Measurements of *WH* and *ZH* production in the $H \to bb$ decay channel in *pp* collisions at 13 TeV with the ATLAS detector

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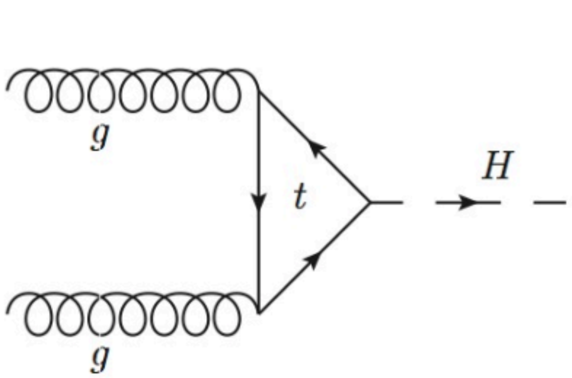
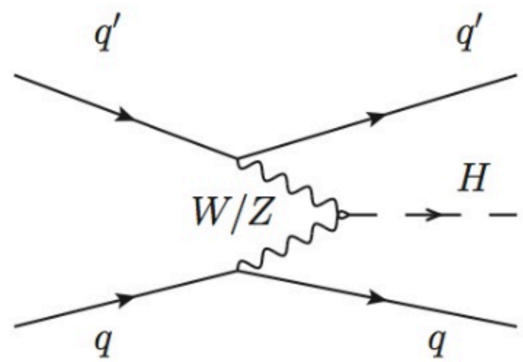
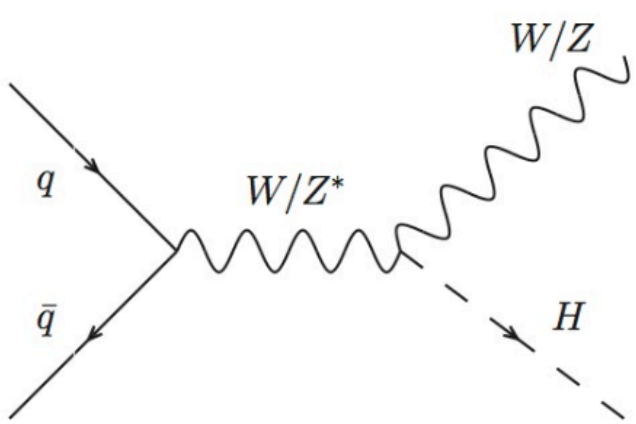
Higgs boson at the LHC



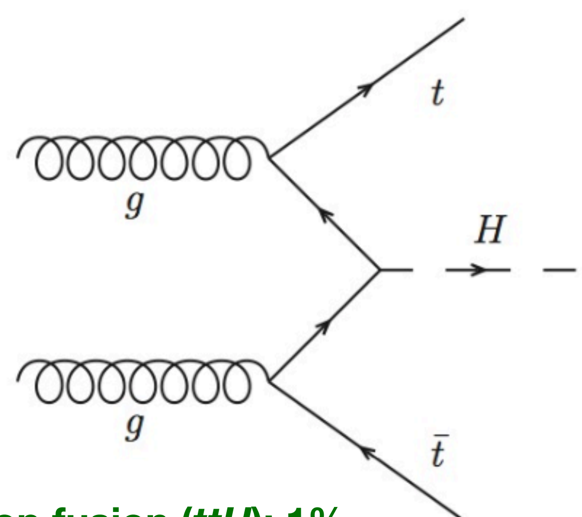
Gluon fusion (ggH): 88%



Vector boson fusion (VBF): 7%

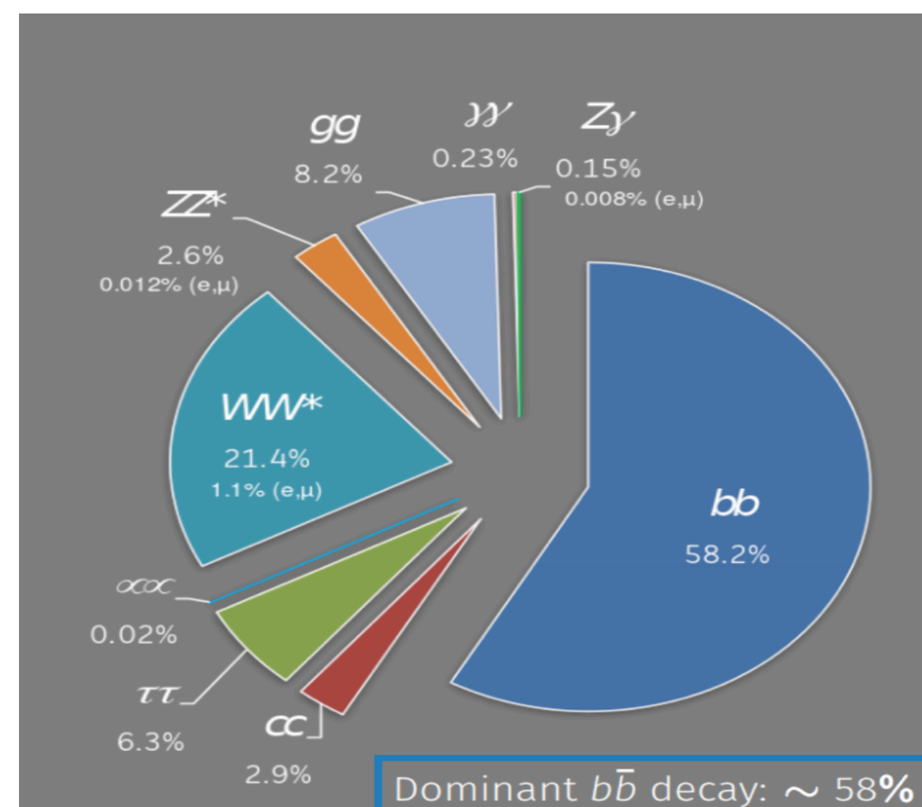


Higgs-strahlung (*VH*): 3%



Top fusion (*ttH*): 1%

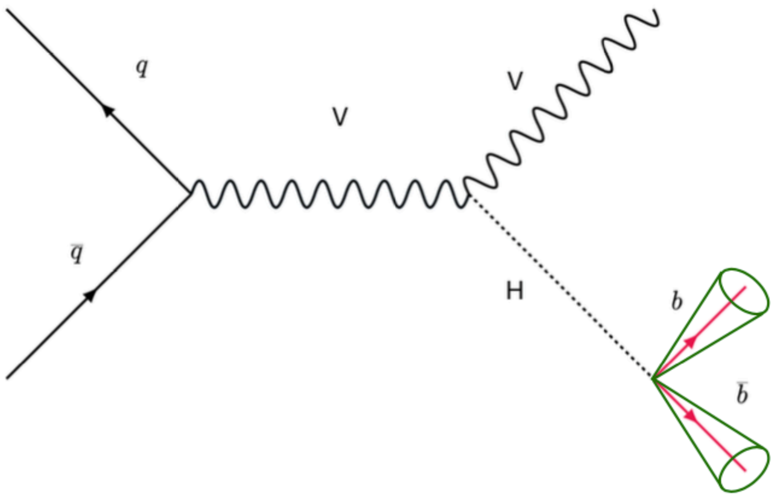
- The Higgs boson has 4 main production modes at the LHC
  - Focusing on the *VH* production mode
- Many decay modes accessible at the LHC
  - Decay to *b*-quarks is the most dominant with BR~58%

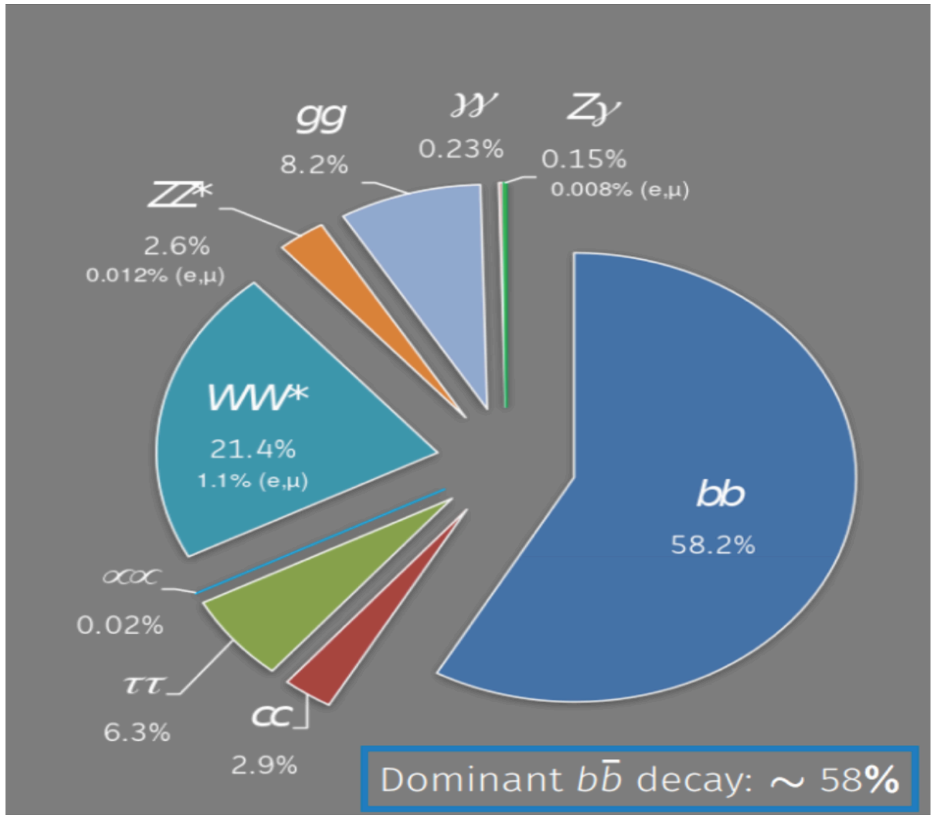


- Study the coupling of the Higgs boson to other particles
  - To assess the compatibility with the Standard Model (or beyond)
  - To bring additional constraints when measured in different channels

Motivations for measuring *VH*, *H*→*bb*

- *H*→ *bb* decay:
  - Allows to measure the coupling of the Higgs boson to *b*-quarks
  - Cannot be measured inclusively: Measured in the *VH* production mode
- *VH* (*WH*/*ZH*) production with leptonic V decays:
  - For efficient trigger and multi-jet background suppression
  - Interesting to measure the Higgs boson coupling to vector boson at high energies
  - The most sensitive channel to measure *H*→ *bb* decay

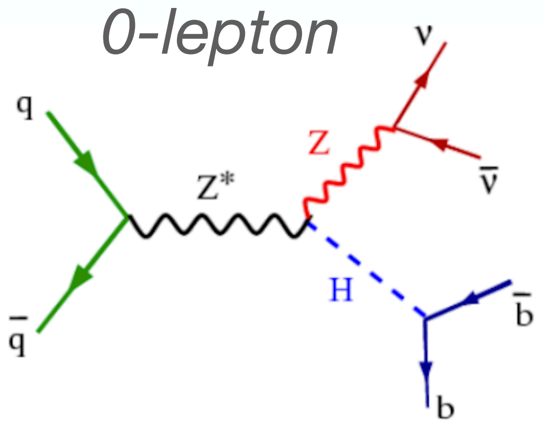




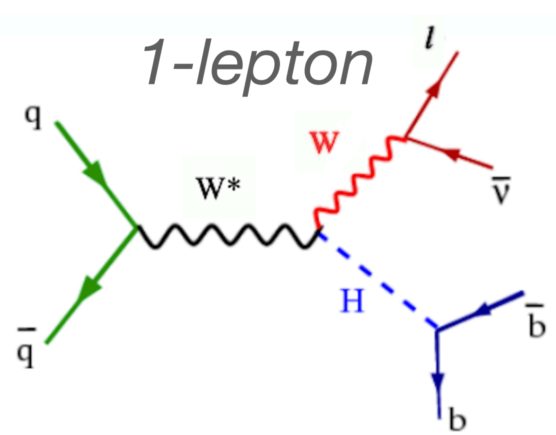
Analysis Strategy

- Analysing 139 fb^{-1} of data collected by ATLAS at 13TeV during Run-2
  - Focus in this talk on the resolved analysis: **arXiv:2007.02873**
  - Similar analysis in boosted topology: **arXiv:2008.02508**
- 3 channels depending on the number of charged lepton (e or μ) in the final state
- Event selection to reject background events
- Event categorisation into signal and control regions
- Multivariate analysis to increase sensitivity
- Two cross-check analyses to validate the results: di-jet mass and diboson analyses
- A binned likelihood fit performed to measure the signal

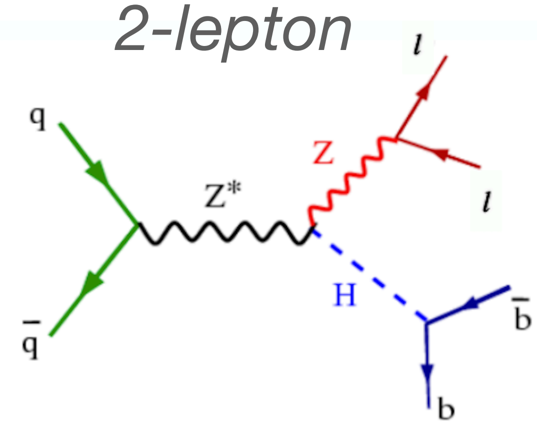
0-lepton



1-lepton



2-lepton



Event Selection

- Selecting events with either 2 jets or 3 jets (>= 3jets in the 2-lepton channel only)
- Selection of exactly 2 *b*-jets events (~70% efficiency) using *b*-tagging
- Selection cuts optimised in the three channels to reject background events

0-lepton	1-lepton	2-lepton

Common cuts

- Leading (sub-leading) jet p_T>45 (20) GeV
- Selection of events with exactly 2 *b*-jets using *b*-tagging

Cuts on the reconstructed vector boson

0-lepton	1-lepton	2-lepton
• MET trigger • 0 isolated lepton	• Single lepton or MET trigger • 1 isolated lepton	• Single lepton trigger • 2 isolated lepton • 81 GeV<m_{ll}< 101 GeV • Leptons of opposite charges for *Z(➔μμ)H* sub-channel

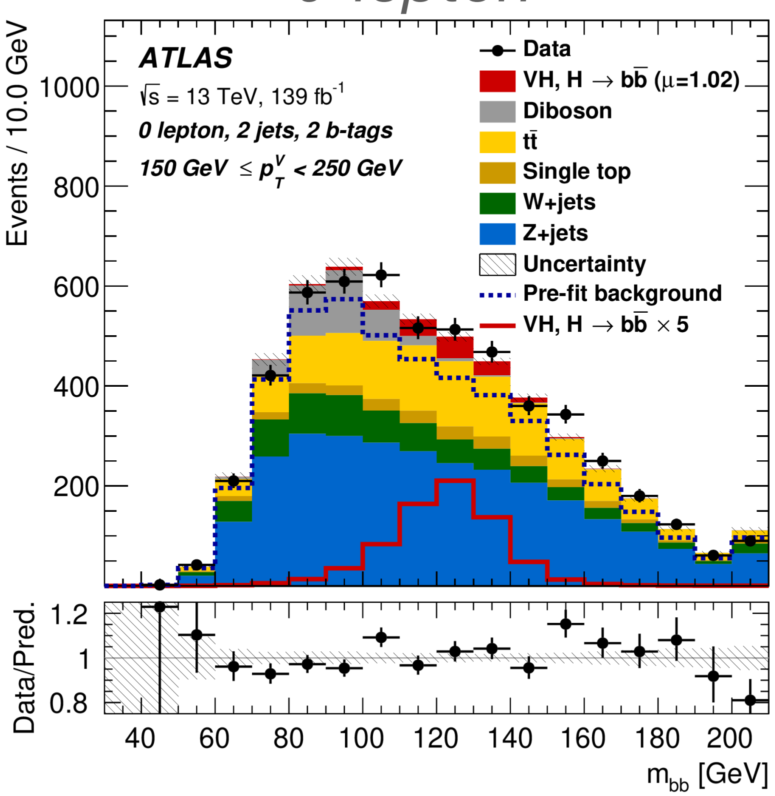
Cuts to reduce QCD multi-jet background

0-lepton	1-lepton	2-lepton
• Anti-QCD angular cuts	• MET > 30GeV in W*(➔eν)H* sub-channel to reduce multi-jet background	

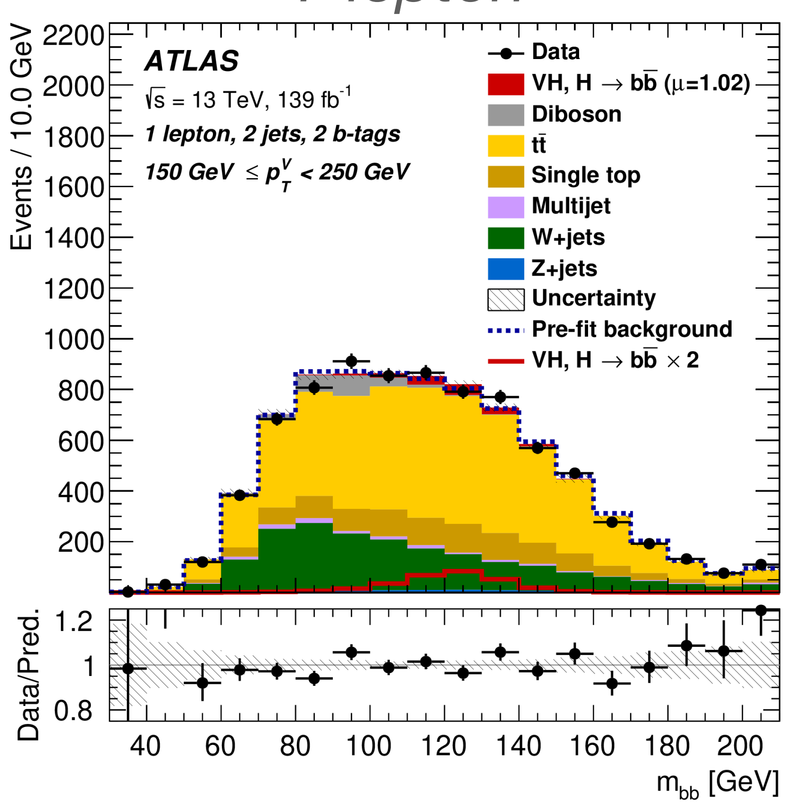
Background composition

- Use state-of-the-art Monte Carlo generators to model dominant backgrounds
  - **W+jets (Sherpa 2.2.1):** dominant in the 0- and 1-lepton channels
  - **Z+jets (Sherpa 2.2.1):** dominant in the 0- and 2-lepton channels
  - **ttbar** and **single-top (PowhegPythia8):** dominant in the 0- and 1-lepton channels
    - Data-driven method used to estimate the **top** background in the 2-lepton channel
  - **Diboson (Sherpa 2.2.1):** present in the 3 channels at lower m_{bb}
- **Multijet:** Small contribution in the 1-lepton channel estimated using data-driven template fit method

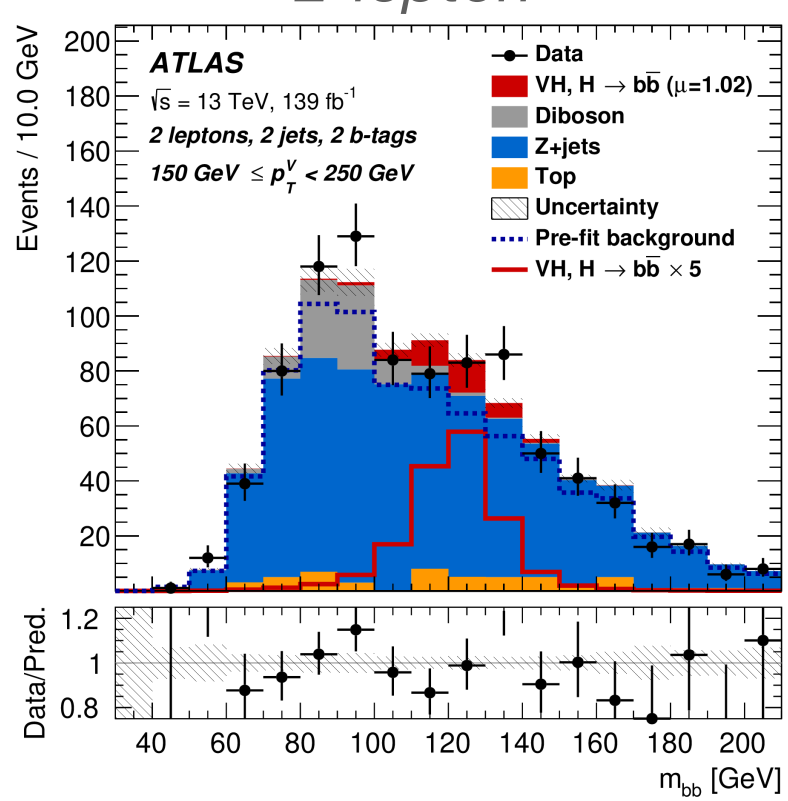
0-lepton



1-lepton



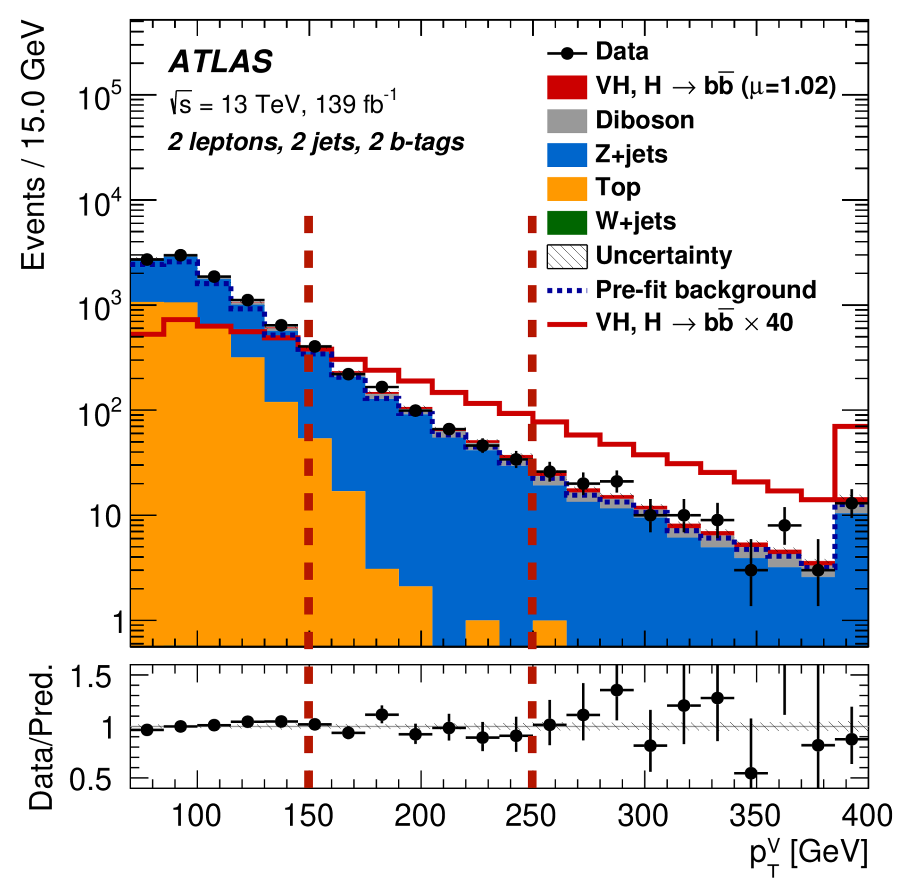
2-lepton



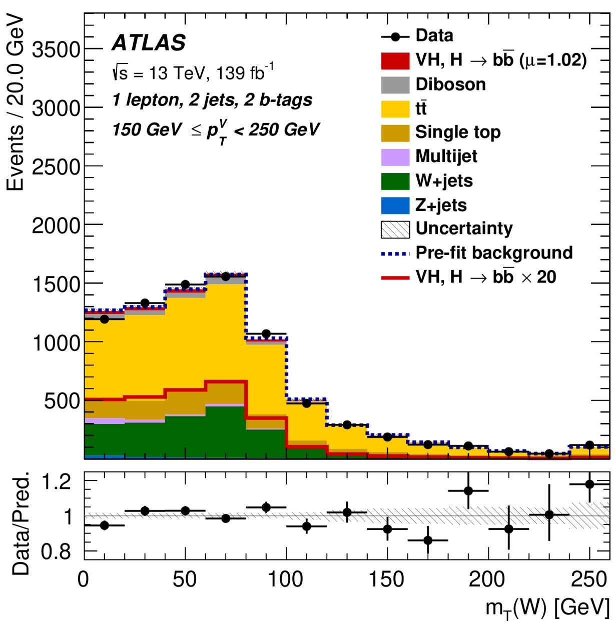
Topology of the signal

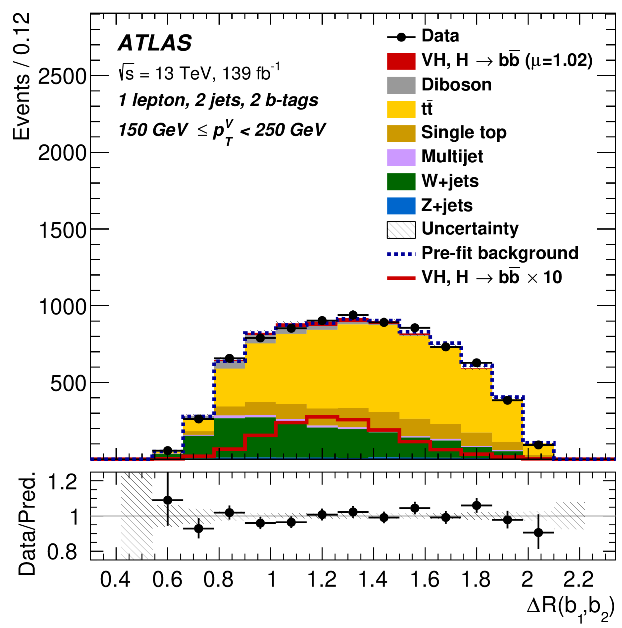
- Signal has a harder p_T^V spectrum than backgrounds
  - Improved sensitivity at high p_T^V
  - Motivation to split the spectrum into bins of p_T^V:
    - $75GeV < p_T^V < 150GeV$ in the 2-lepton channel
    - $150GeV < p_T^V < 250GeV$ and $p_T^V > 250GeV$ in all three lepton channels
- Jets are more collimated at high p_T^V : $\Delta R_{bb} \sim 2m_{bb} / p_T^V$
- p_T^V is a very important variable in the analysis: used in the BDT training and for the event categorisation

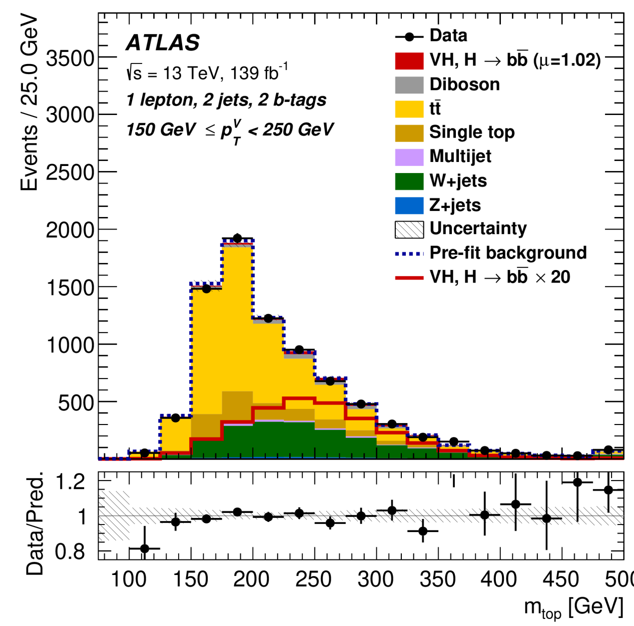
p_T^V →
- 0-lepton: E_T^{miss}
- 1-lepton: $p_T(l + \nu)$
- 2-lepton: $p_T(l^+ + l^-)$

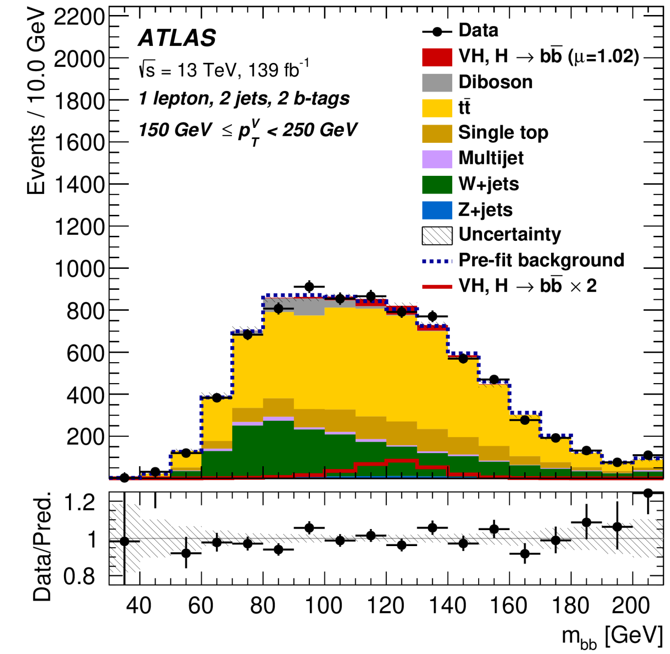


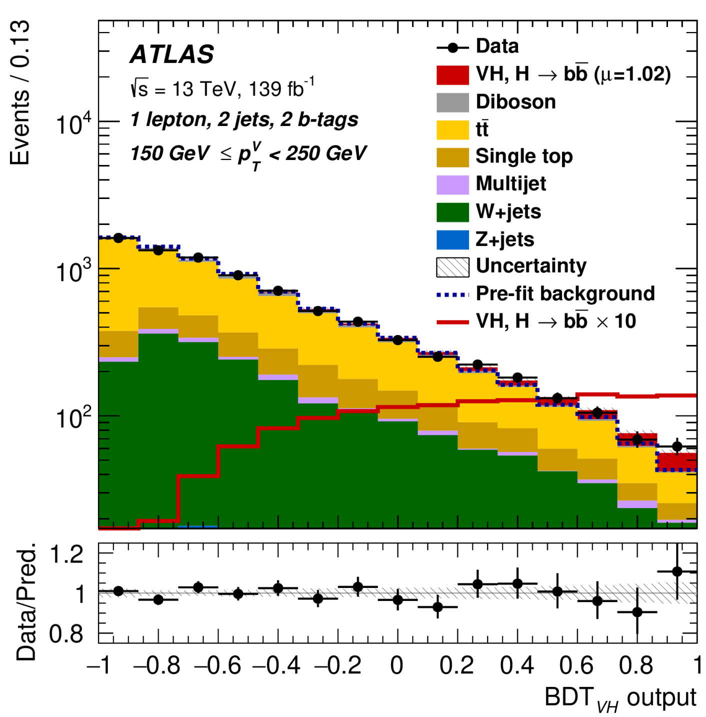
Multivariate Analysis (MVA)







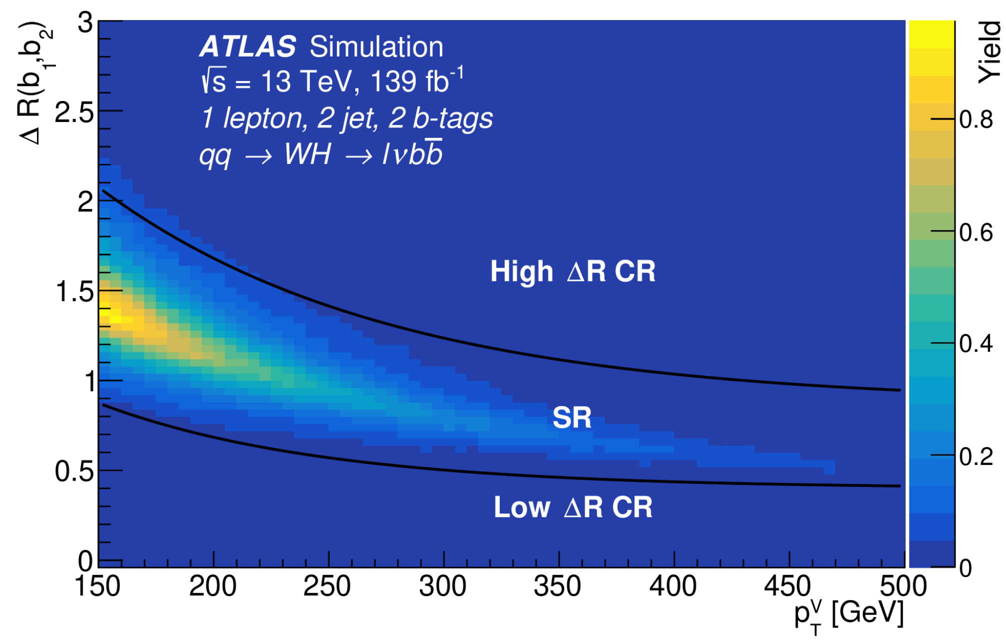


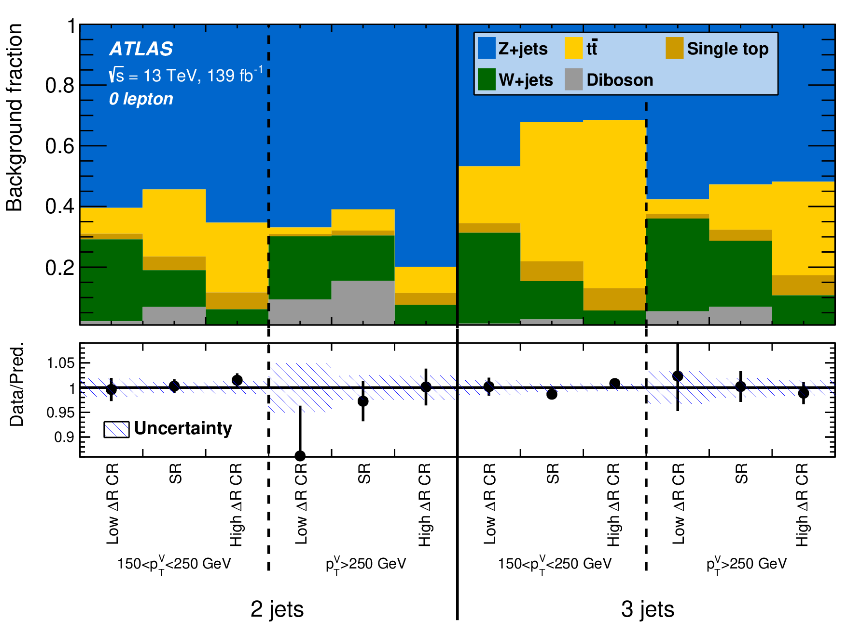


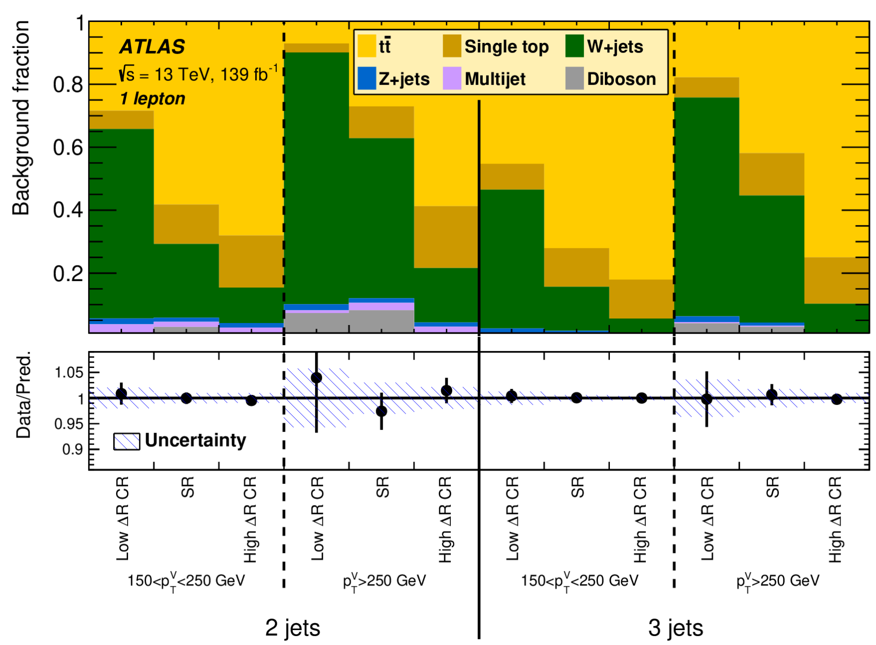
- Using a multivariate analysis to increase the sensitivity
- A BDT is constructed from many kinematic variables
  - m_{bb}, $p^T{}_V$, ΔR_{bb} are the most important variables in the training
  - Tuned and optimised to give the best signal and background separation
  - Is used as a discriminant in the final fit to extract the significance

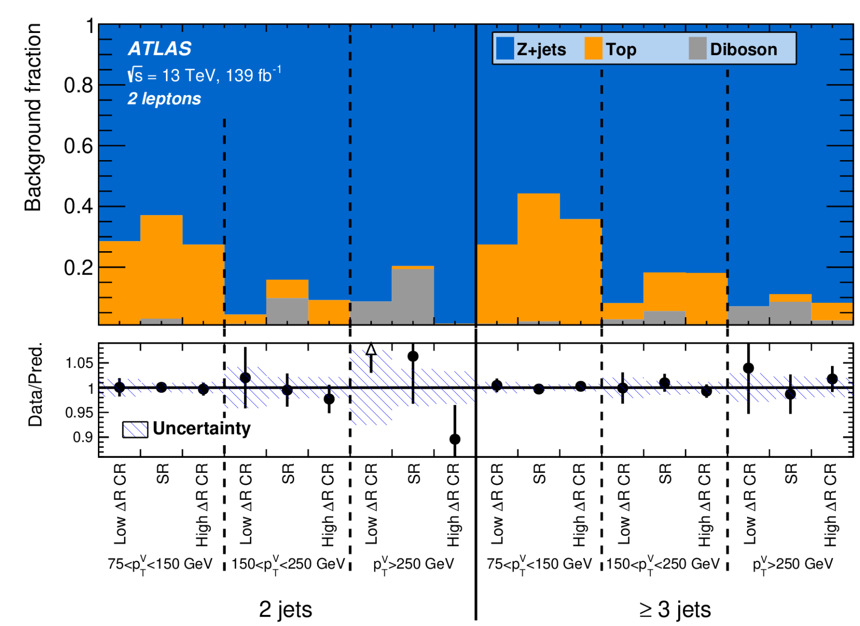
Events categorisation

- Use 2 continuous cuts in the ΔR_{bb}-p_T^V plane to create the Signal Region (SR), the Low and High ΔR Control Regions (CRs)
- Defined from the signal distribution to have:
  - SRs with high S/B ratio
  - CRs rich in backgrounds with low signal acceptance
- The analysis includes 14 signal regions and 28 control regions where:
  - The BDT_{VH}, m_{bb} or the BDT_{VZ} shapes are used in the SR
  - The yields are used in the CRs









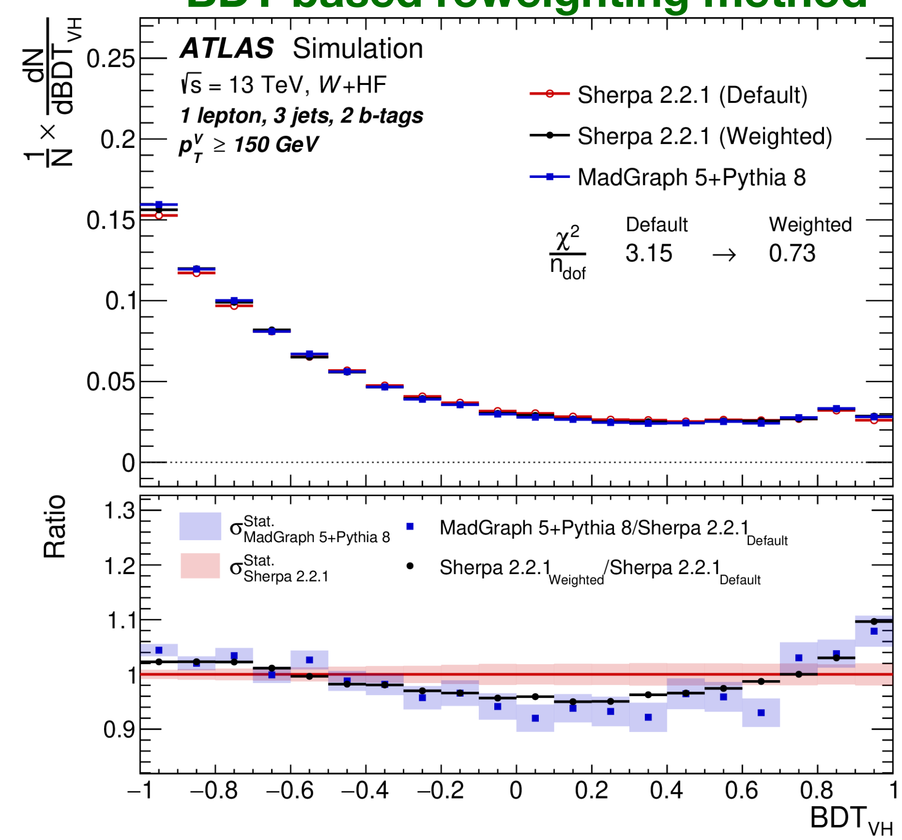
Background modelling

- Normalisations of the main backgrounds floated within the global likelihood fit (ttbar, **W+jets**, **Z+jets**)

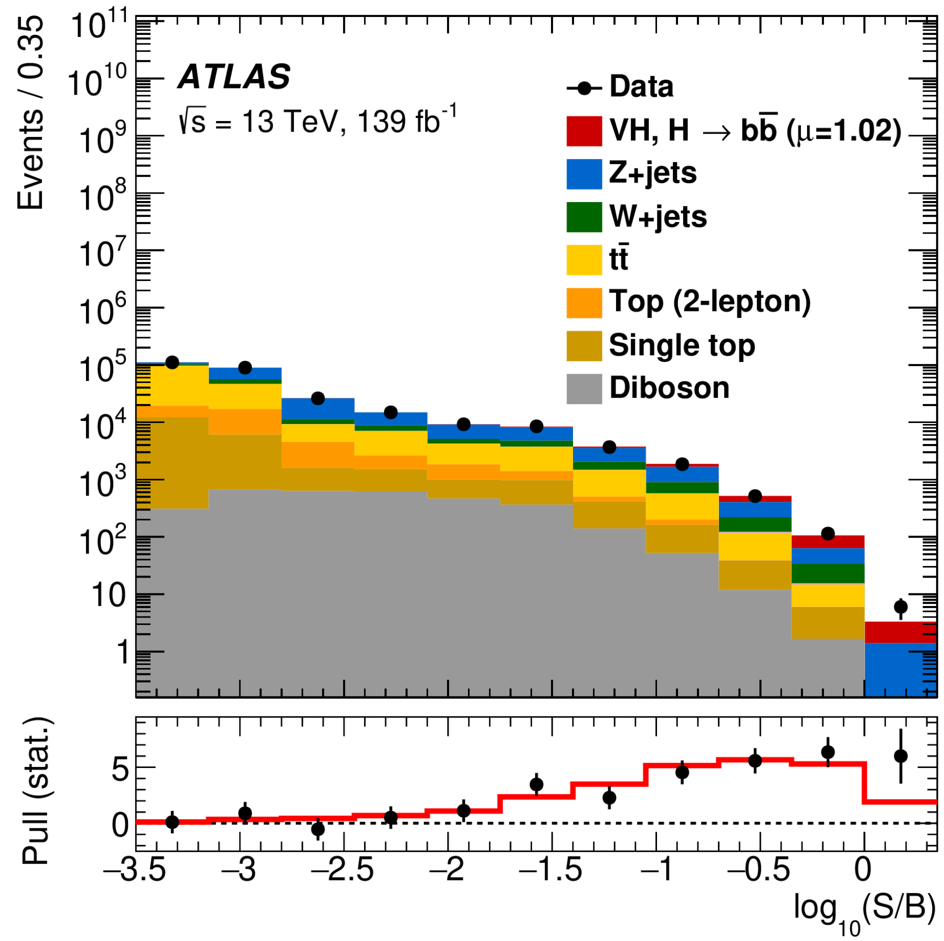
Process and Category	Normalisation factor
$t\bar{t}$ 2-jet	0.98 ± 0.09
$t\bar{t}$ 3-jet	0.93 ± 0.06
$W+$ heavy flavors 2-jet	1.06 ± 0.11
$W+$ heavy flavors 3-jet	1.15 ± 0.09
$Z+$ heavy flavors 2-jet, $75 < p_T^V < 150\,\text{GeV}$	1.28 ± 0.08
$Z+$ heavy flavors 3-jet, $75 < p_T^V < 150\,\text{GeV}$	1.17 ± 0.05
$Z+$ heavy flavors 2-jet, $p_T^V > 150\,\text{GeV}$	1.16 ± 0.07
$Z+$ heavy flavors 3-jet, $p_T^V > 150\,\text{GeV}$	1.09 ± 0.04

- Systematic uncertainties are assigned to Monte Carlo background predictions under two types:
  - Acceptance uncertainties
    - To account for extrapolation between regions/categories and flavour composition
  - Shape uncertainties:
    - To quantify the effect of the change in the Monte Carlo template prediction
    - Derived from the shape variation on the p_T^V distribution and either m_{bb} distribution or using the BDT-based re-weighting method

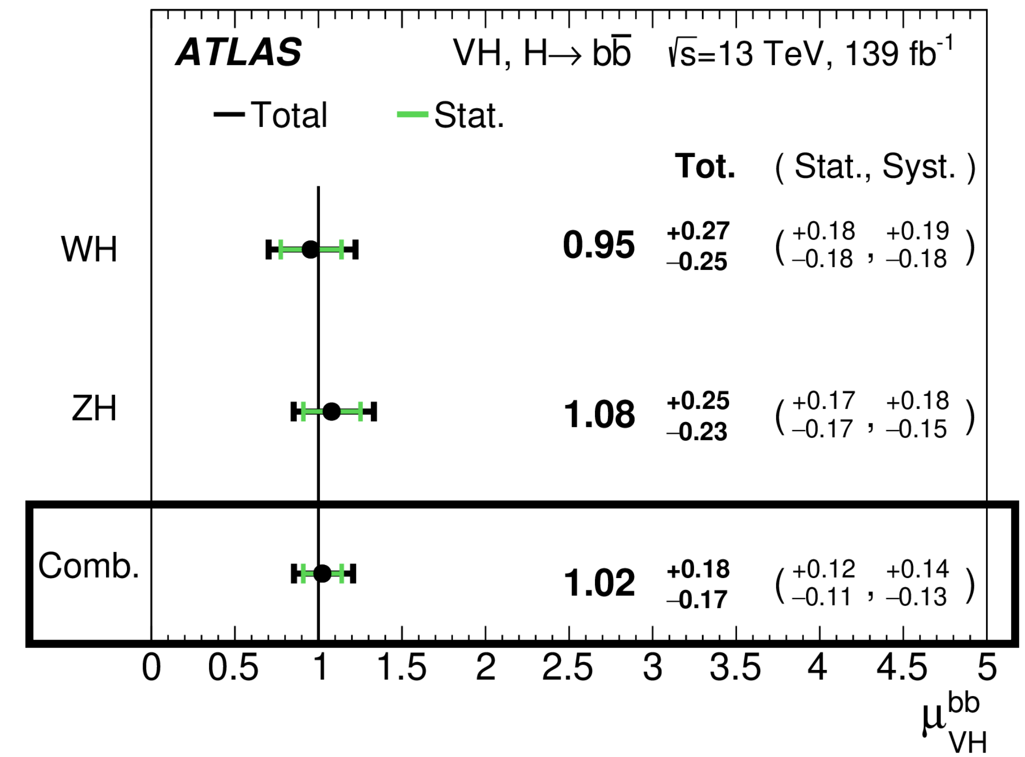
W+jets shape uncertainties using BDT-based reweighting method



Results of the *VH* MVA

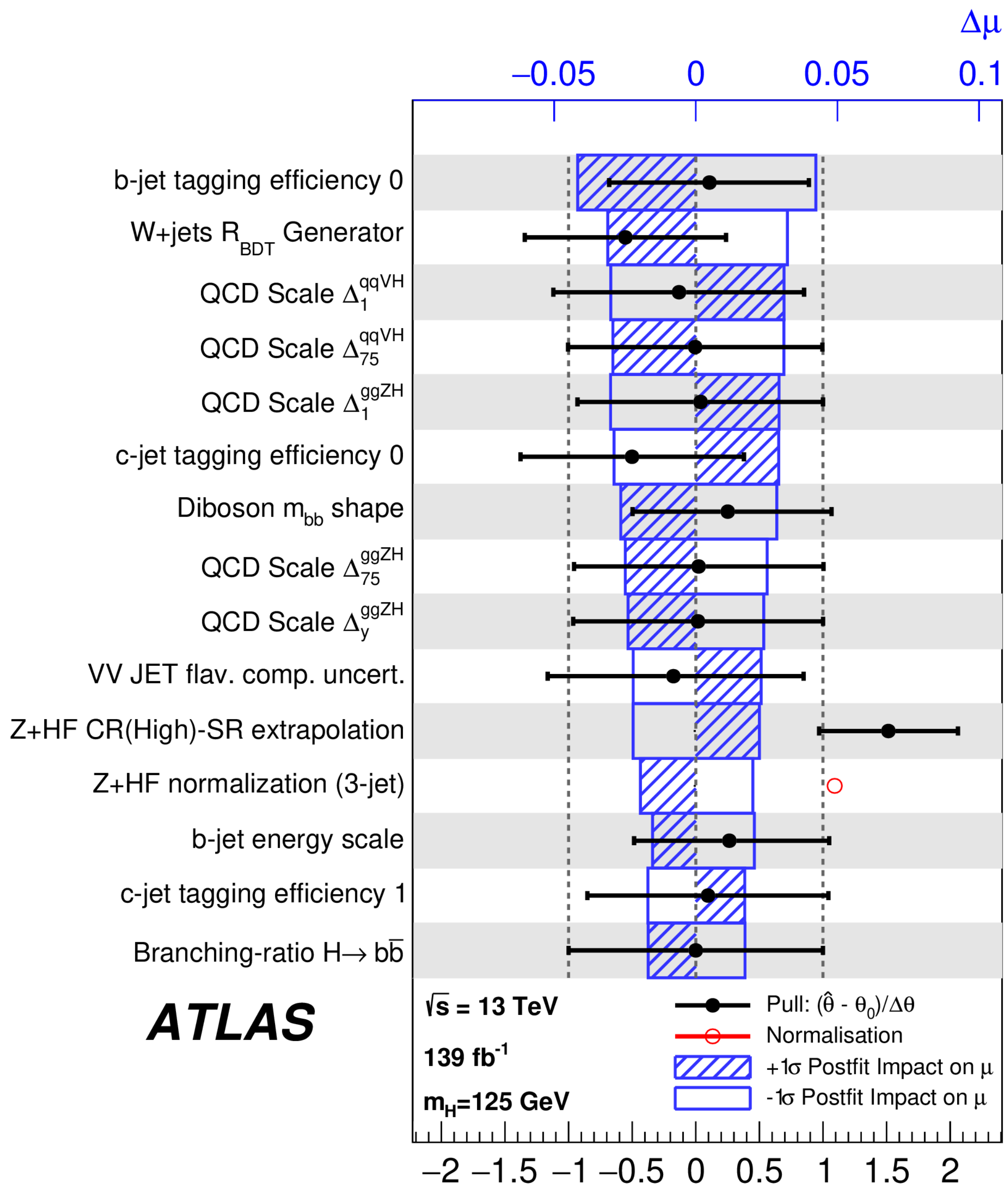


$$\mu = \frac{\sigma \times BR}{\sigma_{\rm SM} \times BR_{\rm SM}}$$



- Results of the MVA measurements using full Run-2 data:
  - Observation of the *VH* signal with 6.7σ (6.7σ expected)
  - Observation of the *ZH* signal with 5.3σ (5.2σ expected)
  - Strong evidence of the *WH* signal with 4.0σ (4.1σ expected)
  - Signal strengths in good agreement with the Standard Model

Impact of the uncertainties

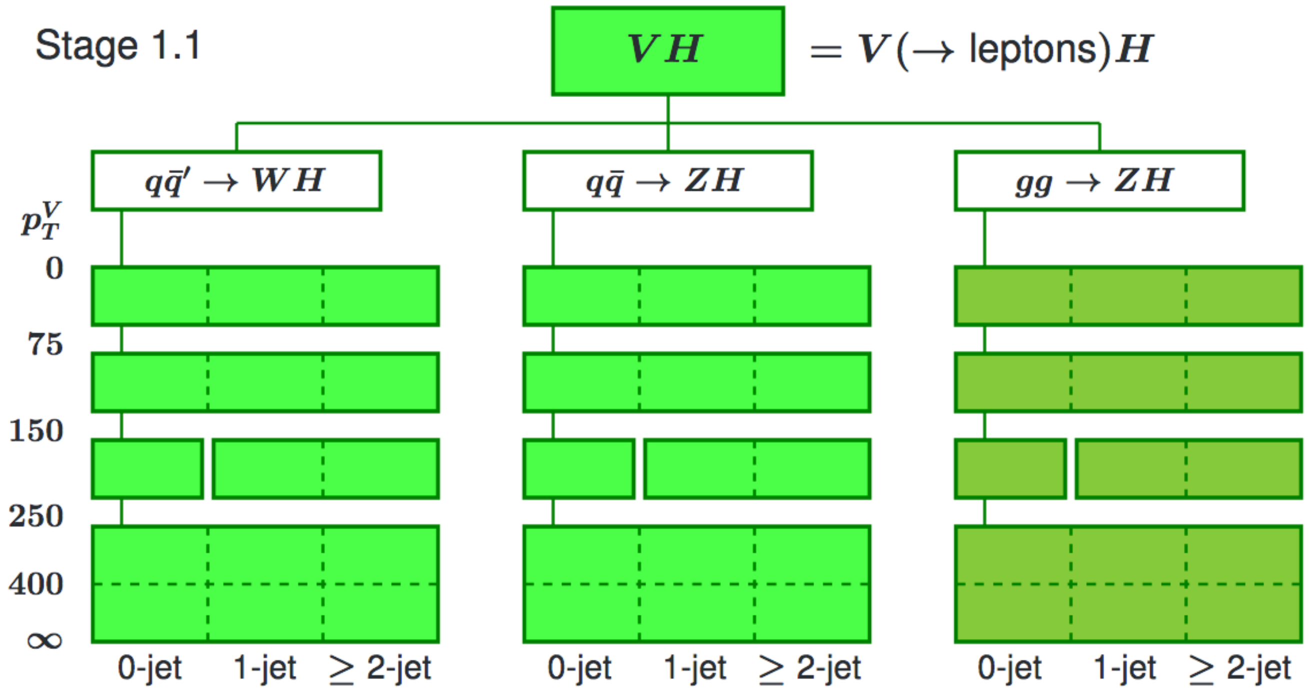


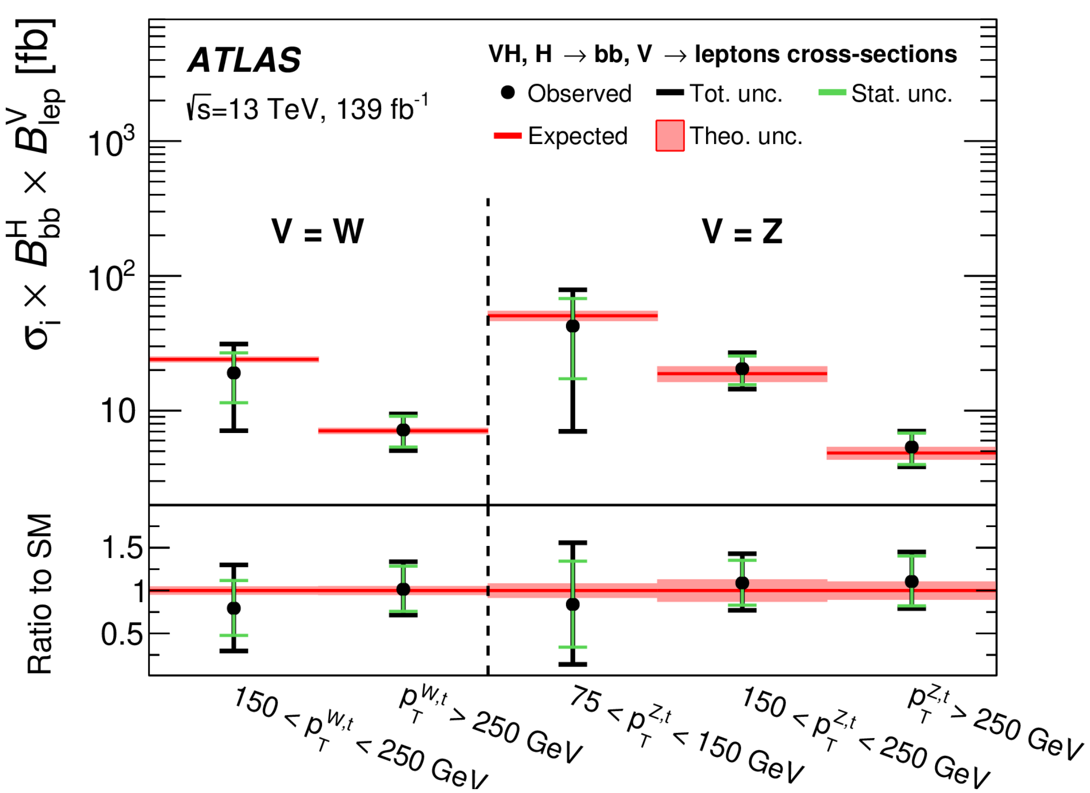
Source of uncertainty		σ_μ VH	WH	ZH
Total		0.177	0.260	0.240
Statistical		0.115	0.182	0.171
Systematic		0.134	0.186	0.168
Statistical uncertainties				
Data statistical		0.108	0.171	0.157
$t\bar{t}$ $e\mu$ control region		0.014	0.003	0.026
Floating normalisations		0.034	0.061	0.045
Experimental uncertainties				
Jets		0.043	0.050	0.057
E_T^{miss}		0.015	0.045	0.013
Leptons		0.004	0.015	0.005
b-tagging	b-jets	0.045	0.025	0.064
	c-jets	0.035	0.068	0.010
	light-flavour jets	0.009	0.004	0.014
Pile-up		0.003	0.002	0.007
Luminosity		0.016	0.016	0.016
Theoretical and modelling uncertainties				
Signal		0.052	0.048	0.072
Z + jets		0.032	0.013	0.059
W + jets		0.040	0.079	0.009
$t\bar{t}$		0.021	0.046	0.029
Single top quark		0.019	0.048	0.015
Diboson		0.033	0.033	0.039
Multi-jet		0.005	0.017	0.005
MC statistical		0.031	0.055	0.038

- Statistical and systematic uncertainties at the same level
- **Signal** and **background** modelling have a significant impact as well as ***b*-tagging** and **MC statistics**

Differential cross-section measurements

- Differential cross-section (STXS) measurements were performed
- STXS measurement in 5 p_T^V bins
- Measured σ*BR in each of the bins in agreement with the SM within uncertainties





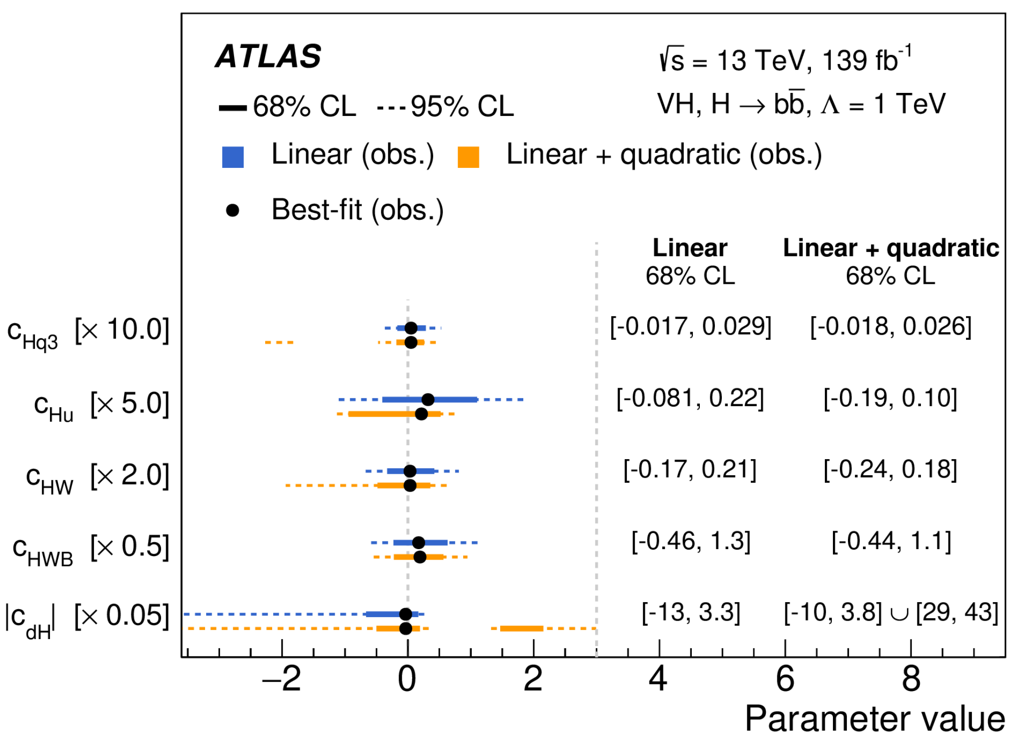
EFT interpretation

- Probe new physics/interactions by constraining EFT operators
  - Using STXS for differential measurements (analysis is sensitive to new physics at high p_T^V)
- Dim-6 operators added in the Warsaw basis:

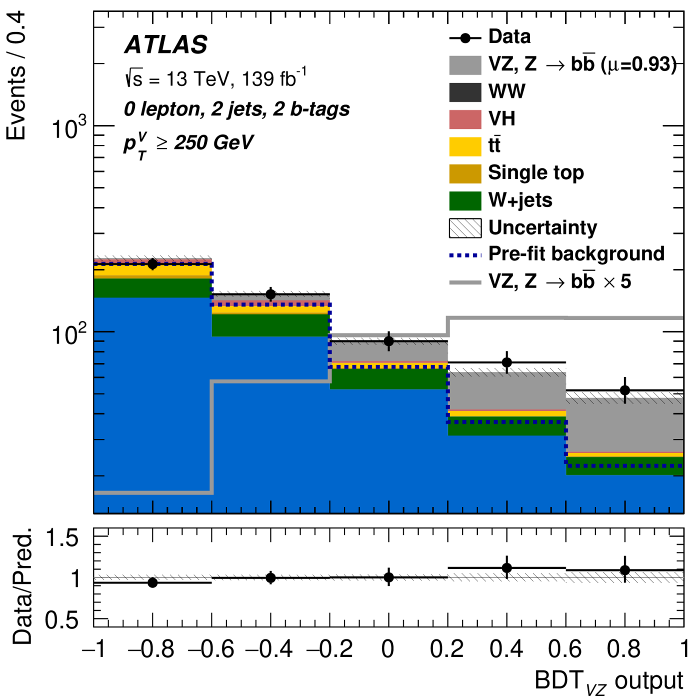
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \mathcal{L}_{dim=6} = \mathcal{L}_{SM} + \frac{c_i}{\Lambda^2} O_i$$

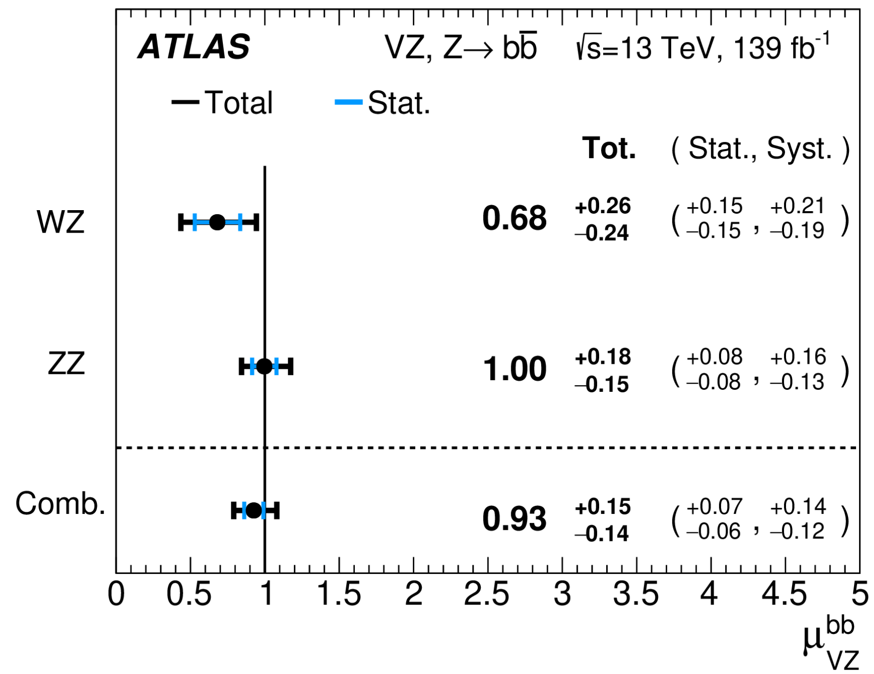
- The *VH* signal is sensitive to ~20 operators

Wilson coefficient	Operator	Impacted vertex	
		Production	Decay
c_{HWB}	$\mathcal{O}_{HWB} = H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$	HZZ	
c_{HW}	$\mathcal{O}_{HW} = H^\dagger H W^I_{\mu\nu} W_I^{\mu\nu}$	HZZ, HWW	
c_{Hq3}	$\mathcal{O}^{(3)}_{Hq} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	$qqZH, qq'WH$	
c_{Hq1}	$\mathcal{O}^{(1)}_{Hq} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	$qqZH$	
c_{Hu}	$\mathcal{O}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	$qqZH$	
c_{Hd}	$\mathcal{O}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	$qqZH$	
c_{dH}	$\mathcal{O}_{dH} = (H^\dagger H)(\bar{q} d H)$		Hbb

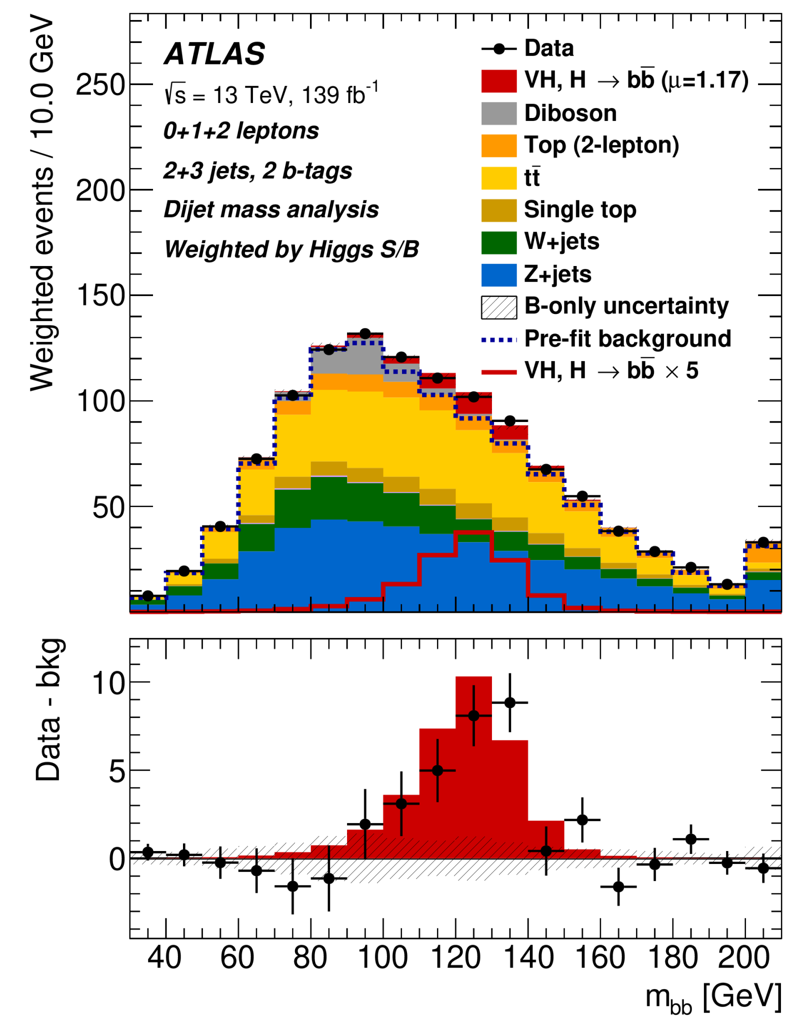


Validation and cross-check



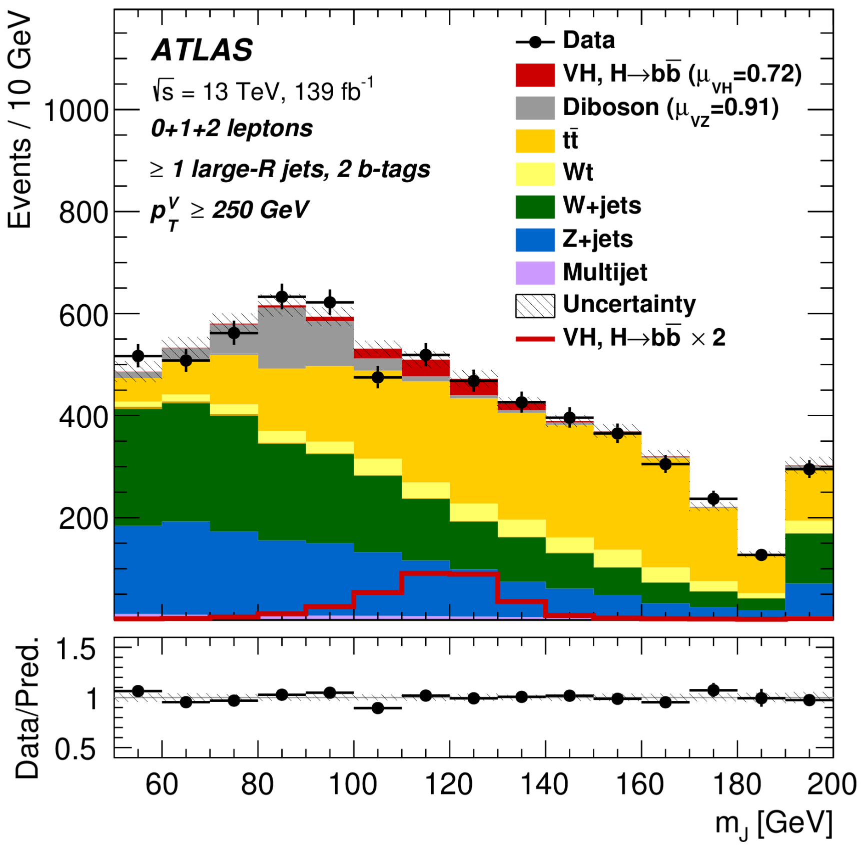


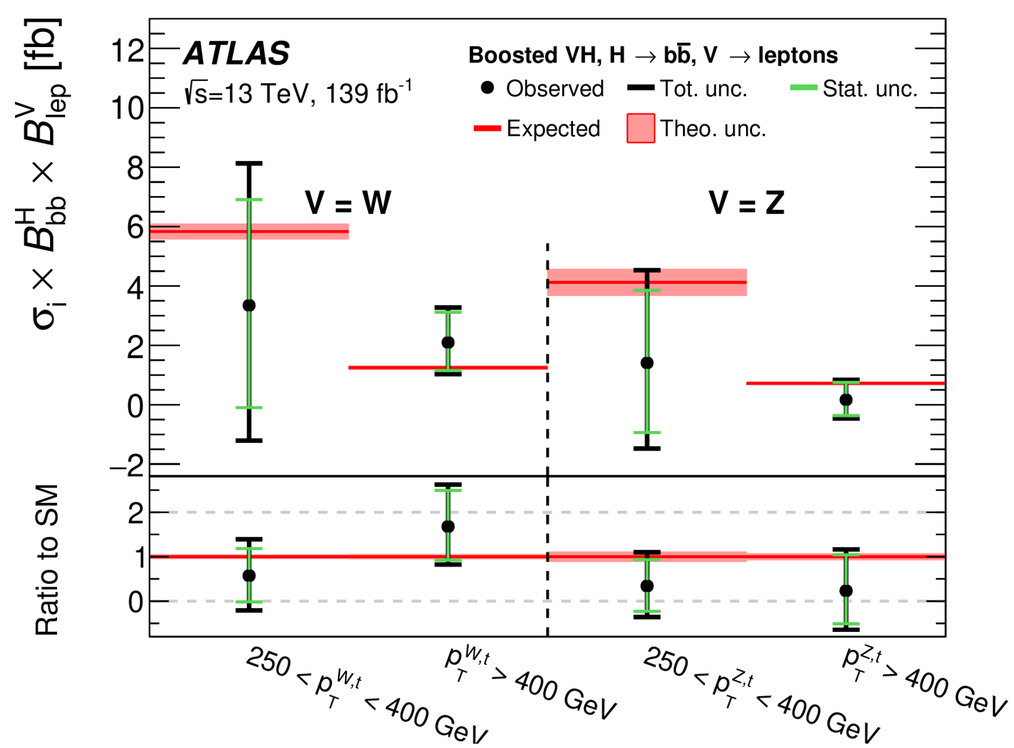
- The diboson analysis is a robust validation of the background model
  - By measuring the signal strength using the BDT_{VZ} as a discriminant
  - The results were shown to be in good agreement with the Standard Model prediction
- The di-jet mass analysis is a good cross-check that focuses on m_{bb}
  - The measurement yields an observation of the *VH* signal with a significance of 5.5σ (4.9σ expected)



The boosted analysis

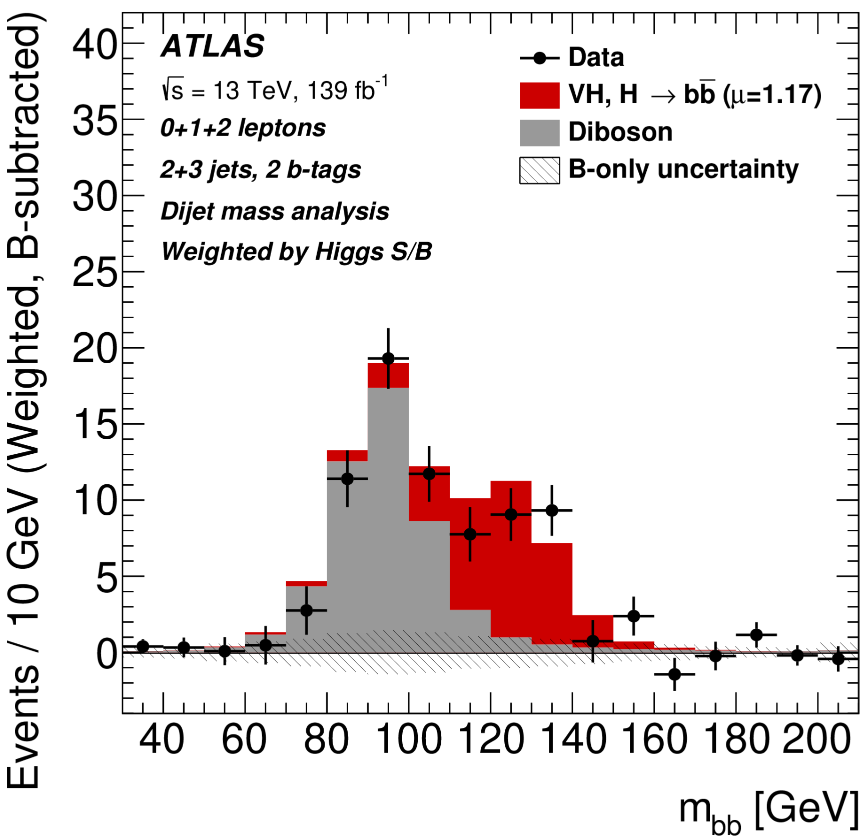
- The analysis uses boosted techniques in the reconstruction of the jets and similar analysis strategy as resolved
- The signal measurement is extracted from a fit to the mass of the large-R jet
- Complementary phase space: 250GeV < p_T^V < 400GeV and p_T^V >400GeV
- STXS measurement in 4 p_T^V bins and results consistent with the SM
    - EFT interpretation of the results
- Currently resolved and boosted are two independent analyses but large overlap in phase space





Conclusion

- *VH, H→bb* analysis performed with full Run-2 data:
  - MVA as the main analysis and di-jet mass and diboson analyses for cross-check and validation
- The results of the *VH* MVA measurements lead to:
  - *VH* (6.7σ) and *ZH* (5.3σ) observations
  - *WH* (4.0σ) first strong evidence
- Observation of the *VH* (5.5σ) signal in the di-jet mass analysis
- Measured σ*BR in 5 STXS bin consistent with the SM predictions
- Results were interpreted in the EFT context
- First Boosted analysis results and STXS measurements
  - Results are all consistent with the SM predictions



Back-up