Observation of the Higgs boson decays to beauty quarks

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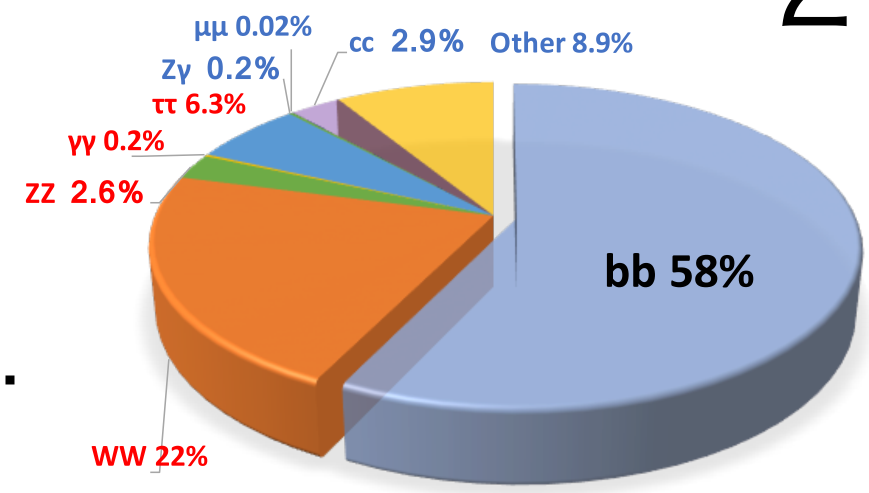
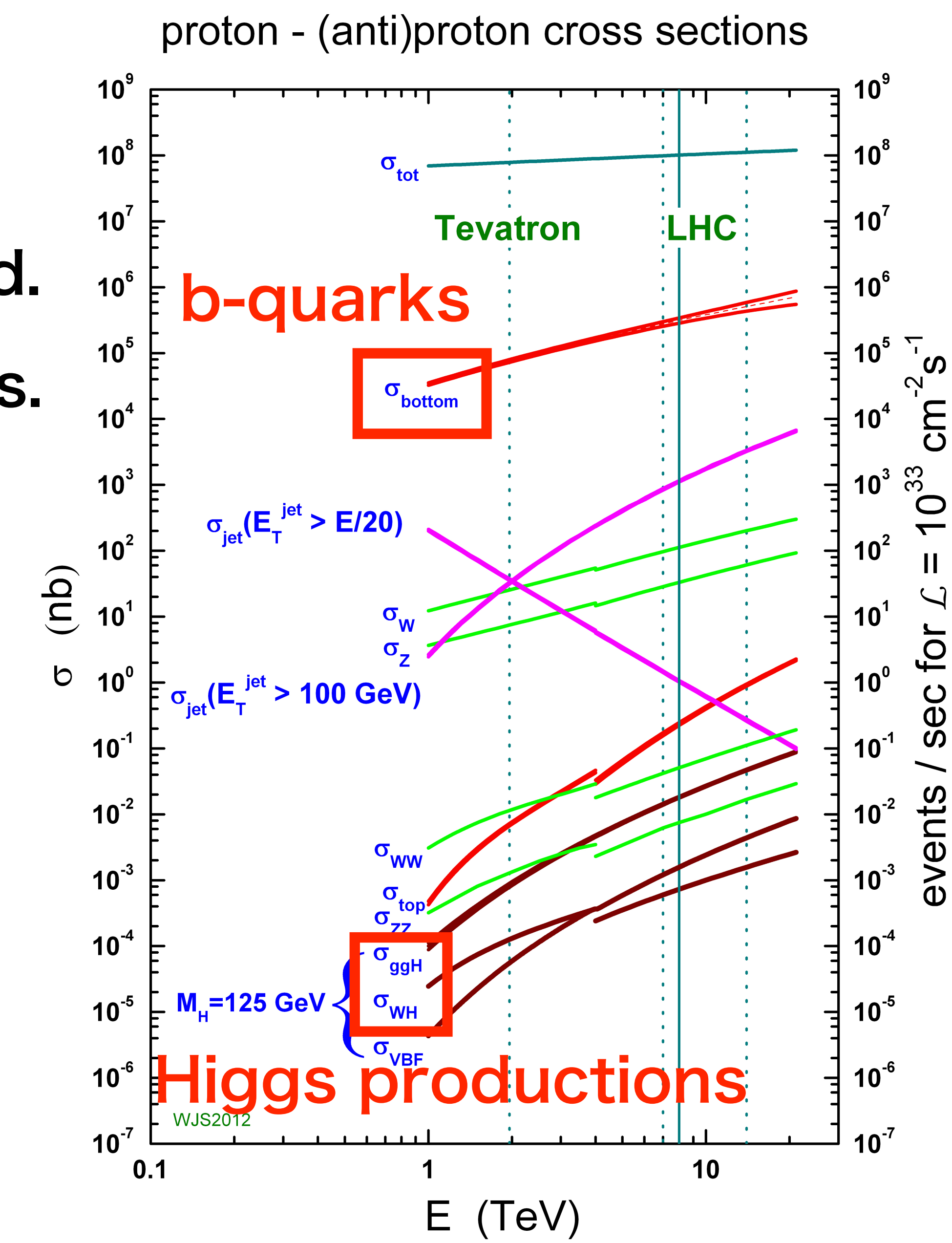
On behalf of the ATLAS Collaboration

Introduction

- H→bb decay
  - Largest branching fraction of ~58 %.
  - Direct measurement of bottom Yukawa coupling.
  - Allows the overall Higgs bosons width to be constrained



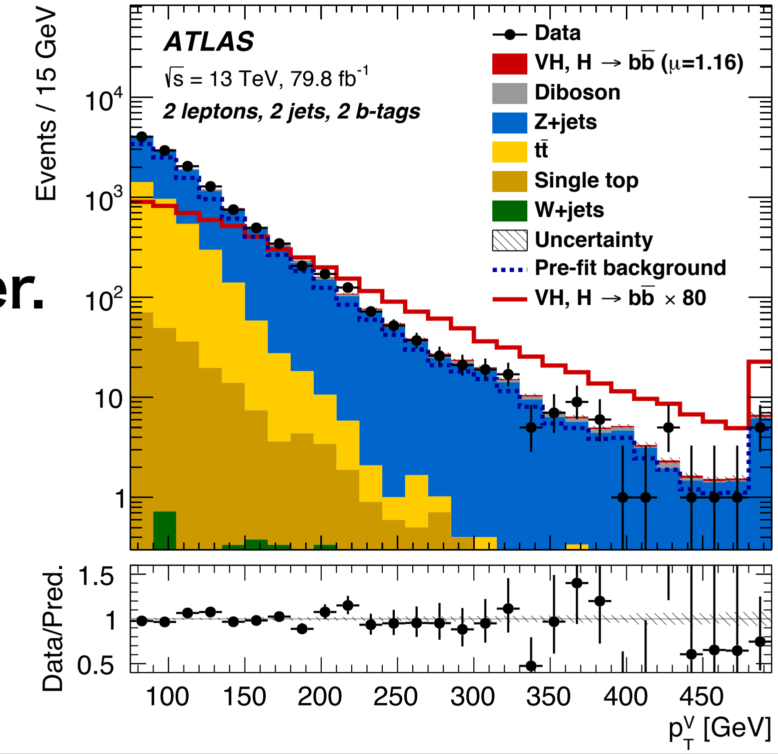
- ggH production: bb final states are difficult to trigger on and discriminate large QCD background.
  - Accessible in ttH, VBF and VH production modes.
  - The VH processes have the highest sensitivity.



V: Vector boson
VBF: Vector Boson Fusion
VH: Vector Boson + Higgs boson
ggH: gluon gluon → Higgs boson

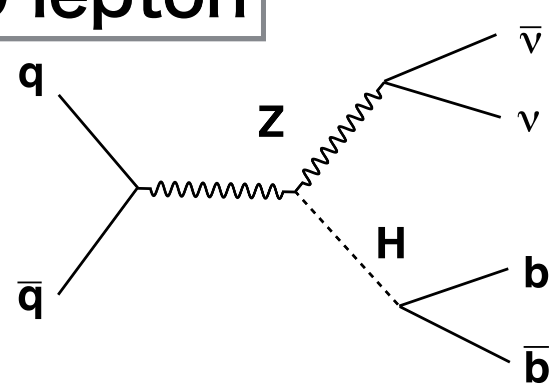
Event selection for VH production

- To suppress large backgrounds:
  - Leptonic decays of weak bosons reduce multi-jet background and provide distinct signature for the trigger.
  - Focus on high p_T^V regime since signal is produced with harder distribution than backgrounds.
- Three analysis categories: 0, 1 or 2 electrons or muons.
- 8 Signal Regions (SRs) are defined.



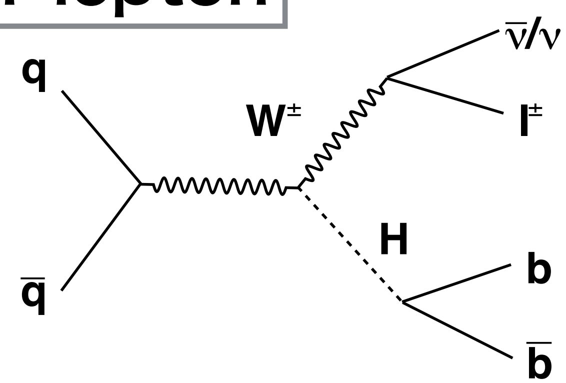
p_T^V = transverse momentum of vector bosons

0 lepton



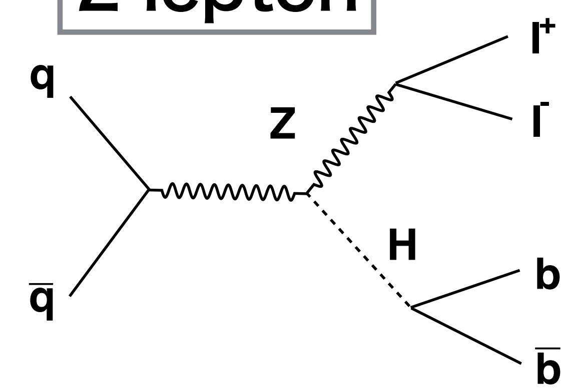
- Missing E_T trigger
- Missing E_T > 150 GeV
- 2 b-tagged
- 2 SRs = (2 jets, 3 jets)

1 lepton



- Single electron or Missing E_T trigger
- One electron or muon
- p_T^W > 150 GeV
- 2 b-tagged
- 2 SRs = (2 jets, 3 jets)

2 lepton



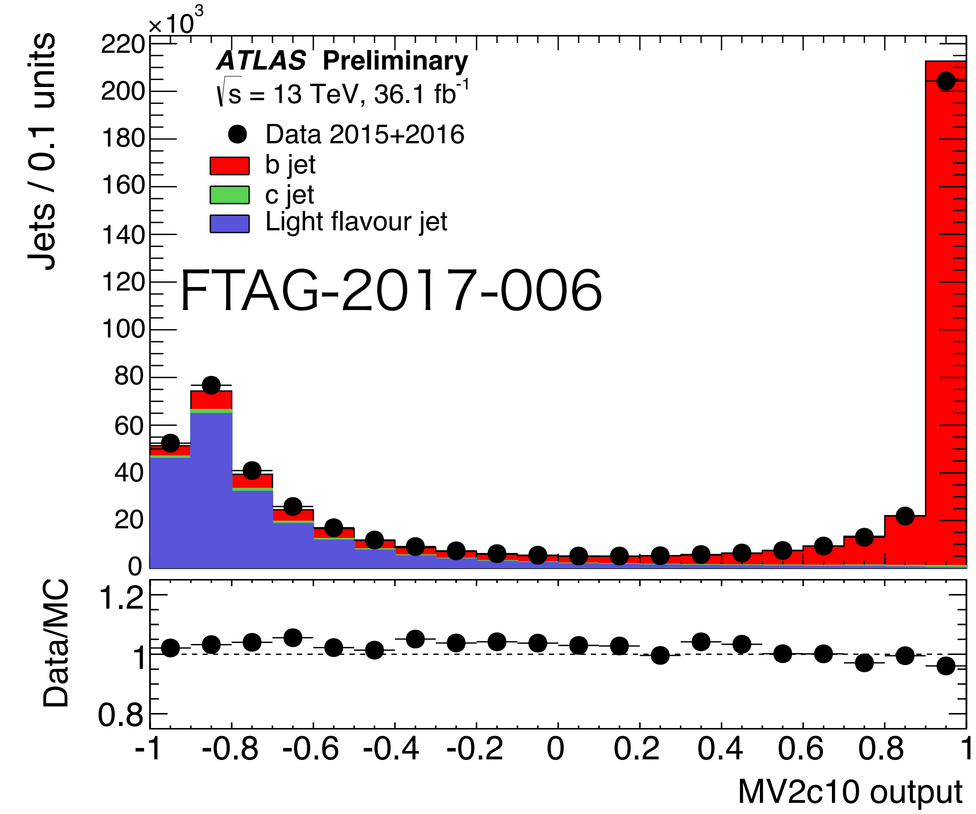
- Single electron or muon trigger
- ee or μμ pair
- $91 < m_{ll} < 101$ GeV
- p_T^Z > 75 GeV
- 2 b-tagged
- 4 SRs: (#jets) × (p_T^Z) =(2 , ≧3)×(75-150 GeV, 150-∞ GeV)

b-jet energy & tagging

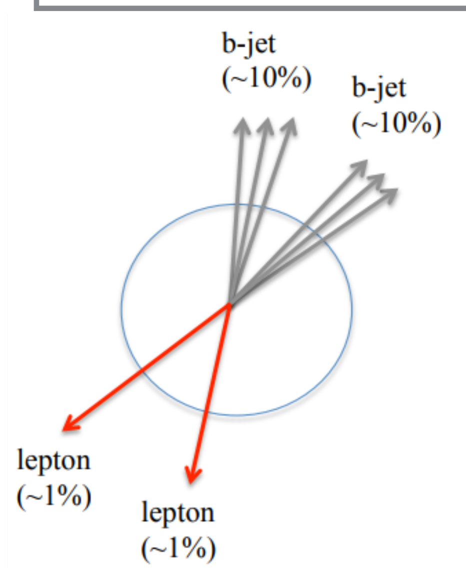
- b-jet tagging
  - Multivariate technique combines information on secondary vertices and track's impact parameters.
  - 70% b-jet tagging efficiency.
  - Mis-tag efficiency for c/light jets are ~13%/~0.3%.

- b-jet energy correction
  - Muon energy recovery for semi-leptonic decay of b-hadrons.
  - Scale b-jet energy by derived factors to recover neutrino (in semi-leptonic decay) and out-of-cone energy.
  - Kinematic fit
    - 2 lepton only
    - Balance of dilepton and two b-jets momenta in the plane transverse to the collision axis.

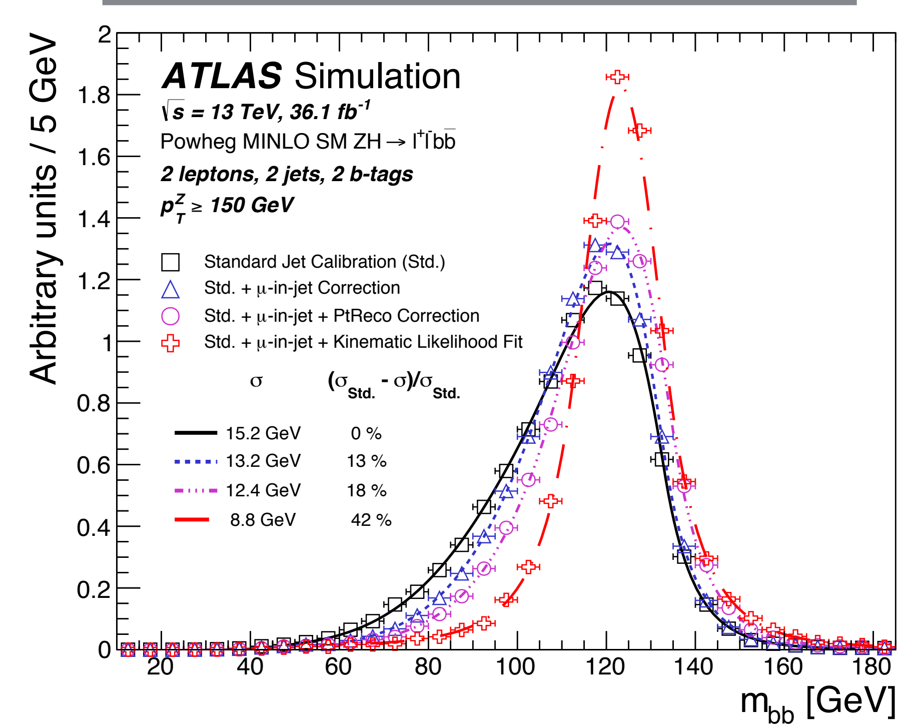
b-tagging discriminant



Kinematic fit



dijet mass resolution



Background components

- **Dominant backgrounds after event selection:**

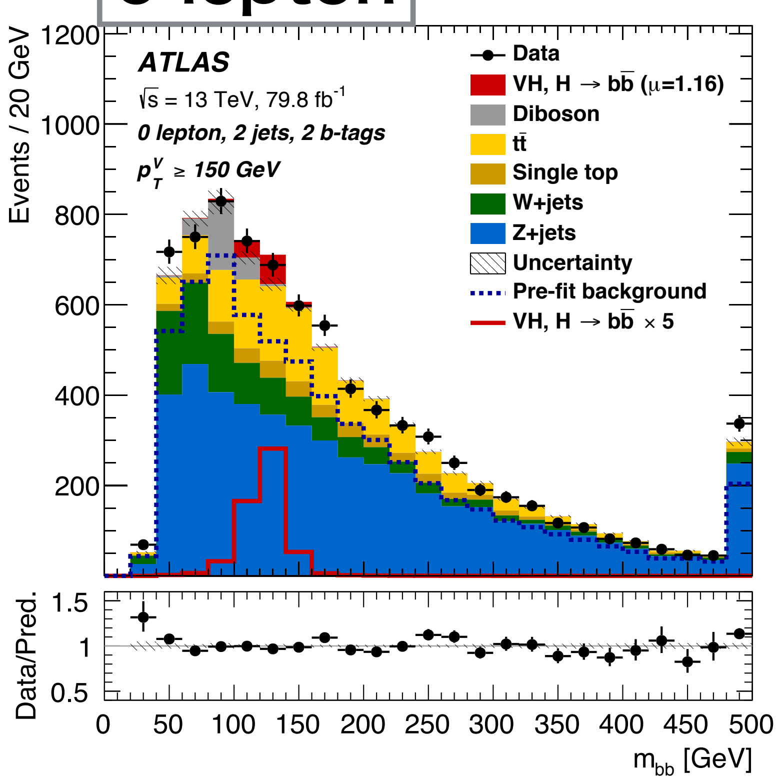
Signal — **VH, H → $b\bar{b}$**

Resonant → used as validation — **Diboson**

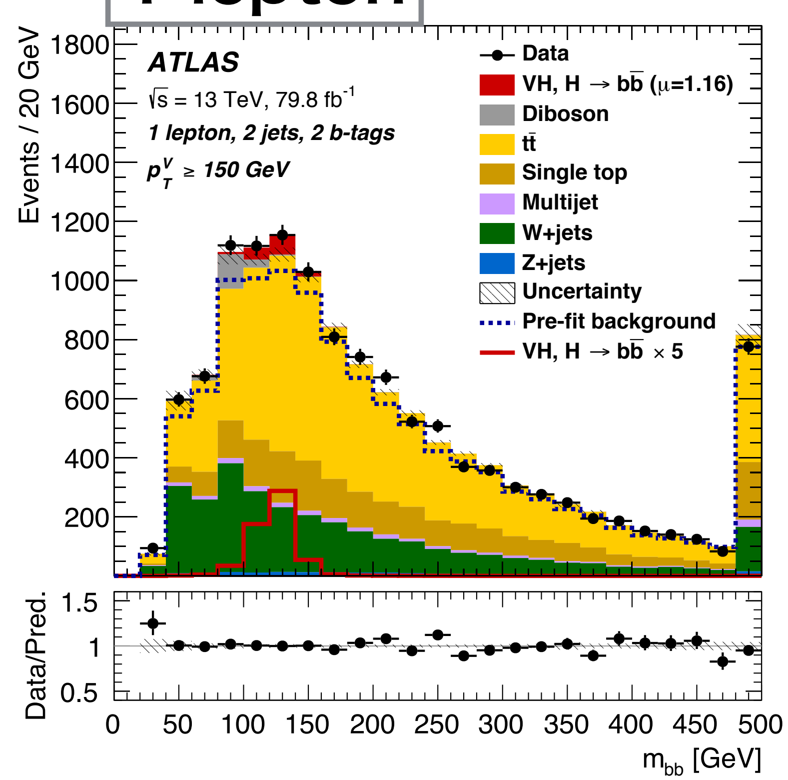
Non-resonant background — **$t\bar{t}$**, **Single top**, **Z+jets**, **W+jets**, **Multijet**

→ estimated by data-driven method

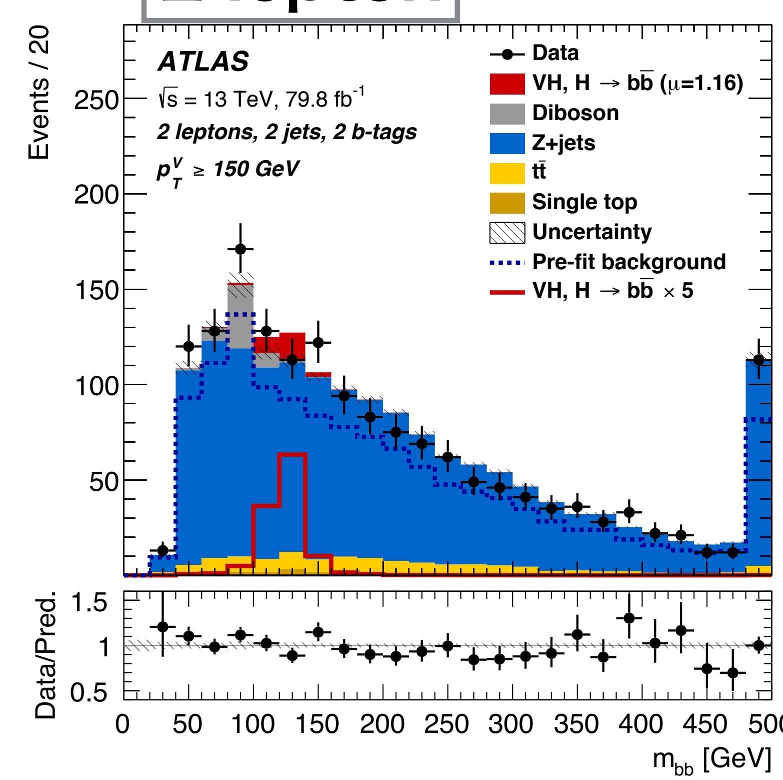
0 lepton



1 lepton



2 lepton

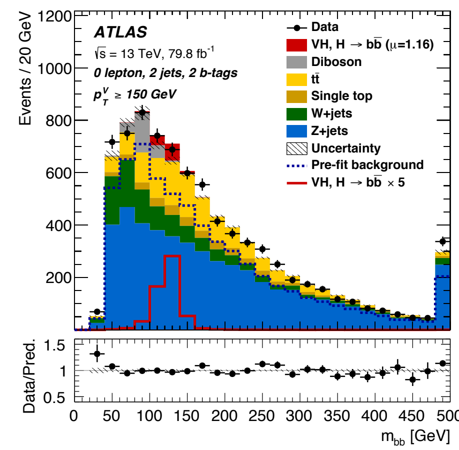


Multivariate analysis

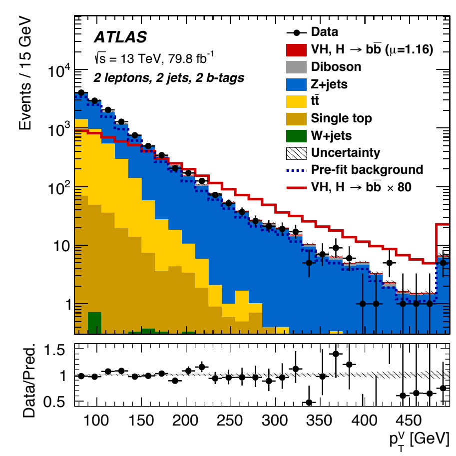
- To further enhance the sensitivity, Boosted Decision Trees (BDTs) are employed to take into account full event topology.
- BDT is separately trained for each SR selection.
- m_{bb}, ΔR_{bb} and p_T^V are most discriminating variables.

Inputs

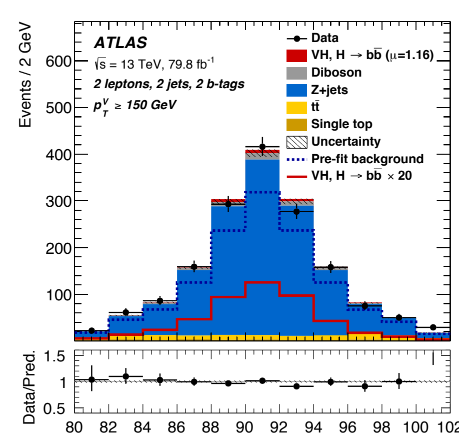
mbb



p_T^V

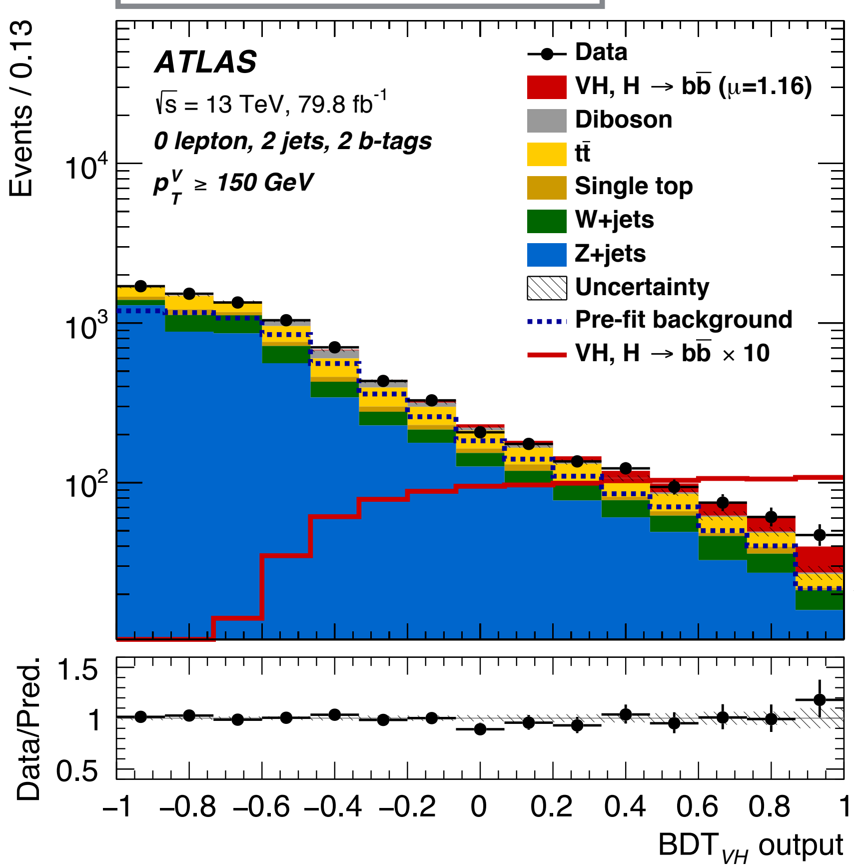


mll



BDT

Output score



List of input variables

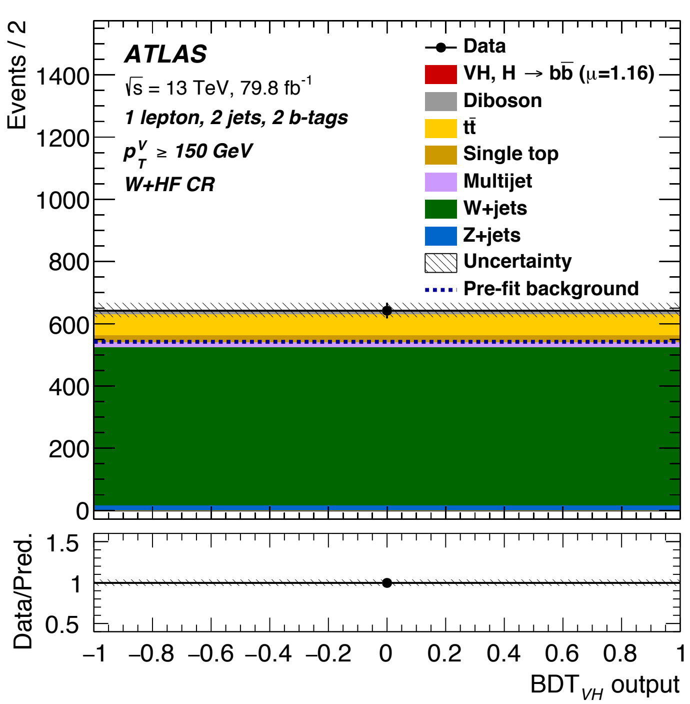
Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	$\times$	$\times$
E_T^{miss}	$\times$	$\times$	
$p_T^{b_1}$	$\times$	$\times$	$\times$
$p_T^{b_2}$	$\times$	$\times$	$\times$
m_{bb}	$\times$	$\times$	$\times$
$\Delta R(\vec{b_1}, \vec{b_2})$	$\times$	$\times$	$\times$
$\lvert\Delta\eta(\vec{b_1},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

Background model and Control Regions

- Theoretical uncertainties of backgrounds are mostly derived by comparing different MC generators and parameters.
- Experimental uncertainties, such as b-jet tagging efficiency uncertainty, are derived in calibration.
- 6 Control Regions (CRs) are defined and fitted simultaneously in the signal extraction procedure to estimate shapes and normalizations of backgrounds.

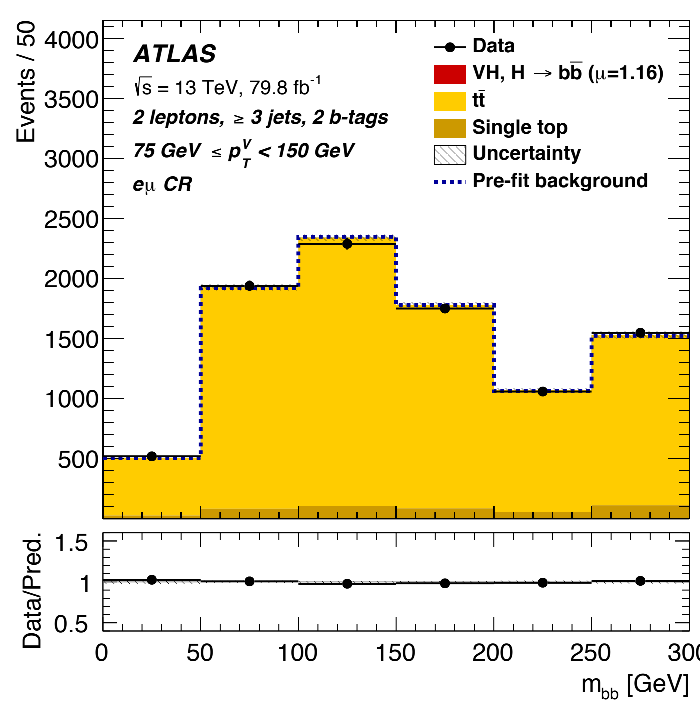
W+heavy flavor CR

- 1 lepton channel
- W+jets background
- M_{bb} < 75GeV and M_{top} > 225GeV
- 75-80 % purity
- Only yield are taken into account
- 2 CRs: 2/3 jets



Top eμ CR

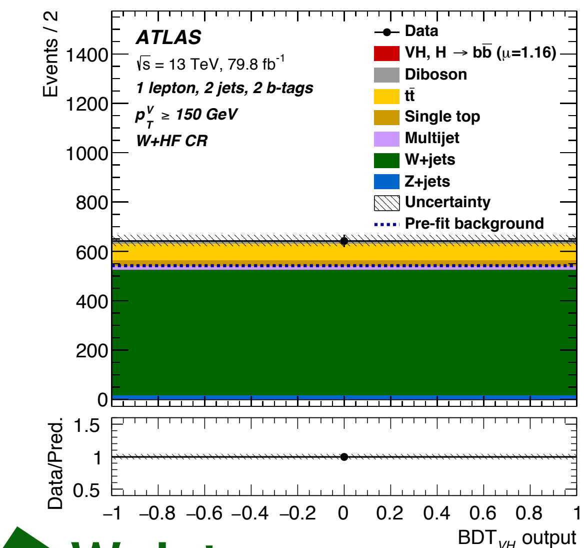
- 2 lepton channel
- ttbar and single top background
- eμ final state
- 99 % purity
- m_{bb} distribution
- 4 CRs: (75< p_T^V <150, p_T^V >150)×(2 jets, ≧3 jets)



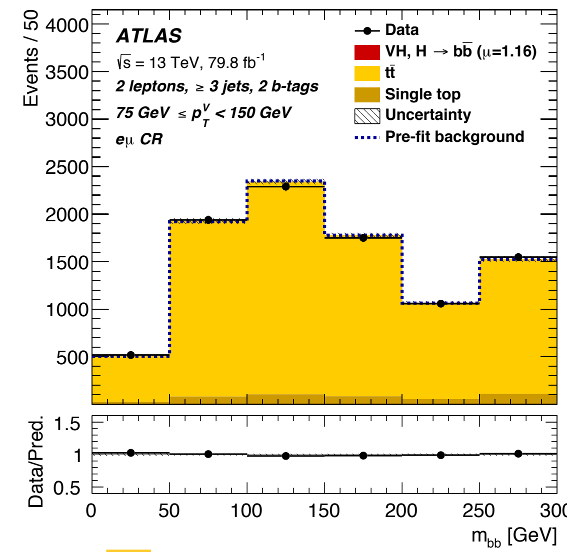
Signal extraction strategy

- Simultaneous profile likelihood fit performed on 8 SRs & 6 CRs.
  - Extracts signal strength (μ), constrains shape/normalization of backgrounds.
- BDT distributions are fitted for SRs.
- Backgrounds
  - CRs & low score bins of SRs provide constraints.
- Signal
  - High score bins are sensitive.

W+heavy flavor CR



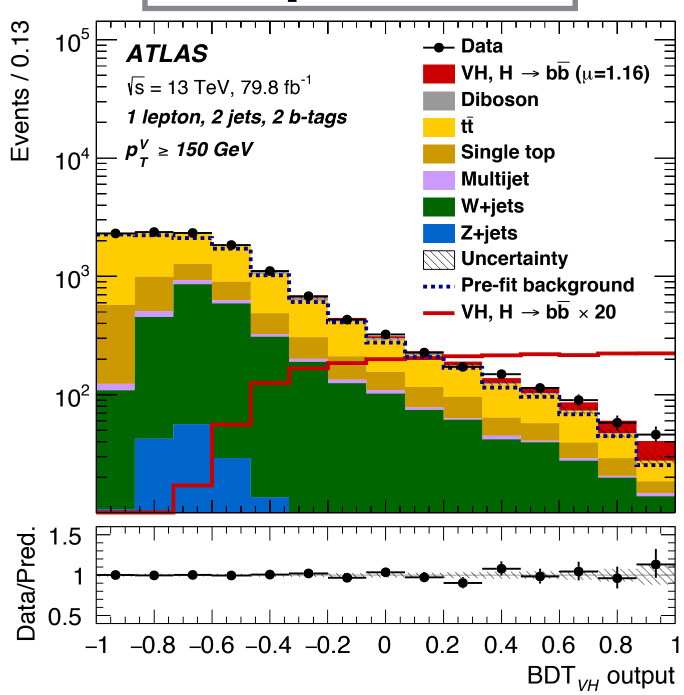
Top eμ CR



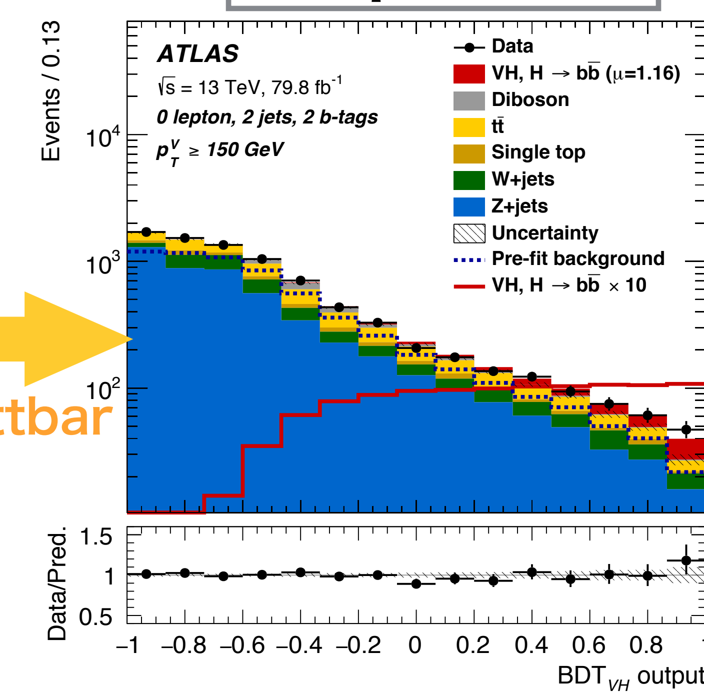
W+jets

ttbar

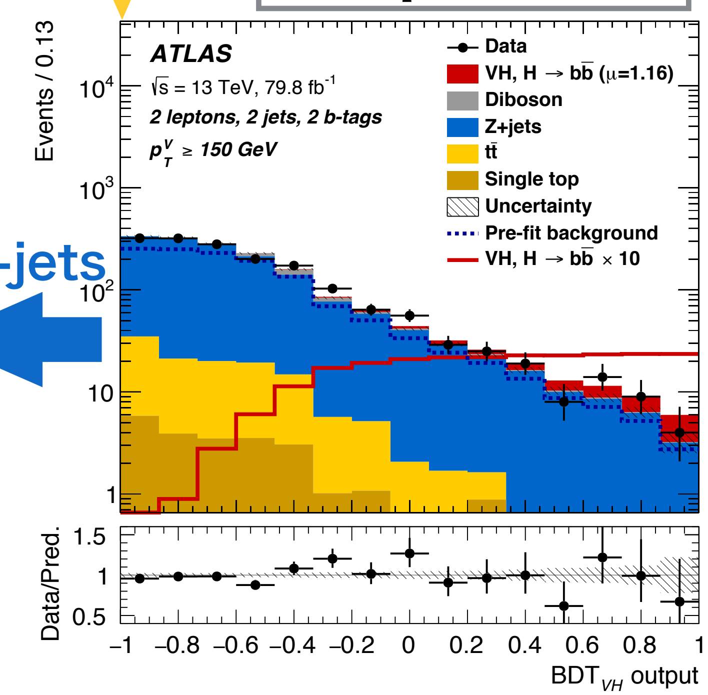
1 lepton SR



0 lepton SR



2 lepton SR



ttbar

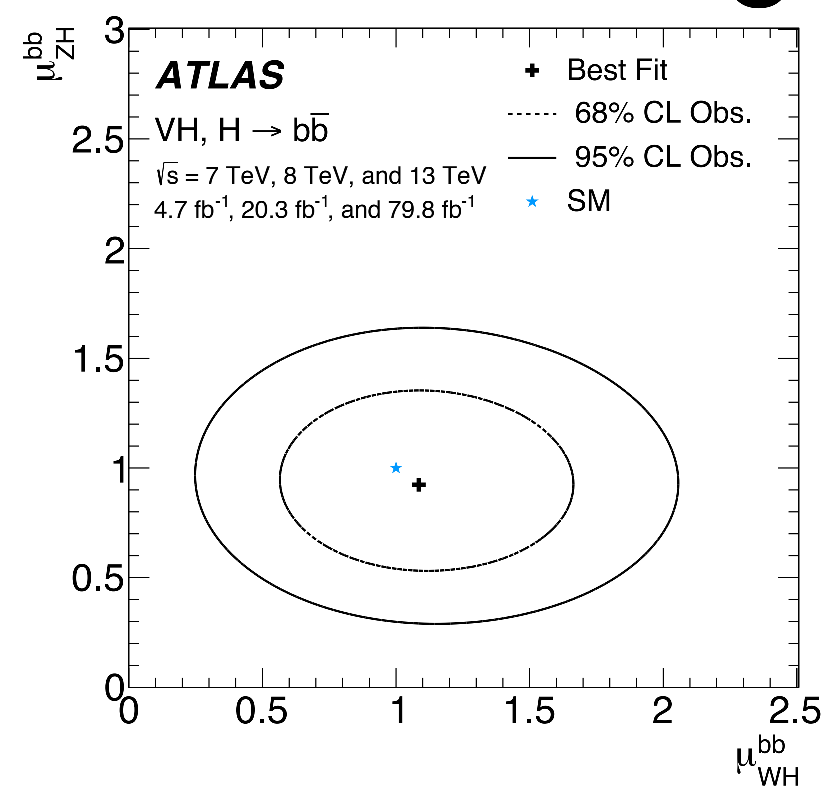
Z+jets

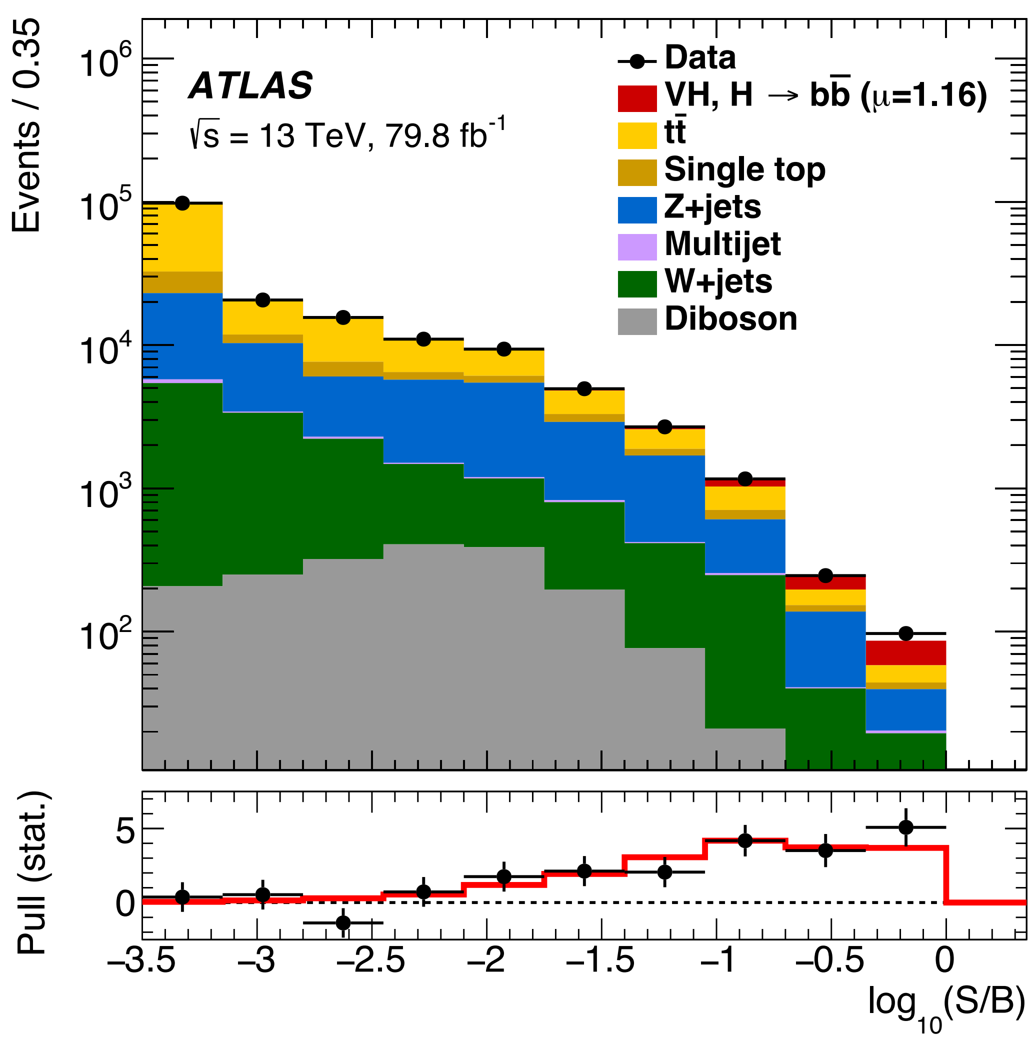
Signal strength

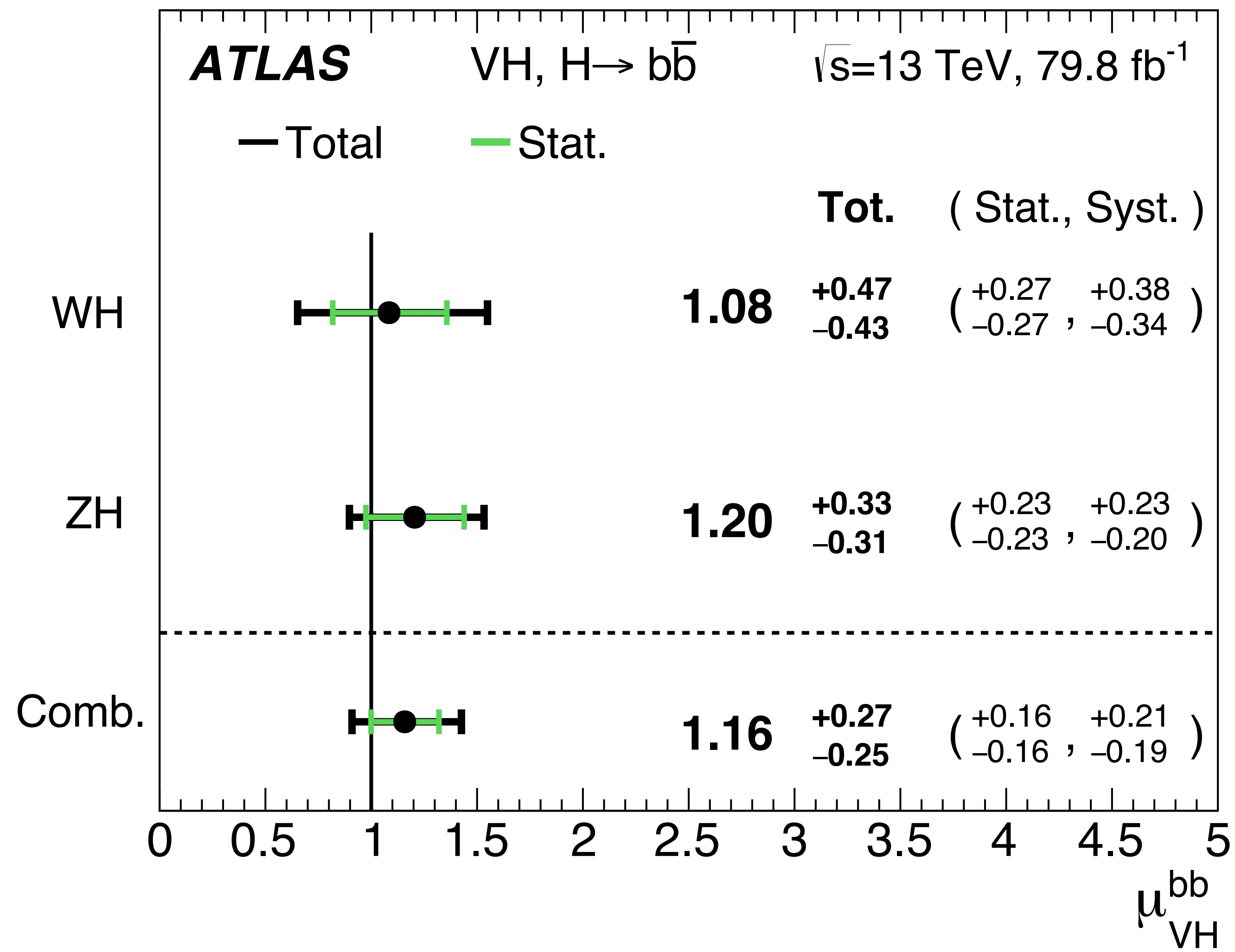
$$\mu = \frac{\sigma \cdot \mathcal{B}_{b\bar{b}}}{(\sigma \cdot \mathcal{B}_{b\bar{b}})_{\rm SM}}$$

Result with 80 fb^{-1} data

- Observed VH H→bb signal at significance of 4.9σ (4.3σ exp.).
- Signal strength μ: 1.16±0.26.
  - Consistent with the SM expectation.
- Determined WH and ZH with small correlation.

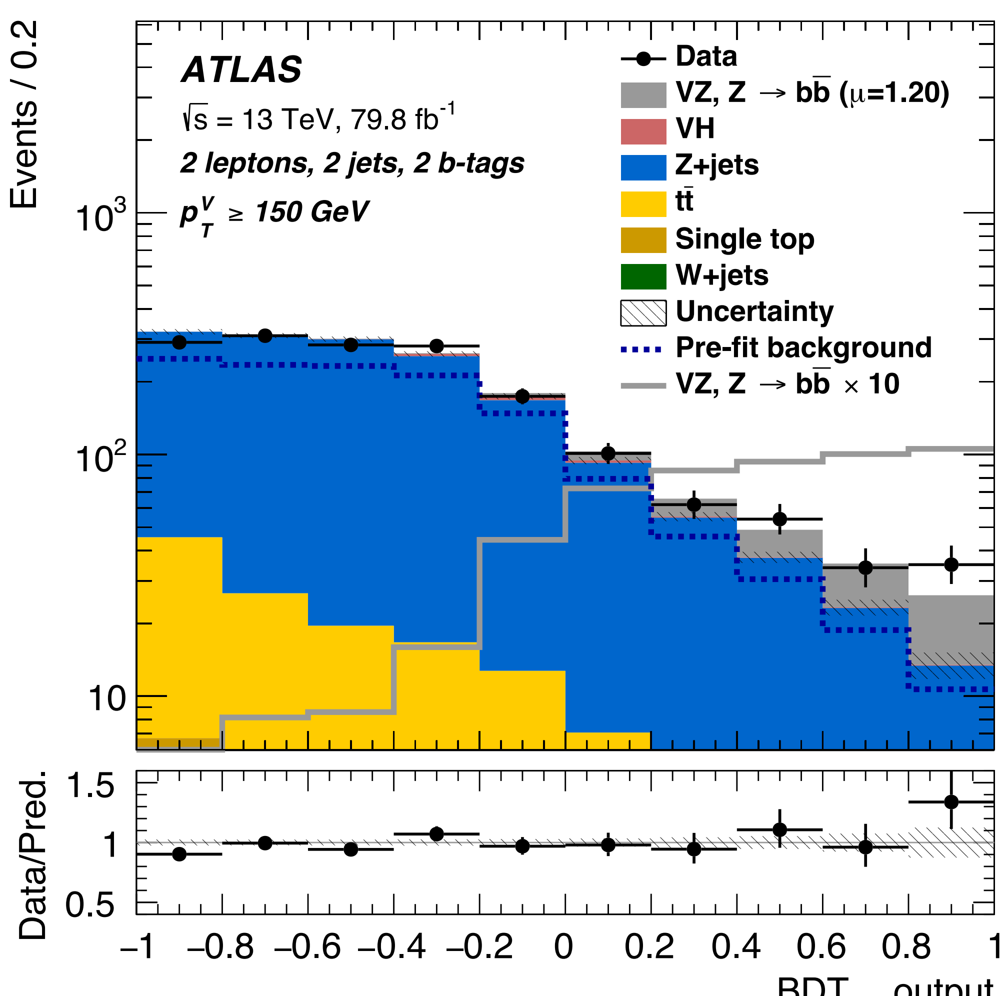


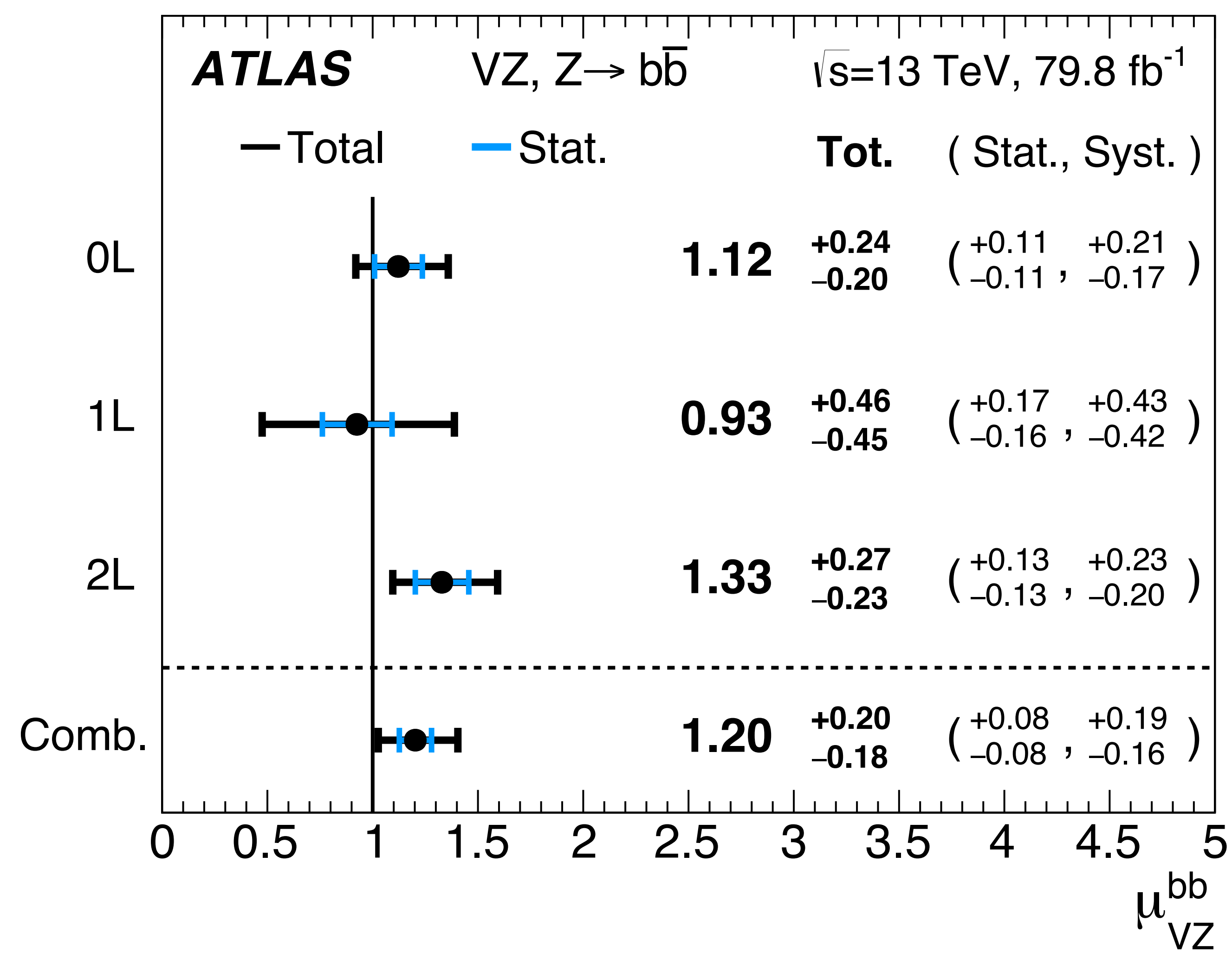




Validation: diboson analysis

- Form dedicated BDTs taking diboson (Z→bb) as the signal and VH as a background.
- Extract signal strength of diboson in the same manner used for Higgs boson.
  - Same event selection, categorization, background modeling are used.
- Signal strength for diboson: $\mu = 1.20 \pm 0.19$.
- <u>Robust validation of background model and analysis technique.</u>



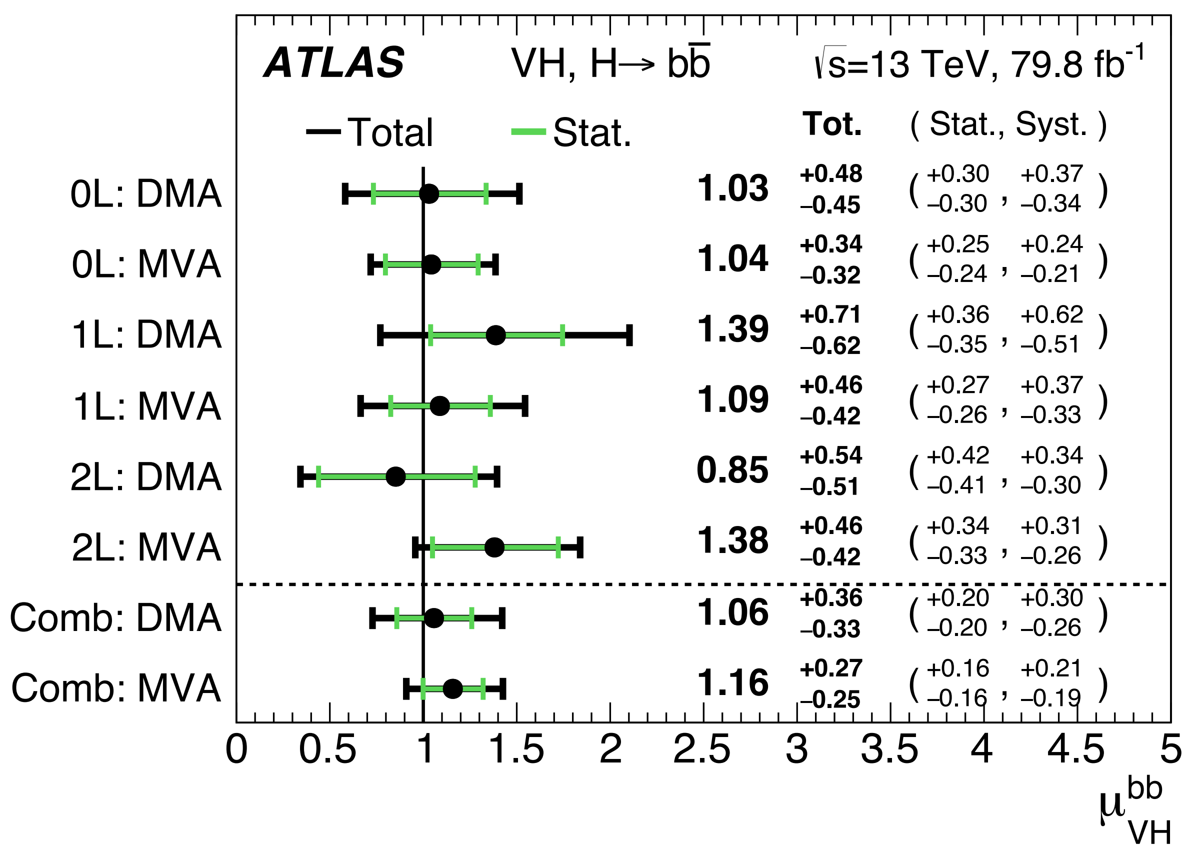


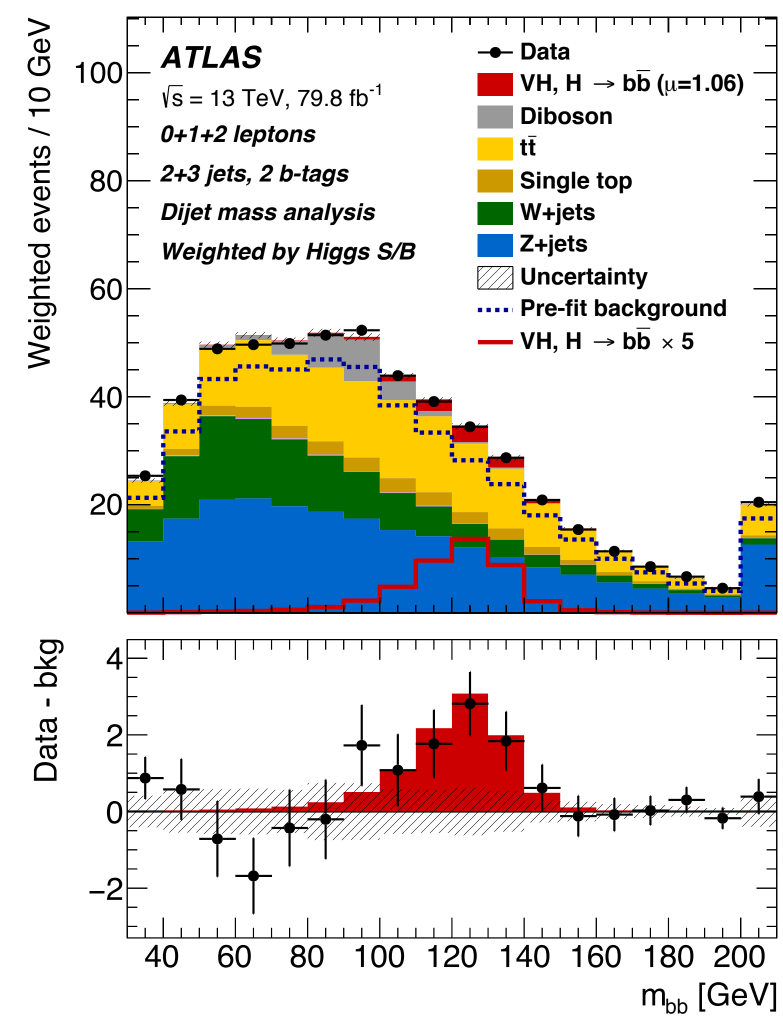
Crosscheck: dijet mass analysis (DMA)

- Use dijet mass distribution as input to fit.
- To improve the sensitivity:
  - Additional cuts are applied in SRs.
  - Additional split into multiple p_T^V regions to exploit better purity at high p_T^V.
- Result
  - μ = 1.06±0.35.
  - Consistent with BDT analysis.

Selection criteria for DMA

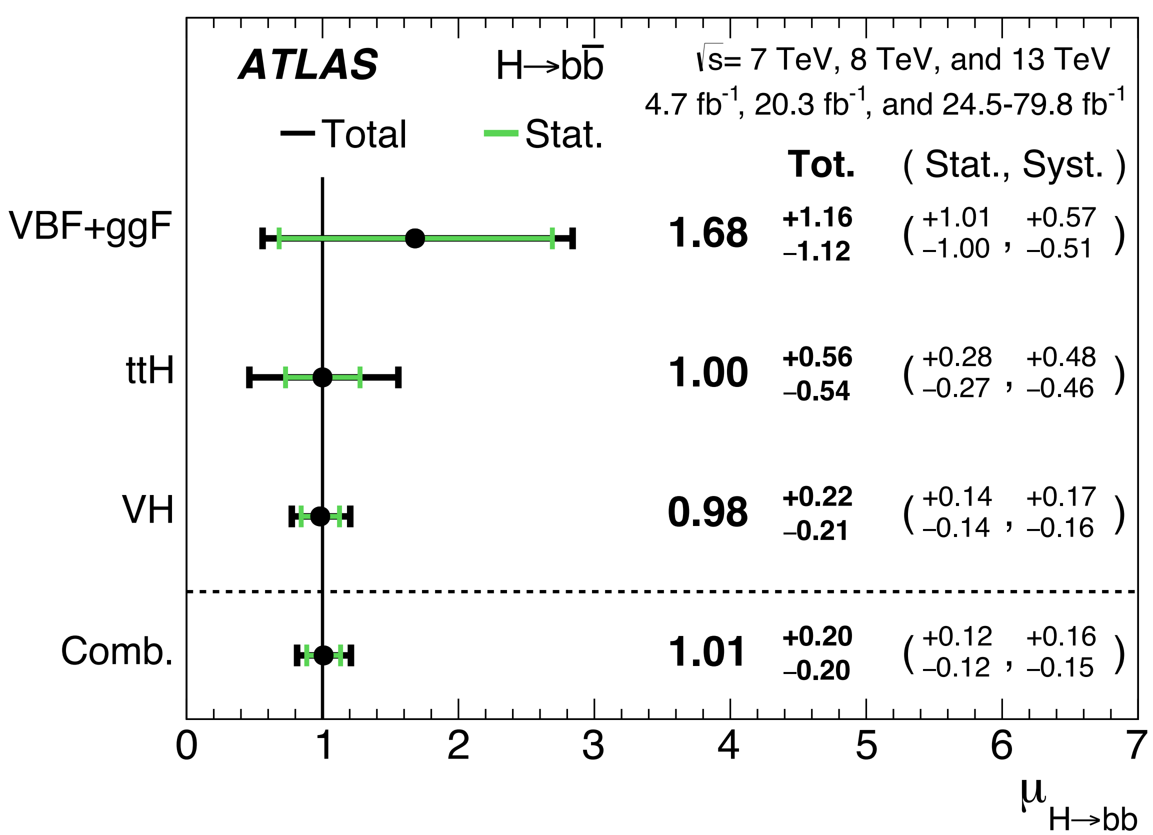
	Channel		
Selection	0-lepton	1-lepton	2-lepton
m_T^W	-	$<$ 120 GeV	-
$E_T^{miss}/\sqrt{S_T}$	-	-	$< 3.5\sqrt{\text{GeV}}$
	p_T^V regions		
p_T^V	75 – 150 GeV (2-lepton only)	150 – 200 GeV	$>$ 200 GeV
$\Delta R(\vec{b}_1, \vec{b}_2)$	<3.0	<1.8	<1.2



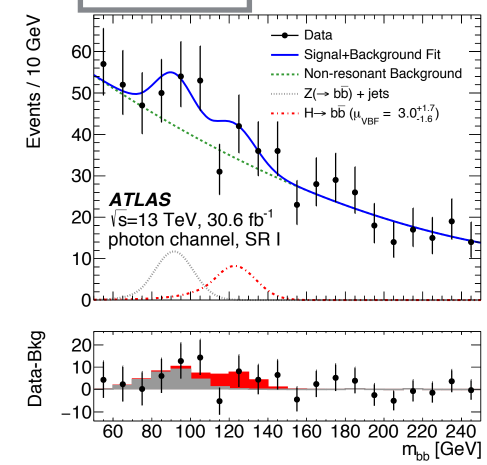


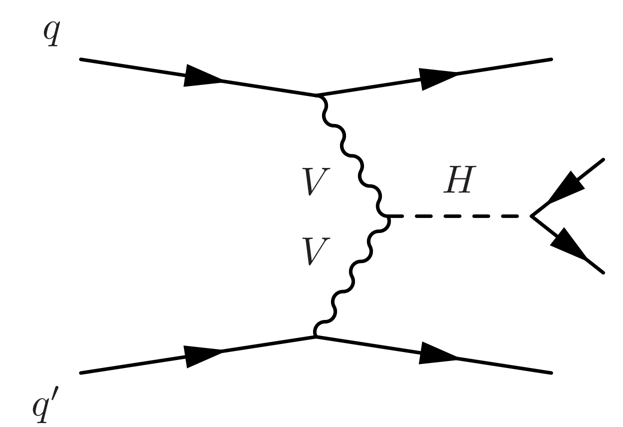
H→bb combination

- Combined with Run 1 & Run 2 results of ttH and VBF production modes.
- Observed H→bb decay at 5.4 σ (5.5 σ exp.) significance.
- Signal strength is 1.01±0.2.



VBF





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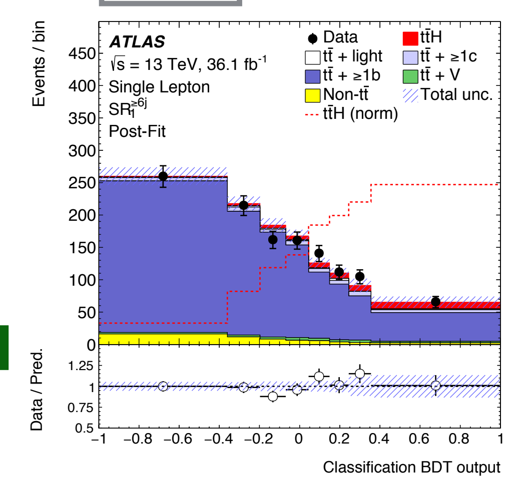
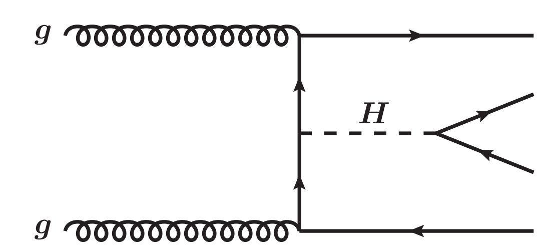
ttH





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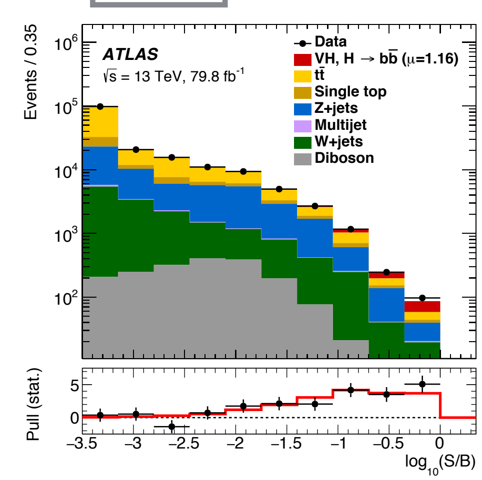
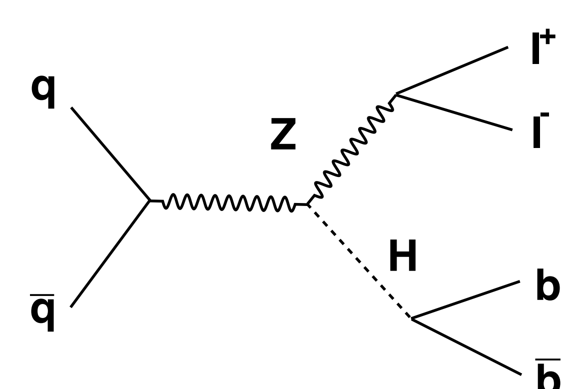
VH





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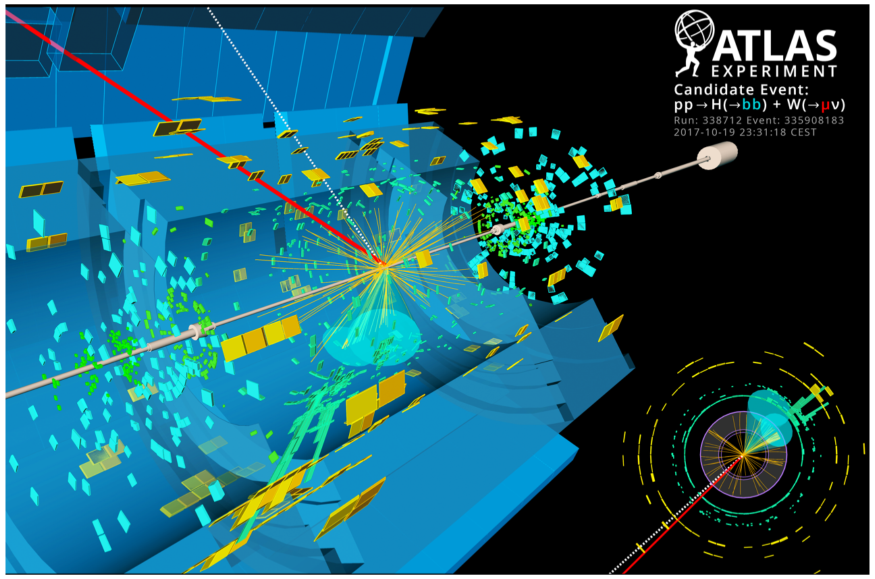
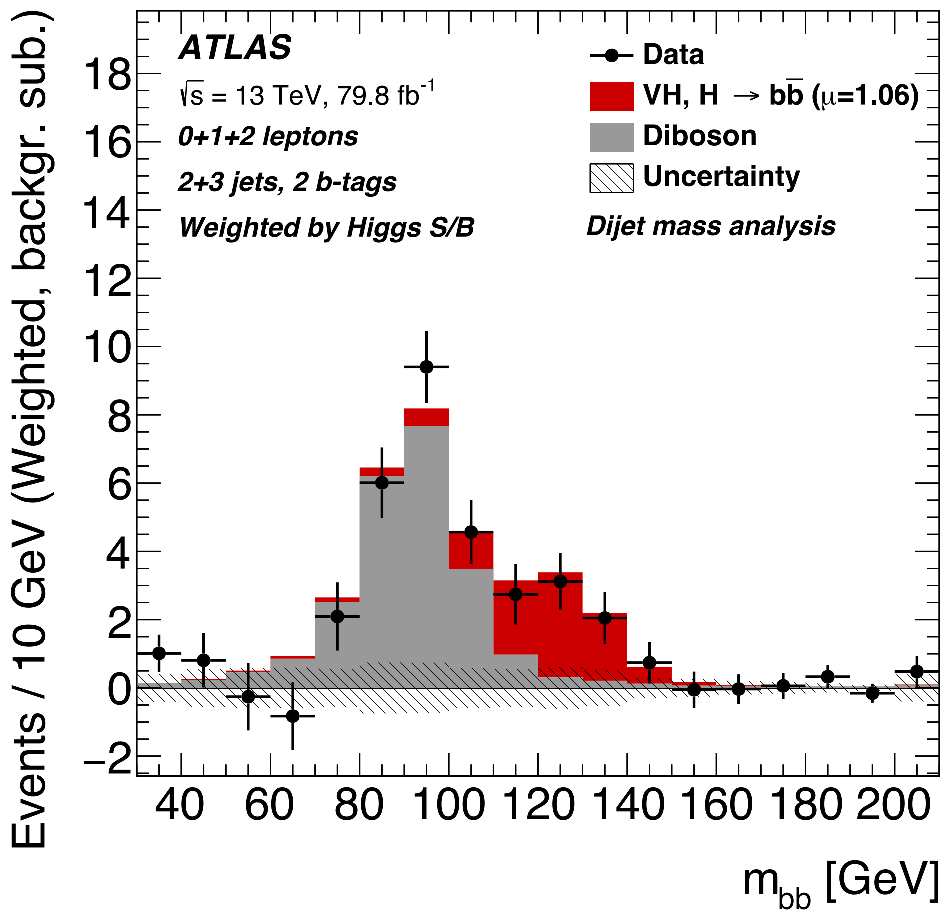
Summary

- VH (H→bb) results with 80 fb^{-1} of Run 2 data.
  - μ=1.16±0.26 with significance of 4.9σ.
  - Robust validation (cross-check) from diboson (dijet mass) analysis.
- Observation of the H→bb decay.
  - Combined ttH, VBF and VH production modes.
  - Significance of 5.4σ.
  - Observed μ=1.01±0.20.
- Observation of VH production at 5.3σ by combining H→γγ and 4l decay modes.
- Now all production modes and the Yukawa coupling to 3rd generation fermions were established.





Additional slides

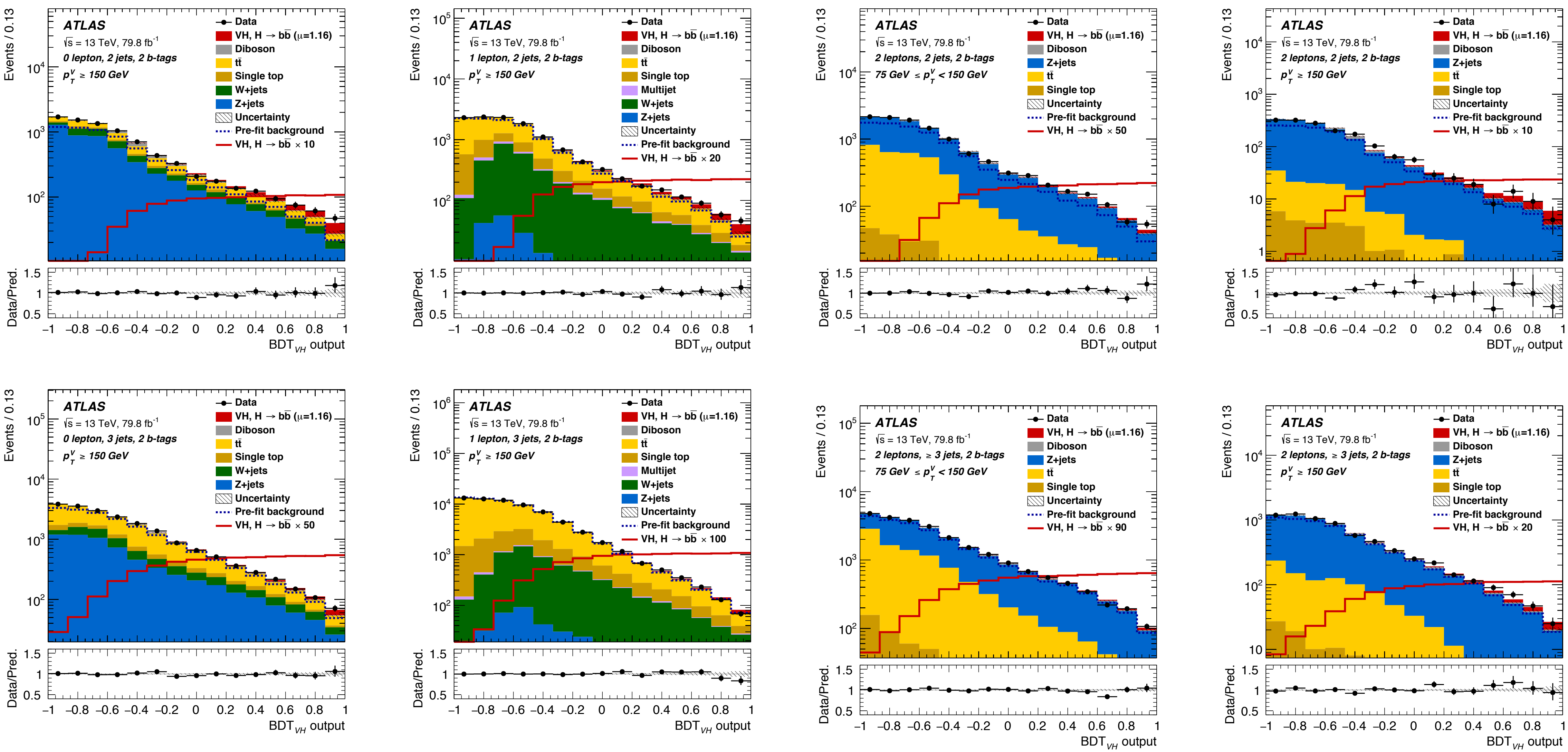
All BDT score distributions

0 lepton | 1 lepton | 2 lepton

75< p_T^Z <150 GeV | p_T^Z > 150 GeV

2 jets

3 jets



All control region distributions

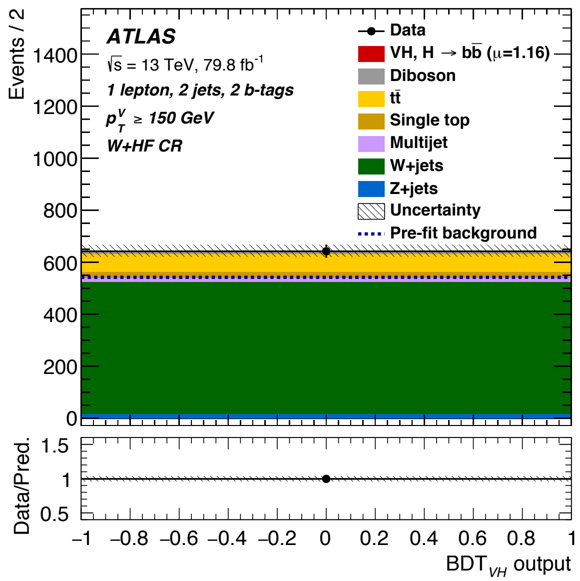
1 lepton W+hf jet CR

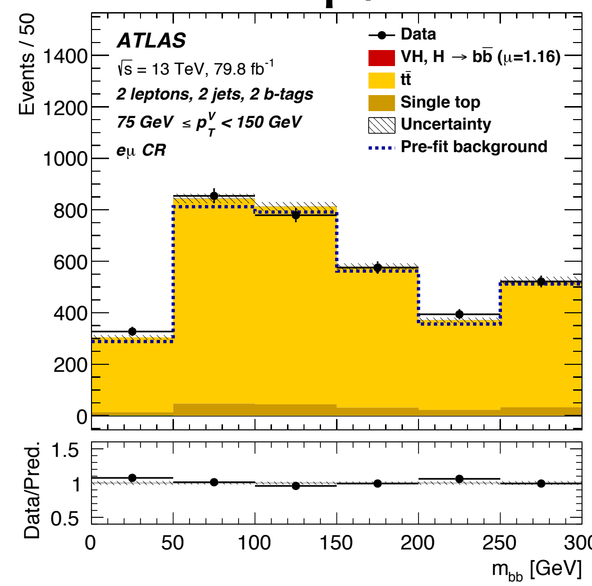
2 lepton top eμ CR

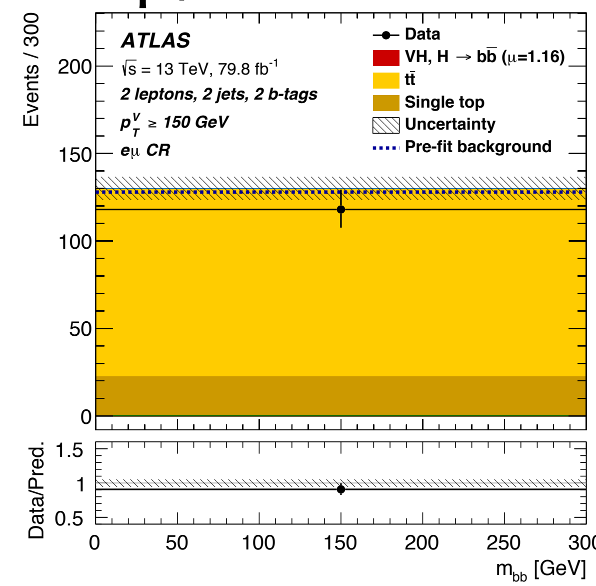
75< p_T^Z <150 GeV

p_T^Z > 150 GeV

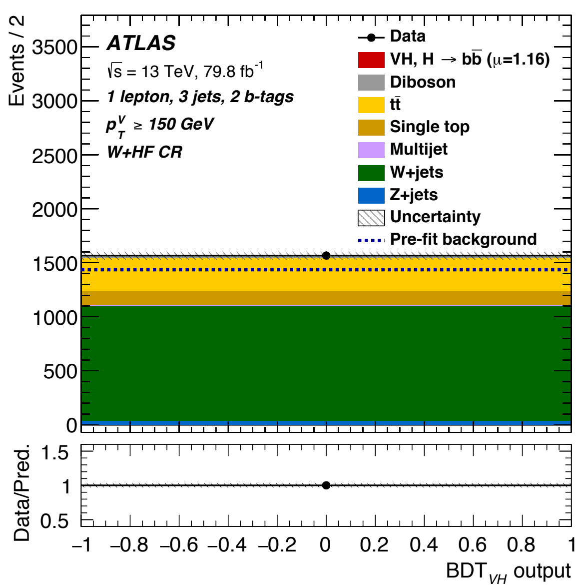
2 jets

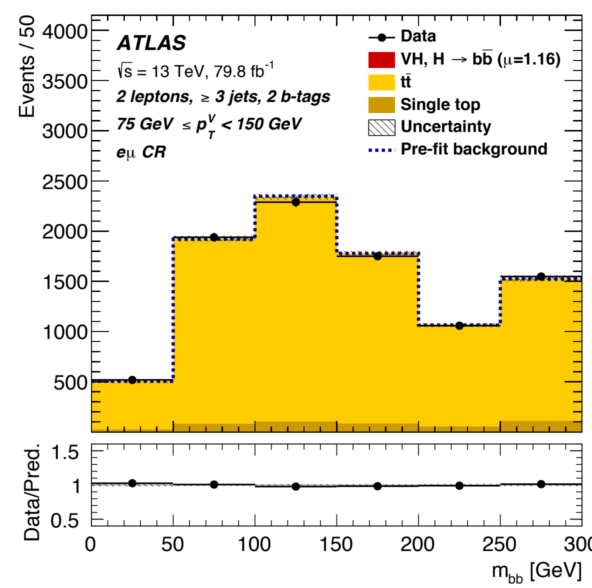


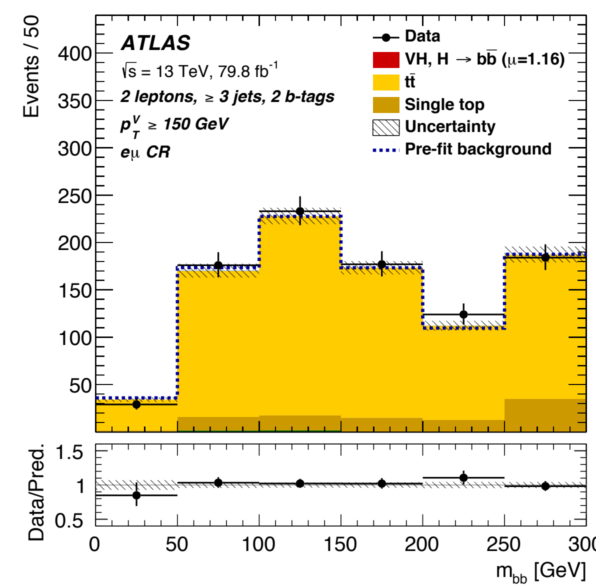




3 jets

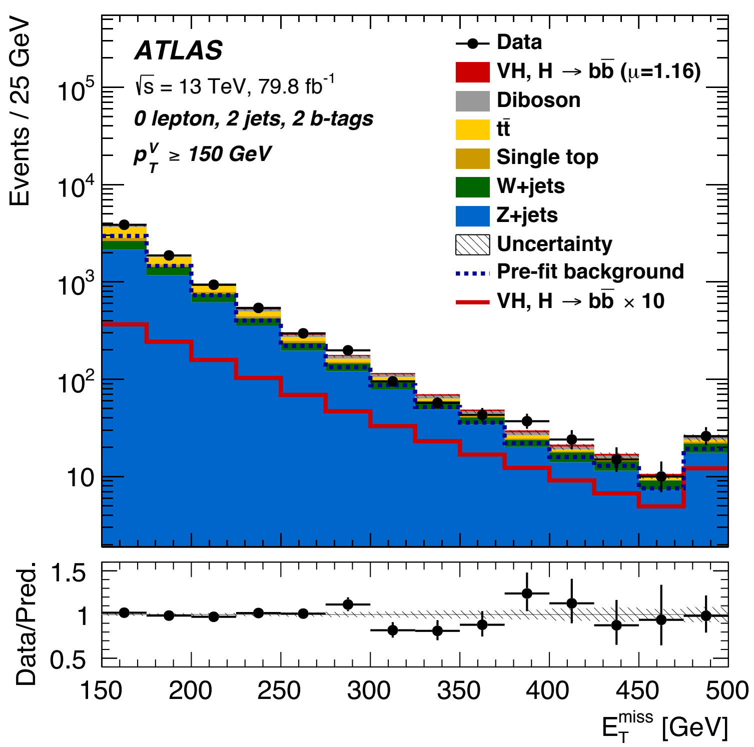




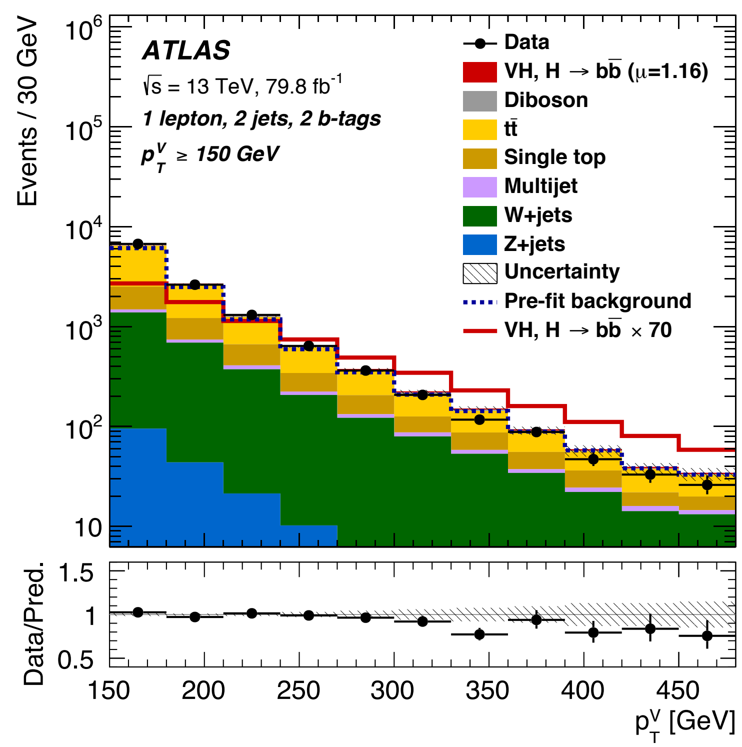


p_T^V distributions

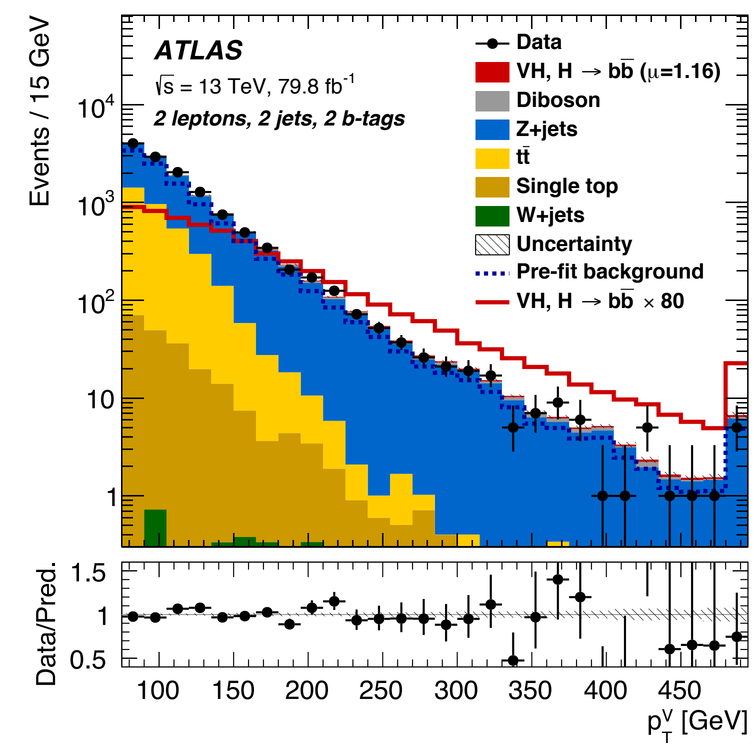
0 lepton



1 lepton



2 lepton



Uncertainties

Systematic		Statistical
Theoretical	Experimental	
‣ Affects both shapes and normalizations ‣ Correlates over bins and analysis regions		‣ Scale as √N ‣ Each bin ‣ No correlation

- Origin
  - Higher order effects
  - Scale uncertainties
  - etc..
- Differences among..
  - Generators
  - Parameters

- Calibration of objects
  - Energy measurements
  - Identification efficiency

- Limited amount of..
  - Data
  - MC

- Deformations of shapes and normalizations by uncertainties are controled by set of parameters.
- Normalization of leading backgrounds are treated as freely floating parameters.

Systematic uncertainties

V+jets and top

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

dibosons

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%

Systematic uncertainties

Systematics related to signal

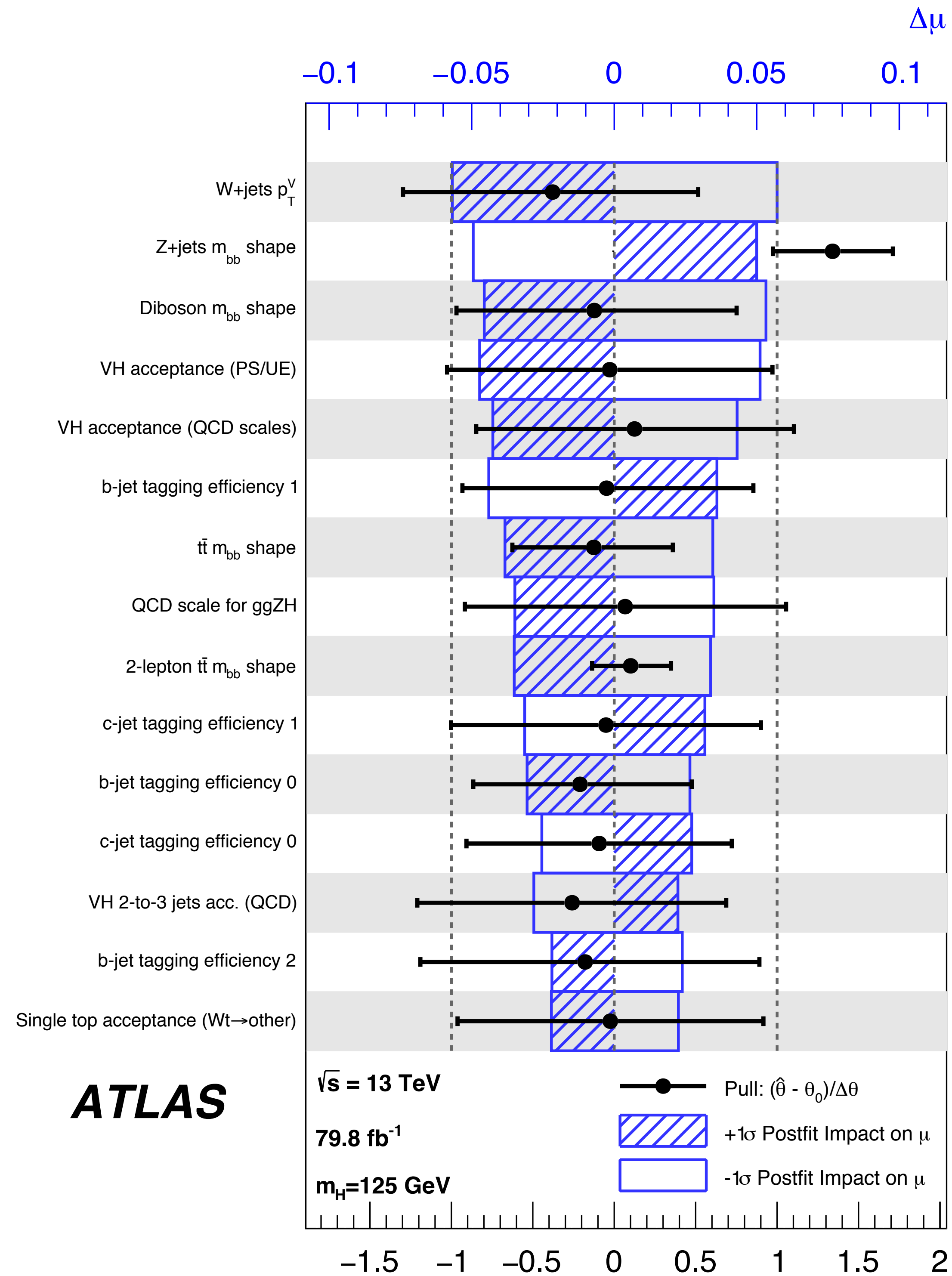
Signal	
Cross-section (scale)	0.7% (qq), 27% (gg)
Cross-section (PDF)	1.9% ($qq \to WH$), 1.6% ($qq \to ZH$), 5% (gg)
$H \to b\bar{b}$ branching fraction	1.7%
Acceptance from scale variations	2.5 – 8.8%
Acceptance from PS/UE variations for 2 or more jets	2.9 – 6.2% (depending on lepton channel)
Acceptance 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

Propagation of the systematic uncertainties

Break down of the uncertainties

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

Impact of the systematics on μ



Event selection for MVA based analysis

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 $\|\eta\| < 2.5$ > 30 GeV for $2.5 < \|\eta\| < 4.5$			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
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

Event selection for dijet 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

Inputs for Boosted Decision Tree

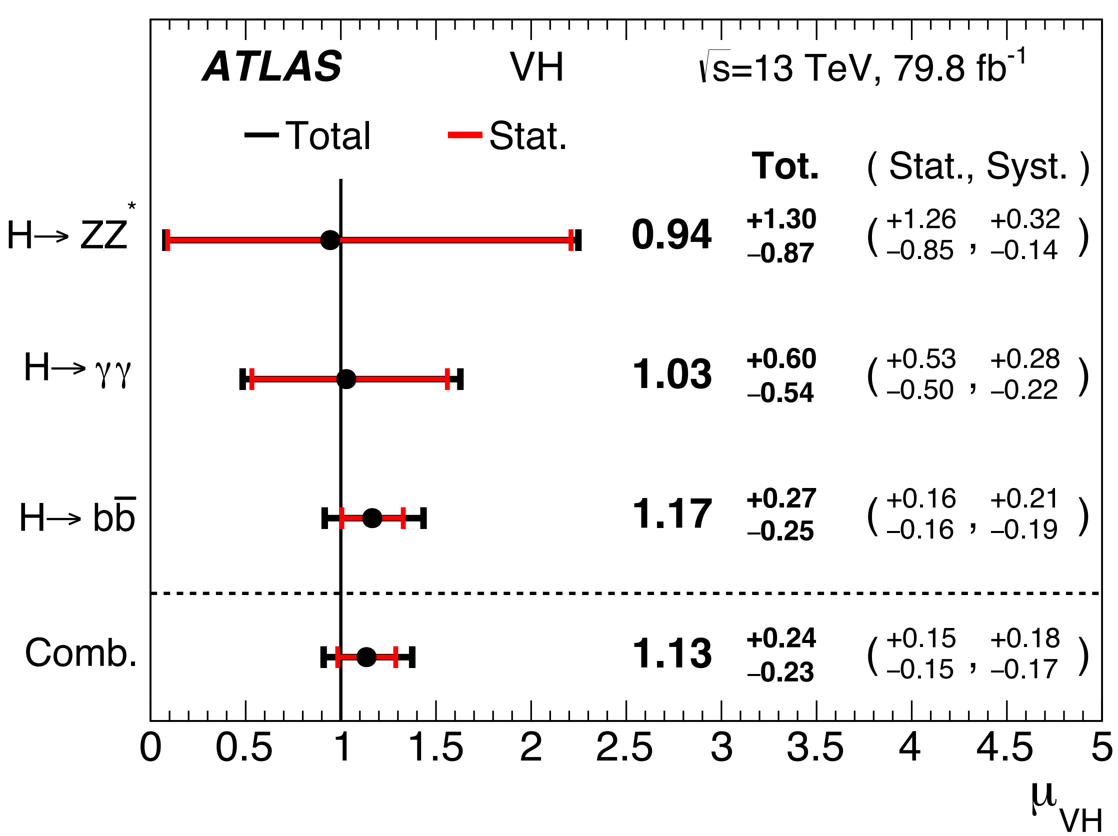
Variable	0-lepton	1-lepton	2-lepton
p_{T}^{V}	$\equiv E_{\mathrm{T}}^{\mathrm{miss}}$	$\times$	$\times$
$E_{\mathrm{T}}^{\mathrm{miss}}$	$\times$	$\times$	
$p_{\mathrm{T}}^{b_1}$	$\times$	$\times$	$\times$
$p_{\mathrm{T}}^{b_2}$	$\times$	$\times$	$\times$
m_{bb}	$\times$	$\times$	$\times$
$\Delta R(\vec{b_1},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

Monte Carlo simulations

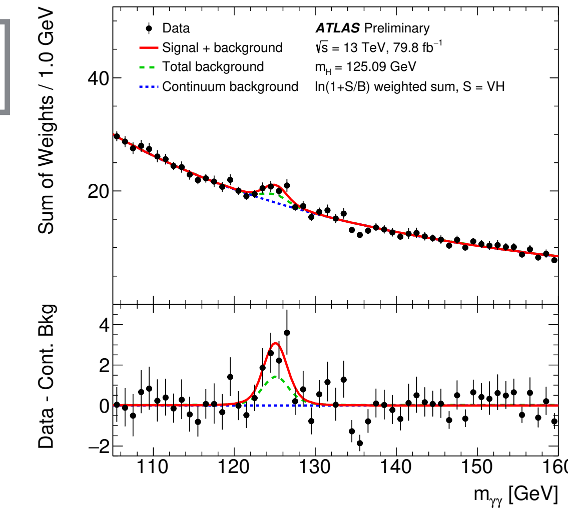
Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order
Signal, mass set to 125 GeV and $b\bar{b}$ branching fraction to 58%					
$qq \to WH$ $\to \ell\nu b\bar{b}$	Powheg-Box v2 [76] + GoSam [79] + MiNLO [80,81]	NNPDF3.0NLO$^{(\star)}$ [77]	Pythia 8.212 [68]	AZNLO [78]	NNLO(QCD)+ 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

VH combination

- Combined with other Run 2 VH results where H→γγ and H→4l decay modes.
- Observed VH production at 5.3σ(4.8σ exp.) significance.
- Signal strength is 1.13±0.24.
- H→bb provides highest sensitivity.



H→γγ



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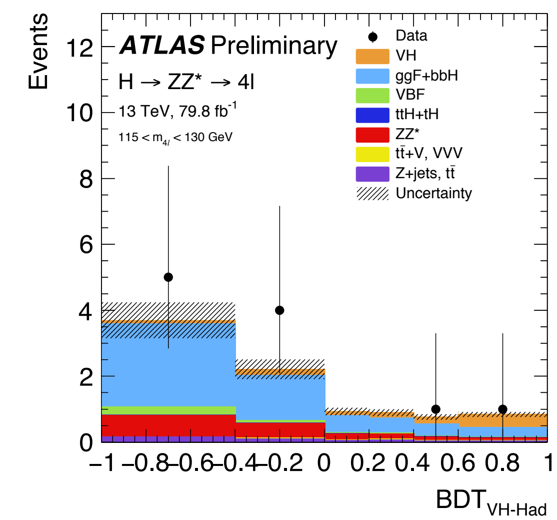
4l



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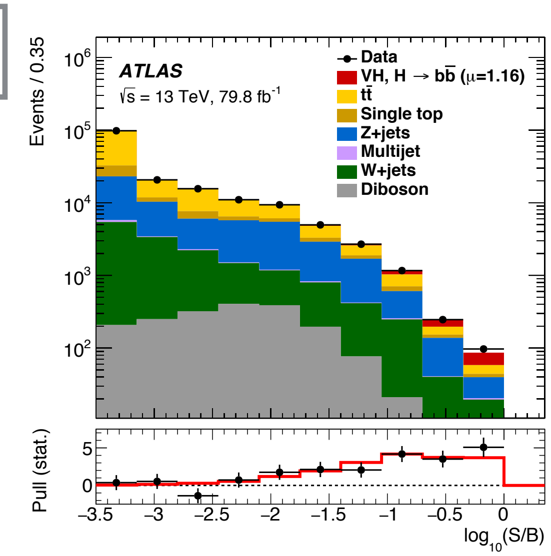
VH



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ttH production mode

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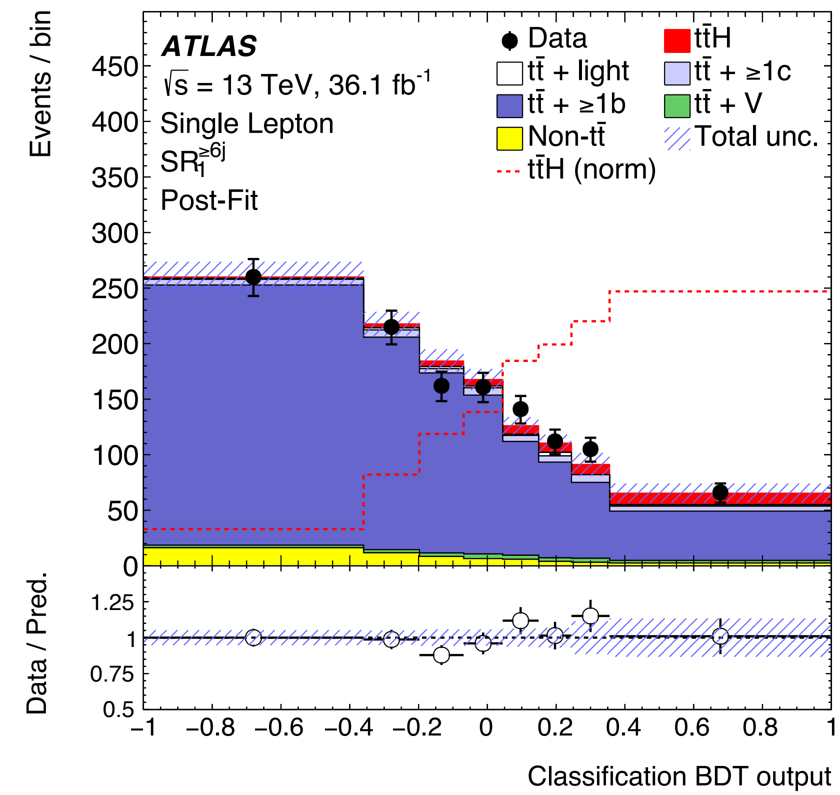
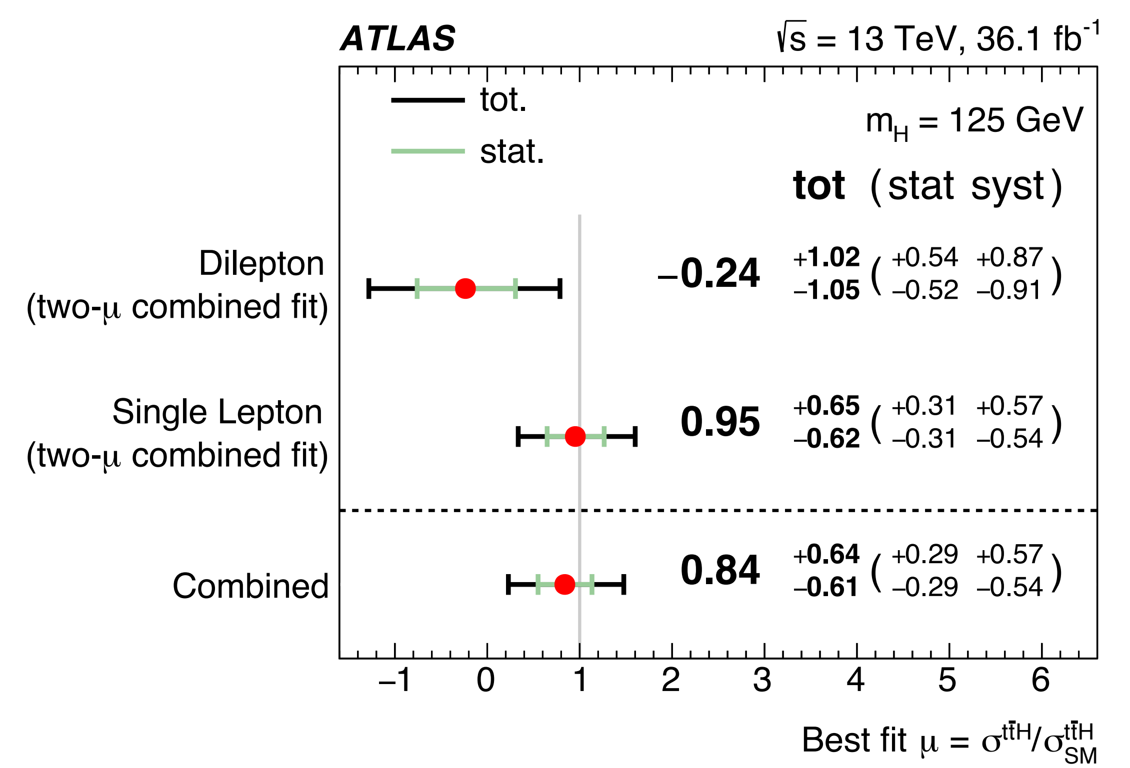
- Single lepton & dilepton channels based on ttbar decay.
- Two stages of BDTs
  - Reconstruction BDT: To associate 4 b-jets to Higgs or top.
  - Classification BDT: To discriminate ttH signals from backgrounds that consist mainly of ttbar+b-jets.
- Simultaneous fit of 9 SRs and 10 CRs.
- Results with 36 fb^{-1} of Run2 data.
  - Sensitivity of 1.4σ (1.6σ exp)
  - Signal strength μ = 0.84±0.63

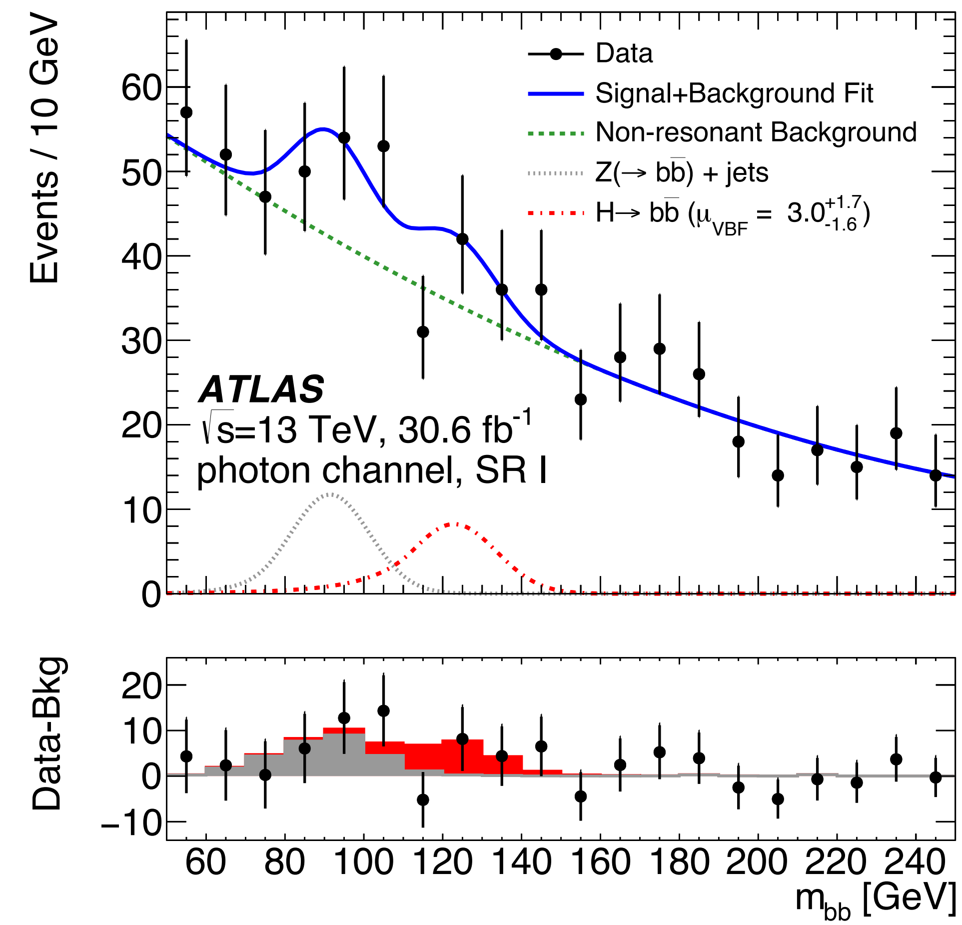




VBF production mode

Phys. Rev. D 98 (2018) 052003

- All hadronic and photon associated channels.
- Backgrounds
  - Resonant: mainly from Z+jets (Z→bb).
  - Non-resonant: mainly from multi-jet and ttbar.
- Boosted Decision Tree to separate signal from backgrounds
  - Trained with signal MC sample and data in the sidebands, $80<m_{bb}<100$, $150<m_{bb}<190$ GeV, as the background.
- Fit to m_{bb} spectrum of data.



- Results with 30.6 fb^{-1} of Run2 data
  - Signal strength: $\mu = 3.0 \pm 1.7$
  - Sensitivity is 1.9σ (0.7σ exp.)