Measurements and interpretations of Higgs boson production using decays to two b-quarks with the ATLAS detector

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on behalf of the ATLAS Collaboration

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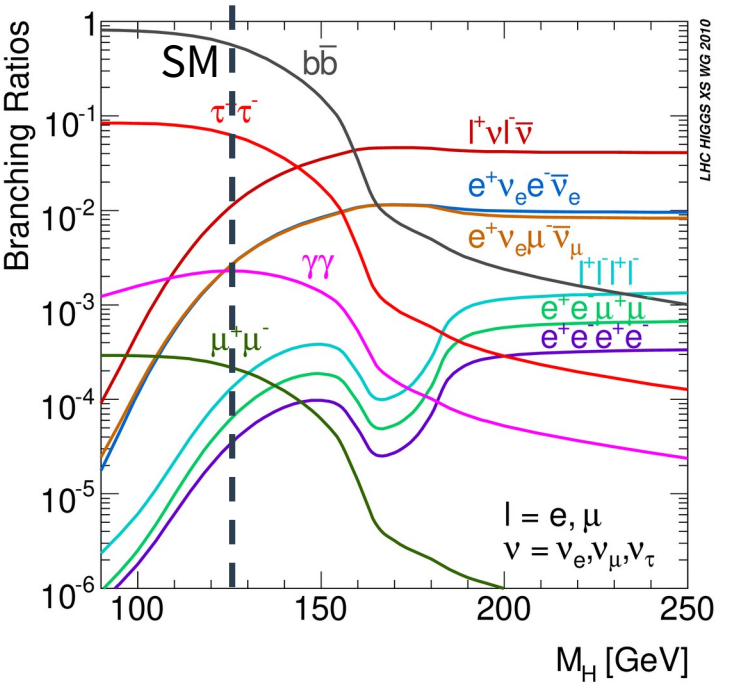
Introduction

- **Higgs boson discovered at the LHC in 2012**
  - Multitude of precision measurements since
- **H→bb decay preferred by Standard Model (SM) Higgs**
  - 4.5 million such decays in Run 2 ATLAS data!
  - Yet observation of H→bb decay only in 2018



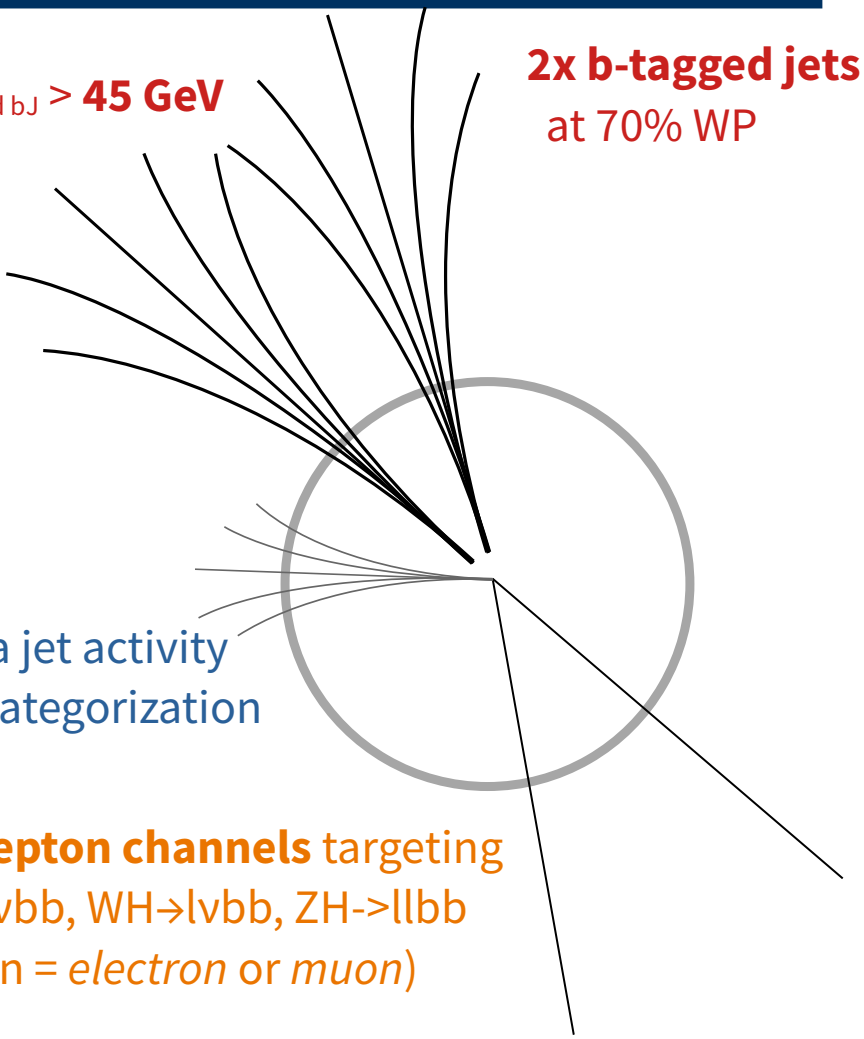
Today's topic:

Overview of ATLAS H→bb analyses for different production mechanisms.

Resolved VH→bb: Selection

HIGG-2018-51

- **Golden channel for SM H→bb**
- **Several updates since first observation in 2018**
  - Use full Run 2 dataset
  - Improved multivariate discriminant
  - Signal region refinement to aid STXS measurement
- **14 signal regions**
  - *n*-channel x extra jet x P^{T}_{V}
- **28 control regions**
  - Upper/lower ΔR_{bb} bands of each SR
  - Used as "1 bin" to normalize backgrounds



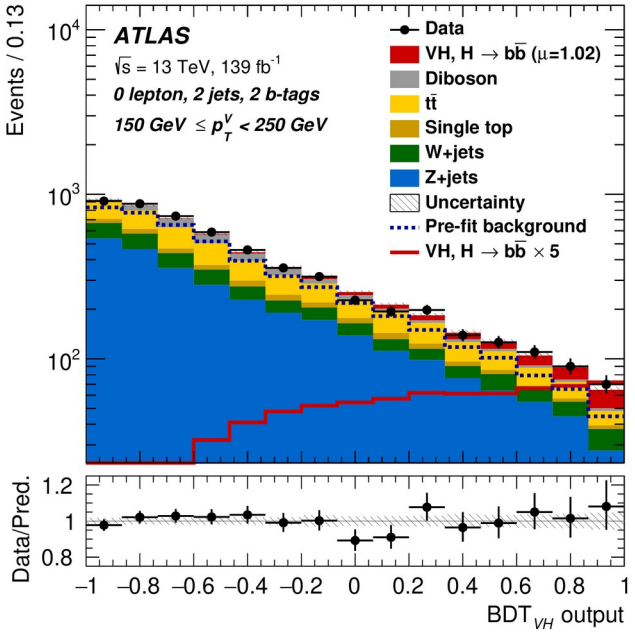
0,1,2 lepton channels targeting
ZH→ννbb, WH→lνbb, ZH->llbb
(lepton = *electron* or *muon*)

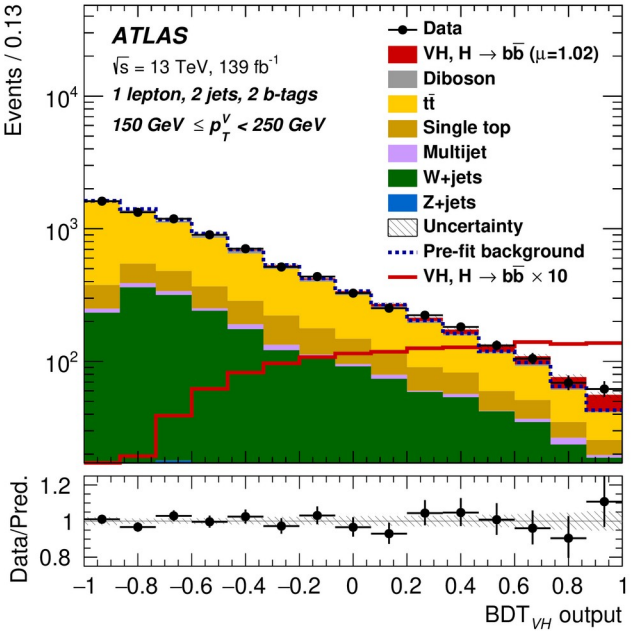
$P^{T}_{V} = p^{T}_{l}$ + MET

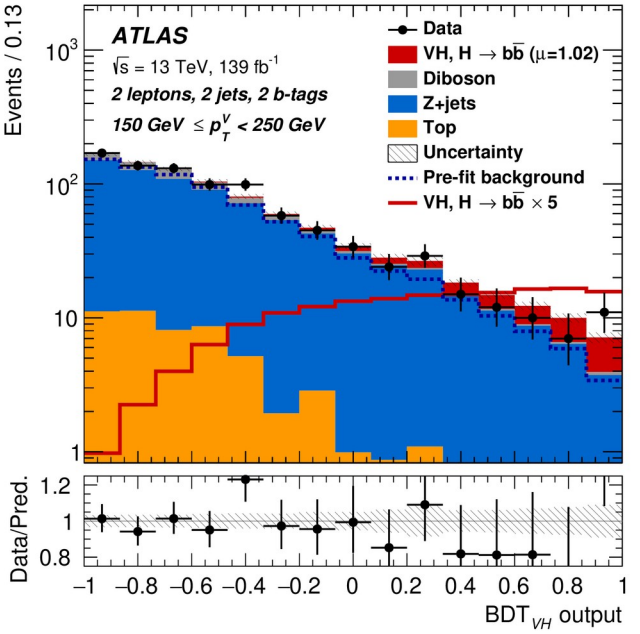
- vector sum
- MET used only when appropriate

Resolved VH→bb: Backgrounds

Simultaneous fit of BDT score distributions of analysis regions.







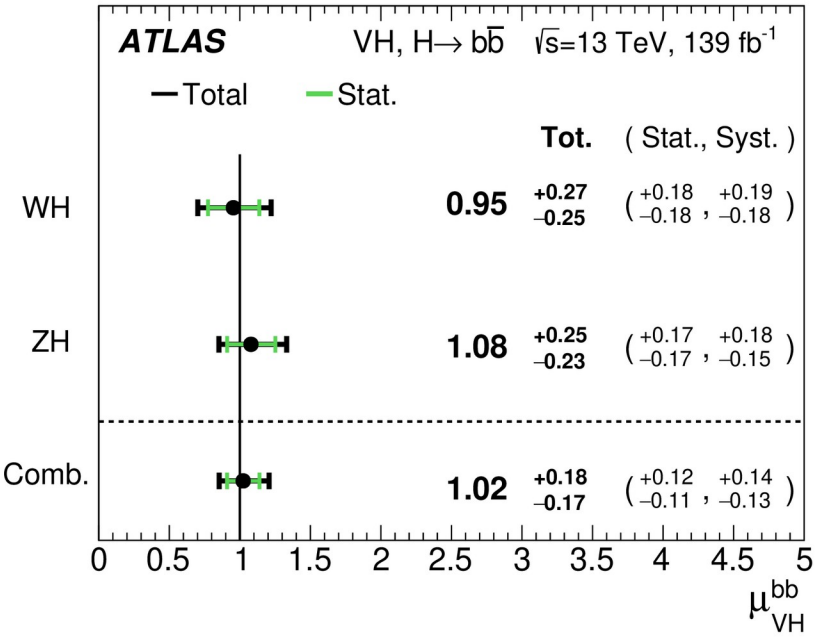
Background shapes are estimated using simulation, with normalization from sideband CR's.

Exceptions: *data-driven* ttbar in 2-lepton and QCD in 1-lepton channels.

Resolved VH→bb: Results

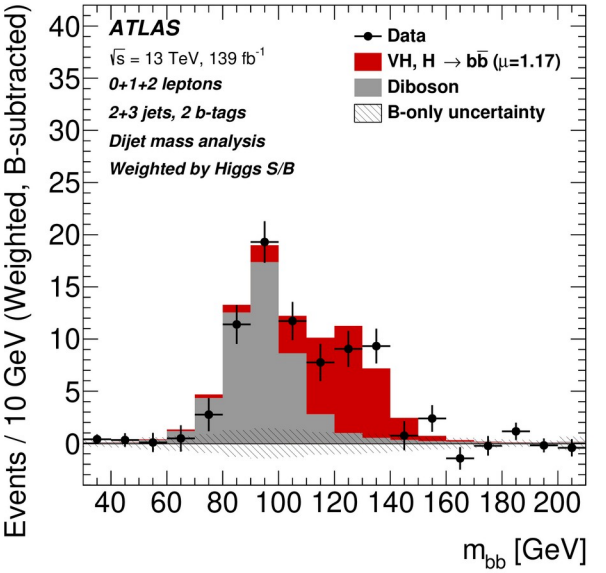
See backup for VZ→bb cross-check!

- VH→bb observed and SM-like
- 6.7σ in comb. fit (6.7σ expected)
  - Was 4.9σ in previous result
- m_{bb} fit used as cross-check
  - sees 5.5σ excess

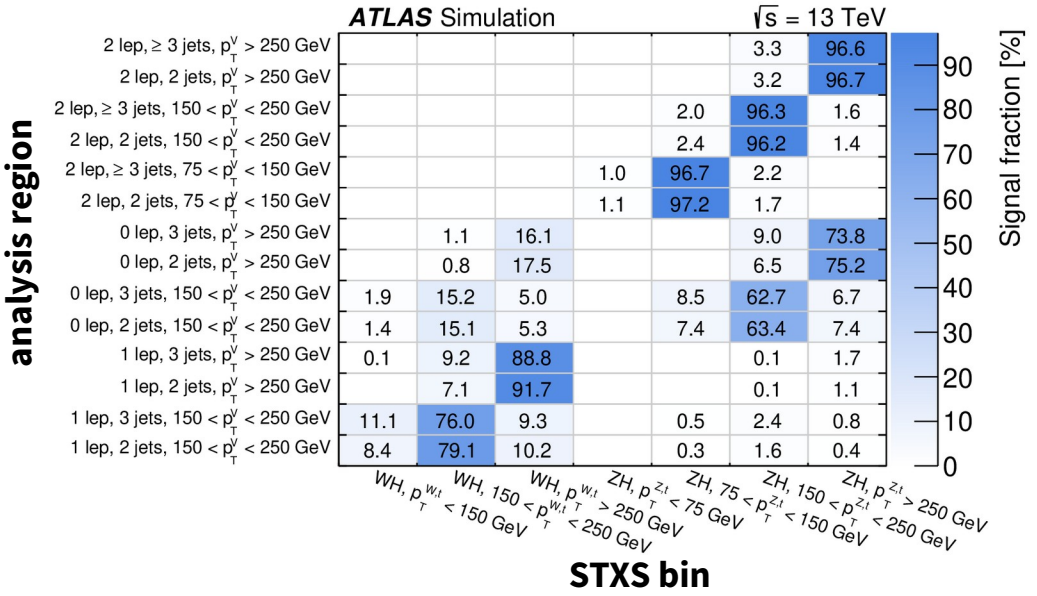


Stat and syst historically to track each other.

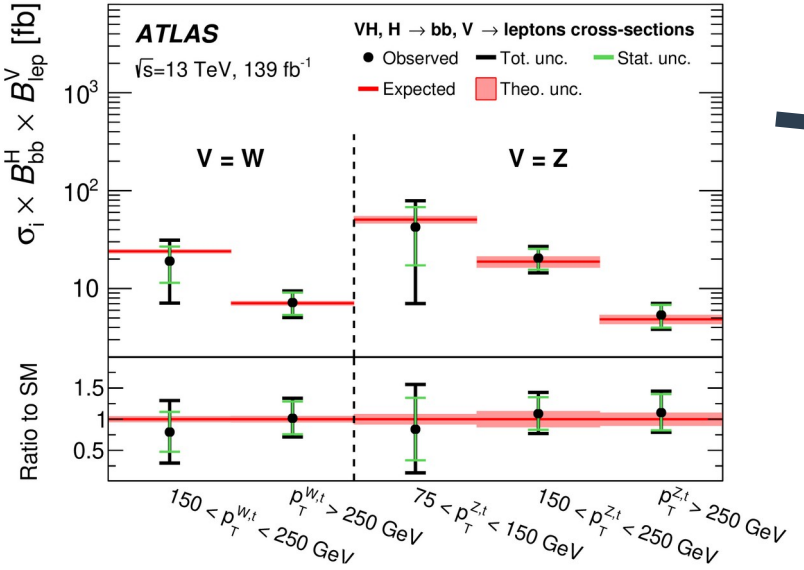
Source of uncertainty	σ_μ VH	WH	ZH
Total	0.177	0.260	0.240
Statistical	0.115	0.182	0.171
Systematic	0.134	0.186	0.168

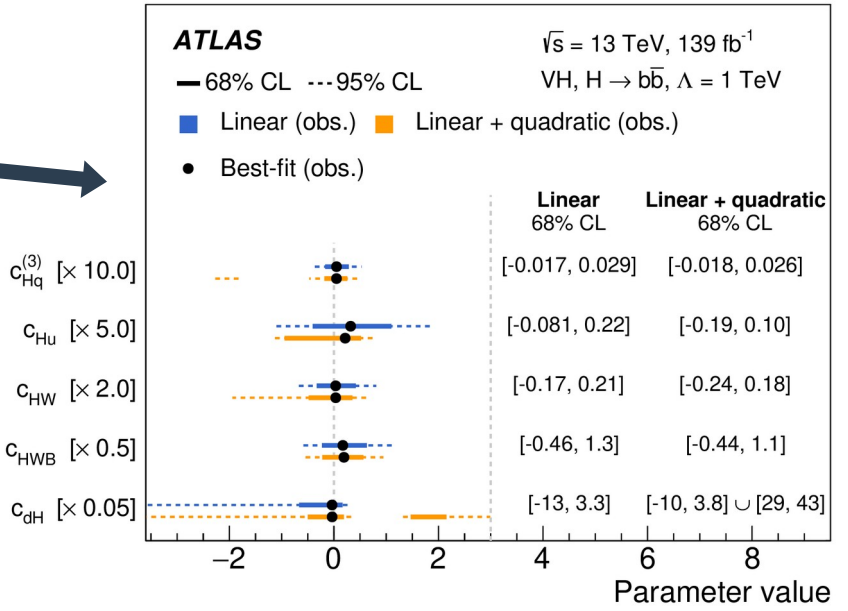


Resolved VH→bb: STXS Measurement



- **Improved orthogonality in STXS bin and analysis regions**
  - Due to region binning in P^{T}_{V}
- **Used to set limits on dim-6 EFT operators**

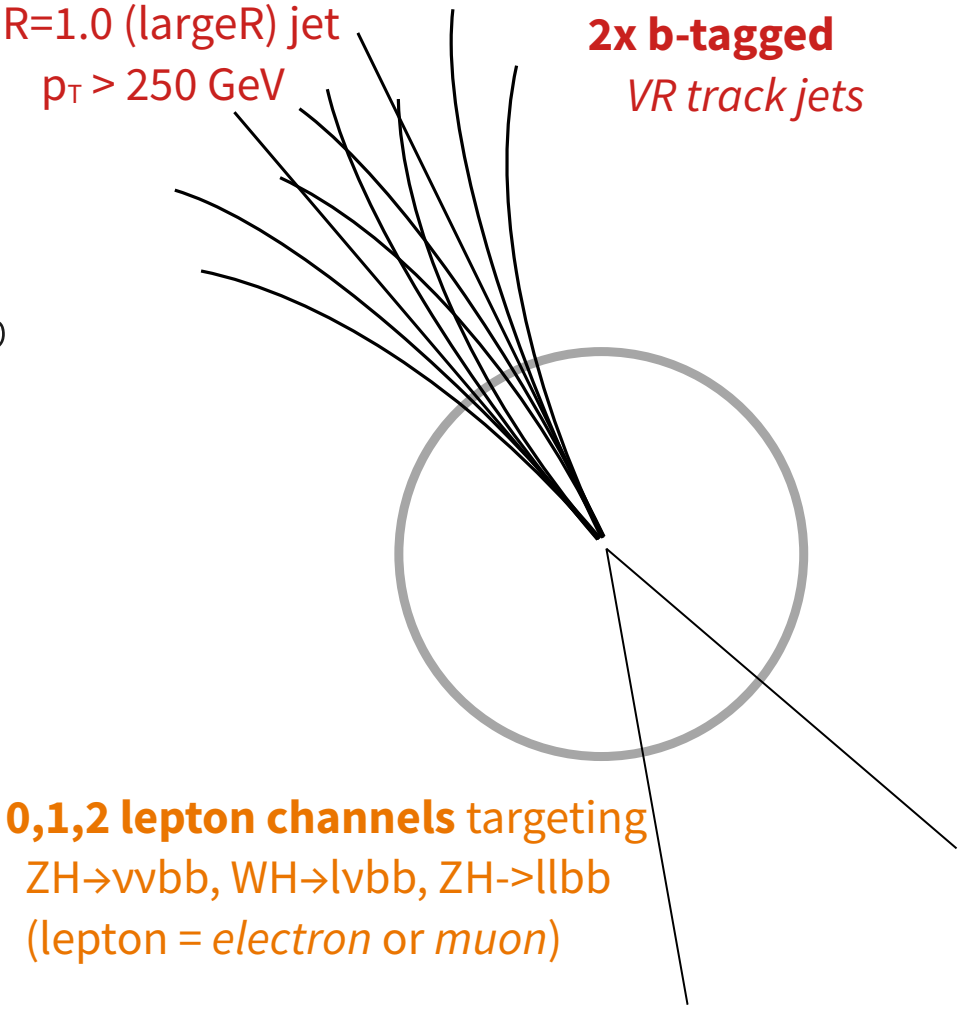




Boosted VH→bb: Selection

HIGG-2018-52

- **Extends VH→bb towards high p_T**
  - Region interesting for BSM physics
  - Recovers efficiency loss due to merged bb
- **Variable cuts instead of BDT**
- **Two P^T_V bins in each channel**
  - [250, 400): significant overlap w/ resolved
  - [400, ∞): recovers efficiency of resolved

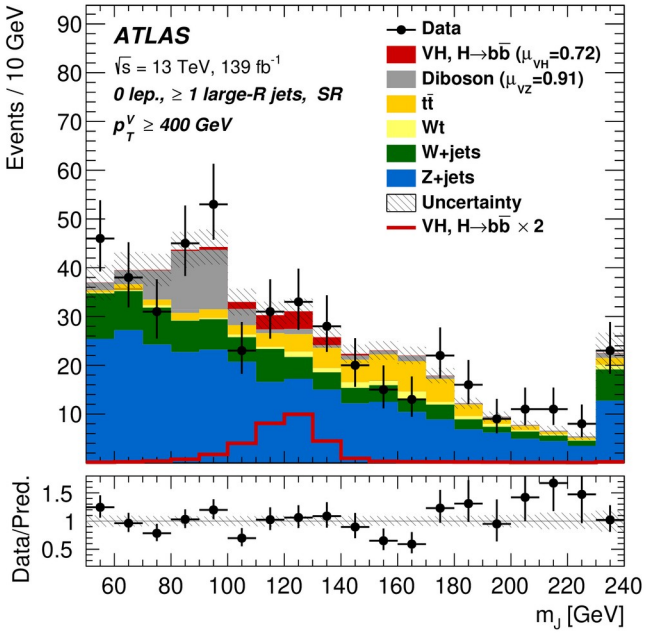


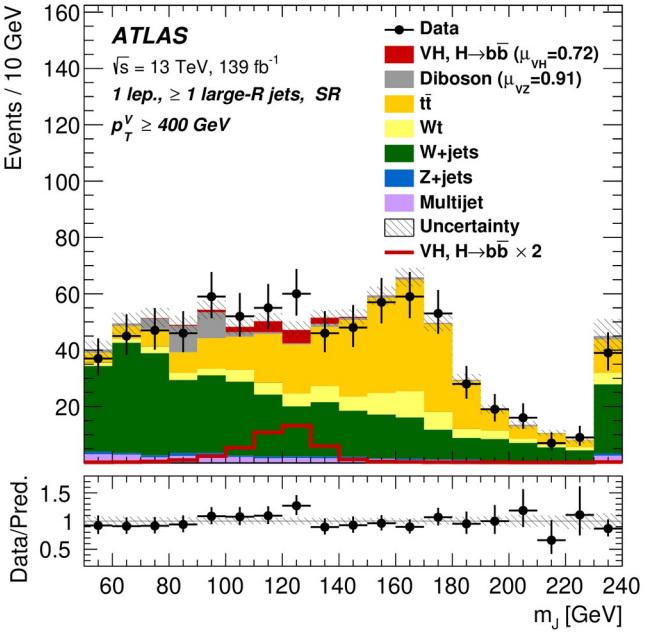
0,1,2 lepton channels targeting
ZH→ννbb, WH→lνbb, ZH->llbb
(lepton = *electron* or *muon*)

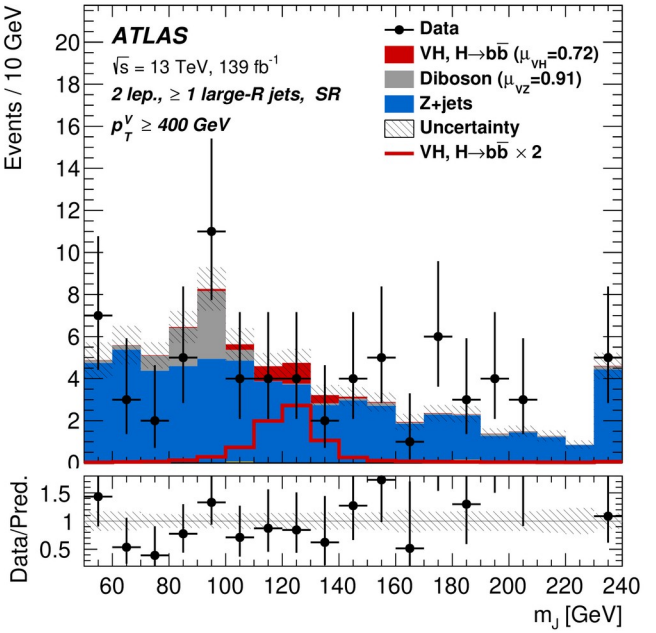
$P^T_V = p^T_l$ + MET
- vector sum
- MET used only when appropriate

Boosted VH→bb: Backgrounds

Simultaneous fit of m_J distributions of 10 SR's + 4 CR's.





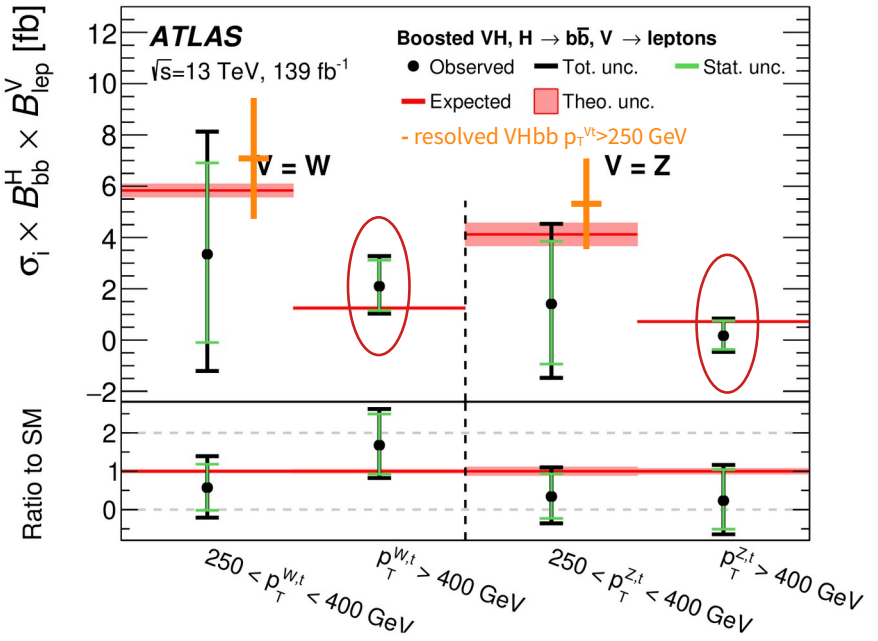


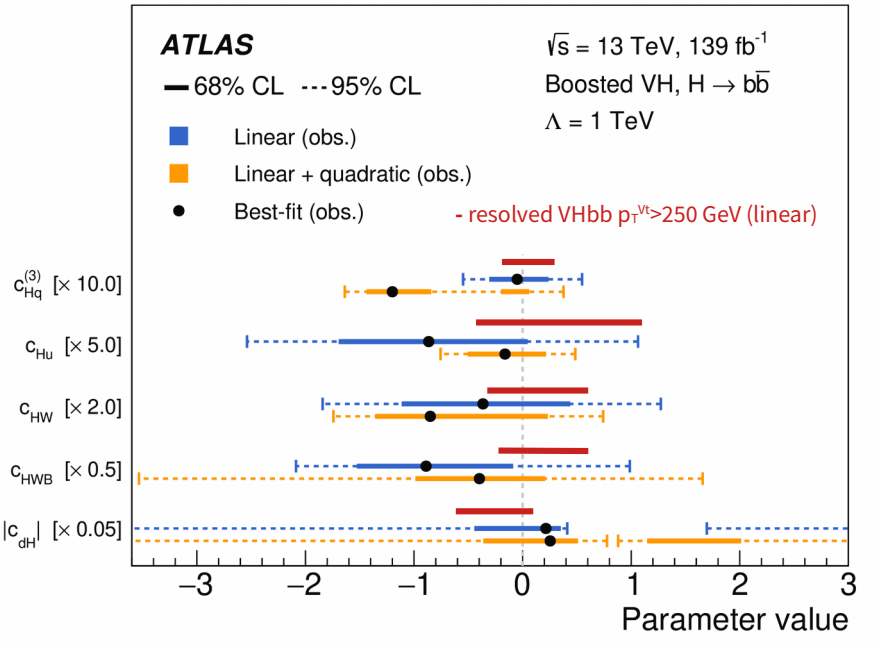
Background shapes are estimated using simulation, with normalization from m_J sidebands.

Exceptions: dedicated ttbar CR for 0,1-lepton; data-driven Multijet

Boosted VH→bb: STXS Interpretation

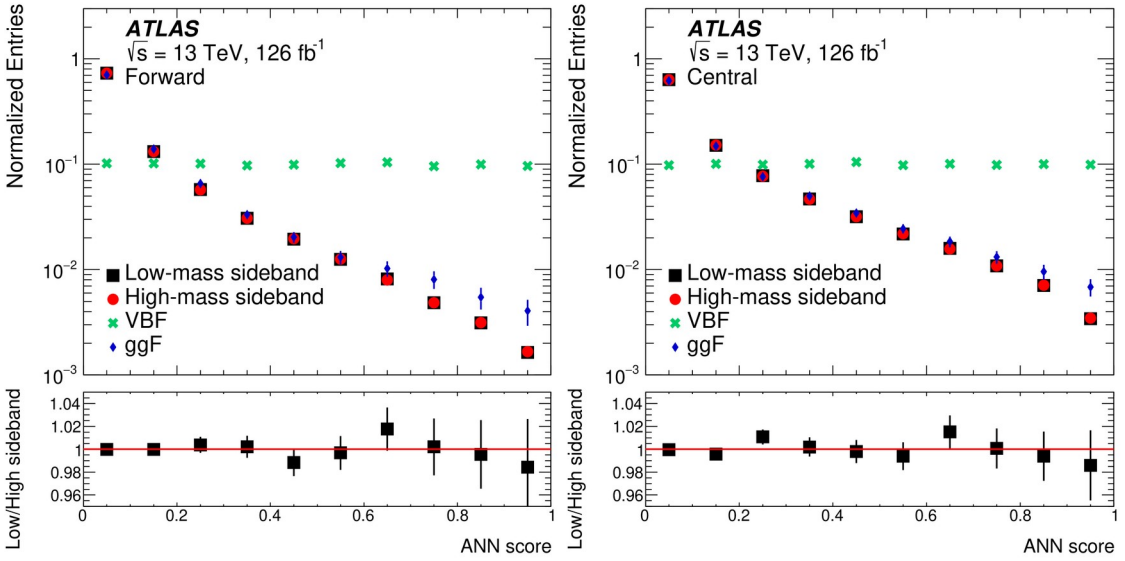
- **Boosted analysis extends p_T^{Vt} range above 400 GeV**
  - $p_T^{Vt} \in$ 250-400 GeV only included as a cross check, boosted is much weaker
- **Also set limits on relevant dim-6 EFT operators**

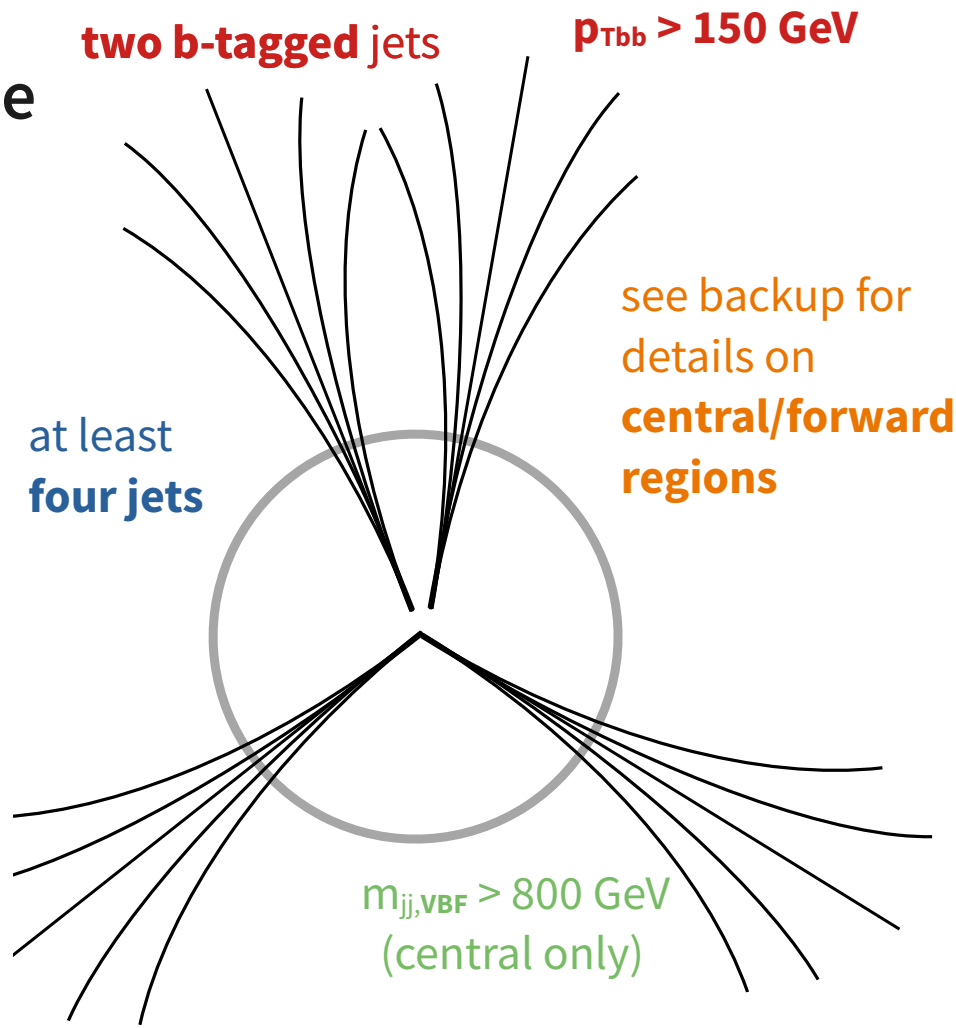




VBF H→bb: Selection

- **Second dominant production mode**
  - Still swamped by multijet background
- **Adverserial NN for QCD rejection**
  - $L = L_{\text{classifier}} - \lambda L_{\text{adversary}}$
  - Decorrelates NN score from m_{bb}
  - Four ANN_{score} bins in each η_{jet} region

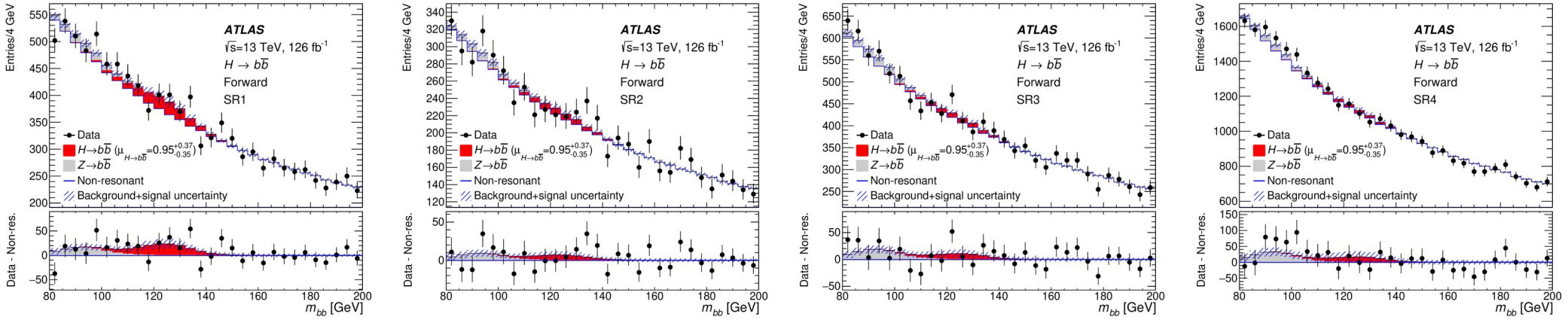




photon and lepton (muon, electron) **veto** applied to remove **overlap** with other Hbb analysis

VBF H→bb: Backgrounds

Simultaneous fit of m_{bb} distributions of 8 SR's.

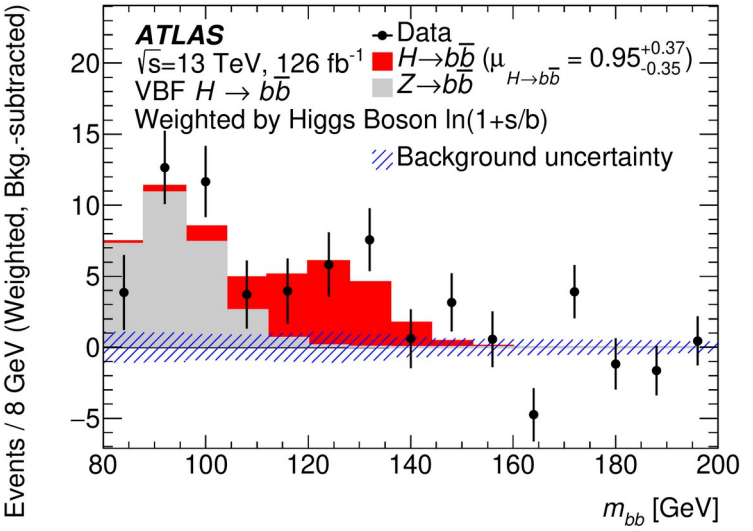


- Z→bb background with simulated b-jets embedded into *real* Z→μμ events
- Non-resonant background is an binned histogram of arbitrary shape
  - Constrained to same shape in different ANN_{score} bins

VBF H→bb: Results

- **Consistent with SM**
  - 2.6σ in combined fit (3.0σ expected)

$$\mu^{bb} = 0.95^{+0.31}_{-0.31}(\text{stat.})^{+0.20}_{-0.17}(\text{syst.})$$



- **STXS measurement**

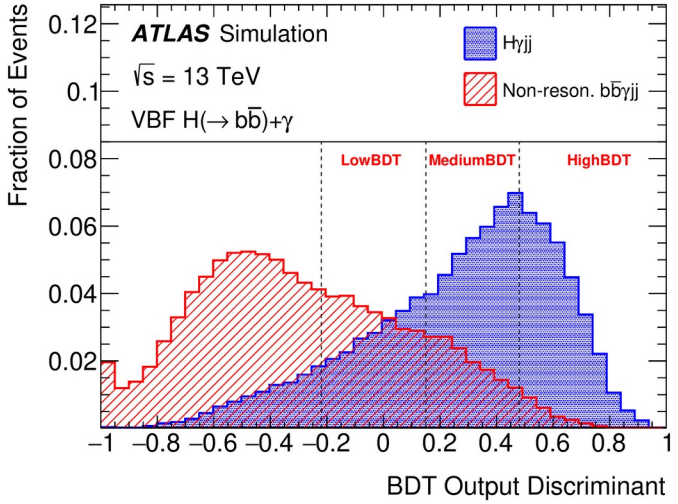
$$\mu^{bb}_{p_{TH}>200GeV} = 0.93 \pm 0.38(\text{stat.})^{+0.24}_{-0.20}(\text{syst.})$$

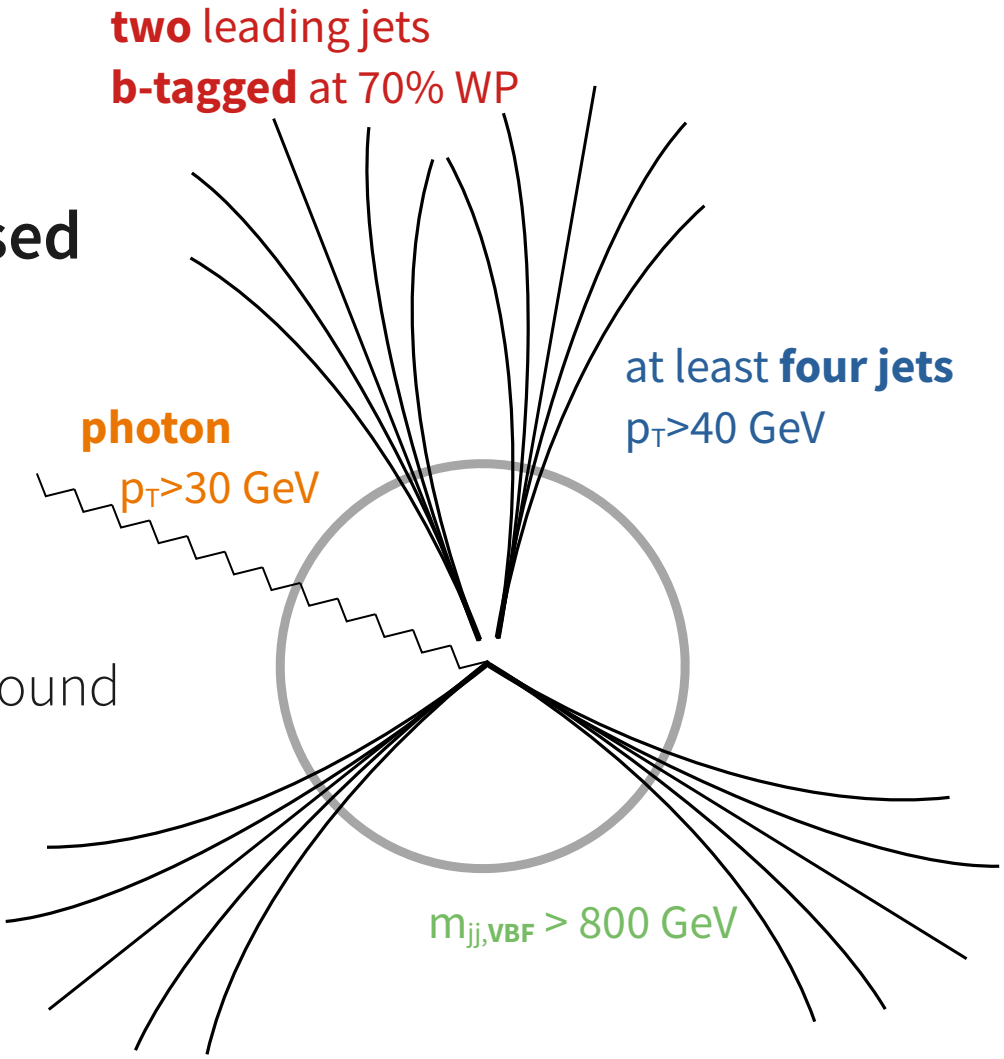
- **Analysis is stat limited, but syst not far behind**

VBF H→bb + photon: Selection

HIGG-2020-14

- **VBF is dominant channel for Hγ**
- **Z-fusion contribution is suppressed**
  - Allows direct measurement of W-fusion
- **Suppresses multijet background**
- **BDT score split into 3 SR's**
  - Trained to reduce non-resonant background



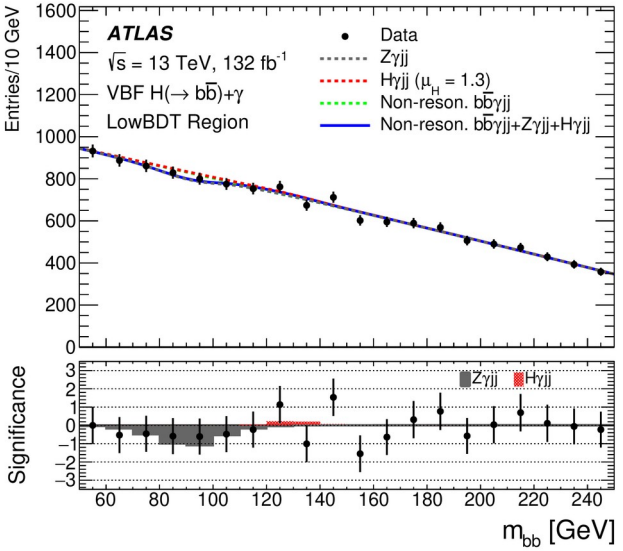


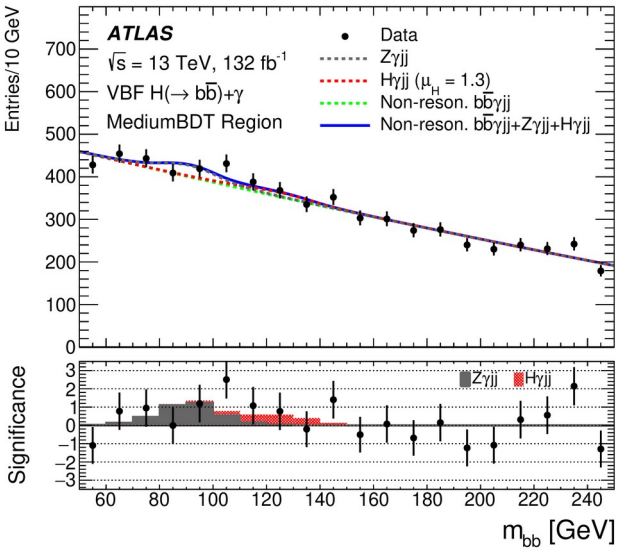
lepton (muon, electron) **veto** applied to remove **overlap with VHbb**

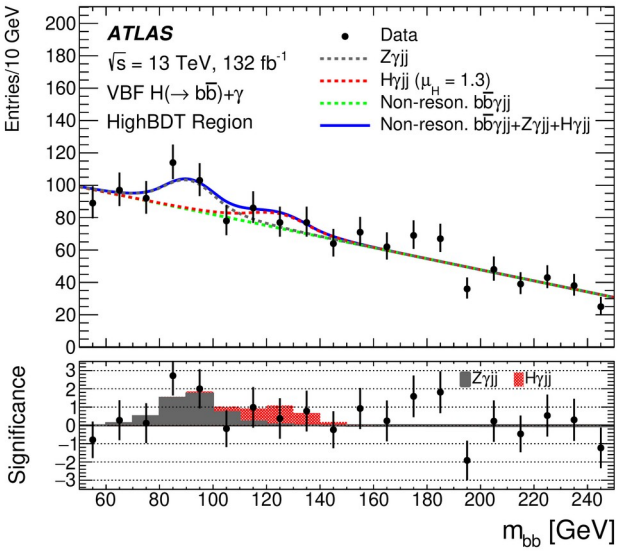
VBF H→bb + photon: Backgrounds

Smooth function for non-resonant backgrounds.

Large amount of validation in high stats MC and m_{bb} sidebands.







Resonant backgrounds (V+jets) templates from simulation.

Normalization uncorrelated between signal regions.

VBF H→bb + photon: Results

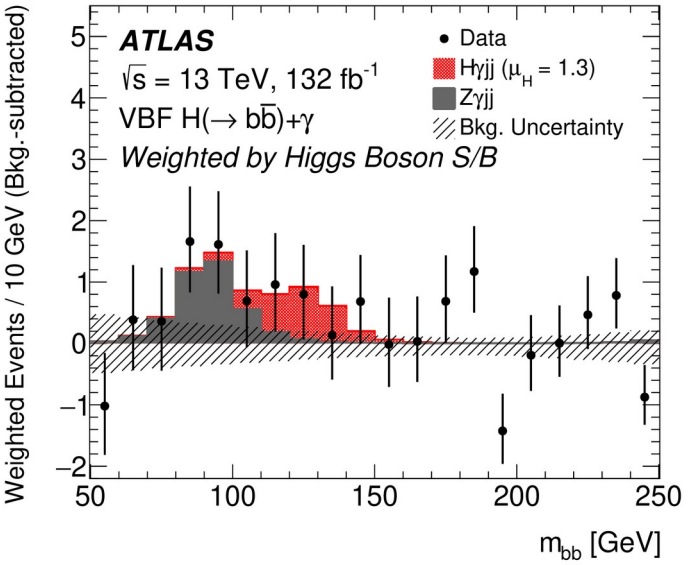
- **VBF Hγ consistent with SM**
  - 1.3σ in combined fit (1.0σ expected)

Region	μ_Z	μ_H*
LowBDT	$-1.3^{+1.2}_{-1.6}$	$3.8^{+7.0}_{-8.3}$
MediumBDT	1.5 ± 1.1	$3.8^{+2.5}_{-2.4}$
HighBDT	1.9 ± 1.2	0.7 ± 1.1

* special 3 PoI fit, not main result

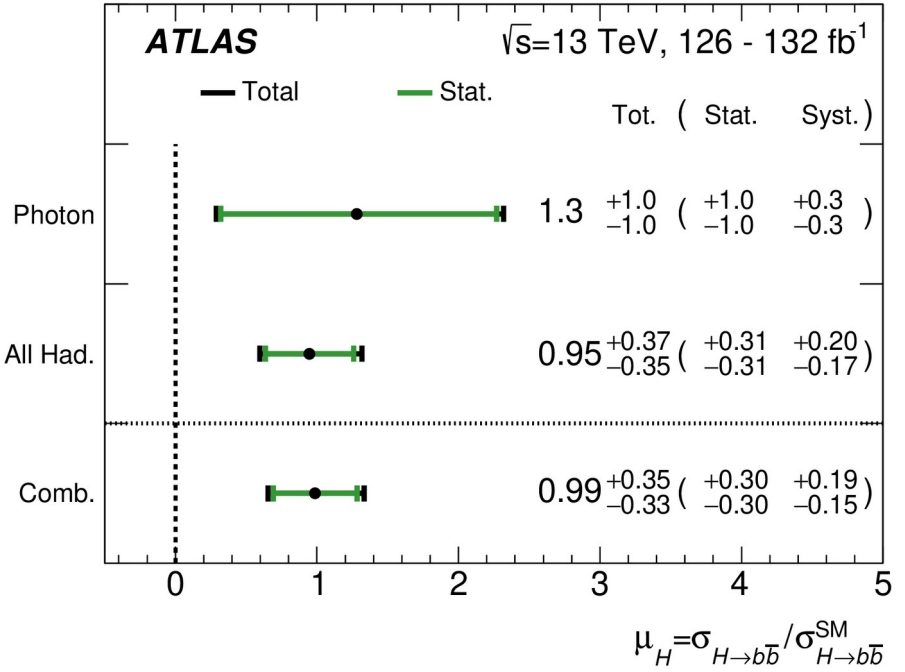
$$\mu_{VBF}^{bb} = 1.3 \pm 1.0(stat.) \pm 0.3(syst.)$$

- **Analysis is stat limited.**



Combination: VBF H→bb + photon AND VBF H→bb

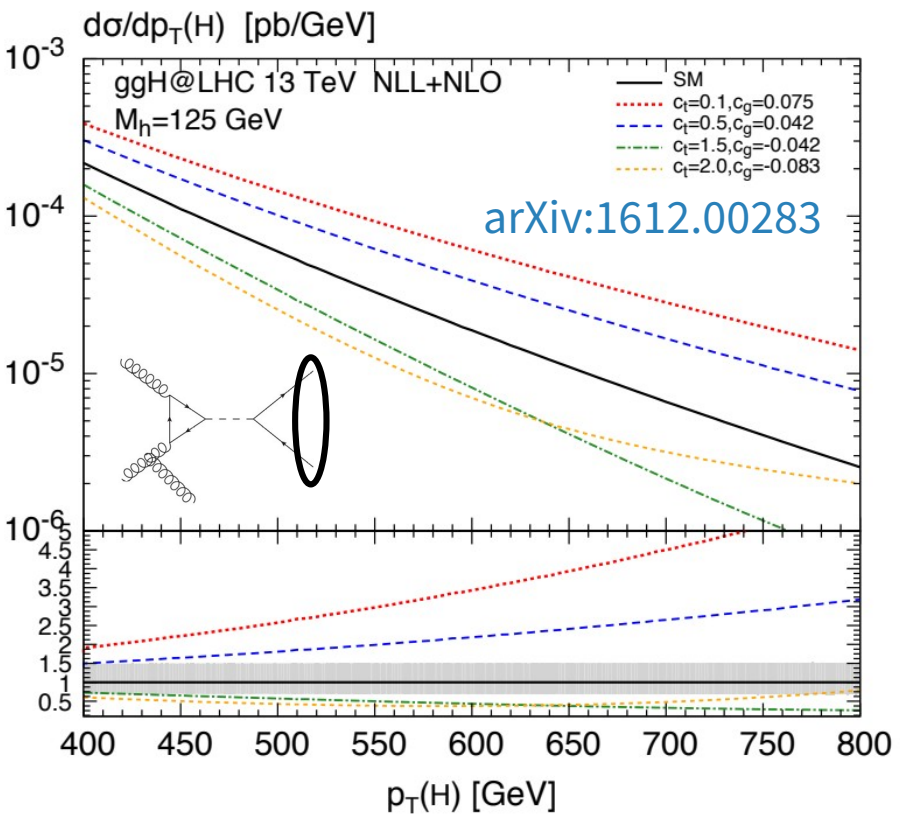
Combination is dominated by all hadronic analysis.



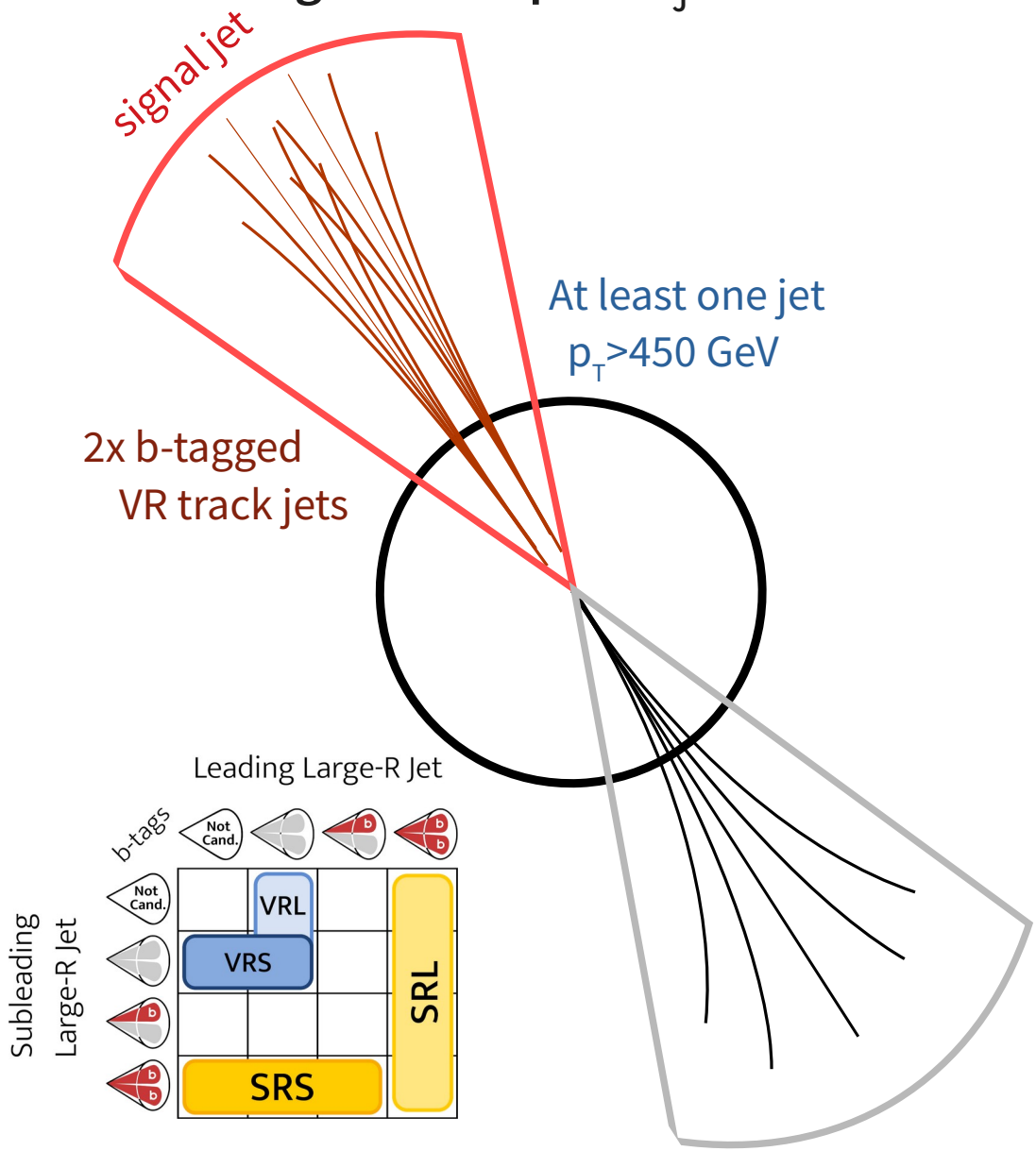
3.0σ observed for inclusive μ^{bb} (3.0σ expected)

Boosted H→bb+jet

ATLAS-CONF-2021-010



Signal: bump in m_J at 125 GeV



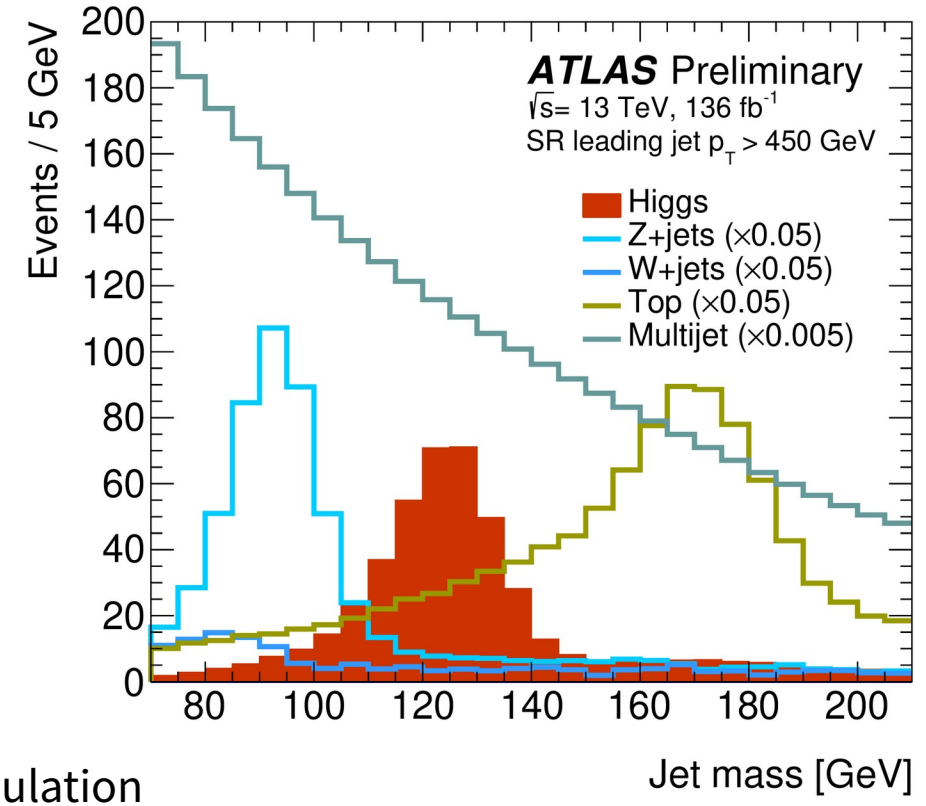
Analysis Goals (V→qq, H→bb)

- Inclusive measurement
- p_T differential measurement (STXS)
- fiducial measurement ($p_{T,truth}$>450 GeV)

Boosted H→bb+jet: Backgrounds

Fit **QCD** with smooth function

- extensively validated in 0-btag region



W/Z + jets

- Shape from simulation
- Fully floating during fit (standard candle)
- Mostly Z+jets after b-tagging

ttbar

- Shape from simulation
- CR_{ttbar} for normalization

Boosted H→bb+jet: Results

- **Far from observing SM H→bb**
  - Also observe no deviations

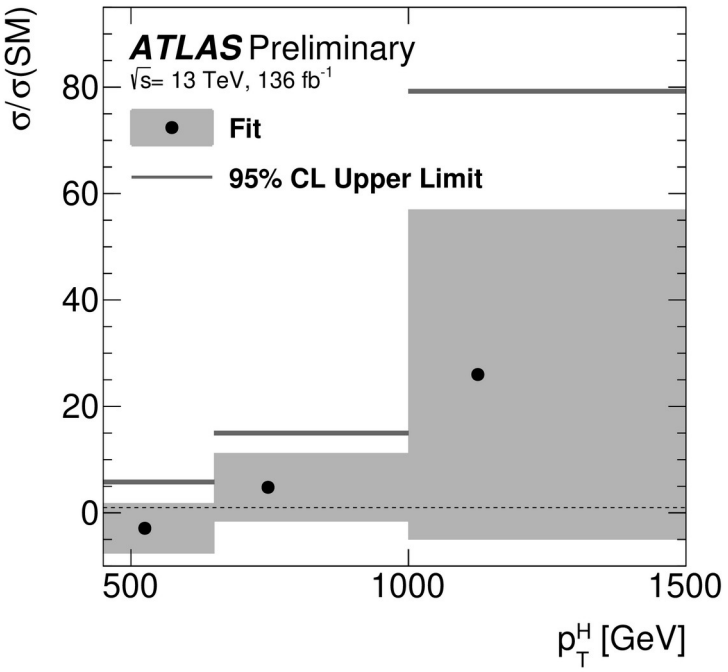
Inclusive

Result	μ_H	μ_Z	$\mu_{t\bar{t}}$
Expected	1.0 ± 3.0	1.00 ± 0.17	1.00 ± 0.07
Observed	1.1 ± 3.6	1.25 ± 0.22	0.81 ± 0.06

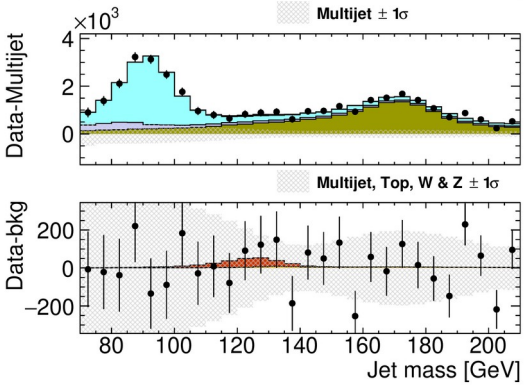
Fiducial

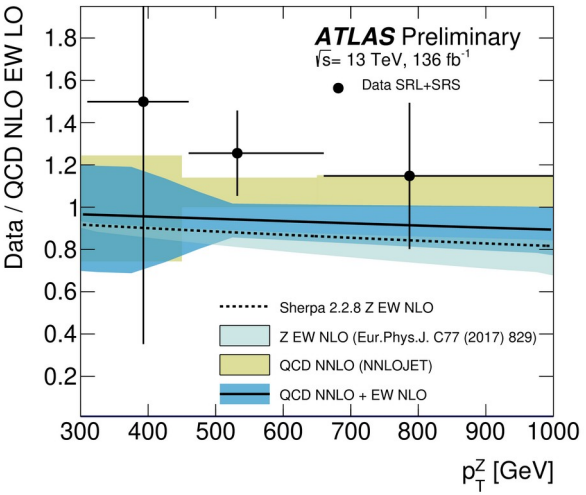
p_T^H/Jet p_T	μ_H Exp.	μ_H Obs.	μ_Z Exp.	μ_Z Obs.	$\mu_{t\bar{t}}$ Exp.	$\mu_{t\bar{t}}$ Obs.
>450 GeV	1.0 ± 3.3	0.7 ± 3.3	1.00 ± 0.18	1.27 ± 0.22	1.00 ± 0.07	0.81 ± 0.06
>1 TeV	1.0 ± 29.0	26 ± 31	1.0 ± 1.6	2.4 ± 1.7	1.0 ± 0.3	0.51 ± 0.19

STXS



- **Very strong Z→bb peak**
  - Good validation of background estimation

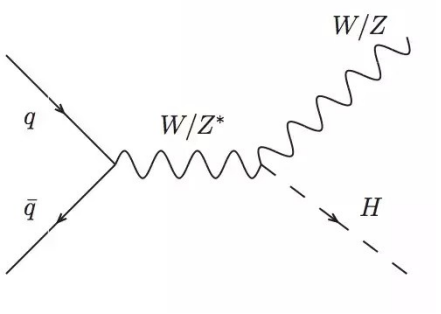




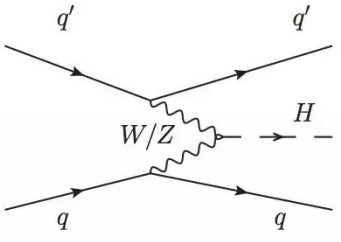
Conclusions

See H. Yang's talk on ttH→bb

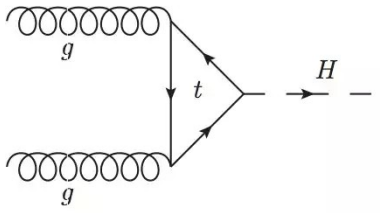
ATLAS has public results on H→bb in the three main production mechanisms using full Run 2 data.



- 6.7σ observation in VH!
- 2.1σ in analysis targeting high p_{TH} regime



- 2.6σ signal for main VBF H→bb
- 1.3σ signal for VBF+γ final state
- 3.0σ after combination



- Targets high p_{TH} regime using boosted H→bb
- 0.3σ signal, but main motivation is BSM

Fiducial measurements in STXS bins provided.

BACKUP

VH→bb BDT

Variable	0-lepton	1-lepton	2-lepton
m_{bb}	×	×	×
$\Delta R(\vec{b_1}, \vec{b_2})$	×	×	×
$p_{\mathrm{T}}^{b_1}$	×	×	×
$p_{\mathrm{T}}^{b_2}$	×	×	×
p_{T}^{V}	$\equiv E_{\mathrm{T}}^{\mathrm{miss}}$	×	×
$\Delta\phi(\vec{V}, \vec{bb})$	×	×	×
$\mathrm{MV2}(b_1)$	×	×	
$\mathrm{MV2}(b_2)$	×	×	
$\lvert\Delta\eta(\vec{b_1}, \vec{b_2})\rvert$	×		
m_{eff}	×		
$p_{\mathrm{T}}^{\mathrm{miss,st}}$	×		
$E_{\mathrm{T}}^{\mathrm{miss}}$	×	×	
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		×	
m_{T}^{W}		×	
$\lvert\Delta y(\vec{V}, \vec{bb})\rvert$		×	
m_{top}		×	
$\lvert\Delta\eta(\vec{V}, \vec{bb})\rvert$			×
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{S_{\mathrm{T}}}$			×
$m_{\ell\ell}$			×
$\cos\theta(\vec{\ell^-}, \vec{Z})$			×
	Only in 3-jet events		
$p_{\mathrm{T}}^{\mathrm{jet}_3}$	×	×	×
m_{bbj}	×	×	×

New variables with respect to observation result

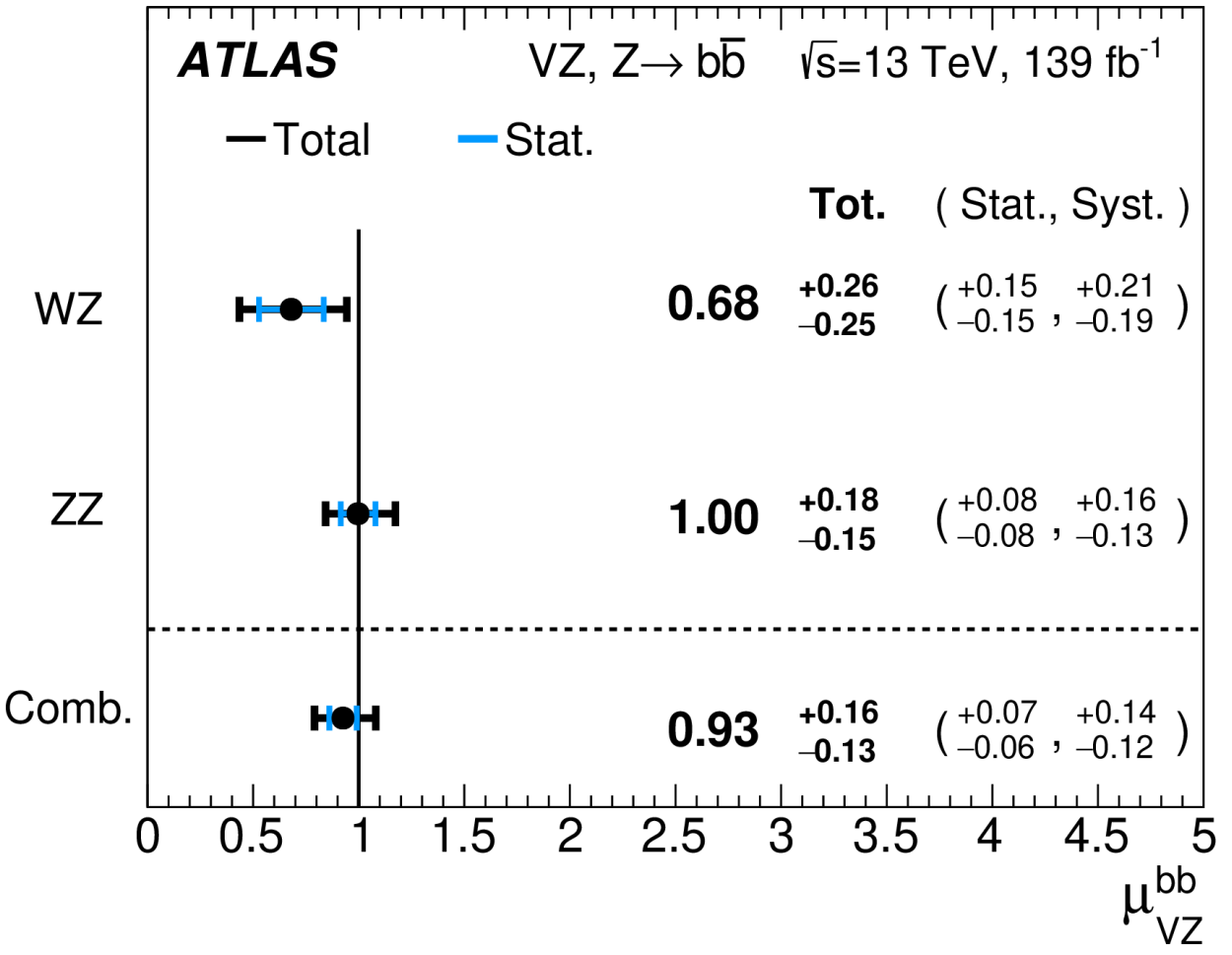
Resolved VH→bb: Uncertainties

Source of uncertainty		σ_μ VH	WH	ZH
Total		0.177	0.260	0.240
Statistical		0.115	0.182	0.171
Systematic		0.134	0.186	0.168
Statistical uncertainties				
Data statistical		0.108	0.171	0.157
$t\bar{t}$ $e\mu$ control region		0.014	0.003	0.026
Floating normalisations		0.034	0.061	0.045
Experimental uncertainties				
Jets		0.043	0.050	0.057
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.015	0.045	0.013
Leptons		0.004	0.015	0.005
b-tagging	b-jets	0.045	0.025	0.064
	c-jets	0.035	0.068	0.010
	light-flavour jets	0.009	0.004	0.014
Pile-up		0.003	0.002	0.007
Luminosity		0.016	0.016	0.016
Theoretical and modelling uncertainties				
Signal		0.072	0.060	0.107
Z + jets		0.032	0.013	0.059
W + jets		0.040	0.079	0.009
$t\bar{t}$		0.021	0.046	0.029
Single top quark		0.019	0.048	0.015
Diboson		0.033	0.033	0.039
Multi-jet		0.005	0.017	0.005
MC statistical		0.031	0.055	0.038

stat and syst are comparable

VH→bb: VZ→bb cross-check

Same process, but BDT trained to enhance VZ→bb.

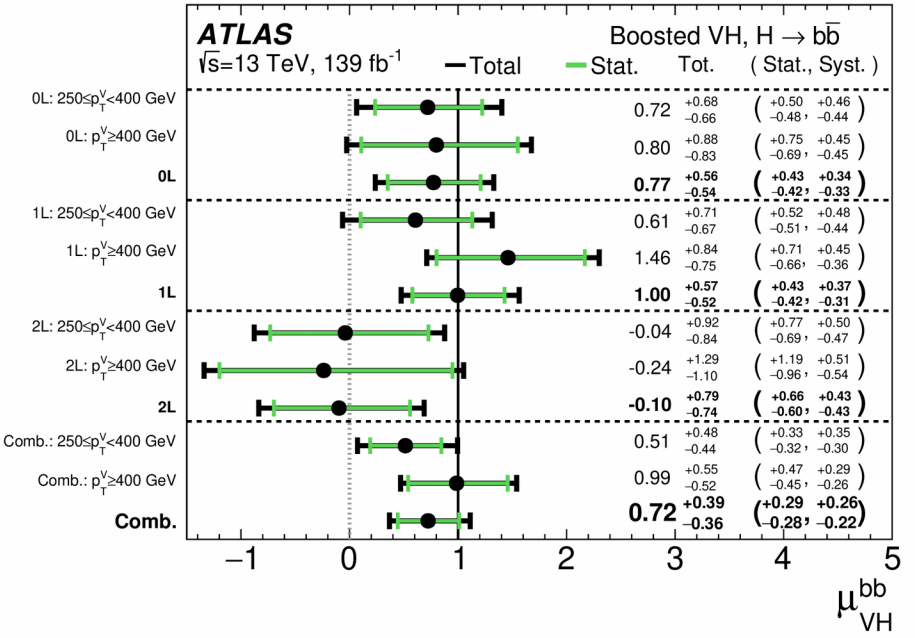


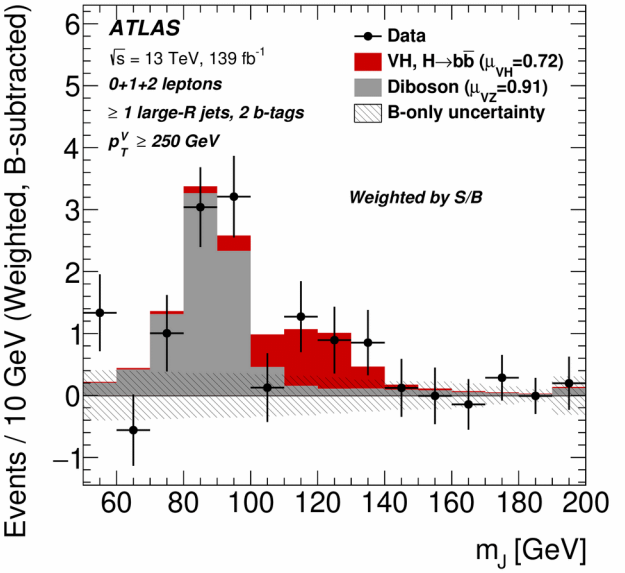
Boosted VH→bb: Results

- **Consistent with SM prediction**
  - 2.1σ in combined fit (2.7σ expected)

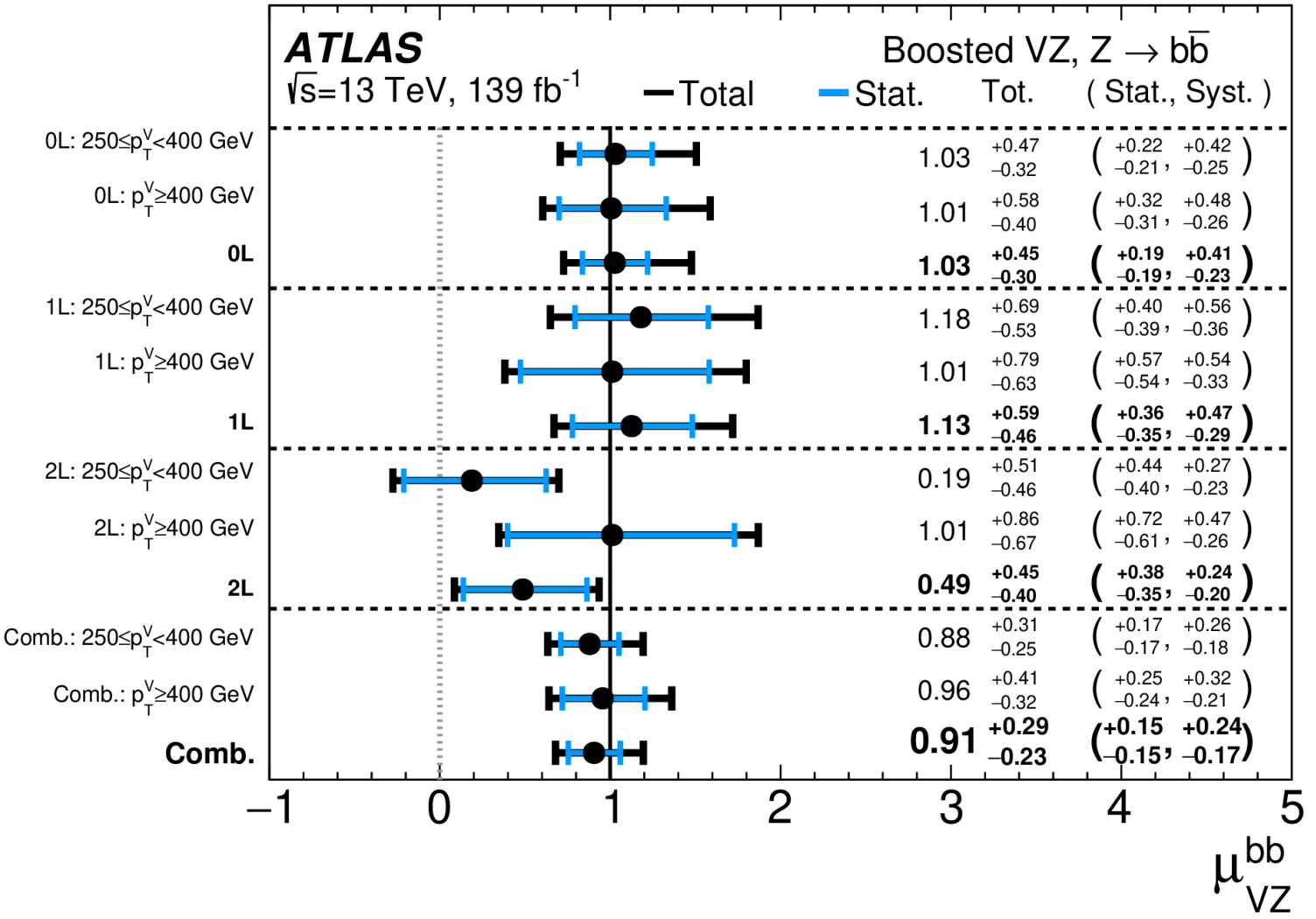
$$\mu_{VH}^{bb} = 0.72^{+0.39}_{-0.36} = 0.72^{+0.29}_{-0.28}(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})$$

Analysis starting to be syst limited!





Boosted VH→bb: VZ→bb cross-check



Boosted VH→bb: Uncertainties

Source of uncertainty		Avg. impact
Total		0.372
Statistical		0.283
Systematic		0.240
Experimental uncertainties		
Small-R jets		0.038
Large-R jets		0.133
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.007
Leptons		0.010
b-tagging	b-jets	0.016
	c-jets	0.011
	light-flavour jets	0.008
	extrapolation	0.004
Pile-up		0.001
Luminosity		0.013
Theoretical and modelling uncertainties		
Signal		0.038
Backgrounds		0.100
$\hookrightarrow Z$ + jets		0.048
$\hookrightarrow W$ + jets		0.058
$\hookrightarrow t\bar{t}$		0.035
$\hookrightarrow$ Single top quark		0.027
$\hookrightarrow$ Diboson		0.032
$\hookrightarrow$ Multijet		0.009
MC statistical		0.092

VBF H→bb: Full Selection

Forward Channel Event Selection	
b_1	≥ 1 b-tagged jet at 77% efficiency working point with $p_{\mathrm{T}} > 85$ GeV and $\lvert\eta\rvert < 2.5$
b_2	≥ 1 b-tagged jet at 85% efficiency working point with $p_{\mathrm{T}} > 65$ GeV and $\lvert\eta\rvert < 2.5$
j_1	≥ 1 jet with $p_{\mathrm{T}} > 60$ GeV and $3.2 < \lvert\eta\rvert < 4.5$
j_2	≥ 1 jet with $p_{\mathrm{T}} > 30$ GeV and $\lvert\eta\rvert < 4.5$
	$p_{\mathrm{T},bb} > 150$ GeV

Central Channel Event Selection	
b_1,b_2	≥ 2 b-tagged jets at 77% efficiency working point with $p_{\mathrm{T}} > 65$ GeV and $\lvert\eta\rvert < 2.5$
j_1	≥ 1 jet with $p_{\mathrm{T}} > 160$ GeV and $\lvert\eta\rvert < 3.1$
j_2	≥ 1 jet with $p_{\mathrm{T}} > 30$ GeV and $\lvert\eta\rvert < 4.5$
	no jets with $p_{\mathrm{T}} > 60$ GeV and $3.2 < \lvert\eta\rvert < 4.5$
	$p_{\mathrm{T},bb} > 150$ GeV, $m_{jj} > 800$ GeV

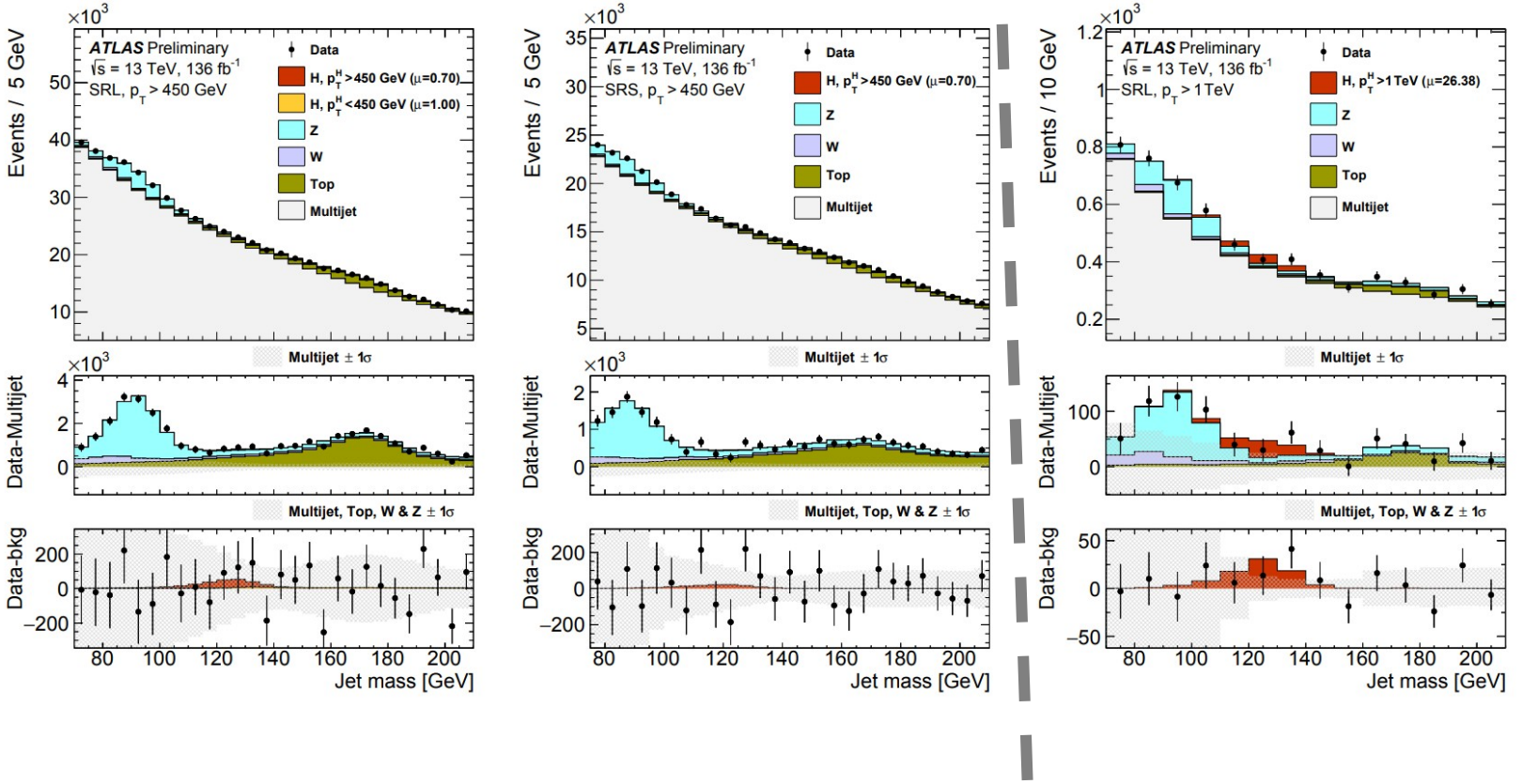
VBF H→bb: Uncertainties

Uncertainty	$\sigma(\mu_{H\to b\bar{b}})$
Statistics	±0.31
NR Background Bias	±0.15
Embedded Z	±0.05
Experimental	+0.10/−0.05
Trigger	+0.07/ − 0.03
Jet	+0.06/ − 0.04
Flavor Tagging	+0.02/ − 0.01
Other	+0.02/ − 0.01
Signal Theory	+0.06/ − 0.03

VBF H→bb + photon: Uncertainties

Source of absolute uncertainty	$\sigma(\mu_H)$ down	$\sigma(\mu_H)$ up
Statistical		
Data statistical	−0.78	+0.80
Bkg. fit shapes	−0.19	+0.22
Bkg. fit normalizations	−0.51	+0.52
Z boson normalizations	−0.15	+0.14
Systematic		
Spurious signal	−0.24	+0.21
Theoretical	−0.01	+0.08
Photon	−0.01	+0.03
Jet	−0.06	+0.20
b-tagging	−0.02	+0.11
Auxiliary	−0.01	+0.04
Total	−0.99	+1.04
Total statistical	−0.96	+0.99
Total systematic	−0.25	+0.32

Boosted H→bb+jet: Fiducial and Inclusive



Inclusive

Result	μ_H	μ_Z	$\mu_{t\bar{t}}$
Expected	1.0 ± 3.0	1.00 ± 0.17	1.00 ± 0.07
Observed	1.1 ± 3.6	1.25 ± 0.22	0.81 ± 0.06

Fiducial

p_T^H/Jet p_T	μ_H		μ_Z		$\mu_{t\bar{t}}$	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
> 450 GeV	1.0 ± 3.3	0.7 ± 3.3	1.00 ± 0.18	1.27 ± 0.22	1.00 ± 0.07	0.81 ± 0.06
> 1 TeV	1.0 ± 29.0	26 ± 31	1.0 ± 1.6	2.4 ± 1.7	1.0 ± 0.3	0.51 ± 0.19

Boosted H→bb+jet: Differential

p_T^H [GeV]	μ_H Exp.	μ_H Obs.
300–450	1 ± 18	−7 ± 17
450–650	1.0 ± 3.3	−2.9 ± 4.7
>650	1.0 ± 6.3	4.8 ± 6.4

μ_H = the four main production modes