Higgs Production in Electroweak Processes from the ATLAS Experiment

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Outline

This talk is aimed for "update of VH and VBF production channels including decays to bb, ττ or what is available".

Only one analysis has been updated since HC2016. Two talks at HC2016:

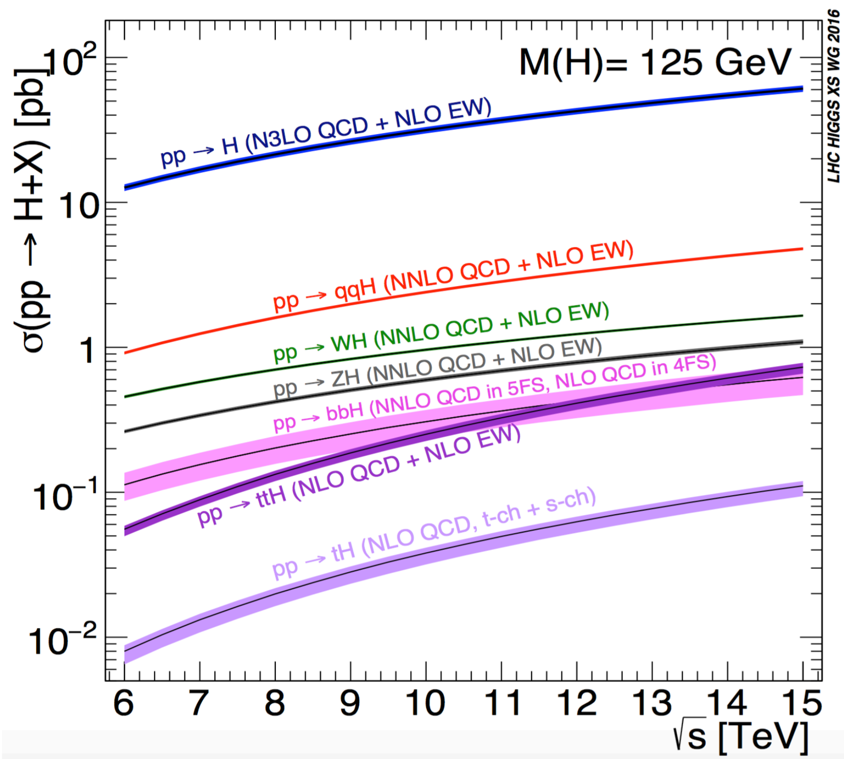
ATLAS SM H→bb: VH, VBF, VBF+γ (12.6 fb^{-1} 13 TeV)

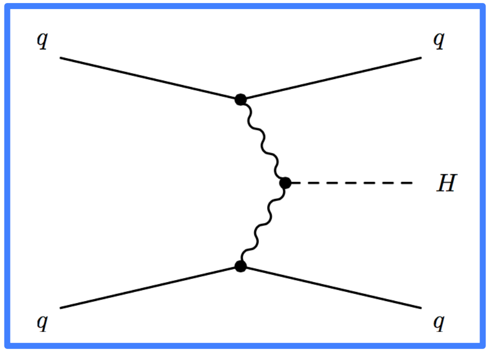
ATLAS SM H→ττ: ggF boosted, VBF, VH from Run I

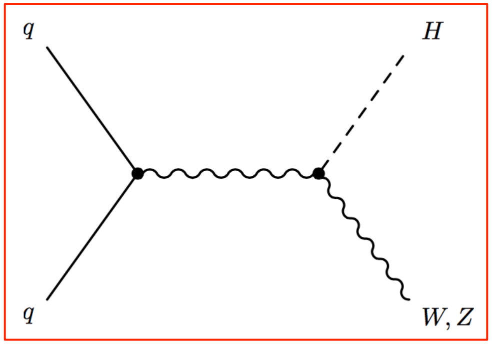
This talk only covers VH, H→bb with 36.1 fb^{-1} (arXiv:1708.03299v2):

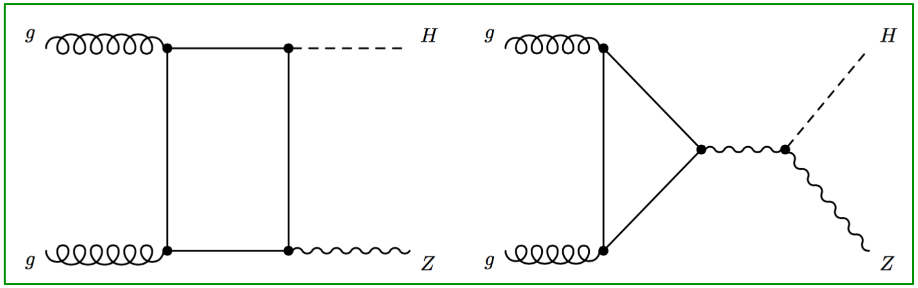
- Introduction
- Analysis strategy
- Systematics estimation (mainly theoretical ones)
- Results
- Summary

Introduction: EW Processes









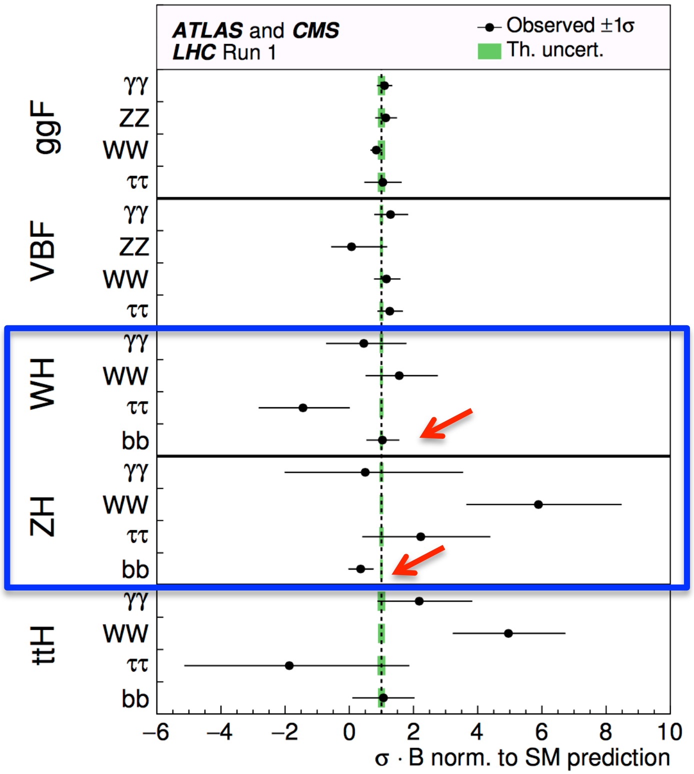
Electroweak processes are the main channels to study H→ττ and H→bb decay modes

Introduction: ATLAS+CMS Run I

JHEP08 (2016) 045

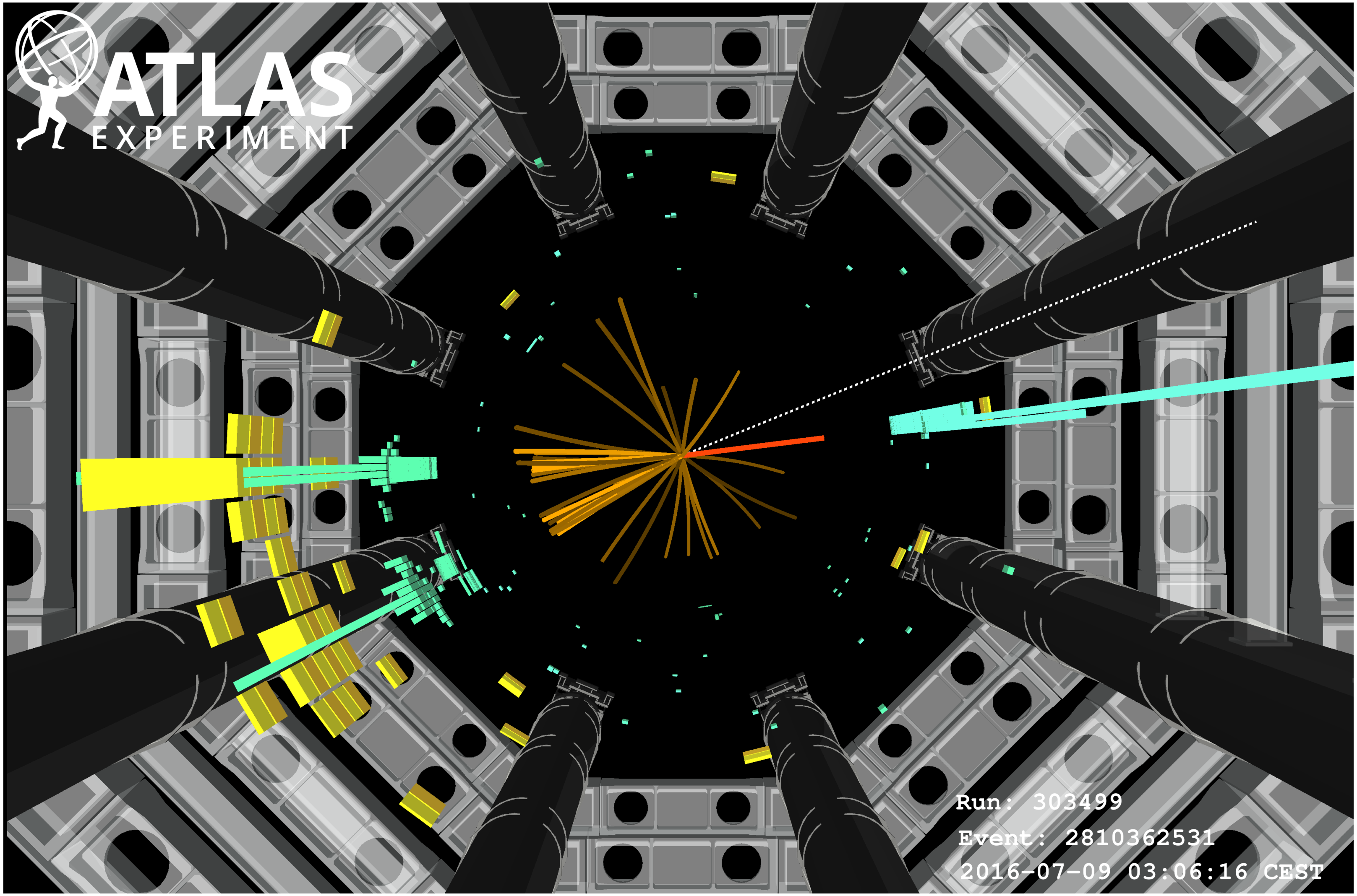
- ✧ Production channels observed: ggF and VBF (5.4σ)
- ✧ Higgs decay modes observed: γγ, ZZ, WW, ττ (5.5σ)
- ✧ The ATLAS + CMS combined result: VH with 3.5σ, H→bb with 2.6σ
- ✧ VH, H→bb is very important for studying both Higgs VH production, and H→bb decay.

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7



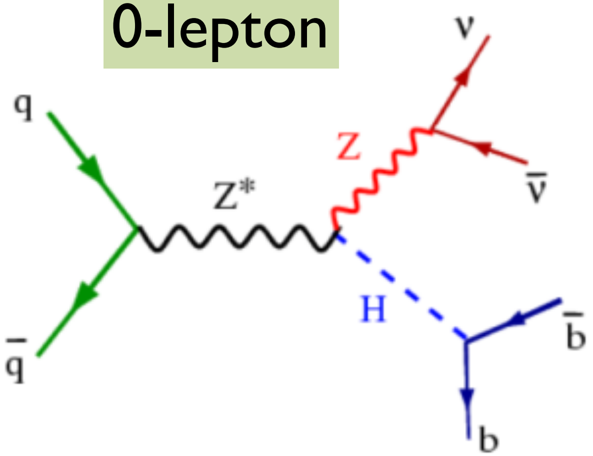
WH/ZH, H→bb

arXiv:1708.03299

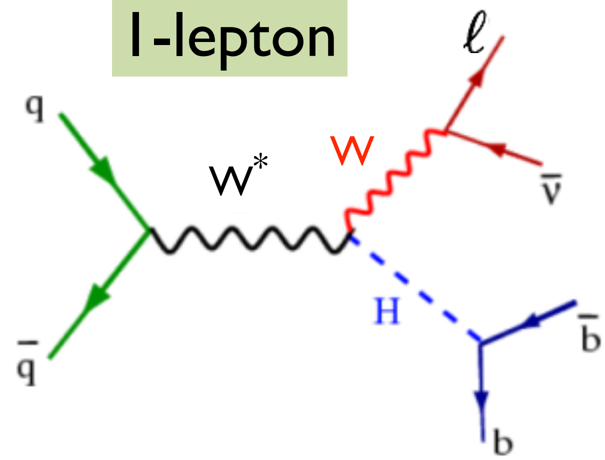


Run II Analysis of WH/ZH, H→bb

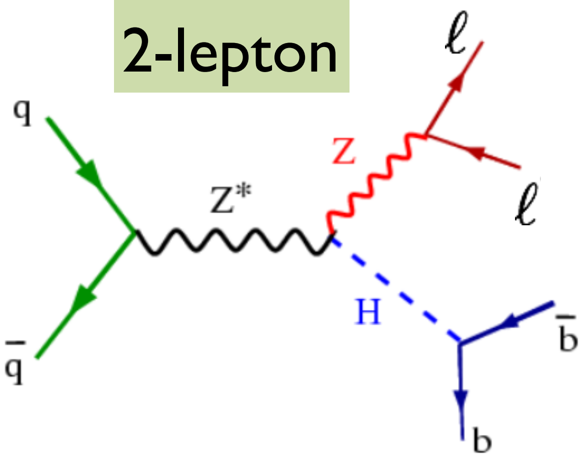
0-lepton



1-lepton



2-lepton

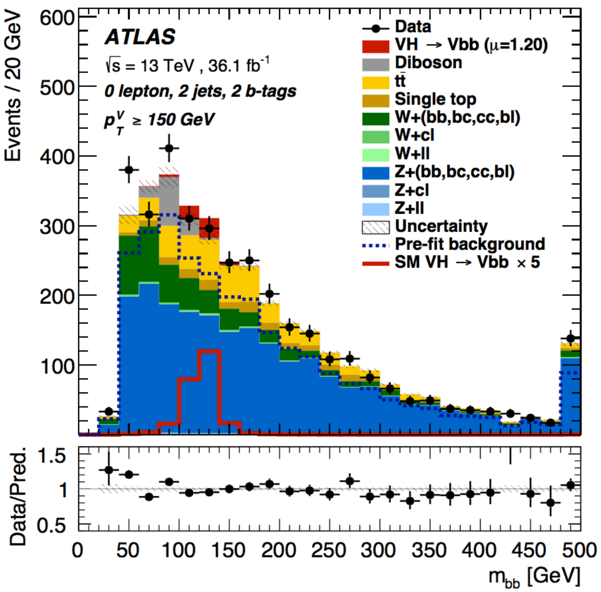


Detailed selections in the back-up

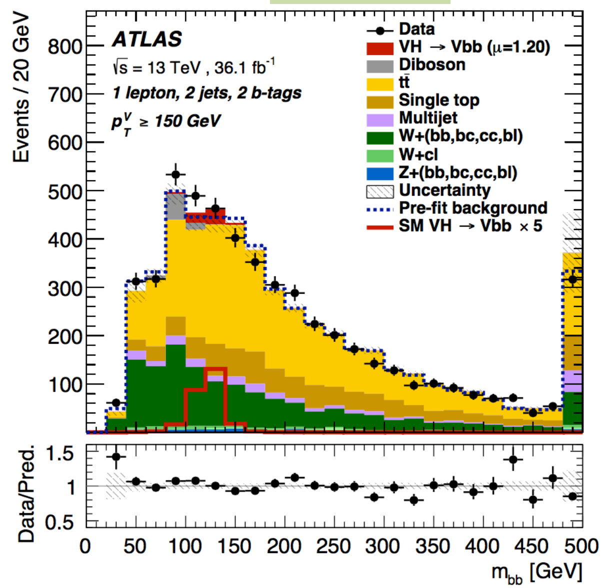
- Categorized into 0-lepton, 1-lepton, and 2-lepton final states (e, μ)
- Single-lepton triggers for 1/2-lepton channels, MET trigger for 0/1-lepton (W→μν)
- Exactly 2 or 3 jets for 0/1-lepton channels, 2 or >=3 jets for 2-lepton
- Exactly 2 b-jets (p_T>20 GeV) at 70% b-tagging efficiency; the leading b-jet with p_T>45 GeV

Background Composition

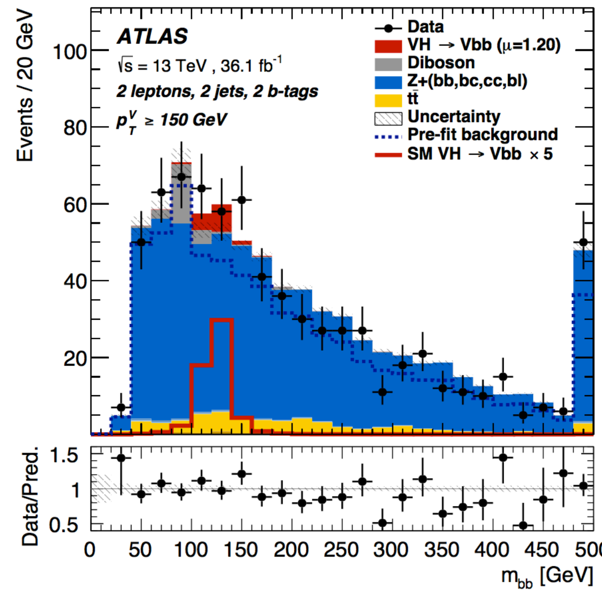
0-lepton



1-lepton



2-lepton

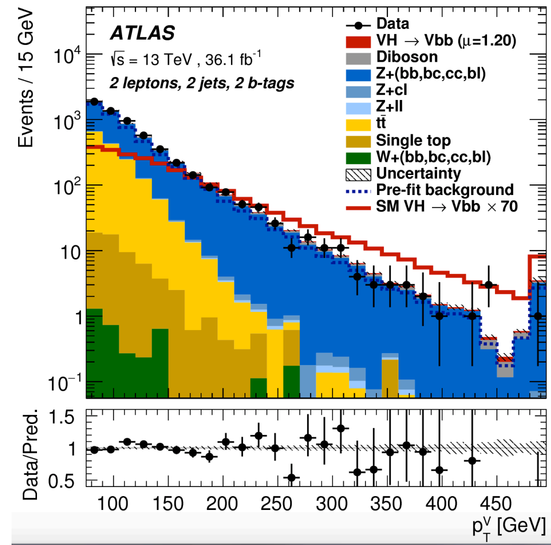


- Main backgrounds: Z+jets, W+jets, ttbar, and single-top
- Dedicated control regions (CR) for background normalizations: W+HF, ttbar
- Resonant diboson VZ, Z→bb background, with lower mbb than VH signal
- Multi-jet background negligible in 0- and 2-lepton, <5% in 1-lepton (data-driven)

Multivariate Analysis (BDT)

Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	$\times$	$\times$
E_T^{miss}	$\times$	$\times$	$\times$
$p_T^{b_1}$	$\times$	$\times$	$\times$
$p_T^{b_2}$	$\times$	$\times$	$\times$
m_{bb}	$\times$	$\times$	$\times$
$\Delta R(\boldsymbol{b}_1, \boldsymbol{b}_2)$	$\times$	$\times$	$\times$
$\lvert\Delta\eta(\boldsymbol{b}_1, \boldsymbol{b}_2)\rvert$	$\times$		
$\Delta\phi(\boldsymbol{V}, \boldsymbol{bb})$	$\times$	$\times$	$\times$
$\lvert\Delta\eta(\boldsymbol{V}, \boldsymbol{bb})\rvert$			$\times$
m_{eff}	$\times$		
$\min[\Delta\phi(\boldsymbol{\ell}, \boldsymbol{b})]$		$\times$	
m_T^W		$\times$	
$m_{\ell\ell}$			$\times$
m_{top}		$\times$	
$\lvert\Delta Y(\boldsymbol{V}, \boldsymbol{bb})\rvert$		$\times$	
	Only in 3-jet events		
$p_T^{jet_3}$	$\times$	$\times$	$\times$
m_{bbj}	$\times$	$\times$	$\times$

Requirement on high $p_T V$ improves S/B



Channel	SR/CR	Categories: 75 GeV $< p_T^V <$ 150 GeV, 2 jets	75 GeV $< p_T^V <$ 150 GeV, 3 jets	$p_T^V >$ 150 GeV, 2 jets	$p_T^V >$ 150 GeV, 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 SRs

6 CRs

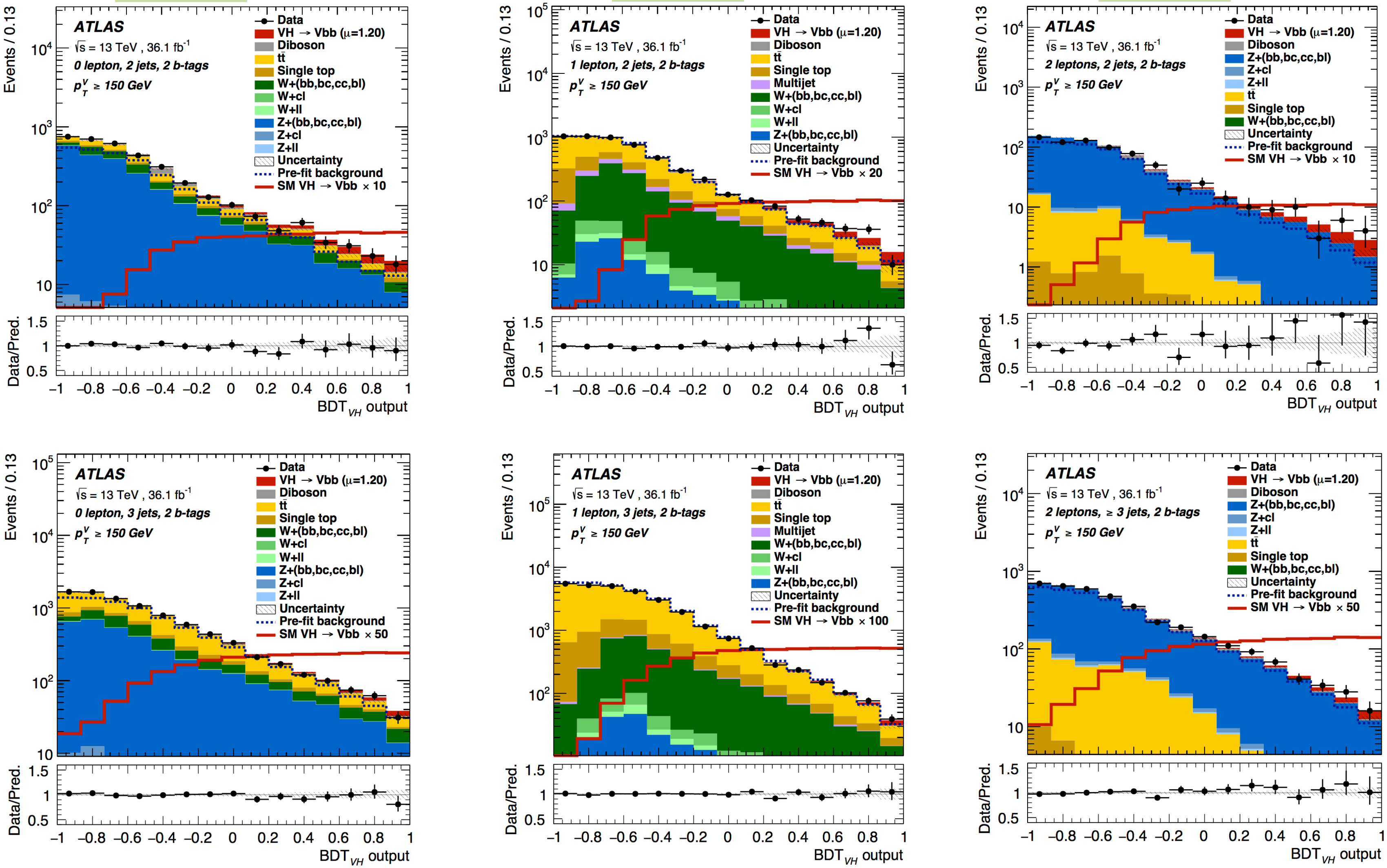
Boosted Decision Trees trained and classified for each signal region separately

Signal Regions ($p_T V > 150$ GeV)

0-lepton | 1-lepton | 2-lepton

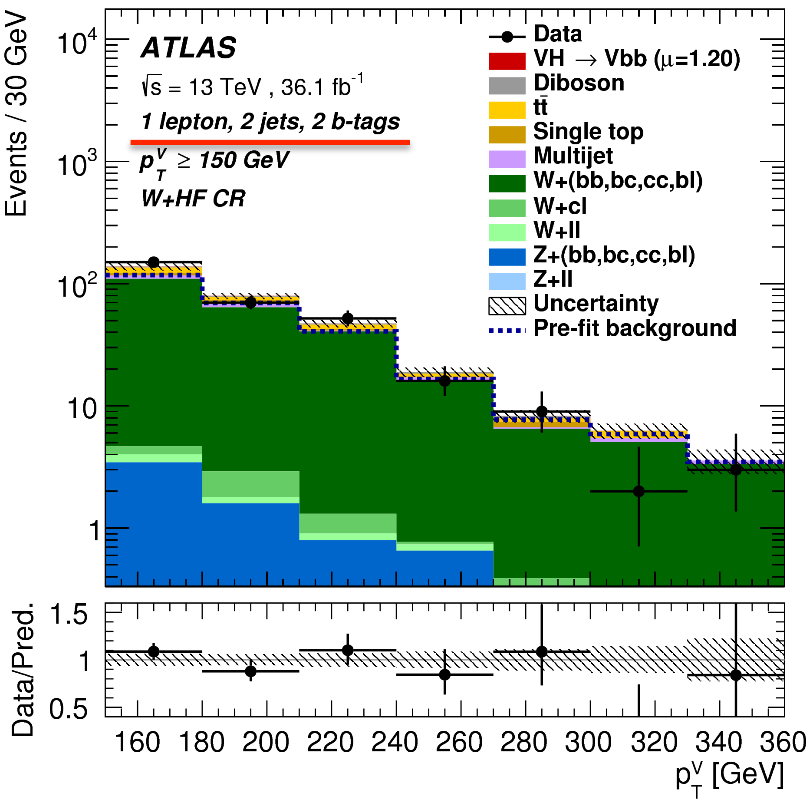
2-Jet SR

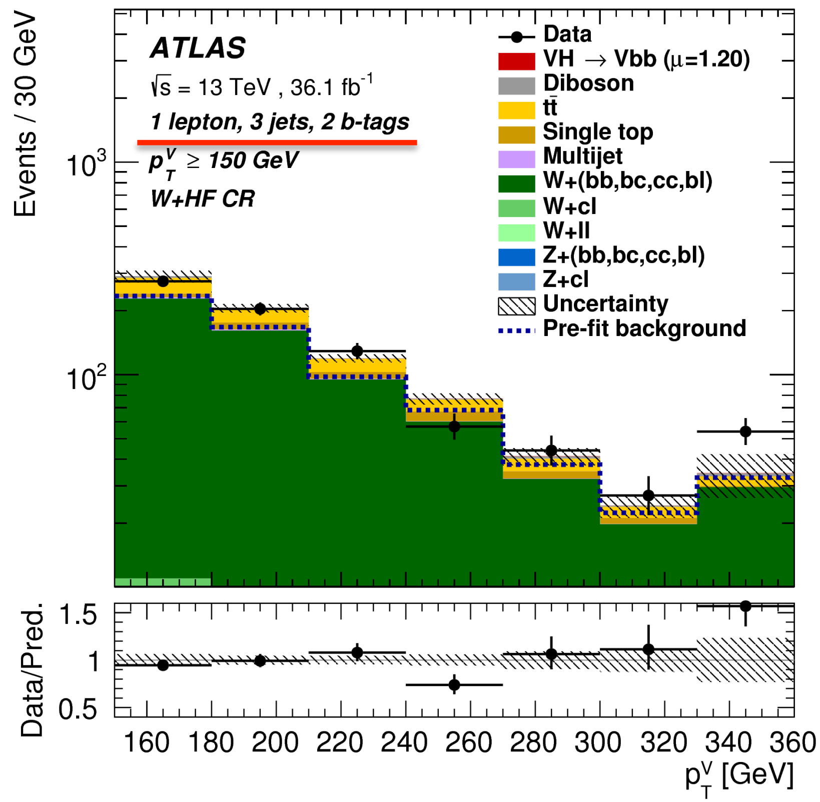
3-Jet (>=3J) SR



Control Regions: W+HF

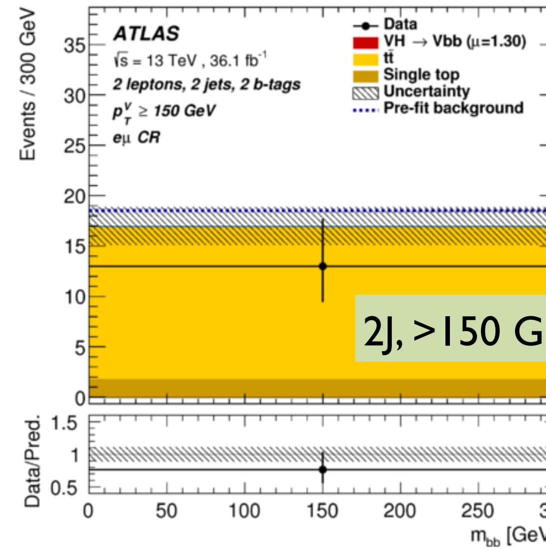
- Heavy flavor (HF): 2 jets from bb, bc, cc, or bl quark pairs
- Two additional selections after nominal cuts: m_{bb} < 75 GeV, m_{top} > 225 GeV
- Predicted purity: 75-78%





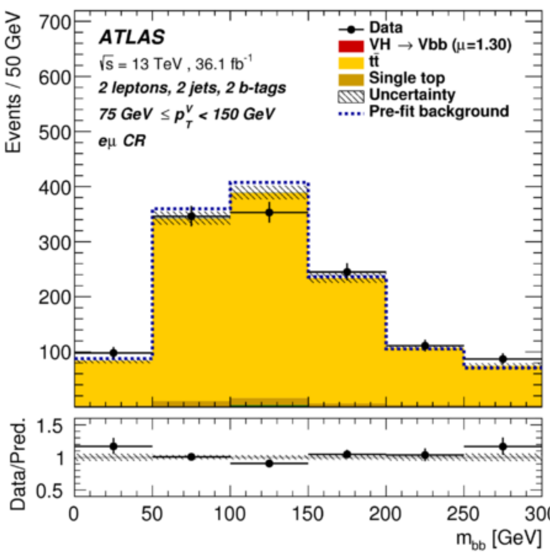
Control Regions: Ttbar

- Four ttbar CR's for the 2-lepton analysis, with eμ final state only
- More than 99% from single top and ttbar, 88-97% ttbar only

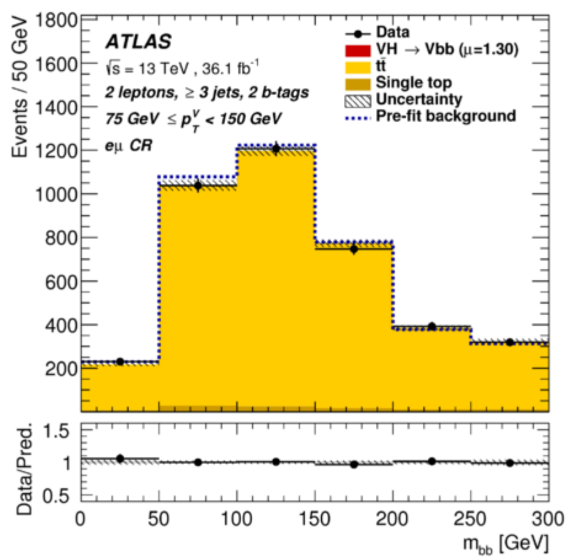


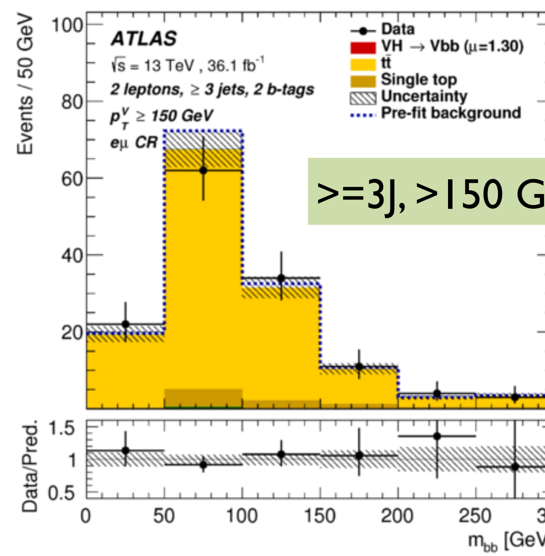
2J, >150 GeV

2J, [75, 150]GeV



>=3J, [75, 150]GeV





>=3J, >150 GeV

Systematic Uncertainties

- Experimental uncertainties
  - Dominant uncertainties: flavour-tagging efficiency correction factors, jet energy scale and the modeling of the jet energy resolution
  - Uncertainties from lepton's reconstruction, identification, isolation and trigger efficiencies with a small impact on the result
  - MET trigger and MET uncertainty from track's uncertainties
  - Luminosity: 2.1% for 2015 data, 3.4% for 2016
- Theoretical uncertainties
  - Samples and methods used
  - Backgrounds
  - Signal
- Impact of uncertainties on the final result

Theoretical Uncertainties: Samples

Nominal samples are generated with PowHeg-Box for signals and top backgrounds, and with Sherpa for V+jets and diboson.

Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order
Signal					
$qq \to WH \to \ell\nu b\bar{b}$	Powheg-Box v2 [37] + GoSam [40] + MiNLO [41, 42]	NNPDF3.0NLO$^{(\star)}$ [38]	Pythia8.212 [31]	AZNLO [39]	NNLO(QCD)+ NLO(EW) [43–49]
$qq \to ZH \to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	Powheg-Box v2 + GoSam + MiNLO	NNPDF3.0NLO$^{(\star)}$	Pythia8.212	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$^{(\star)}$	Pythia8.212	AZNLO	NLO+ NLL [50–54]
Top quark					
$t\bar{t}$	Powheg-Box v2 [55]	NNPDF3.0NLO	Pythia8.212	A14 [56]	NNLO+NNLL [57]
s-channel	Powheg-Box v1 [58]	CT10 [59]	Pythia6.428 [60]	P2012 [61]	NLO [62]
t-channel	Powheg-Box v1 [58]	CT10f4	Pythia6.428	P2012	NLO [63]
Wt	Powheg-Box v1 [64]	CT10	Pythia6.428	P2012	NLO [65]
Vector boson + jets					
$W \to \ell\nu$	Sherpa 2.2.1 [34, 66, 67]	NNPDF3.0NNLO	Sherpa 2.2.1 [68, 69]	Default	NNLO [70]
$Z/\gamma^* \to \ell\ell$	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					
WW	Sherpa 2.1.1	CT10	Sherpa 2.1.1	Default	NLO
WZ	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
ZZ	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO

Fixed: mH = 125 GeV, Br(H→bb) = 58%, mtop = 172. 5 GeV

Theoretical Uncertainties Estimation

- Variations for Powheg + Pythia samples
  - Alternative parton shower Powheg + Herwig++
  - Different matrix element Madgraph_aMC@NLO + Pythia
  - Increase or decrease amount of radiation (corresponding to scale variations)

- Variations for Sherpa samples
  - Scale of renormalization, factorization, or Parton shower/resummation: half or twice of the nominal scale
  - CKKW merging scale from 30 to 15 GeV
  - PDF + α_s variations
  - Comparison to another ME generator/merging approach (e.g. for W+jets to Madgraph5_aMC@NLO)

Theoretical Uncertainties: Top

$t\bar{t}$ (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), 35% (Wt)
Acceptance 3-jet	20% (t-channel), 41% (Wt)
m_{bb}, p_T^V	S (t-channel, Wt)

Shape uncertainty

Process	Normalisation factor
$t\bar{t}$ 0- and 1-lepton	0.90 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	0.97 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	1.04 ± 0.06

Extrapolation uncertainties for top:

- between 0/1 leptons,
- between 2/3-jet regions
- between W+HF CR/SR

Theoretical Uncertainties: W/Z+jets

	Z + jets
$Z + ll$ normalisation	18%
$Z + cl$ normalisation	23%
$Z + bb$ 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%
$W + bb$ 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

V+ll/cl: <1% contribution

Process	Normalisation factor
W + HF 2-jet	1.22 ± 0.14
W + HF 3-jet	1.27 ± 0.14
Z + HF 2-jet	1.30 ± 0.10
Z + HF 3-jet	1.22 ± 0.09

Uncertainty in extrapolation to 0-lepton final state

Uncertainty in extrapolation from CR to SR

Theoretical Uncertainty: Diboson

ZZ	
Normalisation	20%
0-to-2 lepton ratio	6%
Acceptance from scale variations (var.)	10 – 18% (Stewart–Tackmann jet binning method)
Acceptance from PS/UE var. for 2 or more jets	5.6% (0-lepton), 5.8% (2-lepton)
Acceptance from PS/UE var. for 3 jets	7.3% (0-lepton), 3.1% (2-lepton)
m_{bb}, p_T^V, from scale var.	S (correlated with *WZ* uncertainties)
m_{bb}, p_T^V, from PS/UE var.	S (correlated with *WZ* uncertainties)
m_{bb}, from matrix-element var.	S (correlated with *WZ* uncertainties)
WZ	
Normalisation	26%
0-to-1 lepton ratio	11%
Acceptance from scale var.	13 – 21% (Stewart–Tackmann jet binning method)
Acceptance from PS/UE var. for 2 or more jets	3.9%
Acceptance from PS/UE var. for 3 jets	11%
m_{bb}, p_T^V, from scale var.	S (correlated with *ZZ* uncertainties)
m_{bb}, p_T^V, from PS/UE var.	S (correlated with *ZZ* uncertainties)
m_{bb}, from matrix-element var.	S (correlated with *ZZ* uncertainties)
WW	
Normalisation	25%

Theoretical Uncertainties: Signal

- Overall uncertainties estimated according to LHC Higgs Cross Section WG
- Acceptance uncertainties estimated by Stewart-Tackman jet binning method
- Uncertainty from PS/UE has the dominant effect, mainly due to the difference between Pythia8 and Herwig7 parton showers

	Signal
Cross-section (scale)	0.7% (qq), 27% (gg)
Cross-section (PDF)	1.9% ($qq \to WH$), 1.6% ($qq \to ZH$), 5% (gg)
Branching ratio	1.7 %
Acceptance from scale variations (var.)	2.5 – 8.8% (Stewart–Tackmann jet binning method)
Acceptance from PS/UE var. for 2 or more jets	10 – 14% (depending on lepton channel)
Acceptance from PS/UE var. for 3 jets	13%
Acceptance from PDF+α_S var.	0.5 – 1.3%
m_{bb}, p_T^V, from scale var.	S
m_{bb}, p_T^V, from PS/UE var.	S
m_{bb}, p_T^V, from PDF+α_S var.	S
p_T^V from NLO EW correction	S

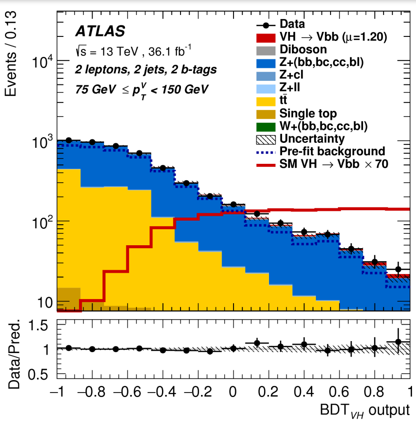
Impact of Systematics Uncertainties

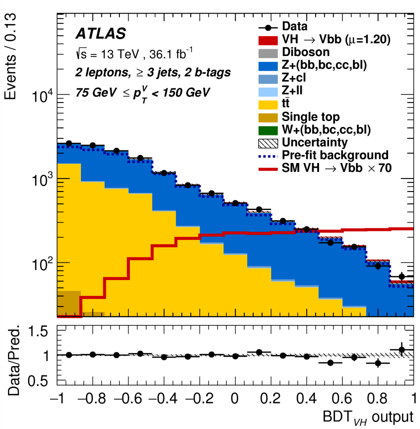
Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
E_T^{miss}		0.03
Leptons		0.01
b-tagging	b-jets	0.09
	c-jets	0.04
	light jets	0.04
	extrapolation	0.01
Pile-up		0.01
Luminosity		0.04
Theoretical and modelling uncertainties		
Signal		0.17
Floating normalisations		0.07
Z + jets		0.07
W + jets		0.07
$t\bar{t}$		0.07
Single top quark		0.08
Diboson		0.02
Multijet		0.02
MC statistical		0.13

- Signal strength: $\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$
- A simultaneous fit to all SR's and CR's can be used to estimate impacts of uncertainties, when all experimental and theoretical sys. considered.
- The analysis is limited by systematical uncertainties: 0.31 (syst.) vs. 0.24 (stat)
- The main sources of uncertainties are: signal modeling, background modeling, MC statistics, b-tagging.

Statistical Analysis Strategy

A simultaneous likelihood fit is performed on 8 signal regions and 6 control regions: 6 SRs (page 9); 4 top CR (page 11); 2 SRs + 2 CRs here

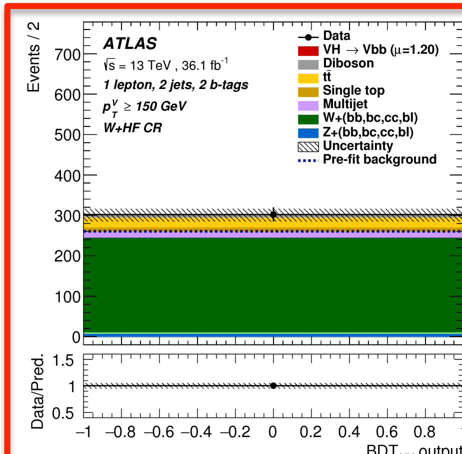


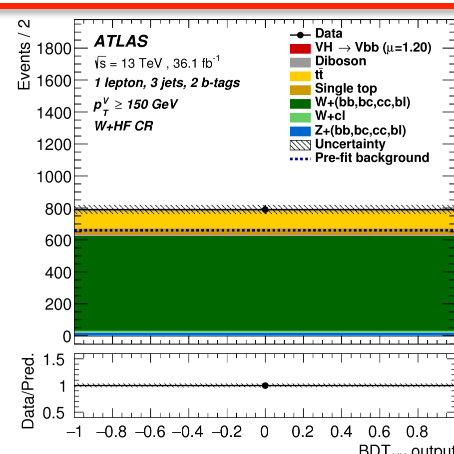


Channel	SR/CR	Categories			
		$75\text{ GeV} < p_T^V < 150\text{ GeV}$		$p_T^V > 150\text{ GeV}$	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	BDT	BDT
1-lepton	SR			BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	W + HF CR	-	-	Yield	Yield
2-lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield	m_{bb}

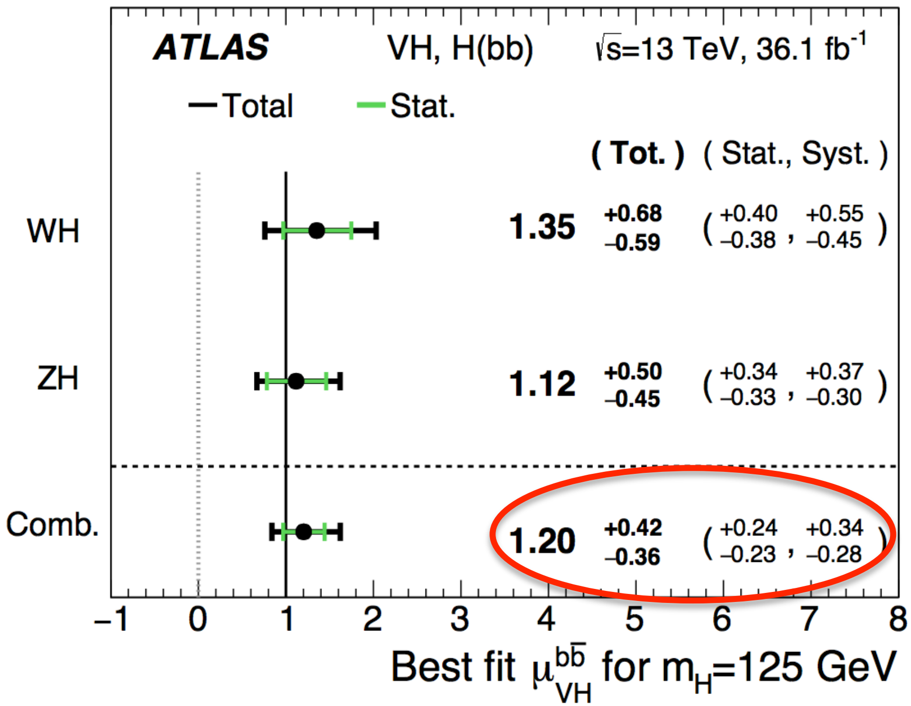
8 SRs

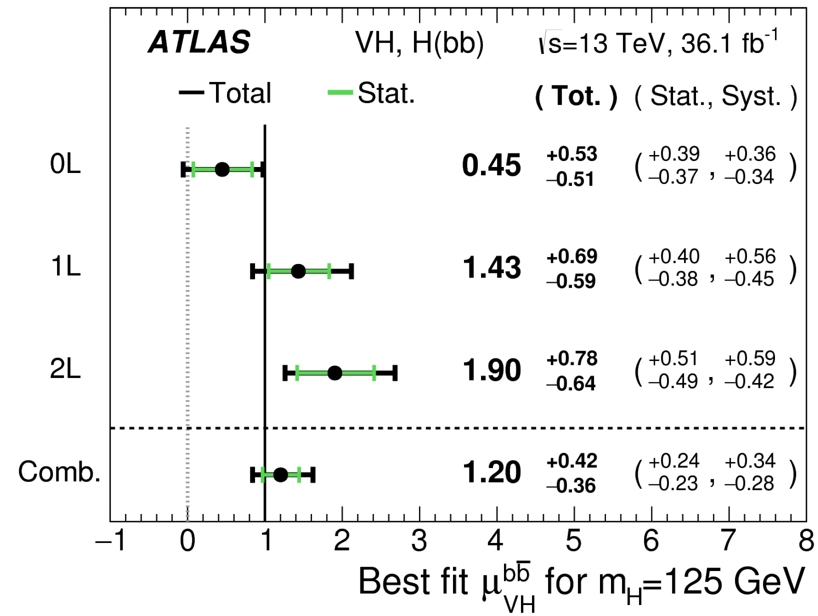
6 CRs





Results with 13 TeV Data (1)





$$\sigma(WH) \times B(H \to b\bar{b}) = 1.08^{+0.54}_{-0.47} \text{ pb}$$

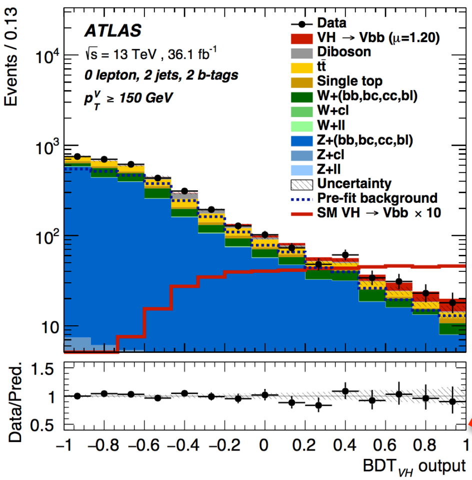
$$\sigma(ZH) \times B(H \to b\bar{b}) = 0.57^{+0.26}_{-0.23} \text{ pb}$$

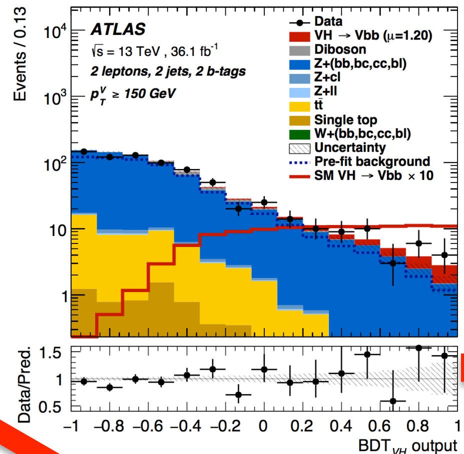
Significance with 36.1 fb^{-1} data:

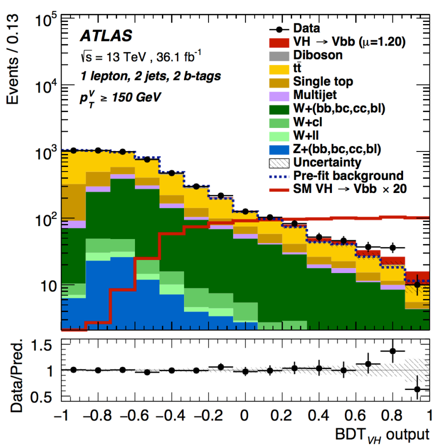
3.5σ observed (3.0σ expected)

Results with 13 TeV Data (2)

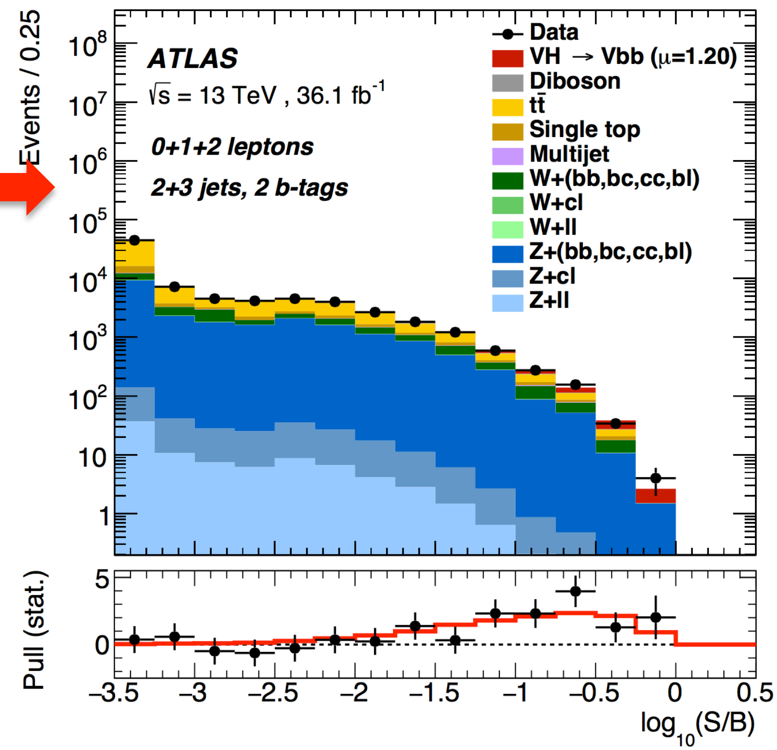
Final-discriminant bins in all regions are combined into bins of log(S/B), with the fitted signal being S and the fitted background B







14 SR+CR regions



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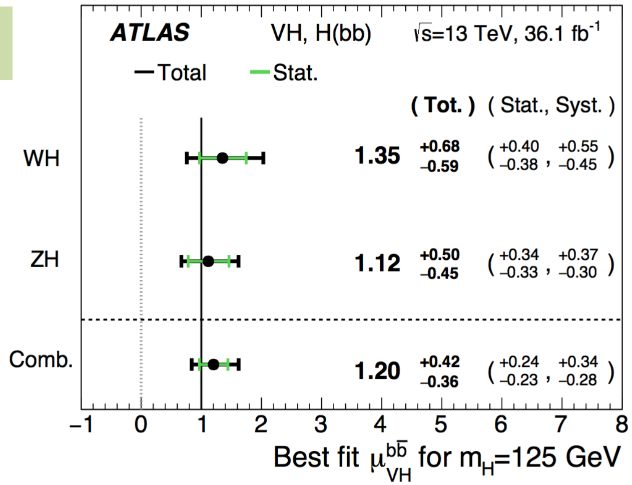
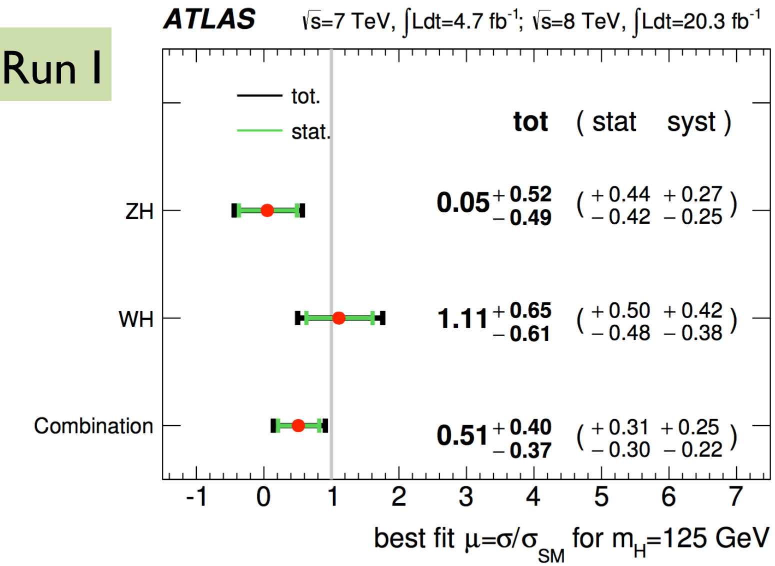
Results from Run I + Run II

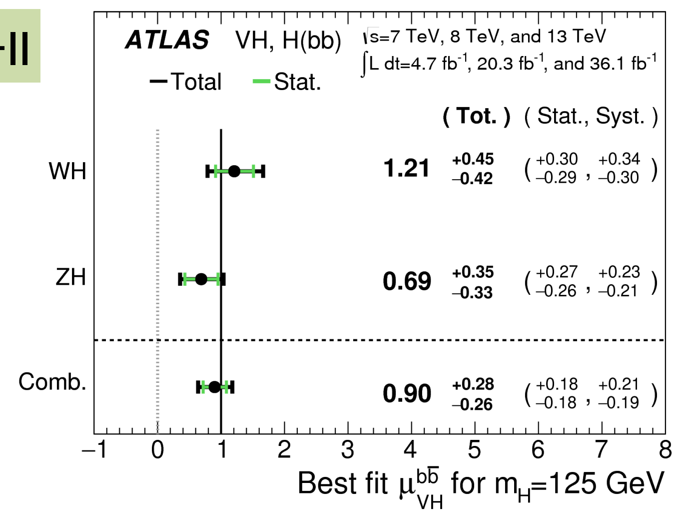
Run II



Run I



Run I+II



Significance with Run I + Run II:

3.6σ observed (4.0σ expected)

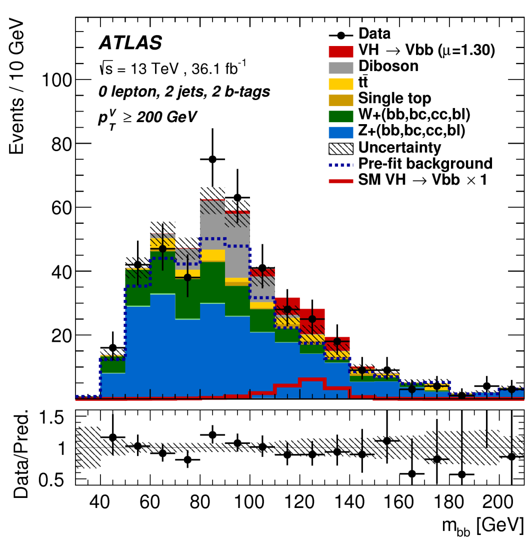
Compatible with SM within 0.4σ.

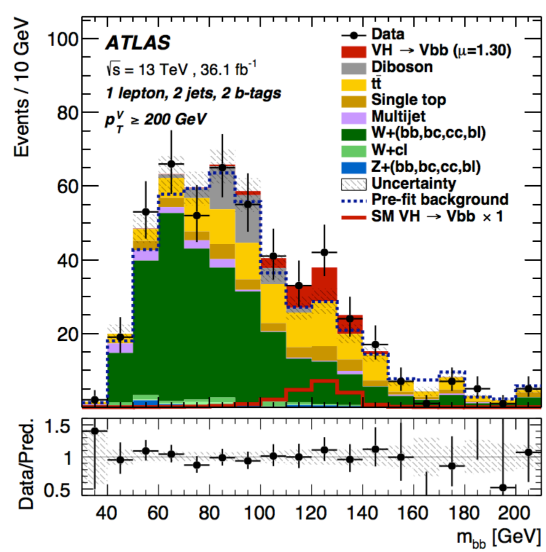
Cross-check: Dijet Mass Analysis (1)

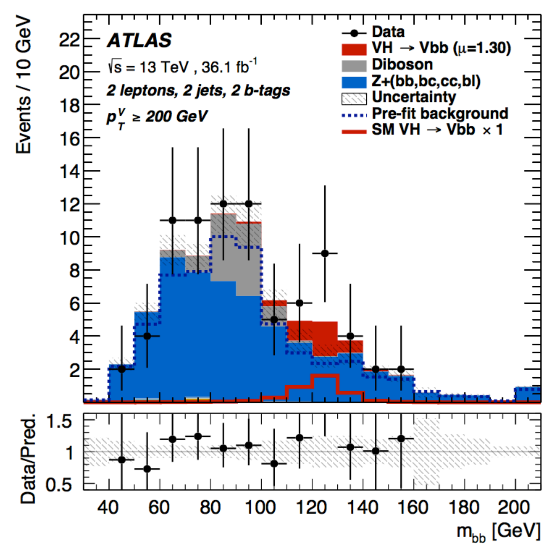
- ✧ Additional selections on top of the MVA analysis
- ✧ 18 analysis regions with an additional p_TV slice (>200 GeV)

Channel			
Selection	0-lepton	1-lepton	2-lepton
m_T^W	-	$<$ 120 GeV	-
$E_T^{miss}/\sqrt{S_T}$	-	-	$< 3.5\sqrt{\text{GeV}}$
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

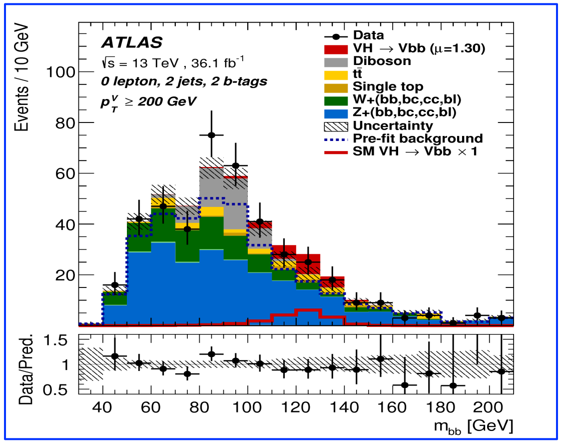
VH, H→bb	Dijet mass	nominal (BDT)
μ	$\mu = 1.30^{+0.28}_{-0.27}(\text{stat.})^{+0.37}_{-0.29}(\text{syst.})$	$\mu = 1.20^{+0.24}_{-0.23}(\text{stat.})^{+0.34}_{-0.28}(\text{syst.})$
Significance	3.5σ obs. (2.8σ exp.)	3.5σ obs. (3.0σ exp.)

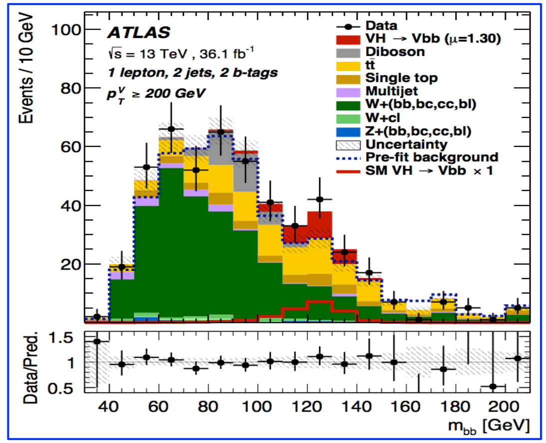


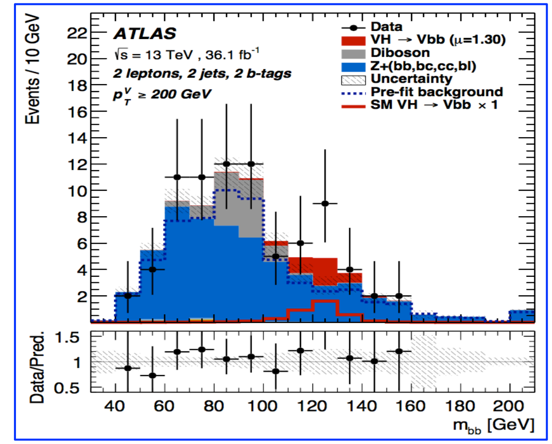




Cross-check: Dijet Mass Analysis (2)



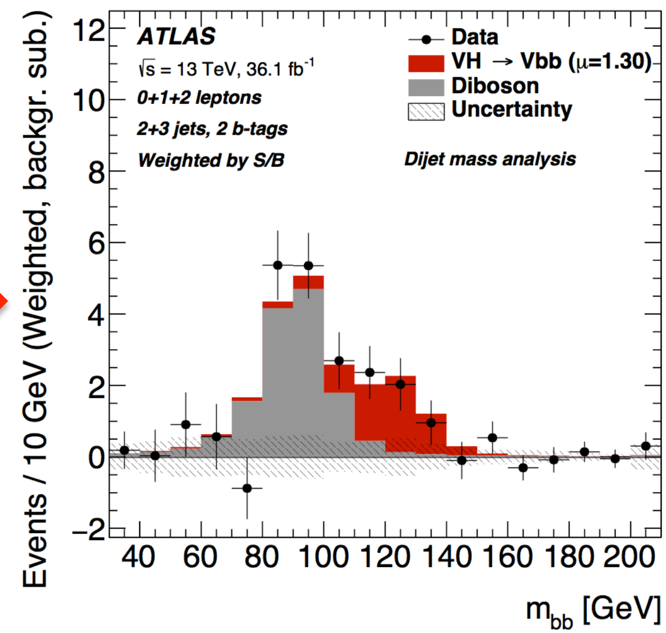




For the mbb distr. in 14 signal regions:

1 Merged all SR regions, weighted by their respective value of the ratio of fitted Higgs boson signal and background yields (S/B)

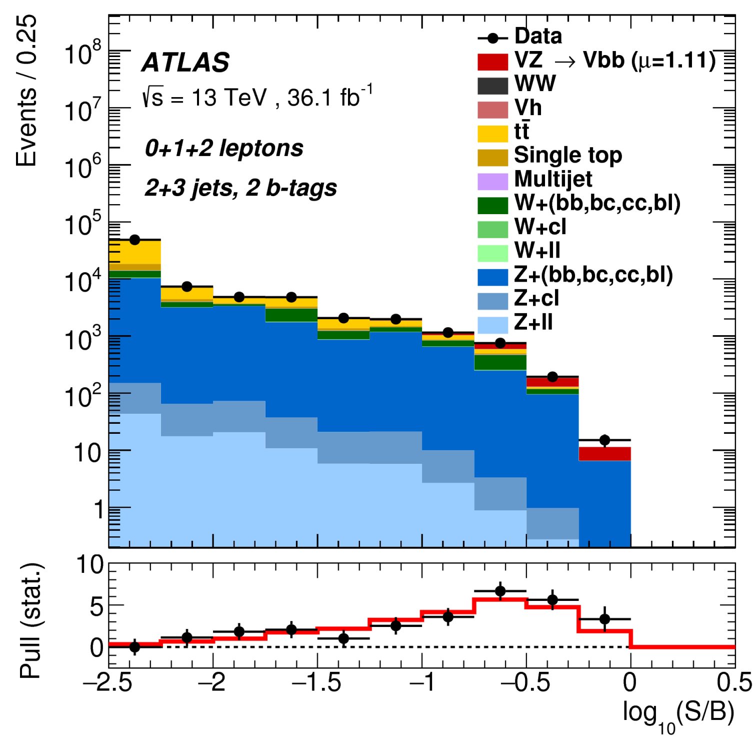
2 Subtracted all backgrounds except for the (W/Z)Z diboson processes



Cross-check: VZ, Z→bb

- Similar analysis as H→bb, except VZ as signal and the VH as one background channel
- BDT training separately for each region with VZ as the signal

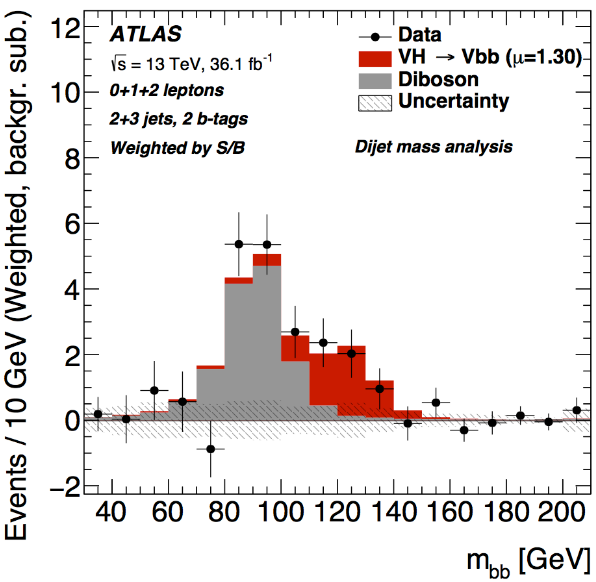
VZ, Z→bb	BDT
μ	$\mu_{VZ} = 1.11^{+0.12}_{-0.11}(\text{stat.})^{+0.22}_{-0.19}(\text{syst.})$
Significance	5.8σ obs. (5.3σ exp.)

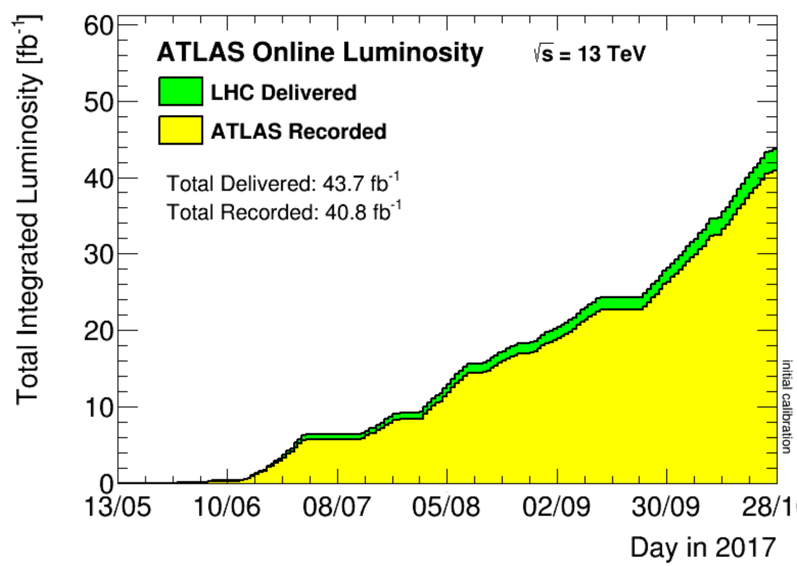


The result agrees with the SM prediction

Summary

- The ATLAS experiment obtained its first evidence of VH, H→bb with 3.6σ (4.0σ expected) with Run II (36 fb^{-1}) + Run I data.
- The results agrees with the SM prediction, with an uncertainty of ~30%.
- With the additional data being and to be collected in Run II, observation and more precise measurements are in sight.





Thanks!

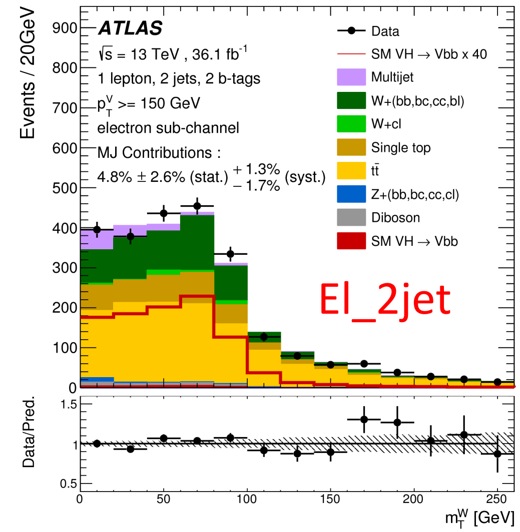
Event Selection

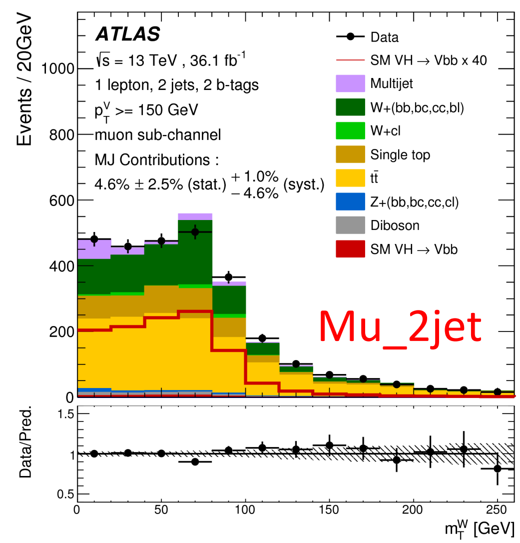
Selection	0-lepton	1-lepton: e sub-channel	1-lepton: μ sub-channel	2-lepton
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton
Leptons	0 loose leptons with $p_{\mathrm{T}} > 7$ GeV	1 tight electron $p_{\mathrm{T}} > 27$ GeV	1 medium muon $p_{\mathrm{T}} > 25$ 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 or 3 jets			Exactly 2 or ≥ 3 jets
Jet p_{T}	> 20 GeV			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
H_{T}	> 120 (2 jets), >150 GeV (3 jets)	–		–
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{\mathrm{jets}})]$	$> 20°$ (2 jets), $> 30°$ (3 jets)	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{bb})$	$> 120°$	–		–
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140°$	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{E}_{\mathrm{T,trk}}^{\mathrm{miss}})$	$< 90°$	–		–
p_{T}^{V} regions	> 150 GeV			(75, 150] GeV, > 150 GeV
Signal regions	✓	$m_{bb} \geq 75$ GeV or $m_{\mathrm{top}} \leq 225$ GeV		Same-flavour leptons Opposite-sign charge ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{\mathrm{top}} > 225$ GeV		Different-flavour leptons

MJ Estimation in 1-lepton Channel

- **Dedicated isolation WPs to further reduce MJ background**
  - Topoetcone20 <3.5GeV for electron channel;
  - Ptcone20<1.25GeV for muon channel
- **Use isolation-inverted region in 1 tag regions to estimate MJ shape**
- **Fit to mTW in 2-tag signal regions to extract MJ normalization**
  - The template for the EW contribution in the signal region is obtained directly from MC predictions
- **Main assumption: shape in isolation-inverted regions are the same as that in SRs. Systematics assigned to cover the difference.**
- **Estimated separately in the electron and muon sub-channels, and in the 2- and 3-jet categories, using similar procedures**

	MJ contamination (2-jet)	MJ contamination (3-jet)
e-channel	4.8%	0.3%
mu-channel	4.6%	0.5%





Signal Cross Section and Acceptance

$m_H = 125$ GeV at $\sqrt{s} = 13$ TeV				
Process	Cross-section × B [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$qq \to ZH \to \ell\ell b\bar{b}$	29.9	< 0.1	< 0.1	7.0
$gg \to ZH \to \ell\ell b\bar{b}$	4.8	< 0.1	< 0.1	15.7
$qq \to WH \to \ell\nu b\bar{b}$	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	–	–