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

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on behalf of the ATLAS collaboration

Workshop on Connecting Insights in Fundamental Physics
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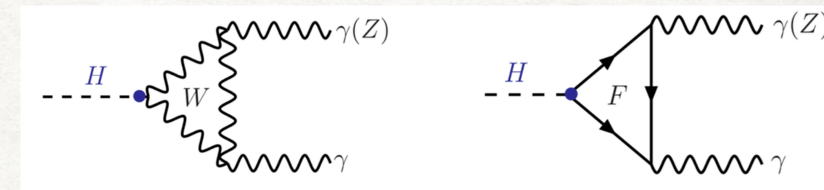
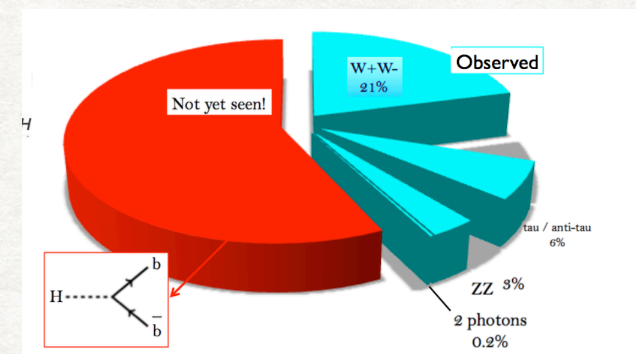
Motivation of VH, H→bb analysis

- Why H→bb decay channel
    - Higgs boson first discovered in 2012 through bosonic decay channels
    - Search for Higgs directly coupling to fermions has been expected
    - H→bb has the largest branching ratio and had not been observed before the results reported here

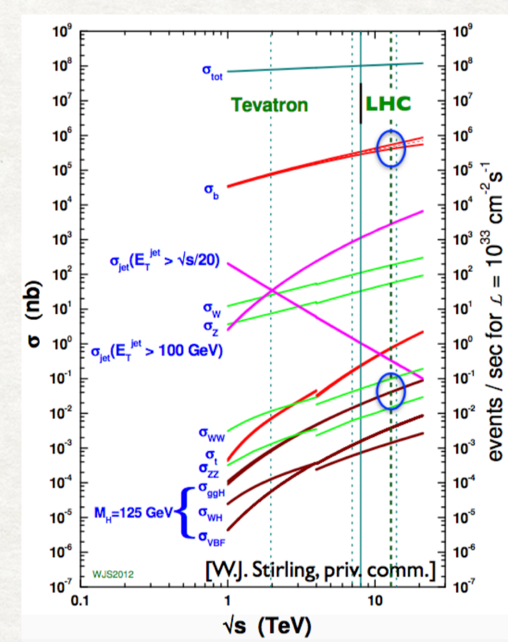


- $\gamma\gamma$ decay channel



- Branching ratio

- Why VH production mode
    - Very large multi-b-jets production cross-section at LHC
    - For VH, the leptonic decay of the vector boson could be well exploited



- Production

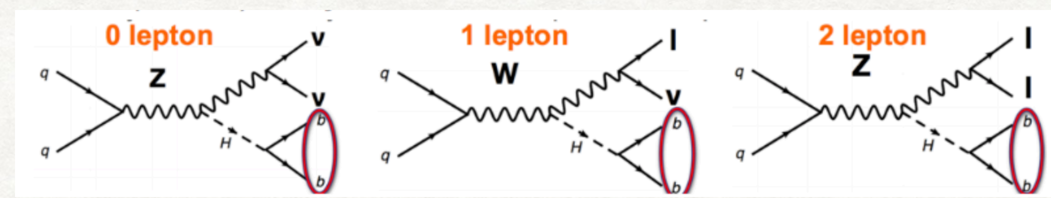
History of VH, H→bb analysis

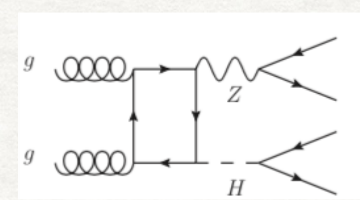
- Tevatron (1.96 TeV)
  - CDF & D0, 2.8 σ for m_H=125GeV [Phys. Rev. Lett. 109 (2012) 071804]
- LHC Run-1 (7,8 TeV)
  - ATLAS, 1.4 (2.6) σ of obs.(exp.) significance [J. High Energy Phys. 01 (2015) 069]
  - CMS, 2.1 σ of local significance [Phys. Rev. D 89 (2014) 012003]
- LHC Run-2 2015-2016 (13TeV)
  - ATLAS, 3.5 (3.0) σ of obs.(exp.) significance [J. High Energy Phys. 12 (2017) 024]
  - CMS, 3.3(2.8) σ of obs.(exp.) significance [Phys. Lett. B 780 (2018) 501]
- LHC Run-2 2015-2017 (13 TeV)

  Focus today
  - ATLAS (combined with Run-1), 4.9 (5.1) σ of obs.(exp.) significance [Physics Letters B 786 (2018) 59–86]
  - CMS (combined with Run-1), 4.8(4.9) σ of obs.(exp.) significance [Phys. Rev. Lett. 121 (2018) 121801]

Analysis strategy

- Search for the Higgs bosons produced in association with vector bosons and decays to bb
- Used 79.8 fb^{-1} of pp collision data collected by ATLAS in 2015 to 2017
- Three decay channels w.r.t. the vector boson decay modes
  - 0 lepton: Z→νν, H→bb
  - 1 lepton: W→lν, H→bb
  - 2 lepton: Z→ll, H→bb





- ZH has additional gg induced diagrams

- Multi-variable algorithm (MVA) is used to enhance the sensitivity
- Combined likelihood fit is performed to estimate the significance and signal strength (μ)

$$\mu = \frac{(\sigma * BR)_{Obs}}{(\sigma * BR)_{SM}}$$

- Additional validation of the robustness - Details in backup
  - Di-jet mass analysis
  - VZ analysis

0-lepton Channel Selection

$ZH(Z \to \nu\nu, H \to bb)$

Z boson selection

- MET trigger: 70,90,110 GeV
- MET > 150 GeV
- Lepton veto: p_T>7 GeV

Higgs boson candidate

- 2 b-tagged jets, p_T>45 (20) GeV
- 1 additional jet max

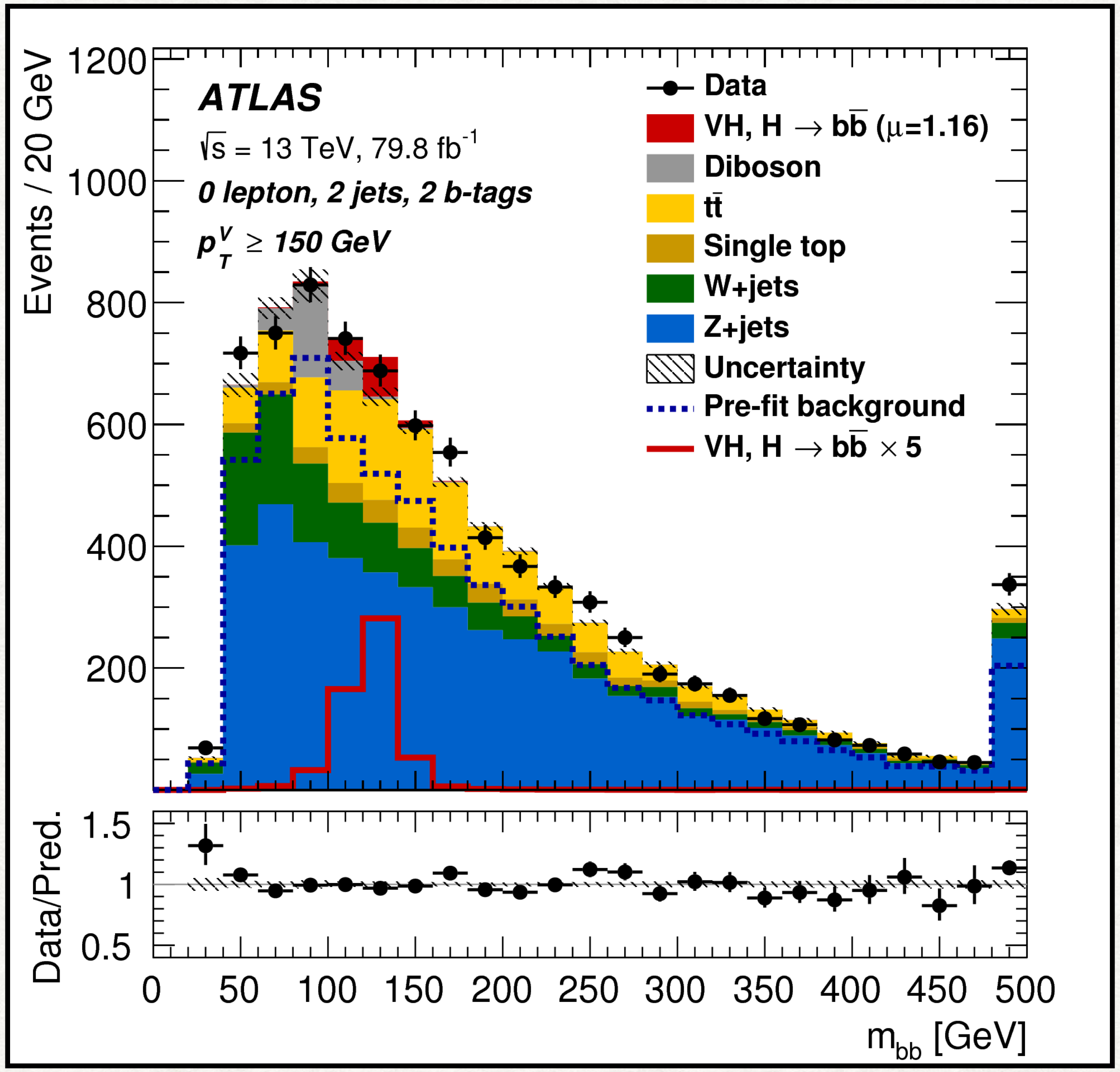
Multijets background reduction

- min|Δφ(MET,jet)|> 20°(2jets)
  > 30°(3jets)
- |Δφ(MET,h)|>120°
- |Δφ(j1,j2)|<140°

Categorization

- Splitted into 2- and 3-jets sub-channels

0 lepton, 2 jets



B-tagging performance [JINST 11 (2016) P04008]

1-lepton Channel Selection

WH(W→lv,H→bb)

W boson selection

- (e-ch) Single electron trigger and (μ-ch) MET trigger
- 1 qualified electron or muon (p_T>27 or 25 GeV)
- Veto additional leptons (p_T>7 GeV)
- P_T(W) >150 GeV

Higgs boson candidate

- 2 b-tagged jets, p_T>45 (20) GeV
- 1 additional jet max

Multijets background reduction

- MET > 30GeV (e-ch)
- Data-driven estimate using fit to M_T(W)

Signal region

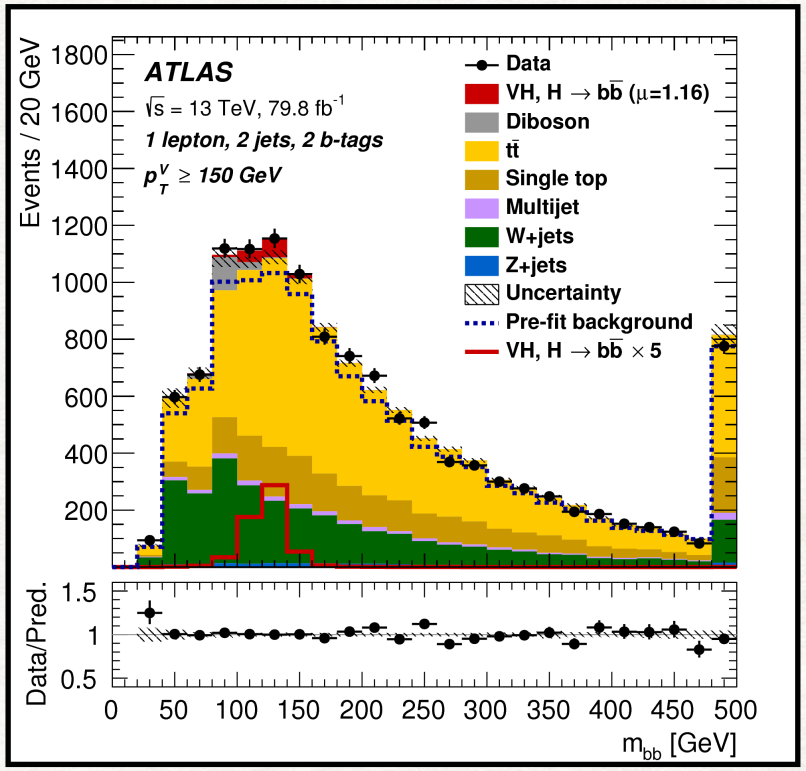
- M(bb)≥75 GeV or M(top)≤225 GeV

W+HF control region (>75% purity)

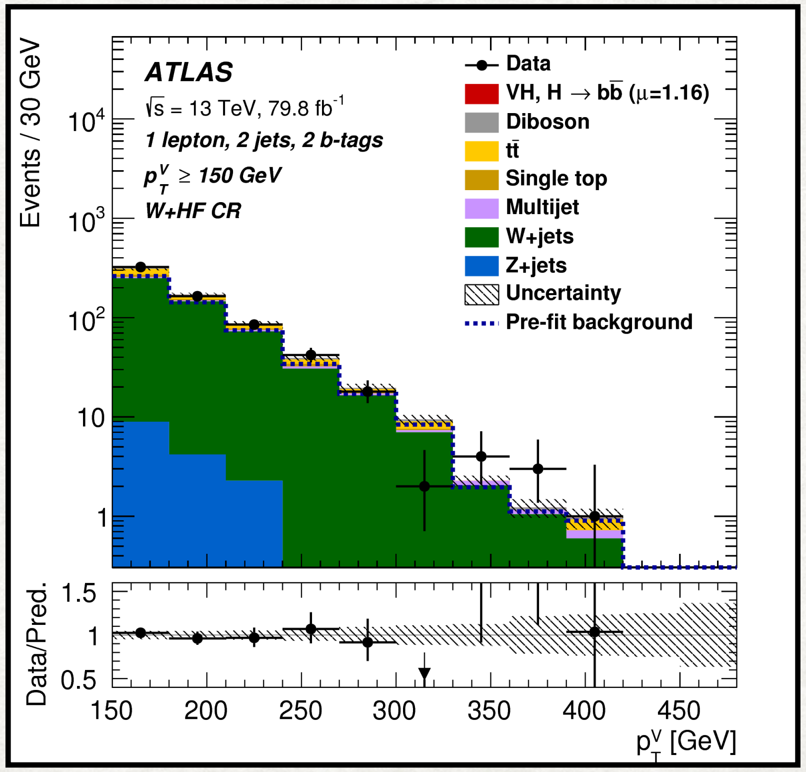
- M(bb)<75 GeV and M(top)>225 GeV

Categorization

- Splitted into 2- and 3-jets sub-channles



1 lepton, 2 jets
Signal region



1 lepton, 2 jets
W+HF control region

2-lepton Channel Selection

ZH(Z→ll, H→bb)

Z boson selection

- Single lepton triggers
- 2 electrons or muons. Leading p_T>27 GeV, sub-leading p_T>7 GeV
- Z mass: 81<M(ll)<101 GeV
- p_T(Z)>75 GeV

Higgs boson candidate

- 2 b-tagged jets, p_T>45 (20) GeV
- 0 or ≥1 additional jets

Signal region

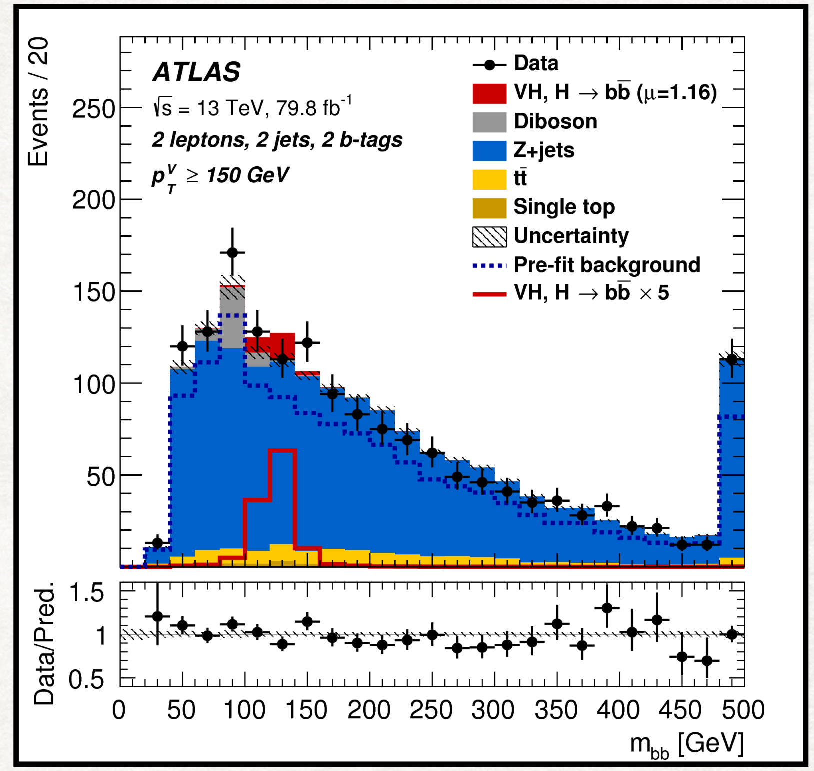
- Same-flavor events (ee/μμ)

Top eμ control region (99% purity)

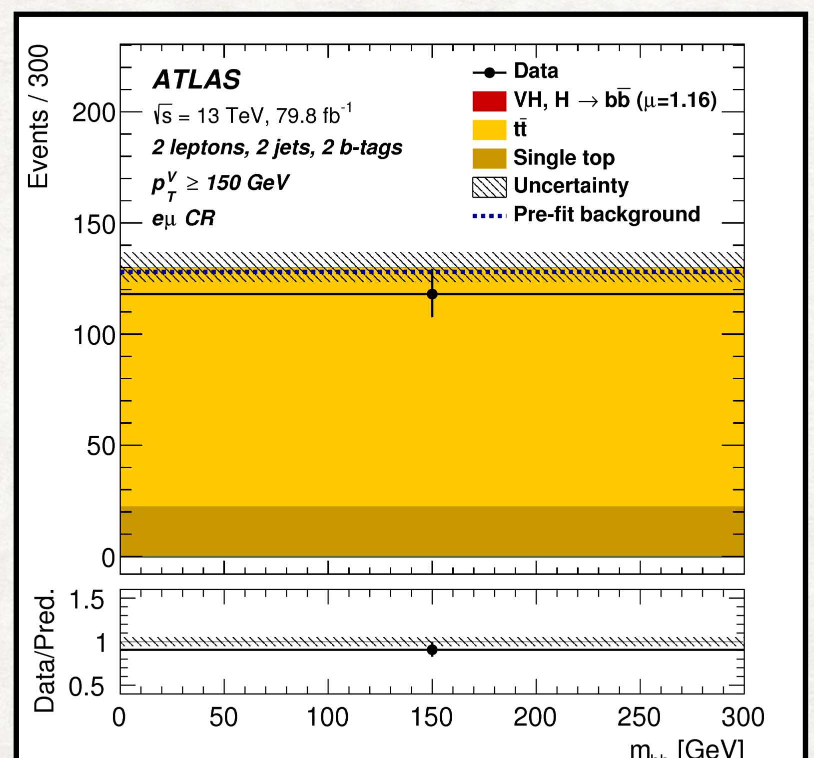
- Opposite-flavor events (eμ)

Categorization

- 2-jets and ≥3-jets
- 75<p_T(Z)<150 GeV and p_T(Z) ≥150 GeV



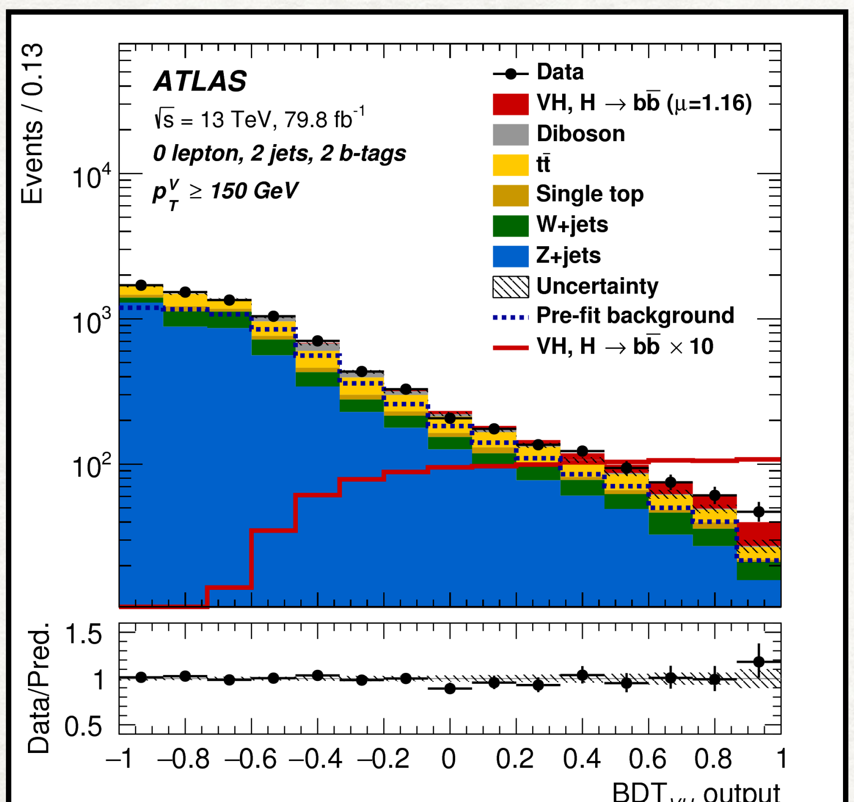
2 lepton, 2 jets, p_T(Z)≥150 GeV
Signal region



2 lepton, 2 jets, p_T(Z)≥150 GeV
Top eμ control region

MVA Analysis

- MVA setup
  - Boosted Decision Tree (BDT) algorithm
  - Trained separately in each category
- Input variables
  - Optimized for each channel
  - Most important ones: m_{bb}, $\Delta R(b,b)$ and $p_T(V)$



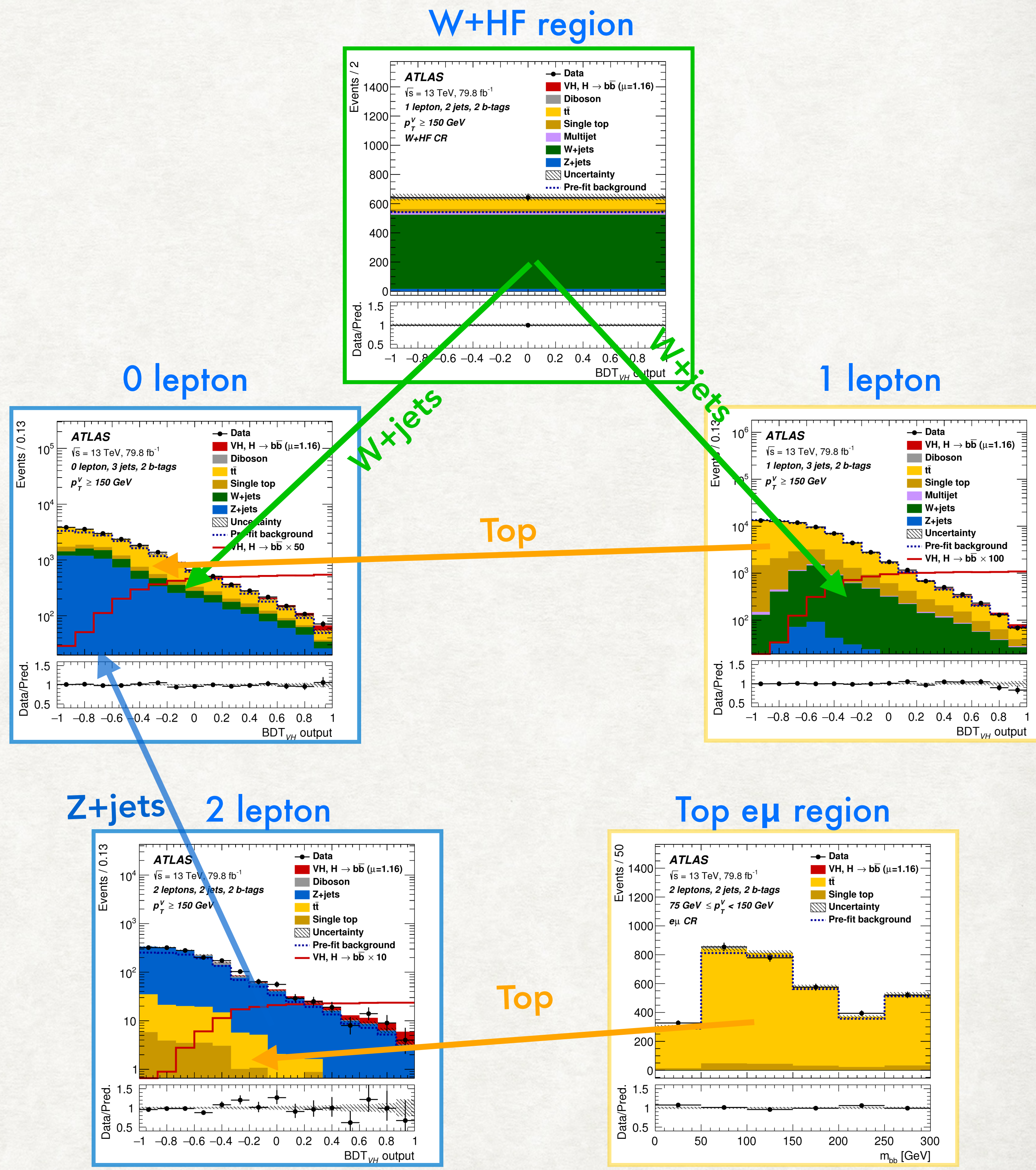
BDT output, 0 lepton 2 jets

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}	$\times$	$\times$	$\times$

BDT input variables

Background modeling

- Use state-of-the-art MC generators
- Constrain from data by using high purity CR regions (Top/W+jets)
- Main backgrounds have floating normalizations and are estimated in the fit (Top/W or Z+jets)
- Parametrize extrapolation uncertainties across regions
- Shape uncertainties on BDT
- Validated in VZ analysis details in backup



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

Normalization factors obtained from fit

Systematic Uncertainties

There are many source of systematics:

- Experimental uncertainties

  B-tagging, Jet energy scale, Jet energy resolution, muons, electrons…

- Simulated sample uncertainties

  Normalization, acceptance, mbb shape and pT(V) shape uncertainties…

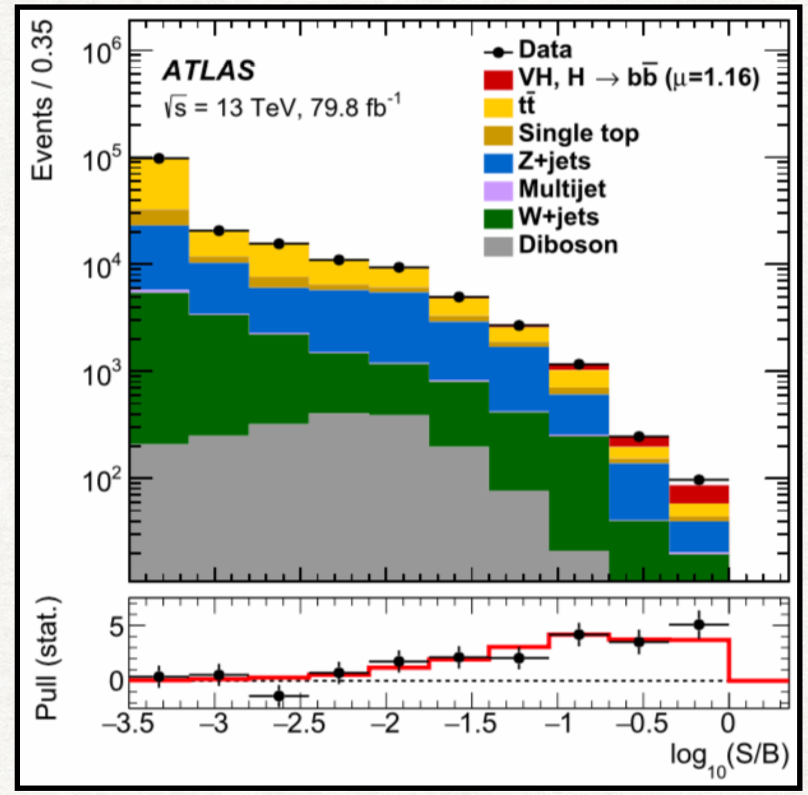
- Multi-jet background uncertainties (1 lepton channel)

  Normalization and shape uncertainties

Details in backup

Statistical Analysis

- Binned likelihood fitting has been performed to extract signal strength and significance.
- The impact of systematics are considered as nuisance parameters
- The likelihood function build on the BDT distributions
- Fit to mBB distributions as cross-check backup



BDT combined

Signal strength

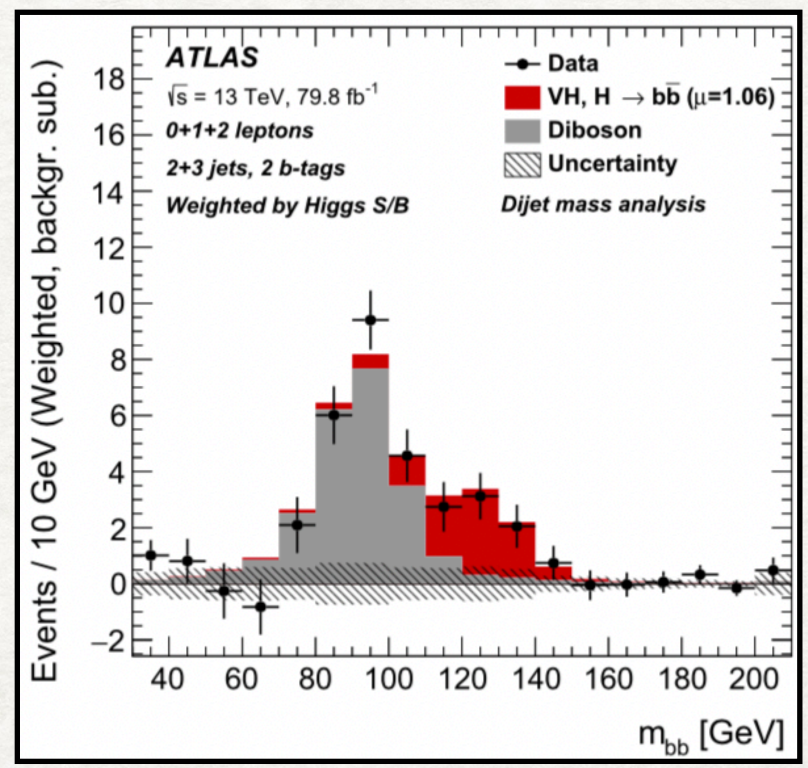
Nuisance Parameter

$$L = \Big(\prod_{b \in bins} Pois(n_b | \mu S_b + B_b)\Big)\Big(\prod_{\theta \in NPs} Gauss(\theta, \sigma_\theta)\Big)$$

Likelihood function

Channel	0-lep	1-lep		2-lep	
Regions	SR	SR	$W+hf$(Sec.4.3.1) CR	SR	$(e-\mu)$(Sec.4.3.2) CR
p_T^V [GeV]	≥ 150	≥ 150		75-150, >150	
# of jets	2,3	2,3		2, 3+	
# of b-tag	2	2		2	
Discriminant	BDT output	BDT output	one bin	BDT output	m_{bb}[1]

Categories and distributions used in the fit

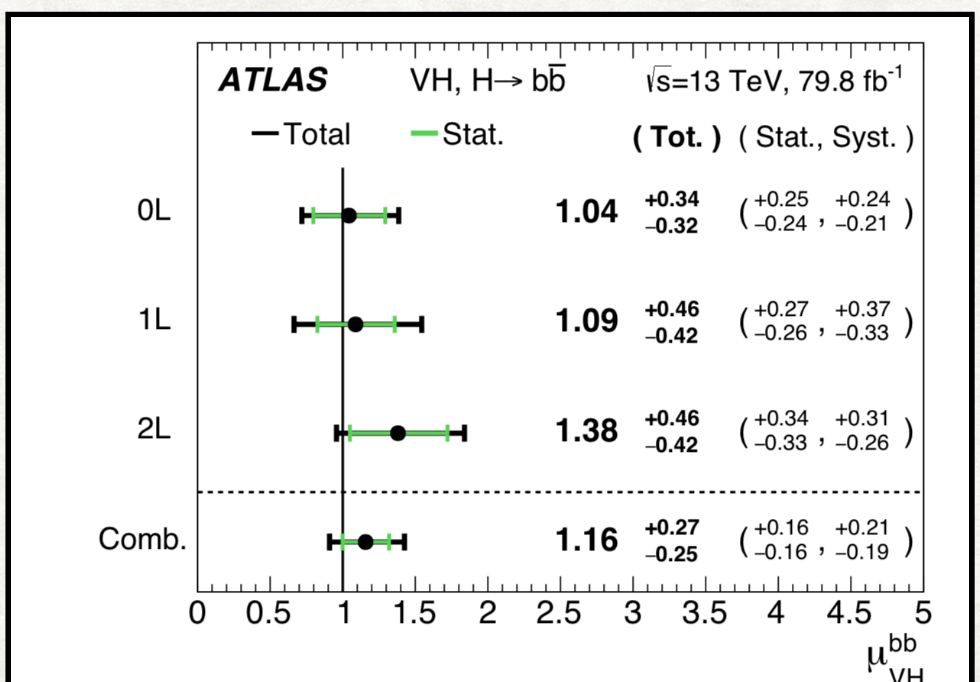


mBB combined

Results: Only Run-2

VH, H→bb

- Significance at **4.9σ (4.3σ exp.)**
- Signal strength $\mu_{VHbb}=1.16\pm0.26$ compatible with SM
- Analysis dominated by systematic uncertainties
- Many important sources of uncertainties
  - B-tagging, signal modeling, background modeling and MC stats



Signal strength

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

Breakdown of uncertainties

Results: Combined with Run-1

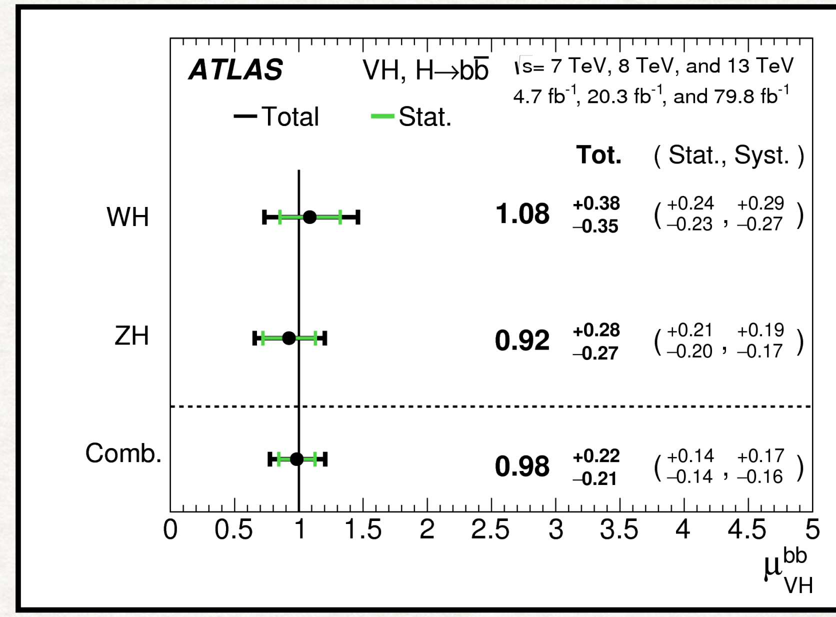
VH, H→bb

- Combined with Run-1 VH(bb) results

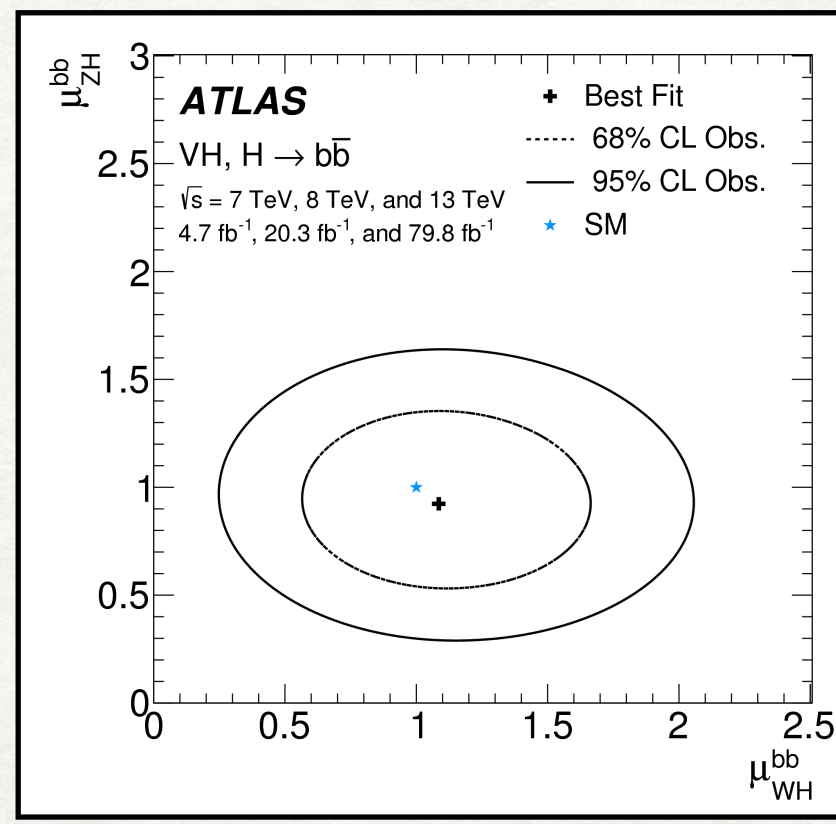
  4.7 fb^{-1} @ 7 TeV

  20.3 fb^{-1} @ 8 TeV

- Significance at **4.9σ (5.1σ exp.)**
- $\mu_{VHbb} = 0.98 \pm 0.21$ compatible with SM
- μ_{WH} and μ_{ZH} compatible with each other



Signal strength

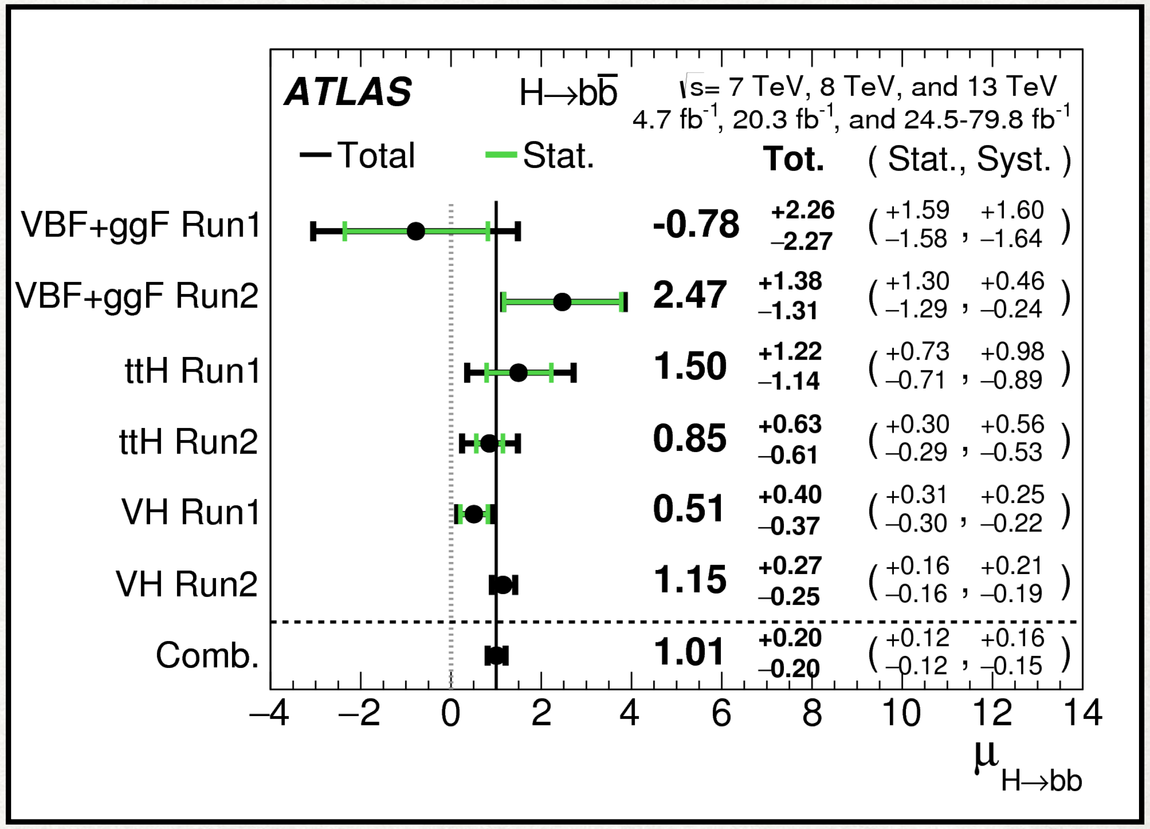


Likelihood contours for signal strength of WH and ZH

Results: Combined with other production modes

H→bb decay

- Combined with Run-1 and Run-2 analyses in VBF, ggF and ttH productions
- Significance at 5.4σ (5.5σ exp.)
- $\mu_{H\to bb} = 1.01 \pm 0.20$ compatible with SM
- Compatibility of 6 measurements



Signal strength

✶Hbb Observed

Results: Combined with other decay channels

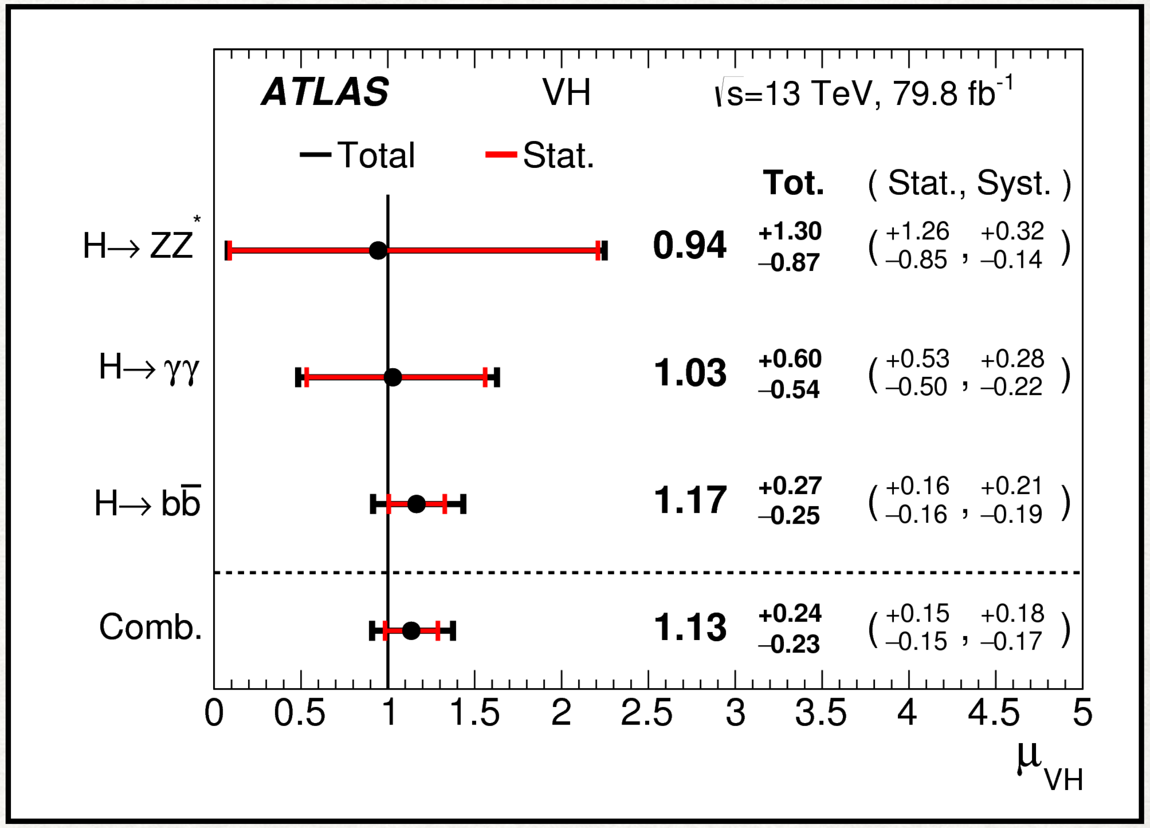
VH production

- Combined with Run-2 analyses in $H\to\gamma\gamma$ and $H\to ZZ^*\to 4l$ decays

- Significance at 5.3σ (4.8σ exp.)

- $\mu_{VH} = 1.13 \pm 0.24$ compatible with SM

- Compatibility of 3 measurements

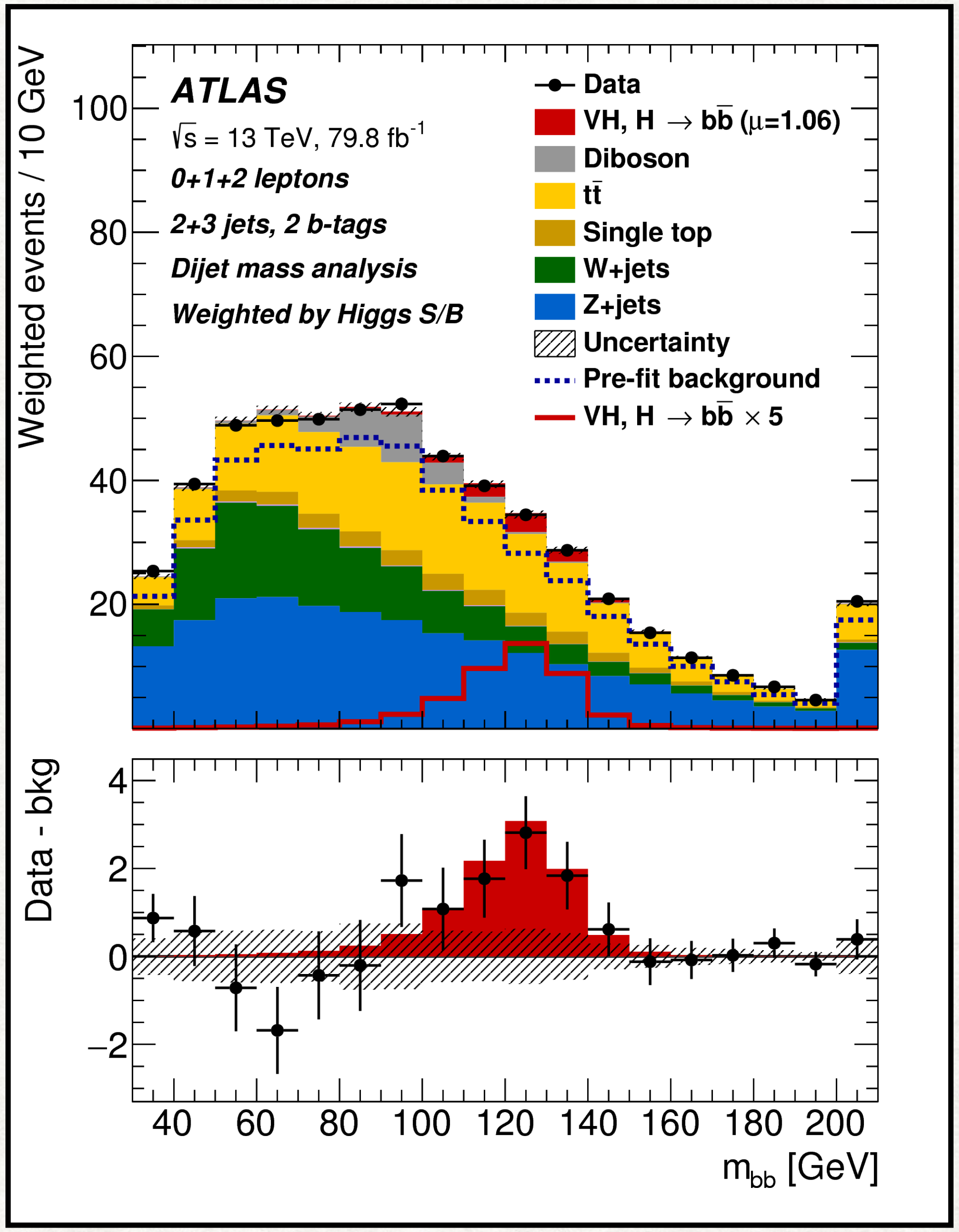


Signal strength

✳VH Observed

Conclusion

- VH, H→bb analysis with 79.8 fb^{-1} of Run-2 data
  - μ_{VHbb}=1.16±0.26 compatible with SM
  - Significance at 4.9σ (4.3σ exp.)
- VH, H→bb analysis combined with Run-1
  - μ_{VH} = 0.98±0.21 compatible with SM
  - Significance at 4.9σ (5.1σ exp.)
- Observation of VH production mode
  - μ_{VH}=1.13±0.24 compatible with SM
  - Significance at 5.3σ (4.8σ exp.)
- Observation of H→bb decay
  - μ_{Hbb}=1.01±0.20 compatible with SM
  - Significance at 5.4 (5.5σ exp.)



Combined m_{bb}

- VHbb process has been used for differential X-section measurement [Phys. Rev. Lett. 121 (2018) 121801]

Backup

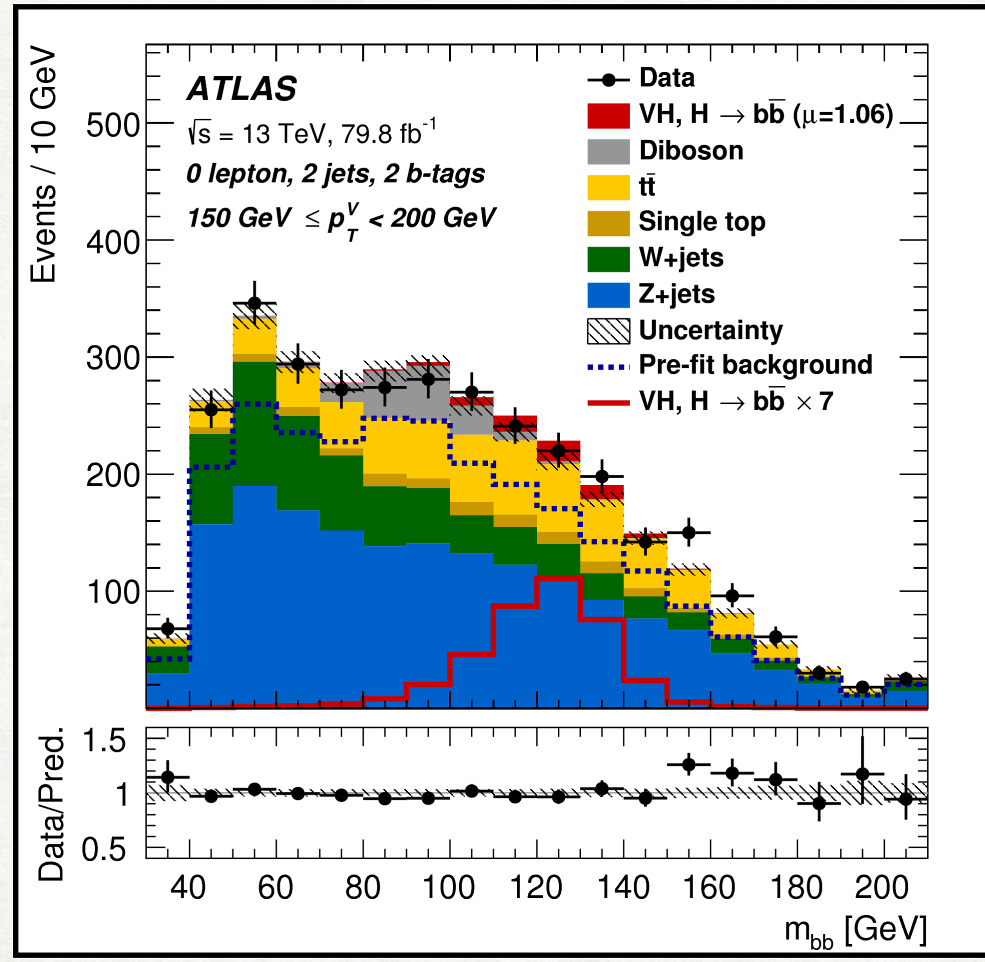
Di-jet mass analysis (I)

Cross-check

- Split into different regions by $p_T(V)$
- $M_T(W)$ cut in 1-lepton
- MET significance cut in 2-lepton
- Adaptive $\Delta R(b,b)$ cuts
- Then fit to di-jet mass distribution

	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

Selections for di-jet mass analysis

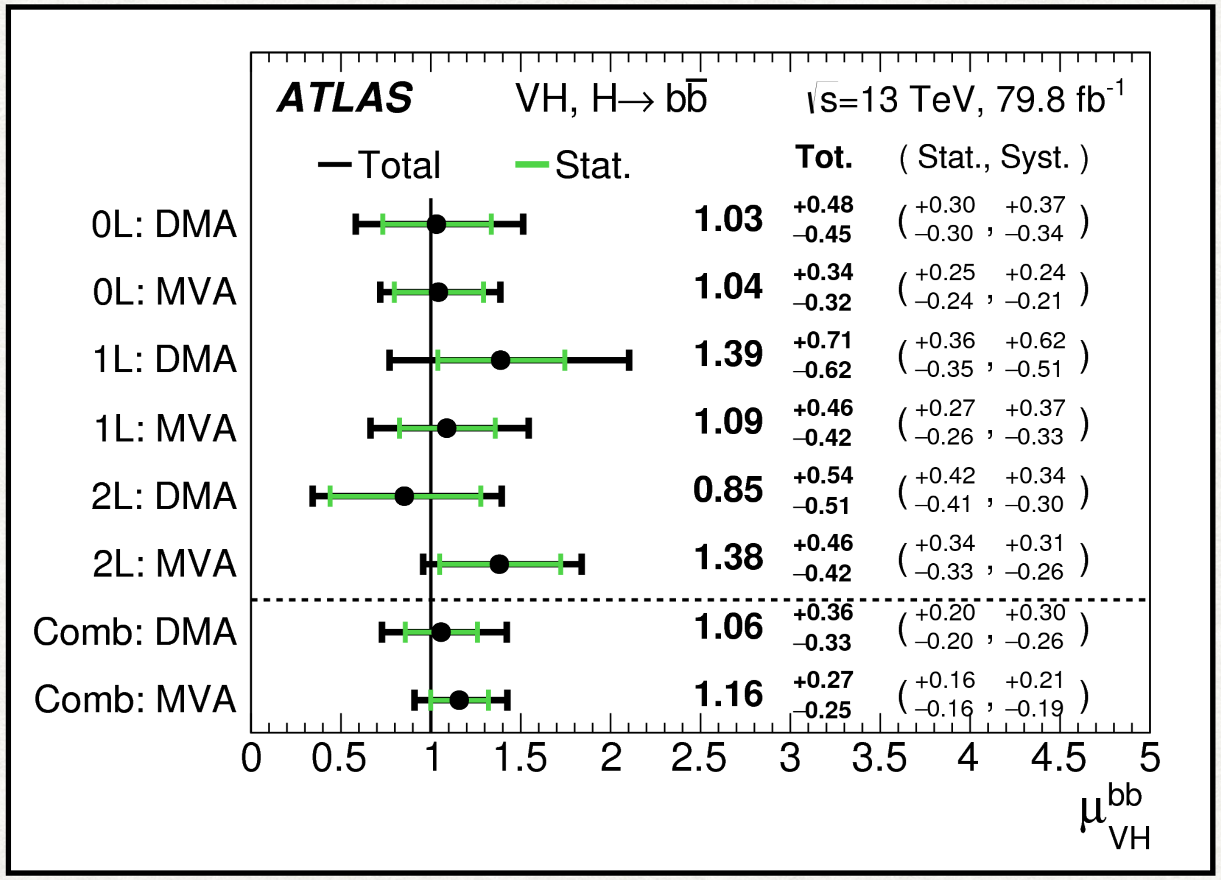


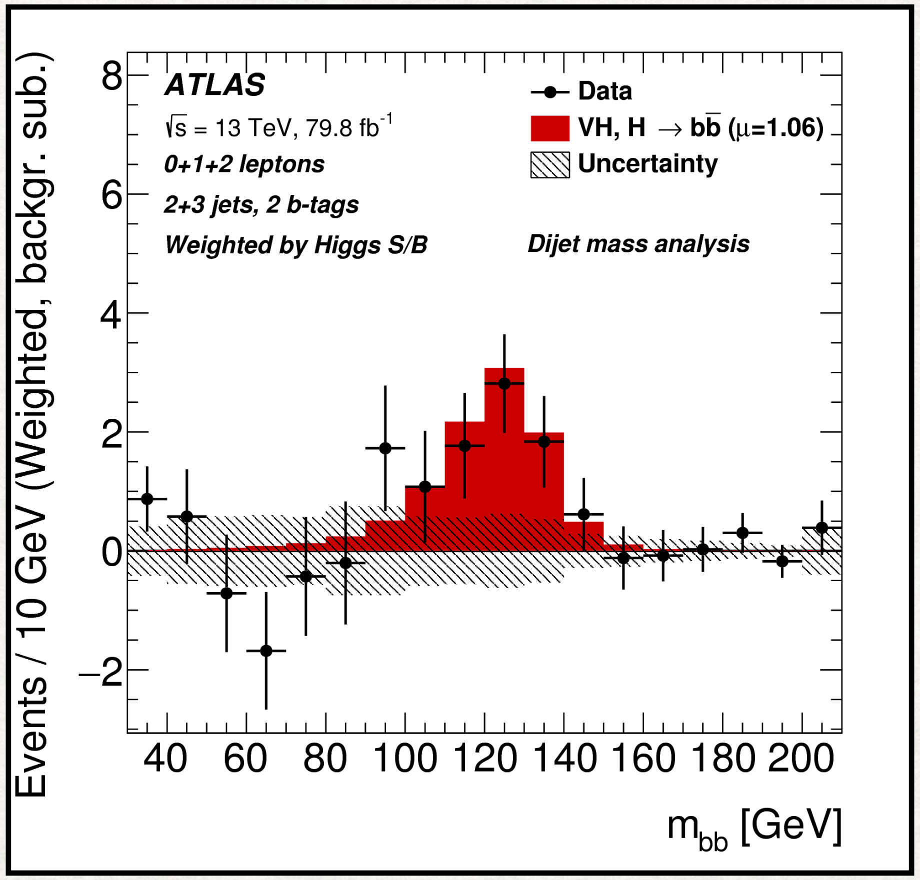
0 lepton, 2jets, 150≤pTV≤200

Di-jet mass analysis (II)

Cross-check

- Significance at **3.6σ (3.5σ exp.)**
- Signal strength **compatible** with MVA analysis in each lepton channel

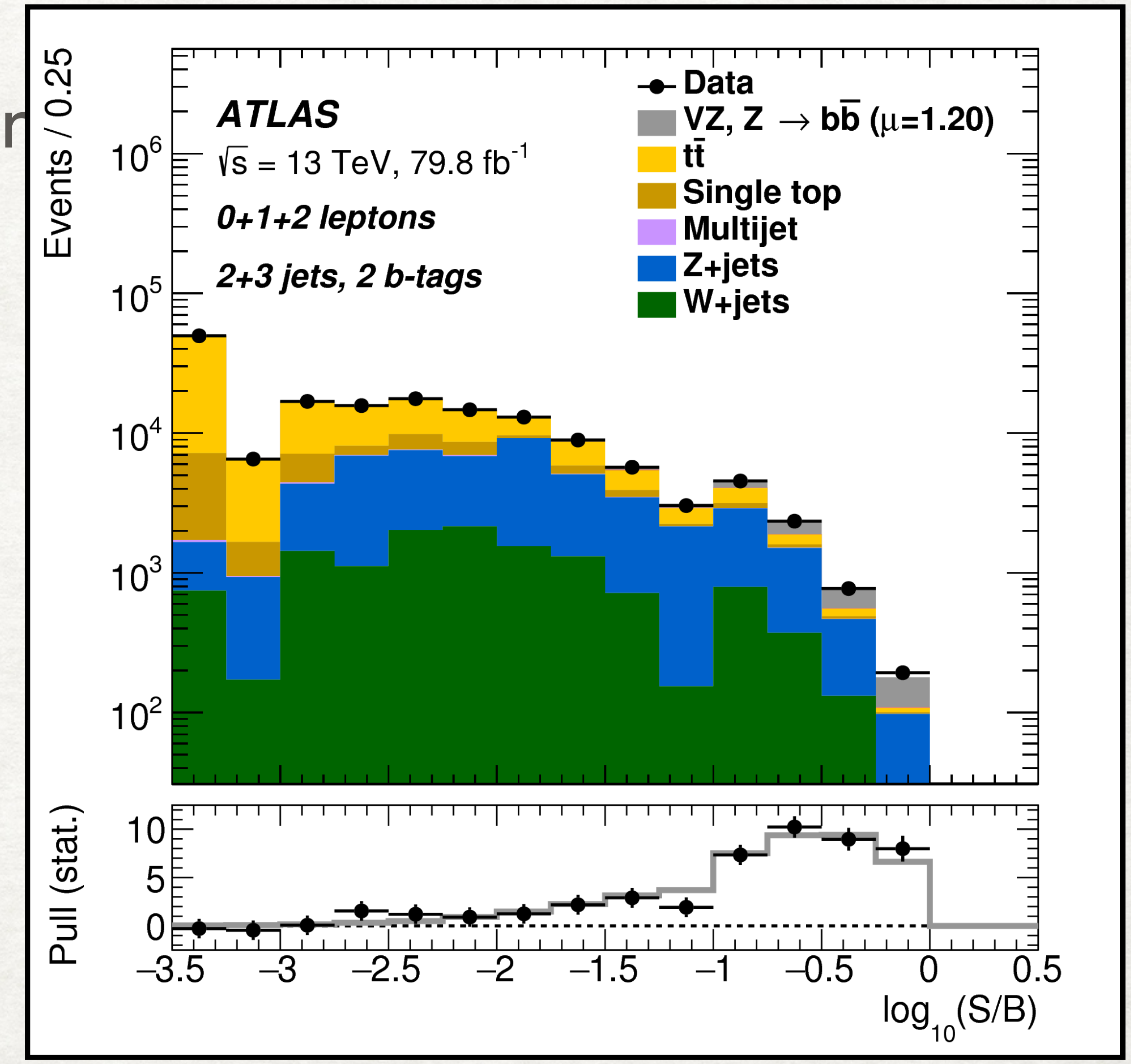




VZ analysis (I)

Cross-check

- Robust validation of background model and associated uncertainties
- Same analysis strategy as VH
- Re-train the BDT to search for VZ sign
    - 0 lepton: $Z \to \nu\nu$, $Z \to bb$
    - 1 lepton: $W \to l\nu$, $Z \to bb$
    - 2 lepton: $Z \to ll$, $Z \to bb$

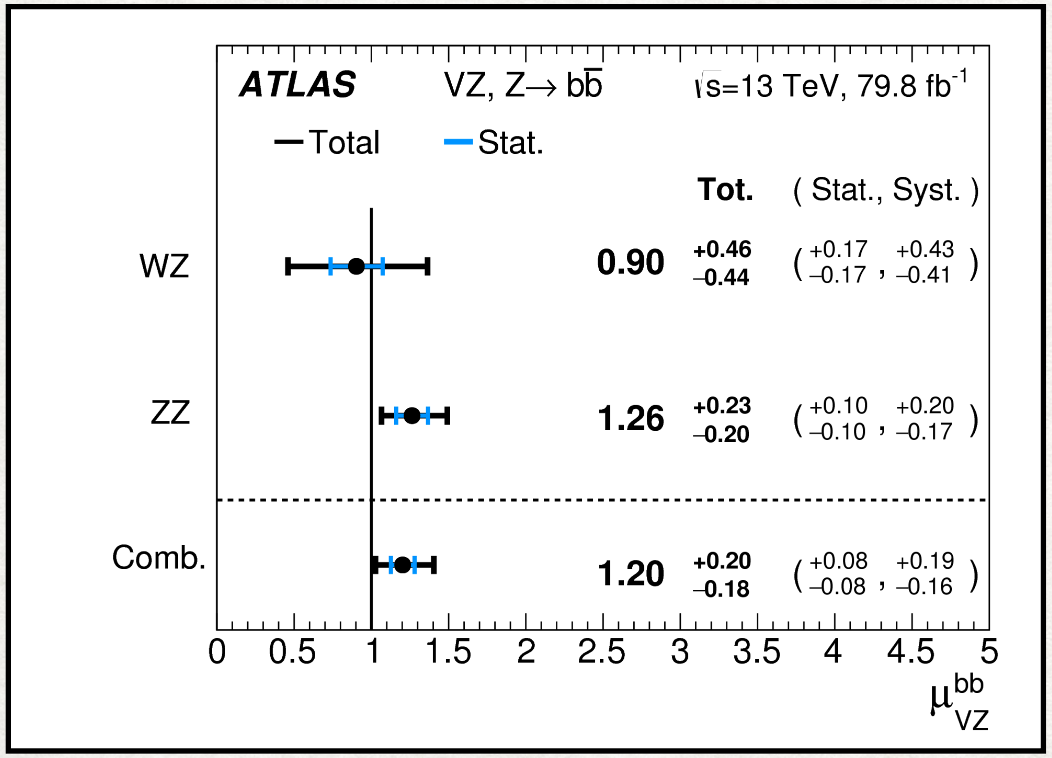


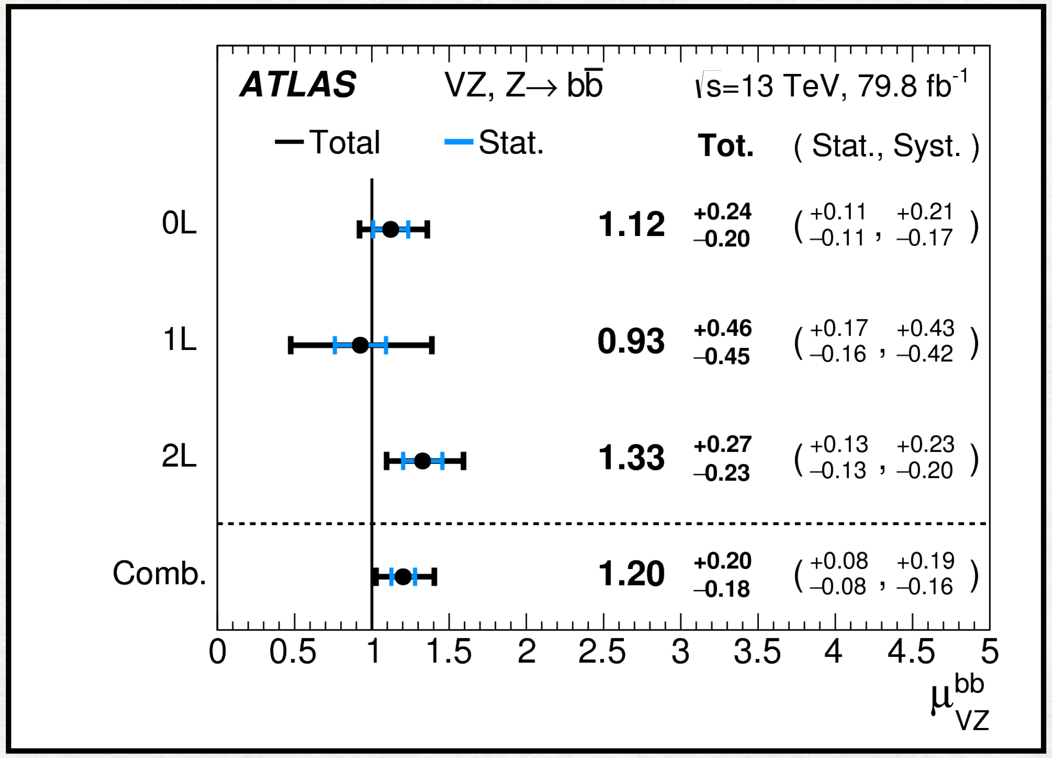
Combined BDT output of VZ

VZ analysis (II)

Cross-check

- Signal strength μ=1.20±0.19 compatible with SM
- Robust validation for VH MVA analysis

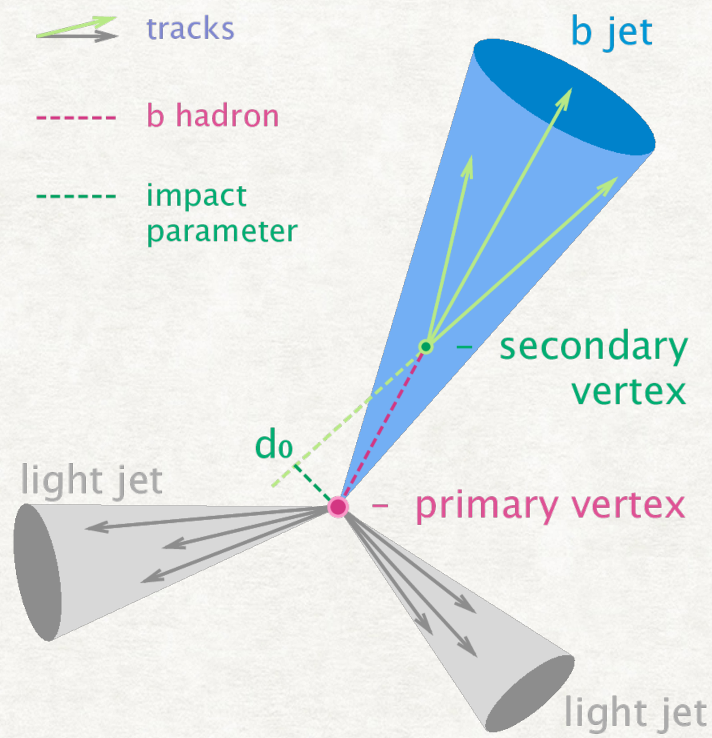




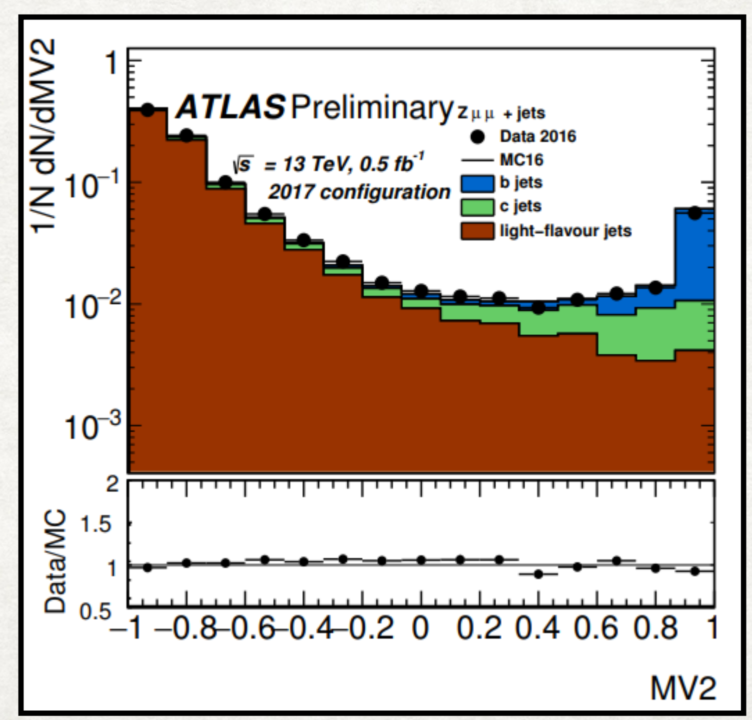
B-tagging

To identify jets from b-quark

- B-tagging
  - Depends on the good operation of the tracker
  - Performance in Run 2 relying on
    - New IBL detector installed in LS1 (2013-2014)
    - Tracking optimized for high-PU and high-p_T
    - Better ML algorithm



- MV2C10 tagger used in this analysis
  - Boosted Decision Tree (BDT) algorithm
  - Exploits the features of b-jets
    - Secondary vertex (SV)
    - Impact parameter (IP)
    - B-hadron decay chain inside jet code (JetFitter)



Rejection of light / c jets 300 / 8 at 70% b-jets efficiency

Event selection for MVA analysis

Selection	0-lepton	1-lepton e sub-channel	 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

Simulation 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

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 modeling

Z + jets, W + jets, ttbar, single top-quark and multi-jet production

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

Background modeling

Diboson

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 modeling

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

Yields

	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