9th of November 2016, Higgs Couplings, SLAC

Search for SM H → $b\bar{b}$ decays at the ATLAS experiment

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Motivation

H→b$\bar{b}$ largest branching ratio

- Probe Higgs coupling to quarks directly
- Constrain total width and help measure absolute couplings
- Experimentally very challenging

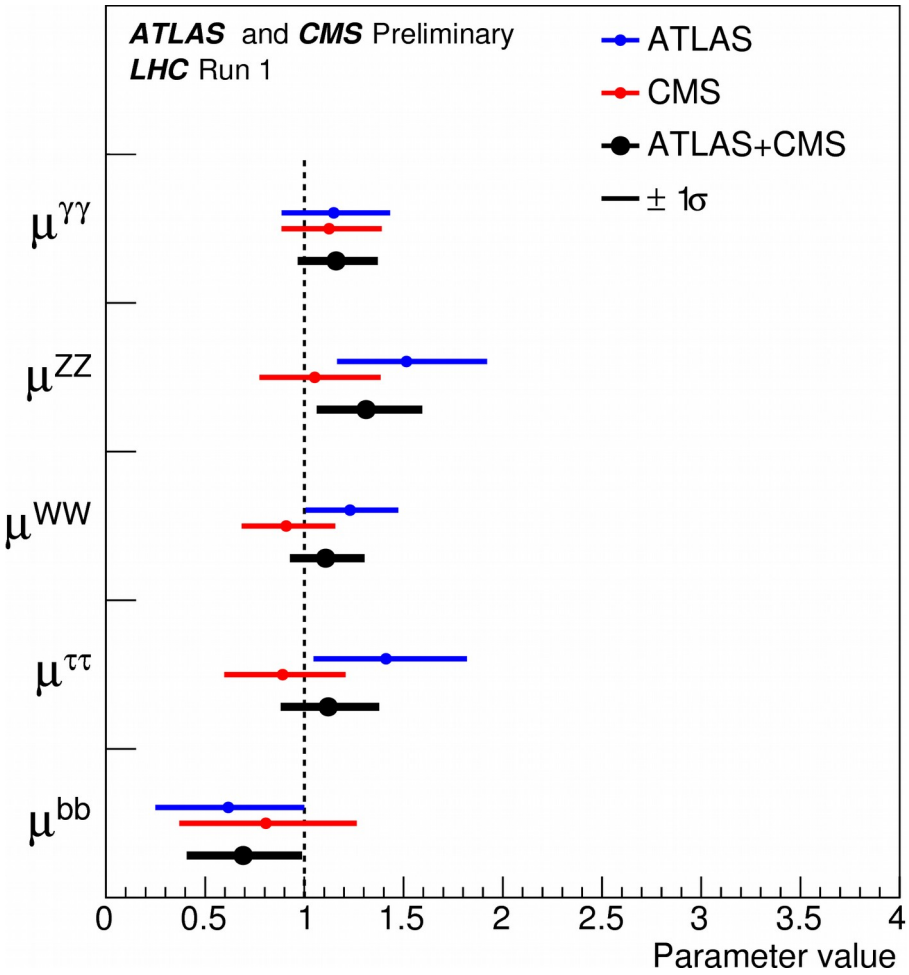
Results from Run 1 for H→b$\bar{b}$

- ATLAS + CMS combined result
- Signal strength for SM H → bb

$$\mu_{b\bar{b}}^{ATLAS+CMS} = 0.70^{+0.29}_{-0.27}$$

→ Compatible with SM Higgs

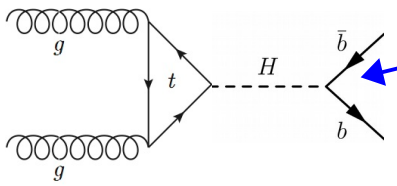
- Observed significance $2.6\,\sigma$
- Expected significance $3.7\,\sigma$



No discovery yet in this channel!

Experimental challenge

- Gluon-gluon fusion (ggF)



H → bb̄

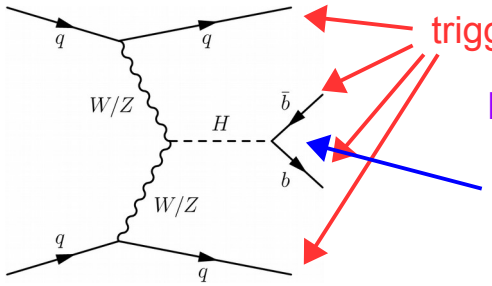
difficult to trigger

overwhelming background

- Vector boson fusion (VBF)

  arXiv:1606.02181 [hep-ex]

  submitted to JHEP



trigger on jets

large background

H → bb̄

- Vector boson fusion with photon

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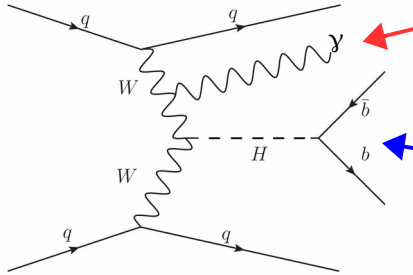


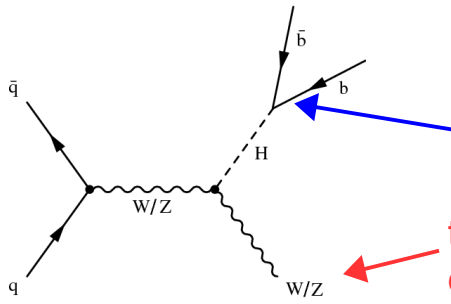
trigger on γ

clean channel, low signal

H → bb̄

- Associated production with W / Z

  ATLAS-CONF-2016-091



best significance

H → bb̄

trigger on e/μ/missing energy from W/Z decay

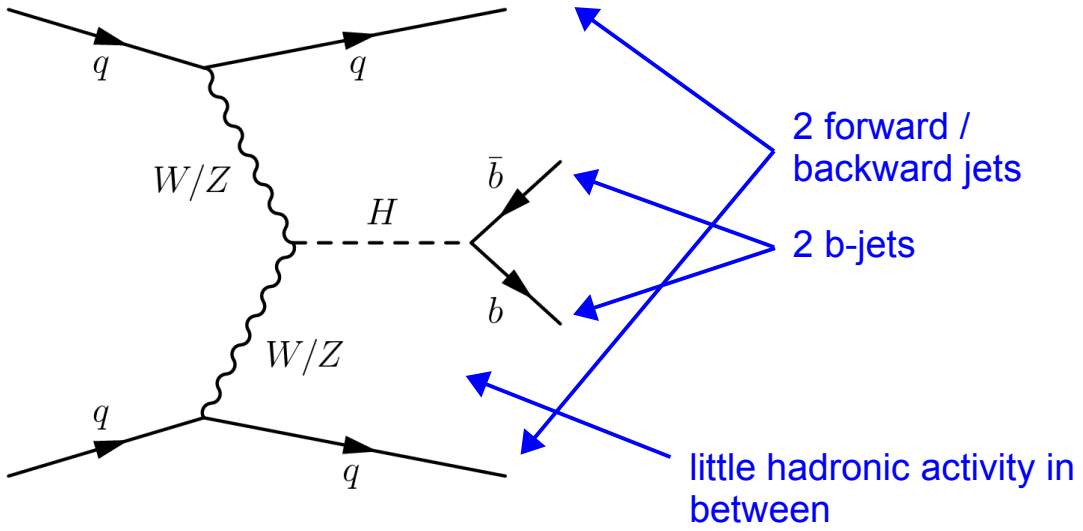
Vector boson fusion H(→bb) + jj

arXiv:1606.02181 [hep-ex]
submitted to JHEP

Analysis with L = 20.2 fb^{-1} at $\sqrt{s}$ = 8 TeV

Signal

- Vector boson fusion
  (small contribution from ggF)
- H(→bb) + jj



Backgrounds

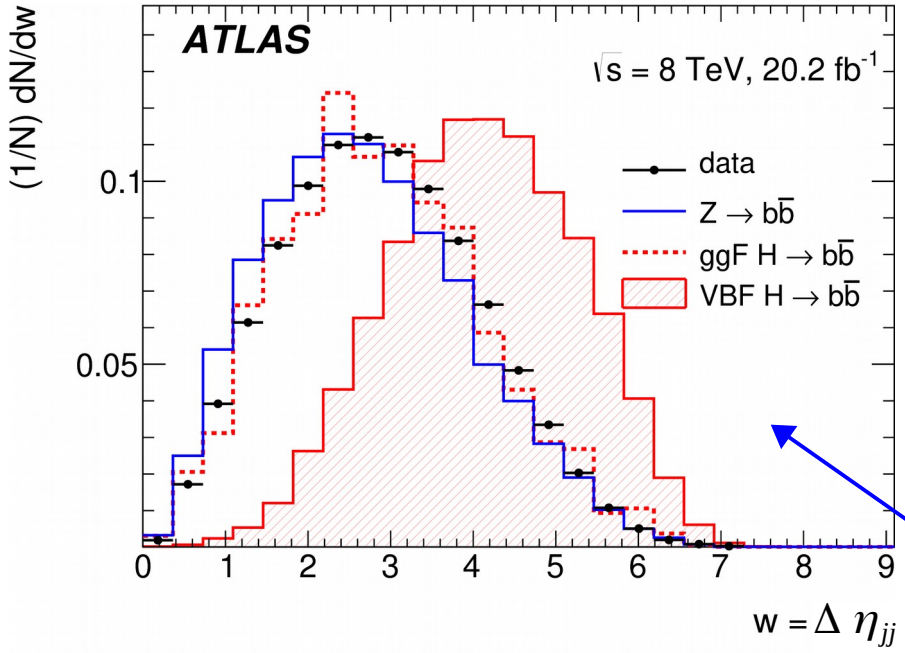
- Resonant:
  Z(→bb) + jj
- Non-resonant:
  Multijet, top quarks,
  W + jets

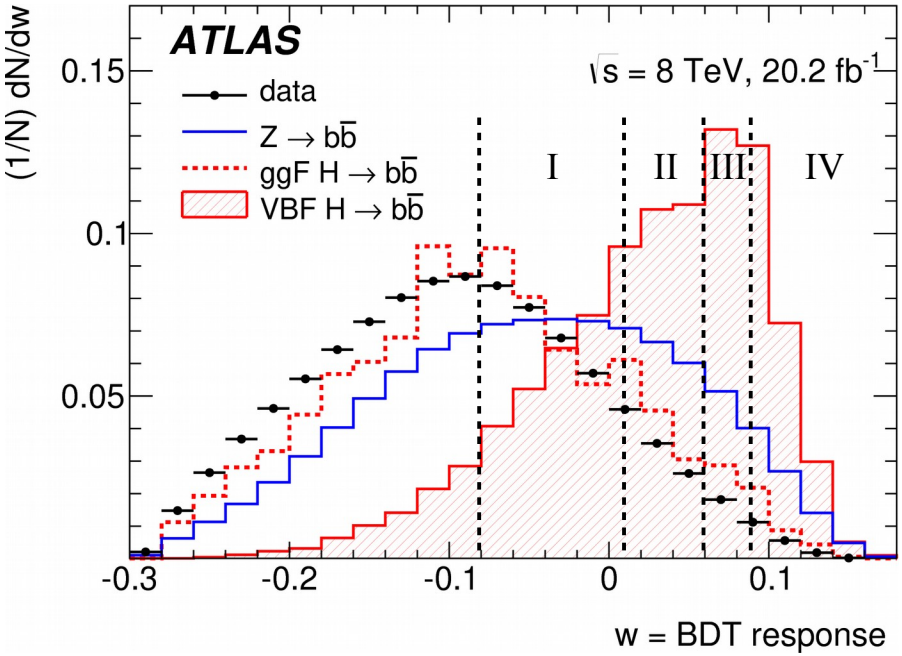
Event preselection

- 4 jets with p_T > 50 GeV, $|\eta|$ < 4.5
  → 2 b-jets with $|\eta|$ < 2.5 (nominal efficiency 70%, c-jet 20%, light-jet 1%)
  → $p_T^{b\bar{b}}$ > 100 GeV

Multivariate analysis

arXiv:1606.02181 [hep-ex]
submitted to JHEP





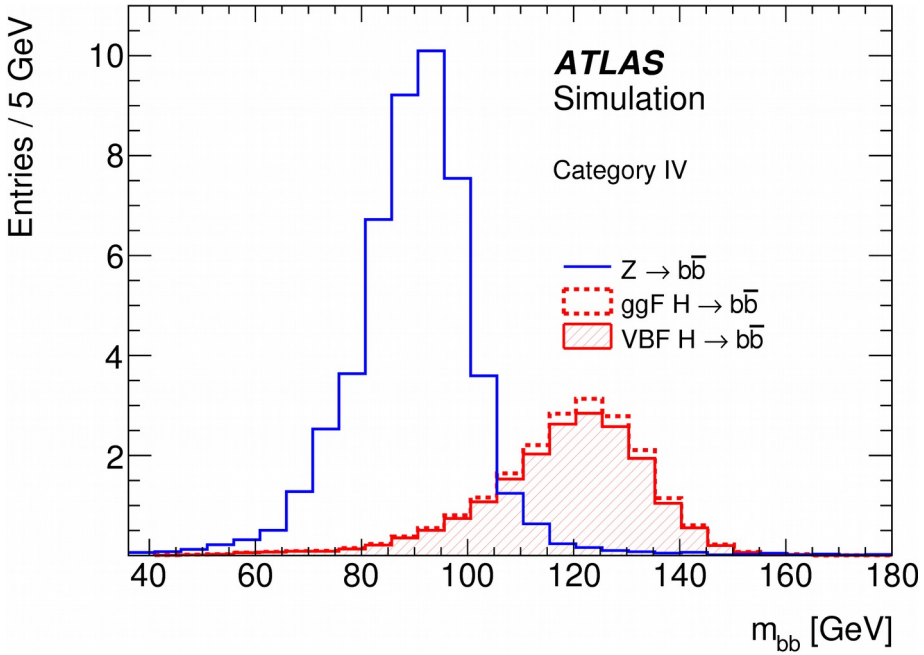
- Boosted decision tree (BDT)
  → discriminate signal (MC) and non-resonant background (data in $m_{b\bar{b}}$ sideband)
  → variables uncorrelated to $m_{b\bar{b}}$

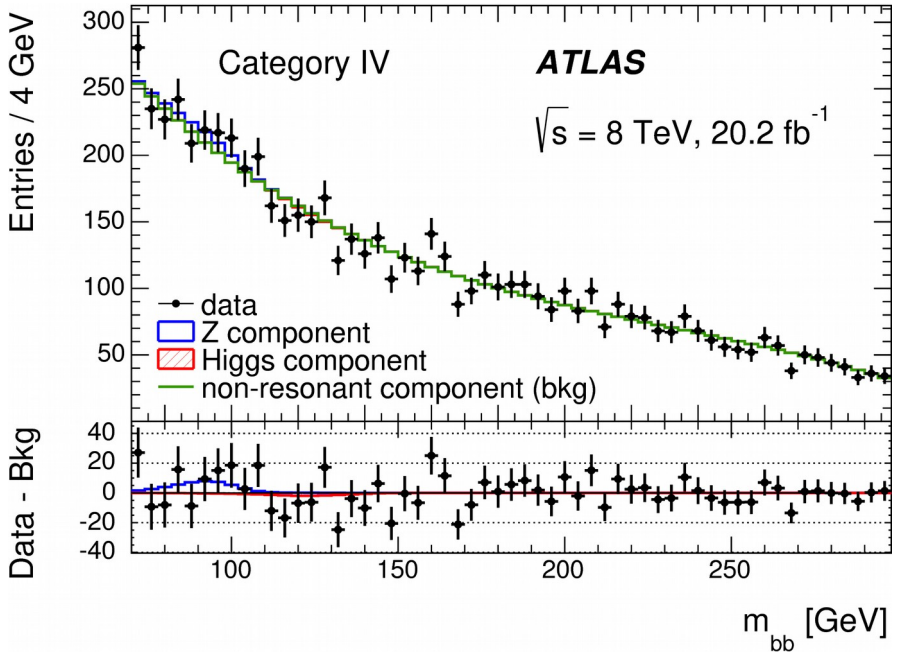
jet width	quark/gluon separation for VBF jets
$\sum_{3}^{\infty} p_T^{j_i}$	activity from additional central jets
m_{jj}	invariant mass of VBF jets
$\Delta\eta_{jj}$	rapidity separation of VBF jets
$max\left(\lvert\eta_{j_1}\rvert,\lvert\eta_{j_2}\rvert\right)$	maximum rapidity of VBF jets
separation	between photon and VBF jets
$\cos(\theta)$	sensitive to production mechanism

- Output categorized into 4 BDT regions
  → more background in region I
  → best significance in region IV

Signal extraction and results

arXiv:1606.02181 [hep-ex]
submitted to JHEP





Shapes

- H(→bb) + jj
- Z(→bb) + jj

} Smoothed distributions from simulations

- Non-resonant backgrounds

} Bernstein polynomial fit to data in m_{bb} sideband (several functions compared)

Fit procedure

- Profile likelihood fit
- 4 BDT categories as function of m_{bb}
- Systematic uncertainties as nuisance parameters

Results

- L = 20.2 fb^{-1} at $\sqrt{s}$ = 8 TeV
- Signal strength

$$\mu^{VBF}_{H(b\bar{b})} = -0.8 \pm 2.3$$

cross-checked using cut-based analysis

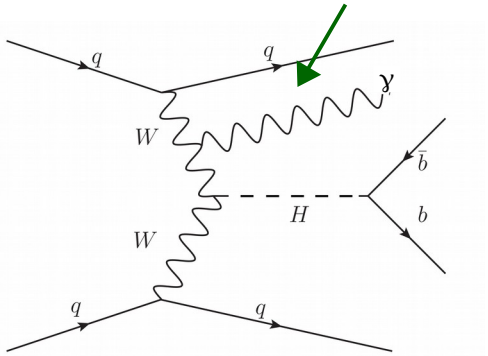
- Dominant uncertainty
  → Non-resonant background modeling (statistics in sideband, functional form)
  → Statistical uncertainty

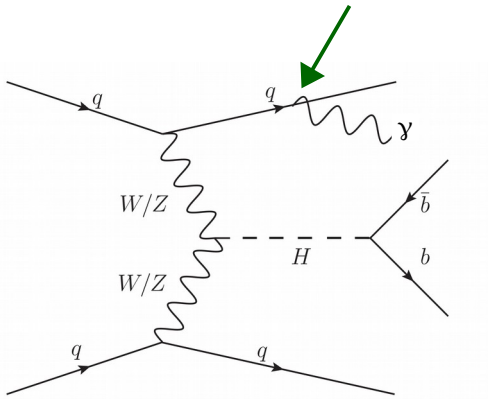
Analysis limited by statistics

Vector boson fusion H(→bb̄) + γ + jj

Analysis with L = 12.6 fb^{-1} at $\sqrt{s}$ = 13 TeV

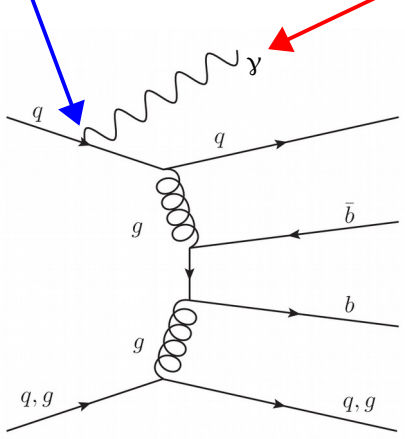
- VBF H → bb̄ analysis suffers from increased jet trigger thresholds
- Additional photon: cleaner events, trigger
- Very similar strategy than VBF H → bb̄
  → only highlight differences here

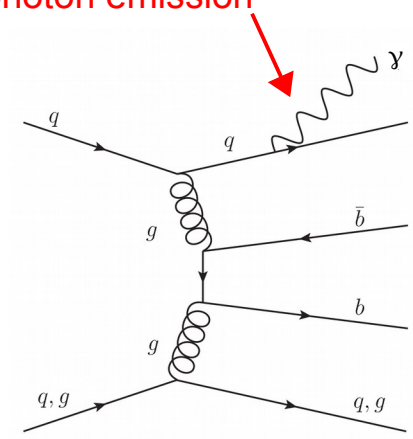




γ suppresses gluon-induced processes

destructive interference from ISR and FSR suppresses central photon emission





Signal

- H(→bb) + γ + VBF jets

Backgrounds

- Resonant Z(→bb) + γ + VBF jets
- Non-resonant production
  Photon suppresses background by more than 1 order of magnitude from simple O(α_{EW})

See also contribution by Peyton Rose (Parallel 2: B)

Event selection

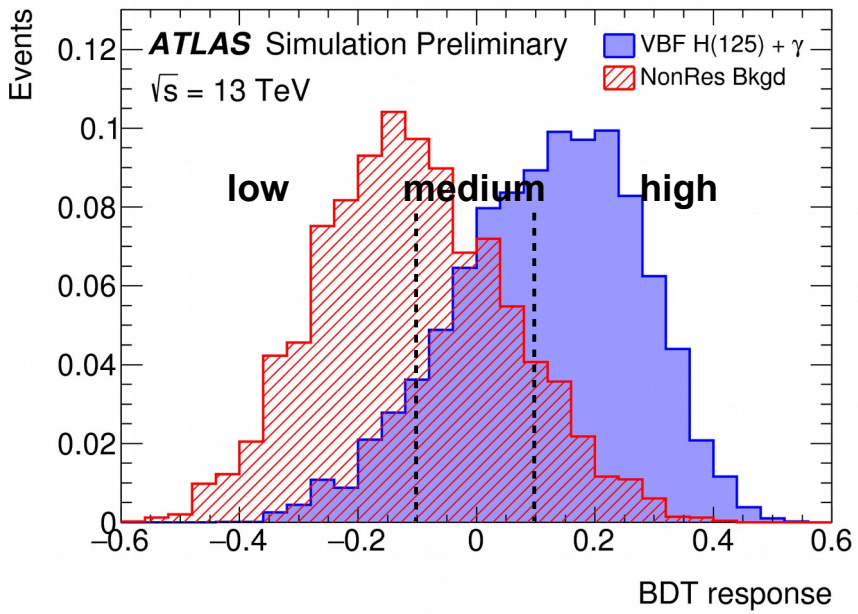
Preselection

- Photon with p_T > 30 GeV, tight identification requirements
- 4 jets with p_T > 40 GeV, $|\eta|$ < 4.5
  - 2 b-jets with $|\eta|$ < 2.5, $p_T^{b\bar{b}}$ > 80 GeV (nominal efficiency 77%,light-jet rejection 130)
  - 2 jets with m_{jj} > 800 GeV

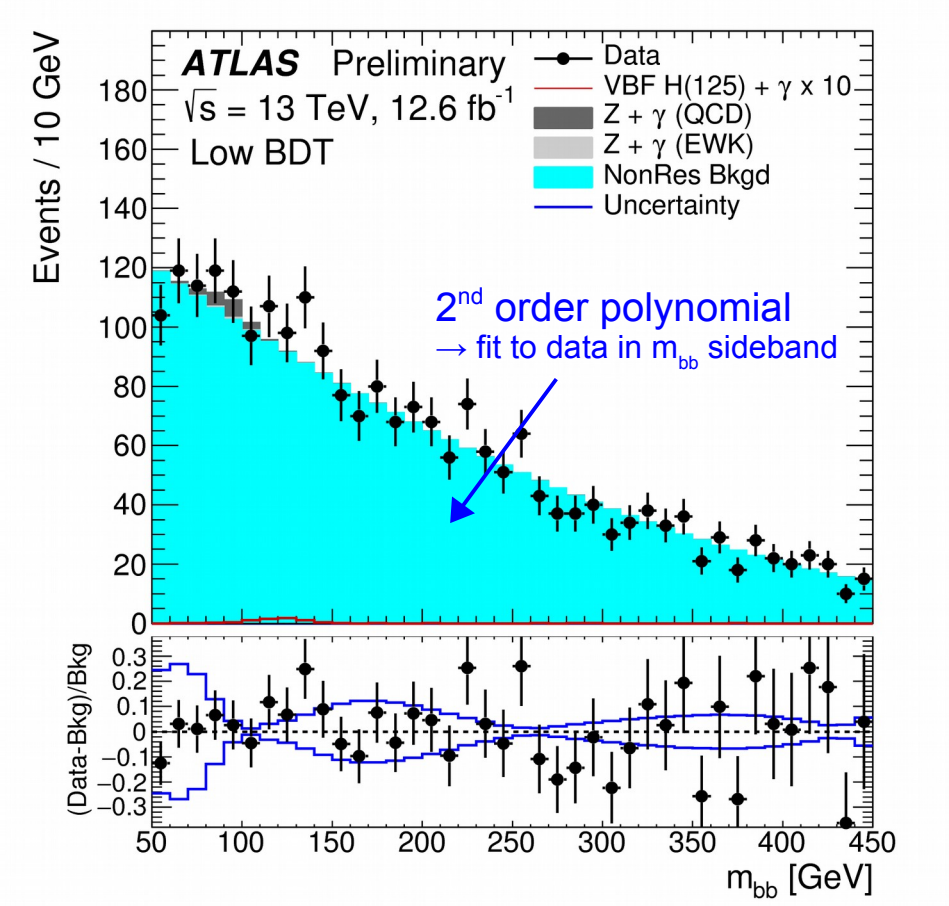
Multivariate analysis

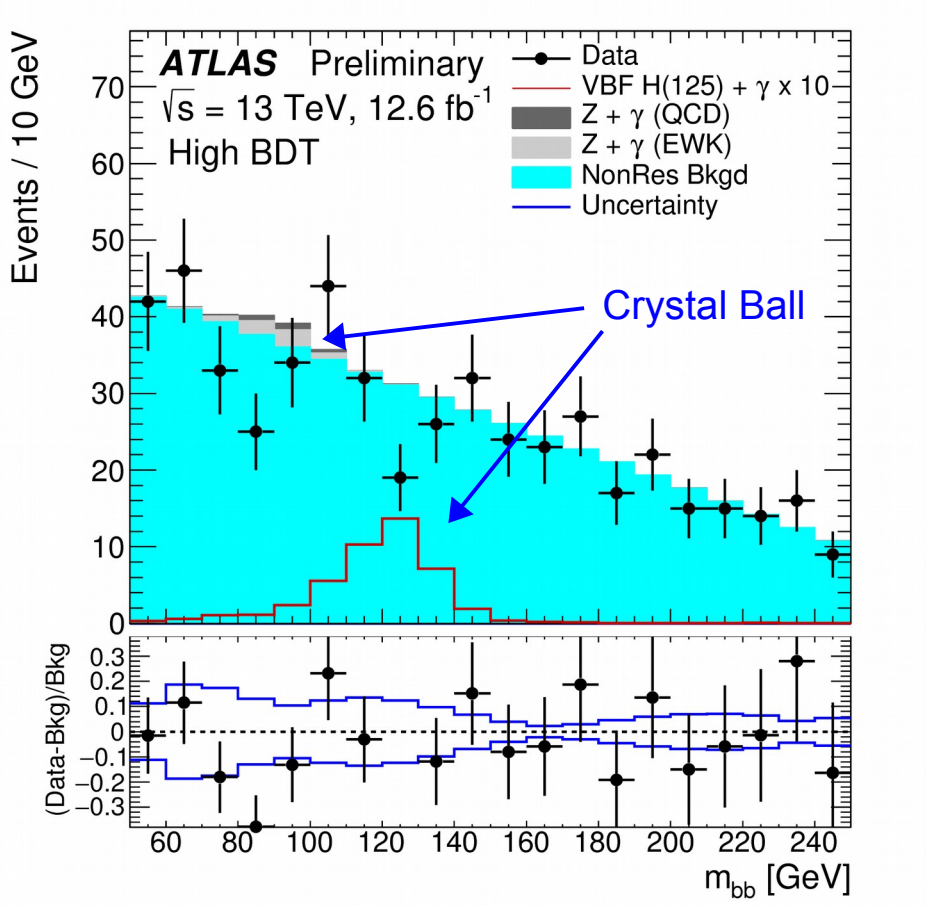
- Boosted decision tree
  - trained with signal and non-resonant backgrounds from simulation
  - variables uncorrelated to m_{bb}
- Division in 3 regions
  - low, medium and high s/b

$\Delta R(jet, \gamma)$	angular separation between photon and b-jets / VBF jets
$centrality(\gamma)$	centrality of photon with respect to VBF jets
m_{jj}	invariant mass of VBF jets
$\Delta \eta_{jj}$	rapidity separation of VBF jets
$jet\ width$	quark/gluon separation for VBF jets
$p_T^{balance}$	separation of resonant and non-resonant processes
H_T^{soft}	soft additional track jets



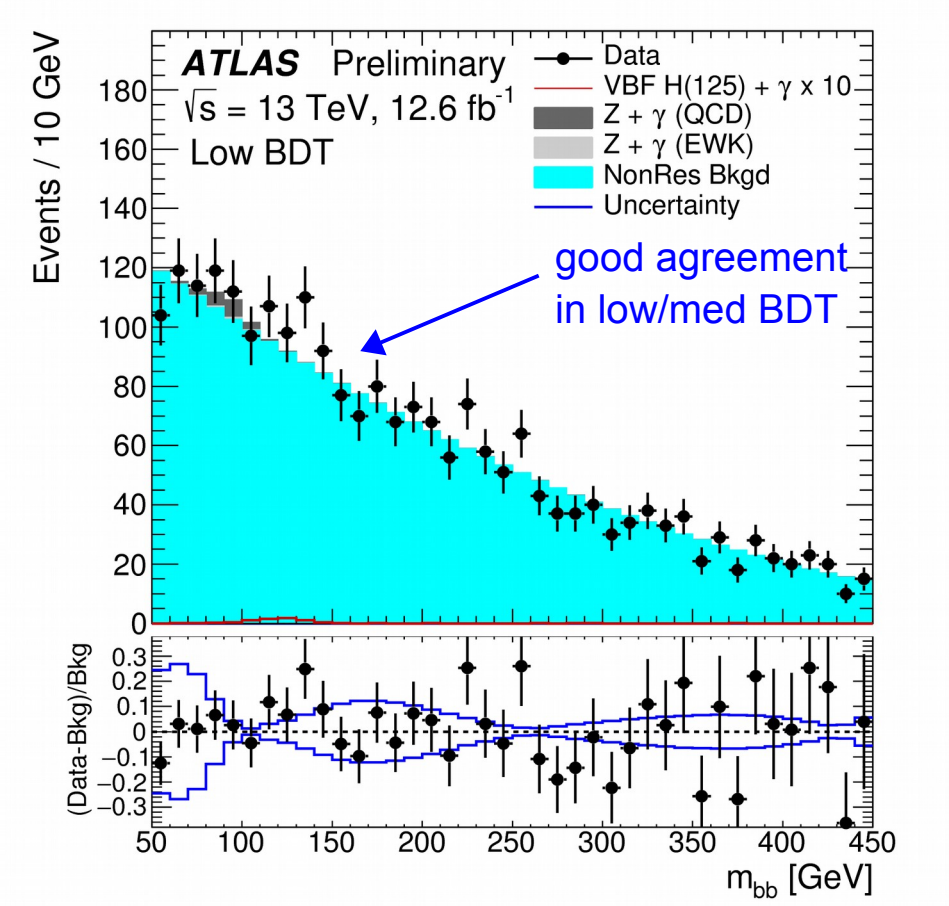
Signal extraction

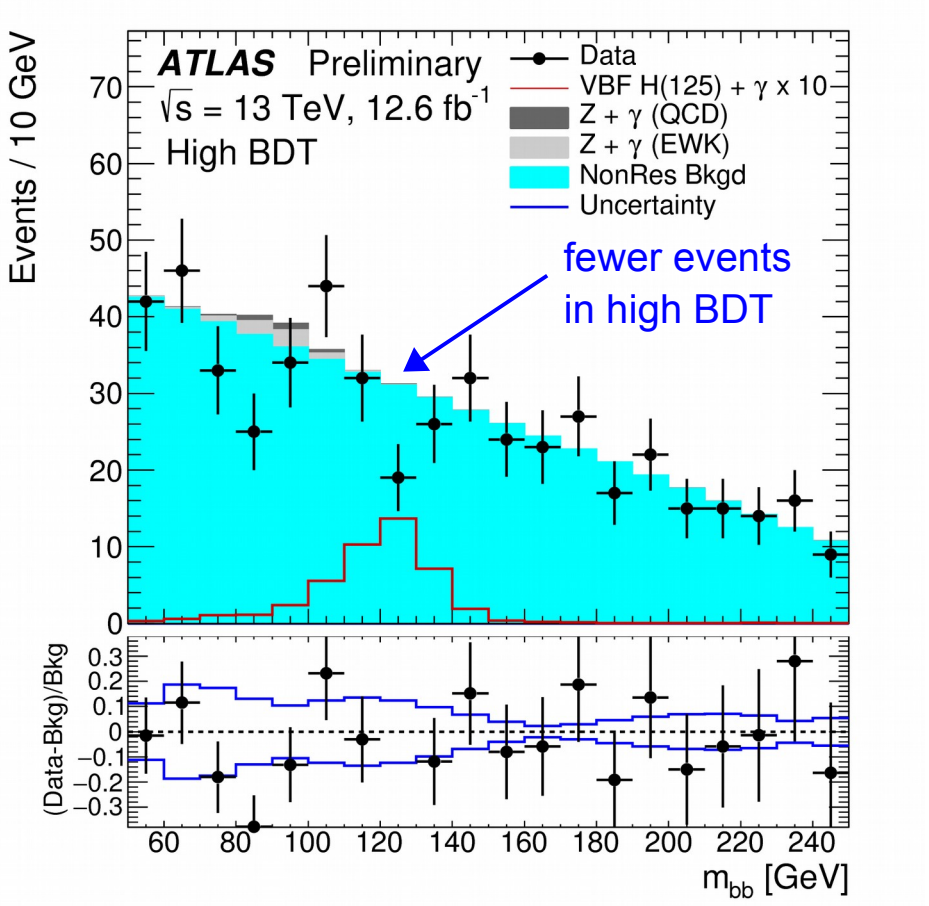




- Profile likelihood fit
  - 3 BDT categories, fit in m_{bb}
  - Systematic uncertainties as nuisance parameters
    → dominated by non-resonant background modeling
    → choice of functional form limited by statistical uncertainty

Results for VBF: H(→bb̄) + γ + jj





- Result with L = 12.6 fb^{-1} at $\sqrt{s}$ = 13 TeV

Signal strength $\mu^{VBF}_{\gamma H(b\bar{b})} = -3.9^{+2.8}_{-2.7}$

Uncertainty dominated by statistics!

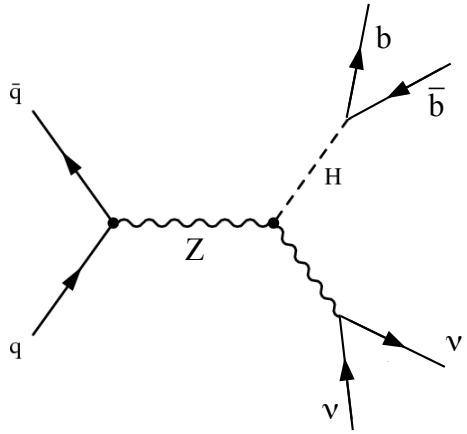
→ Cross-checked searching for Z(→bb̄) + γ + jj $\mu^{VBF}_{\gamma Z(b\bar{b})} = 0.3 \pm 0.8$

Associated production VH(→$b\bar{b}$)

Common event selection

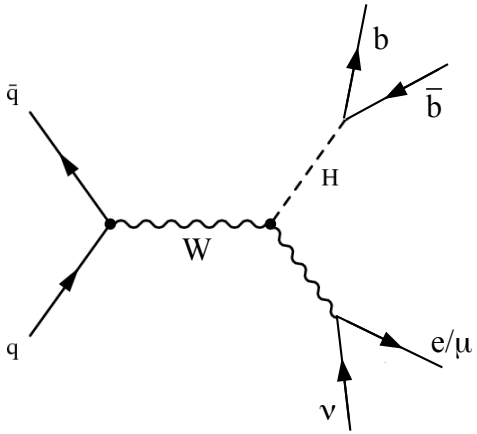
- Leptons (e, μ) from vector boson decay, p_T > 7 GeV, loose identification requirements
- ≥ 2 jets (anti-k_T, R=0.4), with p_T > 45 GeV for leading jet
- = 2 b-tags (70% efficiency working point: light jet rejection 380, charm rejection 12)

0-lepton



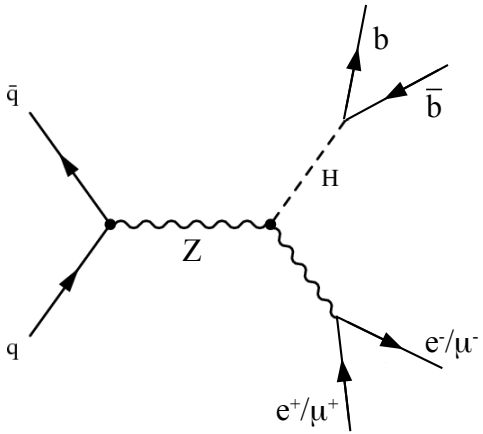
- No leptons
- E_T^{miss} > 150 GeV
- Cuts in dϕ between objects to suppress QCD
- 2 / 3 jets

1-lepton



- 1 lepton with p_T> 25 GeV
  + tight identification requirements
- p_T^W > 150 GeV
- E_T^{miss} > 30 GeV
  (electron only)
- 2 / 3 jets

2-lepton

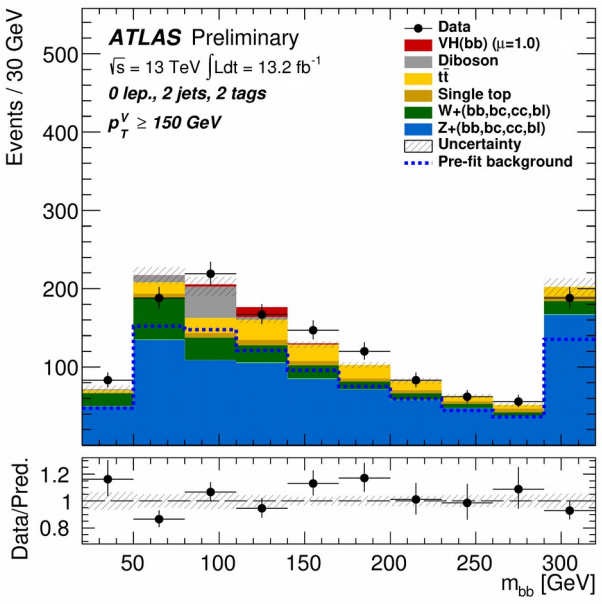


- 1 lepton with p_T > 25 GeV
  1 lepton with p_T > 7 GeV
- 71 < m_{ll} < 121 GeV
- p_T^Z < 150 GeV
  p_T^Z ≥ 150 GeV
- 2 / 3+ jets

Dominant backgrounds

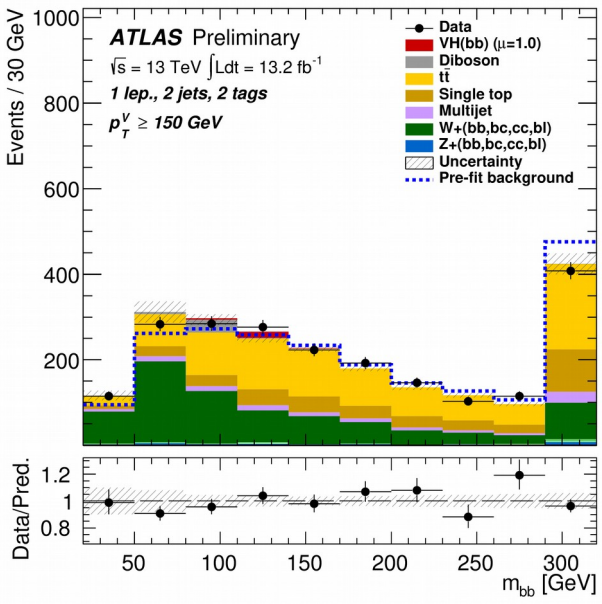
- Backgrounds modeled from simulation
- Background composition depending on decay channel

0-lepton



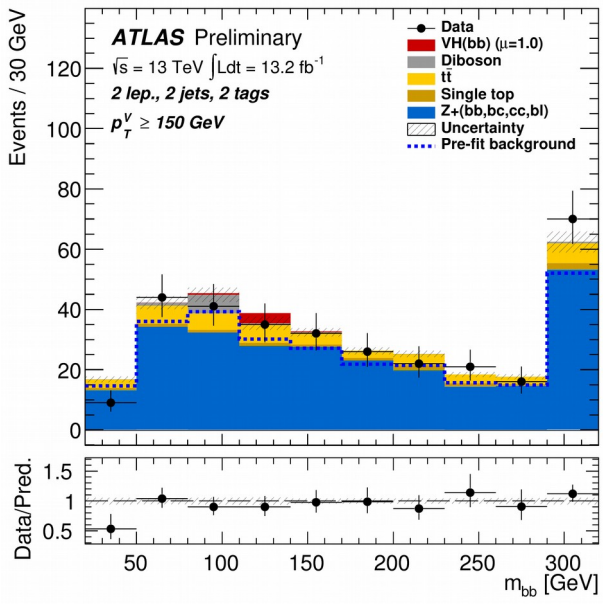
→ Z + b-jets

1-lepton



→ Top-quarks
→ W + b-jets

2-lepton



→ Z + b-jets

- Multijet background efficiently suppressed in associated production
  - Negligible in 0- and 2-lepton after anti-QCD cuts
  - Small contribution in 1-lepton channel, data-driven estimate

Multivariate analysis

- Boosted decision tree (BDT)
- Trained in 8 categories:
  [0-lepton, 1-lepton, 2-lepton] x [2 jets, 3 jets] x [low p_T^V, high p_T^V]

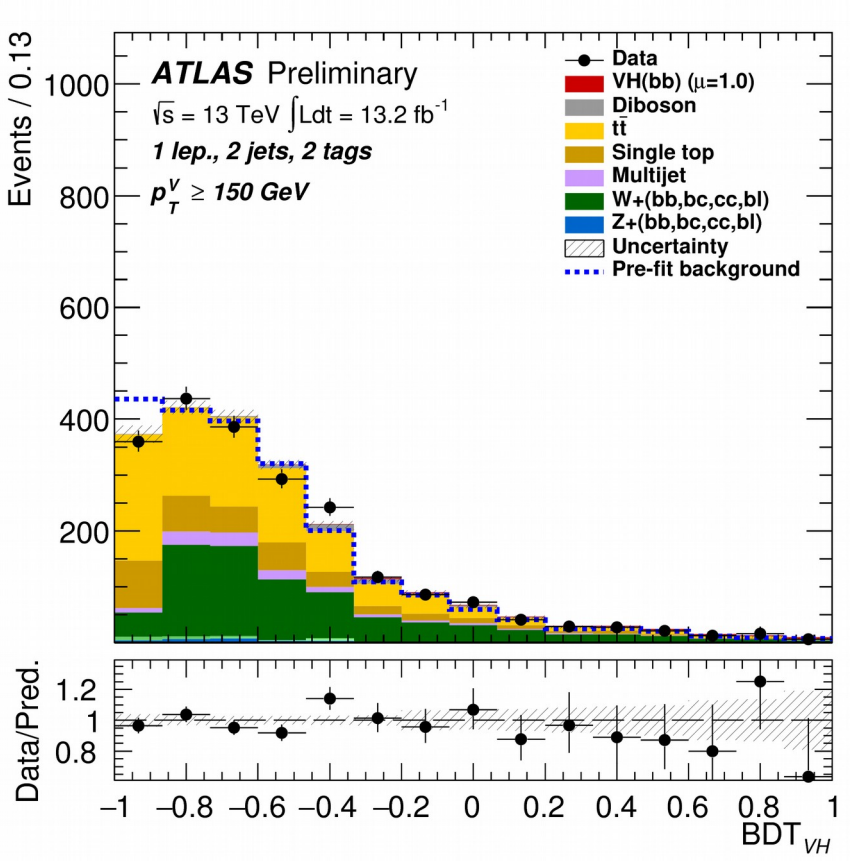
2-lepton only

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

best sensitivity at large p_T^V

best discrimination

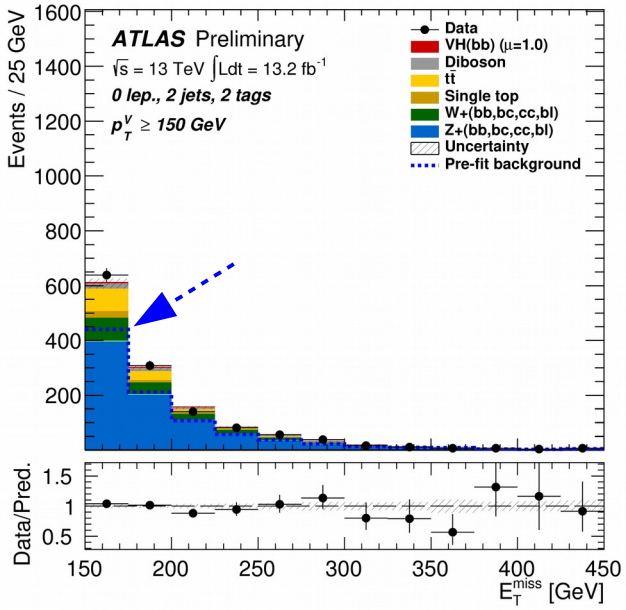
suppress top new in Run 2

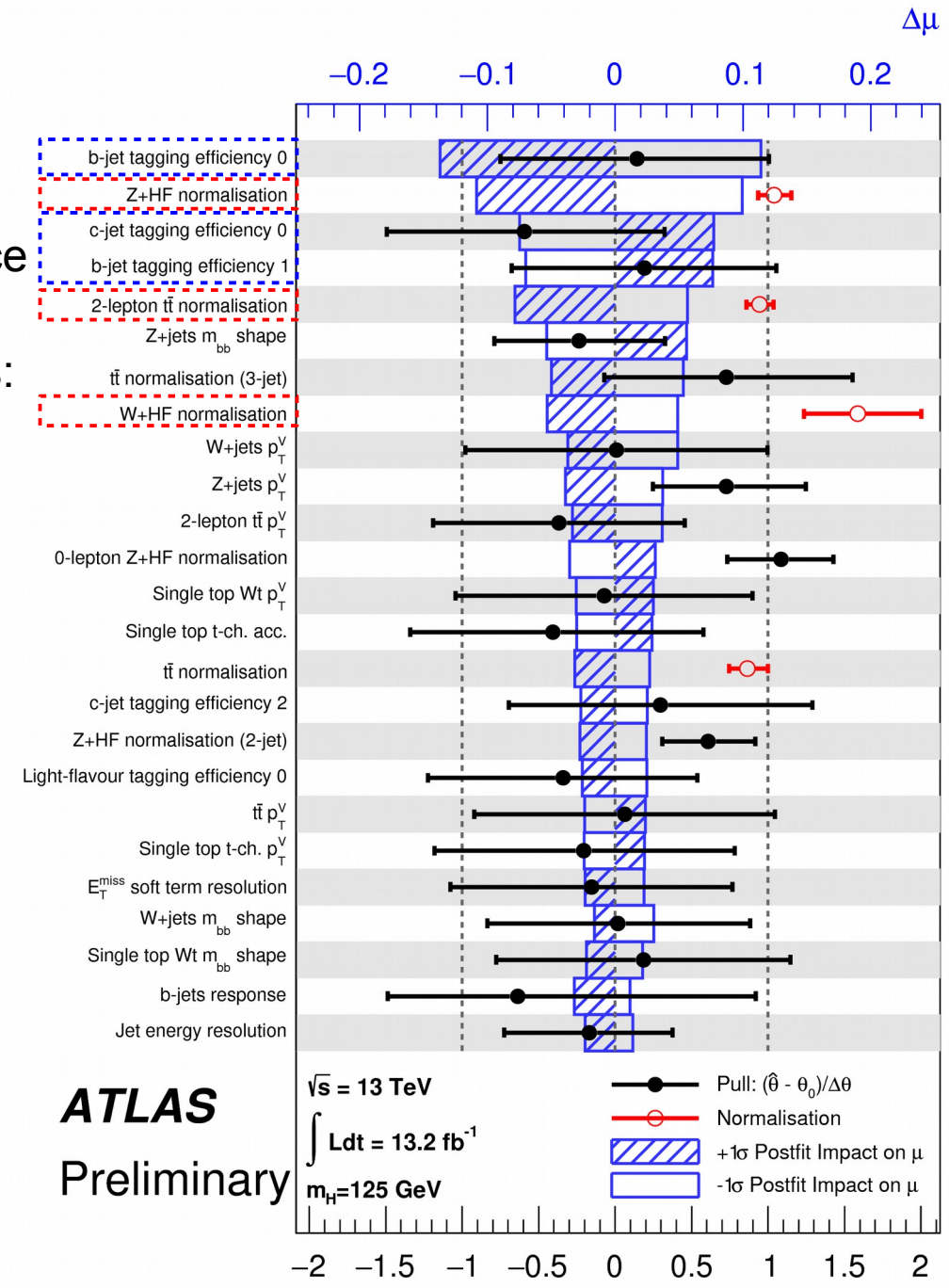


Combined fit

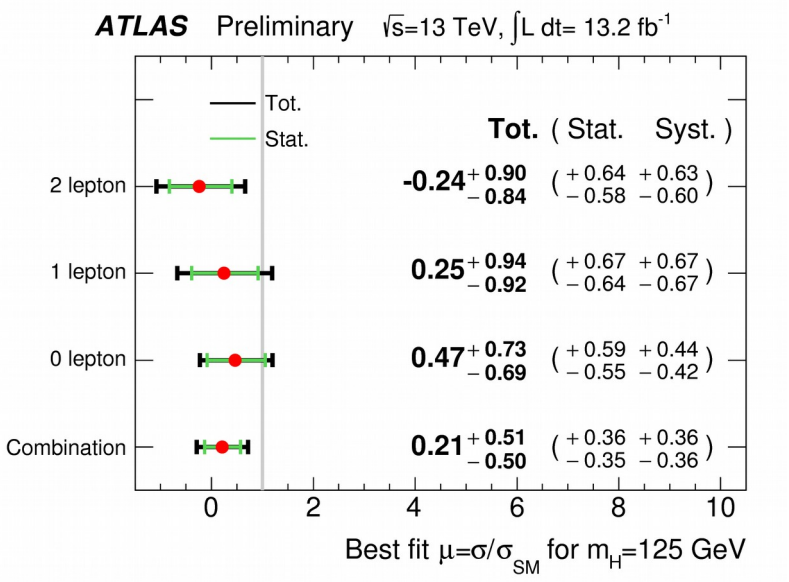
- Profiled likelihood fit
  - 8 BDT discriminants as inputs
  - Systematic uncertainties and floating background normalizations as nuisance parameters
  - Dominating experimental uncertainties: flavor tagging, jet energy scale and resolution
  - Dominating theoretical uncertainties: normalisation of V+HF and tt̄, m_{bb} shape, p_T^V modelling

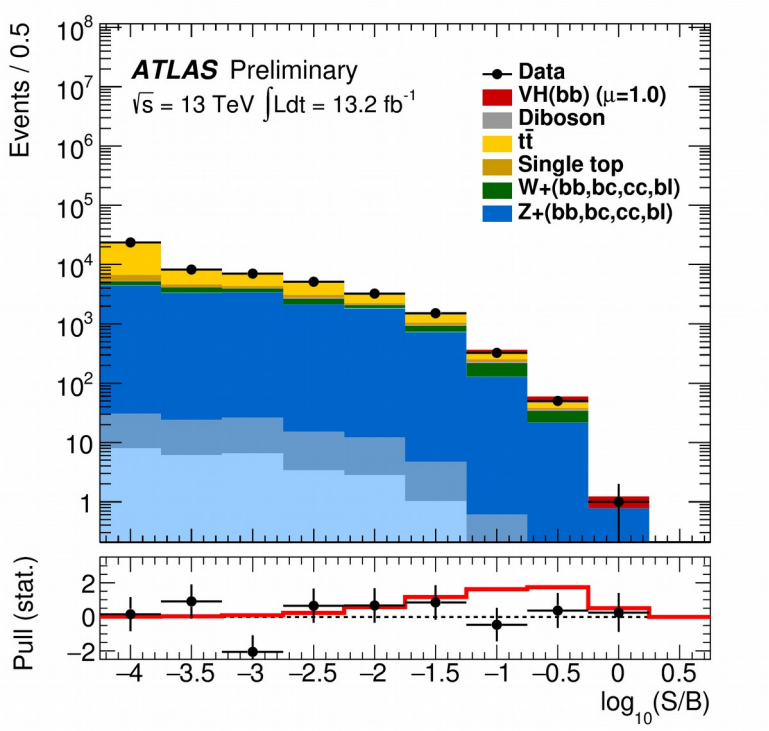
- Post-fit distribution: 0-lepton





Results for VH(→bb̄)





- L = 13.2 fb^{-1} at $\sqrt{s}$ = 13 TeV
- Search for VH(→bb̄)
  - Signal strength (WH+ZH) $\mu_{VH(b\bar{b})} = 0.21^{+0.51}_{-0.50}$
  - → Observed significance 0.42
  - → Expected significance 1.94
  - Systematic and statistical uncertainties of same size
- Cross-checked with VZ(→bb̄)
  - Signal strength $\mu_{VZ(b\bar{b})} = 0.91^{+0.36}_{-0.29}$

Dataset	Limit		p_0		Significance	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
0-lepton	$1.4^{+0.6}_{-0.4}$	2.0	0.07	0.15	1.45	1.02
1-lepton	$2.0^{+0.8}_{-0.6}$	2.1	0.15	0.46	1.04	0.10
2-lepton	$1.8^{+0.7}_{-0.5}$	1.7	0.13	0.57	1.14	−0.17
Combined	$1.0^{+0.4}_{-0.3}$	1.2	0.03	0.34	1.94	0.42

Summary

- Search for $H(\rightarrow b\bar{b})$ + jj in VBF
  - L = 20.2 fb^{-1} at $\sqrt{s}$ = 8 TeV
  - Signal strength $\mu^{VBF}_{H(b\bar{b})} = -0.8 \pm 2.3$
    → Observed 95% CL limit 4.4
    → Expected 95% CL limit 5.4

arXiv:1606.02181 [hep-ex]
submitted to JHEP

- Search for $H(\rightarrow b\bar{b})$ + γ + jj in VBF
  - L = 12.6 fb^{-1} at $\sqrt{s}$ = 13 TeV
  - Signal strength $\mu^{VBF}_{\gamma\, H(b\bar{b})} = -3.9^{+2.8}_{-2.7}$
    → Observed 95% CL limit 4.0
    → Expected 95% CL limit $6.0^{+2.3}_{-1.7}$

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see contribution by Peyton Rose (Parallel 2: B)

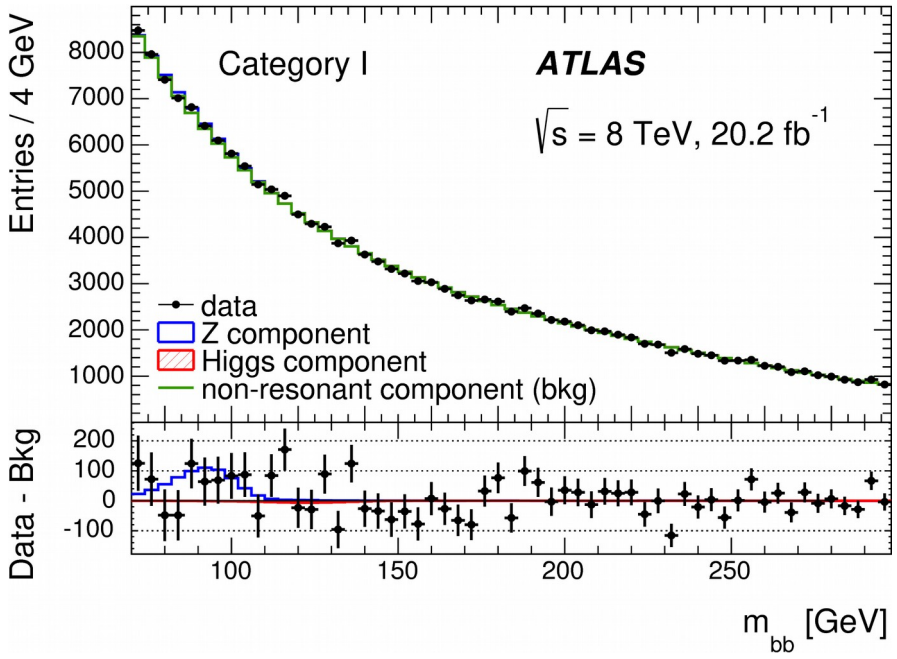
- Search for $VH(\rightarrow b\bar{b})$
  - L = 13.2 fb^{-1} at $\sqrt{s}$ = 13 TeV
  - Signal strength (WH+ZH) $\mu_{VH(b\bar{b})} = 0.21^{+0.51}_{-0.50}$
    → Observed 95% CL limit 1.2
    → Expected 95% CL limit $1.0^{+0.4}_{-0.3}$

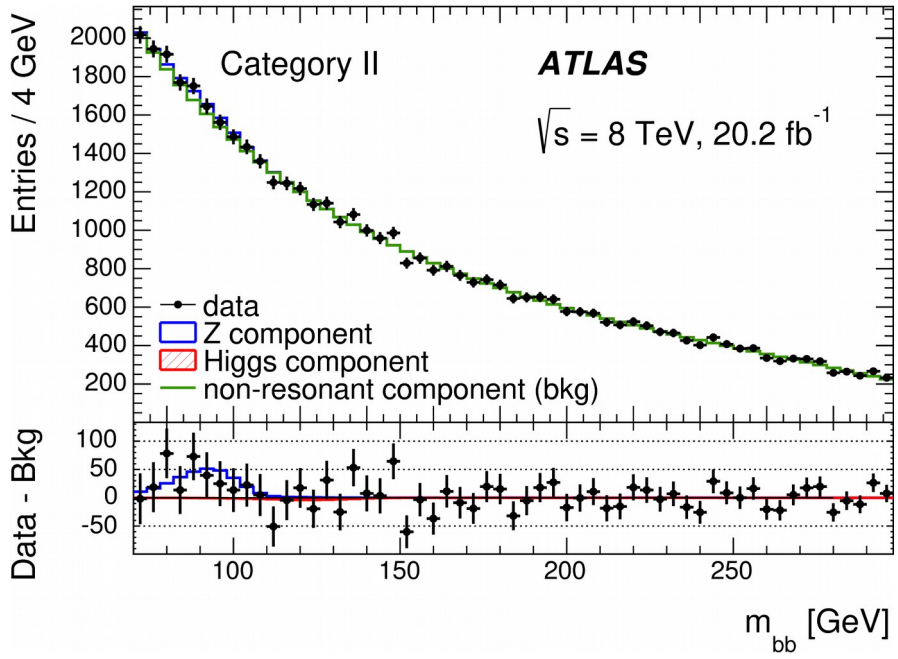
ATLAS-CONF-2016-091

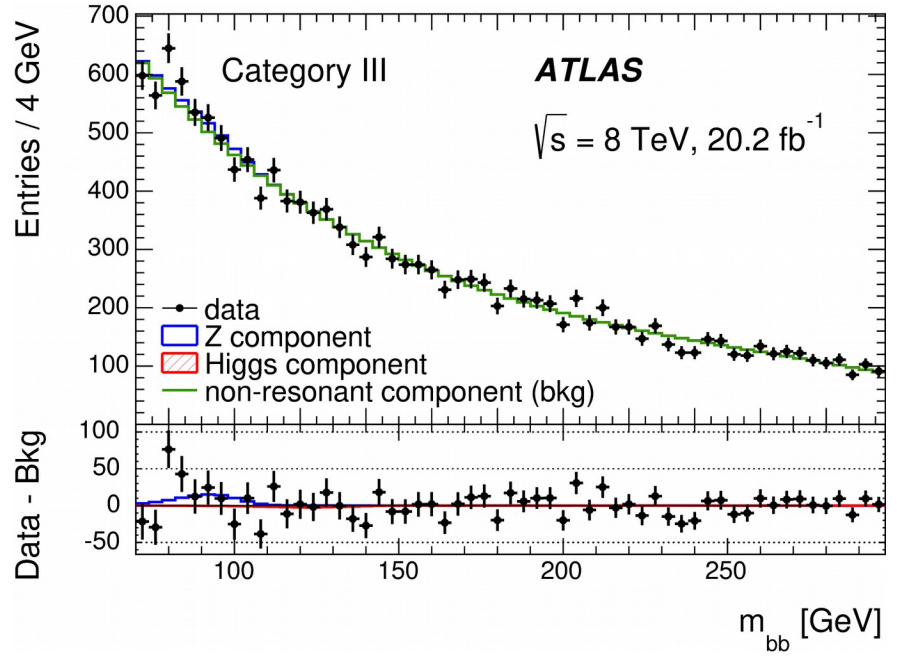
Another 23.0 fb^{-1} recorded by ATLAS waiting to be analyzed!

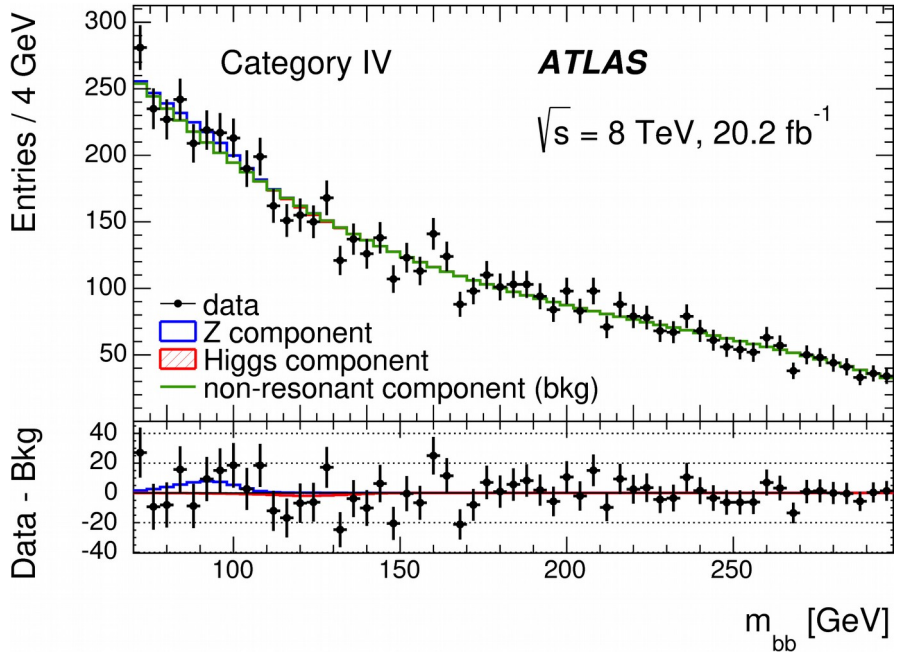
Backup

VBF, H(→$b\bar{b}$)jj: m_{bb} distributions

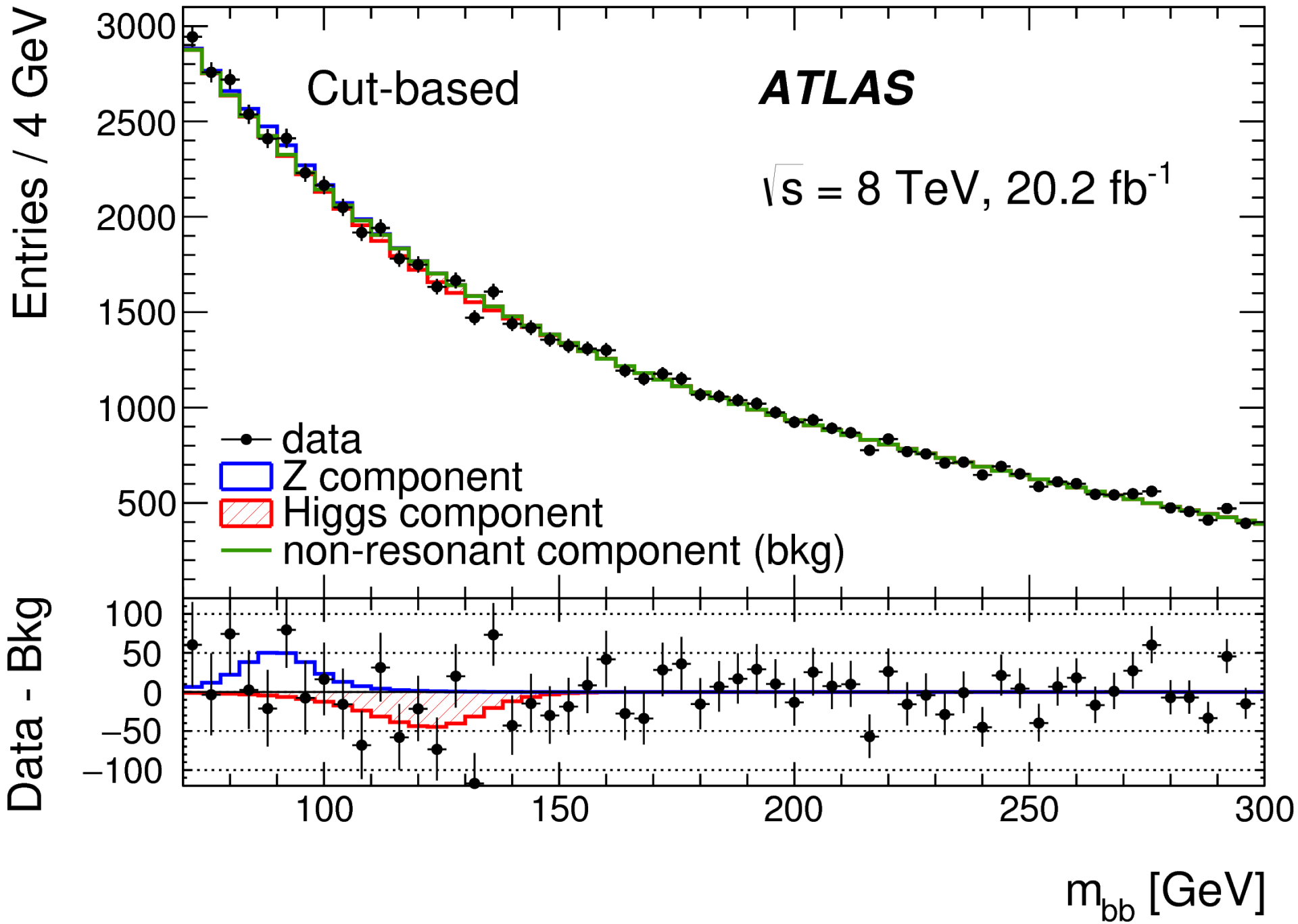








VBF, H(→bb̄)jj: cut-based analysis



VBF, H(→bb̄)jj: tables

- Event yields

Process	Pre-selection	Category I (-0.08 to 0.01)	Category II (0.01 to 0.06)	Category III (0.06 to 0.09)	Category IV (> 0.09)
VBF $H \to bb$	130	39	33	23	19
ggF $H \to b\bar{b}$	94	31	8.5	3.8	1.6
$Z \to b\bar{b}$	3700	1100	350	97	49
Data	554302	176073	46912	15015	6493

- Functions for non-resonant backgrounds

	category I	category II	category III	category IV
Nominal	4^{th} Pol.	3^{rd} Pol.	3^{rd} Pol.	3^{rd} Pol.
Alternative	2^{nd} Pol. $\times$ exponential	3 exponentials	2 exponentials	exponential

- Systematic uncertainties

Source of uncertainty		Uncertainty on μ	
		MVA	Cut-based
Experimental uncertainties	Detector-related	$+0.2/-0.3$	$+1.6/-1.2$
	MC statistics	± 0.4	± 0.1
Theoretical uncertainties	MC signal modelling	± 0.1	± 1.3
	Z yield	$+0.6/-0.5$	± 1.4
Non-resonant background modelling	Choice of function	± 1.0	± 1.0
	Sideband statistics	± 1.7	± 3.7
Statistical uncertainties		± 1.3	
Total		± 2.3	$+4.6/-4.4$

VBF: H(→bb̄) + γ + jj

Uncertainty source	Uncertainty $\Delta\mu$
Non-resonant background uncertainty in medium-BDT region	0.22
Non-resonant background uncertainty in high-BDT region	0.21
Non-resonant background uncertainty in low-BDT region	0.17
Parton shower uncertainty on $H + \gamma$ acceptance	0.16
QCD scale uncertainty on $H + \gamma$ cross section	0.13
Jet energy uncertainty from calibration across η	0.10
Jet energy uncertainty from flavour composition in calibration	0.09
Integrated luminosity uncertainty	0.08

Result	$H(\to b\bar{b}) + \gamma jj$	$Z(\to b\bar{b}) + \gamma jj$
Expected significance	0.4	1.3
Expected p-value	0.4	0.1
Observed p-value	0.9	0.4
Expected limit	$6.0\ ^{+2.3}_{-1.7}$	$1.8\ ^{+0.7}_{-0.5}$
Observed limit	4.0	2.0
Observed signal strength μ	$-3.9\ ^{+2.8}_{-2.7}$	$0.3\ \pm 0.8$

VH(→bb): event selection

Selection	0-lepton	1-lepton	2-lepton
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}}$ (μ sub-channel)	
		Lowest unprescaled single lepton	
Leptons	0 loose lepton	1 tight lepton	2 loose leptons ($\geq$ 1 medium lepton)
Lepton pair	-	-	Same flavour opposite-charge for $\mu\mu$
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV (e sub-channel)	-
m_{ll}	-	-	$71 < m_{ll} < 121$ GeV
S_{T}	> 120 (2 jets), >150 GeV (3 jets)	-	-
Jets	Exactly 2 or 3 signal jets		Exactly 2 or ≥ 3 signal jets
b-jets	2 b-tagged signal jets		
Leading jet p_{T}	> 45 GeV		
$\min\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}},\mathrm{jet})$	$> 20°$	-	-
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}},h)$	$> 120°$	-	-
$\Delta\phi$(jet1,jet2)	$< 140°$	-	-
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}},E_{\mathrm{T},trk}^{\mathrm{miss}})$	$< 90°$	-	-
p_{T}^{V} regions	[0, 150] GeV (2-lepton), [150, ∞] GeV		

VH(→bb): systematic uncertainty on modeling

Z+jets	
Zl normalisation	18%
Zcl normalisation	23%
Zbb normalisation	Floating
Zbc-to-Zbb ratio	14-27%
Zcc-to-Zbb ratio	7-31%
Zbl-to-Zbb ratio	15-38%
0-to-2 lepton ratio	26%
2-to-3 jet ratio	28% (0-lepton) and 25% (2-lepton)
p_{T}^{V}, m_{bb}	S

W+jets	
Wl normalisation	32%
Wcl normalisation	37%
Wbb normalisation	Floating
Wbl-to-Wbb ratio	17% (0-lepton) and 31% (1-lepton)
Wbc-to-Wbb ratio	42% (0-lepton) and 21% (1-lepton)
Wcc-to-Wbb ratio	17% (0-lepton) and 31% (1-lepton)
2-to-3 jet ratio	23%
0-to-1 lepton ratio	17%
p_{T}^{V}, m_{bb}	S

$t\bar{t}$ (all are decorrelated between the 0+1 and 2-lepton channels)	
$t\bar{t}$ normalisation	Floating
2-to-3-jet ratio	9% (0+1-lepton) and 24% (2-lepton)
p_{T}^{V}, m_{bb}	S

Single top	
Cross section	4.4% (s-channel), 4.6% (t-channel), 6% (Wt)
Acceptance 2-jet	16% (t-channel), 25% (Wt)
Acceptance 3-jet	19% (t-channel), 32% (Wt)
m_{bb}, p_{T}^{V}	S (p_{T}^{V} uncorrelated between 2 and 3-jet channels Wt)

ZZ	
Normalisation	20%
0-to-2 lepton ratio	30%
2-to-3 jet ratio	19 %
m_{bb}, p_{T}^{V}	S (correlated with WZ uncertainties)

WZ	
Normalisation	26%
2-to-3 jet ratio	14% (0-lepton) and 11% (1-lepton)
0-to-1 lepton ratio	12%
m_{bb}, p_{T}^{V}	S (correlated with ZZ uncertainties)

WW	
Normalisation	25%

Multi-jet (1-lepton)	
Normalisation	14-81% (electron), 5-50%(muon)
Template variations	S

Signal	
Cross section (scale)	0.7% ($q\bar{q}$), 27% (gg)
Cross section (PDF)	1.9% ($q\bar{q}\rightarrow WH$), 1.6% ($q\bar{q}\rightarrow ZH$), 5% (gg)
Branching ratio	1.7 %
Acceptance (scale)	1.4%–5%
3-jet acceptance (scale)	1.4%–4.7%
p_{T}^{V} shape (scale)	S
Acceptance (PDF)	0.3%–0.7%
p_{T}^{V} shape (NLO EW correction)	S
Acceptance (parton shower)	4%–7.5%

VH(→bb): Comparison of Run 1 and Run 2