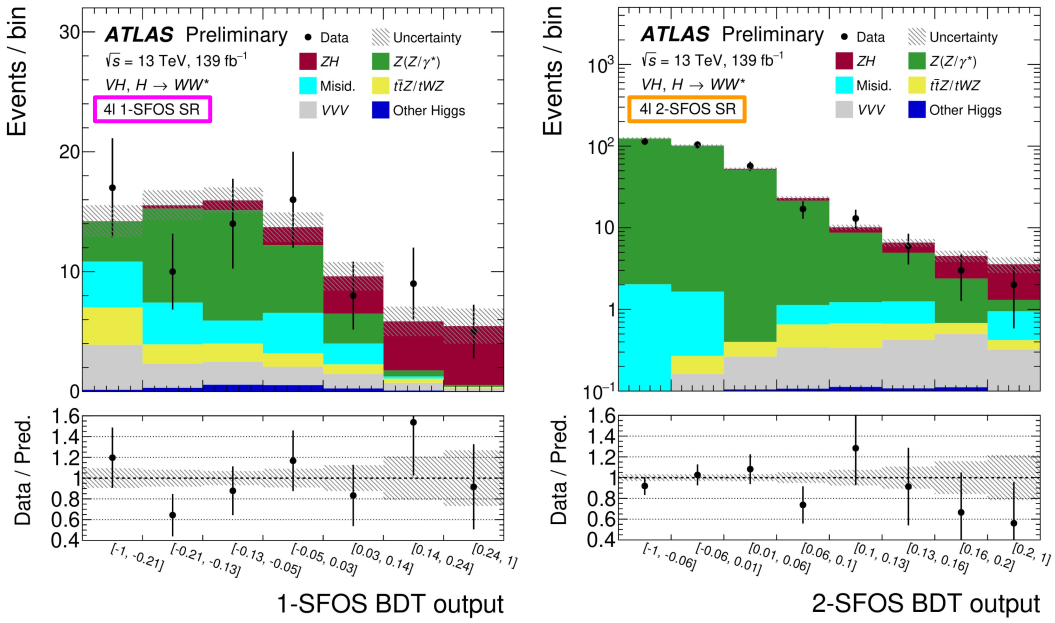
- Requires 3 leptons of total charge ±1, subdivided according to number of same-flavour, opposite-sign (SFOS) lepton pairs:
  - **≥1 → "dominated" by *WZ***
  - **0 → "depleted" in *WZ***
- ANNs separating *WH* from *WZ*, *WWW*, and/or top quark backgrounds
- Dedicated control regions normalizing the *WZ* background



(source: ATLAS-CONF-2022-067)

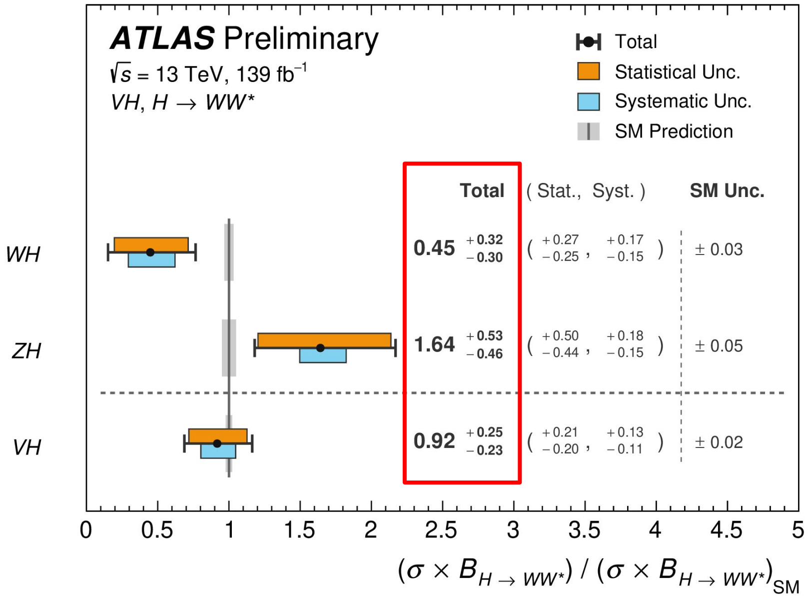
Strategy: 4-lepton channels

- Require 4 leptons of total charge 0, subdivided according to number of SFOS lepton pairs, **1 or 2**
  - Only *ZZ* with *Z*→ττ enters 1-SFOS channel → **more pure in signal**
- Boosted decision trees (BDTs) separating *ZH* and *ZZ* production
- Dedicated control region normalizing *ZZ* background



(source: ATLAS-CONF-2022-067)

Results: cross sections



Measured cross sections times the $H \to WW^*$ branching ratio relative to their expected values as well as their total uncertainties (source: ATLAS-CONF-2022-067)

- MVA distributions for each channel enter the statistical analysis, where the signal cross section is fitted
- Measured both inclusive (*VH*) and resolved (*WH*/*ZH*) cross sections
  - **Good consistency with the SM expectations**
  - And **high precision** on the measured cross section: **26%**
- **4.6σ significance over the background-only hypothesis!**

Results: uncertainties

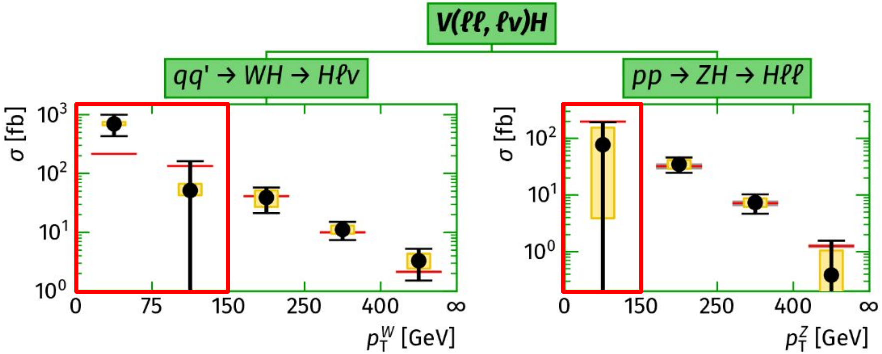
- Uncertainty dominated by **availability of data**
  - **Will benefit from a combination with Run 3 data**
- Other leading sources of systematic uncertainties:
  - *ZH* cross section: muon isolation efficiency and missing higher-order corrections to the SM cross section
  - *WH* cross section: data-driven background estimation, *WWW* modelling, and *WZ* modelling

Source	$\frac{\Delta(\sigma_{VH}\times\mathcal{B}_{H\to WW^*})}{\sigma_{VH}\times\mathcal{B}_{H\to WW^*}}$ [%]	$\frac{\Delta(\sigma_{WH}\times\mathcal{B}_{H\to WW^*})}{\sigma_{WH}\times\mathcal{B}_{H\to WW^*}}$ [%]	$\frac{\Delta(\sigma_{ZH}\times\mathcal{B}_{H\to WW^*})}{\sigma_{ZH}\times\mathcal{B}_{H\to WW^*}}$ [%]
Statistical uncertainties in data	22.3	57.9	28.4
Systematic uncertainties	13.3	36.6	9.9
Statistical uncertainties in simulation	6.4	14.4	5.9
Experimental systematic uncertainties	5.2	9.8	6.0
Electrons	1.2	1.8	1.6
Muons	2.5	2.8	4.1
Jet energy scale	0.7	2.3	0.5
Jet energy resolution	0.6	2.8	0.6
Flavour tagging	0.9	1.4	0.8
Missing transverse momentum	0.6	0.4	0.9
Pile-up	1.1	1.5	0.8
Luminosity	2.3	2.4	2.1
Mis-identified leptons	2.9	7.1	2.7
Charge-flip electrons	1.5	4.5	0.1
Theoretical uncertainties	6.0	18.6	4.7
WH	2.3	2.8	0.1
ZH	0.7	0.7	3.4
WW	1.0	3.3	0.3
$W(Z/\gamma^*)$ 0-jet	3.2	11.3	0.3
$W(Z/\gamma^*)$ ≥1-jets	0.2	0.8	0.4
$Z(Z/\gamma^*)$	0.8	1.5	0.6
VVV	2.4	12.7	0.3
Top	2.9	5.5	2.5
Z+jets	1.8	3.4	1.5
RNN shape uncertainty for $W(Z/\gamma^*)$	8.8	27.3	0.3
Floating normalisations	0.1	0.2	0.1
Total	26.0	71.0	30.1

(source: ATLAS-CONF-2022-067)

Conclusion

- Presented the results of the measurement of *VH* production in the *H*→*WW** decay channel using 139 fb^{-1} of data measured by ATLAS
  - **Results are consistent with the SM expectations**
- *VH* p_T^V spectrum sensitive to BSM effects → will help constrain such effects at low p_T^V
  - Provides a cross-check of *H*→*bb*, which best measures high p_T^V



VH cross sections measured in bins of p_T^V, excluding the *H*→*WW** measurement (source: 2207.00092)

Thank you for listening! Questions?

(While this is cool event display, it corresponds to a *Z→μμ* event, which is a background in all channels!)

Source

Backup

Input variables to MVA discriminants

2-lepton DFOS *VH*

Multiclassifier input variables				
$p_T^{\ell_0}$	$p_T^{\ell_1}$	$\Delta\phi_{\ell\ell}$	$\Delta Y_{\ell\ell}$	$m_{\ell\ell}$
$p_T^{j_0}$	$p_T^{j_1}$	$\Delta\phi_{jj}$	ΔY_{jj}	m_{jj}
m_T	$m_{\tau\tau}$	$m_{\ell_0 j_0}$	$m_{\ell_0 j_1}$	$m_{\ell_1 j_0}$
$m_{\ell_1 j_1}$	H_T	E_T^{miss}	$\mathcal{S}_{miss}$	

2-lepton SS *WH*

Object	p_T	η	ϕ
Lepton	p_T^{ℓ}	η^{ℓ}	ϕ^{ℓ}
Missing transverse momentum	E_T^{miss}	0	ϕ^{miss}
Jet	p_T^{j}	η^{j}	ϕ^{j}

3-lepton *WH*: *Z*-dominated and *Z*-depleted

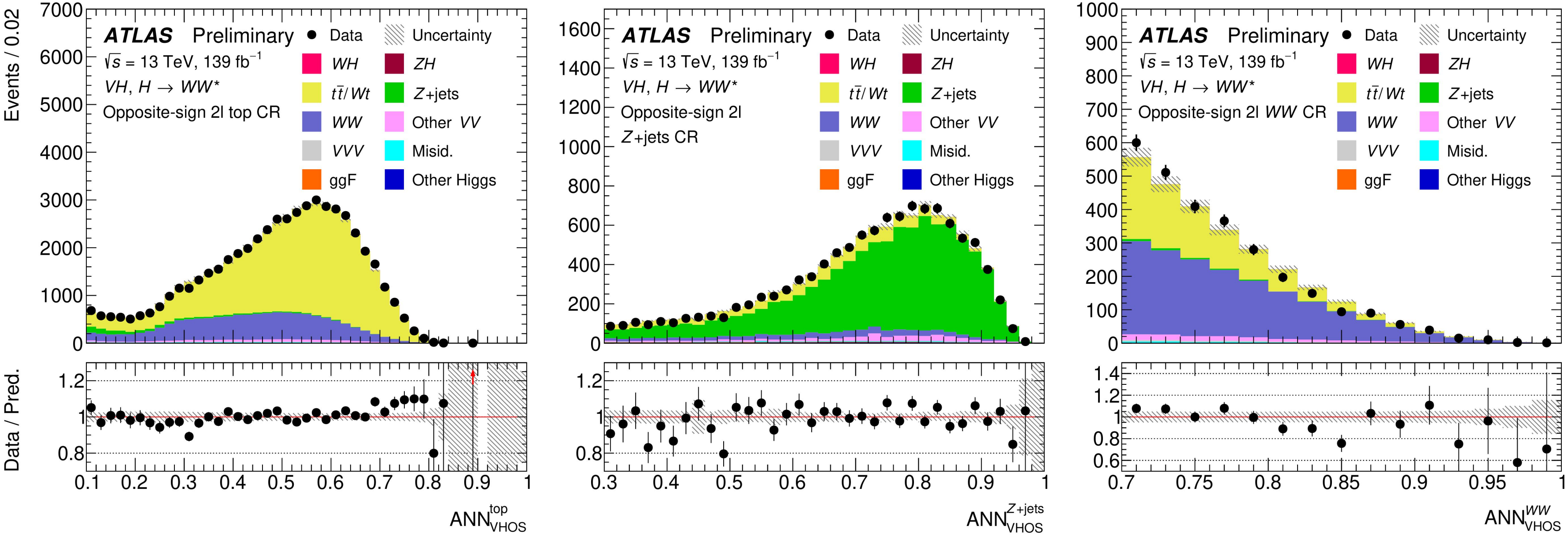
Classifier input variables			
$p_T^{\ell_0}$	$\left\lvert\Sigma_{i=0}^{2}\vec{p}_T^{\,\ell_i}\right\rvert$	$\Delta\eta_{\ell_0\ell_1}$	$\Delta\eta_{\ell_1\ell_2}$
$\Delta\phi_{\ell_0\ell_2}$	$\Delta R_{\ell_0\ell_1}$	$\Delta R_{\ell_0\ell_2}$	$m_{\ell_0\ell_1}$
$m_{\ell_0\ell_2}$	$m_{\ell_1\ell_2}$	$\Delta\phi_{\ell_0,miss}$	$\Delta\phi_{\ell_1,miss}$
$\Delta\phi_{\ell_2,miss}$	E_T^{miss}	m_T^{W}	

Multiclassifier input variables			
E_T^{miss}	$\Delta R_{\ell_0\ell_1}$	$\Delta R_{\ell_0\ell_2}$	$\Delta R_{\ell_1\ell_2}$
$\Delta\eta_{\ell_0\ell_1}$	$\Delta\eta_{\ell_0\ell_2}$	$\Delta\eta_{\ell_1\ell_2}$	$m_{\ell\ell\ell}$
$p_T^{\ell_0}$	$p_T^{\ell_1}$	$p_T^{\ell_2}$	$\left\lvert\Sigma_{i=0}^{2}\vec{p}_T^{\,\ell_i}\right\rvert$
$p_T^{j_0}$	n_{jets}	$n_{b\text{-jets}}$	$\Delta\phi_{\ell_0,miss}$
$m_{\ell_0\ell_1}$	$m_{\ell_0\ell_2}$	$m_{\ell_1\ell_2}$	$\Delta\phi_{\ell_1,miss}$
$m_T^{\ell_0\ell_1}$	$m_T^{\ell_0\ell_2}$	$m_T^{\ell_1\ell_2}$	$\Delta\phi_{\ell_2,miss}$
$\mathcal{S}_{miss}/E_T^{miss}$	F_α		

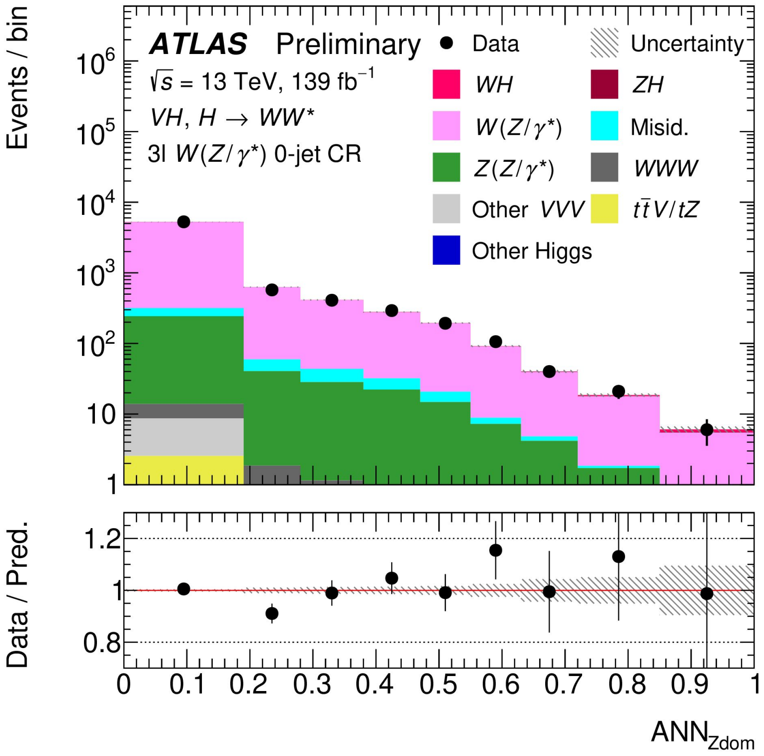
4-lepton *ZH*

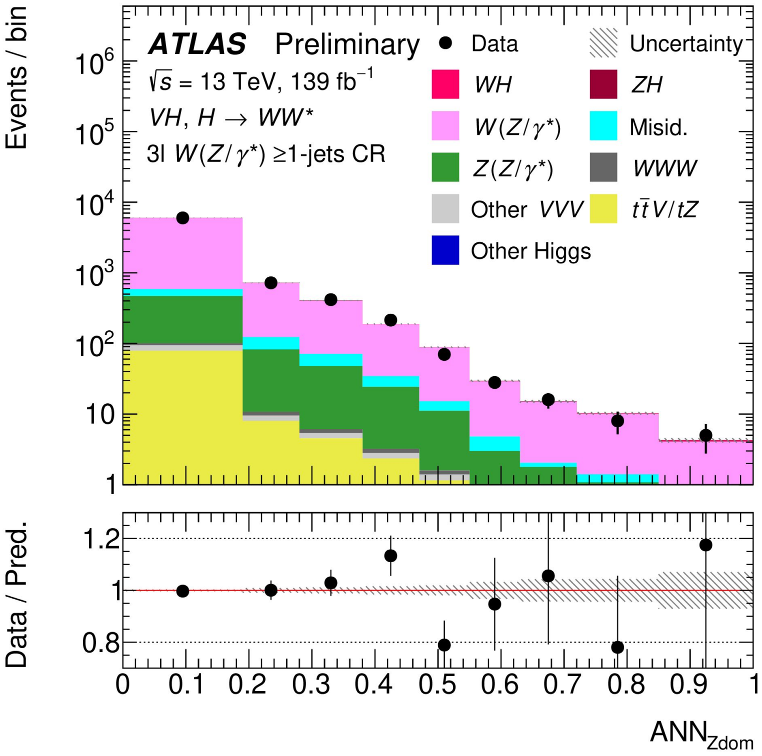
BDT input variables			
n_{jets}	$p_T^{\ell_0}$	$p_T^{\ell_1}$	$p_T^{\ell_2}$
$p_T^{\ell_3}$	E_T^{miss}	$p_T^{4\ell}$	$m_{\ell_2\ell_3}$
$m_{\ell_0\ell_1}$	$m_{4\ell}$	$m_{\tau\tau}$	$\Delta\phi_{\ell_0\ell_1,miss}$
$\Delta\phi_{\ell_0\ell_1}^{boost}$			

Control regions: 2-lepton DFOS *VH*

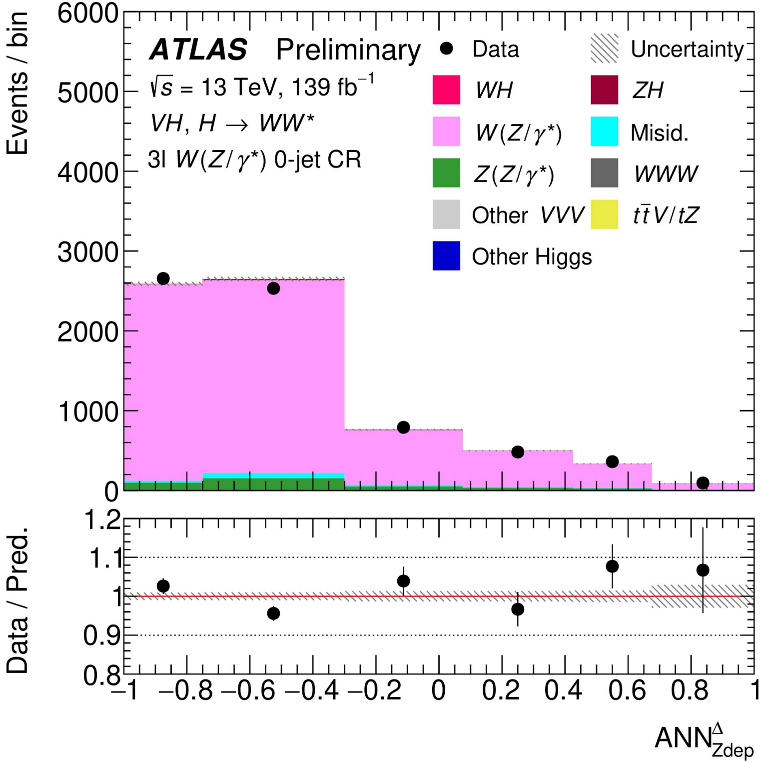


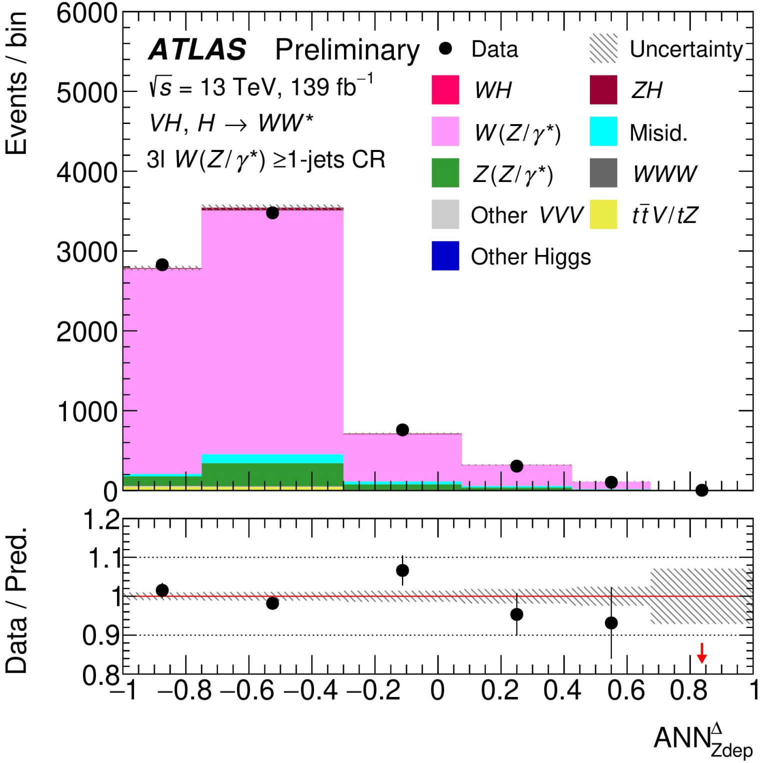
Control regions: 3-lepton *WH* binned in *Z*-dominated MVA score



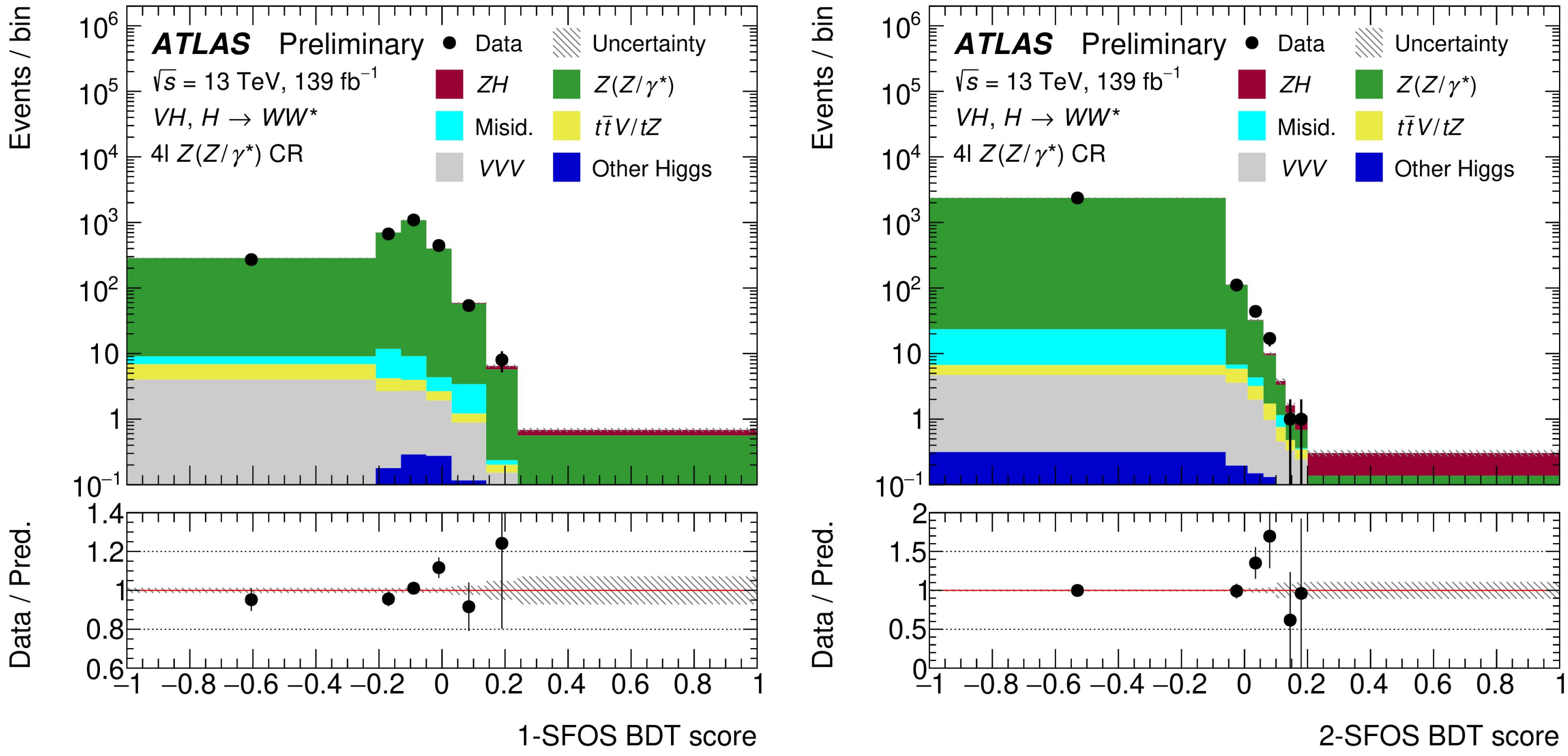


Control regions: 3-lepton *WH* binned in *Z*-depleted MVA score





Control regions: 4-lepton *ZH*



Single-channel results and normalization factors

Channel	POI / Z_0	Expected	Observed
Opposite-sign 2ℓ	μ_{VH}	$1.00^{+1.02}_{-0.98}$	$1.94^{+1.07}_{-1.02}$
	Z_0	1.0	1.9
Same-sign 2ℓ	μ_{WH}	$1.00^{+0.61}_{-0.60}$	-0.08 ± 0.58
	Z_0	1.6	0.0
3ℓ	μ_{WH}	$1.00^{+0.44}_{-0.40}$	$0.64^{+0.42}_{-0.37}$
	Z_0	2.8	1.8
4ℓ	μ_{ZH}	$1.00^{+0.47}_{-0.39}$	$1.59^{+0.54}_{-0.47}$
	Z_0	3.1	4.5
Combined 1-POI	μ_{VH}	$1.00^{+0.27}_{-0.25}$	$0.92^{+0.25}_{-0.23}$
	Z_0	4.7	4.6
Combined 2-POI	μ_{WH}	$1.00^{+0.35}_{-0.33}$	$0.45^{+0.32}_{-0.30}$
	μ_{ZH}	$1.00^{+0.47}_{-0.39}$	$1.64^{+0.55}_{-0.47}$
	Z_0^{WH}	3.3	1.5
	Z_0^{ZH}	3.1	4.6

Normalized via SS signal region

Channel	Background	Normalisation factor
Opposite-sign 2ℓ	Top	$0.99^{+0.31}_{-0.22}$
	Z+jets	$0.87^{+0.15}_{-0.14}$
	WW	$0.89^{+0.27}_{-0.24}$
Same-sign 2ℓ	$W(Z/\gamma^*)$	$0.91^{+0.18}_{-0.16}$
3ℓ	$W(Z/\gamma^*)$ 0-jet	1.03 ± 0.06
	$W(Z/\gamma^*)$ $\geq$1-jets	$0.88^{+0.16}_{-0.15}$
	WWW	$2.18^{+0.73}_{-0.61}$
4ℓ	ZZ	$0.99^{+0.08}_{-0.07}$

Normalized via *Z*-depleted signal region, motivated by excess observed in *WWW* measurement (2201.13045)

2D likelihood contours for observed results