Measurement of VH,H→bb Processes at Low and High Transverse Momenta

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Liverpool HEP Seminar,
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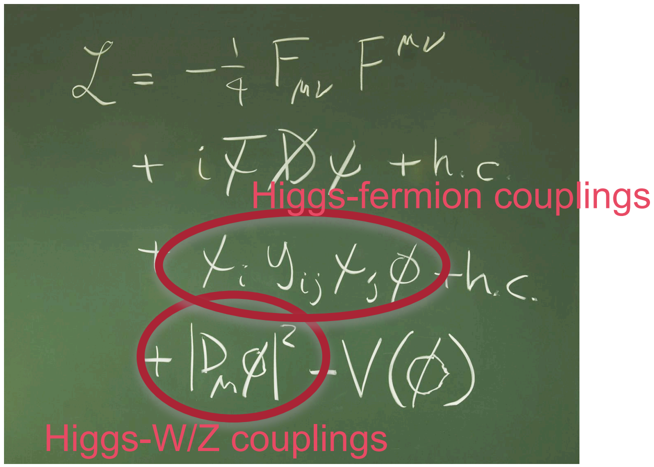
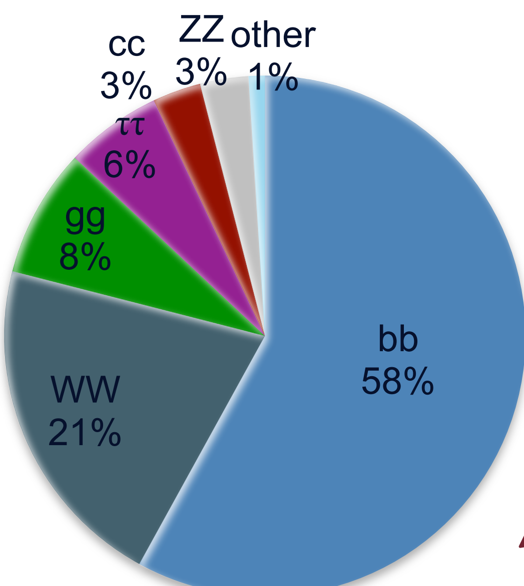
ATLAS EXPERIMENT

UNIVERSITY OF OXFORD

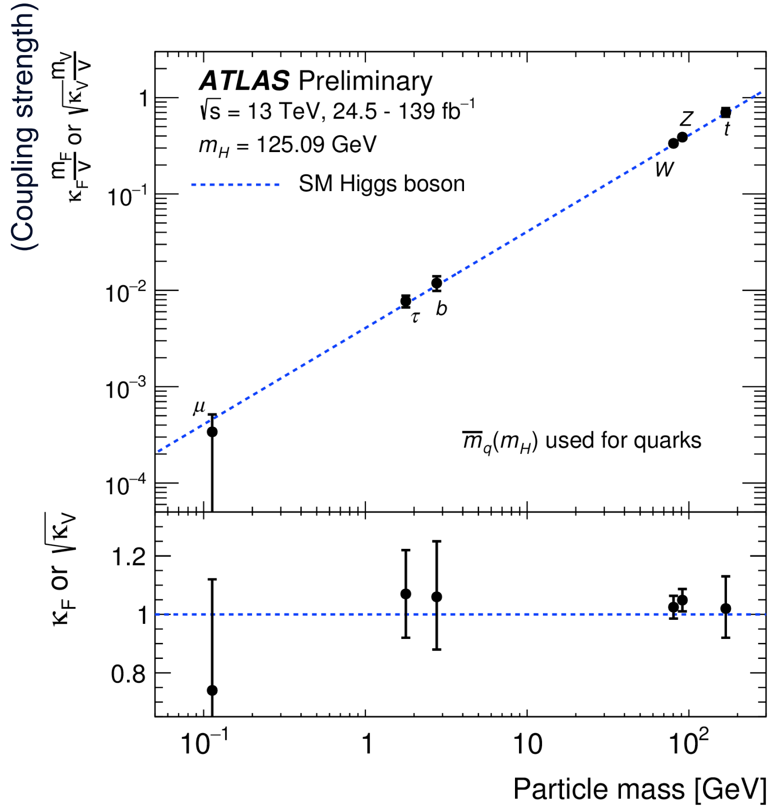
The Standard Model & The Higgs Boson



- (Most) SM particles have non-zero mass
  - → Higgs field present everywhere in universe
  - → Interactions of SM particles with Higgs field generate their masses
  - → New scalar boson associated with field: Higgs boson (H)
- 2012: discovery of new particle consistent with SM Higgs boson → mass ~125 GeV
- m_H = 125 GeV & SM-particle-Higgs coupling proportional to particle's mass
  - → Fixes Higgs boson decay branching ratios



Status of Higgs Boson Measurements

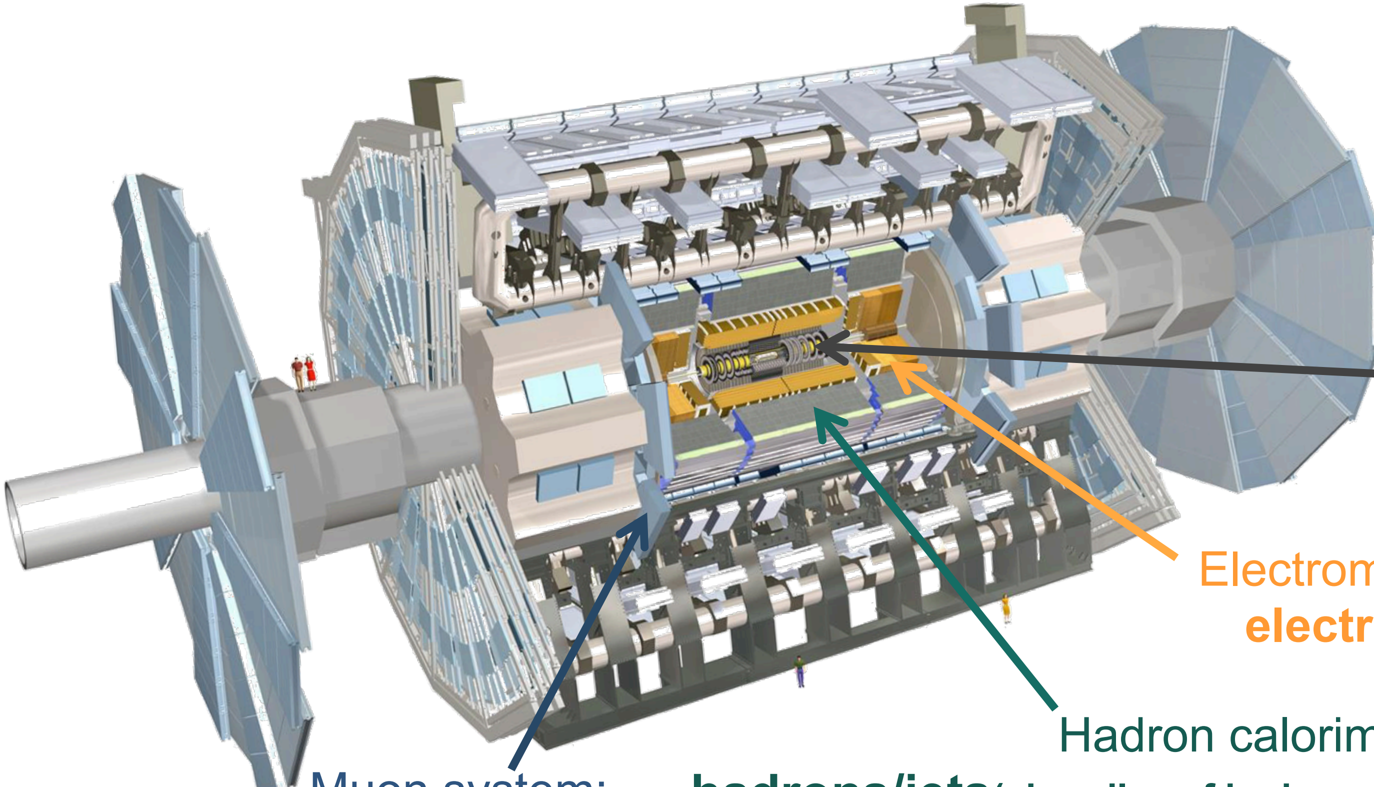


- Most of predicted SM-particle-Higgs interactions probed and many observed

→ (so far) All consistent with SM

- BR(H→bb) ≈ 60% → measure H→bb decays as precise as possible to reduce window for beyond SM Higgs decays
- New physics could enter indirectly and modify differential distributions → visible e.g. in high p_T tails
  - H→bb channel has statistical advantage due to large BR

+ Our Tool to Study Higgs Bosons: The ATLAS Detector

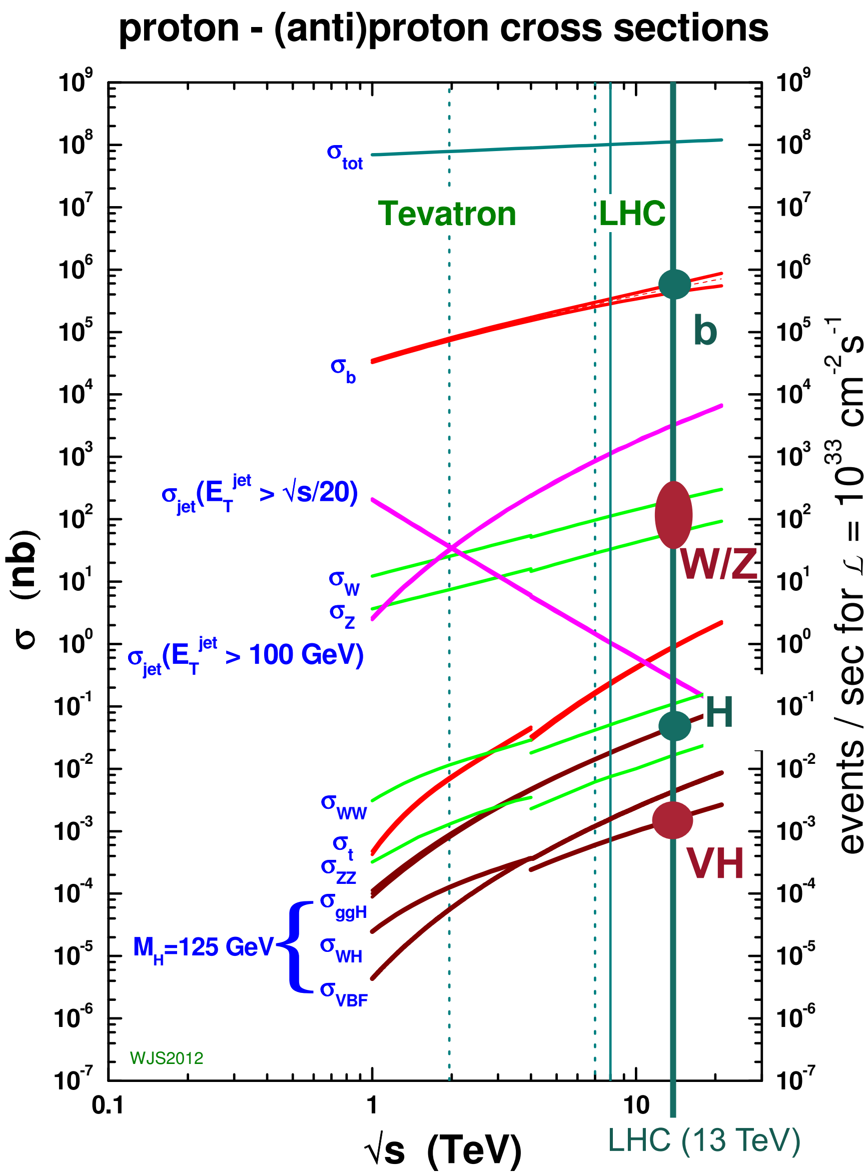


ATLAS data set:

LHC Run2 (2015-2018) = 140 fb^{-1} at 13 TeV → ~8 million Higgs bosons

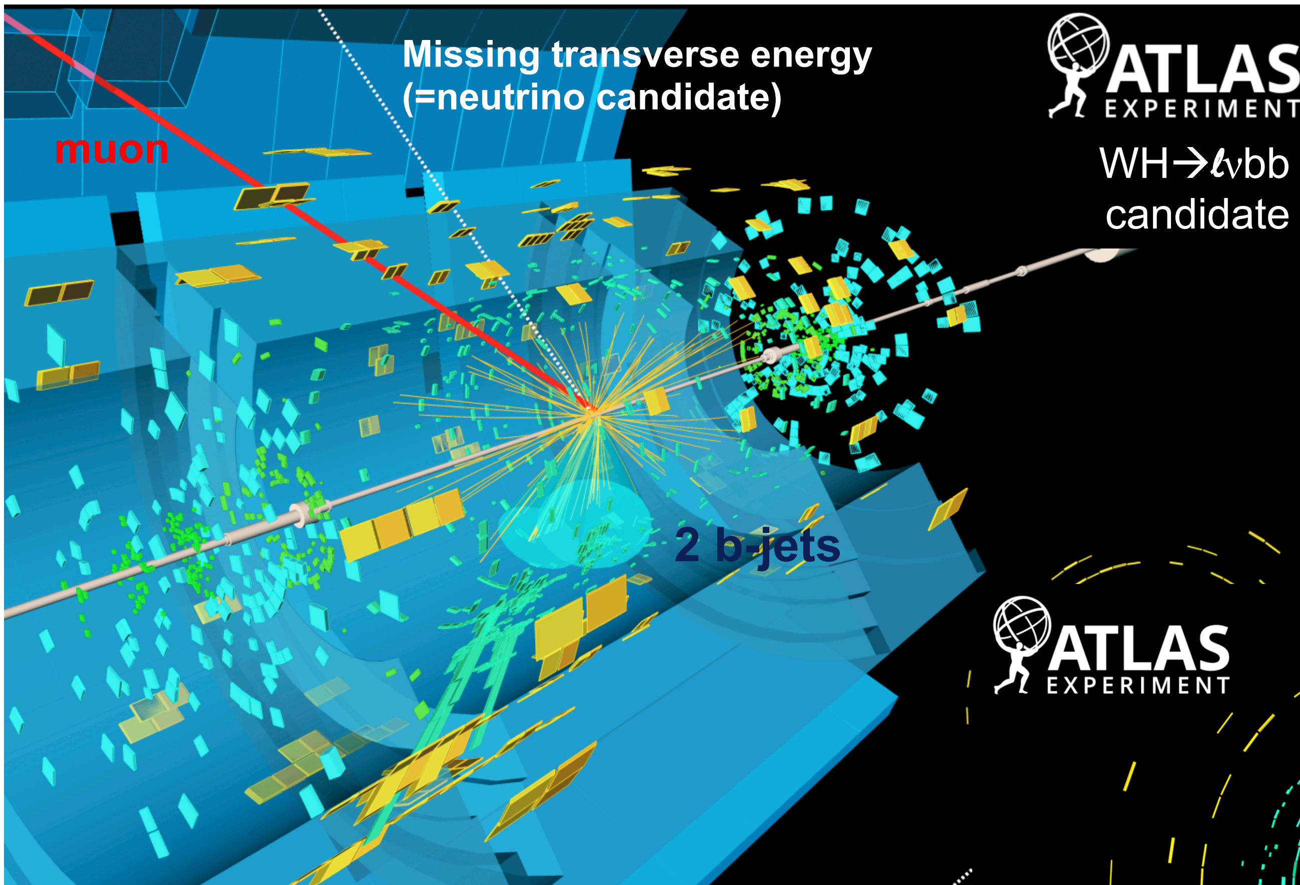
→ **Higgs physics is transitioning to precision measurement era**

H→bb Searches and SM Background Processes

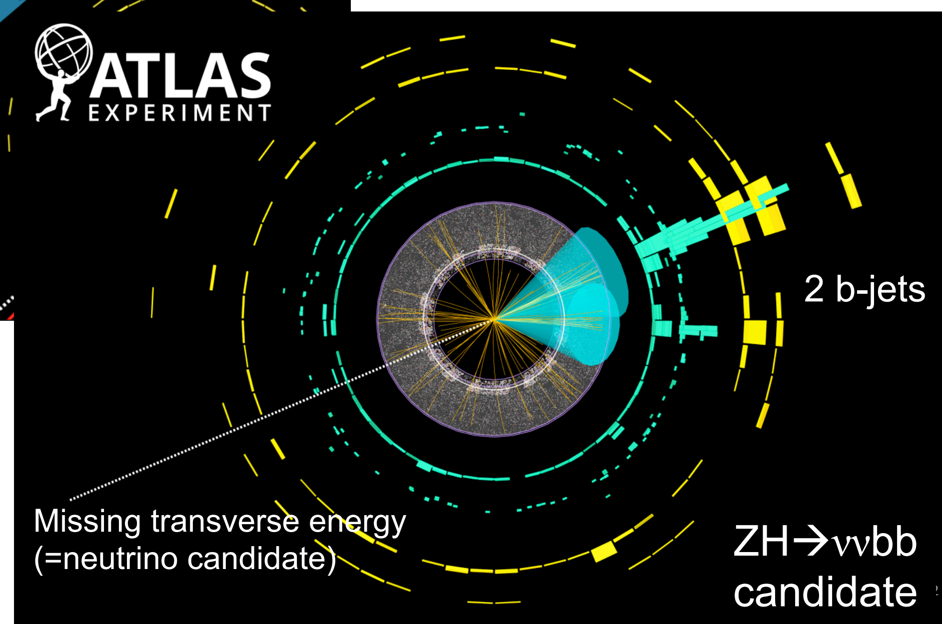


- Production of jets abundant in proton-proton collisions
  - → Impossible to record all events containing (b-)jets
  - → Overwhelming amount of background events
- Target VH production with V→leptons decays
  - → Leptons as trigger signature
  - → Suppression of multi-jet events

VH,H→bb Candidate Events

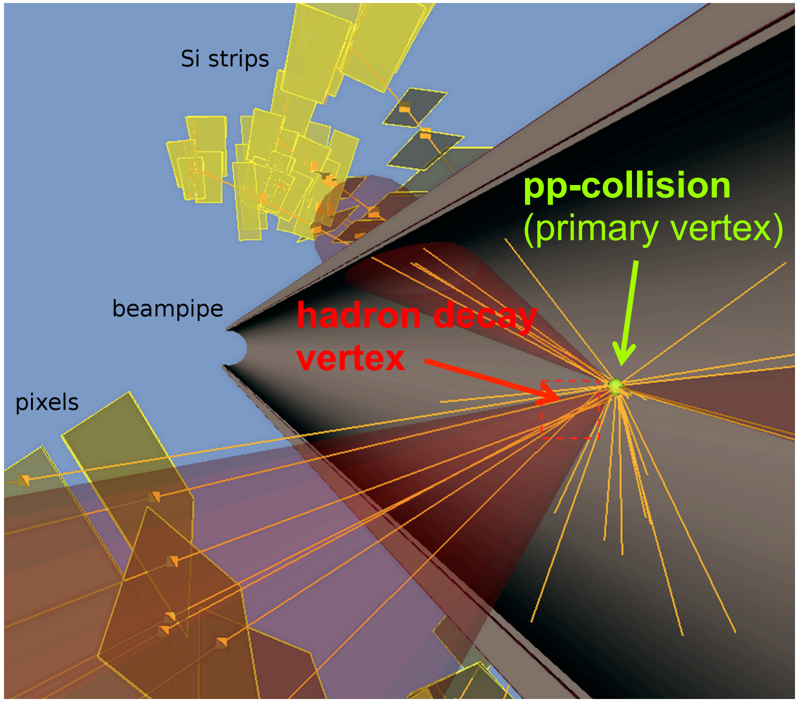


V and H “back-to-back” → p_T^V (good experimental resolution) as proxy for p_T^H (bad experimental resolution)

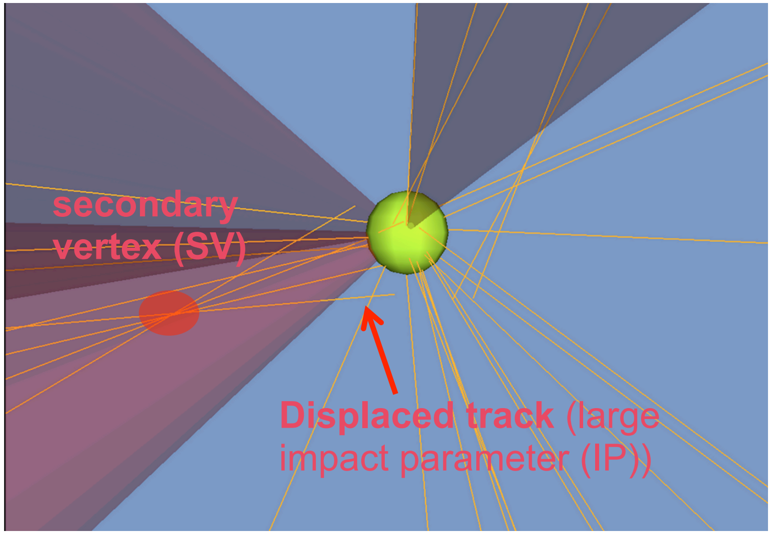


b-Jet Flavour Identification
(“b-tagging”)

- Hadrons containing b-quarks have measureable(*) lifetimes



Zoom →



(*) b-hadrons: cτ ~450 to 500 μm

→Combination of jet kinematics, SV and IP information in multivariate algorithm provides jet flavour ID

(b-jet ID efficiency: ~70%, c-jet rejection eff.: ~90%, light-jet rejection eff.: ~99.7%)

VH,H→bb Analyses, Probing Low and High p_T Signatures

→ Currently low and high p_T VH,H→bb measurements are stand-alone analyses

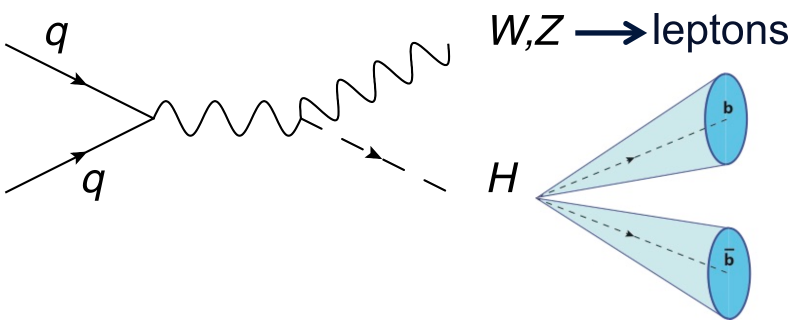
→ **Low p_T analysis:** long history in ATLAS, published multiple times with partial data sets

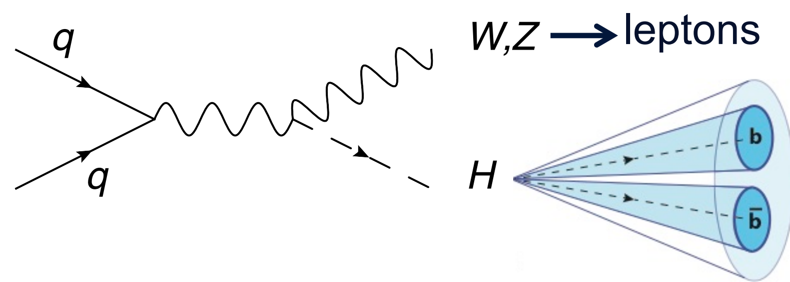
→ **High p_T analysis:** first VH,H→bb ATLAS analysis explicitly probing high p_T

VH, H→bb Signatures

- 3 V boson decay channels targeted:

  ZH→ννbb (“0 leptons”), WH→ℓνbb (“1 lepton”), ZH→ℓℓbb (“2 leptons”)





low transverse momentum

high transverse momentum

$$\Delta R(b_1, b_2) \approx \frac{2 \cdot m_H}{p_T^H}$$

2 **resolved** jets (radius R=0.4)

jets **merge** → 1 large jet (R=1.0) with substructure

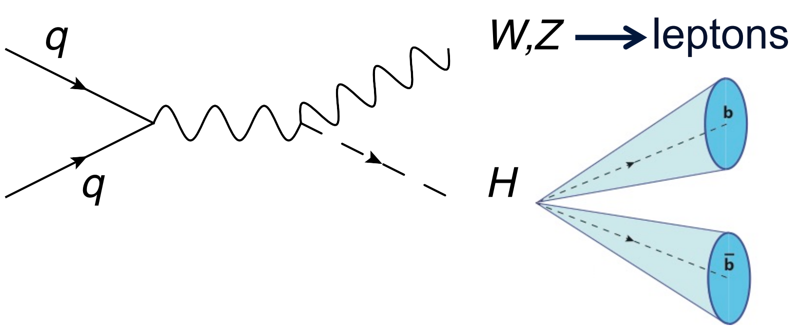
Jargon Alert: “Lepton” = lepton directly visible in detector = muon or electron

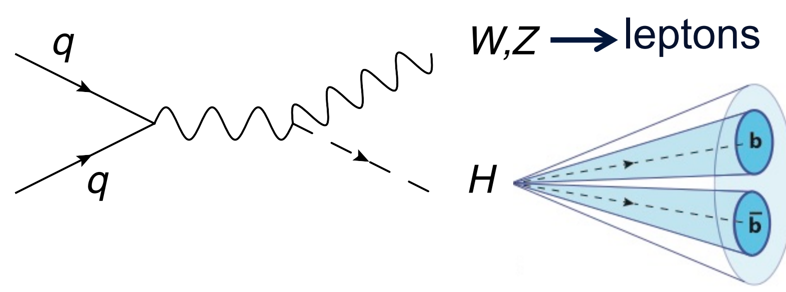
Event Selection

ZH→ννbb
0 electrons or muons
large amount of E^T_{miss}

WH→ℓνbb
1 electron or muon

ZH→ℓℓbb
2 electrons or muons
$m_{\ell\ell}$ consistent with m_Z





0,1 lepton: $\mathbf{E_T^{miss}, p_T^W > 150}$ **GeV**
2 lepton: $\mathbf{p_T^Z > 75}$ **GeV**

Exactly **2 b-tagged R=0.4 jets**
(more non-b-jets allowed)

0,1,2 lepton: $\mathbf{p_T^V > 250}$ **GeV**

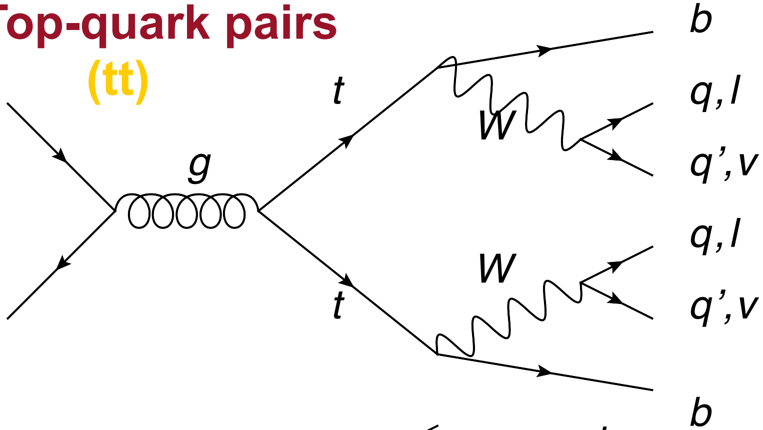
≥1 R=1.0 jet
(highest p_T jet = H candidate)
Inside R=1.0 jet: reconstruct small R
track-based jets for b-tagging

+ more requirements for multijet suppression in 0 lepton and background suppression in merged analysis

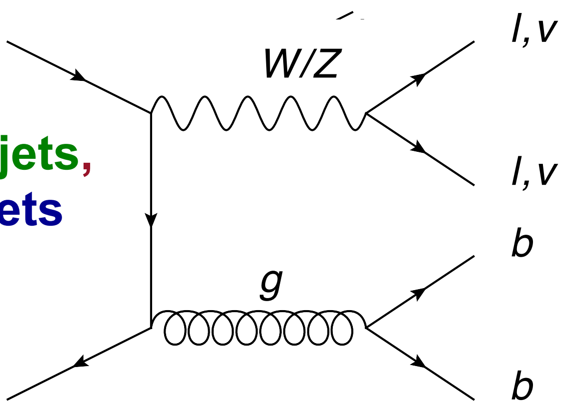
Background Components
(after event selection)

Dominant

Top-quark pairs
(tt)

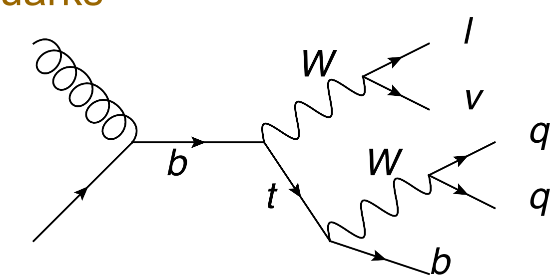


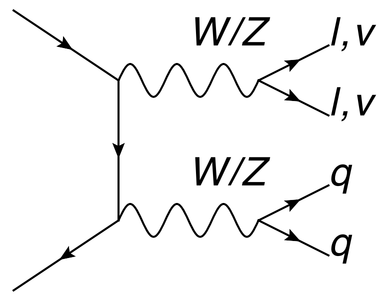
W+jets,
Z+jets



Sub-dominant

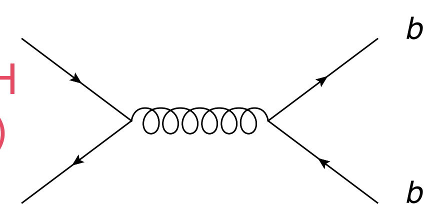
single top quarks





Vector boson pairs
(Diboson)

Multi jets (WH channel only)
(multijet)

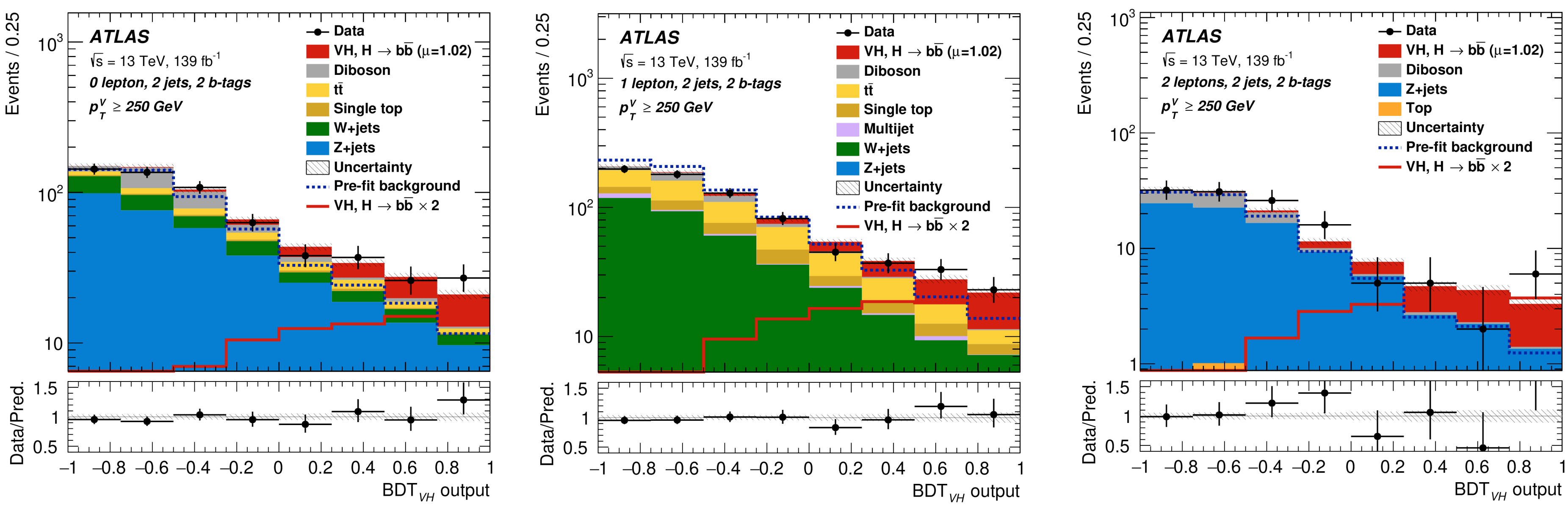


→ Rely on **Monte Carlo (MC) simulations** to predict background processes distributions and normalisations in analysis phase spaces (few exceptions)

Analysis Discriminant,
i.e. extract signal from which distribution?

Resolved

- Machine learning to design **multivariate discriminant** that enhances signal-background separation
- 10 to 15 input variables → newly added variables for full Run 2 analysis: 7-10% improvement

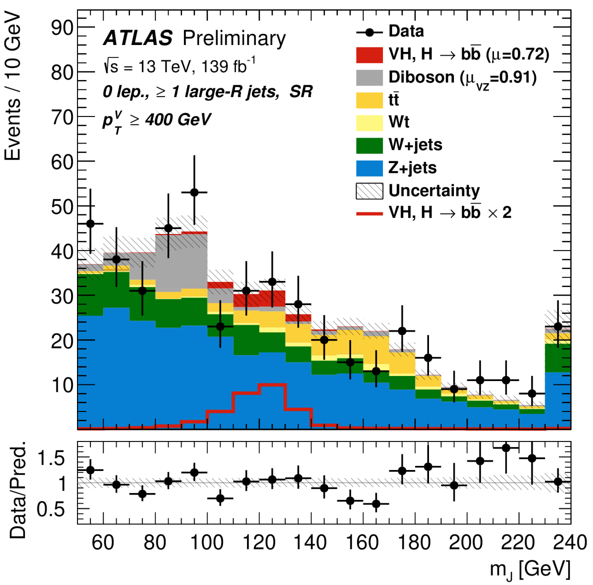


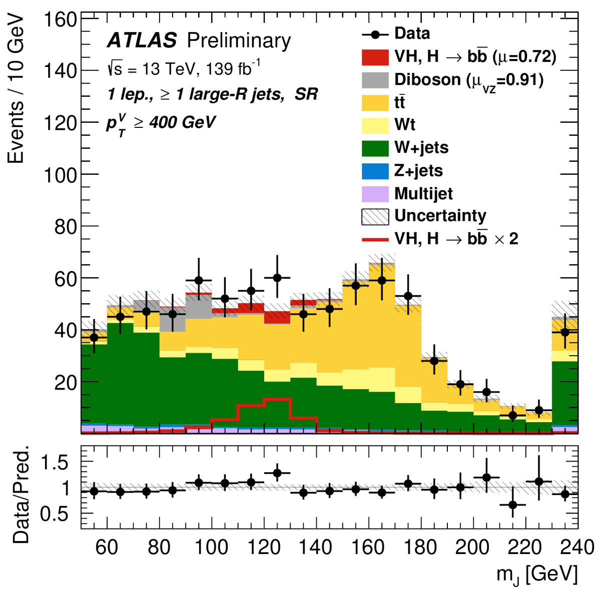
Analysis Discriminant,
i.e. extract signal from which distribution?

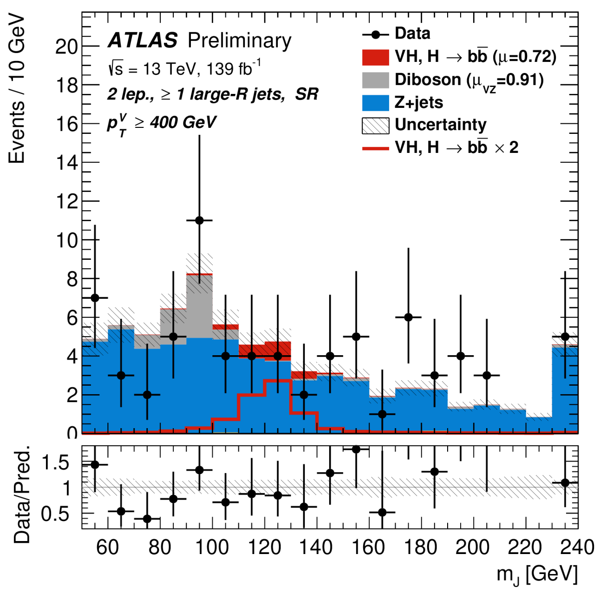
Merged

- **R=1.0 jet invariant mass**

→ "Keeping it simple" for novel analysis in phase space with limited data statistics





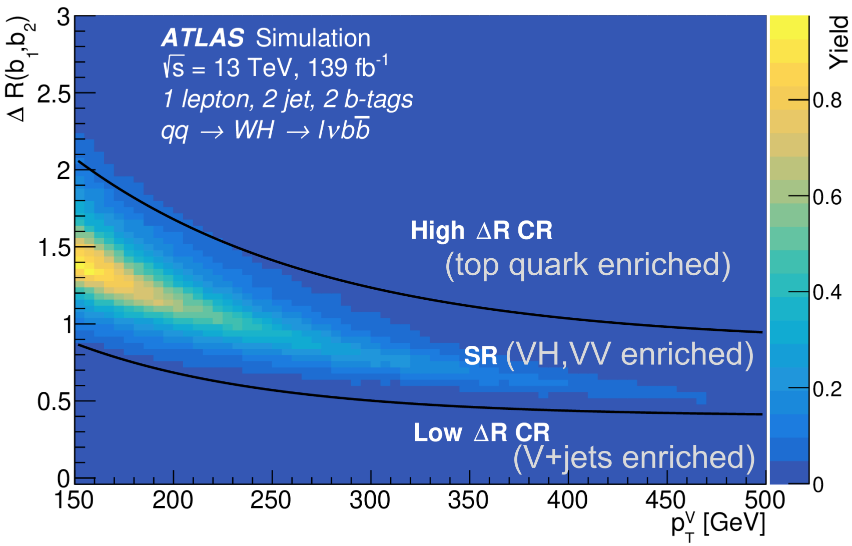


Control Regions (CRs),

i.e. "support" MC predictions with data by selecting phase space enriched in certain background process

Resolved

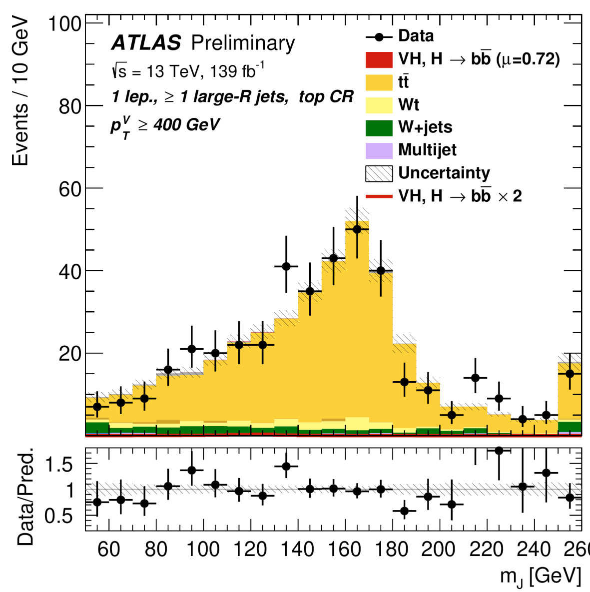
- All channels: **ΔR(b,b) tails** as CRs to normalise background MCs



- 2 lepton: **eμ events** (instead of ee,μμ) → top quark background purity >97% → replace top quark MC with CR data (new for full Run 2)

Merged

- 0,1 lepton: require **additional b-jet** outside R=1.0 jet to normalise tt MCs and control shape of discriminant



Systematic Uncertainties

- Experimental: object reconstruction (resolution, calibration, etc.)
  - Luminosity, electrons, muons, E_T^{miss}, **jets**, **b-tagging**

- Signal and background modelling:
  - Simulations to fix expected background and signal contribution in data → Uncertainties on normalisation, analysis region **acceptance, shape of discriminant** for each process

  → Uncertainties determined by comparison with alternative models

Systematic Uncertainties

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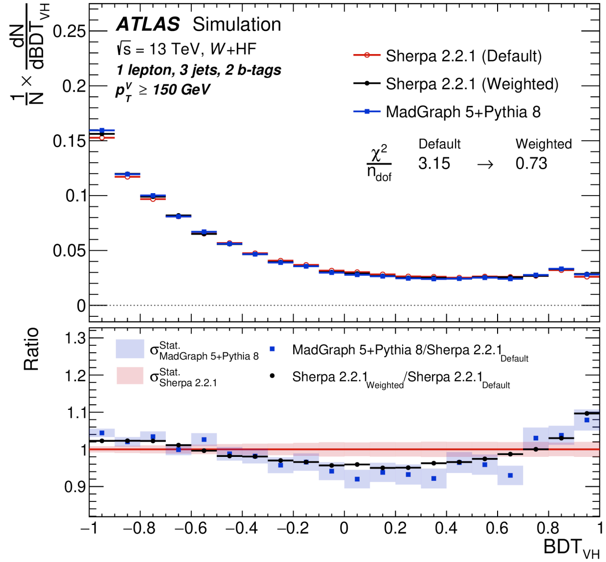
Resolved

- Machine learning based reweighting to parametrise uncertainties on multivariate discriminant's shape

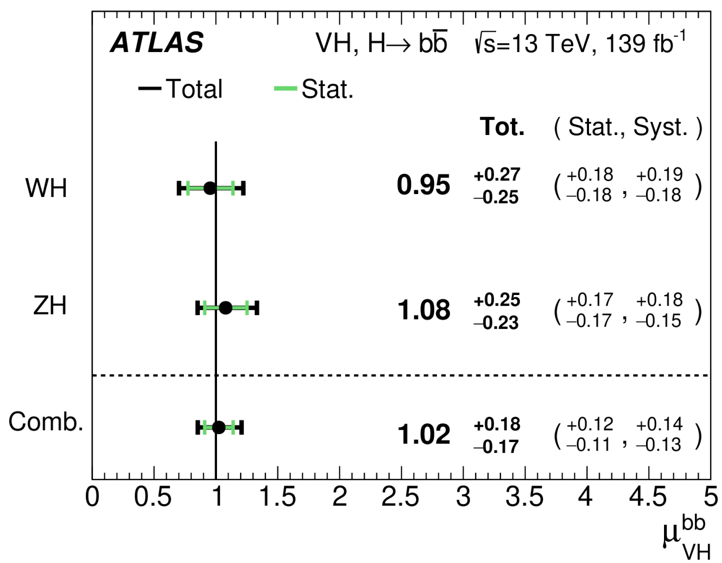
→ Captures variations on all inputs to multivariate discriminant and correlations



VH,H→bb Results

- Fit expected distribution of background+signal to data to extract **signal significance and signal strength** ($\mu = N_{sig.}^{obs.}/N_{sig.}^{exp.}$)
  - Simultaneous fit to **multiple analysis regions** (with varying background composition and signal contribution)
  - (Most) **systematic uncertainties** parametrised as degrees of freedom **with outer constraints**

Resolved



ZH observation (5.3σ)
WH evidence (4.0σ)

$$\mu_{VH}^{bb} = 0.72^{+0.39}_{-0.36} = 0.72^{+0.29}_{-0.28}(\text{stat.})^{+0.26}_{-0.22}(\text{syst.}).$$

VH,H→bb significance:
2.1 σ (expected: 2.7 σ)

VZ,Z→bb signal strength extracted as cross check (simultaneously with VH):

$$\mu_{VZ}^{bb} = 0.91^{+0.29}_{-0.23} = 0.91 \pm 0.15(\text{stat.})^{+0.25}_{-0.17}(\text{syst.}).$$

Merged

Resolved analysis has a VZ,Z→bb as well as a m_{bb} cross check analysis

Limitations to Analysis Sensitivities

Breakdown of uncertainty sources on μ

Resolved

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
$E_{\mathrm{T}}^{\mathrm{miss}}$		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

Resolved: **systematically limited**

Merged: **statistically limited**

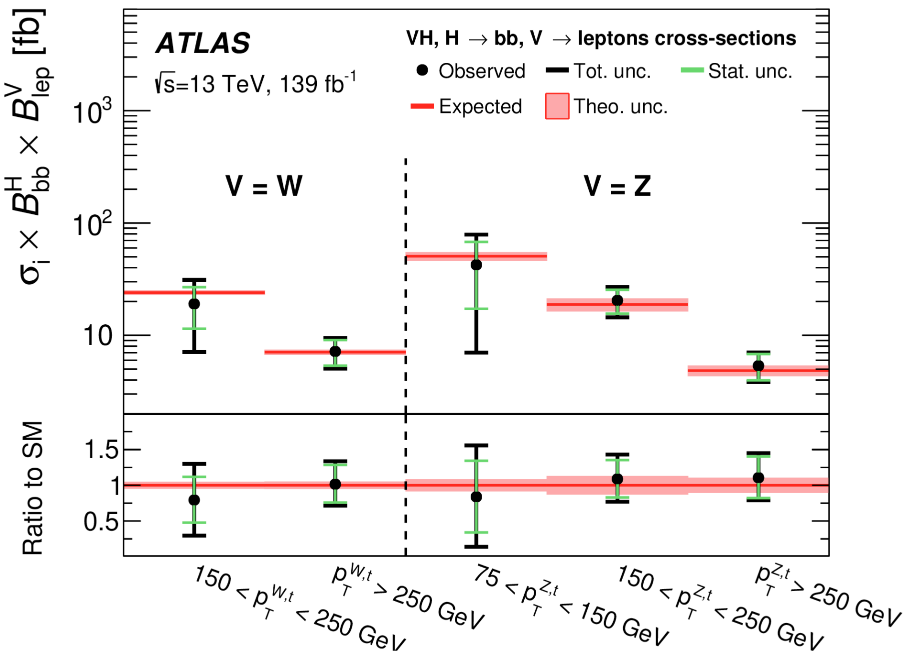
Merged

Source of uncertainty		Avg. impact
Total		0.372
Statistical		0.283
Systematic		0.240
Experimental uncertainties		
small-R jets		0.038
large-R jets		0.133
E_T^{miss}		0.007
Leptons		0.010
b-tagging	b-jets	0.016
	c-jets	0.011
	light-flavour jets	0.008
	extrapolation	0.004
Pile-up		0.001
Luminosity		0.013
Theoretical and modelling uncertainties		
Signal		0.038
Backgrounds		0.100
$\hookrightarrow$ Z + jets		0.048
$\hookrightarrow$ W + jets		0.058
$\hookrightarrow$ $t\bar{t}$		0.035
$\hookrightarrow$ Single top quark		0.027
$\hookrightarrow$ Diboson		0.032
$\hookrightarrow$ Multijet		0.009
MC statistical		0.092

(Simplified) Differential Measurement

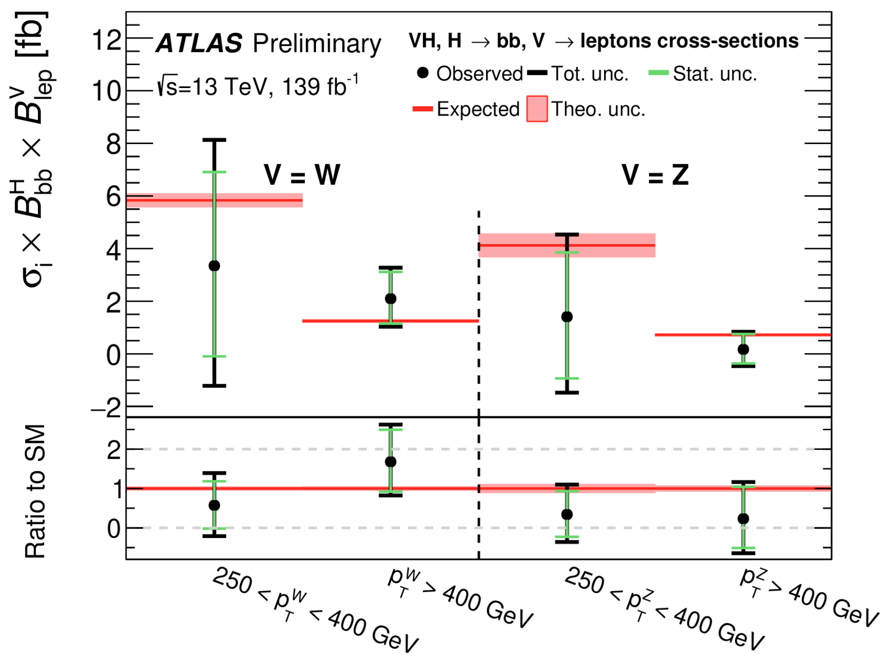
Measurement of [cross section * branching ratio] of WH,H→bb and ZH,H→bb in discrete bins of p_T^V

Resolved



high precision

Merged



Extension of experimental range to high p_T

Measurements have been interpreted as constraints on anomalous couplings (EFT)

Summary

- LHC Run 2 provided an excellent data set to measure VH,H→bb processes with ATLAS
- Two analysis strategies deployed to target **low and high transverse momentum** regimes:
  - "Resolved": 2 well separated b-jets from Higgs decay
    - Analysis improvements increase sensitivity beyond addition of data
    - ZH observation and WH evidence
    - High precision (limited by systematic uncertainties)
  - "Merged": b-jets from Higgs decay merged in single large jet
    - Novel analysis
    - VH,H→bb significance: 2.1 σ
    - Extending reach at high p_T (limited by statistical uncertainties)
- All measurements in **good agreement with SM**

Resolved VH,H→bb Result:

https://arxiv.org/abs/2007.02873

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2018-51/ (all plots/tables including auxiliary material)

Merged VH,H→bb Preliminary Result:

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2020-007/

Backup

Detailed Selection (Resolved)

Selection	0-lepton	1-lepton: e sub-channel	1-lepton: μ sub-channel	2-lepton
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton
Leptons	0 *loose* leptons	Exactly 1 *tight* electron 0 additional *loose* leptons $p_{\mathrm{T}} > 27$ GeV	Exactly 1 *tight* muon 0 additional *loose* leptons $p_{\mathrm{T}} > 25$ GeV	Exactly 2 *loose* leptons $p_{\mathrm{T}} > 27$ GeV Same-flavour Opposite-sign charges ($\mu\mu$)
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–	–	$81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}$
Jet p_{T}	> 20 GeV for $\|\eta\| < 2.5$ > 30 GeV for $2.5 < \|\eta\| < 4.5$			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
Jet categories	Exactly 2 / Exactly 3 jets	Exactly 2 / Exactly 3 jets		Exactly 2 / ≥ 3 jets
H_{T}	> 120 GeV (2 jets), >150 GeV (3 jets)	–		–
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{\mathrm{jets}})]$	$> 20^{\circ}$ (2 jets), $> 30^{\circ}$ (3 jets)	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{bb})$	$> 120^{\circ}$	–		–
$\Delta\phi(\vec{b_1}, \vec{b_2})$	$< 140^{\circ}$	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	$< 90^{\circ}$	–		–
p_{T}^{V} regions	– $150 \text{ GeV} < p_{\mathrm{T}}^{V} < 250 \text{ GeV}$ $p_{\mathrm{T}}^{V} > 250$ GeV	– $150 \text{ GeV} < p_{\mathrm{T}}^{V} < 250 \text{ GeV}$ $p_{\mathrm{T}}^{V} > 250$ GeV		$75 \text{ GeV} < p_{\mathrm{T}}^{V} < 150 \text{ GeV}$ $150 \text{ GeV} < p_{\mathrm{T}}^{V} < 250 \text{ GeV}$ $p_{\mathrm{T}}^{V} > 250$ GeV
Signal regions	$\Delta R(\vec{b_1}, \vec{b_2})$ signal selection			
Control regions	High and low $\Delta R(\vec{b_1}, \vec{b_2})$ side-bands			

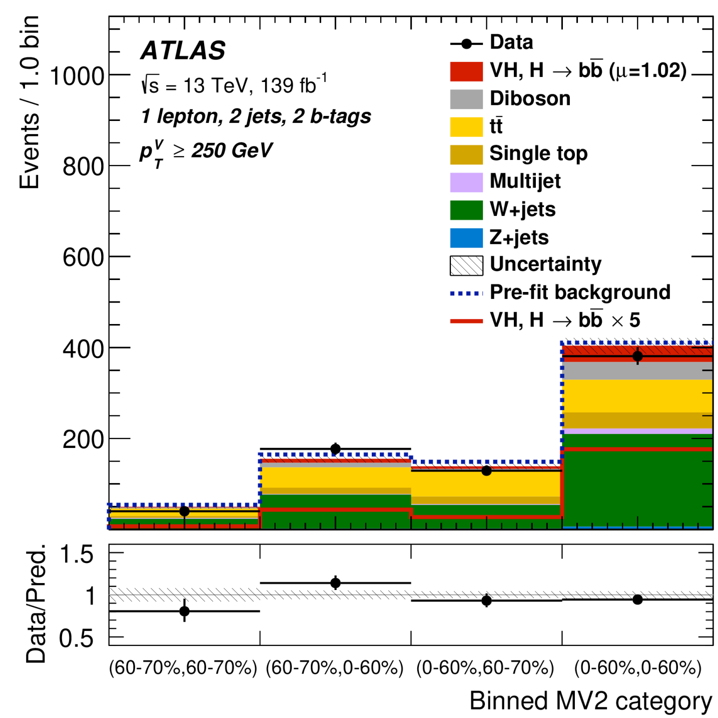
Detailed Selection (Merged)

Selection	0 lepton channel	1 lepton channel: e sub-channel	1 lepton channel: μ sub-channel	2 leptons channel: e sub-channel	2 leptons channel: μ sub-channel
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single electron	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single electron	$E_{\mathrm{T}}^{\mathrm{miss}}$
Leptons	0 *baseline* leptons	1 *signal* lepton $p_{\mathrm{T}} > 27$ GeV no second *baseline* lepton	1 *signal* lepton $p_{\mathrm{T}} > 25$ GeV no second *baseline* lepton	2 *baseline* leptons among which ≥ 1 *signal* lepton, $p_{\mathrm{T}} > 27$ GeV both leptons of the same flavour -	2 *baseline* leptons among which ≥ 1 *signal* lepton, $p_{\mathrm{T}} > 27$ GeV both leptons of the same flavour opposite sign muons
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 250GeV	> 50 GeV	-	-	
p_{T}^{V}	$p_{\mathrm{T}}^{V} > 250$ GeV				
Large-R jets	at least one large-R jet, $p_{\mathrm{T}} > 250$ GeV, $\lvert\eta\rvert < 2.0$				
Track-jets	at least two track-jets, $p_{\mathrm{T}} > 10$ GeV, $\lvert\eta\rvert < 2.5$, associated to the leading large-R jet				
b-jets	leading two track-jets associated to the leading large-R must be b-tagged (MV2c10, 70%)				
m_{J}	> 50 GeV				
min[$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$, small-$R$ jets)]	$> 30°$	-			
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, H_{\mathrm{cand}})$	$> 120°$	-			
$\Delta\phi\ (\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{E}_{\mathrm{T,\ trk}}^{\mathrm{miss}})$	$< 90°$	-			
$\Delta y(V, H_{\mathrm{cand}})$	-	$\lvert\Delta y(V, H_{\mathrm{cand}})\rvert < 1.4$			
$m_{\ell\ell}$	-			66 GeV $< m_{\ell\ell} <$ 116 GeV	
Lepton p_{T} imbalance	-			$(p_{\mathrm{T}}^{\ell_1} - p_{\mathrm{T}}^{\ell_2})/p_{\mathrm{T}}^{Z} < 0.8$	

MVA Set-up

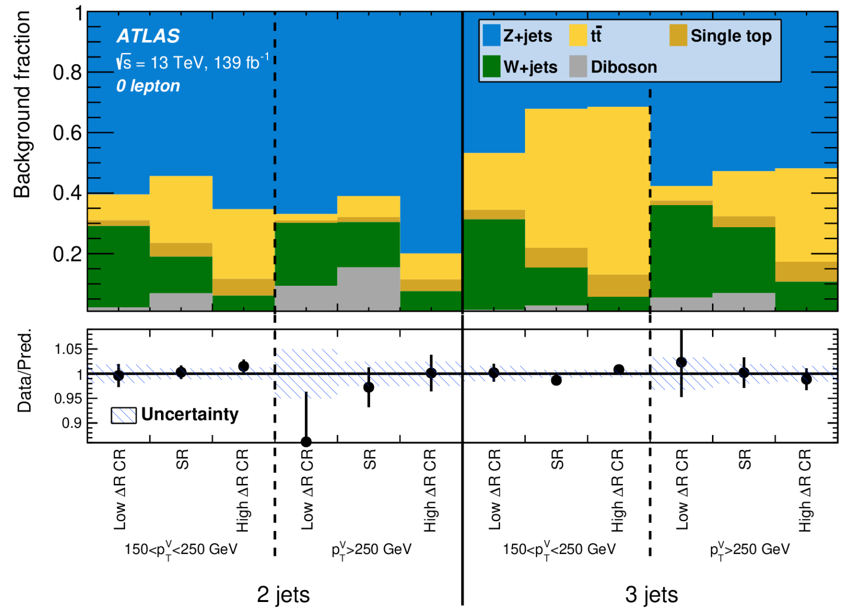
Variable	0-lepton	1-lepton	2-lepton
m_{bb}	$\times$	$\times$	$\times$
$\Delta R(\vec{b_1}, \vec{b_2})$	$\times$	$\times$	$\times$
$p_{\mathrm{T}}^{b_1}$	$\times$	$\times$	$\times$
$p_{\mathrm{T}}^{b_2}$	$\times$	$\times$	$\times$
p_{T}^{V}	$\equiv E_{\mathrm{T}}^{\mathrm{miss}}$	$\times$	$\times$
$\Delta\phi(\vec{V}, \vec{bb})$	$\times$	$\times$	$\times$
New $\mathrm{MV2}(b_1)$	$\times$	$\times$	
New $\mathrm{MV2}(b_2)$	$\times$	$\times$	
$\lvert\Delta\eta(\vec{b_1}, \vec{b_2})\rvert$	$\times$		
m_{eff}	$\times$		
New $p_{\mathrm{T}}^{\mathrm{miss,st}}$	$\times$		
$E_{\mathrm{T}}^{\mathrm{miss}}$	$\times$	$\times$	
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		$\times$	
m_{T}^{W}		$\times$	
$\lvert\Delta y(\vec{V}, \vec{bb})\rvert$		$\times$	
m_{top}		$\times$	
$\lvert\Delta\eta(\vec{V}, \vec{bb})\rvert$			$\times$
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{S_{\mathrm{T}}}$			$\times$
$m_{\ell\ell}$			$\times$
New $\cos\theta(\vec{\ell^-}, \vec{Z})$			$\times$
	Only in 3-jet events		
$p_{\mathrm{T}}^{\mathrm{jet}_3}$	$\times$	$\times$	$\times$
m_{bbj}	$\times$	$\times$	$\times$

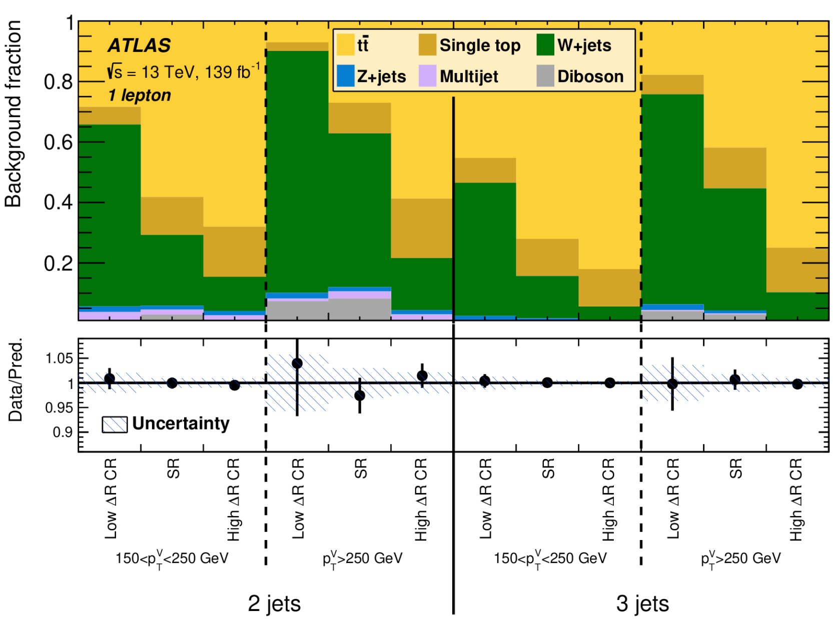
Boosted decision trees (as provided by TMVA framwork) used as machine learning algorithm
→ Using gradient boosting instead of adaptive boosting provided additional performance gain

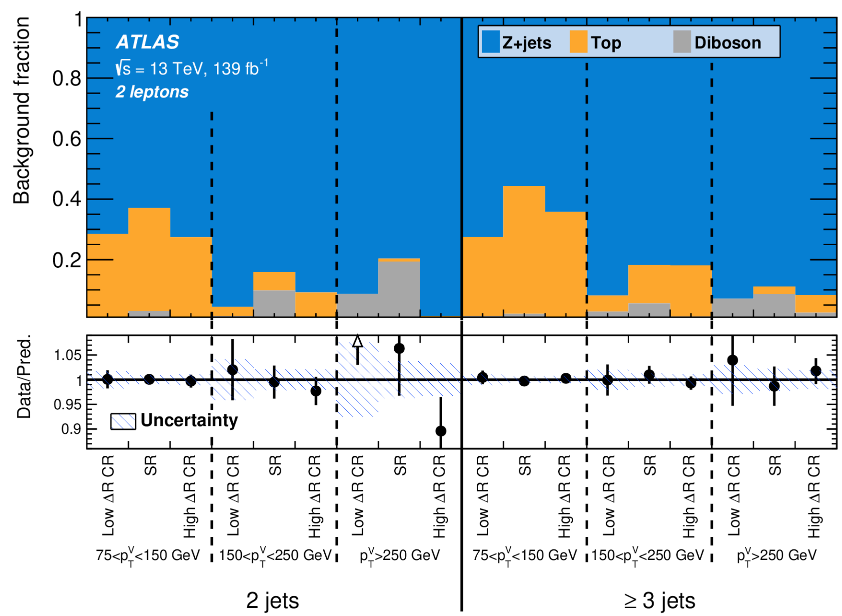


+ Analysis Regions (Resolved)

Channel	Region	Categories: $75\text{ GeV} < p_T^V < 150\text{ GeV}$ 2-jets	$75\text{ GeV} < p_T^V < 150\text{ GeV}$ 3-jets	$150\text{ GeV} < p_T^V < 250\text{ GeV}$ 2-jets	$150\text{ GeV} < p_T^V < 250\text{ GeV}$ 3-jets	$p_T^V > 250\text{ GeV}$ 2-jets	$p_T^V > 250\text{ GeV}$ 3-jets
0-lepton	Low-ΔR-CR	–	–	Yields	Yield	Yield	Yield
	Signal region	–	–	BDT	BDT	BDT	BDT
	High-ΔR-CR	–	–	Yield	Yield	Yield	Yield
1-lepton	Low-ΔR-CR	–	–	Yield	Yield	Yield	Yield
	Signal region	–	–	BDT	BDT	BDT	BDT
	High-ΔR-CR	–	–	Yield	Yield	Yield	Yield
2-lepton	Low-ΔR-CR	Yield	Yield	Yield	Yield	Yield	Yield
	Signal region	BDT	BDT	BDT	BDT	BDT	BDT
	High-ΔR-CR	Yield	Yield	Yield	Yield	Yield	Yield







Analysis Regions (Merged)

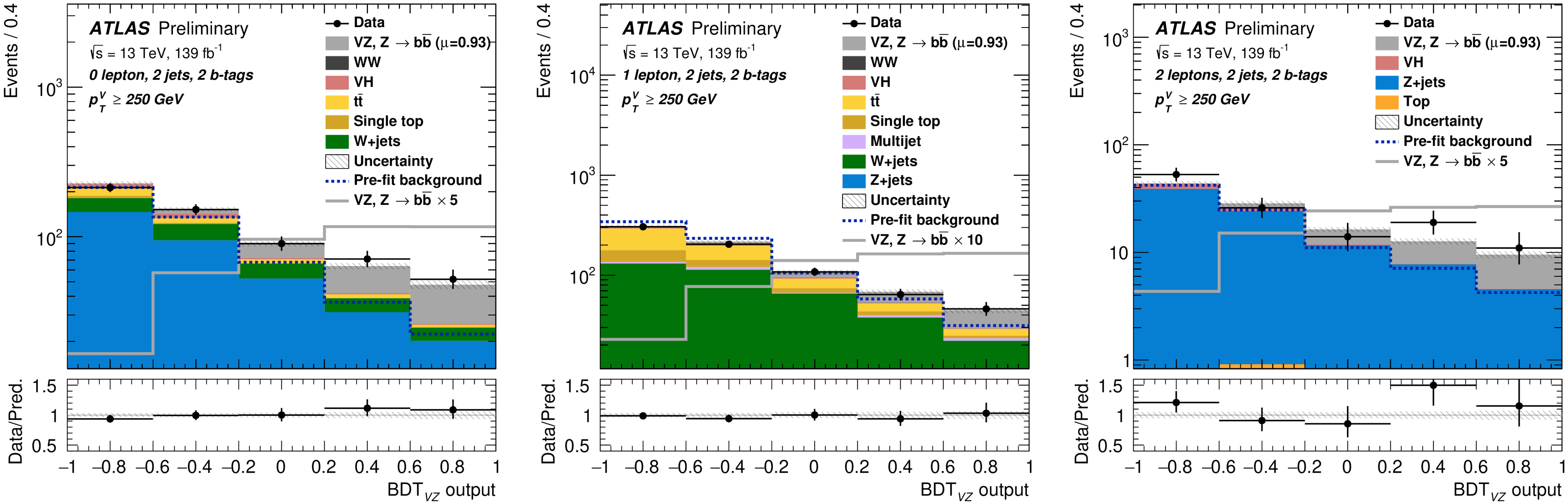
Channel	Categories					
	$250 < p_T^V < 400$ GeV			$p_T^V \geq 400$ GeV		
	0 add. b-track-jets		≥ 1 add. b-track-jets	0 add. b-track-jets		≥ 1 add. b-track-jets
	0 add. small-R jets	≥ 1 add. small-R jets		0 add. small-R jets	≥ 1 add. small-R jets	
0-lepton	HP SR	LP SR	CR	HP SR	LP SR	CR
1-lepton	HP SR	LP SR	CR	HP SR	LP SR	CR
2-lepton	SR			SR		

Uncertainty Breakdown for STXS Measurement (Resolved)

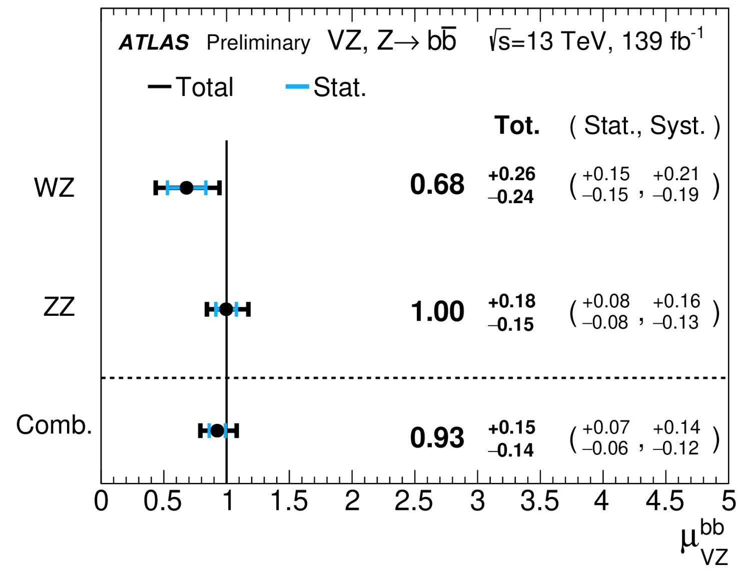
Source of uncertainty		$\sigma_{\sigma\times B}$ w.r.t. the SM prediction		
		$75 < p_{\mathrm{T}}^{Z,\,\mathrm{t}} < 150$ GeV	$150 < p_{\mathrm{T}}^{Z,\,\mathrm{t}} < 250$ GeV	$p_{\mathrm{T}}^{Z,\,\mathrm{t}} > 250$ GeV
Total		0.710	0.330	0.330
Statistical		0.501	0.262	0.291
Systematic		0.503	0.200	0.156
Statistical uncertainties				
Data statistical		0.421	0.243	0.284
$t\bar{t}$ $e\mu$ control region		0.221	0.039	0.023
Floating normalisations		0.181	0.095	0.047
Experimental uncertainties				
Jets		0.266	0.082	0.040
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.235	0.027	0.016
Leptons		0.027	0.007	0.007
b-tagging	b-jets	0.176	0.082	0.041
	c-jets	0.028	0.020	0.006
	light-flavour jets	0.006	0.013	0.015
Pile-up		0.012	0.016	0.017
Luminosity		0.012	0.016	0.017
Theoretical and modelling uncertainties				
Signal		0.110	0.096	0.091
Z + jets		0.271	0.089	0.071
W + jets		0.020	0.019	0.008
$t\bar{t}$		0.108	0.036	0.025
Single top quark		0.044	0.015	0.015
Diboson		0.073	0.044	0.029
Multi-jet		0.009	0.008	0.005
MC statistical		0.168	0.057	0.055

Source of uncertainty		$\sigma_{\sigma\times B}$ w.r.t. the SM prediction	
		150 GeV$< p_{\mathrm{T}}^{W,\,\mathrm{t}} < 250$ GeV	$p_{\mathrm{T}}^{W,\,\mathrm{t}} > 250$ GeV
Total		0.502	0.311
Statistical		0.320	0.263
Systematic		0.386	0.166
Statistical uncertainties			
Data statistical		0.298	0.252
$t\bar{t}$ $e\mu$ control region		0.032	0.007
Floating normalisations		0.157	0.050
Experimental uncertainties			
Jets		0.145	0.054
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.171	0.009
Leptons		0.019	0.018
b-tagging	b-jets	0.049	0.023
	c-jets	0.109	0.060
	light-flavour jets	0.004	0.005
Pile-up		0.017	0.015
Luminosity		0.017	0.015
Theoretical and modelling uncertainties			
Signal		0.035	0.050
Z + jets		0.038	0.011
W + jets		0.159	0.072
$t\bar{t}$		0.152	0.037
Single top quark		0.135	0.032
Diboson		0.040	0.034
Multi-jet		0.015	0.019
MC statistical		0.112	0.068

Diboson Cross Check (Resolved)



- Measured μ compatible with SM

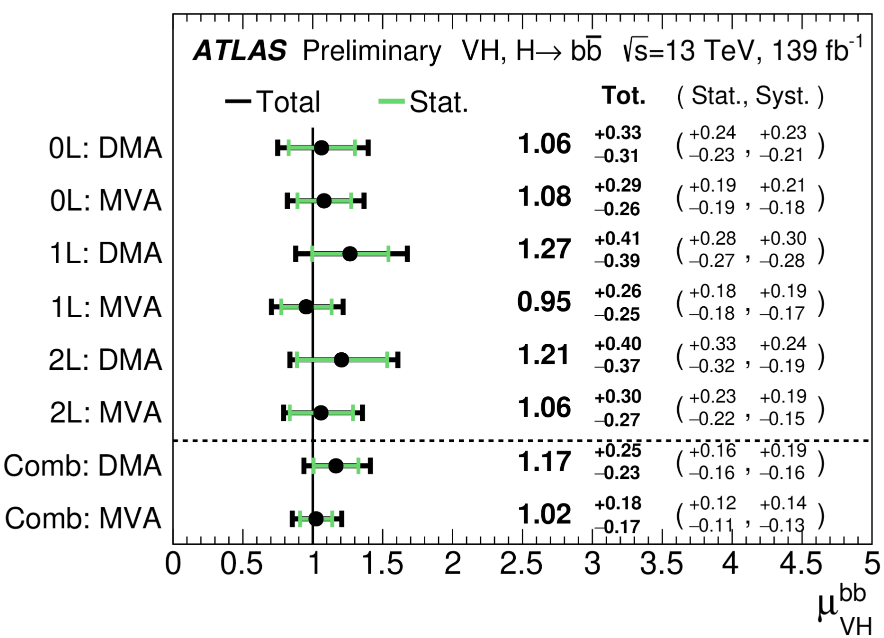


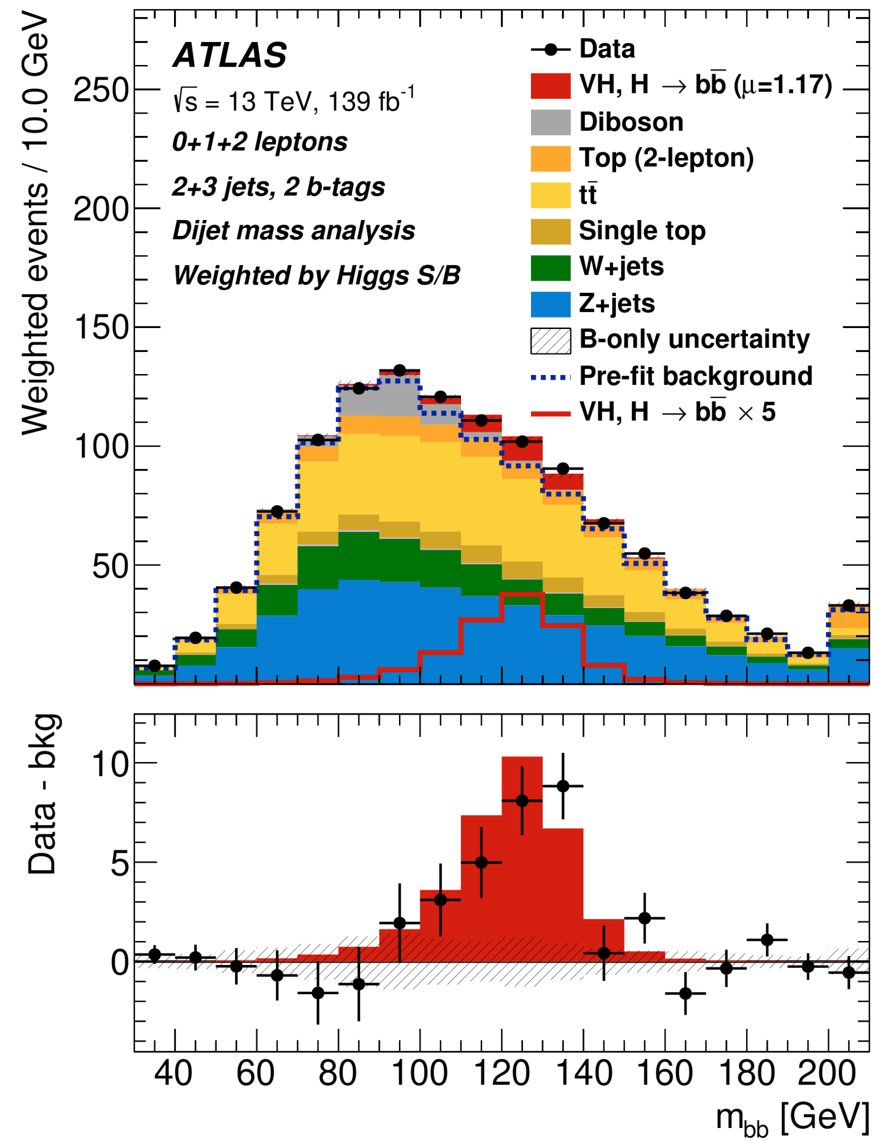
m_{bb} Analysis (Resolved)

all channels combined in 1 plot

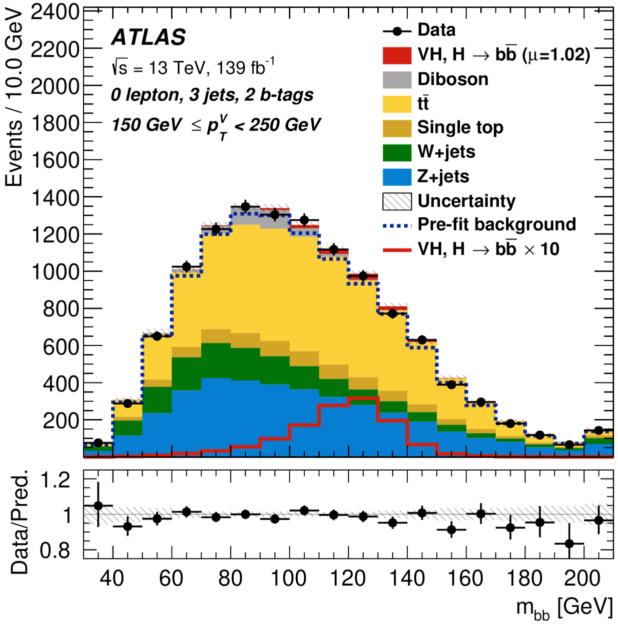
- VH,H→bb significance: 5.5 σ

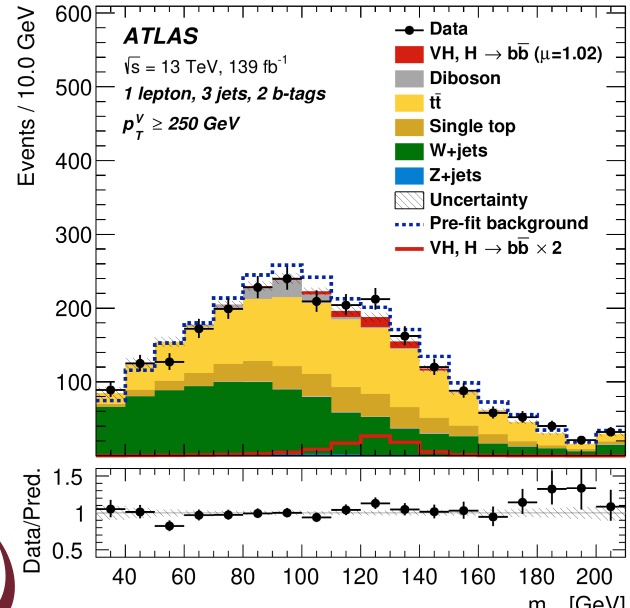
→ 20% decrease in sensitivity w.r.t. MVA



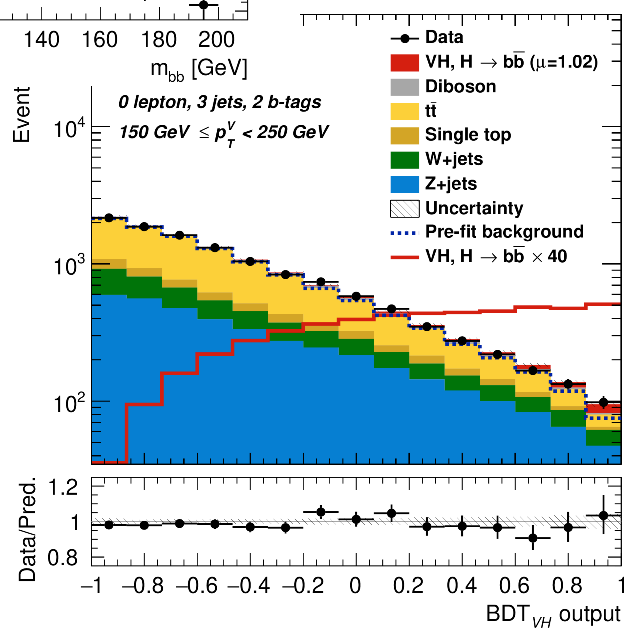


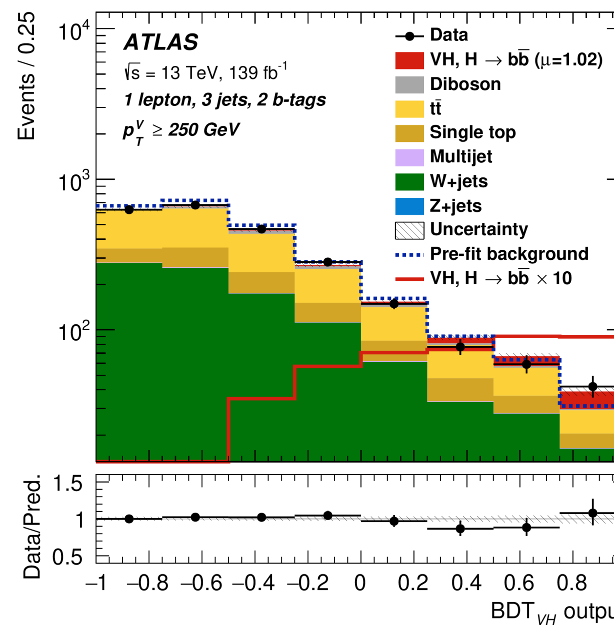
+ m_{bb} vs. MVA Discriminant (Resolved)



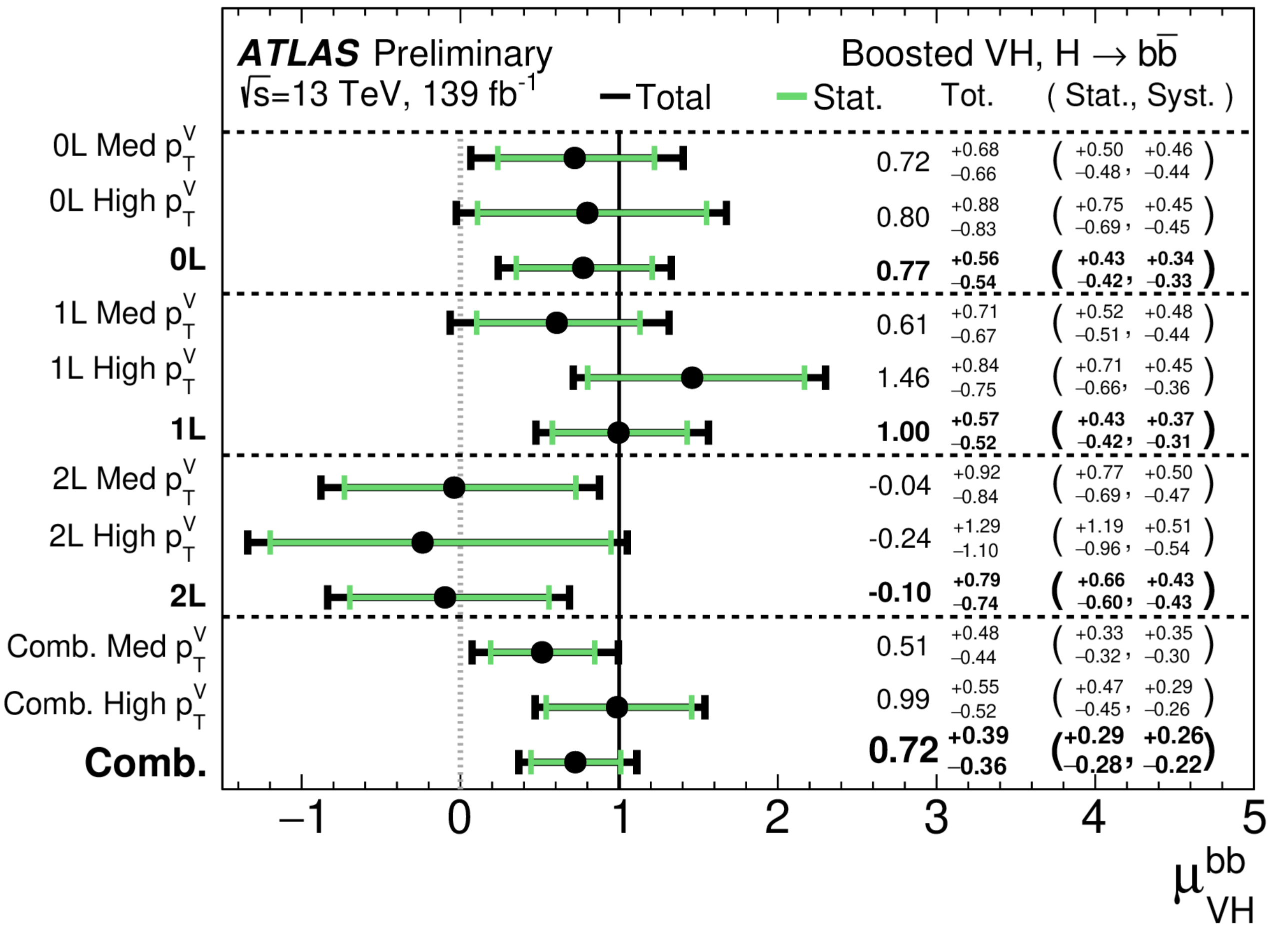


MVA esp. effective in regions with small signal contributions (very low S/B)

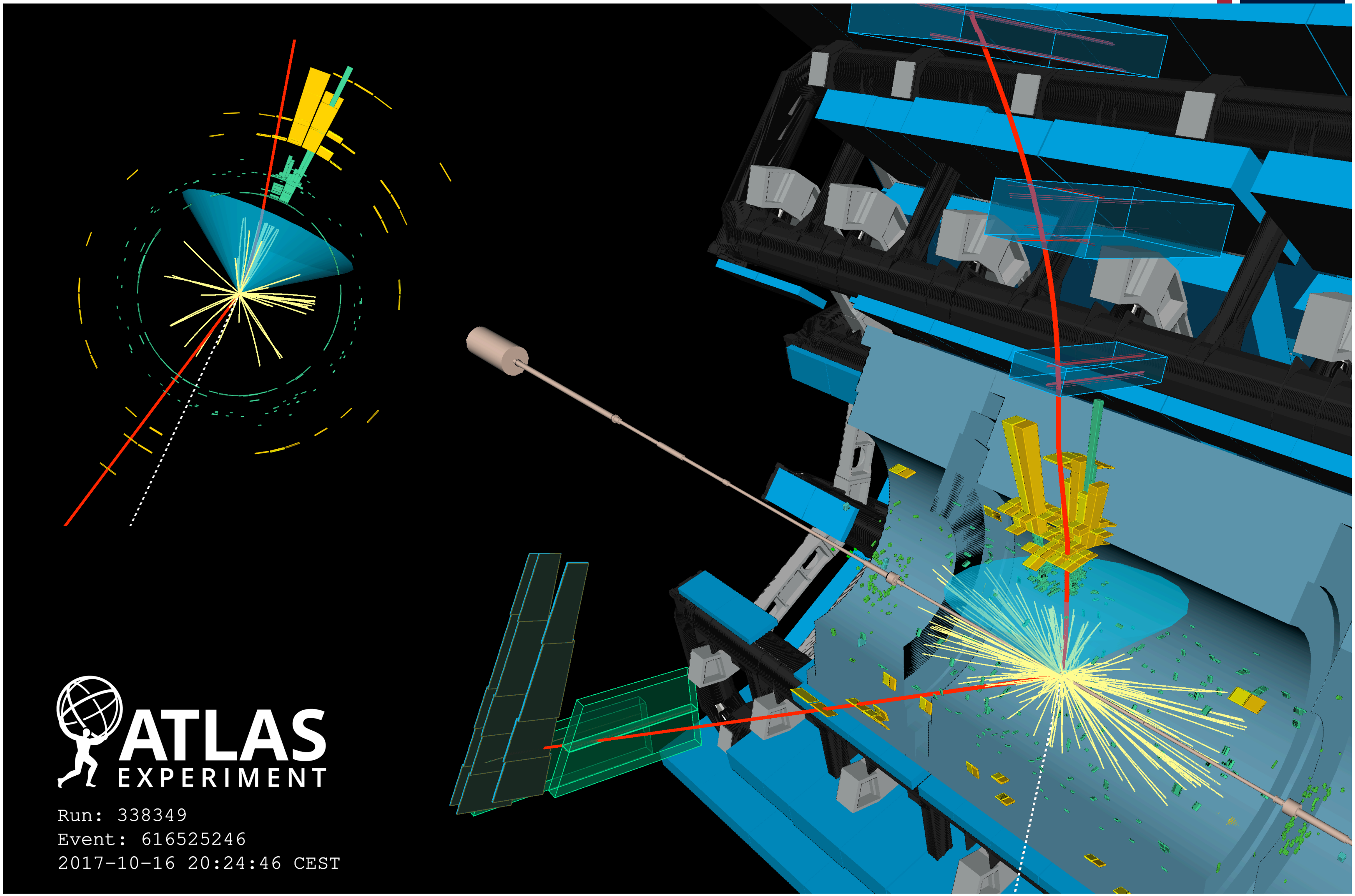




Measured Signal Strength per Analysis Region (Merged)



+ Event Display (Merged)



Beyond Standard Model Interpretation: Anomalous Couplings

- Consider anomalous VH,H→bb couplings in an extension of the SM Lagrangian (SMEFT approach):

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d} \frac{1}{\Lambda^{d-4}} \left(\sum_{i} c_i^{(d)} \mathcal{O}_i^{(d)} \right)$$

Dimension (consider up to d=6)

Scale of new physics (set to 1 TeV)

Coupling modifiers (c_i=0 in SM)

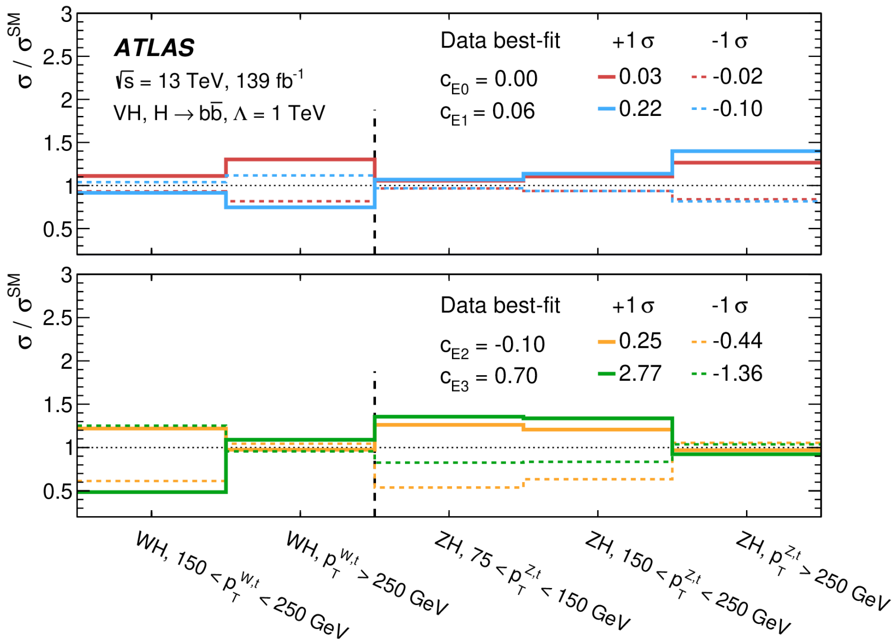
Dimension d operators

- 14 operators affect ZH,H→bb and 7 affect WH,H→bb
  - Aim: set limits → Max. size of new physics effects hiding in data
  - Not enough d.o.f. to have sensitivity to all 20 modifiers simultaneously → Construct eigenvectors of coupling modifiers

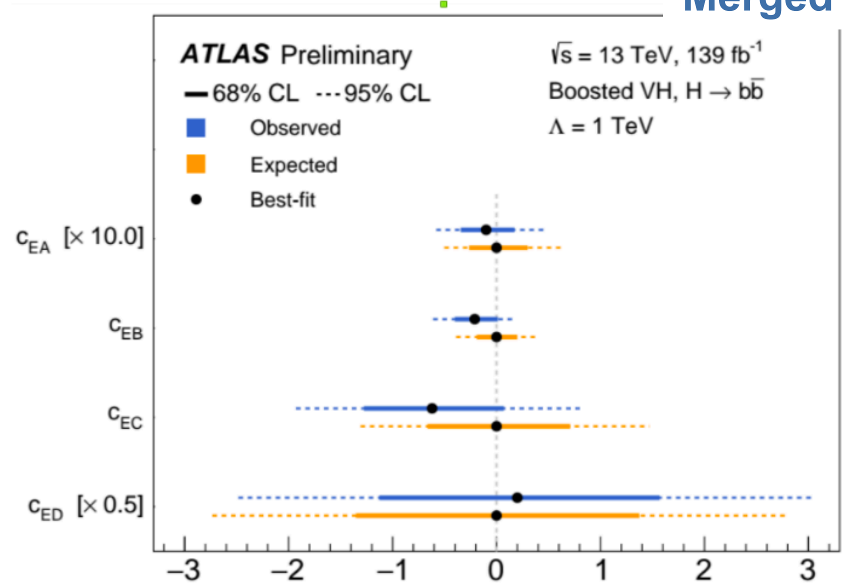
Beyond Standard Model Interpretation: Anomalous Couplings

- Consider anomalous VH,H→bb couplings in an extension of the SM Lagrangian (SMEFT approach):

Resolved



Merged



→ Limits on eigenvectors of coupling modifiers

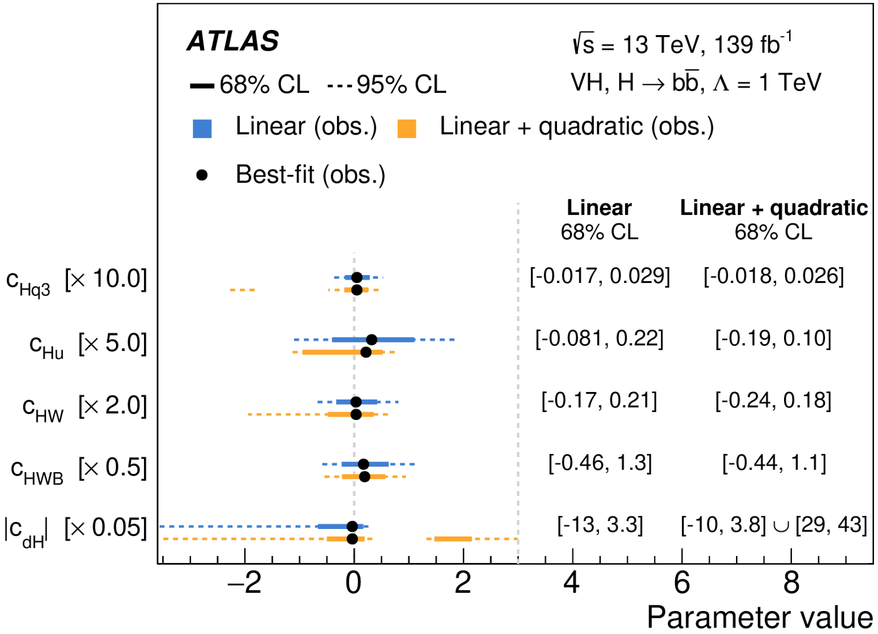
EFT Eigenvector Composition

Resolved

Wilson coefficient	Eigenvalue	Eigenvector
c_{E0}	2000	$0.98 \cdot c_{Hq3}$
c_{E1}	38	$0.85 \cdot c_{Hu} - 0.39 \cdot c_{Hq1} - 0.27 \cdot c_{Hd}$
c_{E2}	8.3	$0.70 \cdot \Delta\mathrm{BR}/\mathrm{BR}_{\mathrm{SM}} + 0.62 \cdot c_{HW}$
c_{E3}	0.2	$0.74 \cdot c_{HWB} + 0.53 \cdot c_{Hq1} - 0.32 \cdot c_{HW}$
c_{E4}	$6.4 \cdot 10^{-3}$	$0.65 \cdot c_{HW} - 0.60 \cdot \Delta\mathrm{BR}/\mathrm{BR}_{\mathrm{SM}} + 0.35 \cdot c_{Hq1}$

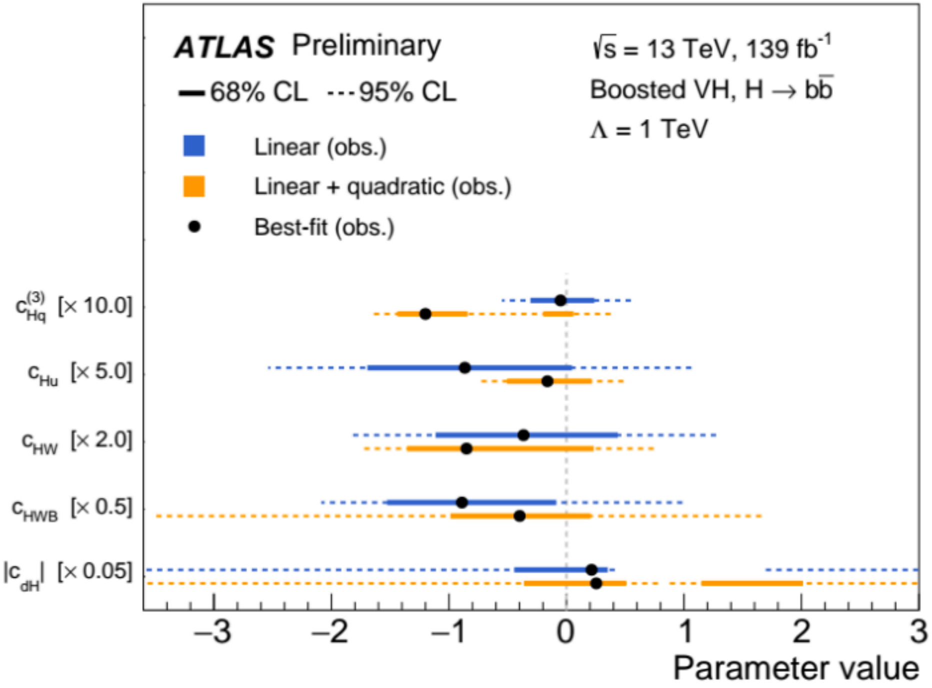
1D Fits of EFT Operators

Resolved



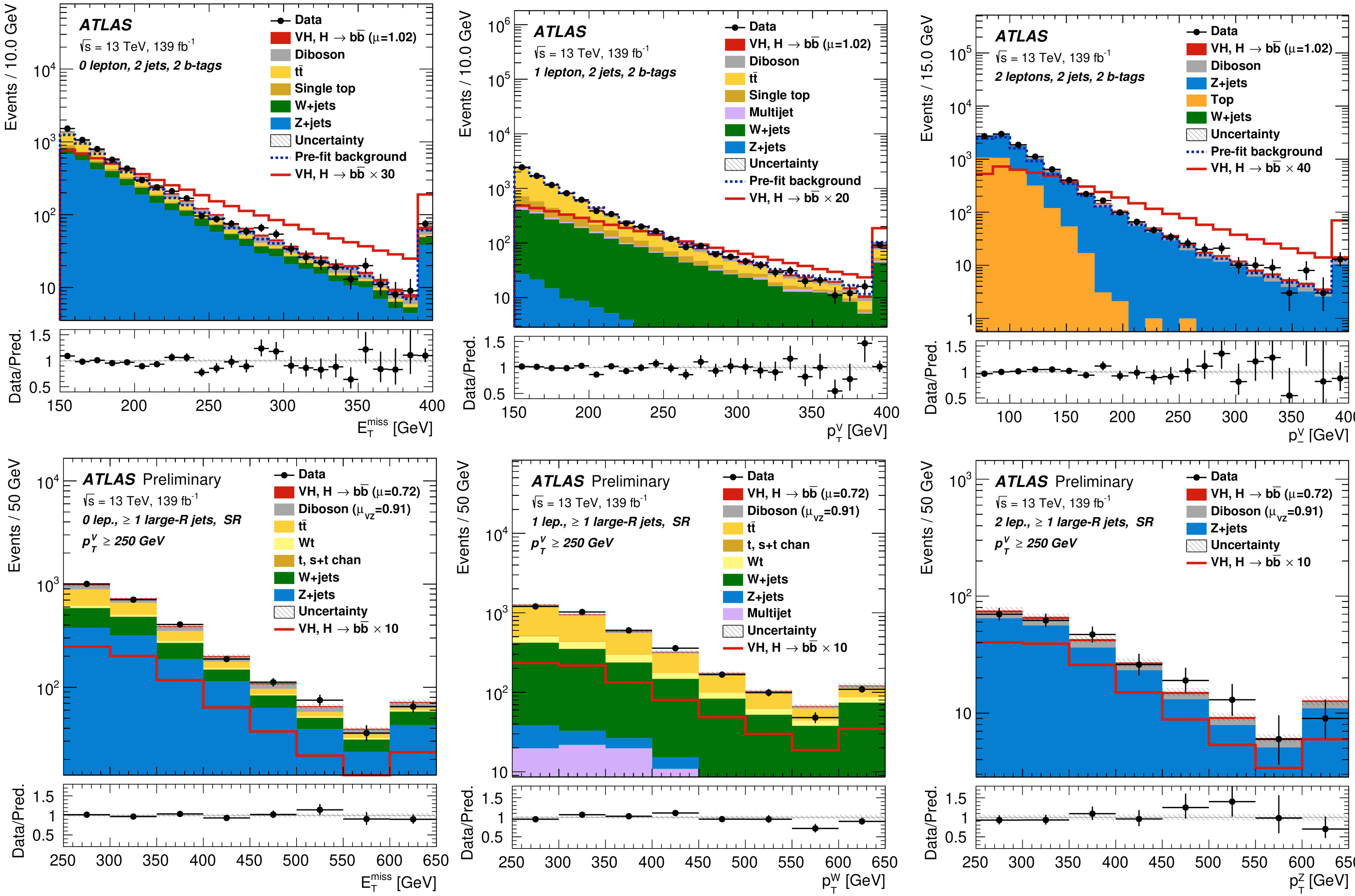
→ Each operator constrained separately (all other operators set to 0)

Merged



p_T^V Distributions

top row = resolved analysis
bottom row = merged analysis



VH,H→bb Analysis Improvement (Resolved)