Higgs boson couplings to quarks and leptons with the ATLAS experiment

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On behalf of The ATLAS Collaboration

Phenomenology 2021 Symposium

ATLAS EXPERIMENT

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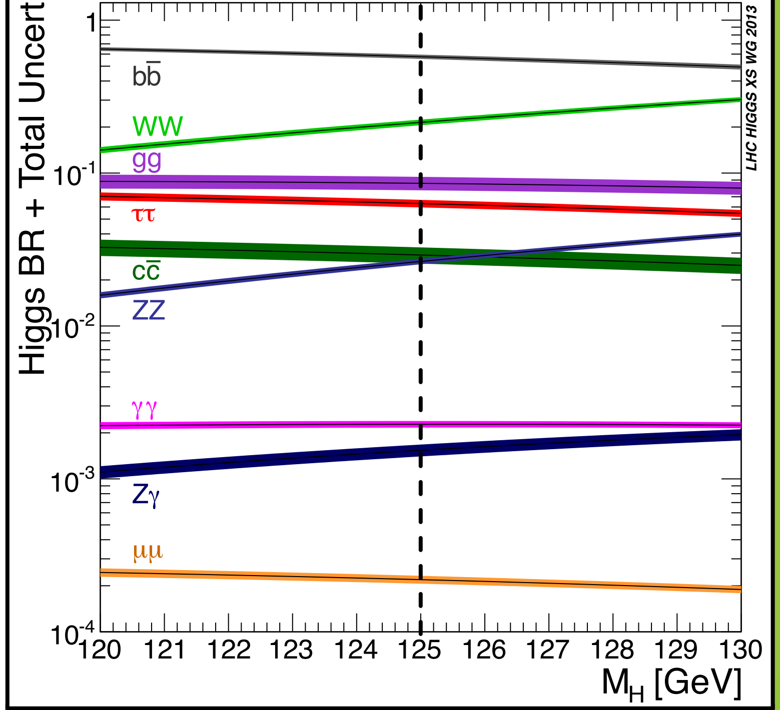
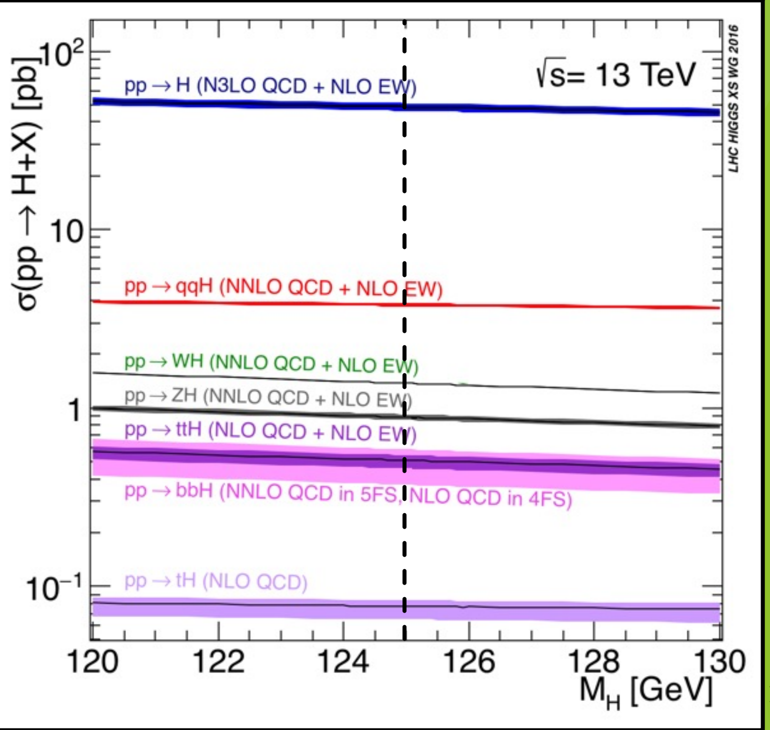
Introduction

- The $b\bar{b}$ decay mode has the highest branching fraction
  - with a predicted rate of $\mathcal{B}(H \rightarrow b\bar{b}) = 58.1\%$
- The $\mu\mu$ decay mode offers the best opportunity to study the interactions to 2nd-generation fermions at the LHC
  - with a predicted rate of $\mathcal{B}(H \rightarrow \mu\mu) = (2.17 \pm 0.04)\times 10^{-4}$
- There are four main production mechanisms for the Standard Model Higgs boson:
  - Gluon-gluon fusion has the largest cross-section but is difficult for Higgs boson decays to b-quarks due to high levels of background. However, it can be a probe of extremely high momentum scales
  - VH is the most sensitive production channel at hadron colliders when the Higgs boson decays to *b*-quarks
  - VBF has the second-largest cross-section but has a hard experimental signature for Higgs boson decays to *b*-quarks
  - ttH, despite only contributing about 1% to the total Higgs production cross-section, allows a direct measurement of the top-quark Yukawa coupling





Top: Higgs production cross-sections
Bottom: Higgs decay branching ratios
[CERN Yellow Report 4]
LHCHXSWG

Jet Reconstruction

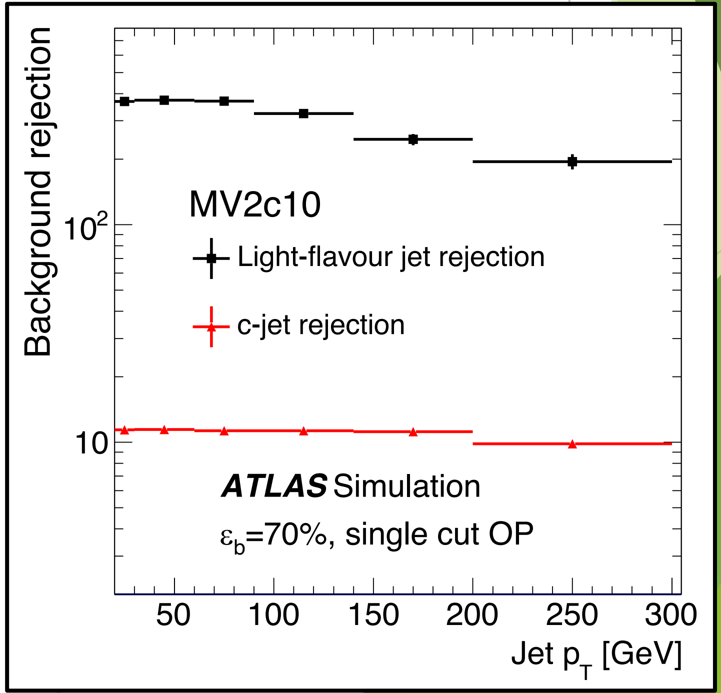
- The analyses all use the anti-k_t algorithm to reconstruct jets with different radii depending on the topology involved
  - LCTopo = reconstructed from topoclusters calibrated at the local hadronic scale
  - EMTopo = reconstructed from topoclusters calibrated at the electromagnetic scale
  - PFlow = reconstructed from particle flow objects constructed from calorimeter energy clusters and tracks

Analysis	Type of Jet	Radius	p_T [GeV]
Boosted $H \to b\bar{b}$	LCTopo	1.0 (Large-R)	> 250
VBF $H \to b\bar{b}$	PFlow	0.4 (Small-R)	> 30
VBF $H(\to b\bar{b}) + \gamma$	EMTopo	0.4 (Small-R)	> 20
VH, $H \to b\bar{b}$ Resolved	EMTopo	0.4 (Small-R)	$> 20/30$
VH, $H \to b\bar{b}$ Boosted	LCTopo	1.0 (Large-R)	> 250
$t\bar{t}H$, $H \to b\bar{b}$	EMTopo	0.4 (Small-R)	> 25
$H \to \mu\mu$	PFlow	0.4 (Small-R)	$> 25/30$

b-tagging

- All the analyses use a multivariate b-tagging algorithm to identify b-jets
  - it is a boosted decision tree that takes inputs from a range of kinematic properties of b-jets as well as outputs of lower-level algorithms that are based on properties of the relatively long lifetime of b-hadrons
- Single-cut operating points are defined on the BDT discriminant distribution such that an average efficiency of b-jets in simulated $t\bar{t}$ events is ensured
- Some of the analyses use a 'pseudo-continuous' calibration so that they can mix different operating points for different regions or jets

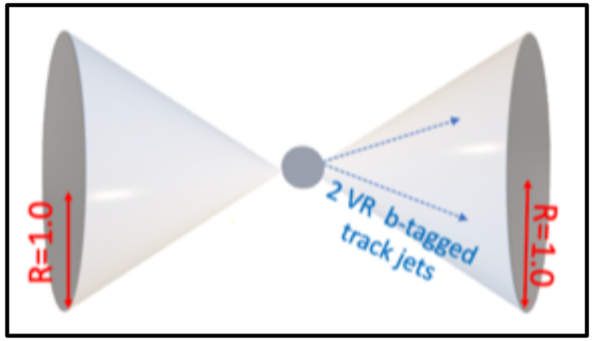
ϵ_b	Rejection		
	c-jet	τ-jet	Light-flavour jet
60%	23	140	1200
70%	8.9	36	300
77%	4.9	15	110
85%	2.7	6.1	25

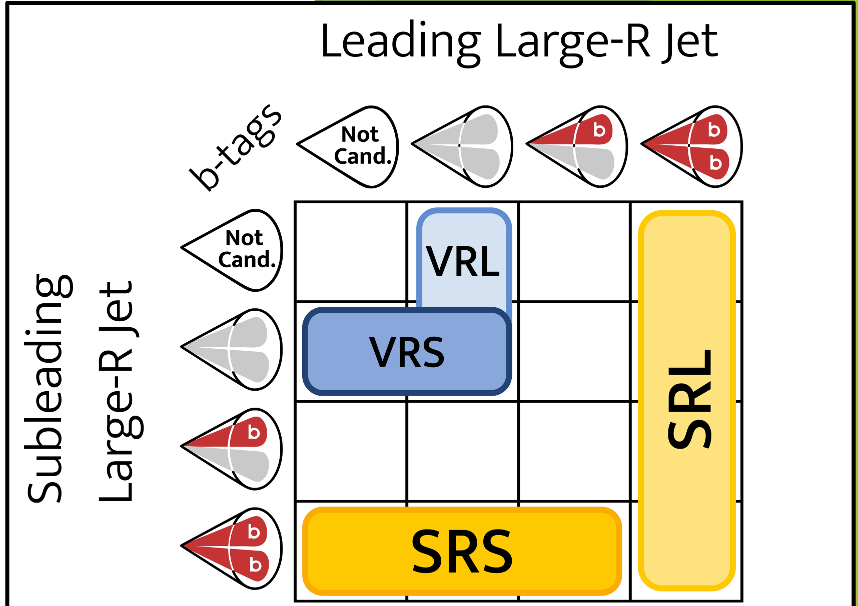


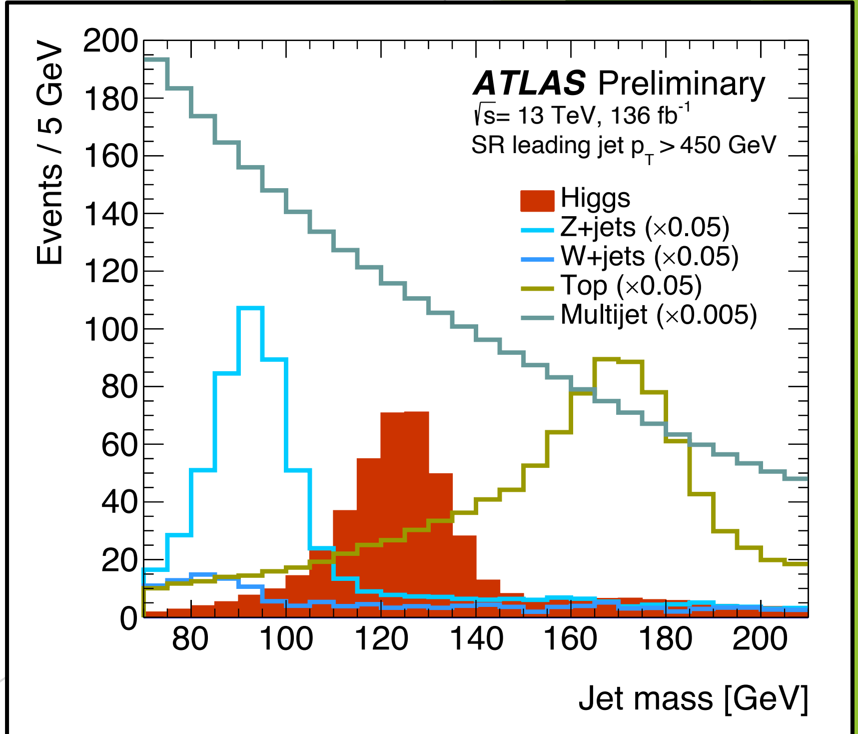
Boosted $H \rightarrow b\bar{b}$: Analysis Overview

ATLAS-CONF-2021-10

- Boosted decays allow access to the high-p_T Higgs spectrum
- New physics contributions could increase the Higgs cross-section by up to 50% at high- p_T
- At high-p_T, the *b*-jets become highly collimated inside a large-R jet
- Both the leading and sub-leading jets are considered as possible Higgs candidates to define the signal and validation regions
- A dedicated $t\bar{t}$ control region is used to determine the $t\bar{t}$ yield
- The analysis is designed to be sensitive to ggF production, whilst still including the other production modes







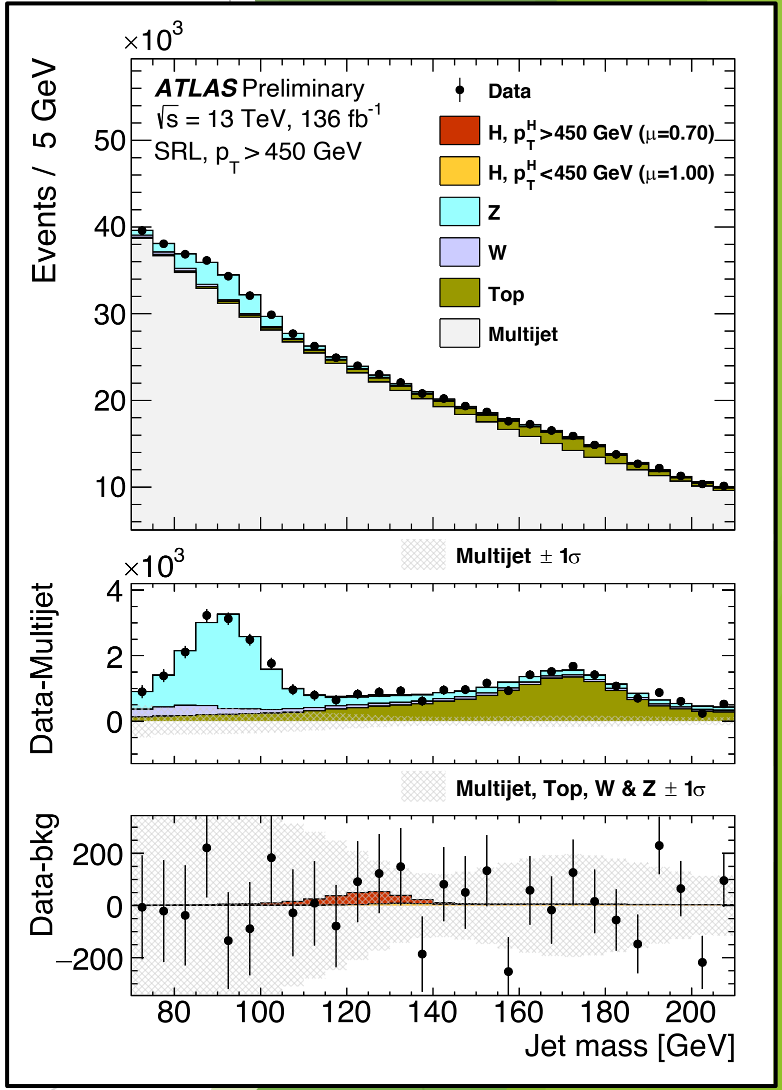
Boosted $H \rightarrow b\bar{b}$: Fiducial Measurement

- A binned maximum-likelihood fit to the jet mass spectrum is performed to extract the signal
- The **fiducial measurements** offer an easy comparison to theoretical predictions
- Phase space defined as $|\eta_H| < 2.0$ and $p_T^H > 450$ GeV and $p_T^H > 1$ TeV
  - The $p_T^H > 1$ TeV region probes a new domain of highly-boosted Higgs
- The extracted signal strengths are:

$$\mu_H(p_T^H > 450 \text{ GeV}) = 0.7 \pm 3.3$$
$$\mu_H(p_T^H > 1 \text{ TeV}) = 26 \pm 31$$

corresponding to measured cross-sections of:

$$\sigma_H(p_T^H > 450 \text{ GeV}) = 13 \pm 52(\text{stat.}) \pm 32(\text{syst.}) \pm 3(\text{theory}) \text{ fb}$$
$$\sigma_H(p_T^H > 1 \text{ TeV}) = 3.4 \pm 3.9(\text{stat.}) \pm 1.0(\text{syst.}) \pm 0.8(\text{theory}) \text{ fb}$$



Boosted $H \to b\bar{b}$: Differential Measurement

- The **differential measurements** offer enhanced sensitivity to BSM effects
- The extracted signal strengths are:

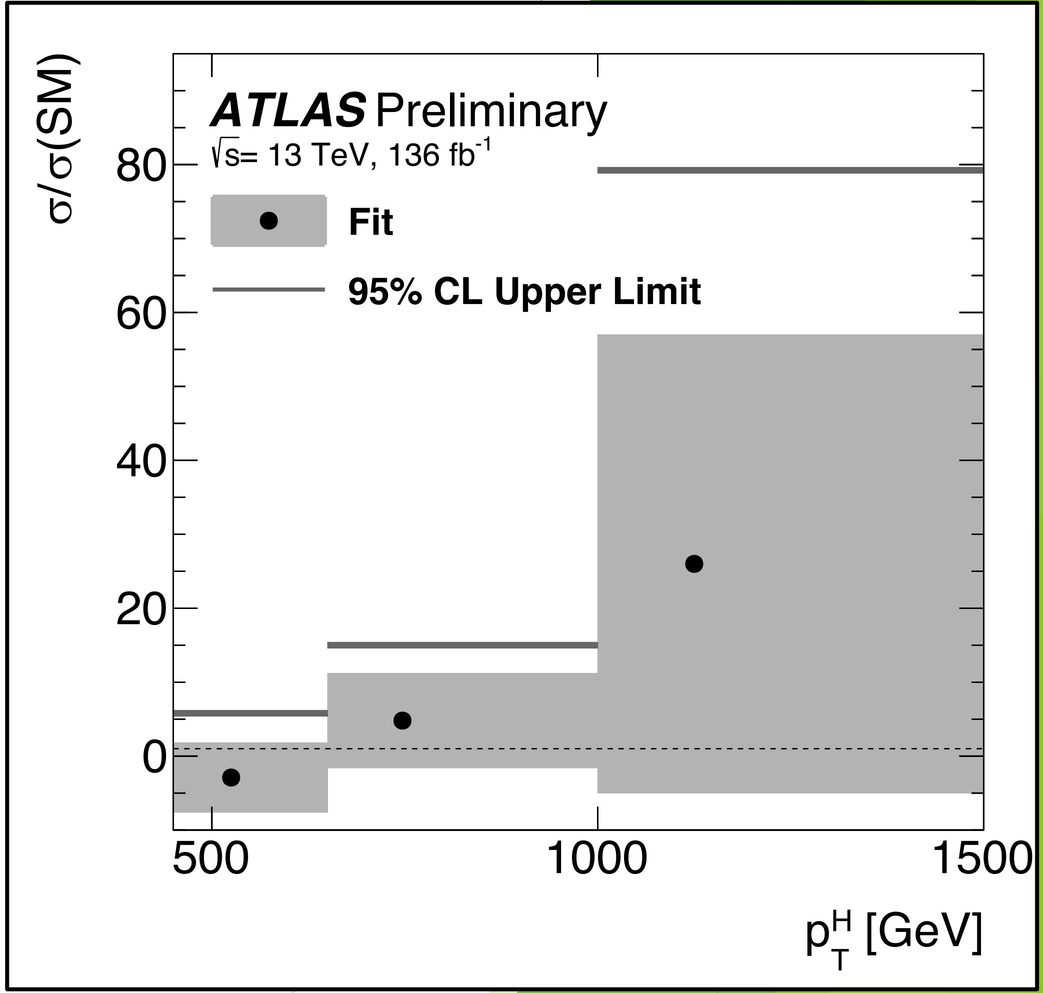
p_T^H [GeV]	μ_H Exp.	μ_H Obs.
300–450	1 ± 18	-7 ± 17
450–650	1.0 ± 3.3	-2.9 ± 4.7
>650	1.0 ± 6.3	4.8 ± 6.4

leading to 95% confidence level upper limits:

$\sigma_H(300 < p_T^H < 450\ \text{GeV}) < 2.8$ pb

$\sigma_H(450 < p_T^H < 650\ \text{GeV}) < 91$ fb

$\sigma_H(p_T^H > 650\ \text{GeV}) < 40.5$ fb



VBF Production: Analyses Overview

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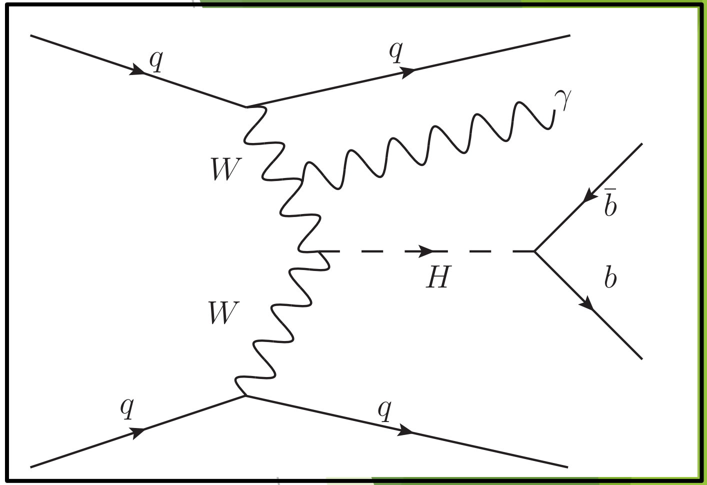
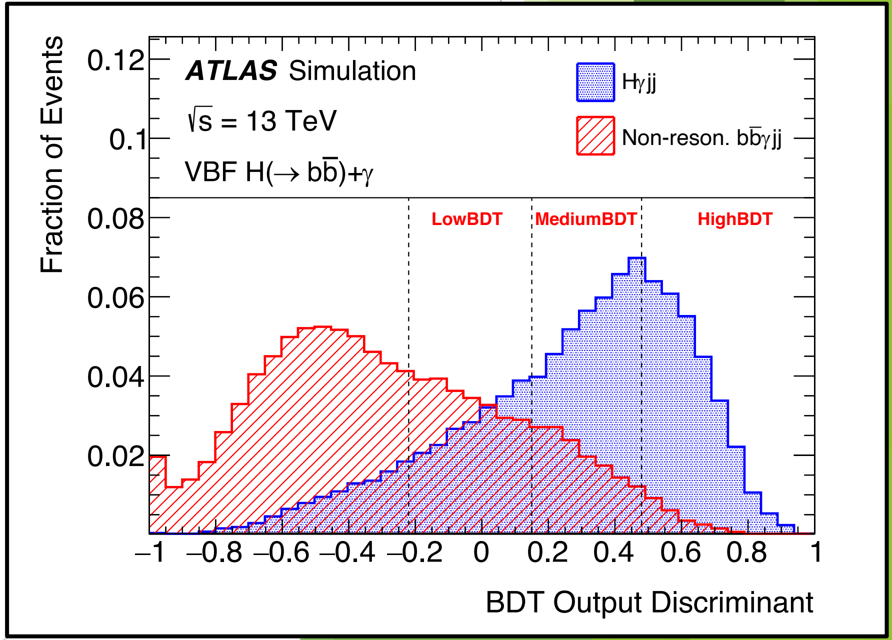
VBF $H(\rightarrow b\bar{b}) + \gamma$



- When there is a photon present in the final state, the VBF production mode has a cross-section twice as large as all the other production modes combined
- There is destructive interference between matrix elements for initial- and final-state radiation, suppressing contributions from Z boson fusion and the dominant multi-jet non-resonant background
- The high-p_T photon also allows for efficient triggering
- A boosted decision tree with 10 kinematic input variables is trained on MC to separate signal and background
  - the BDT output defines 3 signal regions



VBF $H + \gamma$: Results

- The signal strength is extracted from an extended unbinned maximum-likelihood fit to the m_{bb} distribution simultaneously in all 3 signal regions
- μ_H and μ_{VBF} are single parameters of interest common to all 3 signal regions

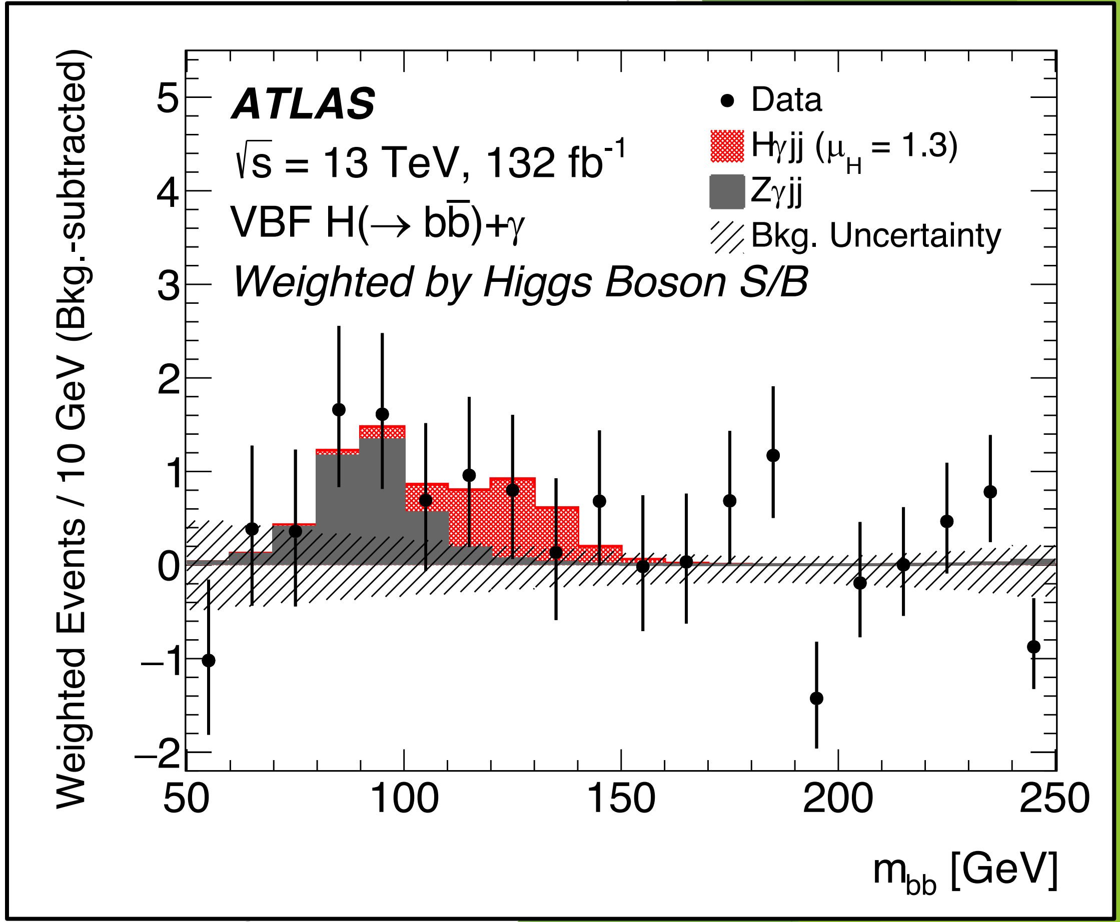
$$\mu_{VBF} = \mu_H = 1.3 \pm 1.0$$

corresponding to an observed significance of 1.3σ for μ_H

- There are separate, uncorrelated μ_Z parameters of interest for each signal region

$$\mu_Z^{HighBDT} = 1.9 \pm 1.2 \qquad \mu_Z^{MediumBDT} = 1.5 \pm 1.1$$

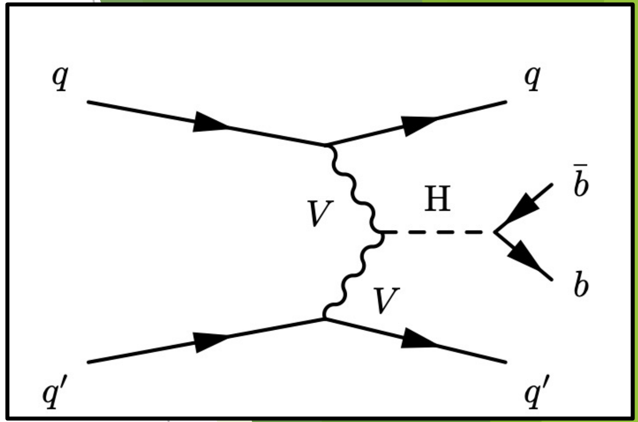
$$\mu_Z^{LowBDT} = -1.3^{1.2}_{-1.6}$$



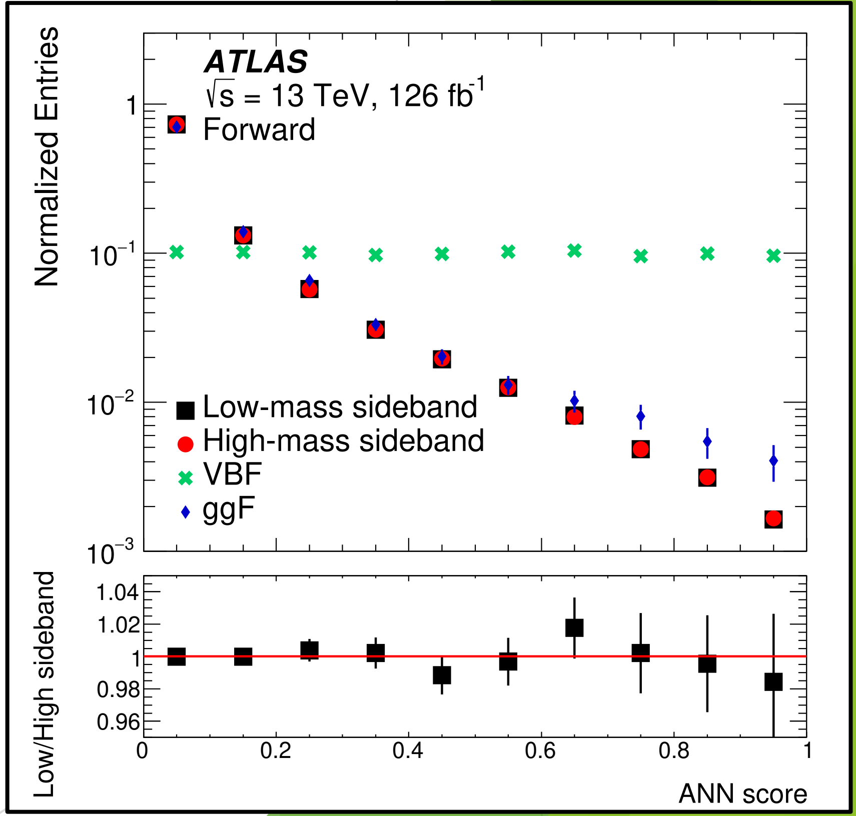
VBF Production: Analyses Overview

arXiv:2011.08280

VBF $H \to b\bar{b}$



- Event selection is orthogonal to the $H + \gamma$ analysis so that a combination measurement can also be performed
- 2 orthogonal analysis channels determined by the presence or absence of a high-p_T forward jet
- An adversarial neural network is constructed using 12 kinematic input variables, such that the classifier output is independent of the di-b-jet mass
  - 5 signal regions per channel are created based on the classifier score

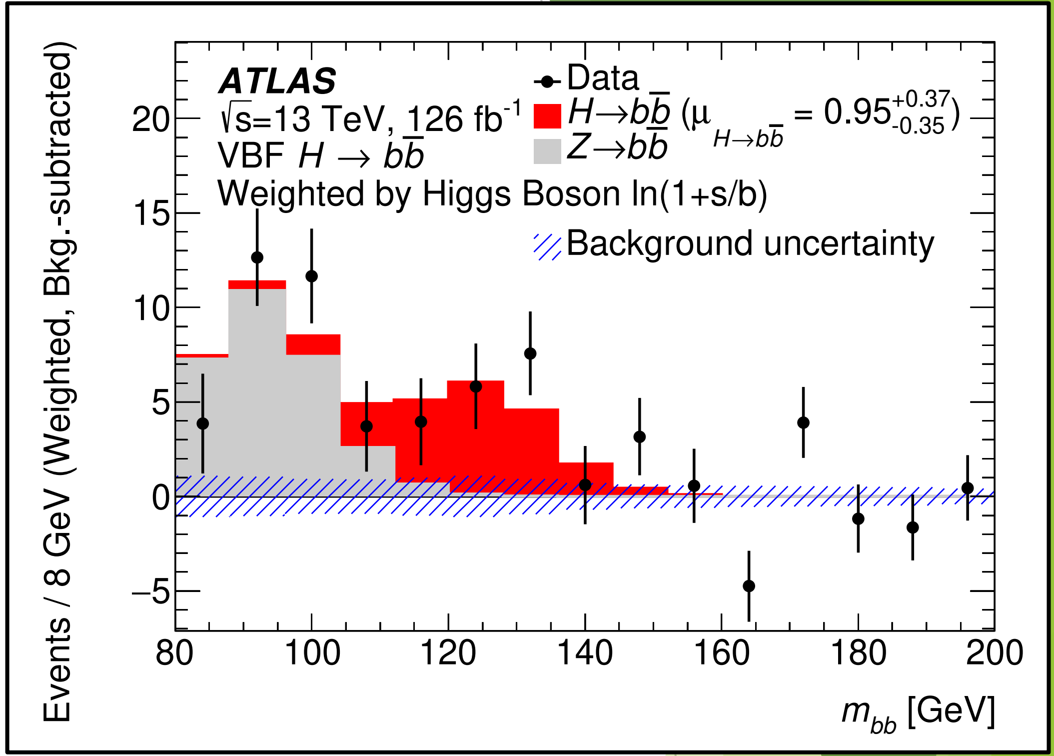


VBF H: Results

- The signal strength is extracted from an extended binned maximum-likelihood fit to the m_{bb} distribution simultaneously in all 10 signal regions yielding

$$\mu_{VBF,H\to b\bar{b}} = 0.95^{+0.32}_{-0.32}(\text{stat.})^{+0.20}_{-0.17}(\text{syst.})$$

corresponding to an observed significance of 2.6σ



- The result is also combined with the result from the $H\gamma$ analysis in a combine likelihood fit sharing the Higgs boson signal strength as a common parameter of interest:

$$\mu_{H\to b\bar{b}} = 0.99^{+0.30}_{-0.30}(\text{stat.})^{+0.10}_{-0.15}(\text{syst.})$$

corresponding to an observed significance of 3.0σ

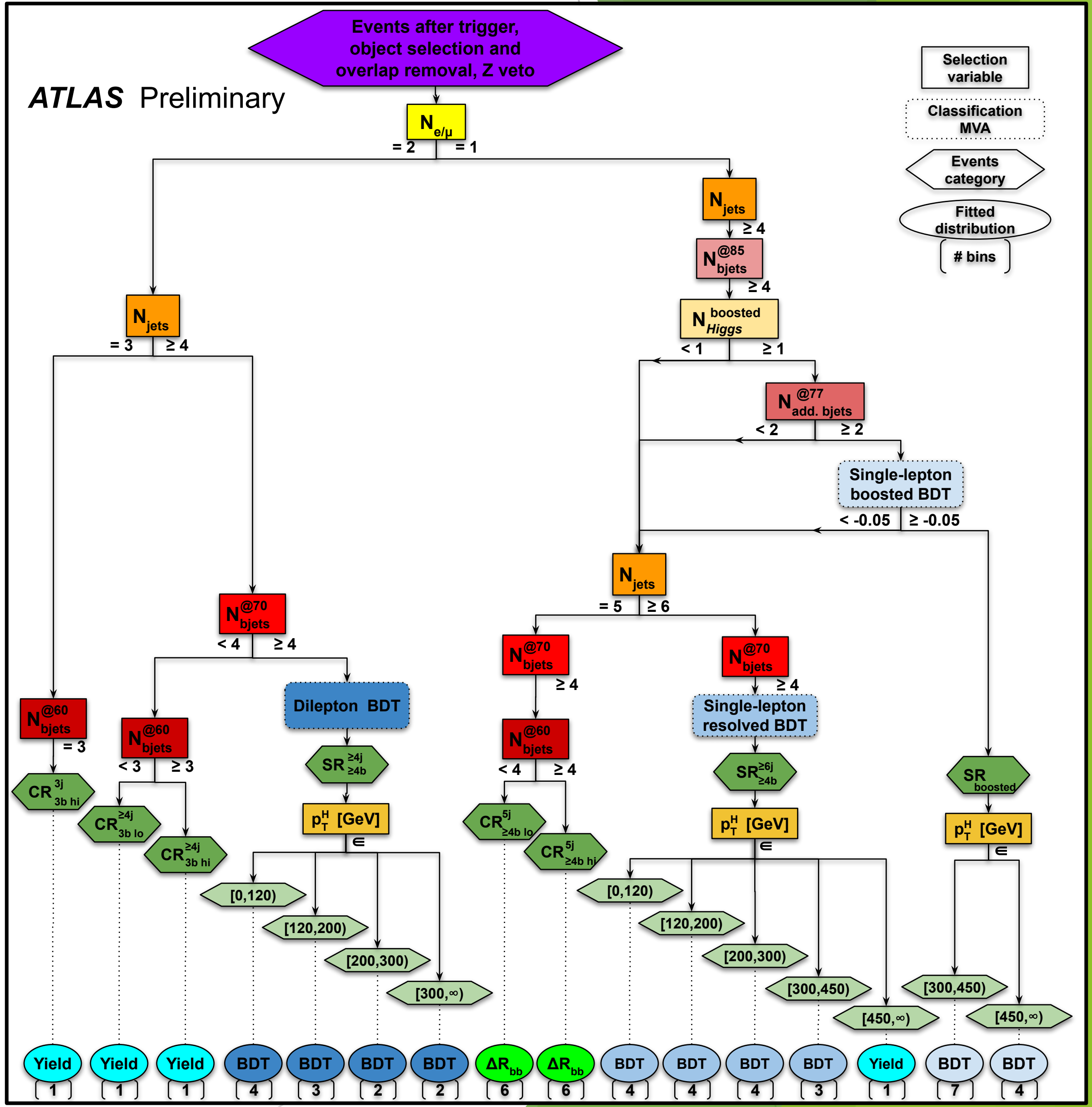
$$\mu_{VBF,H\to b\bar{b}} = 0.99^{+0.30}_{-0.30}(\text{stat.})^{+0.18}_{-0.16}(\text{syst.})$$

corresponding to an observed significance of 2.9σ

$t\bar{t}H(H \to b\bar{b})$: Analysis Overview

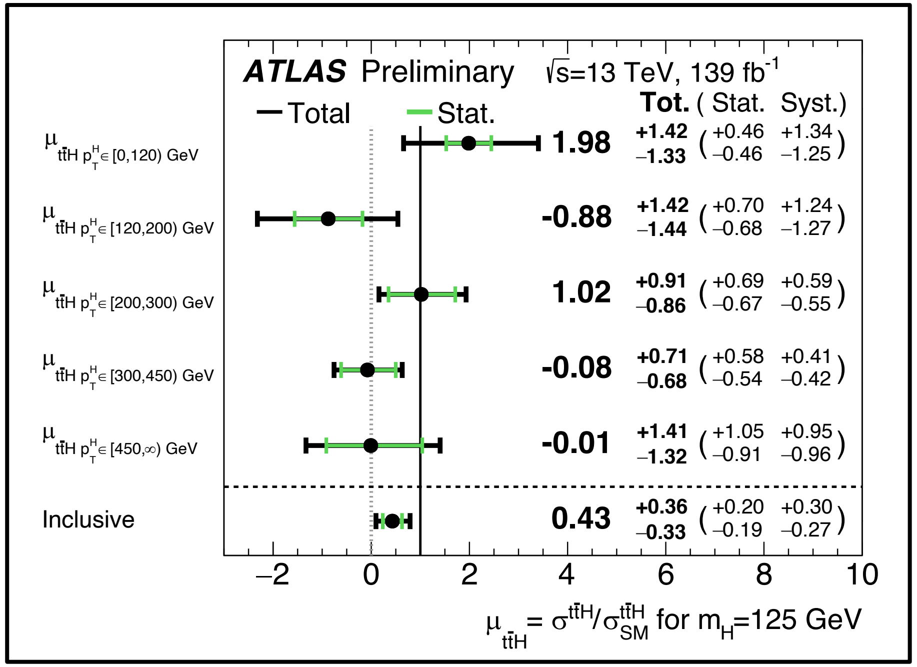
ATLAS-CONF-2020-058

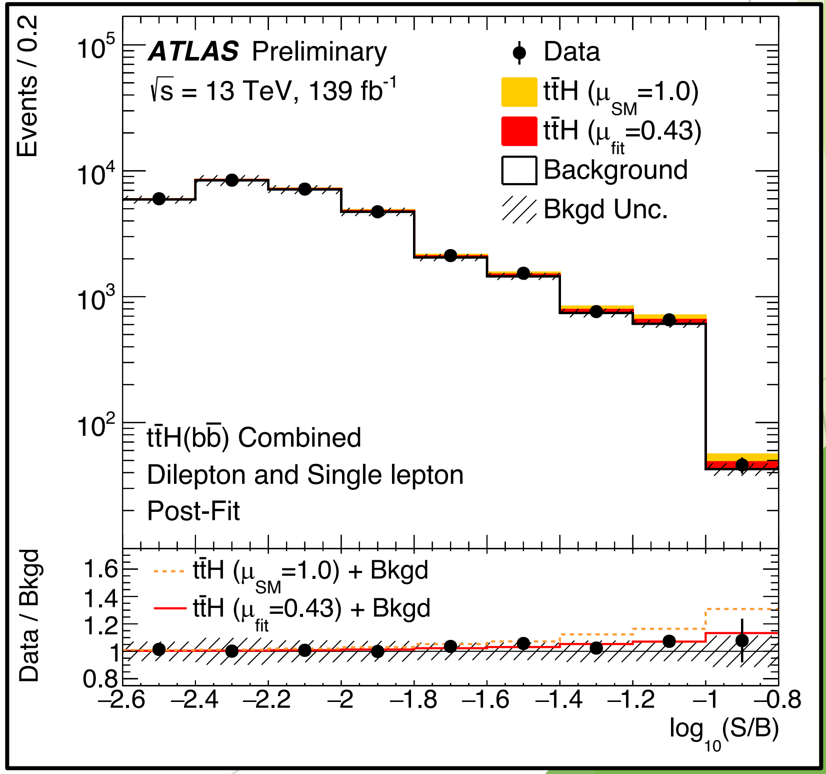
- The analysis is split into 2 regions: dilepton and single-lepton
- Events are further categorized into a total of 16 regions: 11 signal regions and 5 control regions
  - In the single-lepton channel, a boosted signal region is considered split into 2 p_T^H bins
  - The dilepton and single-lepton resolved signal regions are further split into 4 or 5 reconstructed p_T^H bins, respectively
  - All control regions are inclusive in p_T^H
- The $H \to b\bar{b}$ decay mode accounts for at least 94% of $t\bar{t}H$ events in the signal regions
- Multivariate classifiers are used in 2 parts of the analysis:
  - identifying Higgs boson candidates
  - classifying $t\bar{t}H$ signal events



$t\bar{t}H(H \to b\bar{b})$: Results

- A profile-likelihood fit is performed to a combination of the classification boosted decision tree distribution in the signal regions and the event yield or ΔR_{bb}^{avg} distributions in the dilepton or single-lepton control regions respectively
- The extracted inclusive signal strength is $\mu = 0.43^{+0.20}_{-0.19}(\text{stat.})^{+0.30}_{-0.27}(\text{syst.})$ corresponding to an observed significance of 1.3σ
- The first differential measurement of the $t\bar{t}H$ signal strength is also performed in bins of truth p_T^H

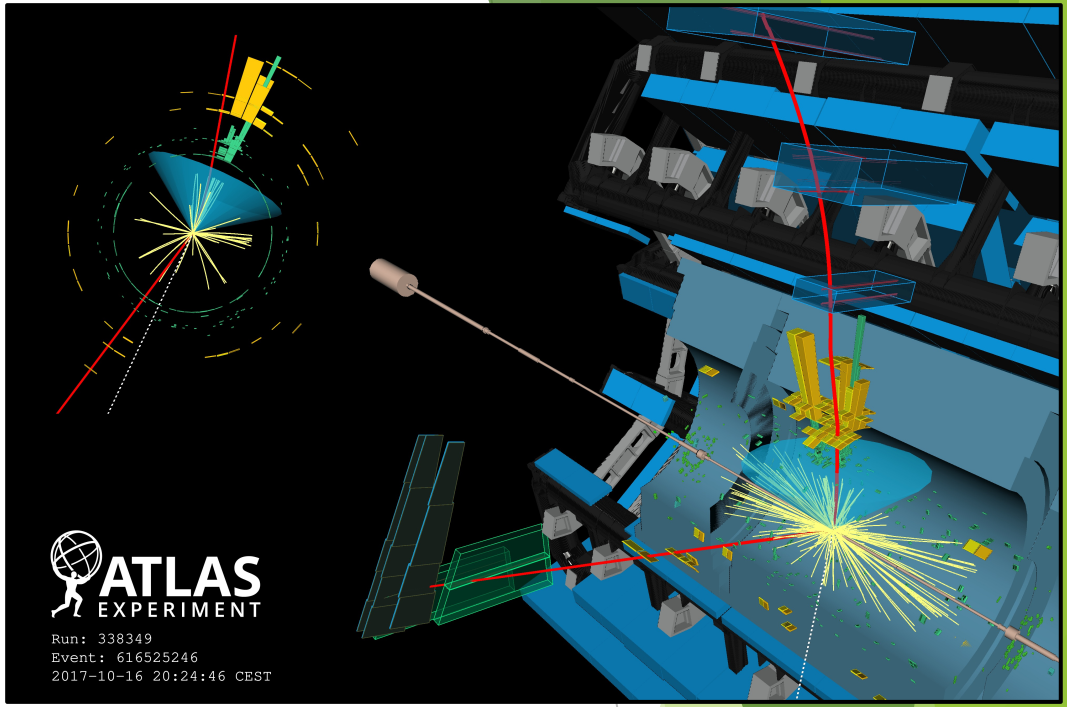




$VH, H \rightarrow b\bar{b}$: Analyses Overview

Eur. Phys. J. C 81 (2021) 178 Phys. Lett. B 816 (2021) 136204

- The leptonic decay of the vector boson enables efficient triggering and a large reduction of the multi-jet background
- Both analyses measure the cross-section for associated production in several p_T regions and constrain anomalous couplings in a Standard Model effect field theory
- Three signatures are explored: $ZH \rightarrow \nu\nu b\bar{b}$, $WH \rightarrow l\nu b\bar{b}$ and $ZH \rightarrow llb\bar{b}$ in 3 (2) p_T regions for the resolved (boosted) analysis



Candidate event for $WH \rightarrow \mu\nu b\bar{b}$

Resolved

- Performs a binned maximum-likelihood fit to a total of **42 regions**: 14 signal regions and 28 control regions
- Discriminating variable: outputs of **boosted decision trees** are trained in 8 regions, evaluated in each signal region

Boosted

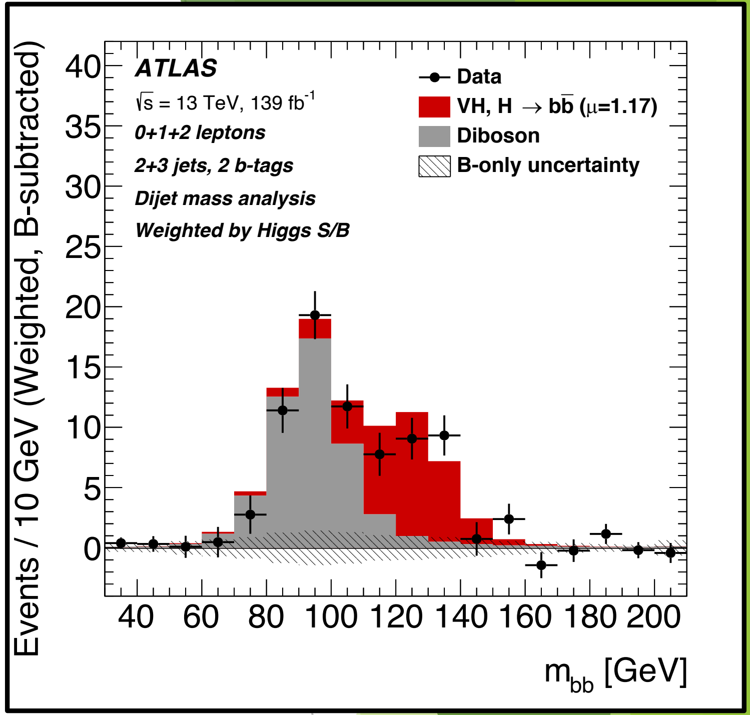
- Performs a binned profile-maximum-likelihood fit to a total of **14 regions:** 10 signal regions and 4 control regions
- Discriminating variable: Higgs-candidate **jet mass distribution**

$VH, H \to b\bar{b}$: Resolved Results

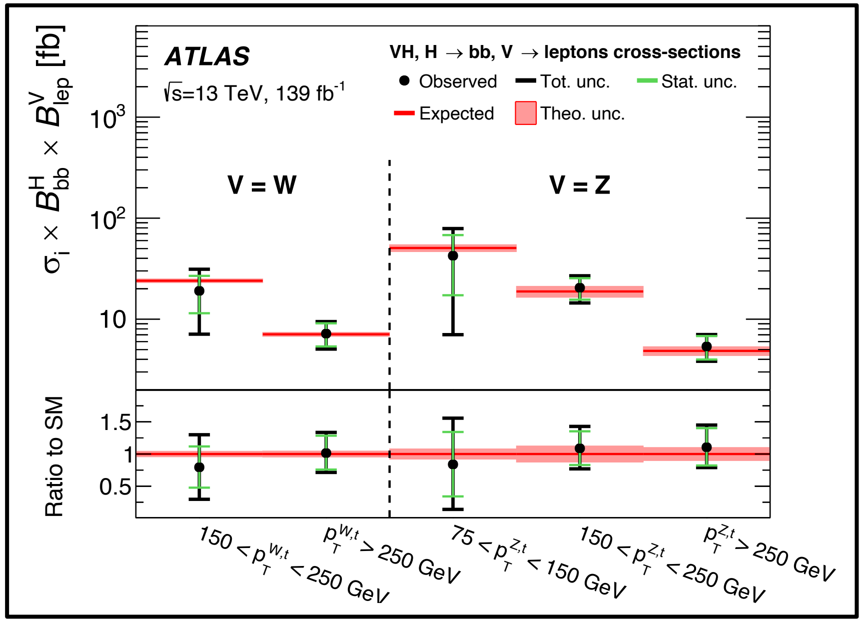
- Evidence for the WH production mode and an observation of the ZH production mode were reported:

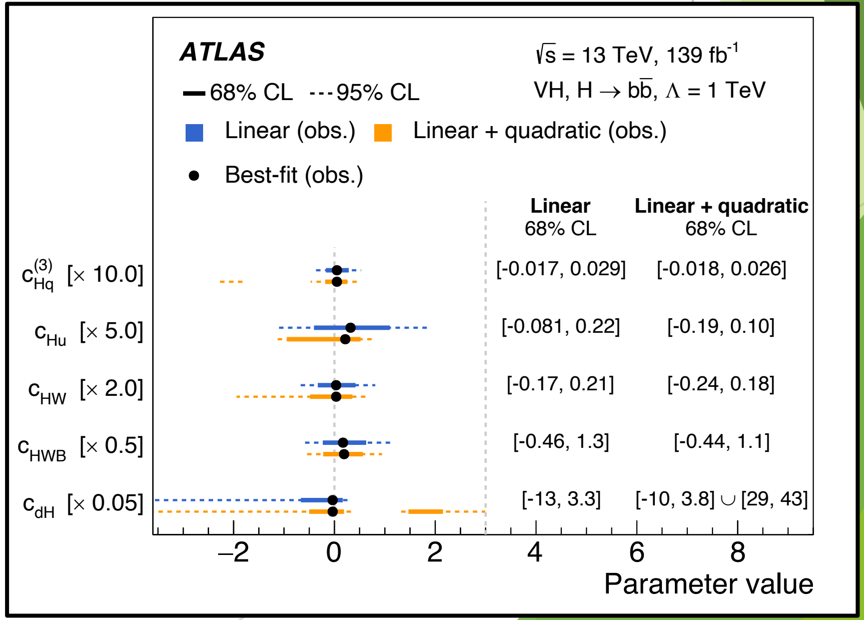
$$\mu_{WH}^{bb} = 0.95_{-0.25}^{+0.27}$$
$$\mu_{ZH}^{bb} = 1.08_{-0.23}^{+0.25}$$

corresponding to observed significances of 4.0σ and 5.3σ, respectively



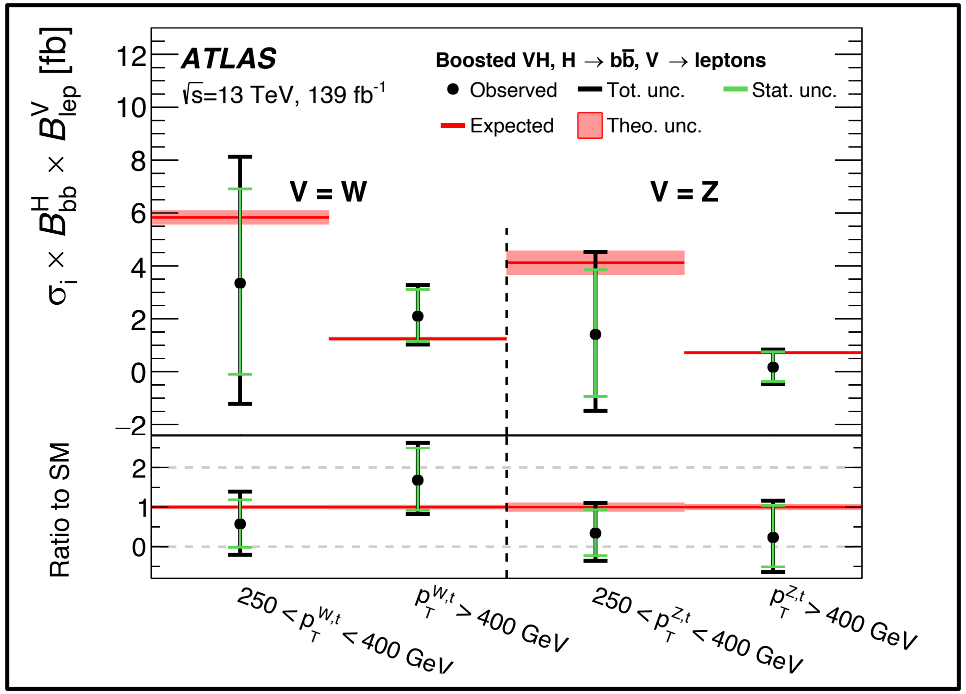
- Simplified p_T-dependent cross-sections are measured
- Limits are set in the context of an SMEFT interpretation

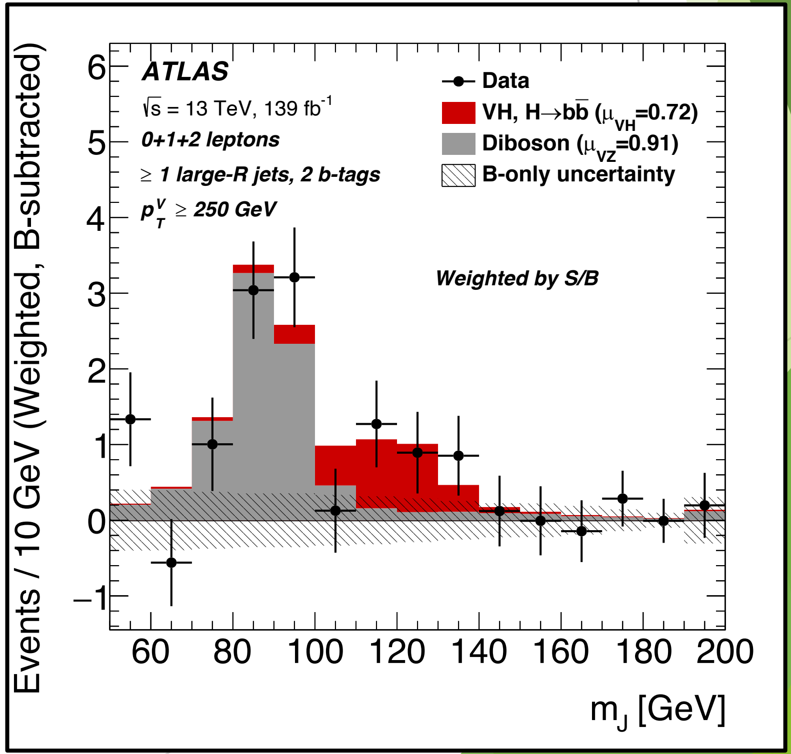




$VH, H \to b\bar{b}$: Boosted Results

- The signal strength parameters are extracted simultaneously with μ_{VZ}^{bb}
  - The overall single VH signal strength is $\mu_{VH}^{bb} = 0.72^{+0.39}_{-0.36}$ corresponding to an observed significance of 2.1σ
  - The cross-section is measured in the in simplified p_T-dependent regions
  - Limits are also set on the coefficients of the effective Lagrangian operators that affect VH production and the $H \to b\bar{b}$ decay

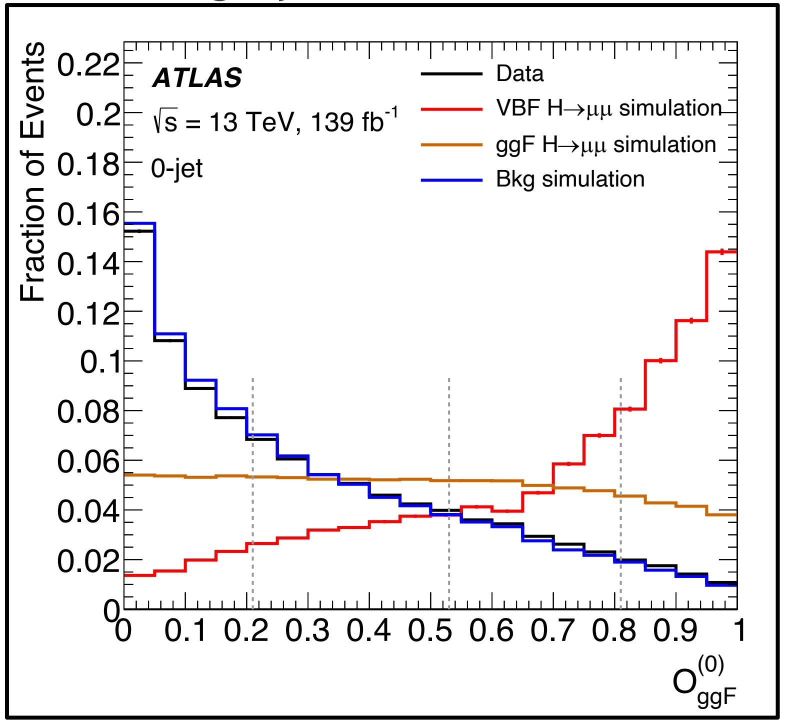


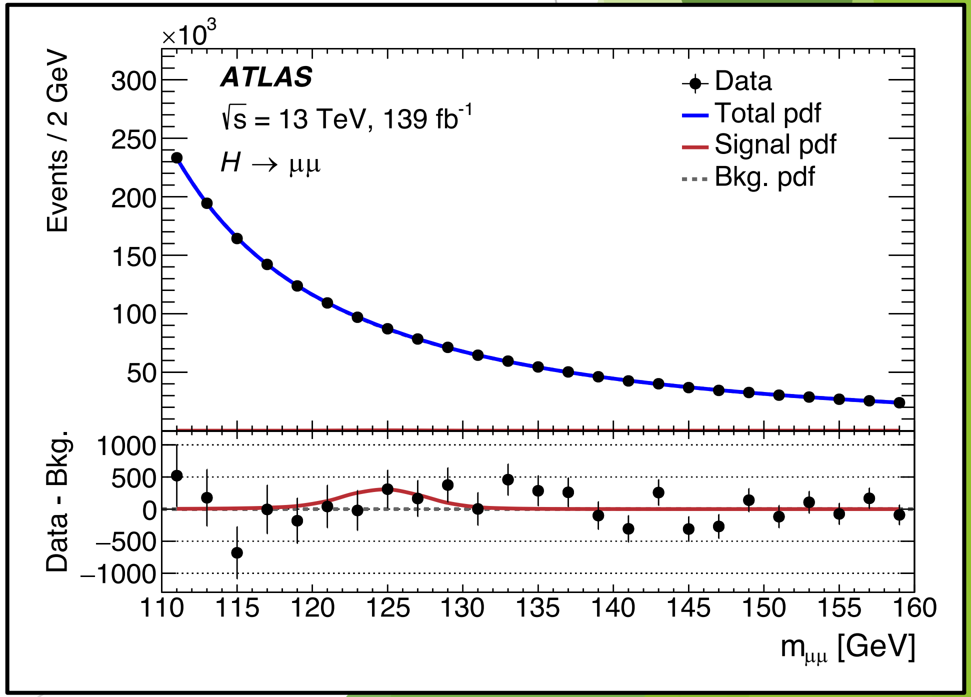


$H \rightarrow \mu\mu$: Analysis Overview

Phys. Lett. B 812 (2021) 135980

- Events with 2 oppositely-charged muons are selected and classified into 20 mutually exclusive categories
  - based on the number of additional electrons or muons and the number of jets and *b*-tagged jets
- Events are selected to each category in an exclusive order so that there is no overlap:
  - $t\bar{t}H$, VH, VBF+ggF
- Boosted decision trees for each category are trained to enhance the signal sensitivity, giving the 20 categories:
  - 1 $t\bar{t}H$
  - 2 VH 3-lepton categories
  - 1 VH 4-lepton category
  - 4 VBF categories
  - 12 ggF categories





$H \to \mu\mu$: Results

- A simultaneous binned maximum-likelihood fit to the 20 dimuon mass distributions is used to extract the signal yield
- The best-fit value for the combined signal strength is

$$\mu = 1.2 \pm 0.6$$

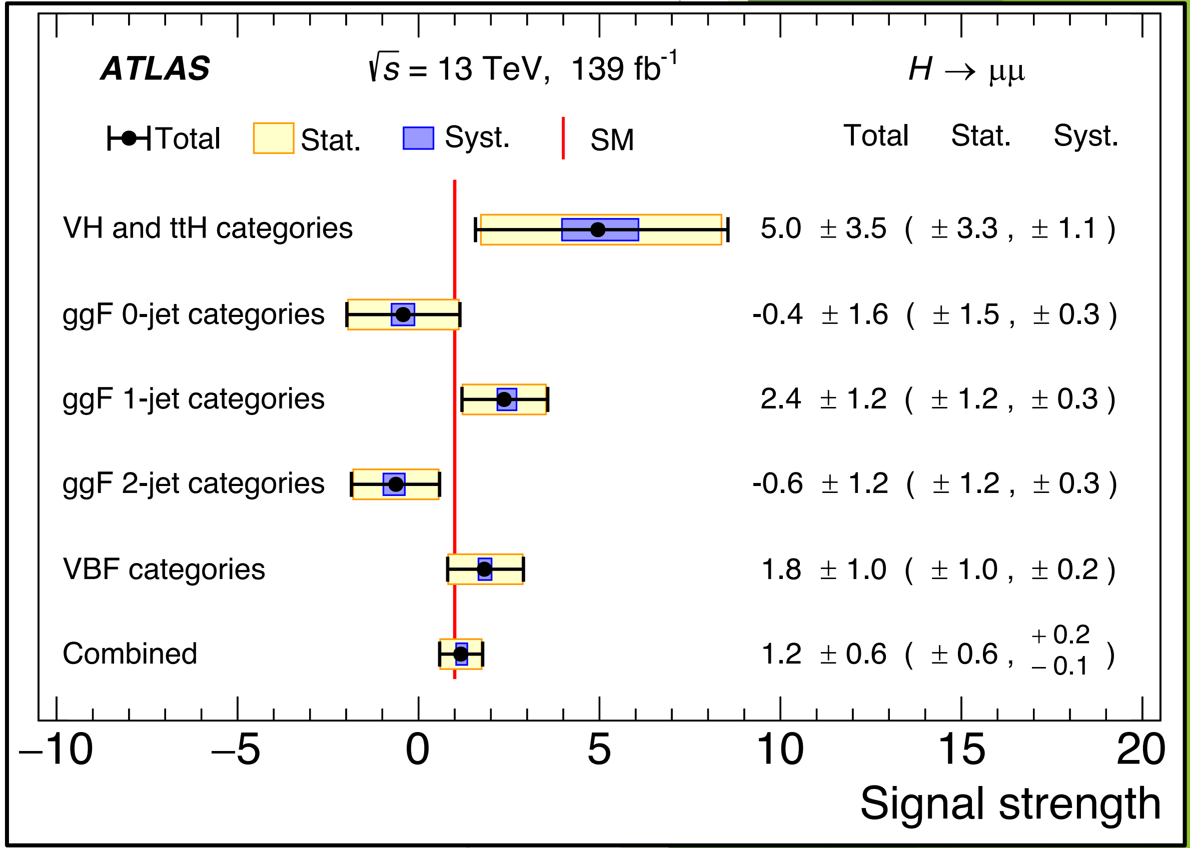
corresponding to an observed significance of 2.0σ

- An upper limit on the signal strength at the 95% confidence level is also computed:

$$\mu < 2.2$$

- The corresponding upper limit at the 95% confidence level on the branching ratio is:

$$\mathcal{B}(H \to \mu\mu) < 4.7\times10^{-4}$$



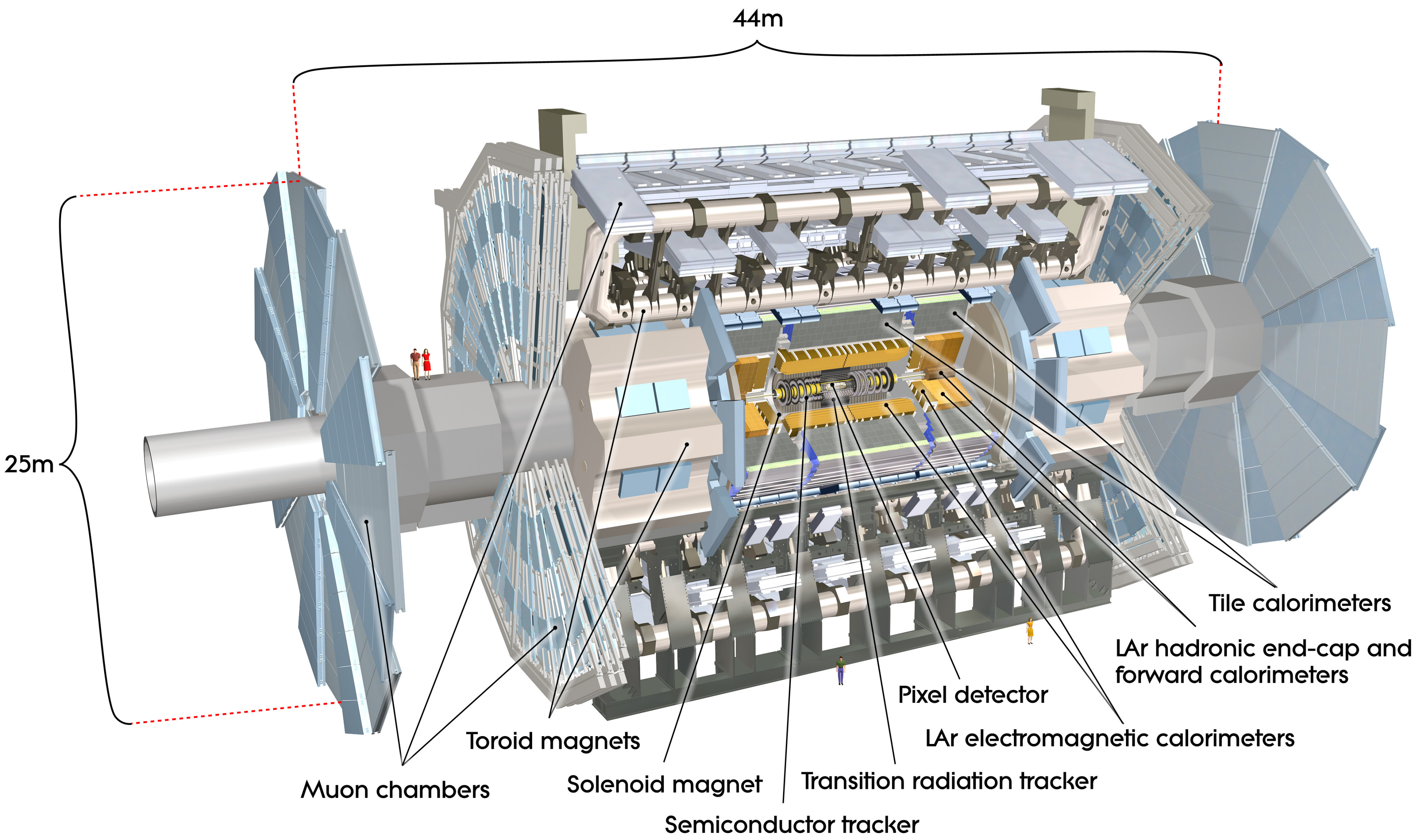
Conclusions

- ATLAS has made a lot of progress in measurements of $H \to b\bar{b}$ and searches for $H \to \mu\mu$ decays
  - 7 analyses updating previous results using the full Run 2 dataset and extending the covered p_T range have been presented
- The analyses probe all 4 main Higgs production modes with many analyses getting a significantly improved sensitivity compared to previous results
- Previous ATLAS results in the $H \to c\bar{c}$ and $H \to \tau\tau$ channels are included in the table for completeness

Analysis	Observed Signal Strength
Boosted $H \to b\bar{b}$	$\mu_H = 0.7 \pm 3.3$
VBF $H \to b\bar{b}$	$\mu_{VBF} = 0.95^{+0.38}_{-0.36}$
VBF $H(\to b\bar{b}) + \gamma$	$\mu_{VBF} = 1.3 \pm 1.0$
VBF Combined	$\mu_{VBF} = 0.99^{+0.36}_{-0.34}$
VH, $H \to b\bar{b}$ Resolved	$\mu_{VH} = 1.02^{+0.18}_{-0.17}$
VH, $H \to b\bar{b}$ Boosted	$\mu_{VH} = 0.72^{+0.39}_{-0.36}$
$t\bar{t}H \to b\bar{b}$	$\mu_{t\bar{t}H} = 0.43^{+0.33}_{-0.33}$
ZH, $H \to c\bar{c}$	$\mu_{ZH} = -69 \pm 101$
$H \to \mu\mu$	$\mu_H = 1.6 \pm 0.6$
$H \to \tau\tau$	$\mu_H = 1.09^{+0.35}_{-0.30}$

Additional Material

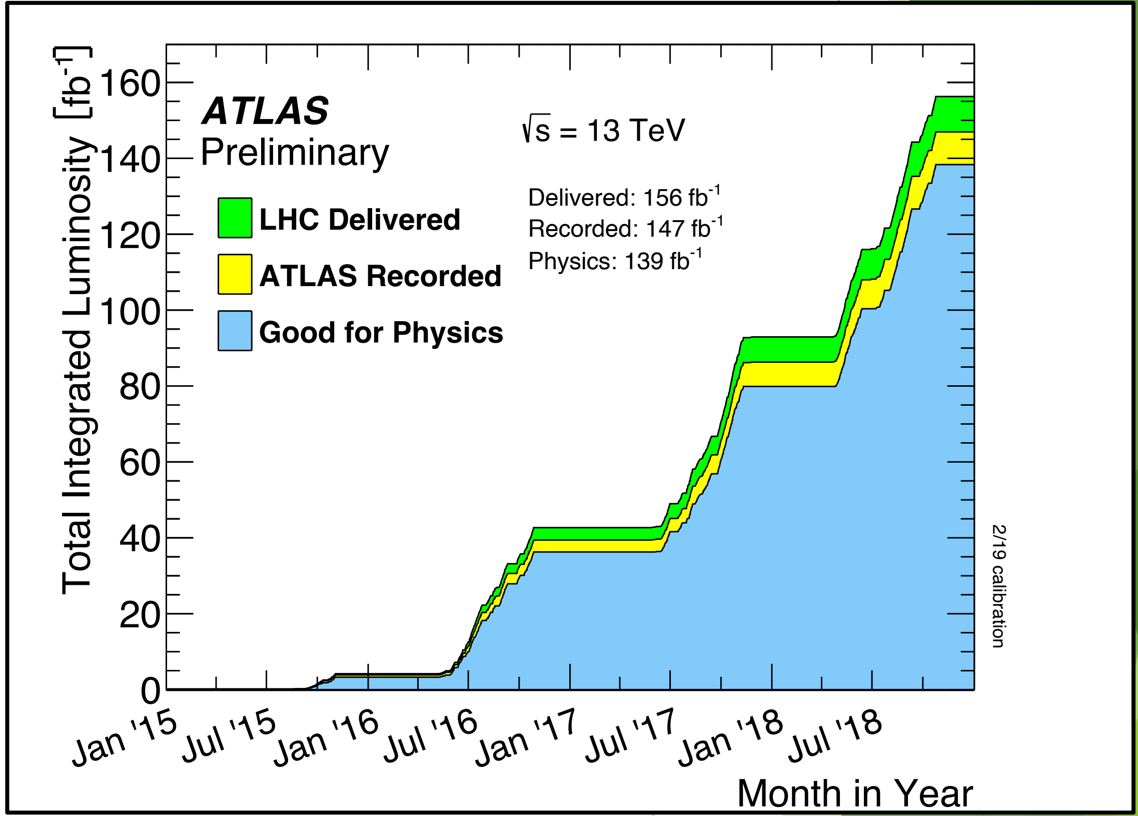
ATLAS Detector



Run 2 Luminosity

- Total $139\ \mathrm{fb}^{-1}$ with an uncertainty of 1.7% of 'good-for-physics' integrated luminosity for Run 2

Analysis	Luminosity $[\mathrm{fb}^{-1}]$
Boosted $H \to b\bar{b}$	136
VBF H	126
VBF $H + \gamma$	132
VH Resolved	139
VH Boosted	139
$t\bar{t}H$	139
$H \to \mu\mu$	139



Boosted $H \to b\bar{b}$: Event Selection Summary

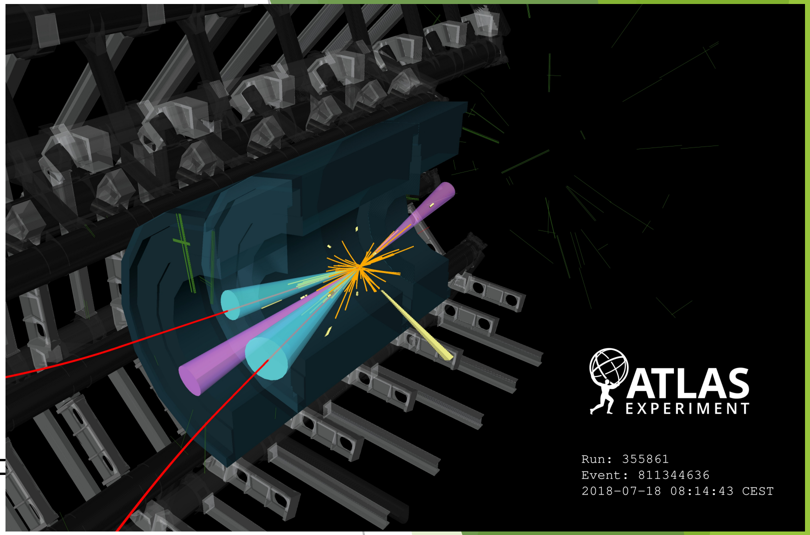
	Inclusive		Fiducial				Differential	
Signal Regions								
Jet Order*	Lead	Sublead	Lead	Sublead	Lead	Sublead	Lead	Sublead
Jet p_T [GeV]	>450	>250	>450	>450	>1000	–	450–650, 650–1000	250–450, 450–650, 650–1000
Fiducial Volumes								
p_T^H [GeV]	–	–	>450	>450	>1000	–	450–650, >650	300–450, 450–650, >650
$t\bar{t}$ Control Regions								
J_t p_T [GeV]	>250		>450		>1000		250–450, 450–650, 650–1000	

VBF H: Event Selection Summary

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

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

VBF $H + \gamma$: Event Selection Summary



Trigger	L1	≥ 1 photon with $E_{\mathrm{T}} > 22\,\mathrm{GeV}$
	HLT	≥ 1 photon with $E_{\mathrm{T}} > 25\,\mathrm{GeV}$ ≥ 4 jets (or ≥ 3 jets and ≥ 1 b-jet) with $E_{\mathrm{T}} > 35\,\mathrm{GeV}$ and $\lvert\eta\rvert < 4.9$ $m_{jj} > 700\,\mathrm{GeV}$
Offline		≥ 1 photon with $E_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$ ≥ 2 b-jets with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$ ≥ 2 jets with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ and $\lvert\eta\rvert < 4.5$ $m_{jj} > 800\,\mathrm{GeV}$ $p_{\mathrm{T}}(b\bar{b}) > 60\,\mathrm{GeV}$ No electrons ($p_{\mathrm{T}} > 25\,\mathrm{GeV}, \lvert\eta\rvert < 2.47$) or muons ($p_{\mathrm{T}} > 25\,\mathrm{GeV}, \lvert\eta\rvert < 2.5$)

$t\bar{t}H(H \to b\bar{b})$: Event Selection Summary

Region	Dilepton				Single-lepton			
	$\mathrm{SR}^{\geq 4j}_{\geq 4b}$	$\mathrm{CR}^{\geq 4j}_{3b\ \mathrm{hi}}$	$\mathrm{CR}^{\geq 4j}_{3b\ \mathrm{lo}}$	$\mathrm{CR}^{3j}_{3b\ \mathrm{hi}}$	$\mathrm{SR}^{\geq 6j}_{\geq 4b}$	$\mathrm{CR}^{5j}_{\geq 4b\ \mathrm{hi}}$	$\mathrm{CR}^{5j}_{\geq 4b\ \mathrm{lo}}$	$\mathrm{SR}_{\mathrm{boosted}}$
#leptons	$= 2$				$= 1$			
#jets	≥ 4			$= 3$	≥ 6	$= 5$		≥ 4
#b-tag @85%	–				≥ 4			
#b-tag @77%	–				–			$\geq 2^{\dagger}$
#b-tag @70%	≥ 4	$= 3$			≥ 4			–
#b-tag @60%	–	$= 3$	< 3	$= 3$	–	≥ 4	< 4	–
#boosted cand.	–				0			≥ 1
Fit input	BDT	Yield			BDT/Yield	$\Delta R^{\mathrm{avg}}_{bb}$		BDT

$VH \rightarrow b\bar{b}$: Resolved Event Selection Summary

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	Exactly 1 *tight* electron 0 additional *loose* leptons $p_{\mathrm{T}} > 27$ GeV	Exactly 1 *tight* muon 0 additional *loose* leptons $p_{\mathrm{T}} > 25$ GeV	Exactly 2 *loose* leptons $p_{\mathrm{T}} > 27$ GeV Same-flavour Opposite-sign charges ($\mu\mu$)
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–	–	$81 \text{ GeV} < m_{\ell\ell} < 101$ GeV
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			
Jet categories	Exactly 2 / Exactly 3 jets	Exactly 2 / Exactly 3 jets		Exactly 2 / ≥ 3 jets
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	– $150 \text{ GeV} < p_{\mathrm{T}}^{V} < 250$ GeV $p_{\mathrm{T}}^{V} > 250$ GeV	– $150 \text{ GeV} < p_{\mathrm{T}}^{V} < 250$ GeV $p_{\mathrm{T}}^{V} > 250$ GeV		$75 \text{ GeV} < p_{\mathrm{T}}^{V} < 150$ GeV $150 \text{ GeV} < p_{\mathrm{T}}^{V} < 250$ GeV $p_{\mathrm{T}}^{V} > 250$ GeV
Signal regions	$\Delta R(\vec{b_1}, \vec{b_2})$ signal selection			
Control regions	High and low $\Delta R(\vec{b_1}, \vec{b_2})$ side-bands			

$VH \to b\bar{b}$: Resolved BDT Variables

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

$VH \to b\bar{b}$: Boosted Event Selection Summary

Selection	0 lepton channel	1 lepton channel		2 leptons channel	
		e sub-channel	μ sub-channel	e sub-channel	μ sub-channel
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single electron	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single electron	$E_{\mathrm{T}}^{\mathrm{miss}}$
Leptons	0 *baseline* leptons	1 *signal* lepton $p_{\mathrm{T}} > 27$ GeV	$p_{\mathrm{T}} > 25$ GeV	2 *baseline* leptons among which ≥ 1 *signal* lepton, $p_{\mathrm{T}} > 27$ GeV both leptons of the same flavour -	opposite sign muons
		no second *baseline* lepton			
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 250 GeV	> 50 GeV	-	-	
p_{T}^{V}	$p_{\mathrm{T}}^{V} > 250$ GeV				
Large-R jets	at least one large-R jet, $p_{\mathrm{T}} > 250$ GeV, $\lvert\eta\rvert < 2.0$				
Track-jets	at least two track-jets, $p_{\mathrm{T}} > 10$ GeV, $\lvert\eta\rvert < 2.5$, matched to the leading large-R jet				
b-jets	leading two track-jets matched to the leading large-R must be b-tagged (MV2c10, 70%)				
m_{J}	> 50 GeV				
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \text{small-}R \text{ jets})]$	$> 30^{\circ}$	-			
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, H_{\mathrm{cand}})$	$> 120^{\circ}$	-			
$\Delta\phi\ (\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{E}_{\mathrm{T,\ trk}}^{\mathrm{miss}})$	$< 90^{\circ}$	-			
$\Delta y(V, H_{\mathrm{cand}})$	-	$\lvert\Delta y(V, H_{\mathrm{cand}})\rvert < 1.4$			
$m_{\ell\ell}$	-			66 GeV $< m_{\ell\ell} <$ 116 GeV	
Lepton p_{T} imbalance	-			$(p_{\mathrm{T}}^{\ell_1} - p_{\mathrm{T}}^{\ell_2})/p_{\mathrm{T}}^{Z} < 0.8$	

$VH \to b\bar{b}$: Boosted Analysis Regions

Channel	Categories					
	$250 < p_{\mathrm{T}}^{V} < 400$ GeV			$p_{\mathrm{T}}^{V} \geq 400$ GeV		
	0 add. b-track-jets		≥ 1 add. b-track-jets	0 add. b-track-jets		≥ 1 add. b-track-jets
	0 add. small-R jets	≥ 1 add. small-R jets		0 add. small-R jets	≥ 1 add. small-R jets	
0-lepton	HP SR	LP SR	CR	HP SR	LP SR	CR
1-lepton	HP SR	LP SR	CR	HP SR	LP SR	CR
2-lepton	SR			SR		

$H \to \mu\mu$: Event Selection Summary

	Selection
Common preselection	Primary vertex Two opposite-charge muons Muons: $\|\eta\| < 2.7$, $p_T^{lead} > 27$ GeV, $p_T^{sublead} > 15$ GeV (except VH 3-lepton)
Fit Region	$110 < m_{\mu\mu} < 160$ GeV
Jets	$p_T > 25$ GeV and $\|\eta\| < 2.4$ or with $p_T > 30$ GeV and $2.4 < \|\eta\| < 4.5$
$t\bar{t}H$ Category	at least one additional e or μ with $p_T > 15$ GeV, at least one b-jet (85% WP)
VH 3-lepton Categories	$p_T^{sublead} > 10$ GeV, one additional e (μ) with $p_T > 15(10)$ GeV, no b-jets (85% WP)
VH 4-lepton Category	at least two additional e or μ with $p_T > 8, 6$ GeV, no b-jets (85% WP)
ggF +VBF Categories	no additional μ, no b-jets (60% WP)