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Observation of H ->bb decays and VH production with the ATLAS detector

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On behalf of the ATLAS Collaboration

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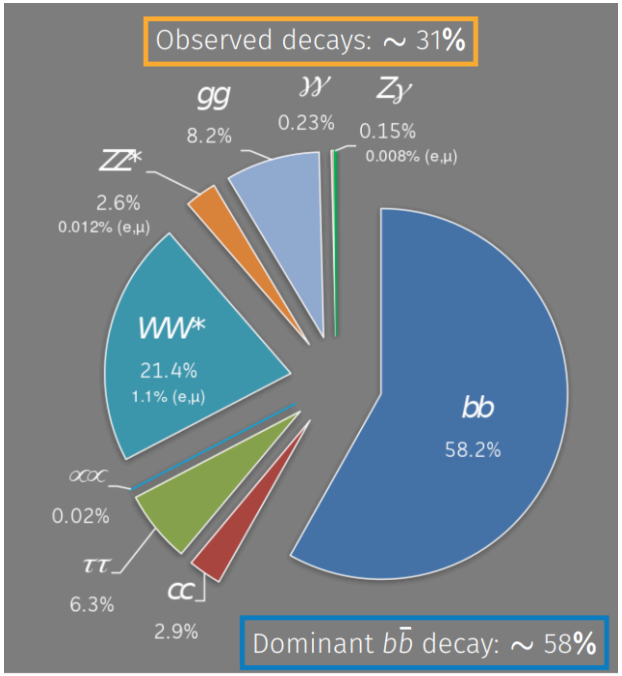
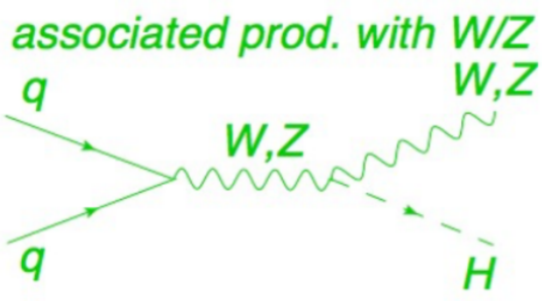
Introduction

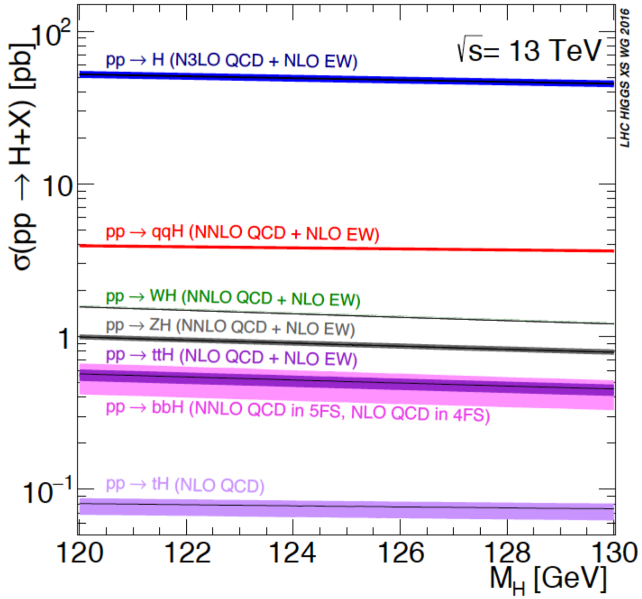
➢ Why V (W/Z)H, H→bb

- The dominant decay (BR~58%) of the SM Higgs boson is to pairs of b-quarks
  - Measurement of the Yukawa coupling to down type quarks
  - Constrain the Higgs boson decay width



- VH production mode is the most sensitive channel to detect H → bb decays
  - The leptonic decay of the vector boson allows for efficient triggering and significant reduction of the multi-jet (MJ) backgrounds

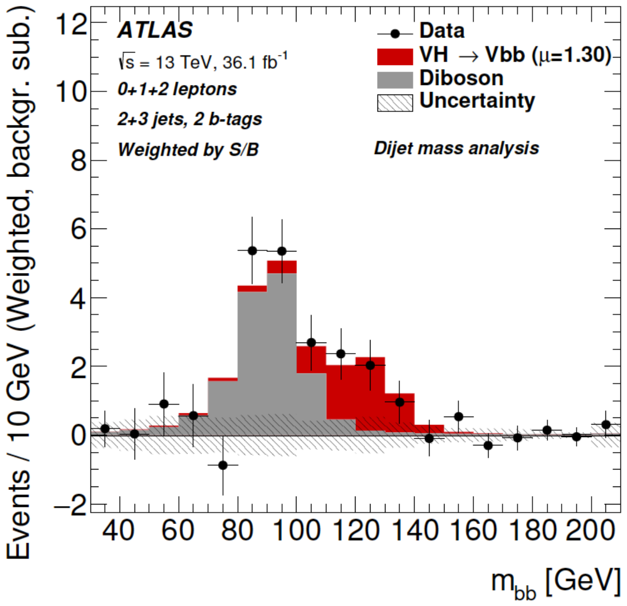




Introduction

➢ Run 2 evidence result at EPS 2017 (36.1 fb^{-1}) (JHEP12(2017)024)

- Evidence for VH(bb) with a significance of 3.5 σ (3.0 σ exp.) and a mu (signal strength) value of 1.20 +/-0.39



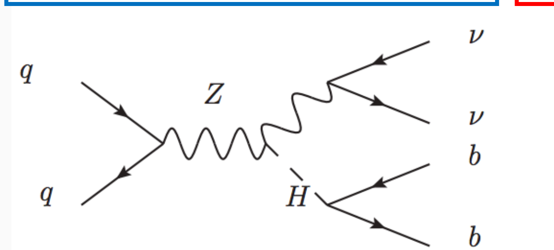
➢ This talk will focus on Run2 VH, H→bb measurement with the full 2015-2017 data (79.8 fb^{-1})

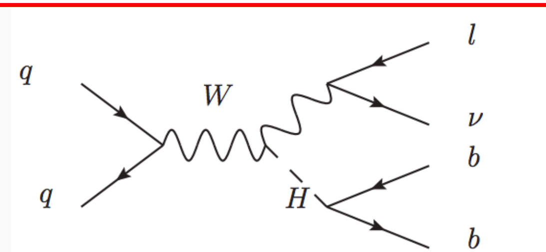
- To achieve the observation of H→bb decay and VH production mode, the result is also combined with:
  - the Run 1 analysis
  - other searches for bb decays of the Higgs boson
  - other searches in the VH production mode

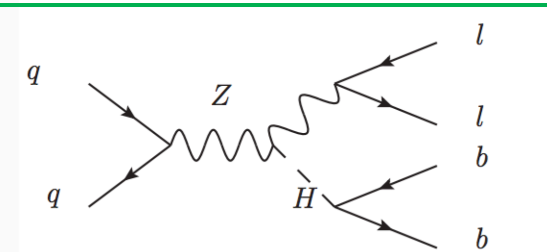
Event Selection

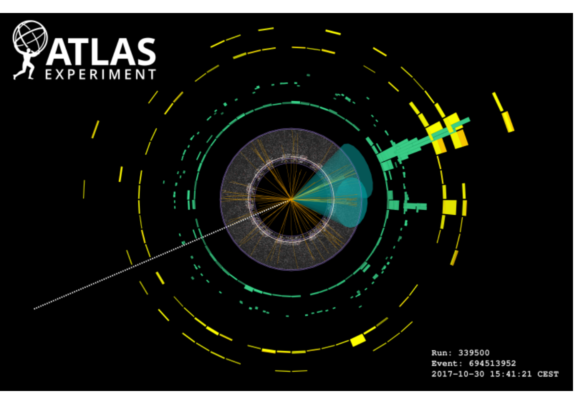
- Leptonic decays of Z/W for background rejection and trigger →3 channels : 0,1,2 leptons
- Exactly 2 b-tagged jets (70% b-tagging efficiency), Leading (Sub-leading) jet p_T>45 (20) GeV, with 0 or 1 (>=1 for 2-lepton channel) additional jet

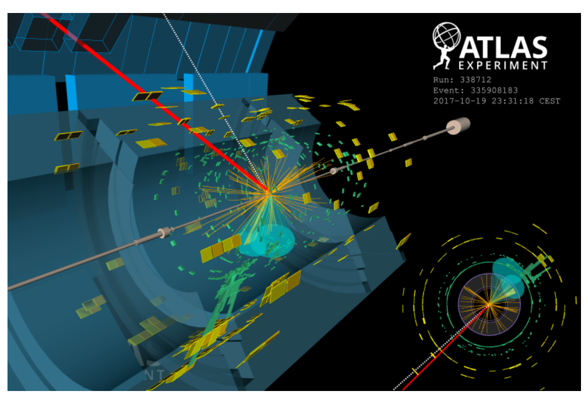
0-Lepton	1-Lepton	2-Lepton
E_T^{miss} trigger	Single-electron or E_T^{miss} trigger	Single-lepton trigger
Veto leptons p_T>7 GeV	Exactly one isolated lepton p_T>25 (27)GeV for muon (electron)	2 electrons or muons p_T>27 (7) GeV
$p_T^Z(E_T^{miss})$ > 150GeV	$p_T^W(l,\nu)$ > 150GeV	$p_T^Z(l,l)$ [75-150GeV] or >150GeV
Angular cuts to remove MJ	E_T^{miss} >30 GeV in electron channel	81 < m_{ll} < 101 GeV

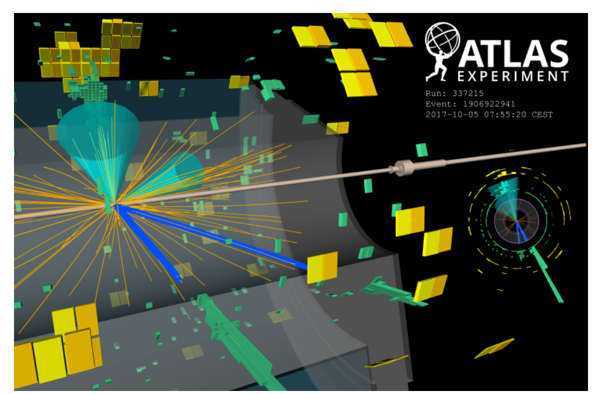




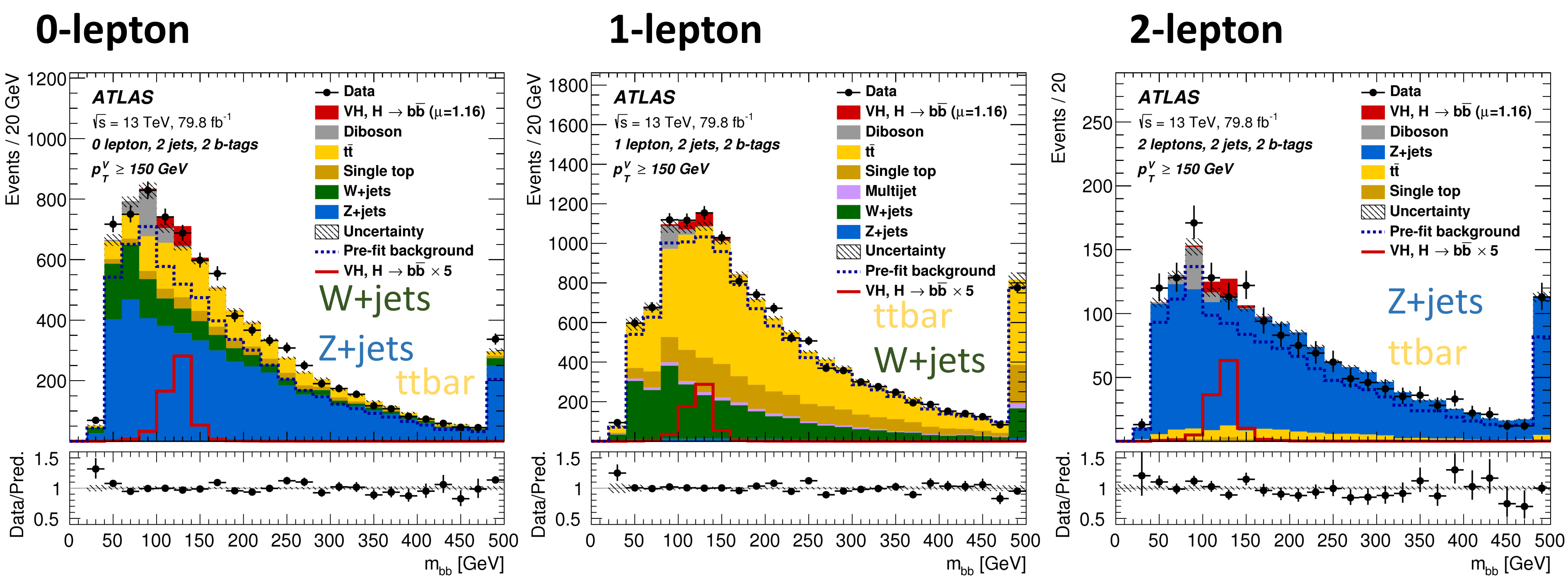








Main Backgrounds after Event Selection



Non-resonant backgrounds from W/Z+jets, ttbar and single-top

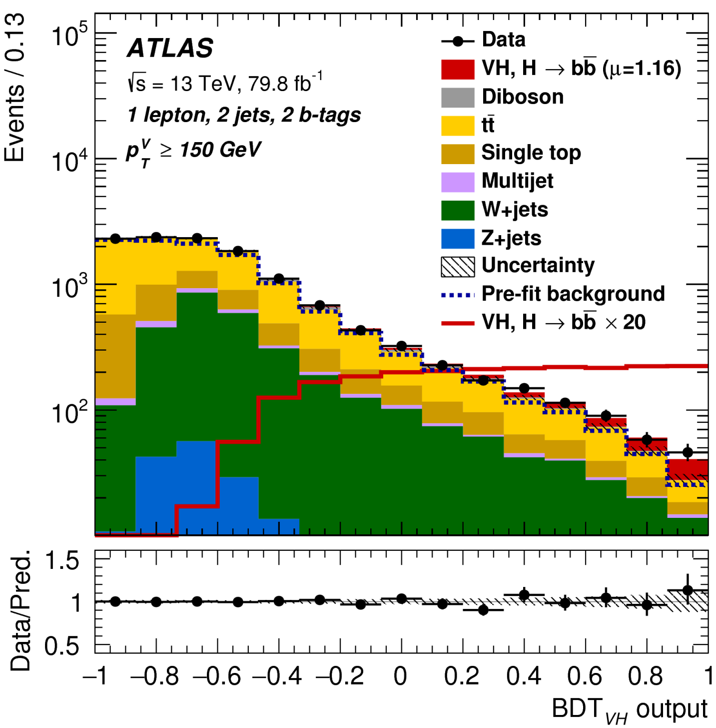
Resonant VZ, Z → bb background, used to validate the analysis procedure

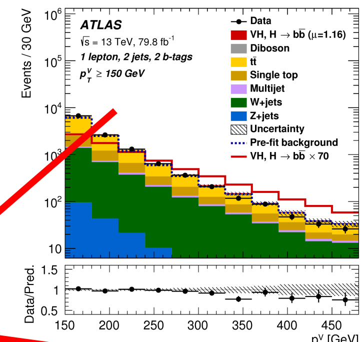
Small residual multi-jet background component in 1-lepton channel (<3%)

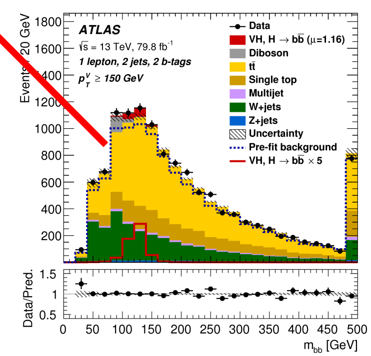
Multivariate Analysis (MVA)

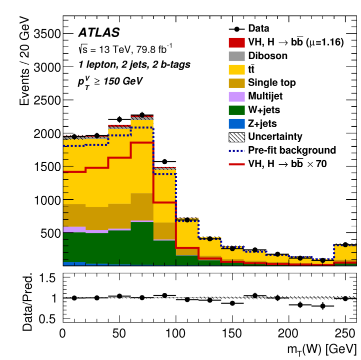
- MVA setup
  - Use simple and robust Boosted Decision Tree (BDT)
  - Input variables and training parameters tuned to yield best sensitivity
- Inputs Variables
  - Kinematic variables, some specific to 3-jet regions
  - m_{bb}, $\triangle R_{bb}$, p_T^V most important ones

Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	×	×
E_T^{miss}	×	×	
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\lvert\Delta\eta(b_1, b_2)\rvert$	×		
$\Delta\phi(V, bb)$	×	×	×
$\lvert\Delta\eta(V, bb)\rvert$			×
m_{eff}	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
$E_T^{miss}/\sqrt{S_T}$			×
m_{top}		×	
$\lvert\Delta Y(V, bb)\rvert$		×	
Only in 3-jet events			
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×









Fit Model

- Perform a binned maximum likelihood fit simultaneously in different categories to extract signal significance / signal strength (μ)

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

Channel	SR/CR	Categories			
		75 GeV $< p_T^V <$ 150 GeV		$p_T^V >$ 150 GeV	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	BDT	BDT
1-lepton	SR	-	-	BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	W + HF CR	-	-	Yield	Yield
2-lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield	m_{bb}

- 8 Signal Regions (SR)

- 2 W+HF (heavy flavor) control regions (CRs) in 1-lepton channel (Purity:~75%)

  m_{top} > 225 GeV && m_{bb} < 75 GeV.

  Use only the normalization info in the fit

- 4 Top eμ CRs in 2-lepton (Purity: ~99%)

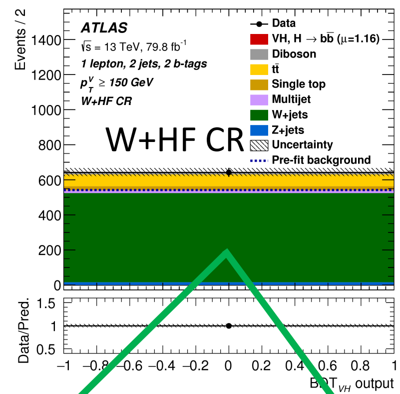
  Use m_{bb} distribution (or only the normalization info) in the fit

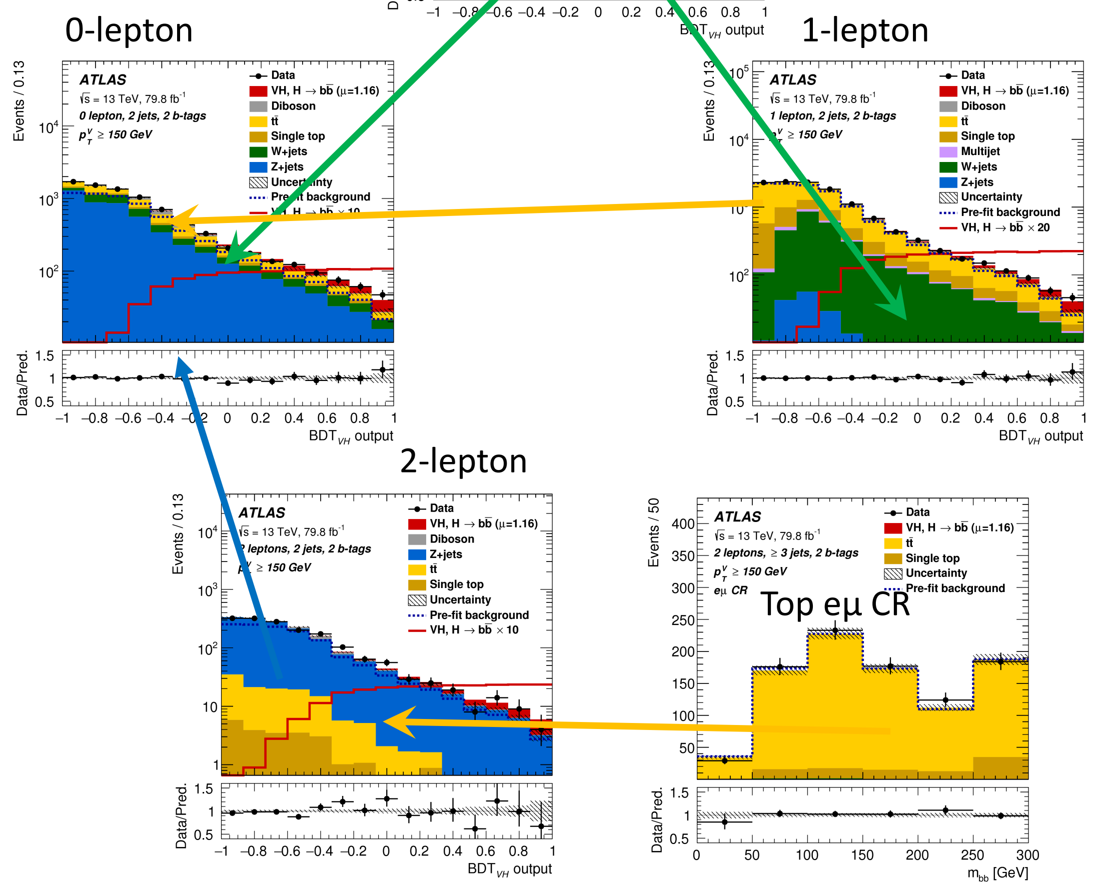
Background Modelling

- Use state-of-the-art MC generators (except MJ which is modelled in 1-lepton using a data-driven method)
- Constrain (shape and normalization) from data by using high purity control regions
- Main background normalizations floating in the fit

Process	Normalisation factor
$t\bar{t}$ 0- and 1-lepton	0.98 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	1.06 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	0.95 ± 0.06
$W+$HF 2-jet	1.19 ± 0.12
$W+$HF 3-jet	1.05 ± 0.12
$Z+$HF 2-jet	1.37 ± 0.11
$Z+$HF 3-jet	1.09 ± 0.09

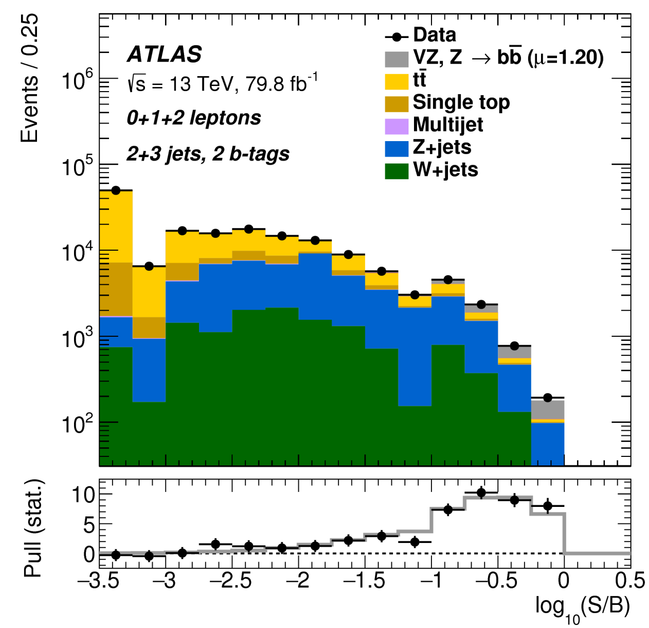
- Parametrize extrapolation uncertainties across regions as uncertainties on ratios of yields
- Shape uncertainties on BDTs

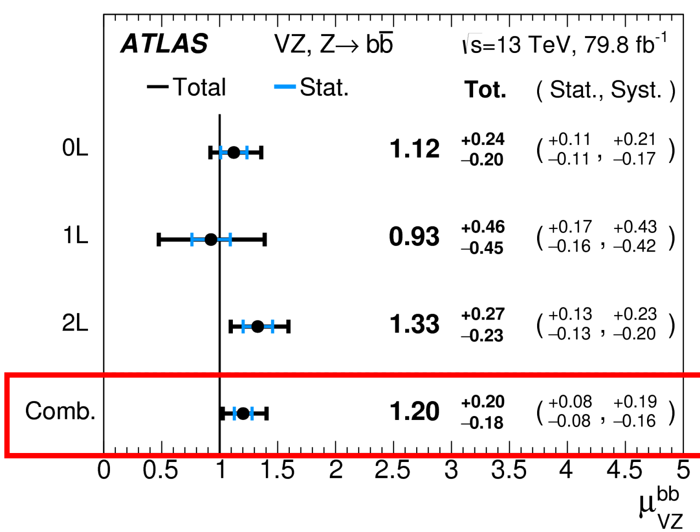


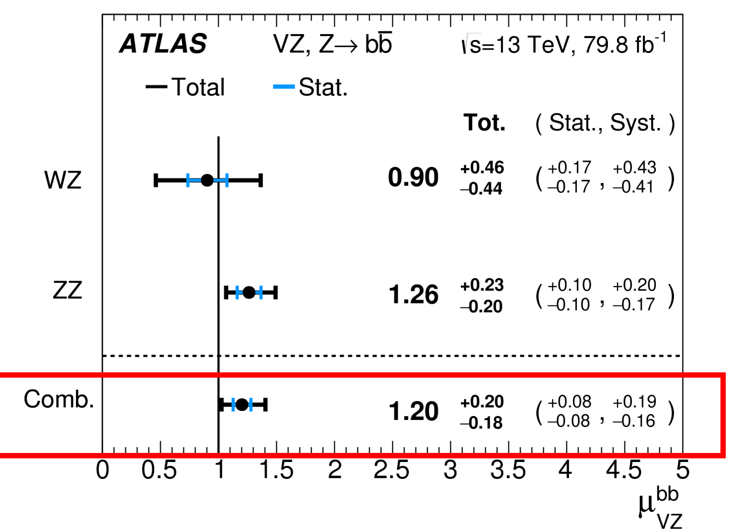


An Useful Standard Candle : Diboson MVA analysis

- Same analysis strategy as the VH MVA analysis
  - Re-train the BDTs to look for WZ+ZZ instead of VH
  - The yield of VZ is typically 2-3 times higher than those of VH
  - Robust validation of background model and associated uncertainties
- Very clear diboson signal, good agreement between channels

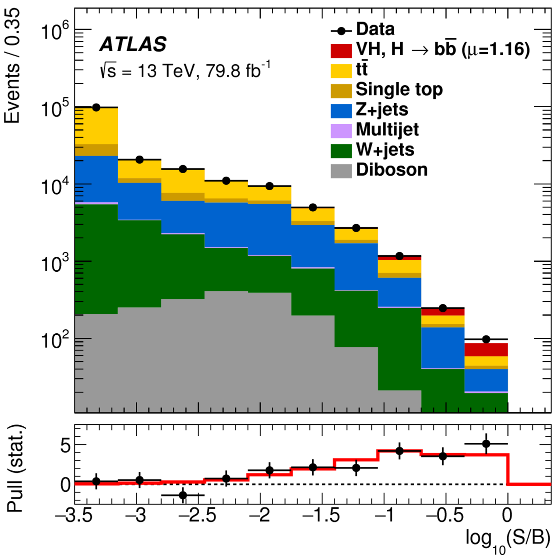


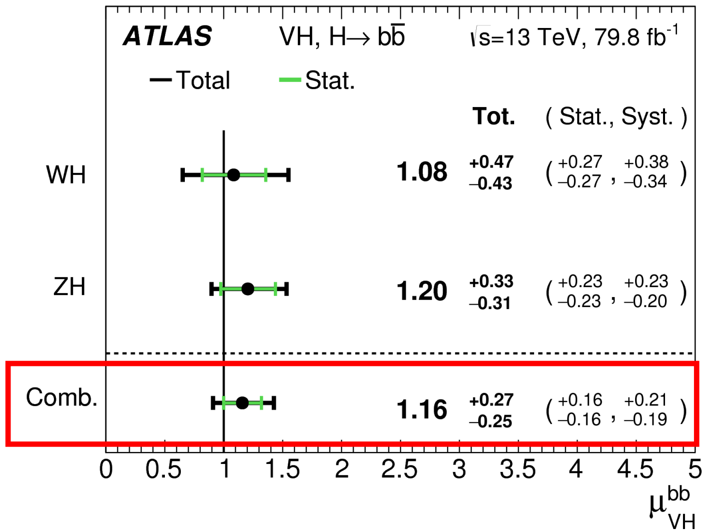




VH MVA analysis results

- Significance of VH(bb) signal at 4.9 σ (4.3 σ exp.)
  - Signal strength compatible with SM





- Individual production modes significances
  - 2.5 σ (2.3 σ exp.) for WH
  - 4.0 σ (3.5 σ exp.) for ZH

Signal strength	Signal strength	p_0 Exp.	p_0 Obs.	Significance Exp.	Significance Obs.
0-lepton	$1.04^{+0.34}_{-0.32}$	$9.5 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$	3.1	3.3
1-lepton	$1.09^{+0.46}_{-0.42}$	$8.7 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	2.4	2.6
2-lepton	$1.38^{+0.46}_{-0.42}$	$4.0 \cdot 10^{-3}$	$3.3 \cdot 10^{-4}$	2.6	3.4
VH, $H \to b\bar{b}$ combination	$1.16^{+0.27}_{-0.25}$	$7.3 \cdot 10^{-6}$	$5.3 \cdot 10^{-7}$	4.3	4.9

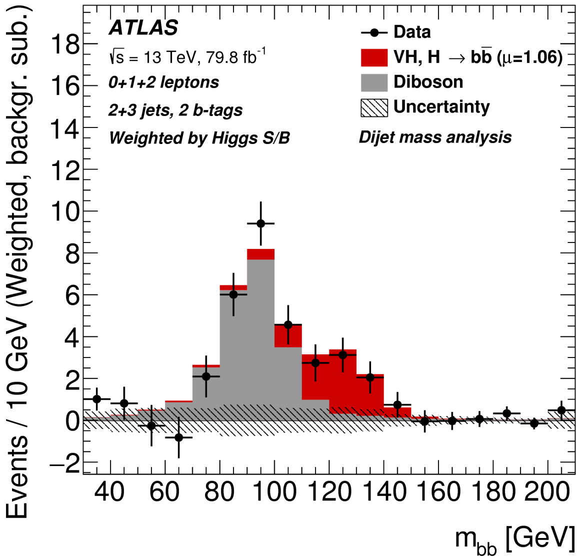
- The compatibility test of μ among three channels: 80%.

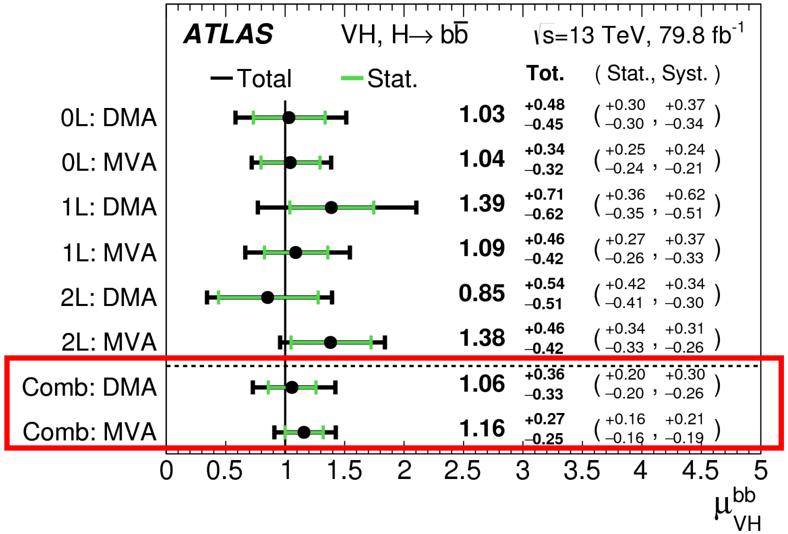
Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	b-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

measurement dominated by systematics (signal and background modelling, MC statistics, b-tagging)

Cross check: Di-jet mass analysis (DMA)

- Important cross-check to test robustness of result
  - Additional p_T^V Split at 200 GeV
  - Additional cuts on ΔR_{bb} (p_T^V dependent), m_T^W (1 lepton), E_T^{miss} significance (2 lepton)
  - Fit m_{bb} instead of BDT output



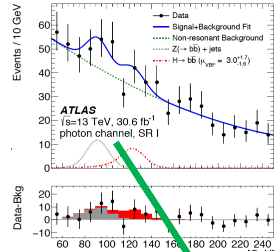


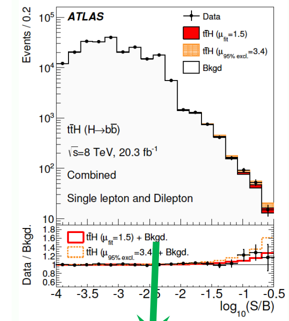
- Significance of VH(bb) signal at 3.6 σ (3.5 σ exp.)

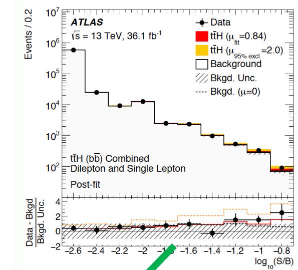
- Consistent with MVA result in all channels

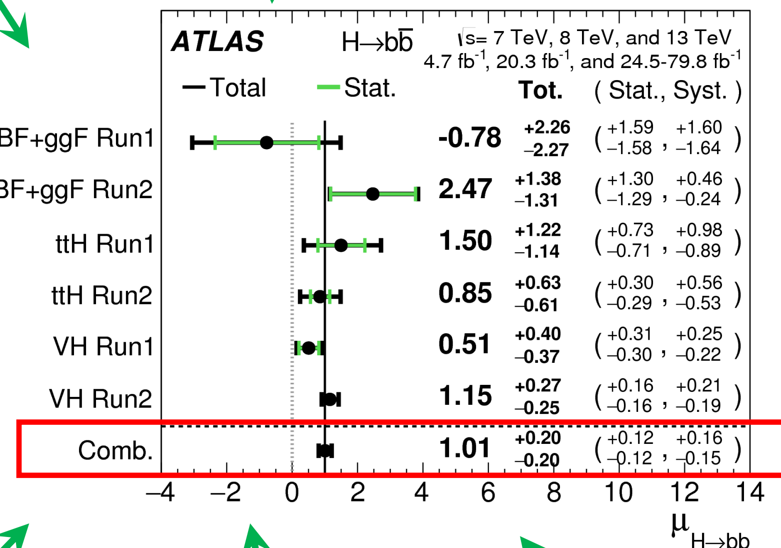
Combination of H→bb searches

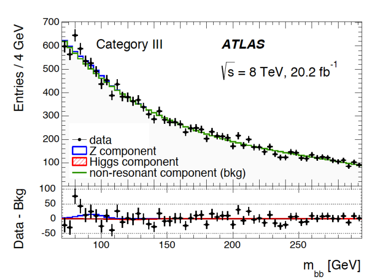
- Combine Run 1 and Run 2 analyses in VH, VBF(*) and ttH production modes
  - Results assume SM Higgs boson production cross-section
  - Only H→bb branching ratio is correlated across the six analyses
- Observation of H→bb decays at 5.4 σ (5.5 σ exp.)
- Main contributions from VH channels (contributions of VBF and ttH channels 1.5σ and 1.9 σ)
- Compatibility of the 6 measurements 54%

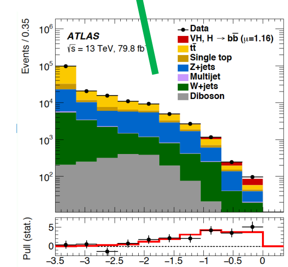


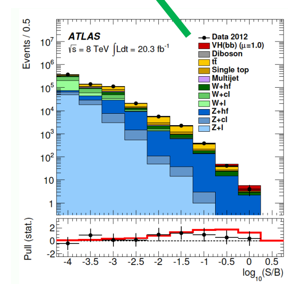








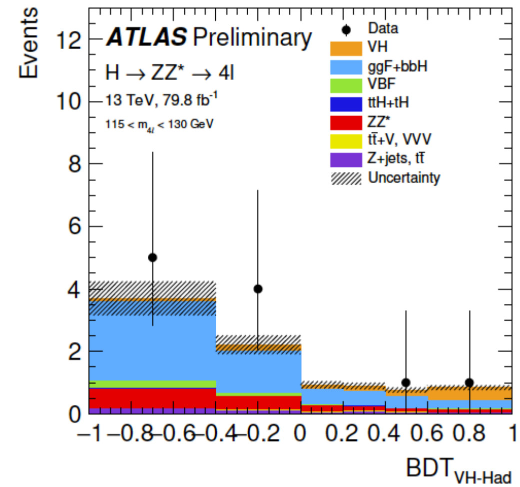


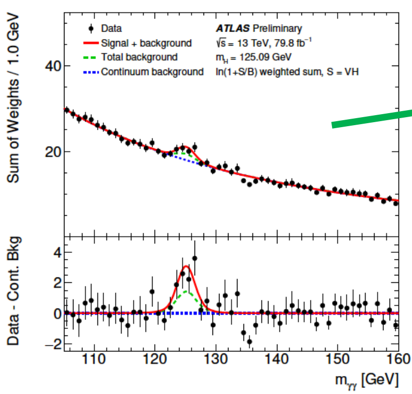


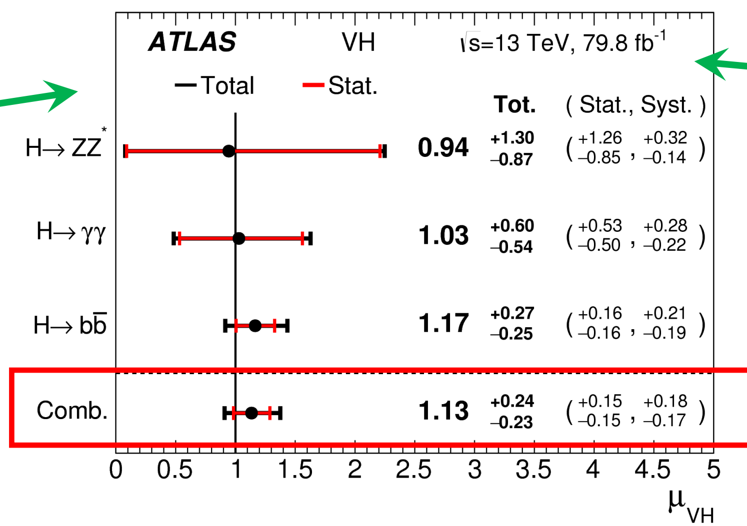
(See Zhijun's talk for more details)

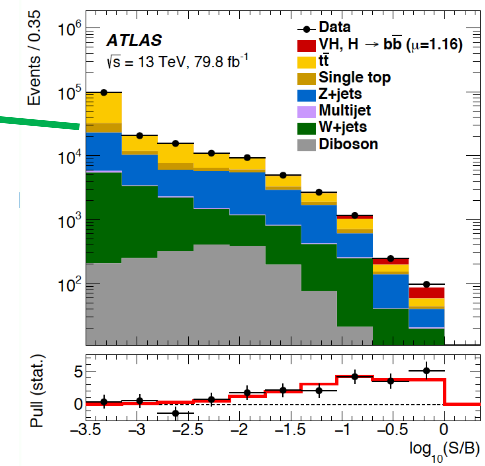
Combination of VH searches

- Combine Run 2 analyses in bb, γγ and 4l decays
  - Updated analyses with 2015-2017 Run 2 data in all channels
  - γγ and 4l analyses have both leptonic and hadronic categories
  - Results assume SM Higgs boson branching fractions
- Observation of VH production at 5.3 σ (4.8 σ exp.)
- Main contributions from bb channels (contributions of 4l and γγ channels 1.1σ and 1.9 σ)
- Compatibility of the 3 measurements 96%









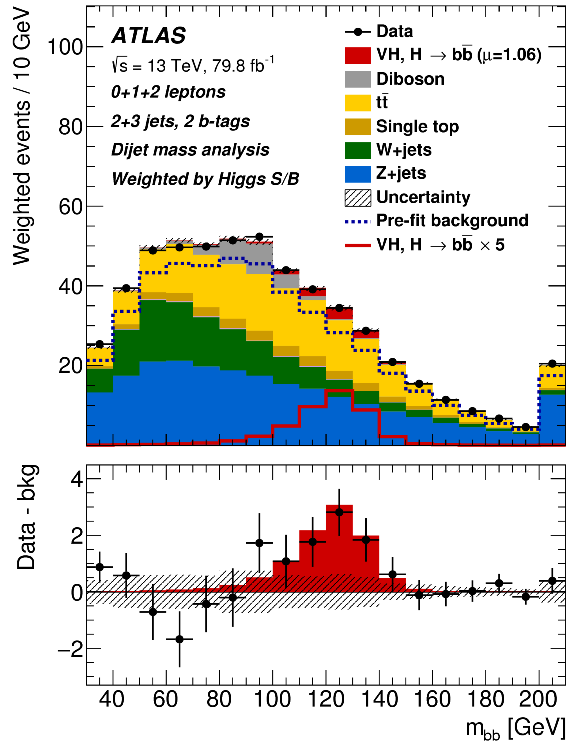
Conclusions

➢ VH(bb) analysis carried out on full 2015-17 dataset

- With Run 2 79.8 fb^{-1} dataset, found strong evidence for VH(bb) with a significance of 4.9 σ (4.3 σ exp.) and a mu value of 1.16 +/-0.26

➢ With full Hbb combination, 5.4 (5.5) σ observed (exp.) for H→bb with mu value of 1.01 +/- 0.20

➢ With Run 2 VH combination, 5.3 (4.8) σ observed (exp.) for VH with mu value of 1.13 +/- 0.24



These results provide an observation of the H → bb decay mode, and also of the Higgs boson being produced in association with a vector boson

SDU (Lianliang Ma; Mario Sousa; Yanhui Ma) contribution:

- Supporting note co-editor; Analysis approval talk;
- Main 1-lepton analyzer: data/MC validation; multijet estimation; optimization; provide inputs;
- Statistical analysis for the final results.

Back Up

Event Selection

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 with $p_{\mathrm{T}} > 7$ GeV	1 *tight* electron $p_{\mathrm{T}} > 27$ GeV	1 *tight* muon $p_{\mathrm{T}} > 25$ GeV	2 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV ≥ 1 lepton with $p_{\mathrm{T}} > 27$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–		81 GeV $< m_{\ell\ell} <$ 101 GeV
Jets	Exactly 2 / Exactly 3 jets			Exactly 2 / ≥ 3 jets
Jet p_{T}	> 20 GeV for $\lvert\eta\rvert < 2.5$ > 30 GeV for $2.5 < \lvert\eta\rvert < 4.5$			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
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 GeV			75 GeV $< p_{\mathrm{T}}^{V} <$ 150 GeV, > 150 GeV
Signal regions	–	$m_{bb} \geq 75$ GeV or $m_{\mathrm{top}} \leq 225$ GeV		Same-flavour leptons Opposite-sign charges ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{\mathrm{top}} > 225$ GeV		Different-flavour leptons Opposite-sign charges

Signal and Backgrounds Samples

Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order
Signal, mass set to 125 GeV and $b\bar{b}$ branching fraction to 58%					
$qq \to WH \to \ell\nu b\bar{b}$	Powheg-Box v2 [76] + GoSam [79] + MiNLO [80,81]	NNPDF3.0NLO$^{(\star)}$ [77]	Pythia 8.212 [68]	AZNLO [78]	NNLO(QCD)+ NLO(EW) [82–88]
$qq \to ZH \to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	Powheg-Box v2 + GoSam + MiNLO	NNPDF3.0NLO$^{(\star)}$	Pythia 8.212	AZNLO	NNLO(QCD)$^{(\dagger)}$+ NLO(EW)
$gg \to ZH \to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	Powheg-Box v2	NNPDF3.0NLO$^{(\star)}$	Pythia 8.212	AZNLO	NLO+ NLL [89–93]
Top quark, mass set to 172.5 GeV					
$t\bar{t}$	Powheg-Box v2 [94]	NNPDF3.0NLO	Pythia 8.230	A14 [95]	NNLO+NNLL [96]
s-channel	Powheg-Box v2 [97]	NNPDF3.0NLO	Pythia 8.230	A14	NLO [98]
t-channel	Powheg-Box v2 [97]	NNPDF3.0NLO	Pythia 8.230	A14	NLO [99]
Wt	Powheg-Box v2 [100]	NNPDF3.0NLO	Pythia 8.230	A14	Approximate NNLO [101]
Vector boson + jets					
$W \to \ell\nu$	Sherpa 2.2.1 [71, 102, 103]	NNPDF3.0NNLO	Sherpa 2.2.1 [104, 105]	Default	NNLO [106]
$Z/\gamma^* \to \ell\ell$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
$Z \to \nu\nu$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
Diboson					
$qq \to WW$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$qq \to WZ$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$qq \to ZZ$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$gg \to VV$	Sherpa 2.2.2	NNPDF3.0NNLO	Sherpa 2.2.2	Default	NLO

Signal and Backgrounds Samples

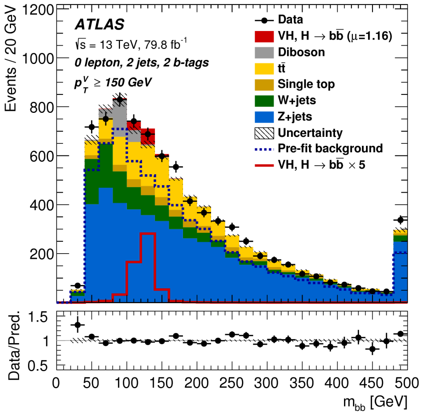
➢ Signal

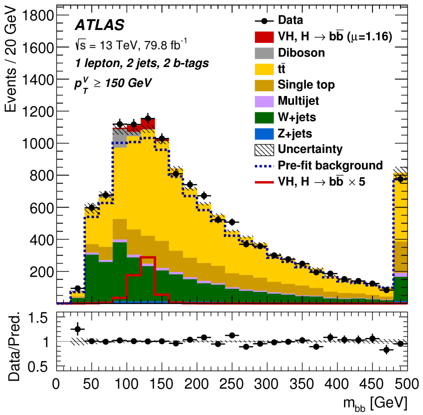
- Both qqVH and ggZH using latest Powheg+MiNLO + Pythia8 samples

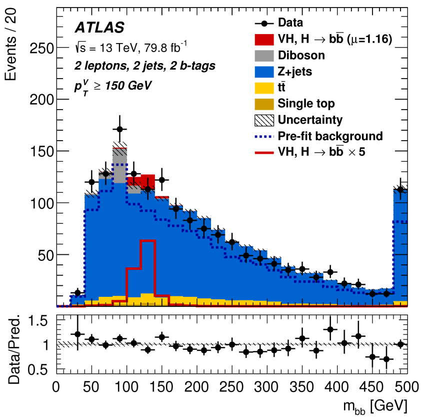
➢ Background

- V (W/Z)+jets : Sherpa 2.2.1 with jet flavor filter
- Dibson : Sherpa 2.2.1 for quark induced samples (qqVV). After EPS, include also gluon induced (ggVV) samples with Sherpa 2.2.2
- ttbar : Powheg+Pythia8, 2-lepton also incorporates di-lepton filtered sample. Dedicated MET filter ttbar samples also used in 0 lepton
- Single-top : updated to Powheg+Pythia8 samples since EPS
- Multijet

Negligible in 0 and 2 lepton (confirmed by lots of detailed studies), data-driven in 1 lepton channel (fraction: ~2-3%)

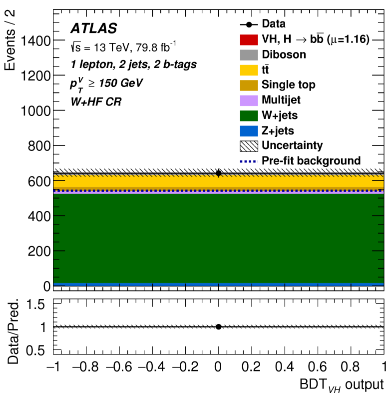


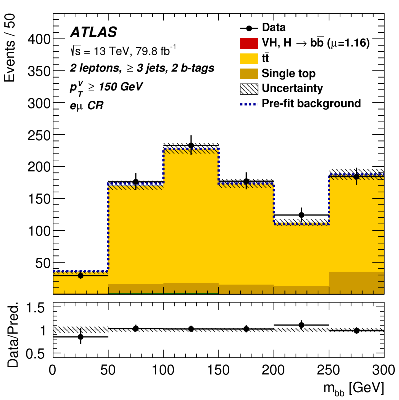




Signal and Control Regions

Channel	SR/CR	Categories			
		$75\text{ GeV} < p_T^V < 150\text{ GeV}$		$p_T^V > 150\text{ GeV}$	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	BDT	BDT
1-lepton	SR	-	-	BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	W + HF CR	-	-	Yield	Yield
2-lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield	m_{bb}





- With total 8 signal regions and 6 control regions
- A highly pure (>70%) 1L W +hf CR to provide additional constraint and validation of W + hf normalization
  - Mtop>225GeV and mBB<75GeV
  - Implemented as a single bin in the fit
- 2L Top eμ CR with very high top purity (>99%) and same kinematics selectios as ttbar in SR
  - Constrains top background normalization and shape
  - mbb discriminant is used in the fit

Additional cuts for di-jet mass analysis

	Channel		
Selection	0-lepton	1-lepton	2-lepton
m_{T}^{W}	-	< 120 GeV	-
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{S_{\mathrm{T}}}$	-	-	$< 3.5\sqrt{\mathrm{GeV}}$

	p_{T}^{V} regions		
p_{T}^{V}	$75-150$ GeV (2-lepton only)	$150-200$ GeV	> 200 GeV
$\Delta R(\vec{b}_1,\vec{b}_2)$	<3.0	<1.8	<1.2

Signal acceptance

Process	$\sigma \times \mathcal{B}$ [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$qq \to ZH \to \ell\ell b\bar{b}$	29.9	<0.1	0.1	6.0
$gg \to ZH \to \ell\ell b\bar{b}$	4.8	<0.1	0.2	13.5
$qq \to WH \to \ell\nu b\bar{b}$	269.0	0.2	1.0	–
$qq \to ZH \to \nu\nu b\bar{b}$	89.1	1.9	–	–
$gg \to ZH \to \nu\nu b\bar{b}$	14.3	3.5	–	–

Background Modelling

Z + jets	
$Z+ll$ normalisation	18%
$Z+cl$ normalisation	23%
Z + HF normalisation	Floating (2-jet, 3-jet)
$Z+bc$-to-$Z+bb$ ratio	30 – 40%
$Z+cc$-to-$Z+bb$ ratio	13 – 15%
$Z+bl$-to-$Z+bb$ ratio	20 – 25%
0-to-2 lepton ratio	7%
m_{bb}, p_T^V	S
W + jets	
$W+ll$ normalisation	32%
$W+cl$ normalisation	37%
W + HF normalisation	Floating (2-jet, 3-jet)
$W+bl$-to-$W+bb$ ratio	26% (0-lepton) and 23% (1-lepton)
$W+bc$-to-$W+bb$ ratio	15% (0-lepton) and 30% (1-lepton)
$W+cc$-to-$W+bb$ ratio	10% (0-lepton) and 30% (1-lepton)
0-to-1 lepton ratio	5%
W + HF CR to SR ratio	10% (1-lepton)
m_{bb}, p_T^V	S
$t\bar{t}$ (all are uncorrelated between the 0+1- and 2-lepton channels)	
$t\bar{t}$ normalisation	Floating (0+1-lepton, 2-lepton 2-jet, 2-lepton 3-jet)
0-to-1 lepton ratio	8%
2-to-3-jet ratio	9% (0+1-lepton only)
W + HF CR to SR ratio	25%
m_{bb}, p_T^V	S
Single top-quark	
Cross-section	4.6% (s-channel), 4.4% (t-channel), 6.2% (Wt)
Acceptance 2-jet	17% (t-channel), 55% ($Wt(bb)$), 24% (Wt(other))
Acceptance 3-jet	20% (t-channel), 51% ($Wt(bb)$), 21% (Wt(other))
m_{bb}, p_T^V	S (t-channel, $Wt(bb)$, Wt(other))
Multi-jet (1-lepton)	
Normalisation	60 – 100% (2-jet), 90 – 140% (3-jet)
BDT template	S

ZZ	
Normalisation	20%
0-to-2 lepton ratio	6%
Acceptance from scale variations	10 – 18%
Acceptance from PS/UE variations for 2 or more jets	6%
Acceptance from PS/UE variations for 3 jets	7% (0-lepton), 3% (2-lepton)
m_{bb}, p_T^V, from scale variations	S (correlated with WZ uncertainties)
m_{bb}, p_T^V, from PS/UE variations	S (correlated with WZ uncertainties)
m_{bb}, from matrix-element variations	S (correlated with WZ uncertainties)
WZ	
Normalisation	26%
0-to-1 lepton ratio	11%
Acceptance from scale variations	13 – 21%
Acceptance from PS/UE variations for 2 or more jets	4%
Acceptance from PS/UE variations for 3 jets	11%
m_{bb}, p_T^V, from scale variations	S (correlated with ZZ uncertainties)
m_{bb}, p_T^V, from PS/UE variations	S (correlated with ZZ uncertainties)
m_{bb}, from matrix-element variations	S (correlated with ZZ uncertainties)
WW	
Normalisation	25%

Signal Modelling

Signal	
Cross-section (scale)	0.7% (qq), 27% (gg)
Cross-section (PDF)	1.9% ($qq \to WH$), 1.6% ($qq \to ZH$), 5% (gg)
$H \to b\bar{b}$ branching fraction	1.7%
Acceptance from scale variations	2.5 – 8.8%
Acceptance from PS/UE variations for 2 or more jets	2.9 – 6.2% (depending on lepton channel)
Acceptance from PS/UE variations for 3 jets	1.8 – 11%
Acceptance from PDF+α_S variations	0.5 – 1.3%
m_{bb}, p_T^V, from scale variations	S
m_{bb}, p_T^V, from PS/UE variations	S
m_{bb}, p_T^V, from PDF+α_S variations	S
p_T^V from NLO EW correction	S

Post-fit yields---signal region

	0-lepton $p_T^V > 150\,GeV$, 2-b-tag		1-lepton $p_T^V > 150\,GeV$, 2-b-tag		2-lepton $75\,GeV < p_T^V < 150\,GeV$, 2-$b$-tag		2-lepton $p_T^V > 150\,GeV$, 2-b-tag	
Process	2-jet	3-jet	2-jet	3-jet	2-jet	≥3-jet	2-jet	≥3-jet
$Z + ll$	17 ± 11	27 ± 18	2 ± 1	3 ± 2	14 ± 9	49 ± 32	4 ± 3	30 ± 19
$Z + cl$	45 ± 18	76 ± 30	3 ± 1	7 ± 3	43 ± 17	170 ± 67	12 ± 5	88 ± 35
Z + HF	4770 ± 140	5940 ± 300	180 ± 9	348 ± 21	7400 ± 120	14160 ± 220	1421 ± 34	5370 ± 100
$W + ll$	20 ± 13	32 ± 22	31 ± 23	65 ± 48	< 1	< 1	< 1	< 1
$W + cl$	43 ± 20	83 ± 38	139 ± 67	250 ± 120	< 1	< 1	< 1	< 1
W + HF	1000 ± 87	1990 ± 200	2660 ± 270	5400 ± 670	2 ± 0	13 ± 2	1 ± 0	4 ± 1
Single top quark	368 ± 53	1410 ± 210	2080 ± 290	9400 ± 1400	188 ± 89	440 ± 200	23 ± 7	93 ± 26
$t\bar{t}$	1333 ± 82	9150 ± 400	6600 ± 320	50200 ± 1400	3170 ± 100	8880 ± 220	104 ± 6	839 ± 40
Diboson	254 ± 49	318 ± 90	178 ± 47	330 ± 110	152 ± 32	355 ± 68	52 ± 11	196 ± 35
Multi-jet e sub-ch.	–	–	100 ± 100	41 ± 35	–	–	–	–
Multi-jet μ sub-ch.	–	–	138 ± 92	260 ± 270	–	–	–	–
Total bkg.	7850 ± 90	19020 ± 140	12110 ± 120	66230 ± 270	10960 ± 100	24070 ± 150	1620 ± 30	6620 ± 80
Signal (post-fit)	128 ± 28	128 ± 29	131 ± 30	125 ± 30	51 ± 11	86 ± 22	28 ± 6	67 ± 17
Data	8003	19143	12242	66348	11014	24197	1626	6686

Post-fit yields---control region

	1-lepton $p_T^V > 150\,GeV$, 2-b-tag		2-lepton $75\,GeV < p_T^V < 150\,GeV$, 2-$b$-tag		2-lepton $p_T^V > 150\,GeV$, 2-b-tag	
Process	2-jet	3-jet	2-jet	≥3-jet	2-jet	≥3-jet
Z + HF	15.1 ± 1.4	33 ± 2.5	2.5 ± 0.2	2.1 ± 0.2	< 1	< 1
$W + ll$	2.1 ± 1.5	3.8 ± 2.6	–	–	–	–
$W + cl$	8.4 ± 4.1	13.5 ± 6.6	–	< 1	–	–
W + HF	498 ± 34	1044 ± 92	2.5 ± 0.3	8.4 ± 1.0	< 1	3.3 ± 0.4
Single top quark	23.8 ± 5.4	122 ± 23	189 ± 90	450 ± 210	22.4 ± 7.1	93 ± 27
$t\bar{t}$	68 ± 18	307 ± 77	3243 ± 98	8690 ± 210	107.3 ± 6.7	807 ± 37
Diboson	13.4 ± 3.7	22.6 ± 7.5	–	< 1	–	< 1
Multi-jet e sub-ch.	8.3 ± 8.5	3.6 ± 2.9	–	–	–	–
Multi-jet μ sub-ch.	6.9 ± 4.6	13 ± 13	–	–	–	–
Total bkg.	644 ± 23	1563 ± 39	3437 ± 58	9153 ± 95	130.1 ± 6.7	905 ± 27
Signal (post-fit)	< 1	2.3 ± 0.6	< 1	< 1	< 1	< 1
Data	642	1567	3450	9102	118	923

Significance

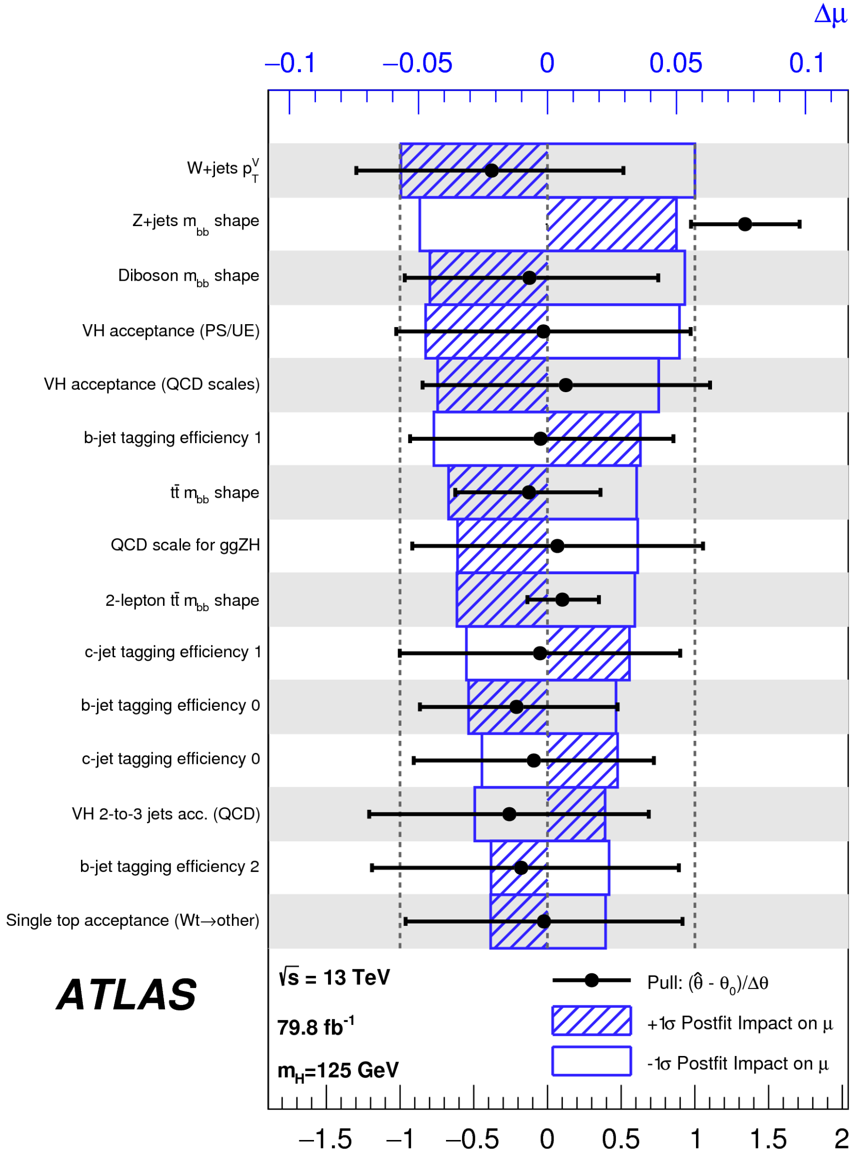
Signal strength	Signal strength	p_0		Significance	
		Exp.	Obs.	Exp.	Obs.
0-lepton	$1.04^{+0.34}_{-0.32}$	$9.5 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$	3.1	3.3
1-lepton	$1.09^{+0.46}_{-0.42}$	$8.7 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	2.4	2.6
2-lepton	$1.38^{+0.46}_{-0.42}$	$4.0 \cdot 10^{-3}$	$3.3 \cdot 10^{-4}$	2.6	3.4
VH, $H \to b\bar{b}$ combination	$1.16^{+0.27}_{-0.25}$	$7.3 \cdot 10^{-6}$	$5.3 \cdot 10^{-7}$	4.3	4.9

The probability that the signal strengths measured in the three lepton channels are compatible is 80%.

Channel	Significance	
	Exp.	Obs.
VBF+ggF	0.9	1.5
$t\bar{t}H$	1.9	1.9
VH	5.1	4.9
$H \to b\bar{b}$ combination	5.5	5.4

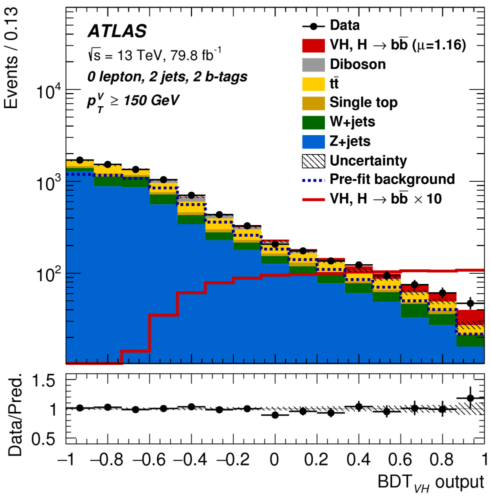
Channel	Significance	
	Exp.	Obs.
$H \to ZZ^* \to 4\ell$	1.1	1.1
$H \to \gamma\gamma$	1.9	1.9
$H \to b\bar{b}$	4.3	4.9
VH combined	4.8	5.3

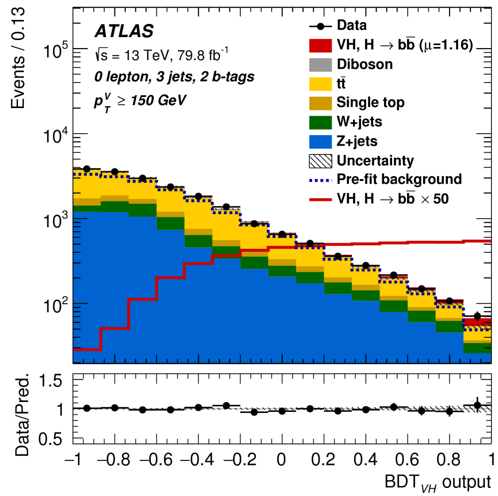
Ranking

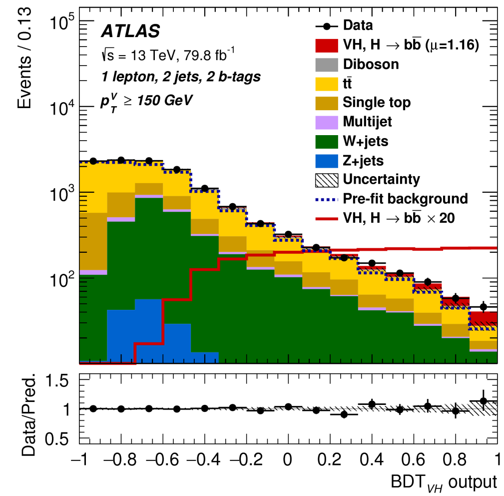


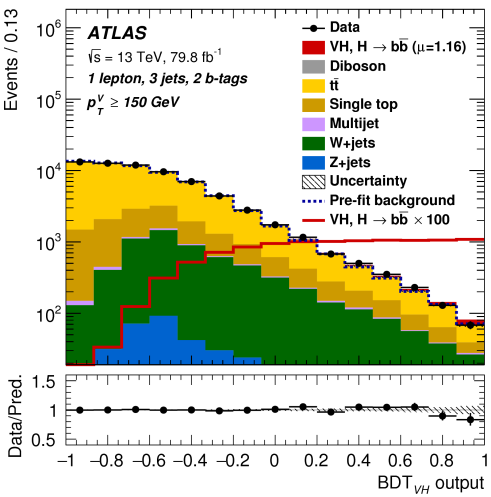
Δμ
−0.1
−0.05
0
0.05
0.1
W+jets p_T^V
Z+jets m_{bb} shape
Diboson m_{bb} shape
VH acceptance (PS/UE)
VH acceptance (QCD scales)
b-jet tagging efficiency 1
$t\bar{t}$ m_{bb} shape
QCD scale for ggZH
2-lepton $t\bar{t}$ m_{bb} shape
c-jet tagging efficiency 1
b-jet tagging efficiency 0
c-jet tagging efficiency 0
VH 2-to-3 jets acc. (QCD)
b-jet tagging efficiency 2
Single top acceptance (Wt→other)
ATLAS
$\sqrt{s}$ = 13 TeV
79.8 fb^{-1}
m_H=125 GeV
Pull: $(\hat{\theta} - \theta_0)/\Delta\theta$
+1σ Postfit Impact on μ
-1σ Postfit Impact on μ
−1.5
−1
−0.5
0
0.5
1
1.5
2

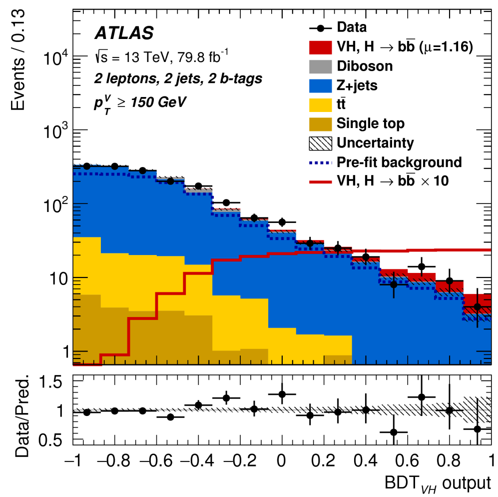
Post-fit plots VH MVA

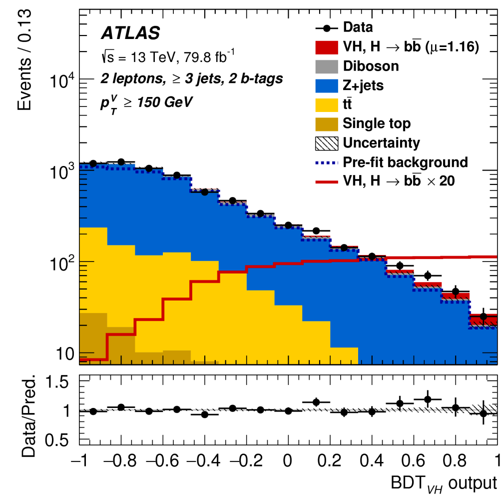




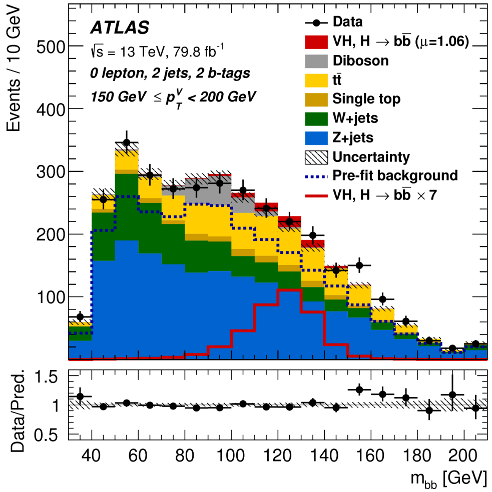


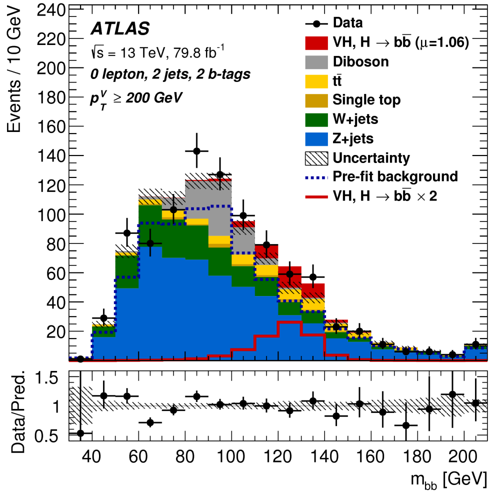


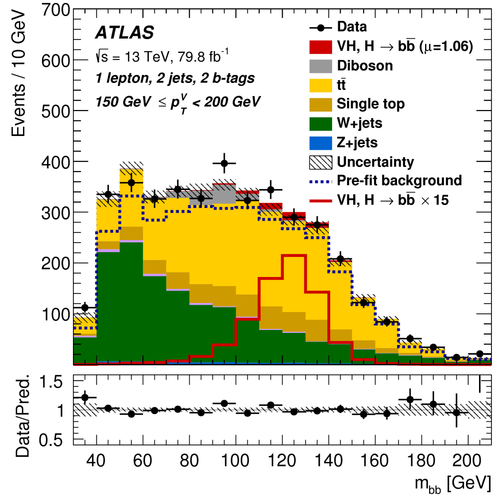


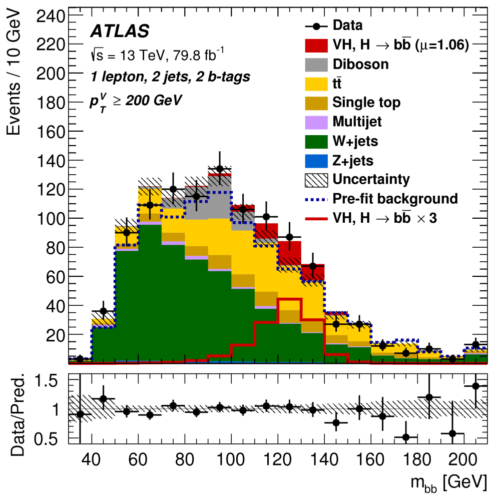


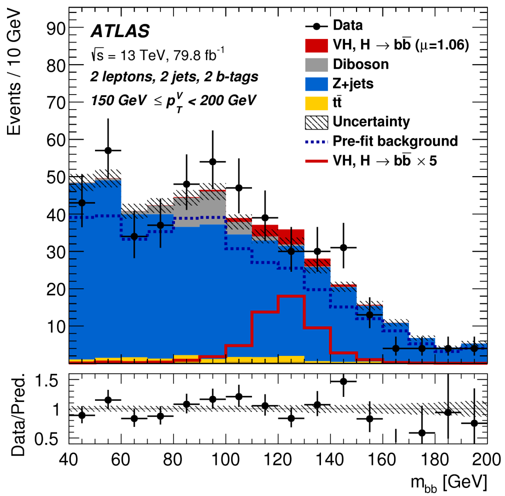
Post-fit plots VH di-jet mass analysis

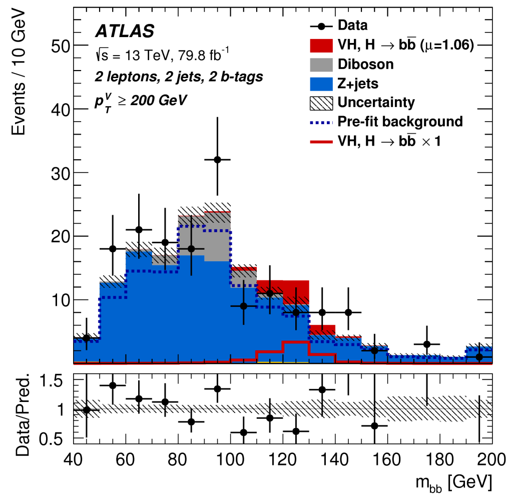




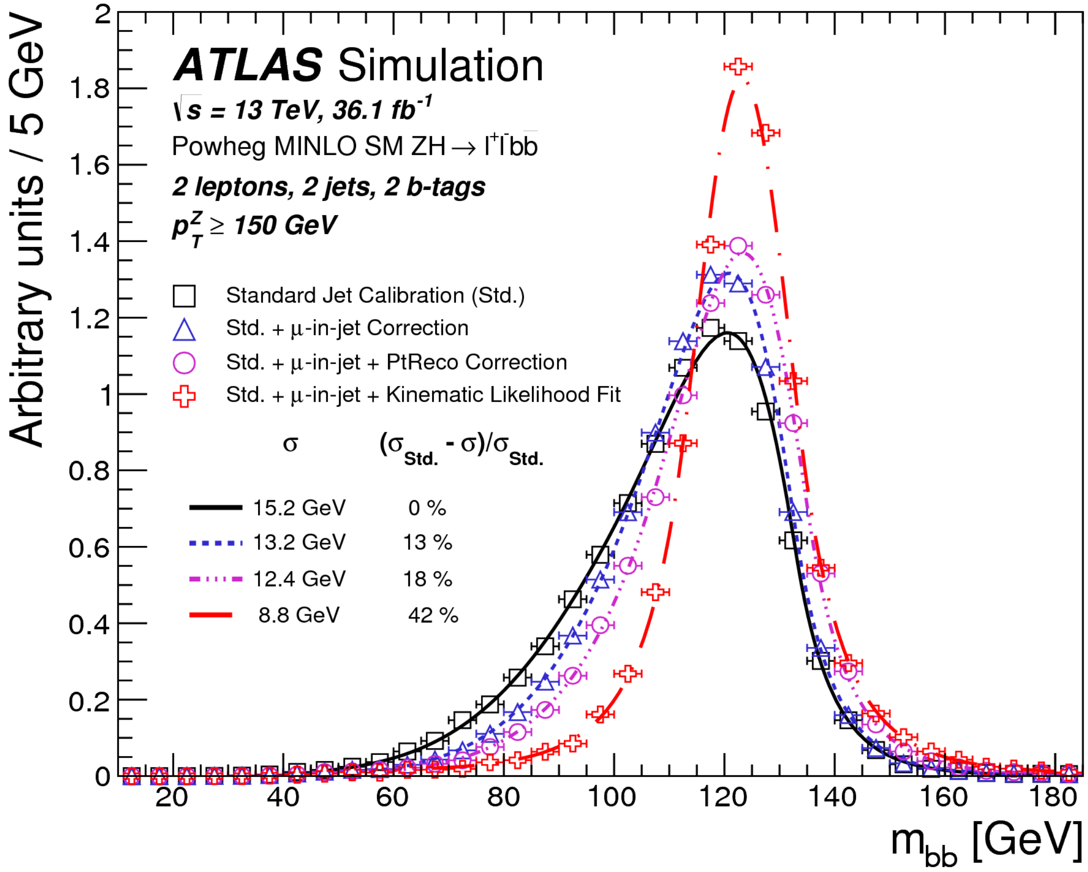








Jet energy correction



- muon-in-jet correction in all three channels;
- PtReco in 0- and 1-lepton channel;
- Kinematic fit in 2-lepton channel;

- m_{bb}: invariant mass of the dijet system constructed from the two b-tagged jets
- $\Delta R(b_1, b_2)$: distance in η and ϕ between the two b-tagged jets
- $p_T^{b_1}$: transverse momentum of the b-tagged jet in the dijet system with the higher p_T
- $p_T^{b_2}$: transverse momentum of the b-tagged jet in the dijet system with the lower p_T
- p_T^V: transverse momentum of the vector bosos; given by E_T^{miss} in the 0 lepton channel, vectorial sum of E_T^{miss} and the transverse momentum of the lepton in the 1 lepton channel and vectorial sum of the transverse momenta of the two leptons in the 2 lepton channel
- $\Delta\phi(V, bb)$: distance in ϕ between the vector boson candidate, i.e. E_T^{miss} in the 0 lepton channel, E_T^{miss} and the lepton in the 1 lepton channel and the di-lepton system in the 2 lepton channel, and the Higgs boson candidate, i.e. the dijet system constructed from the two b-tagged jets
- p_T^{jet3}: transverse momentum of the jet with the highest transverse momentum amongst the jets that are not b-tagged; only used for events with 3 or more jets
- m_{bbj}: invariant mass of the two b-tagged jets and the jet with the highest transverse momentum amongst the jets that are not b-tagged; only used for events with 3 or more jets

0 lepton channel uses two additional variables:

- $|\Delta\eta(b_1, b_2)|$: distance in η between the two b-tagged jets
- m_{eff} : scalar sum of E_T^{miss} and the p_T of all jets present in the event

1 lepton channel uses two additional variables:

- E_T^{miss}: missing transverse energy of the event
- $min[\Delta\phi(l, b)]$: distance in ϕ between the lepton and the closest b-tagged jet
- m_T^W : transverse mass of the W boson candidate, more details see 5.3
- $\Delta Y(V, bb)$: difference in rapidity between the Higgs boson candidate and W boson candidate, the four-vector of the neutrino in the W boson decay is estimated as explained in Section 5.3 for m_{top}.
- m_{top}: reconstructed mass of the leptonically decaying top quark, more details see Section 5.3

2 lepton channel uses three additional variables:

- E_T^{miss} significance: quasi-significance of the E_T^{miss} in the event, defined as $E_T^{miss}/\sqrt{S_T}$ with S_T the scalar sum of the p_T of the leptons and jets in the event.
- $|\Delta\eta(V, bb)|$: distance in η between the dilepton and dijet system of the b-tagged jets
- m_{ll}: invariant mass of the dilepton system