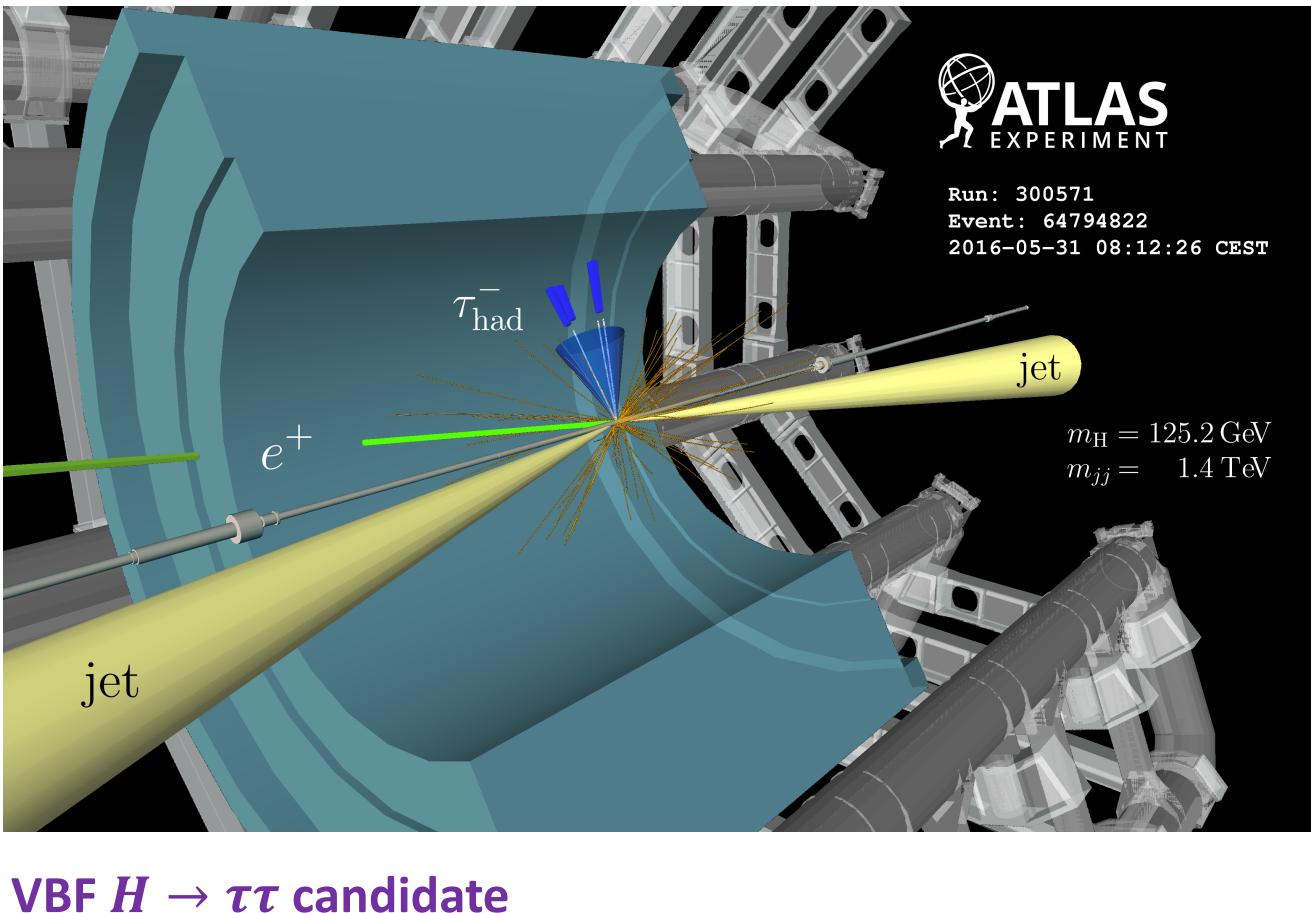


Results on SM Higgs Boson to Fermion Decays



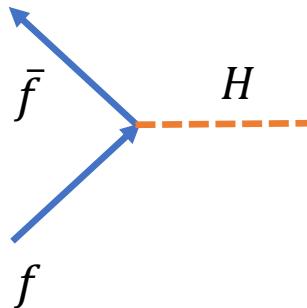
PRD 98 (2018) 052003



Kathrin Becker (Freiburg) on behalf of the ATLAS collaboration
Higgs Hunting 2019, Orsay/Paris, July 29, 2019

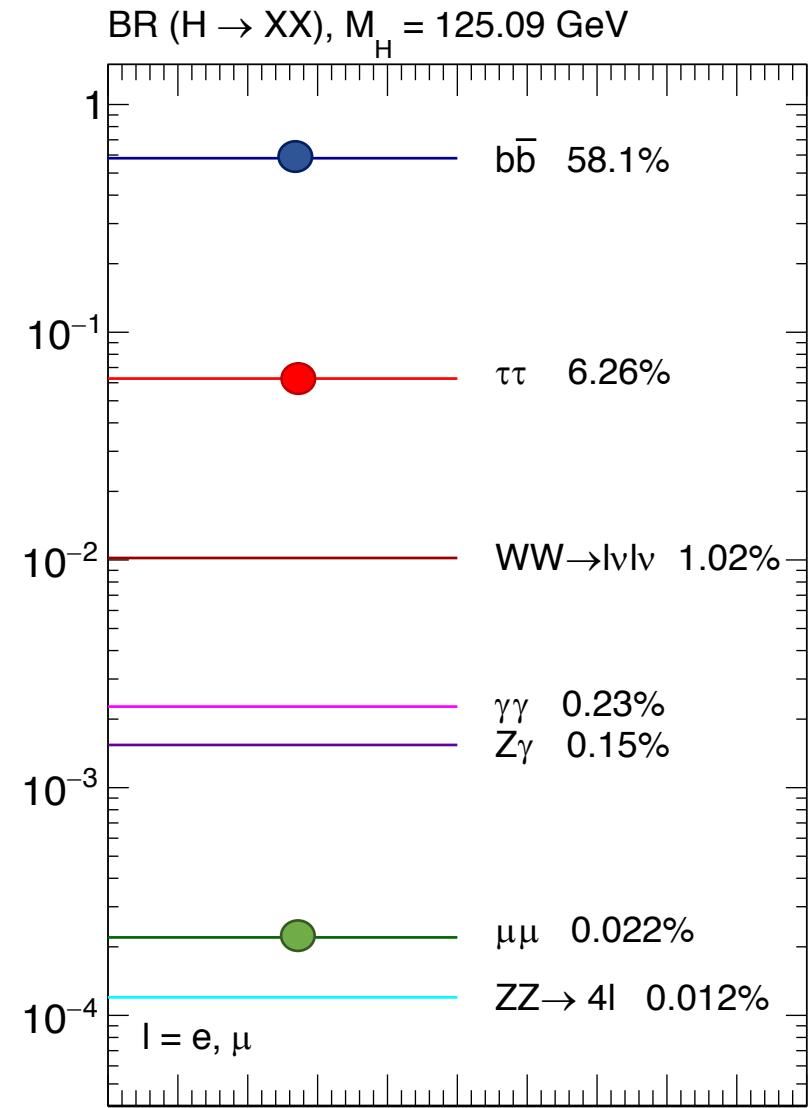
Higgs boson decays to fermions

- Higgs coupling to fermions via ad-hoc Yukawa couplings $\propto m_f/v$
 - BSM scenarios predict changes in Yukawa couplings



→ Experimental determination of Yukawa coupling

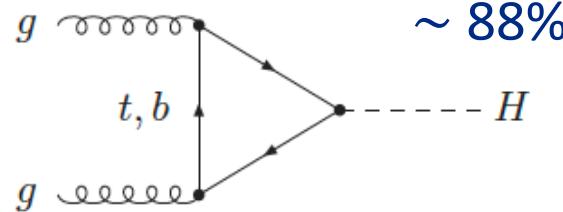
- In this presentation:
 - $H \rightarrow b\bar{b}$ (58%)
 - $H \rightarrow \tau\tau$ (6.3%)
 - $H \rightarrow \mu\mu$ (0.022%)
- Results on $t\bar{t}H$ in Margherita Spalla's presentation
- Results on $H \rightarrow cc$, $H \rightarrow vv$, and LFV in Loan Truong's presentation



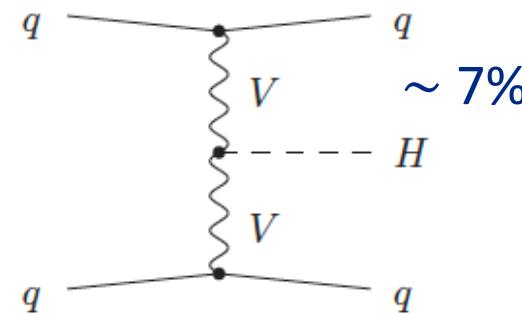
Overview on $H \rightarrow bb$ analyses

- Largest branching ratio, but difficult channel due to large backgrounds
- Most sensitive production mode: **VH production**
 - First STXS measurements
- Also measurements done for **ggF** and **VBF** production modes
 - Complementary to measurements in $H \rightarrow$ bosons

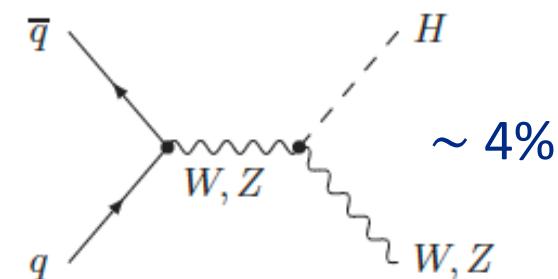
Gluon fusion (ggF)



Vector boson fusion (VBF)



Higgs-Strahlung (VH)



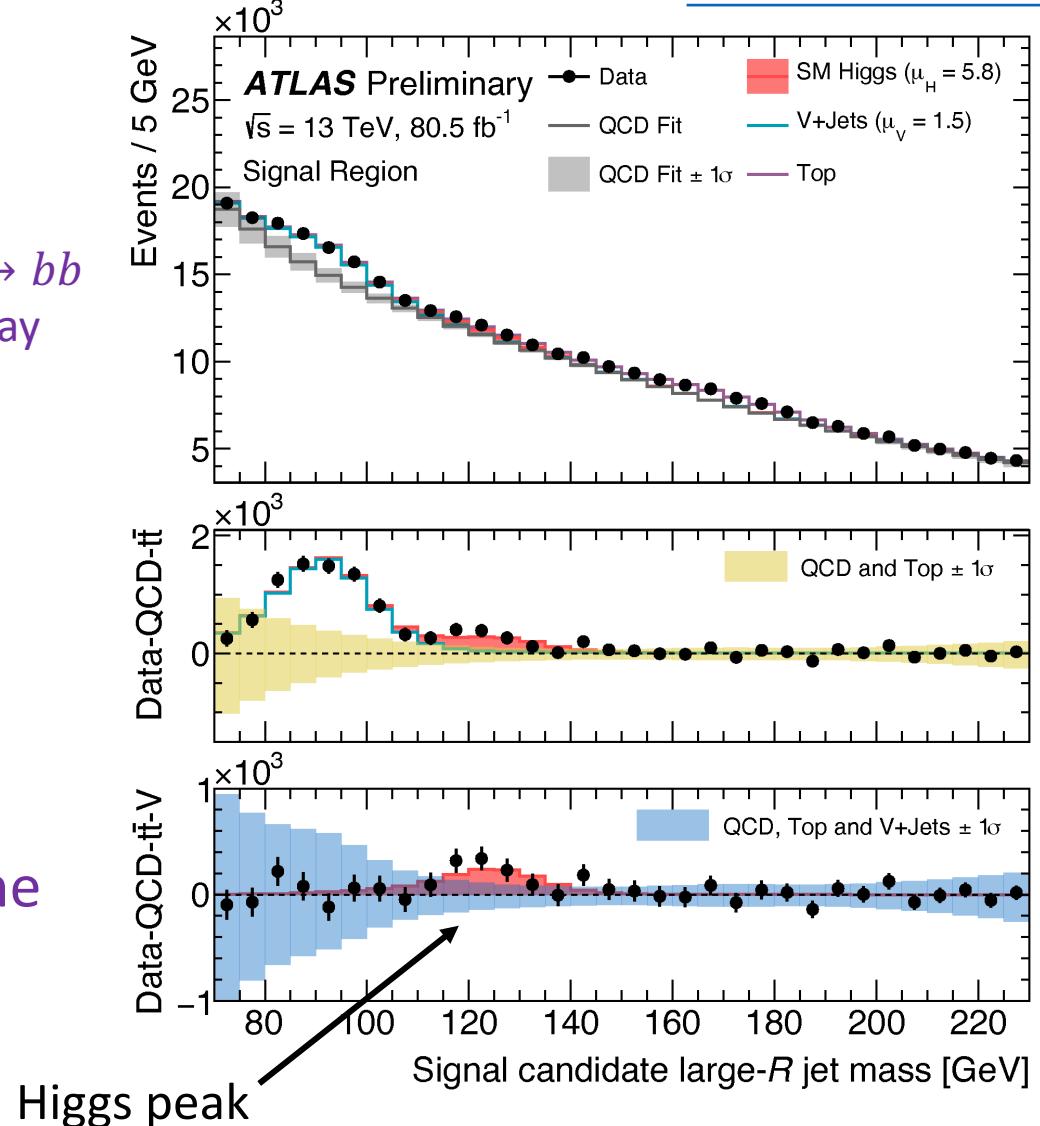
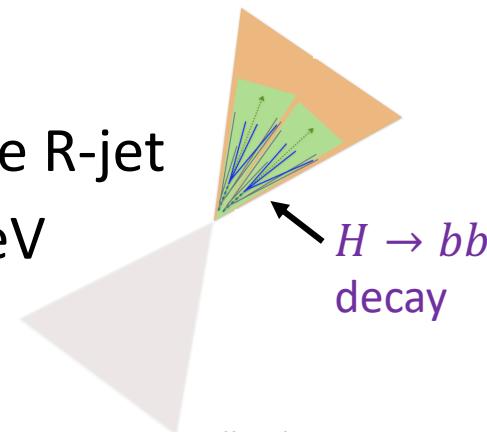
$H \rightarrow bb$ analysis targeting boosted $gg \rightarrow Hj$

80.5 fb^{-1}

2/3 of Run 2

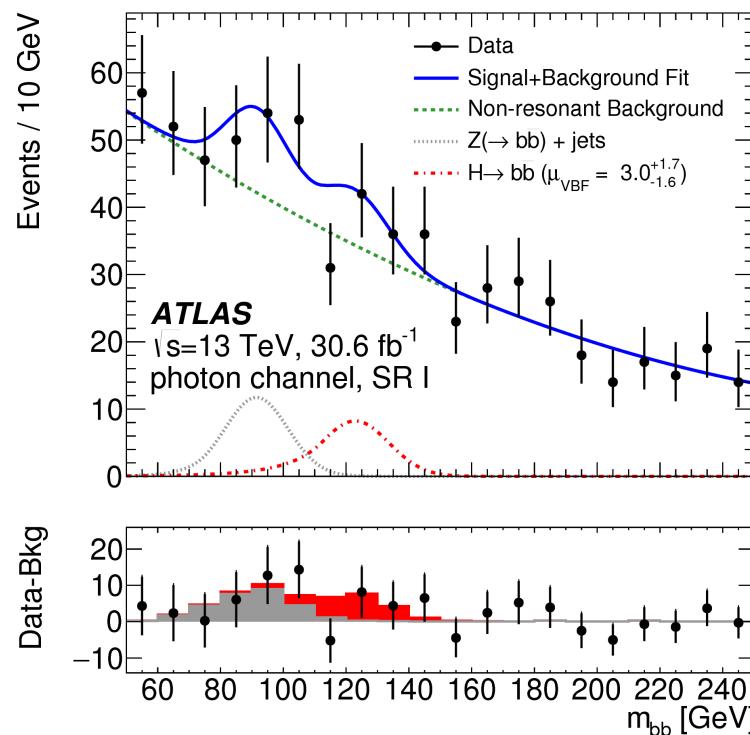
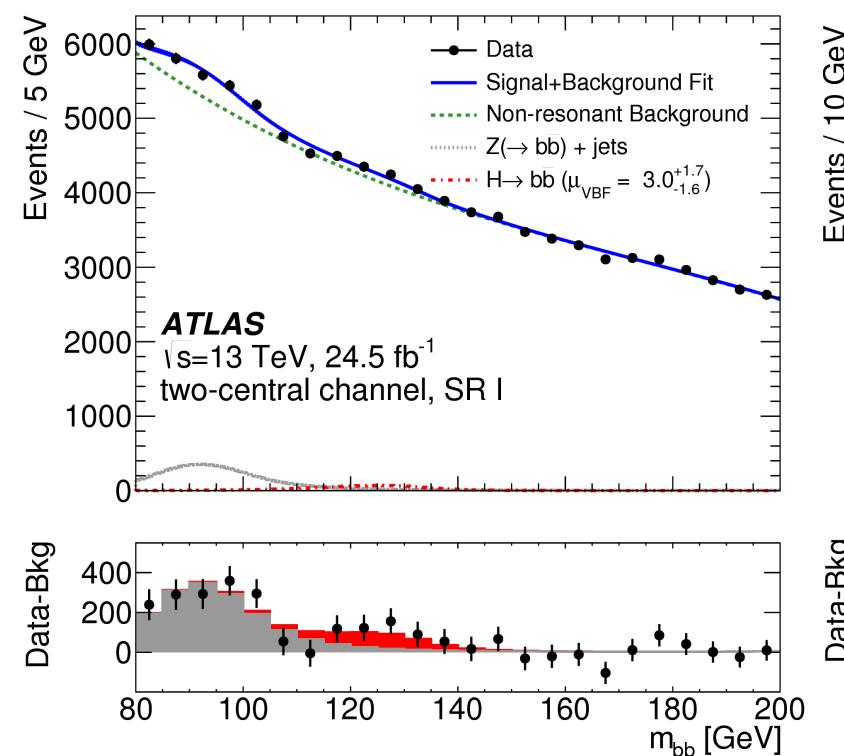
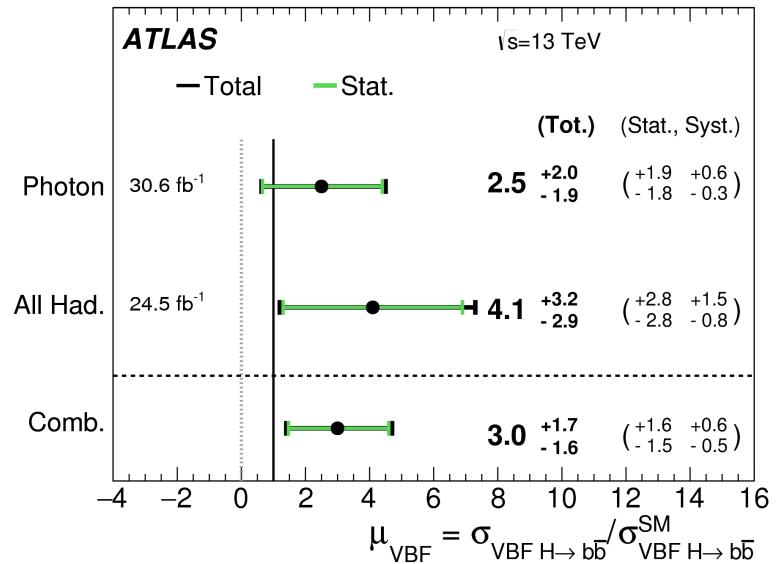
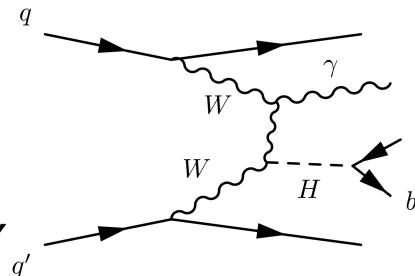
[ATLAS-CONF-2018-052](#)

- Boosted analysis: 2 large-R jets
- 2 b-tagged track jets in one large R-jet
- Higgs-candidate jet: $p_T > 480 \text{ GeV}$
- Fit to the jet-mass spectrum
- Significance: 1.6σ obs. (0.28σ exp.)
- Needs more data
- Analysis is sensitive to $p_T^H > 480 \text{ GeV}$
- Promising analysis to test for deviations from the SM and to include in STXS cross sections!



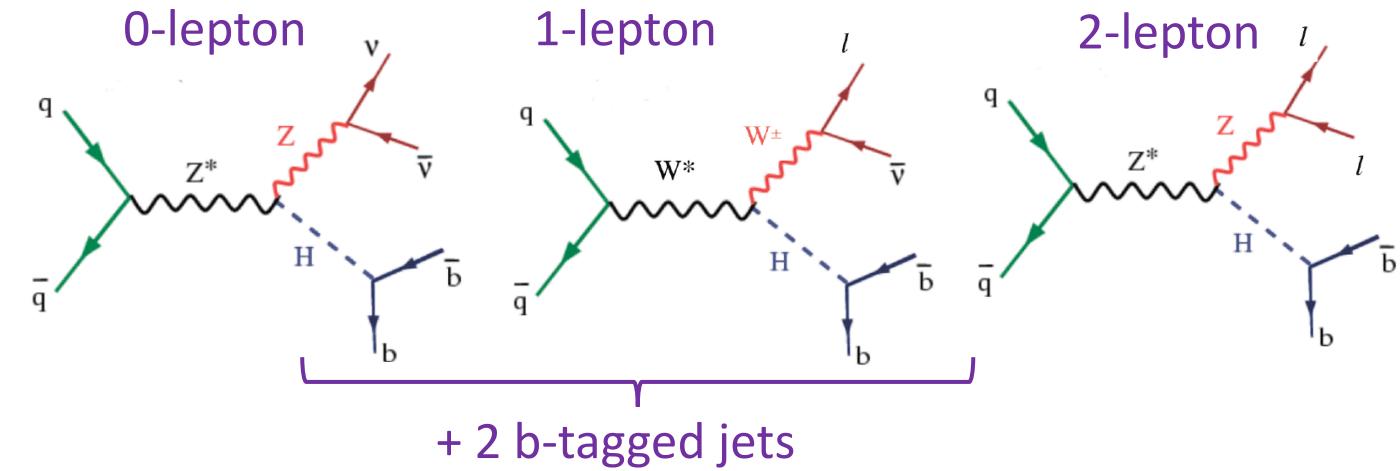
$H \rightarrow b\bar{b}$ analysis targeting VBF

- Three analysis channels:
 - 2 b-tagged jets + forward jet(s)
 - 2 b-tagged jets + 2 central jets
 - 2 b-tagged jets + 2 forward jets + central high- p_T γ
- Use BDT to select signal regions (Total of 9)

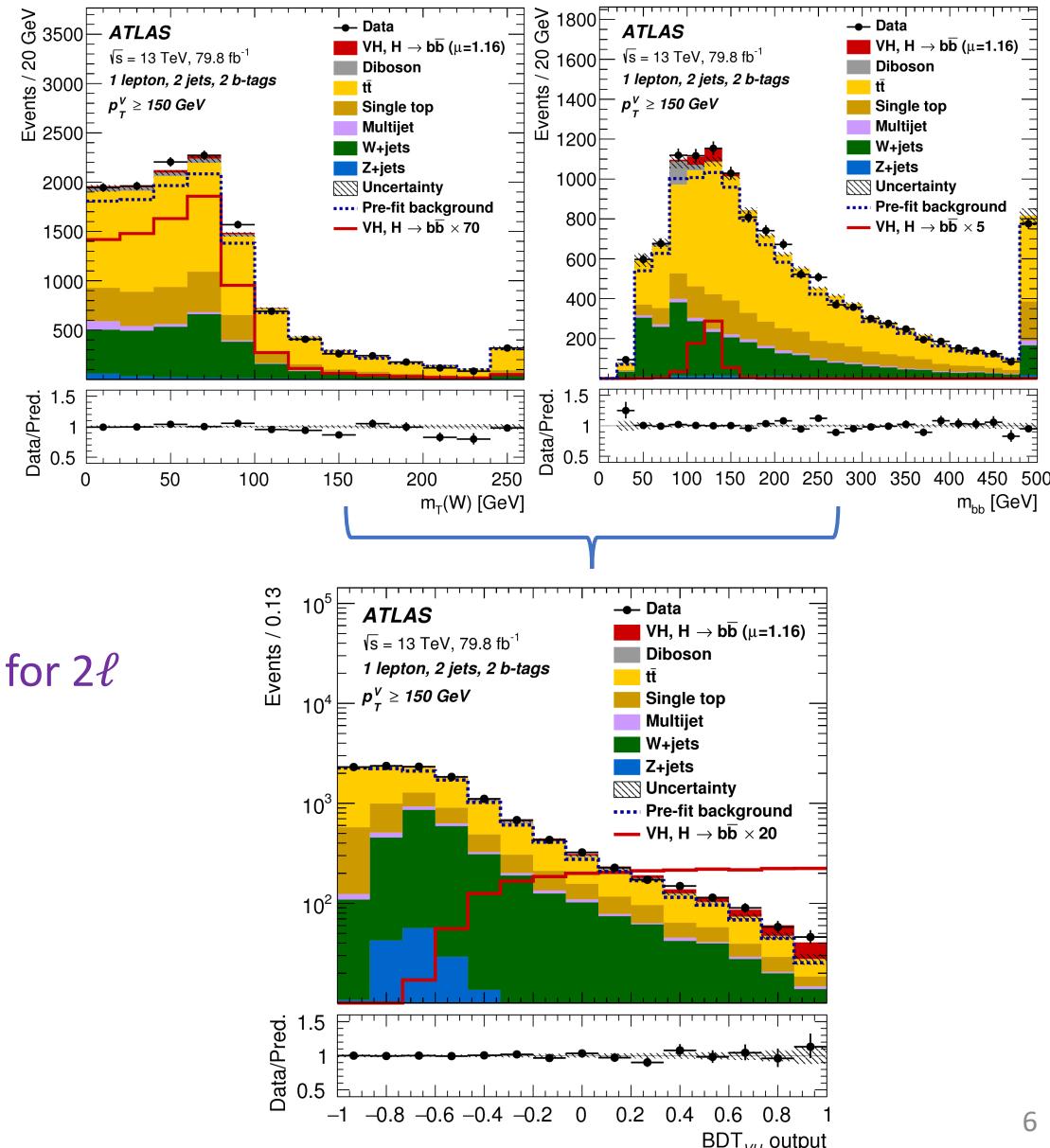


- Fit to the m_{bb} spectrum
- Significance: 1.9σ obs. (0.7σ exp.)
- Observed signal strength for the Higgs boson:
 $\mu_H = 2.5 \pm 1.3(\text{stat.}) \pm 0.6(\text{syst.})$
- Statistically limited, more data needed

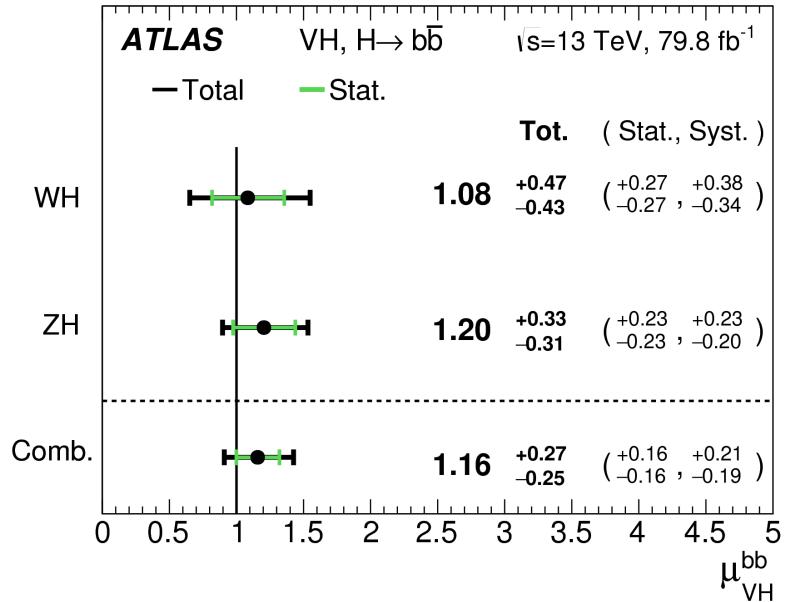
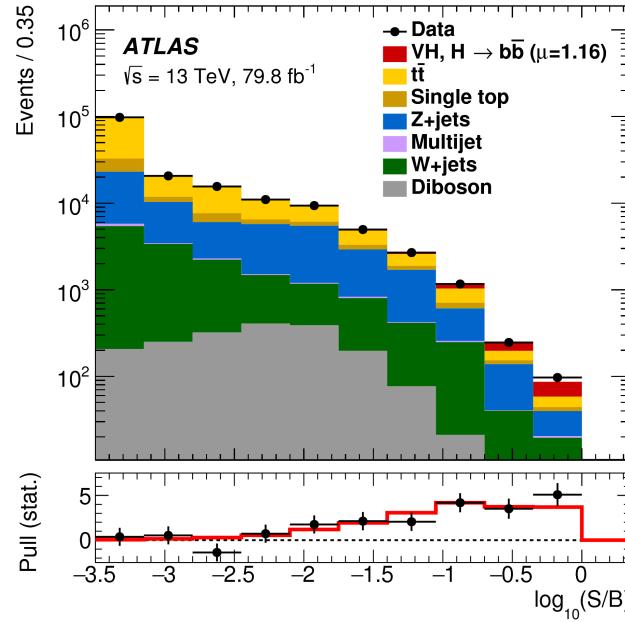
$H \rightarrow b\bar{b}$ analysis targeting VH



- 8 SR defined:
 - 2 or 3 jets (= 3 jets for 0ℓ , 1ℓ , ≥ 3 jets for 2ℓ)
 - $p_T(V)$ regions: > 150 GeV for 0ℓ , 1ℓ ; [75-150, > 150] GeV for 2ℓ
- BDTs to separate VH signal and backgrounds
 - Final discriminant in the analysis
- Main backgrounds ($t\bar{t}$, $V+HF$) modelled by MC and normalized to data
 - Simultaneous fit of all SRs and dedicated CRs



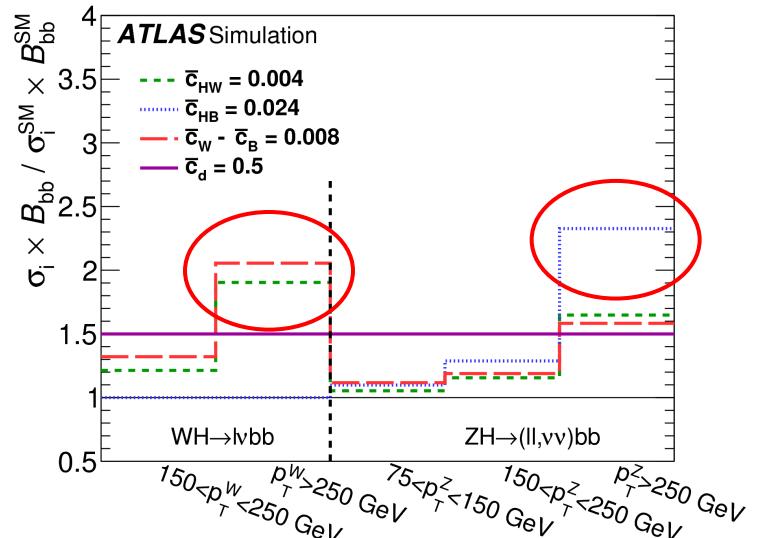
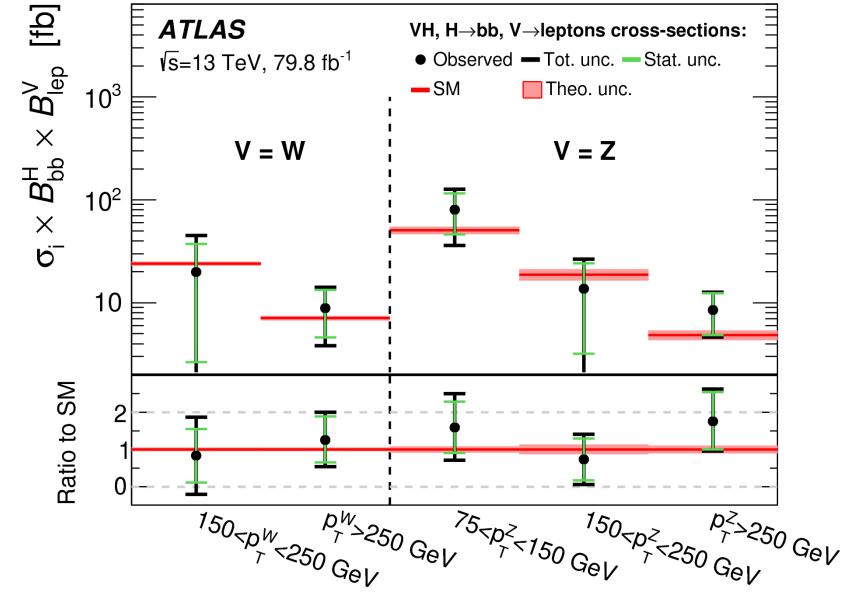
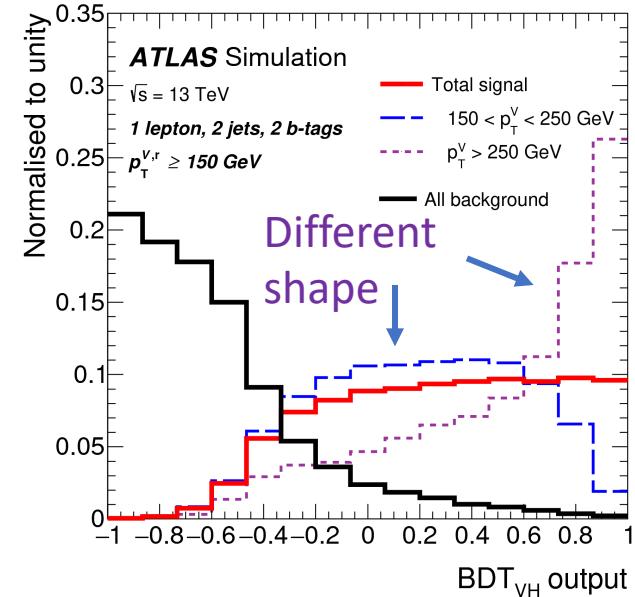
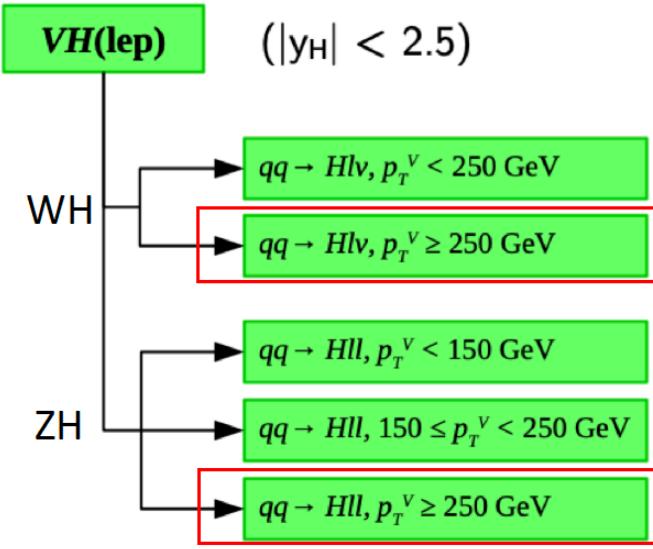
$H \rightarrow bb$ analysis targeting VH



- Observed significance of 4.9σ (4.3σ exp.)
- Systematics important for measurement
- **Observation of $H \rightarrow bb$** when combining with other production modes (ggF, VBF, $t\bar{t}H$): 5.4σ (5.5σ exp.)
- **Observation of VH production** when combining with $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$: 5.3σ (4.8σ exp.)
- Does not just probe Yukawa coupling to b-quark, but also most sensitive channel for VH production

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	0.061
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
$Z + \text{jets}$	0.055
$W + \text{jets}$	0.060
$t\bar{t}$	0.050
Single top quark	0.028
Diboson	0.054
Multi-jet	0.005
MC statistical	0.070

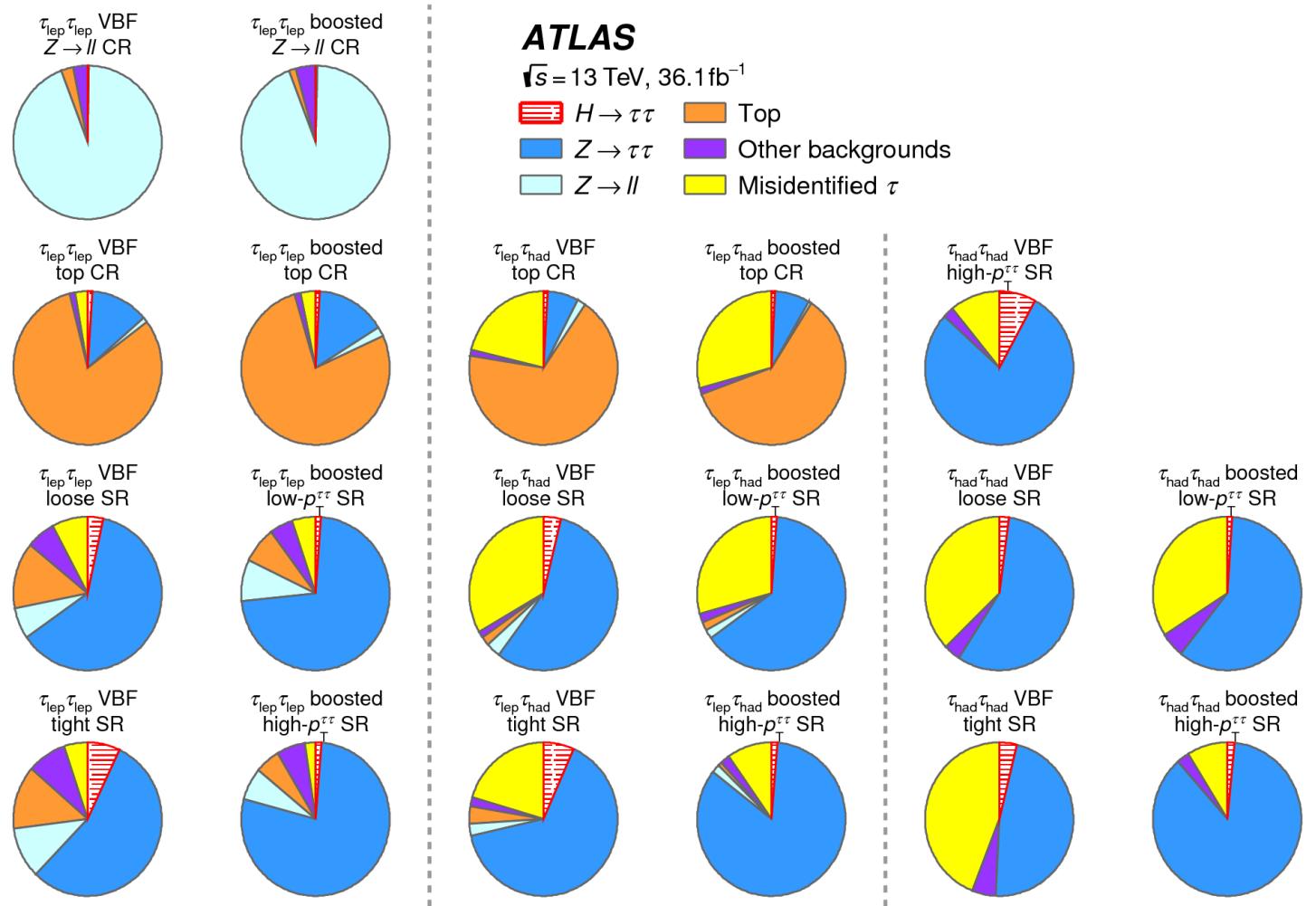
Study VH with $H \rightarrow bb$ (STXS)



- Use same BDTs to measure STXS bins as function of $p_T(V)$
- Five cross sections: $WH p_T(V)$: [150-250, > 250] GeV and $ZH p_T(V)$: [75-150, 150-250, > 250] GeV
- All results consistent with SM, still statistics dominated
- Systematics from background modelling and MC statistics
- Impact from signal theory uncertainties small
- Sensitivity to EFT couplings, information on 95% CL limits in the backup

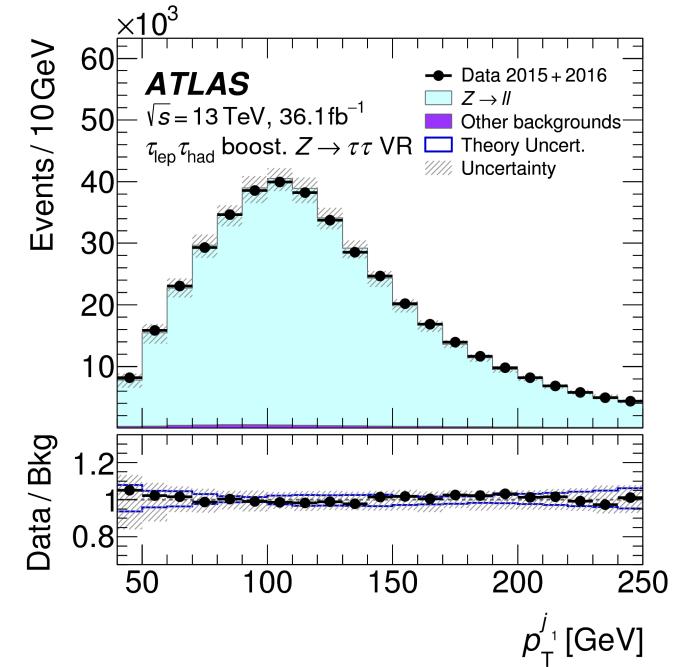
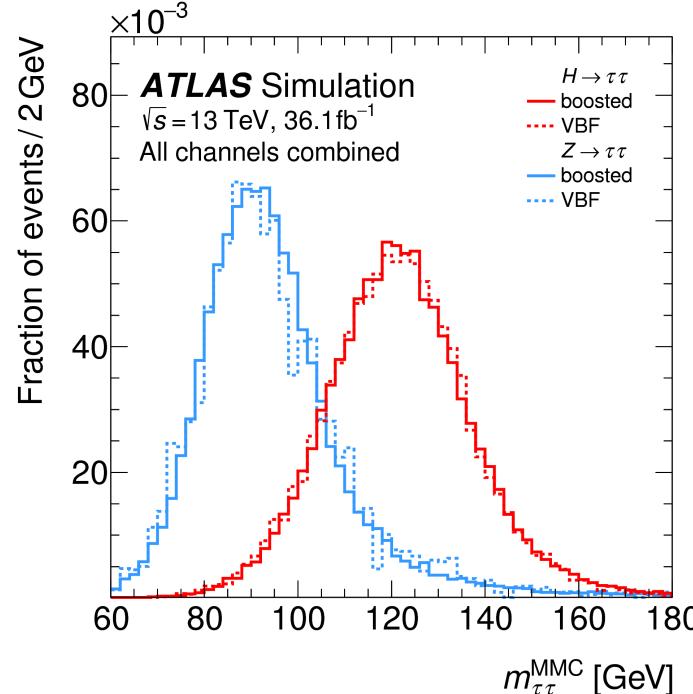
$H \rightarrow \tau\tau$ analysis

- Analysis targets VBF and boosted $gg \rightarrow Hj$ production
- Three τ -decay channels:
 $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$
- Analysis strategy:
 - Cut-based approach
 - Categorisation (13 SRs)
 - 6 control regions
- Dominant backgrounds
 - $Z \rightarrow \tau\tau$ production
 - Mis-identified τ -leptons



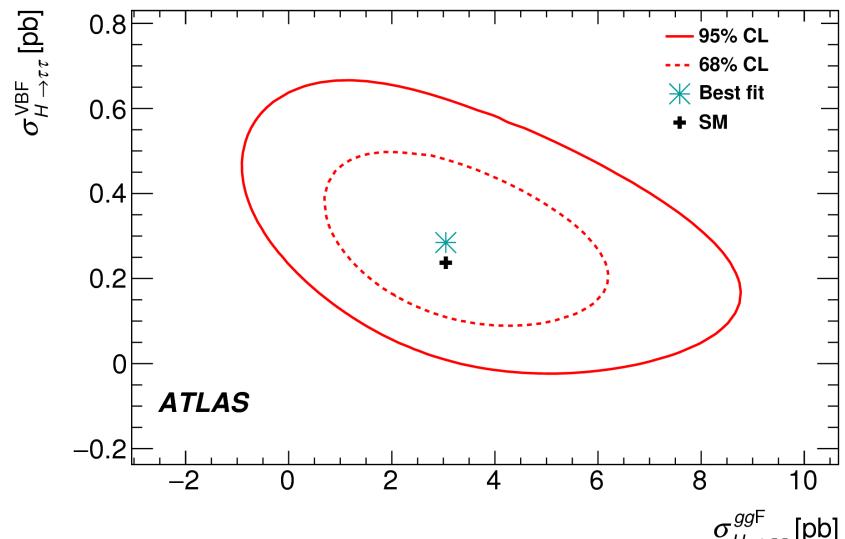
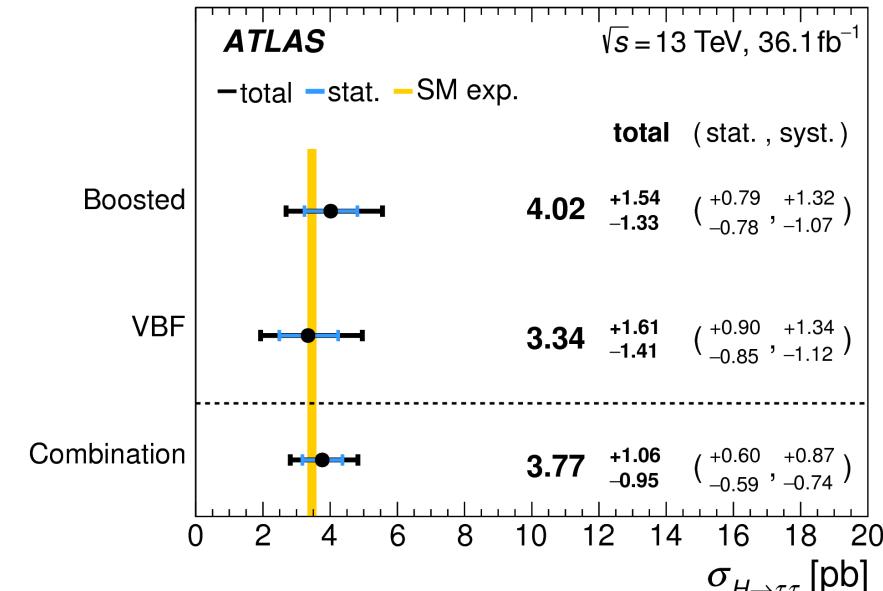
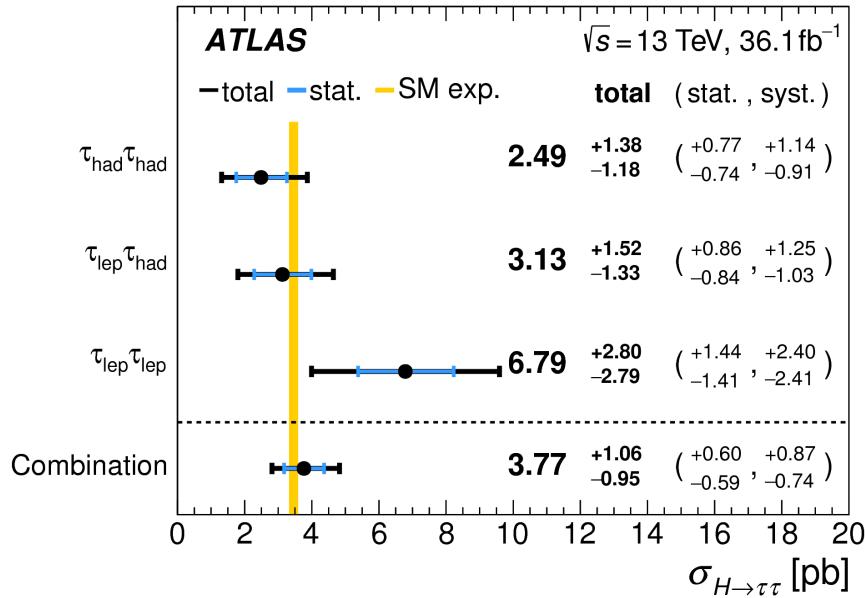
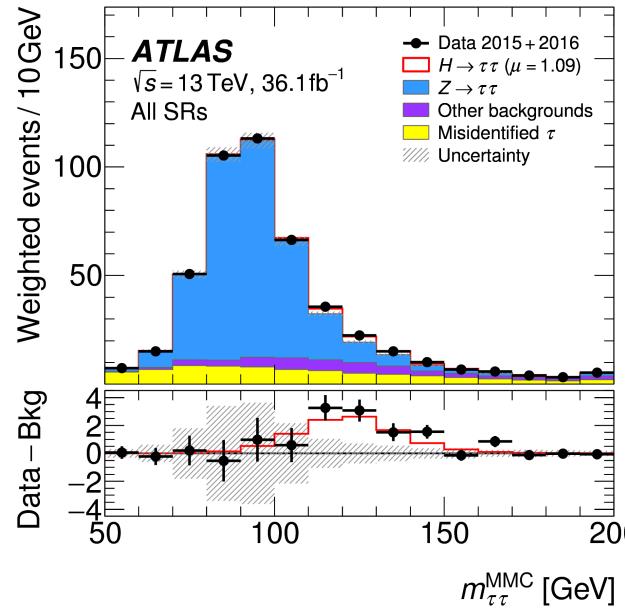
$H \rightarrow \tau\tau$: Backgrounds and systematics

- Background estimation:
 - Mis-identified τ -decays: data-driven
 - $Z \rightarrow \tau\tau$ modelled by MC, validated in $Z \rightarrow \ell\ell$ validation region
 - $Z \rightarrow \tau\tau$ normalized in Z -peak of reconstructed $m_{\tau\tau}$



- Largest systematic uncertainties:
 - MC statistics
 - Theory uncertainties on the ggF signal
 - Jet energy resolution
 - Normalization of the $Z \rightarrow \tau\tau$ background
 - τ -energy scale and identification

$H \rightarrow \tau\tau$: Results

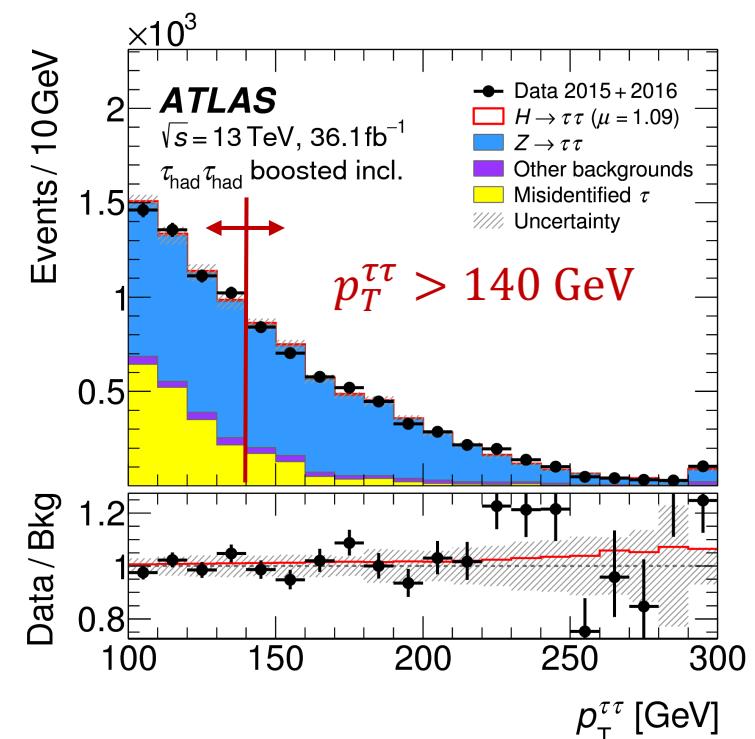
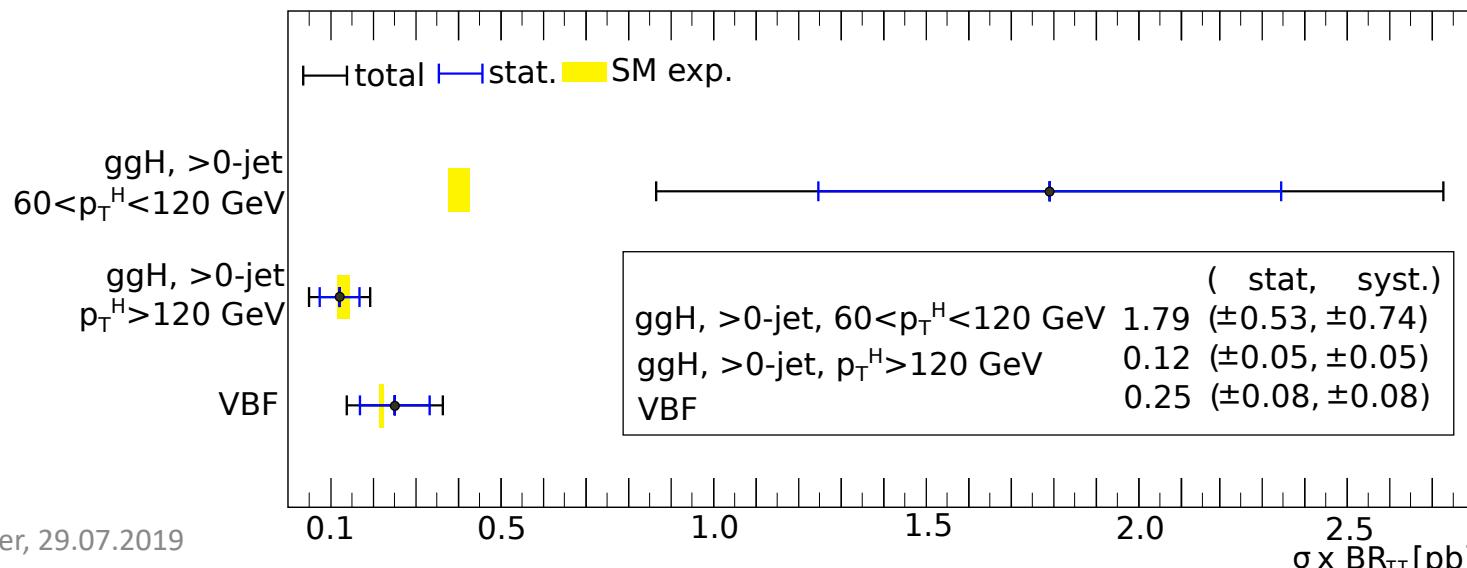


- Fit of $m_{\tau\tau}^{\text{MMC}}$ to extract signal
- Observed significance of 4.4σ (4.1σ exp.)
- Observation of $H \rightarrow \tau\tau$ when combining with Run 1: 6.4σ (5.4σ exp.)**
- Similar contributions from statistical and systematic uncertainties

$H \rightarrow \tau\tau$ STXS measurement

Three cross sections measured:

- VBF cross section
- Two merged bins ggF bins:
 - $60 \text{ GeV} < p_T^H < 120 \text{ GeV}, N_{jets} \geq 1 \rightarrow 52\% \text{ precision}$
 - $p_T^H > 120 \text{ GeV}, N_{jets} \geq 1 \rightarrow 60\% \text{ precision}$
- BUT: decrease in sensitivity for ggF bins due to clash between analysis optimisation and STXS definition

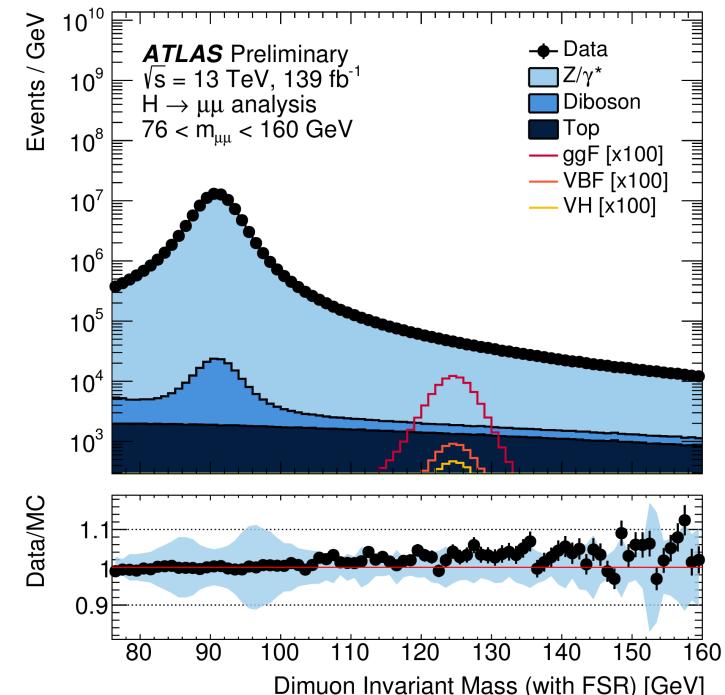
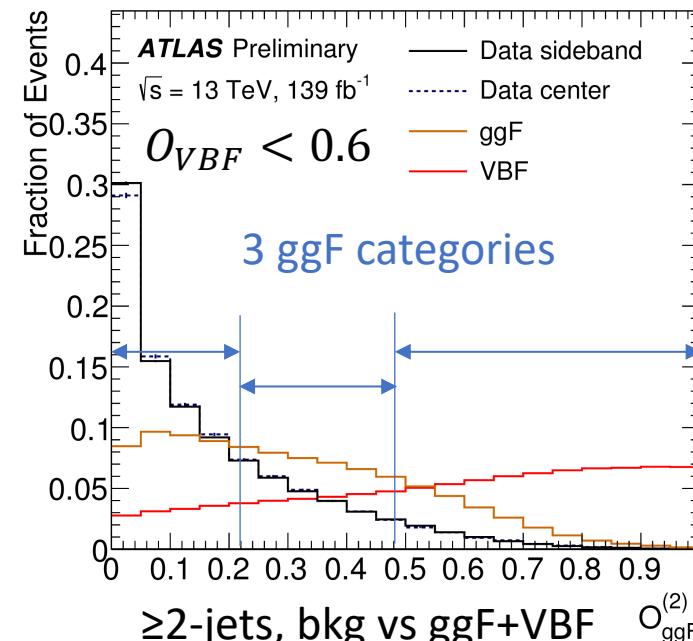
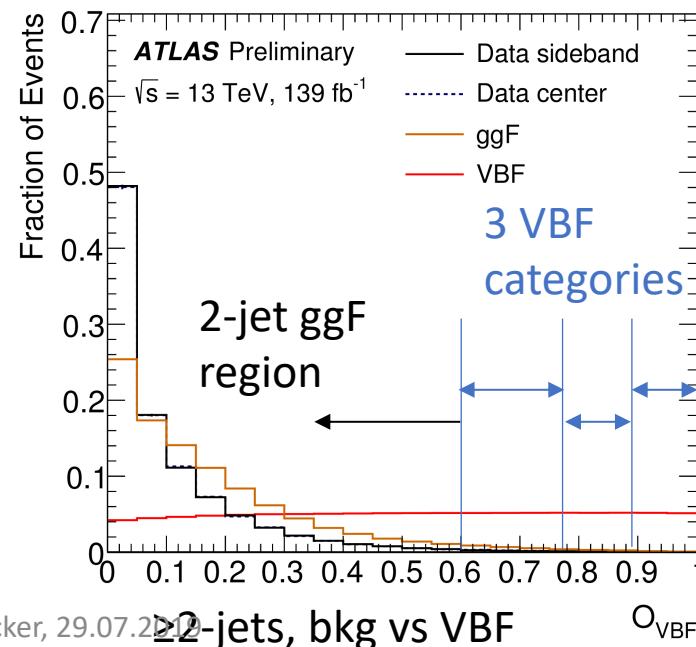


From Table 11 in
PRD 99 (2019) 072001

Search for $H \rightarrow \mu\mu$

Young scientist presentation by M. Zgubic

- Most sensitive channel to access Higgs couplings to 2nd generation fermions
 - High muon mass resolution
 - $\text{BR}(H \rightarrow \mu\mu) = 2 \times 10^{-4}$
- Signal is a narrow resonance over smoothly falling backgrounds (mainly Drell-Yan, Top, Diboson)
- BDTs trained against the background in 0-jet, 1-jet and ≥ 2 -jets categories (ggF and VBF)

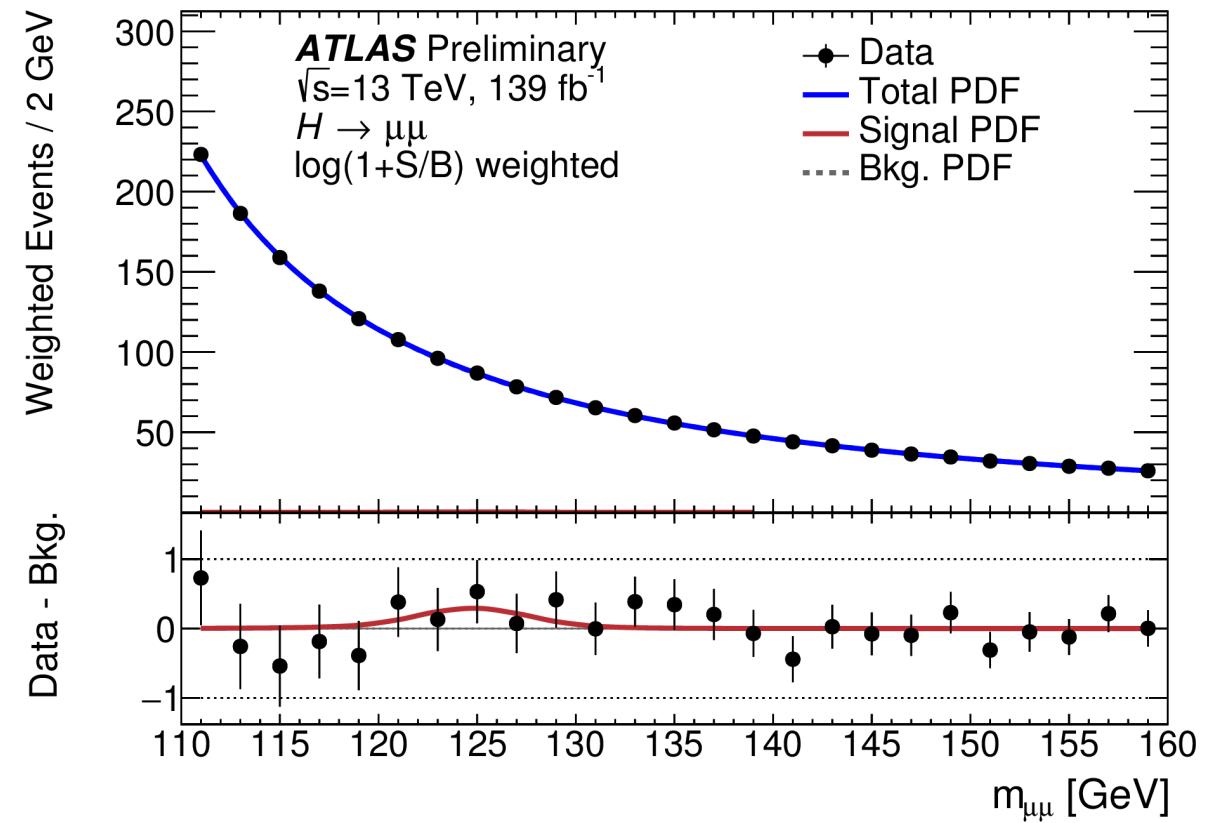


+ 3 categories each for
ggF 0-jet and 1-jet
= 12 SR categories

VBF categories have best S/B

Search for $H \rightarrow \mu\mu$

- Fit to $m_{\mu\mu}$ in 12 categories to extract signal
- Signal modelling: double-sided Crystal Ball
- Background estimation:
 - Important due to very low S/B
→ per mill level description of background
 - $m_{\mu\mu}$ background model parametrized by analytical functions
 - Core function to model DY mass shape
 - Empirical function to correct distortions
- Uncertainties on μ (absolute value):
 - Signal theory: 0.08
 - Signal exp. : 0.07
 - Spurious signal: 0.06
 - Data stat.: 0.7



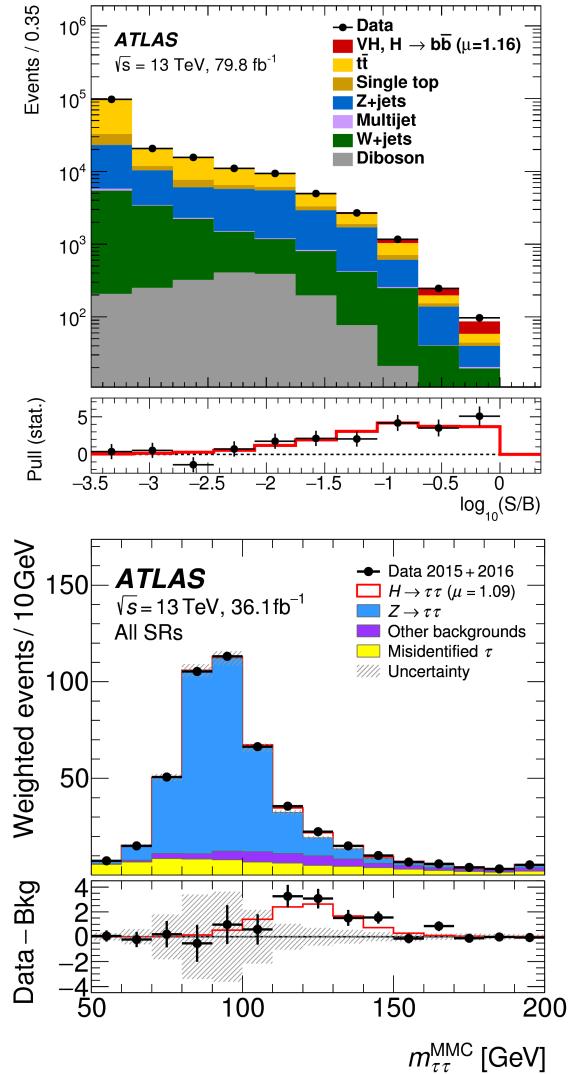
- Results:
 - Upper limits: $1.7 (1.3) \times \sigma_{SM}$ obs. (exp.)
 - Signal strength: $\mu = 0.5 \pm 0.7$
 - Significance: $0.8\sigma (1.5\sigma)$ obs. (exp.)

Conclusion

- Observation of Higgs decays to b-quarks and τ -leptons
 - All results consistent with the Standard Model
- Higgs to fermions measurements also probe production modes:
 - First measurements in kinematic bins of the STXS framework
 - Complementary measurements to $H \rightarrow bosons$
- Access to 2nd generation fermions is approaching
 - Upper limit of $1.7 (1.3) \times \sigma_{SM}$ for $H \rightarrow \mu\mu$ decay

Thank you for listening!

- $t\bar{t}H$ results: Margherita Spalla
- Rare decay results: Loan Truong
- More on $H \rightarrow \mu\mu$: Miha Zgubic



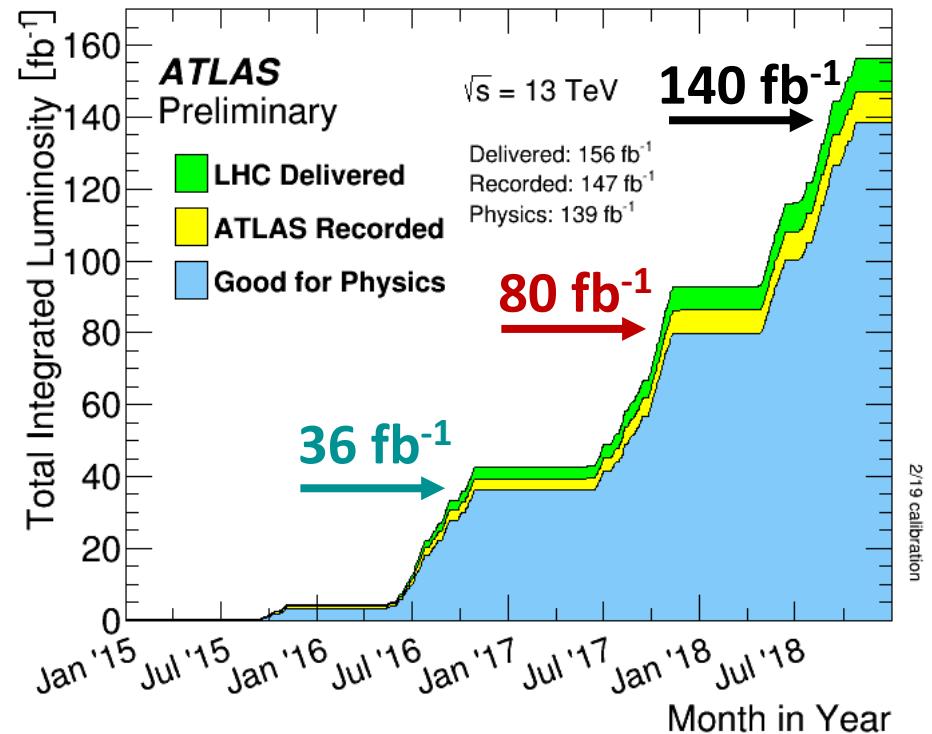
BACK-UP

The pp collision dataset

Focus on results from LHC Run 2 (2015-2018)

LHC Run	\sqrt{s}	Luminosity
Run 1	7+8 TeV	25 fb^{-1}
Run 2	13 TeV	36 fb^{-1} 80 fb^{-1} 140 fb^{-1}

$\rightarrow \frac{1}{4}$ of Run 2
 $\rightarrow \frac{2}{3}$ of Run 2



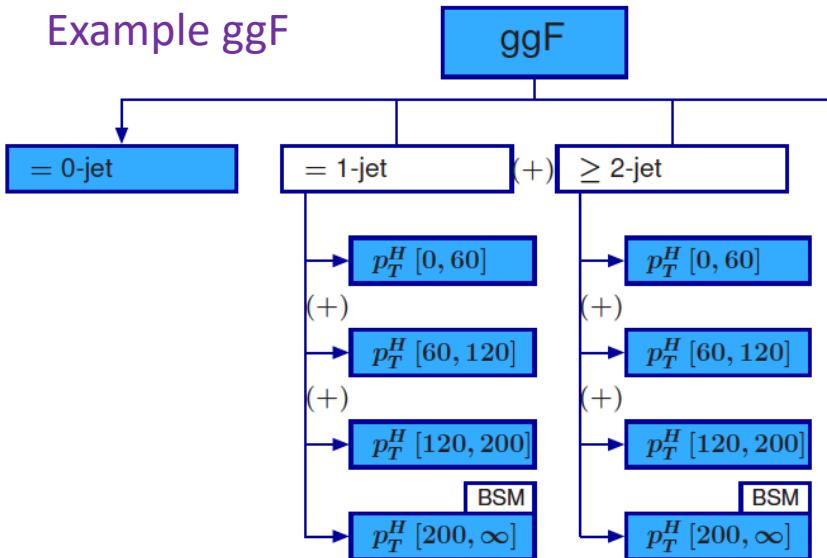
Run 1: 0.5 million produced Higgs-boson events

\rightarrow Run 2: 8 million produced Higgs-boson events

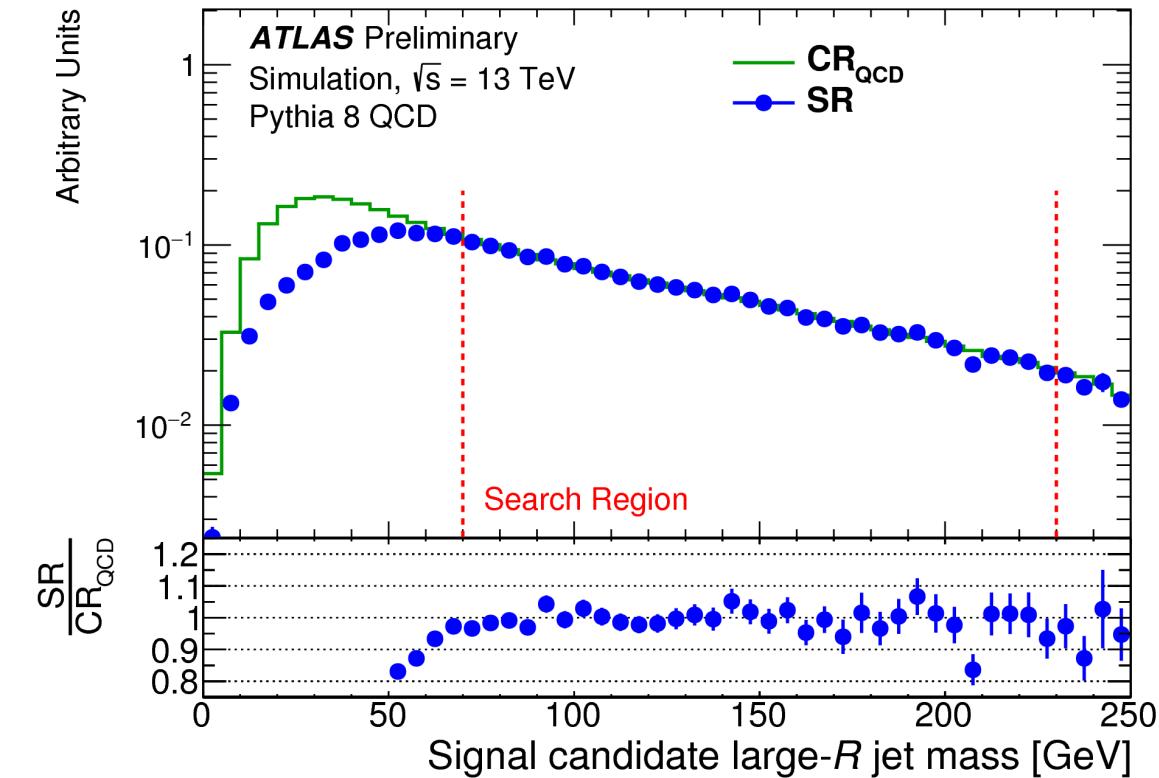
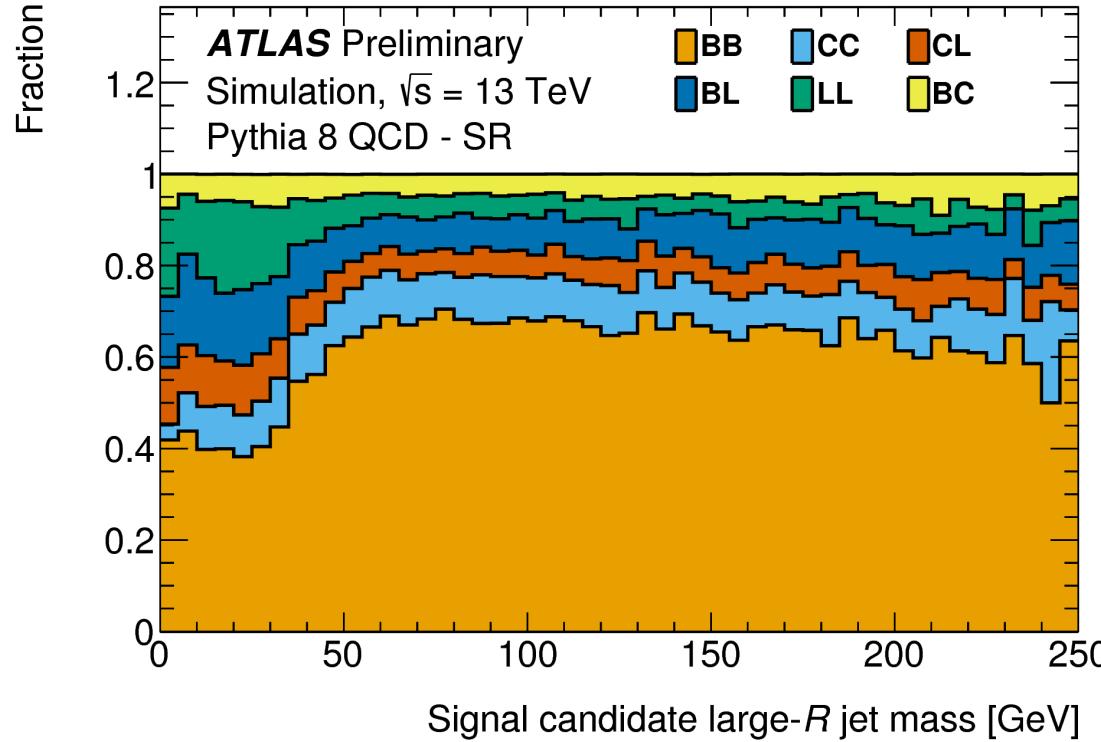
Simplified Template Cross sections (STXS)

- Proposed at Les Houches '15 ([Proceedings](#)) and detailed in LHC Higgs XS Working group ([YR4](#))

- Goals:
 - Measure cross-sections per production modes (ggF, VBF, VH, ttH) in different phase spaces (Signal Templates: PtH, PtV, ...) → Bins predefined
 - reducing model dependency and maximizing sensitivity to BSM effects
 - Combine different decay channels → increase sensitivity
- No background subtraction/unfolding needed
→ BUT: experimental category matching roughly one bin needed



$H \rightarrow bb$ analysis, $gg \rightarrow Hj$: background estimation



(a) Predicted flavour composition of the dijet background in the SR based on the truth-matched hadron content of the two leading- p_T track-jets associated to the signal candidate large- R jet, with the B/C labels indicating the presence of a b/c-quark and L indicating the presence of a light quark or a gluon. (b) The expected shape of the dijet background in the SR and CR_{QCD} normalised to the same event count between 70 GeV < m_j < 230 GeV.

$H \rightarrow bb$ analysis, $gg \rightarrow Hj$: background estimation

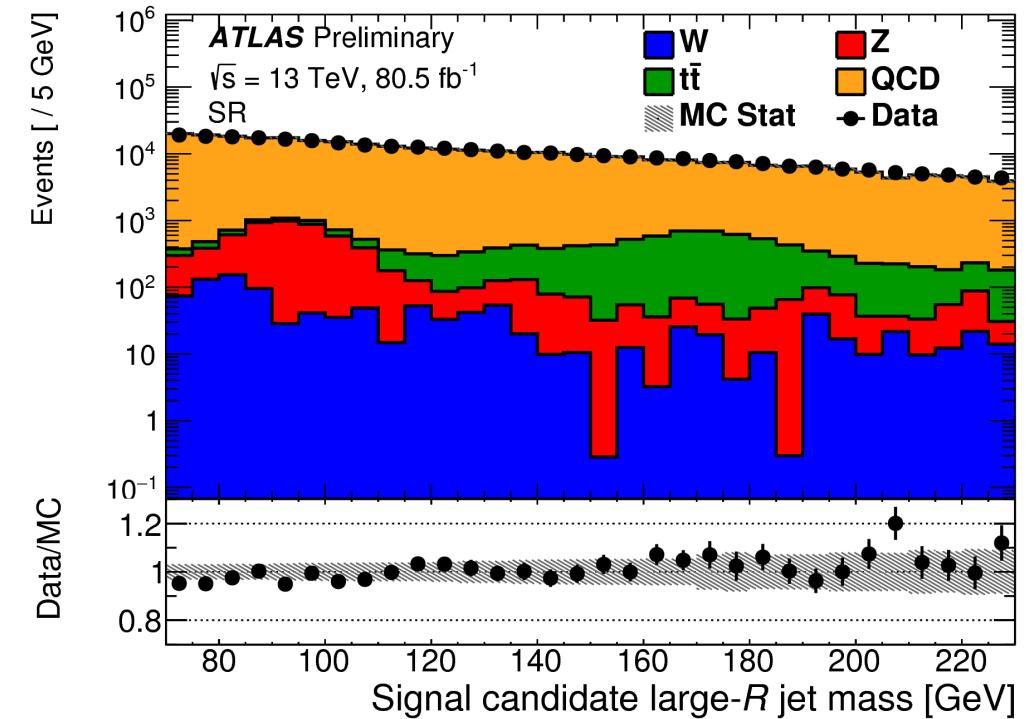
Process	CR _{QCD} Eff. (%)	CR _{QCD} Yield 80.5 fb ⁻¹	CR _{QCD} Yield 1.4 fb ⁻¹	SR Eff. (%)	SR Yield 80.5 fb ⁻¹
$Z \rightarrow q\bar{q} + \text{jets}$	46.2	84400	1470	3.4	6200
$W \rightarrow q\bar{q} + \text{jets}$	51.3	219000	3810	0.4	1500
$t\bar{t}$	25.9	110900	1929	2.5	10550
$H \rightarrow bb$ (ggF)	23.6	140	2	19.4	115
$H \rightarrow b\bar{b}$ (VBF)	15.8	41	1	20.7	53
$H \rightarrow b\bar{b}$ (WH)	32.4	71	1	12.0	26
$H \rightarrow b\bar{b}$ (ZH)	30.5	40	1	15.8	21
$H \rightarrow bb$ (Total)	24.3	292	5	17.9	216
Z' ($m = 100$ GeV)	43.9	87700	1530	4.1	8200
Z' ($m = 125$ GeV)	43.6	82800	1440	3.8	7300
Z' ($m = 150$ GeV)	43.5	78300	1360	3.7	6700
Z' ($m = 175$ GeV)	42.8	71100	1240	3.3	5550
Z' ($m = 200$ GeV)	41.8	64800	1127	3.2	4910
Data	38.7	29883000	519710	0.6	484600

The efficiencies and yields in the CR_{QCD} and SR for the non-QCD background, the Higgs boson and Z' boson signals and data. The yields in the CR_{QCD} are given for the full luminosity 80.5 fb⁻¹ and for the luminosity employed, as explained in Section 6, for the background estimate of the non-resonant dijet process. The efficiencies are relative to leading large- R jet p_T>480 GeV requirement.

$H \rightarrow bb$ analysis, $gg \rightarrow Hj$: Yields

		CR _{QCD}	SR
$V + \text{jets}$	$Z + \text{jets}$	0.28	0.80
	$W + \text{jets}$	0.72	0.20
$t\bar{t}$	All hadronic	0.58	0.63
	Semi-leptonic	0.38	0.34
	Dileptonic	0.04	0.03
$H \rightarrow b\bar{b}$	ggF	0.49	0.53
	VBF	0.17	0.25
	WH	0.21	0.12
	ZH	0.12	0.10

The fractional composition of the different resonant contributions in the defined regions. The fraction is evaluated using the given contribution type as the total.



$H \rightarrow bb$ analysis, $gg \rightarrow Hj$: Systematics

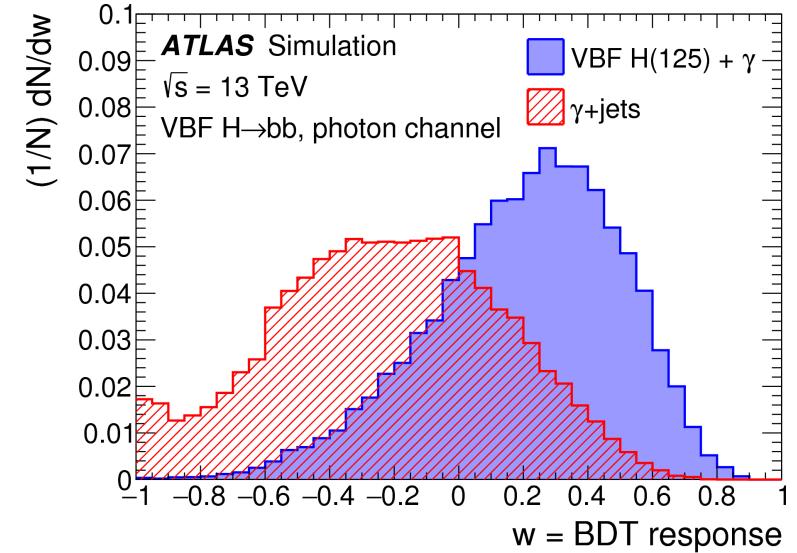
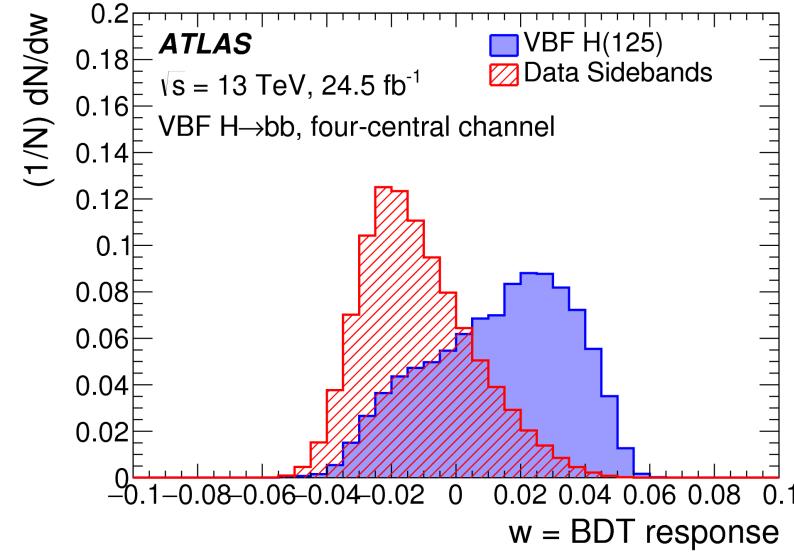
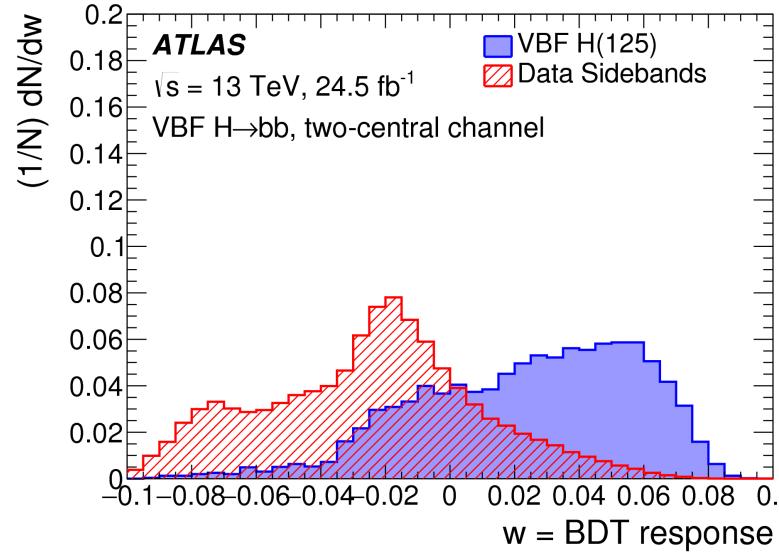
Source	Type	Impact on Signals ($\sqrt{\Delta\sigma^2}/\mu$)			
		V+jets	Higgs	Z' (100 GeV)	Z' (175 GeV)
Jet energy and mass scale	Norm. & Shape	15%	14%	23%	18%
Jet mass resolution	Norm. & Shape	20%	17%	30%	20%
$V + j$ jets modeling	Shape	9%	4%	4%	< 1%
$t\bar{t}$ modeling	Shape	< 1%	1%	< 1%	11%
b -tagging (b)	Normalisation	11%	12%	11%	15%
b -tagging (c)	Normalisation	3%	1%	3%	5%
b -tagging (l)	Normalisation	4%	1%	4%	7%
$t\bar{t}$ scale factor	Normalisation	2%	3%	2%	58%
Luminosity	Normalisation	2%	2%	2%	3%
Alternative QCD function	Norm. & Shape	4%	4%	3%	17%
W/Z and QCD (Theory)	Normalisation	14%	—	—	—
Higgs (Theory)	Normalisation	—	30%	—	—

$H \rightarrow bb, VBF$: Trigger and selection

Two-central channel		
Trigger	L1	≥ 2 central jets with $E_T > 40, 25$ GeV ≥ 1 forward jet with $E_T > 20$ GeV
	HLT	≥ 2 central b -jets at 70%, 85% efficiency working points with $E_T > 80, 60$ GeV ≥ 1 forward jet with $E_T > 45$ GeV
Offline		≥ 2 b -jets at 70%, 85% efficiency working points with $p_T > 95, 70$ GeV and $ \eta < 2.5$ ≥ 1 jet with $p_T > 60$ GeV and $3.2 < \eta < 4.4$ ≥ 1 jet with $p_T > 20$ GeV and $ \eta < 4.4$ $p_T(bb) > 160$ GeV
Four-central channel		
Trigger	L1	≥ 4 central jets with $E_T > 15$ GeV
	HLT	≥ 2 central b -jets at 70% (or 60%) efficiency working point with $E_T > 45$ GeV (or 35 GeV)
Offline		≥ 2 b -jets at 70% efficiency working point with $p_T > 55$ GeV and $ \eta < 2.5$ ≥ 2 jets with $p_T > 55$ GeV and $ \eta < 2.8$ No jet with $p_T > 60$ GeV and $3.2 < \eta < 4.4$ $p_T(bb) > 150$ GeV
Photon channel		
Trigger	L1	≥ 1 photon with $E_T > 22$ GeV
	HLT	≥ 1 photon with $E_T > 25$ GeV ≥ 4 jets (or ≥ 3 jets and ≥ 1 b -jet at 77% efficiency working point) with $E_T > 35$ GeV and $ \eta < 4.9$ $m_{jj} > 700$ GeV
Offline		≥ 1 photon with $E_T > 30$ GeV and $ \eta < 1.37$ or $1.52 < \eta < 2.37$ ≥ 2 b -jets at 77% efficiency working point with $p_T > 40$ GeV and $ \eta < 2.5$ ≥ 2 jets with $p_T > 40$ GeV and $ \eta < 4.4$ $m_{jj} > 800$ GeV $p_T(bb) > 80$ GeV

$H \rightarrow bb$, VBF: BDTs and SR definition

24.5-30.6 fb^{-1}
 $\frac{1}{4}$ of Run 2



Region	SR IV	SR III	SR II	SR I
<i>Four-central</i>	$(0.002, 0.015]$	$(0.015, 0.026]$	$(0.026, 0.033]$	> 0.033
<i>Two-central</i>			< -0.006	≥ -0.006
<i>Photon</i>		< -0.05	$[-0.05, 0.30]$	> 0.30

$H \rightarrow bb, VBF$: Yields

Channel	two-central		four-central				photon		
Region	SR I	SR II	SR I	SR II	SR III	SR IV	SR I	SR II	SR III
VBF	101.2 ± 2.0	22.2 ± 0.9	51.6 ± 1.1	28.4 ± 0.9	43.1 ± 1.0	41.9 ± 1.1	6.2 ± 0.1	5.5 ± 0.1	2.3 ± 0.1
ggF	23.8 ± 2.6	75.7 ± 6.1	11.3 ± 2.2	13.2 ± 1.5	43.4 ± 3.8	127.0 ± 6.5	0.5 ± 0.2	0.3 ± 0.1	0.8 ± 0.3
VH	0.2 ± 0.2	6.0 ± 1.2	1.2 ± 0.9	0.7 ± 0.3	3.9 ± 0.8	28.9 ± 2.6	<0.1	<0.1	<0.1
$t\bar{t}H$	2.0 ± 0.2	14.6 ± 0.7	0.3 ± 0.1	1.0 ± 0.1	5.7 ± 0.3	20.2 ± 0.5	<0.1	<0.1	0.4 ± 0.1

Expected numbers of signal events within the Higgs boson mass window of $100 \text{ GeV} < m_{bb} < 140 \text{ GeV}$ estimated from simulations. Statistical uncertainties are shown for the predictions from simulations

Channel	Two-central		Four-central				Photon		
Region	SR I	SR II	SR I	SR II	SR III	SR IV	SR I	SR II	SR III
Higgs boson	340^{+120}_{-130}	165^{+50}_{-29}	167^{+60}_{-58}	101^{+40}_{-21}	183^{+50}_{-46}	304^{+100}_{-51}	$21.1^{+7.7}_{-7.1}$	$20.1^{+9.5}_{-7.2}$	$10.6^{+7.8}_{-4.1}$
Z+jets ($Z\gamma$)	470^{+140}_{-180}	230^{+210}_{-230}	22^{+80}_{-22}	197^{+90}_{-95}	720^{+190}_{-180}	$1\,260^{+270}_{-250}$	$5.8^{+3.3}_{-3.6}$	$1.1^{+5.8}_{-1.1}$	$9.8^{+7.8}_{-7.9}$
Non-resonant bkg	$34\,620^{+310}_{-280}$	$95\,620^{+420}_{-420}$	$12\,870^{+150}_{-190}$	$19\,340^{+200}_{-240}$	$59\,340^{+340}_{-340}$	$146\,930^{+630}_{-510}$	$140.4^{+6.1}_{-6.8}$	518^{+10}_{-13}	$1\,296^{+18}_{-19}$
Data	35 496	95 802	13 139	19 611	60 314	148 413	162	565	1 270

Numbers of signal, background and data events within the Higgs boson mass window of $100 \text{ GeV} < m_{bb} < 140 \text{ GeV}$. Signal and background yields are derived from the combined fit for the extraction of μ_{VBF} . Uncertainties include both the statistical and systematic uncertainties.

$H \rightarrow bb$, VBF: Systematics and results

Results	Inclusive production			VBF production		
	All-hadronic	Photon	Combined	All-hadronic	Photon	Combined
Expected significance	0.5σ	0.6σ	0.8σ	0.4σ	0.6σ	0.7σ
Observed significance	1.4σ	1.3σ	1.9σ	1.4σ	1.4σ	1.9σ
Expected limit on signal strength	$4.1^{+1.9}_{-1.2}$	$3.4^{+1.5}_{-1.0}$	$2.5^{+1.0}_{-0.7}$	$5.9^{+2.6}_{-1.7}$	$3.7^{+1.6}_{-1.0}$	$3.0^{+1.3}_{-0.8}$
Observed limit on signal strength	6.8	5.5	4.8	9.7	6.1	5.9
Expected signal strength	1.0 ± 1.9	1.0 ± 1.7	1.0 ± 1.2	1.0 ± 2.8	1.0 ± 1.8	1.0 ± 1.5
Observed signal strength	$2.7^{+2.2}_{-2.0}$	$2.3^{+1.9}_{-1.7}$	$2.5^{+1.4}_{-1.3}$	$4.1^{+3.2}_{-2.9}$	$2.5^{+2.0}_{-1.9}$	$3.0^{+1.7}_{-1.6}$

Uncertainty	$\sigma(\mu_H)$	$\sigma(\mu_{VBF})$
Total stat. uncertainty	+1.3 -1.3	+1.6 -1.5
Data stat. uncertainty	+0.6 -0.6	+0.9 -0.9
Non-resonant bkg	+1.0 -1.0	+1.2 -1.2
Z+jets normalization	+0.5 -0.5	+0.5 -0.5
Total syst. uncertainty	+0.6 -0.4	+0.6 -0.5
Higgs boson modeling	+0.3 -0.1	+0.2 -0.1
JES/JER	+0.3 -0.2	+0.4 -0.2
b-tagging (incl. trigger)	+0.2 -0.1	+0.2 -0.1
Other exp. uncertainty	+0.4 -0.3	+0.4 -0.4
Total	+1.4 -1.3	+1.7 -1.6

$H \rightarrow bb, VH$: Selection

Selection	0-lepton	1-lepton		2-lepton
		e sub-channel	μ sub-channel	
Trigger	E_T^{miss}	Single lepton	E_T^{miss}	Single lepton
Leptons	0 <i>loose</i> leptons with $p_T > 7$ GeV	1 <i>tight</i> electron $p_T > 27$ GeV	1 <i>tight</i> muon $p_T > 25$ GeV	2 <i>loose</i> leptons with $p_T > 7$ GeV ≥ 1 lepton with $p_T > 27$ GeV
E_T^{miss}	> 150 GeV	> 30 GeV	—	—
$m_{\ell\ell}$	—	—	—	$81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}$
Jets	Exactly 2 / Exactly 3 jets	Exactly 2 / ≥ 3 jets		
Jet p_T		> 20 GeV for $ \eta < 2.5$		
		> 30 GeV for $2.5 < \eta < 4.5$		
b -jets		Exactly 2 b -tagged jets		
Leading b -tagged jet p_T		> 45 GeV		
H_T	> 120 GeV (2 jets), > 150 GeV (3 jets)	—	—	
$\min[\Delta\phi(\vec{E}_T^{\text{miss}}, \text{jets})]$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)	—	—	
$\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{bb})$	$> 120^\circ$	—	—	
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^\circ$	—	—	
$\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{p_T^{\text{miss}}})$	$< 90^\circ$	—	—	
p_T^V regions	> 150 GeV	$75 \text{ GeV} < p_T^V < 150 \text{ GeV}, > 150 \text{ GeV}$		
Signal regions	—	$m_{bb} \geq 75$ GeV or $m_{\text{top}} \leq 225$ GeV	Same-flavour leptons Opposite-sign charges ($\mu\mu$ sub-channel)	
Control regions	—	$m_{bb} < 75$ GeV and $m_{\text{top}} > 225$ GeV	Different-flavour leptons Opposite-sign charges	

$H \rightarrow bb, VH$: Signal acceptance and background normalisation

79.8 fb⁻¹
2/3 of Run 2

Process	$\sigma \times \mathcal{B}$ [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$qq \rightarrow ZH \rightarrow \ell\ell b\bar{b}$	29.9	<0.1	0.1	6.0
$gg \rightarrow ZH \rightarrow \ell\ell b\bar{b}$	4.8	<0.1	0.2	13.5
$qq \rightarrow WH \rightarrow \ell\nu b\bar{b}$	269.0	0.2	1.0	—
$qq \rightarrow ZH \rightarrow \nu\nu b\bar{b}$	89.1	1.9	—	—
$gg \rightarrow ZH \rightarrow \nu\nu b\bar{b}$	14.3	3.5	—	—

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
$W + \text{HF}$ 2-jet	1.19 ± 0.12
$W + \text{HF}$ 3-jet	1.05 ± 0.12
$Z + \text{HF}$ 2-jet	1.37 ± 0.11
$Z + \text{HF}$ 3-jet	1.09 ± 0.09

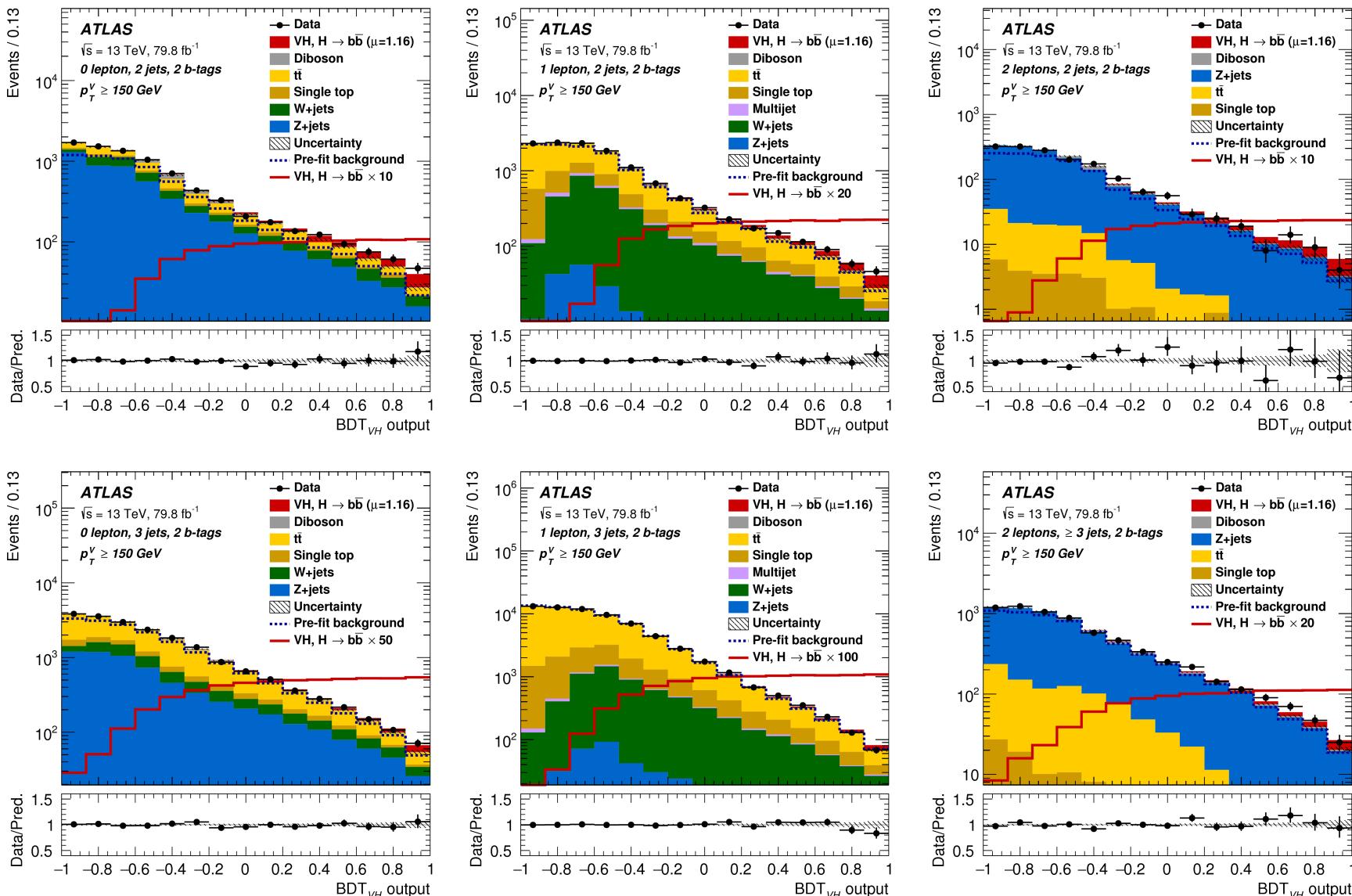
$H \rightarrow bb, VH$: Samples

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%					
$qq \rightarrow WH$ $\rightarrow \ell\nu b\bar{b}$	POWHEG-Box v2 [76] + GoSAM [79] + MiNLO [80,81]	NNPDF3.0NLO ^(*) [77]	PYTHIA 8.212 [68]	AZNLO [78]	NNLO(QCD)+ NLO(EW) [82–88]
$qq \rightarrow ZH$ $\rightarrow \nu\nu b\bar{b}/\ell\ell b\bar{b}$	POWHEG-Box v2 + GoSAM + MiNLO	NNPDF3.0NLO ^(*)	PYTHIA 8.212	AZNLO	NNLO(QCD) ^(†) + NLO(EW)
$gg \rightarrow ZH$ $\rightarrow \nu\nu b\bar{b}/\ell\ell b\bar{b}$	POWHEG-Box v2	NNPDF3.0NLO ^(*)	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					
$W \rightarrow \ell\nu$	SHERPA 2.2.1 [71, 102, 103]	NNPDF3.0NNLO	SHERPA 2.2.1 [104, 105]	Default	NNLO [106]
$Z/\gamma^* \rightarrow \ell\ell$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NNLO
$Z \rightarrow \nu\nu$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NNLO
Diboson					
$qq \rightarrow WW$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NLO
$qq \rightarrow WZ$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NLO
$qq \rightarrow ZZ$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NLO
$gg \rightarrow VV$	SHERPA 2.2.2	NNPDF3.0NNLO	SHERPA 2.2.2	Default	NLO

79.8 fb⁻¹
2/3 of Run 2

$H \rightarrow bb, VH$: BDTs for each SR

Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{\text{miss}}$		
E_T^{miss}	×	×	
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(\vec{b}_1, \vec{b}_2)$	×	×	×
$ \Delta\eta(\vec{b}_1, \vec{b}_2) $	×		
$\Delta\phi(\vec{V}, \vec{bb})$	×	×	×
$ \Delta\eta(\vec{V}, \vec{bb}) $			×
m_{eff}	×		
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
$E_T^{\text{miss}}/\sqrt{S_T}$			×
m_{top}		×	
$ \Delta Y(\vec{V}, \vec{bb}) $		×	
Only in 3-jet events			
$p_T^{\text{jet}_3}$	×	×	×
m_{bbj}	×	×	×



$H \rightarrow bb, VH$: Uncertainties on signal and background modelling

$Z + \text{jets}$	
$Z + ll$ normalisation	18%
$Z + cl$ normalisation	23%
$Z + \text{HF}$ normalisation	Floating (2-jet, 3-jet)
$Z + bc\text{-to-}Z + bb$ ratio	30 – 40%
$Z + cc\text{-to-}Z + bb$ ratio	13 – 15%
$Z + bl\text{-to-}Z + bb$ ratio	20 – 25%
0-to-2 lepton ratio	7%
m_{bb}, p_T^V	S
$W + \text{jets}$	
$W + ll$ normalisation	32%
$W + cl$ normalisation	37%
$W + \text{HF}$ normalisation	Floating (2-jet, 3-jet)
$W + bl\text{-to-}W + bb$ ratio	26% (0-lepton) and 23% (1-lepton)
$W + bc\text{-to-}W + bb$ ratio	15% (0-lepton) and 30% (1-lepton)
$W + cc\text{-to-}W + bb$ ratio	10% (0-lepton) and 30% (1-lepton)
0-to-1 lepton ratio	5%
$W + \text{HF CR to SR ratio}$	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)
$W + \text{HF CR to SR ratio}$	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% ($Wt(\text{other})$)
Acceptance 3-jet	20% (t -channel), 51% ($Wt(bb)$), 21% ($Wt(\text{other})$)
m_{bb}, p_T^V	S (t -channel, $Wt(bb)$, $Wt(\text{other})$)
Multi-jet (1-lepton)	
Normalisation	60 – 100% (2-jet), 90 – 140% (3-jet)
BDT template	S

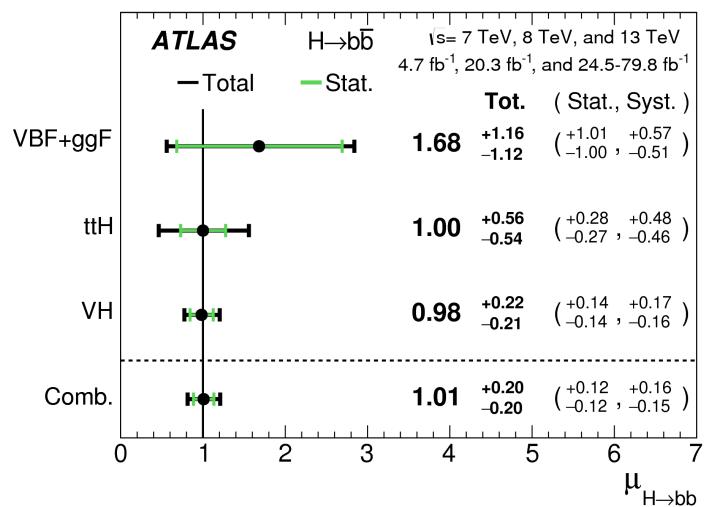
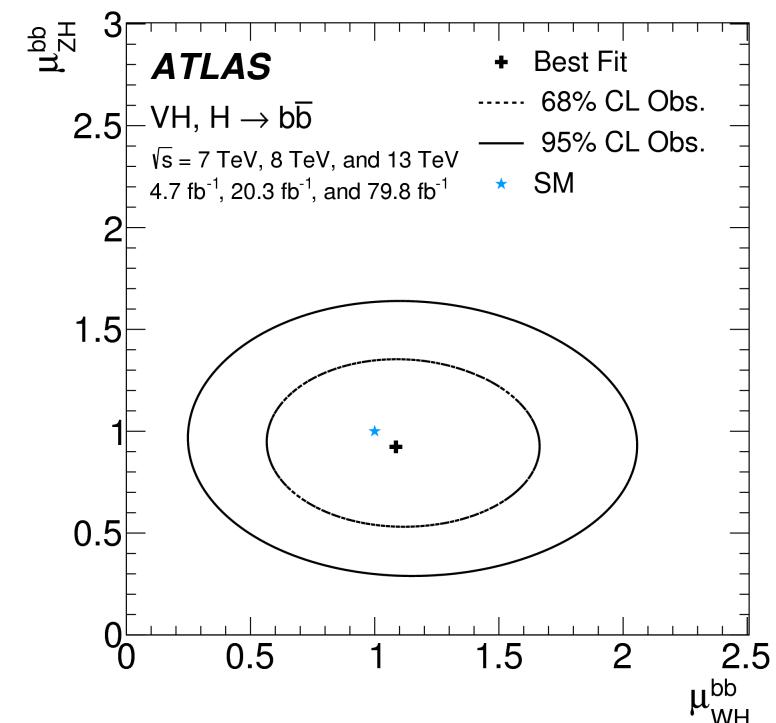
ZZ	
Normalisation	20%
0-to-2 lepton ratio	6%
Acceptance from scale variations	10 – 18%
Acceptance from PS/UE variations for 2 or more jets	6%
Acceptance from PS/UE variations for 3 jets	7% (0-lepton), 3% (2-lepton)
m_{bb}, p_T^V , from scale variations	S (correlated with WZ uncertainties)
m_{bb}, p_T^V , 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	
Cross-section (scale)	0.7% (qq), 27% (gg)
Cross-section (PDF)	1.9% ($qq \rightarrow WH$), 1.6% ($qq \rightarrow ZH$), 5% (gg)
$H \rightarrow b\bar{b}$ 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

$H \rightarrow bb, VH$: Yields

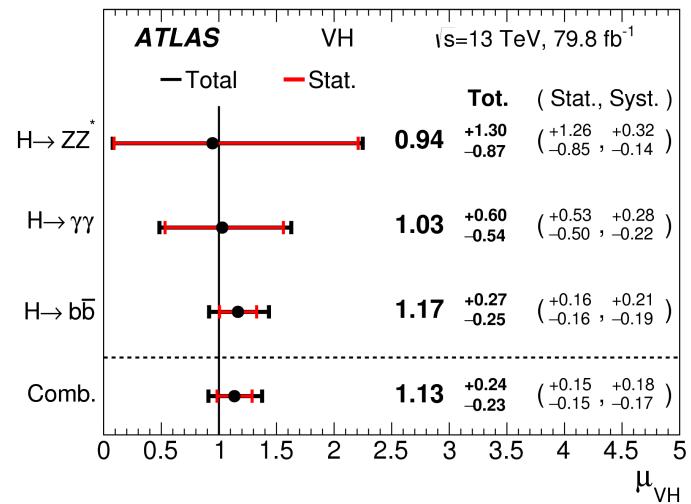
Process	0-lepton $p_T^V > 150\text{ GeV}, 2\text{-}b\text{-tag}$		1-lepton $p_T^V > 150\text{ GeV}, 2\text{-}b\text{-tag}$		2-lepton $75\text{ GeV} < p_T^V < 150\text{ GeV}, 2\text{-}b\text{-tag}$		$p_T^V > 150\text{ GeV}, 2\text{-}b\text{-tag}$	
	2-jet	3-jet	2-jet	3-jet	2-jet	$\geq 3\text{-jet}$	2-jet	$\geq 3\text{-jet}$
$Z + ll$	17 \pm 11	27 \pm 18	2 \pm 1	3 \pm 2	14 \pm 9	49 \pm 32	4 \pm 3	30 \pm 19
$Z + cl$	45 \pm 18	76 \pm 30	3 \pm 1	7 \pm 3	43 \pm 17	170 \pm 67	12 \pm 5	88 \pm 35
$Z + \text{HF}$	4770 \pm 140	5940 \pm 300	180 \pm 9	348 \pm 21	7400 \pm 120	14160 \pm 220	1421 \pm 34	5370 \pm 100
$W + ll$	20 \pm 13	32 \pm 22	31 \pm 23	65 \pm 48	< 1	< 1	< 1	< 1
$W + cl$	43 \pm 20	83 \pm 38	139 \pm 67	250 \pm 120	< 1	< 1	< 1	< 1
$W + \text{HF}$	1000 \pm 87	1990 \pm 200	2660 \pm 270	5400 \pm 670	2 \pm 0	13 \pm 2	1 \pm 0	4 \pm 1
Single top quark	368 \pm 53	1410 \pm 210	2080 \pm 290	9400 \pm 1400	188 \pm 89	440 \pm 200	23 \pm 7	93 \pm 26
$t\bar{t}$	1333 \pm 82	9150 \pm 400	6600 \pm 320	50200 \pm 1400	3170 \pm 100	8880 \pm 220	104 \pm 6	839 \pm 40
Diboson	254 \pm 49	318 \pm 90	178 \pm 47	330 \pm 110	152 \pm 32	355 \pm 68	52 \pm 11	196 \pm 35
Multi-jet e sub-ch.	—	—	100 \pm 100	41 \pm 35	—	—	—	—
Multi-jet μ sub-ch.	—	—	138 \pm 92	260 \pm 270	—	—	—	—
Total bkg.	7850 \pm 90	19020 \pm 140	12110 \pm 120	66230 \pm 270	10960 \pm 100	24070 \pm 150	1620 \pm 30	6620 \pm 80
Signal (post-fit)	128 \pm 28	128 \pm 29	131 \pm 30	125 \pm 30	51 \pm 11	86 \pm 22	28 \pm 6	67 \pm 17
Data	8003	19143	12242	66348	11014	24197	1626	6686

$H \rightarrow bb, VH$: Results

Signal strength	Signal strength	p_0		Significance	
		Exp.	Obs.	Exp.	Obs.
0-lepton	$1.04^{+0.34}_{-0.32}$	$9.5 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$	3.1	3.3
1-lepton	$1.09^{+0.46}_{-0.42}$	$8.7 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	2.4	2.6
2-lepton	$1.38^{+0.46}_{-0.42}$	$4.0 \cdot 10^{-3}$	$3.3 \cdot 10^{-4}$	2.6	3.4
$VH, H \rightarrow b\bar{b}$ combination	$1.16^{+0.27}_{-0.25}$	$7.3 \cdot 10^{-6}$	$5.3 \cdot 10^{-7}$	4.3	4.9



Channel	Significance	
	Exp.	Obs.
VBF+ggF	0.9	1.5
$t\bar{t}H$	1.9	1.9
VH	5.1	4.9
$H \rightarrow b\bar{b}$ combination	5.5	5.4



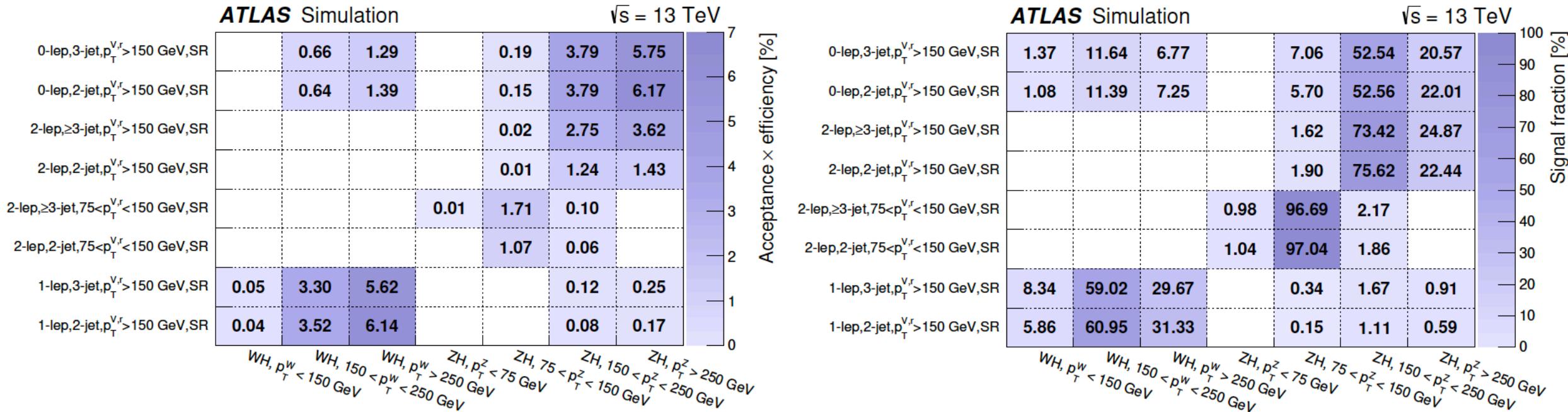
Channel	Significance	
	Exp.	Obs.
$H \rightarrow ZZ^* \rightarrow 4\ell$	1.1	1.1
$H \rightarrow \gamma\gamma$	1.9	1.9
$H \rightarrow b\bar{b}$	4.3	4.9
VH combined	4.8	5.3

$H \rightarrow bb, VH$: STXS result extraction

Channel	Categories					
	$75 \text{ GeV} < p_T^{V,r} < 150 \text{ GeV}$		$p_T^{V,r} > 150 \text{ GeV}$		2 jets	≥ 3 jets
	2 jets	≥ 3 jets	2 jets	3 jets		
0-lepton	–	–	SR	SR	–	–
1-lepton						
$m_{bb} \geq 75 \text{ GeV}$ or $m_{top} \leq 225 \text{ GeV}$	–	–	SR	SR	–	–
$m_{bb} < 75 \text{ GeV}$ and $m_{top} > 225 \text{ GeV}$	–	–	CR	CR	–	–
2-lepton						
ee and $\mu\mu$ channels	SR	SR	SR	–	SR	
$e\mu$ channel	CR	CR	CR	–	CR	

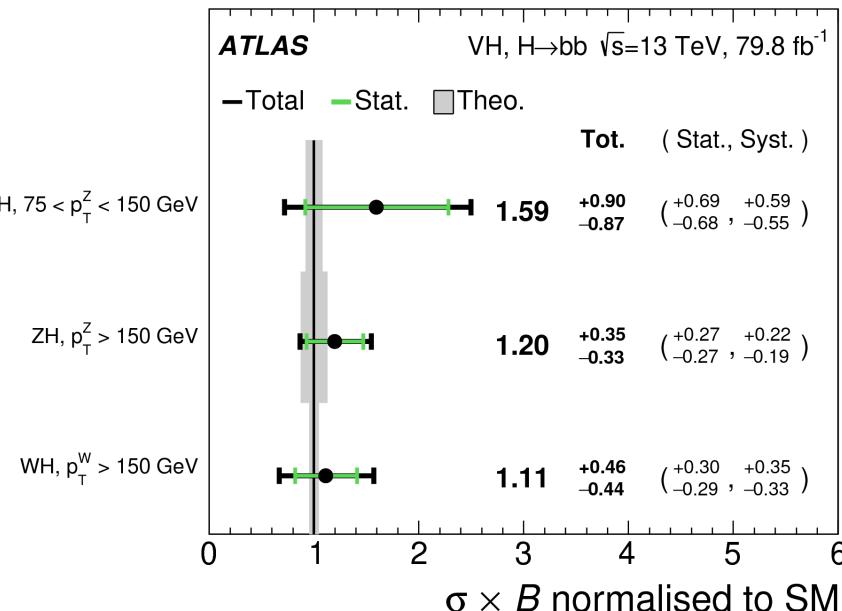
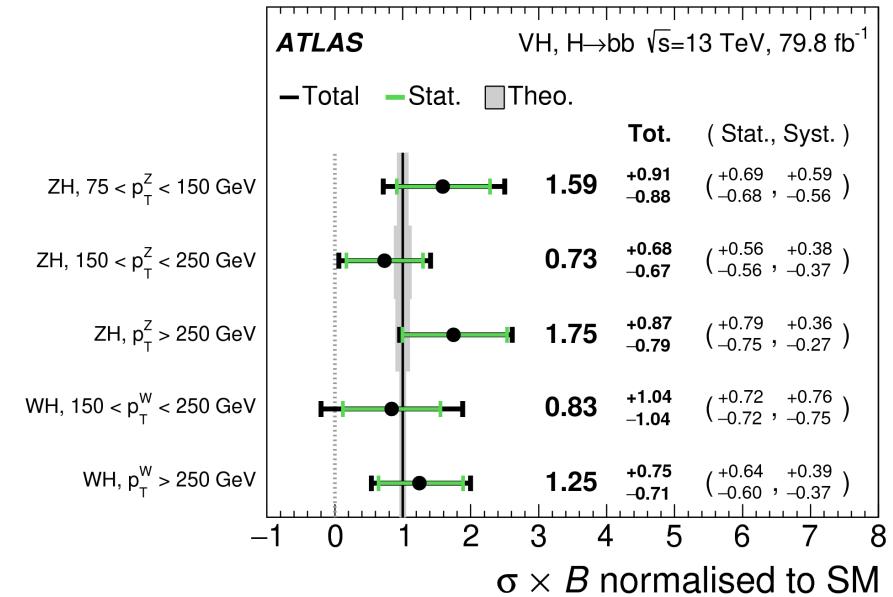
Merged region 3-POI scheme	Merged region 5-POI scheme	Stage 1 (modified) STXS region	Reconstructed-event categories with largest sensitivity		
			N_{lep}	$p_T^{V,r}$ interval	N_{jet}
$WH, p_T^W > 150 \text{ GeV}$	$WH, 150 < p_T^W < 250 \text{ GeV}$	$q\bar{q} \rightarrow WH, 150 < p_T^W < 250 \text{ GeV}, 0\text{-jet}$ $q\bar{q} \rightarrow WH, 150 < p_T^W < 250 \text{ GeV}, \geq 1\text{-jet}$	1	$> 150 \text{ GeV}$	2, 3
	$WH, p_T^W > 250 \text{ GeV}$	$q\bar{q} \rightarrow WH, p_T^W > 250 \text{ GeV}$			
$ZH, 75 < p_T^Z < 150 \text{ GeV}$	$ZH, 75 < p_T^Z < 150 \text{ GeV}$	$q\bar{q} \rightarrow ZH, 75 < p_T^Z < 150 \text{ GeV}$ $gg \rightarrow ZH, 75 < p_T^Z < 150 \text{ GeV}$	2	75–150 GeV	2, ≥ 3
	$ZH, 150 < p_T^Z < 250 \text{ GeV}$	$q\bar{q} \rightarrow ZH, 150 < p_T^Z < 250 \text{ GeV}, 0\text{-jet}$ $gg \rightarrow ZH, 150 < p_T^Z < 250 \text{ GeV}, 0\text{-jet}$ $q\bar{q} \rightarrow ZH, 150 < p_T^Z < 250 \text{ GeV}, \geq 1\text{-jet}$ $gg \rightarrow ZH, 150 < p_T^Z < 250 \text{ GeV}, \geq 1\text{-jet}$			
$ZH, p_T^Z > 250 \text{ GeV}$		$q\bar{q} \rightarrow ZH, p_T^Z > 250 \text{ GeV}$ $gg \rightarrow ZH, p_T^Z > 250 \text{ GeV}$	0	$> 150 \text{ GeV}$	2, 3

$H \rightarrow bb, VH$: STXS signal acceptance & fraction

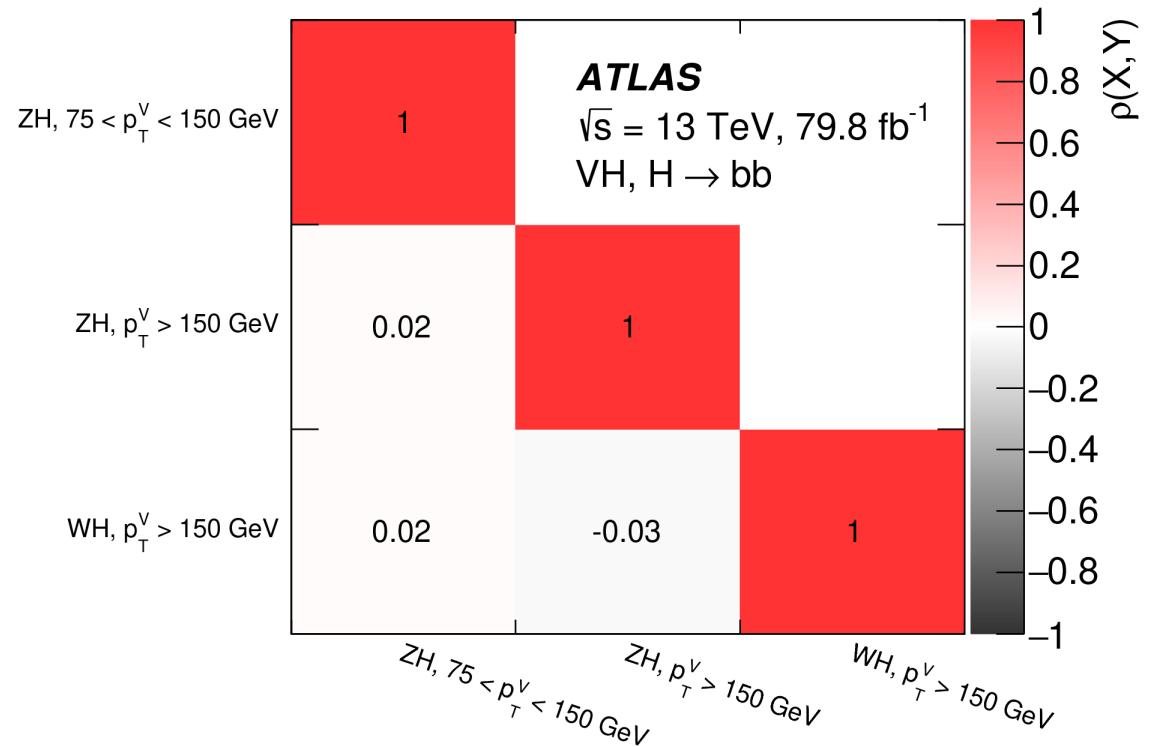
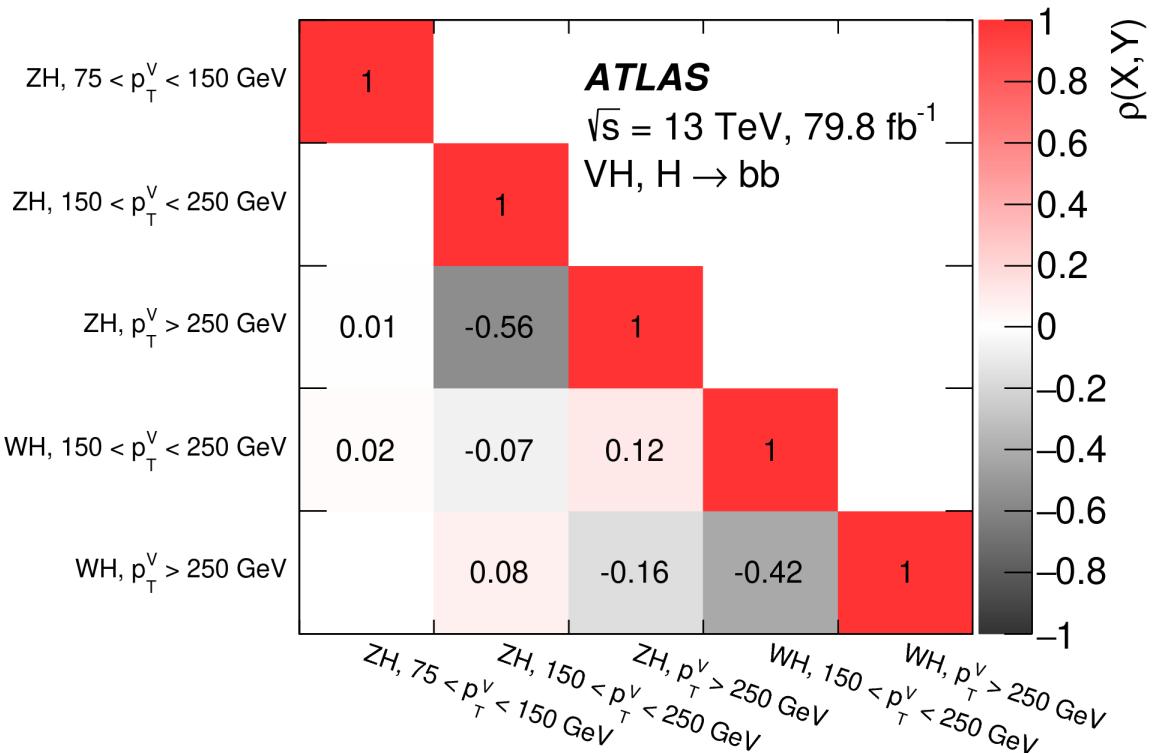


$H \rightarrow b\bar{b}$, VH : STXS results

Measurement region ($ y_H < 2.5, H \rightarrow b\bar{b}$)	SM prediction [fb]	Result [fb]	Stat. unc. [fb]	Syst. unc. [fb]		
				Th. sig.	Th. bkg.	Exp.
5-POI scheme						
$W \rightarrow \ell\nu; 150 < p_T^V < 250 \text{ GeV}$	24.0 \pm 1.1	20 \pm 25	\pm 17	\pm 2	\pm 13	\pm 9
$W \rightarrow \ell\nu; p_T^V > 250 \text{ GeV}$	7.1 \pm 0.3	8.8 \pm 5.2	\pm 4.4	\pm 0.5	\pm 2.5	\pm 0.9
$Z \rightarrow \ell\ell, \nu\nu; 75 < p_T^V < 150 \text{ GeV}$	50.6 \pm 4.1	81 \pm 45	\pm 35	\pm 10	\pm 21	\pm 19
$Z \rightarrow \ell\ell, \nu\nu; 150 < p_T^V < 250 \text{ GeV}$	18.8 \pm 2.4	14 \pm 13	\pm 11	\pm 1	\pm 6	\pm 3
$Z \rightarrow \ell\ell, \nu\nu; p_T^V > 250 \text{ GeV}$	4.9 \pm 0.5	8.5 \pm 4.0	\pm 3.7	\pm 0.8	\pm 1.2	\pm 0.6
3-POI scheme						
$W \rightarrow \ell\nu; p_T^V > 150 \text{ GeV}$	31.1 \pm 1.4	35 \pm 14	\pm 9	\pm 2	\pm 9	\pm 4
$Z \rightarrow \ell\ell, \nu\nu; 75 < p_T^V < 150 \text{ GeV}$	50.6 \pm 4.1	81 \pm 45	\pm 35	\pm 10	\pm 21	\pm 19
$Z \rightarrow \ell\ell, \nu\nu; p_T^V > 150 \text{ GeV}$	23.7 \pm 3.0	28.4 \pm 8.1	\pm 6.4	\pm 2.4	\pm 3.6	\pm 2.3



$H \rightarrow bb, VH$: STXS correlations

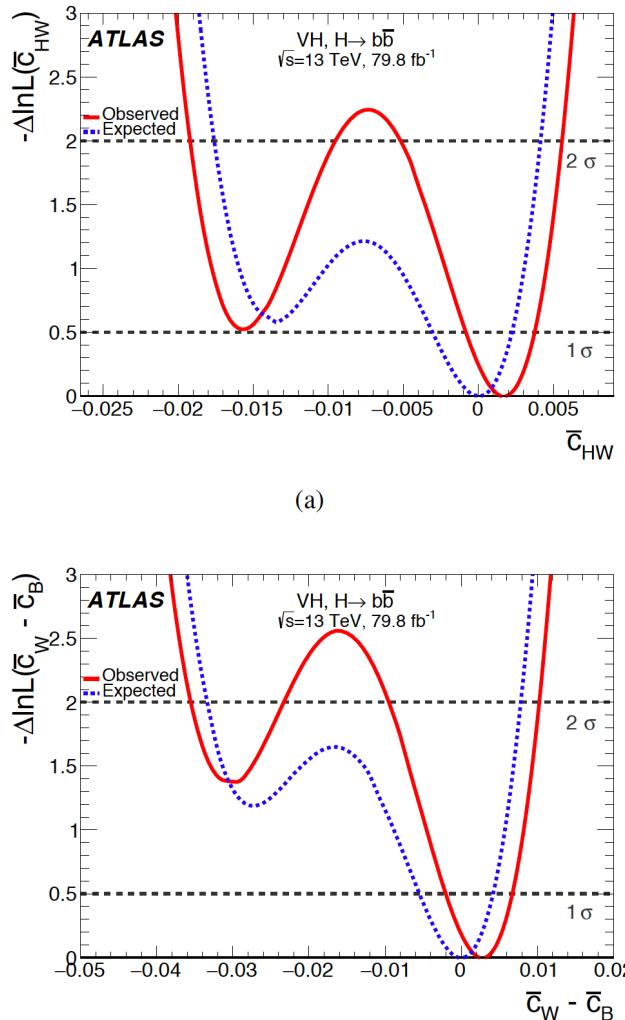


$H \rightarrow bb, VH$: Using STXS results in EFT fit

- Parametrize BSM physics in terms of Effective Lagrangian expansion of $\left(\frac{v}{\Lambda}\right)^{D-4}$
 - Λ new physics scale assumed to be well above LHC reach
- Assumption $O^{(6)}$ dominant at LHC: focus on $D=6 \rightarrow c_i$ (Wilson coefficient in SILH basis):

$$\bar{c}_{HW} = \frac{m_W^2}{g} \frac{c_{HW}}{\Lambda^2}, \quad \bar{c}_{HB} = \frac{m_W^2}{g'} \frac{c_{HB}}{\Lambda^2}, \quad \bar{c}_W = \frac{m_W^2}{g} \frac{c_W}{\Lambda^2}, \quad \bar{c}_B = \frac{m_W^2}{g'} \frac{c_B}{\Lambda^2}, \quad \bar{c}_d = v^2 \frac{c_d}{\Lambda^2},$$
 - 5 operators are relevant for $VH \rightarrow bb$: $(c_W + c_B)$ constrained by EW meas.
 \rightarrow 4 operators considered
- **Use 5 $VH \rightarrow bb$ STXS cross-section to set limit on 4 EFT c_i**
- Fit only 1 c_i at a time to data - Other c_i assumed to be 0

$H \rightarrow bb, VH$: Using STXS results in EFT fit



- All c_i compatible with SM
- 95% CL limits derived

Coefficient	Expected interval	Observed interval
Results at 68% confidence level		
\bar{c}_{HW} (interference only)	[-0.003, 0.002] [-0.002, 0.003]	[-0.001, 0.004] [-0.001, 0.005]
\bar{c}_{HB} (interference only)	[-0.066, 0.013] [-0.016, 0.016]	[-0.078, -0.055] \cup [0.005, 0.019] [-0.005, 0.030]
$\bar{c}_W - \bar{c}_B$ (interference only)	[-0.006, 0.005] [-0.005, 0.005]	[-0.002, 0.007] [-0.002, 0.008]
\bar{c}_d (interference only)	[-1.5, 0.3] [-0.4, 0.4]	[-1.6, -0.9] \cup [-0.3, 0.4] [-0.2, 0.7]
Results at 95% confidence level		
\bar{c}_{HW} (interference only)	[-0.018, 0.004] [-0.005, 0.005]	[-0.019, -0.010] \cup [-0.005, 0.006] [-0.003, 0.008]
\bar{c}_{HB} (interference only)	[-0.078, 0.024] [-0.033, 0.033]	[-0.090, 0.032] [-0.022, 0.049]
$\bar{c}_W - \bar{c}_B$ (interference only)	[-0.034, 0.008] [-0.009, 0.010]	[-0.036, -0.024] \cup [-0.009, 0.010] [-0.006, 0.014]
\bar{c}_d (interference only)	[-1.7, 0.5] [-0.8, 0.8]	[-1.9, 0.7] [-0.6, 1.1]

$H \rightarrow \tau\tau$ selection

Analysis channel	Trigger	Analysis p_T requirement [GeV]	
		2015	2016
$\tau_{\text{lep}}\tau_{\text{lep}}$ & $\tau_{\text{lep}}\tau_{\text{had}}$	Single electron	25	27
	Single muon	21	27
$\tau_{\text{lep}}\tau_{\text{lep}}$	Dielectron	15 / 15	18 / 18
	Dimuon	19 / 10	24 / 10
	Electron+muon	18 / 15	18 / 15
$\tau_{\text{had}}\tau_{\text{had}}$	Di- $\tau_{\text{had-vis}}$	40 / 30	40 / 30

$e e/\mu\mu$	$\tau_{\text{lep}}\tau_{\text{lep}}$	$e\mu$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
	$N_{e/\mu}^{\text{loose}} = 2, N_{\tau_{\text{had-vis}}}^{\text{loose}} = 0$ e/μ : Medium, gradient iso.		$N_{e/\mu}^{\text{loose}} = 1, N_{\tau_{\text{had-vis}}}^{\text{loose}} = 1$ e/μ : Medium, gradient iso.	$N_{e/\mu}^{\text{loose}} = 0, N_{\tau_{\text{had-vis}}}^{\text{loose}} = 2$
	Opposite charge $m_{\tau\tau}^{\text{coll}} > m_Z - 25 \text{ GeV}$		$\tau_{\text{had-vis}}$: Medium Opposite charge $m_T < 70 \text{ GeV}$	$\tau_{\text{had-vis}}$: Tight Opposite charge
30 < $m_{\ell\ell} < 75 \text{ GeV}$	$30 < m_{\ell\ell} < 100 \text{ GeV}$	$E_T^{\text{miss}} > 55 \text{ GeV}$	$E_T^{\text{miss}} > 20 \text{ GeV}$	$E_T^{\text{miss}} > 20 \text{ GeV}$
$E_T^{\text{miss, hard}} > 55 \text{ GeV}$		$E_T^{\text{miss}} > 20 \text{ GeV}$		
	$\Delta R_{\tau\tau} < 2.0$		$\Delta R_{\tau\tau} < 2.5$	$0.8 < \Delta R_{\tau\tau} < 2.5$
	$ \Delta\eta_{\tau\tau} < 1.5$		$ \Delta\eta_{\tau\tau} < 1.5$	$ \Delta\eta_{\tau\tau} < 1.5$
	$0.1 < x_1 < 1.0$		$0.1 < x_1 < 1.4$	$0.1 < x_1 < 1.4$
	$0.1 < x_2 < 1.0$		$0.1 < x_2 < 1.2$	$0.1 < x_2 < 1.4$
	$p_T^{j_1} > 40 \text{ GeV}$		$p_T^{j_1} > 40 \text{ GeV}$	$p_T^{j_1} > 70 \text{ GeV}, \eta_{j_1} < 3.2$
	$N_{b\text{-jets}} = 0$		$N_{b\text{-jets}} = 0$	

$H \rightarrow \tau\tau$ categories and CRs

Signal Region	Inclusive	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
VBF	High- $p_T^{\tau\tau}$	$p_T^{j_2} > 30 \text{ GeV}$ $ \Delta\eta_{jj} > 3$	—	$p_T^{\tau\tau} > 140 \text{ GeV}$ $\Delta R_{\tau\tau} < 1.5$
	Tight	$m_{jj} > 400 \text{ GeV}$ $\eta_{j_1} \cdot \eta_{j_2} < 0$	$m_{jj} > 800 \text{ GeV}$	Not VBF high- $p_T^{\tau\tau}$
	Loose	Central leptons	$m_{jj} > 500 \text{ GeV}$ $p_T^{\tau\tau} > 100 \text{ GeV}$	$m_{jj} > (1550 - 250 \cdot \Delta\eta_{jj}) \text{ GeV}$
Boosted	High- $p_T^{\tau\tau}$	Not VBF	Not VBF tight	
	Low- $p_T^{\tau\tau}$	$p_T^{\tau\tau} > 100 \text{ GeV}$	$p_T^{\tau\tau} > 140 \text{ GeV}$ $\Delta R_{\tau\tau} < 1.5$	
			Not boosted high- $p_T^{\tau\tau}$	

Region	Selection	Background	Channel	Normalization factors
				VBF Boosted
$\tau_{\text{lep}}\tau_{\text{lep}}$ VBF $Z \rightarrow \ell\ell$ CR	$\tau_{\text{lep}}\tau_{\text{lep}}$ VBF incl. selection, $80 < m_{\ell\ell} < 100 \text{ GeV}$, SF	$Z \rightarrow \ell\ell$ (CR)	$\tau_{\text{lep}}\tau_{\text{lep}}$	$0.88^{+0.34}_{-0.30}$ $1.27^{+0.30}_{-0.25}$
$\tau_{\text{lep}}\tau_{\text{lep}}$ boosted $Z \rightarrow \ell\ell$ CR	$\tau_{\text{lep}}\tau_{\text{lep}}$ boosted incl. selection, $80 < m_{\ell\ell} < 100 \text{ GeV}$, SF	Top (CR)	$\tau_{\text{lep}}\tau_{\text{lep}}$	1.19 ± 0.09 1.07 ± 0.05
$\tau_{\text{lep}}\tau_{\text{lep}}$ VBF top CR	$\tau_{\text{lep}}\tau_{\text{lep}}$ VBF incl. selection, inverted b -jet veto	Top (CR)	$\tau_{\text{lep}}\tau_{\text{had}}$	$1.53^{+0.30}_{-0.27}$ 1.13 ± 0.07
$\tau_{\text{lep}}\tau_{\text{lep}}$ boosted top CR	$\tau_{\text{lep}}\tau_{\text{lep}}$ boosted incl. selection, inverted b -jet veto	Fake- $\tau_{\text{had-vis}}$ (data-driven)	$\tau_{\text{had}}\tau_{\text{had}}$	1.12 ± 0.12
$\tau_{\text{lep}}\tau_{\text{had}}$ VBF top CR	$\tau_{\text{lep}}\tau_{\text{had}}$ VBF incl. selection, inverted b -jet veto, $m_T > 40 \text{ GeV}$	$Z \rightarrow \tau\tau$ (fit in each SR)	$\tau_{\text{lep}}\tau_{\text{had}}, \tau_{\text{lep}}\tau_{\text{had}}, \tau_{\text{had}}\tau_{\text{had}}$	$1.04^{+0.10}_{-0.09}$ 1.11 ± 0.05
$\tau_{\text{lep}}\tau_{\text{had}}$ boosted top CR	$\tau_{\text{lep}}\tau_{\text{had}}$ boosted incl. selection, inverted b -jet veto, $m_T > 40 \text{ GeV}$			

$H \rightarrow \tau\tau$ observed yields

	$\tau_{\text{lep}}\tau_{\text{lep}}$ VBF		$\tau_{\text{lep}}\tau_{\text{lep}}$ boosted	
	Loose	Tight	Low- $p_T^{\tau\tau}$	High- $p_T^{\tau\tau}$
$Z \rightarrow \tau\tau$	151 \pm 13	107 \pm 12	2977 \pm 90	2687 \pm 64
$Z \rightarrow \ell\ell$	15.1 \pm 4.9	20.3 \pm 6.6	360 \pm 54	236 \pm 31
Top	33.0 \pm 6.4	25.1 \pm 4.5	321 \pm 50	189 \pm 29
VV	11.8 \pm 2.2	10.7 \pm 1.5	194.1 \pm 8.5	195.3 \pm 8.8
Misidentified τ	18.3 \pm 9.6	9.6 \pm 4.8	209 \pm 92	80 \pm 35
$ggF, H \rightarrow WW^*$	1.2 \pm 0.2	1.4 \pm 0.3	11.8 \pm 2.6	16.4 \pm 1.7
VBF, $H \rightarrow WW^*$	1.7 \pm 0.2	4.1 \pm 0.5	2.9 \pm 0.3	2.9 \pm 0.3
$ggF, H \rightarrow \tau\tau$	2.6 \pm 0.9	1.8 \pm 0.9	34.4 \pm 9.2	33.8 \pm 9.5
VBF, $H \rightarrow \tau\tau$	5.3 \pm 1.5	11.3 \pm 3.0	7.7 \pm 2.1	8.2 \pm 2.3
$WH, H \rightarrow \tau\tau$	< 0.1	< 0.1	2.5 \pm 0.7	3.1 \pm 0.9
$ZH, H \rightarrow \tau\tau$	< 0.1	< 0.1	1.3 \pm 0.4	1.6 \pm 0.4
$t\bar{t}H, H \rightarrow \tau\tau$	< 0.1	0.1 \pm 0.1	1.5 \pm 0.5	1.2 \pm 0.4
Total background	232 \pm 13	178 \pm 12	4075 \pm 61	3408 \pm 54
Total signal	8.0 \pm 2.2	13.2 \pm 3.5	47 \pm 12	48 \pm 12
Data	237	188	4124	3444

$H \rightarrow \tau\tau$ observed yields

	$\tau_{\text{lep}}\tau_{\text{had}}$ VBF		$\tau_{\text{lep}}\tau_{\text{had}}$ boosted	
	Loose	Tight	Low- $p_T^{\tau\tau}$	High- $p_T^{\tau\tau}$
$Z \rightarrow \tau\tau$	178 \pm 18	323 \pm 21	4187 \pm 92	5347 \pm 82
$Z \rightarrow \ell\ell$	10.0 \pm 3.0	12.7 \pm 3.1	130 \pm 37	115 \pm 16
Top	5.8 \pm 1.6	17.9 \pm 4.6	121 \pm 20	57 \pm 10
Misidentified τ	103 \pm 16	101 \pm 15	1895 \pm 80	605 \pm 29
Other backgrounds	4.0 \pm 1.6	9.3 \pm 1.9	115.0 \pm 7.8	129.0 \pm 8.8
$ggF, H \rightarrow \tau\tau$	3.8 \pm 1.1	7.1 \pm 1.9	62 \pm 16	66 \pm 22
VBF, $H \rightarrow \tau\tau$	7.6 \pm 2.2	24.7 \pm 6.8	11.9 \pm 3.4	14.0 \pm 4.0
$WH, H \rightarrow \tau\tau$	< 0.1	0.1 \pm 0.0	3.9 \pm 1.1	5.4 \pm 1.4
$ZH, H \rightarrow \tau\tau$	< 0.1	< 0.1	1.8 \pm 0.5	2.8 \pm 0.7
$t\bar{t}H, H \rightarrow \tau\tau$	< 0.1	< 0.1	0.1 \pm 0.0	0.2 \pm 0.1
Total background	301 \pm 17	463 \pm 21	6448 \pm 81	6253 \pm 80
Total signal	11.5 \pm 3.2	32.0 \pm 8.2	80 \pm 20	89 \pm 26
Data	318	496	6556	6347

	$\tau_{\text{had}}\tau_{\text{had}}$ VBF			$\tau_{\text{had}}\tau_{\text{had}}$ boosted	
	Loose	Tight	High- $p_T^{\tau\tau}$	Low- $p_T^{\tau\tau}$	High- $p_T^{\tau\tau}$
$Z \rightarrow \tau\tau$	67.3 \pm 9.2	100 \pm 12	141 \pm 12	3250 \pm 130	3582 \pm 82
Misidentified τ	45.0 \pm 5.4	96.4 \pm 9.2	20.0 \pm 2.9	1870 \pm 140	364 \pm 53
Other backgrounds	4.4 \pm 1.4	11.6 \pm 1.7	4.4 \pm 0.7	281 \pm 21	109.9 \pm 9.2
$ggF, H \rightarrow \tau\tau$	1.1 \pm 0.4	2.0 \pm 0.7	3.5 \pm 1.0	41 \pm 11	48 \pm 14
VBF, $H \rightarrow \tau\tau$	1.4 \pm 0.5	6.4 \pm 1.8	11.2 \pm 3.0	9.0 \pm 3.4	10.7 \pm 2.9
$WH, H \rightarrow \tau\tau$	< 0.1	< 0.1	< 0.1	3.3 \pm 0.9	4.4 \pm 1.2
$ZH, H \rightarrow \tau\tau$	< 0.1	< 0.1	< 0.1	2.4 \pm 0.7	2.9 \pm 0.8
$t\bar{t}H, H \rightarrow \tau\tau$	< 0.1	< 0.1	< 0.1	1.6 \pm 0.5	1.9 \pm 0.5
Total background	116.7 \pm 9.4	208 \pm 12	165 \pm 12	5401 \pm 78	4057 \pm 64
Total signal	2.6 \pm 0.8	8.6 \pm 2.4	14.9 \pm 3.8	57 \pm 15	68 \pm 18
Data	121	220	179	5455	4103

$H \rightarrow \tau\tau$ systematics

Source of uncertainty	Impact $\Delta\sigma/\sigma_{H \rightarrow \tau\tau}$ [%]	
	Observed	Expected
Theoretical uncert. in signal	+13.4 / -8.7	+12.0 / -7.8
Background statistics	+10.8 / -9.9	+10.1 / -9.7
Jets and E_T^{miss}	+11.2 / -9.1	+10.4 / -8.4
Background normalization	+6.3 / -4.4	+6.3 / -4.4
Misidentified τ	+4.5 / -4.2	+3.4 / -3.2
Theoretical uncert. in background	+4.6 / -3.6	+5.0 / -4.0
Hadronic τ decays	+4.4 / -2.9	+5.5 / -4.0
Flavor tagging	+3.4 / -3.4	+3.0 / -2.3
Luminosity	+3.3 / -2.4	+3.1 / -2.2
Electrons and muons	+1.2 / -0.9	+1.1 / -0.8
Total systematic uncert.	+23 / -20	+22 / -19
Data statistics	± 16	± 15
Total	+28 / -25	+27 / -24

$H \rightarrow \mu\mu$: Selection

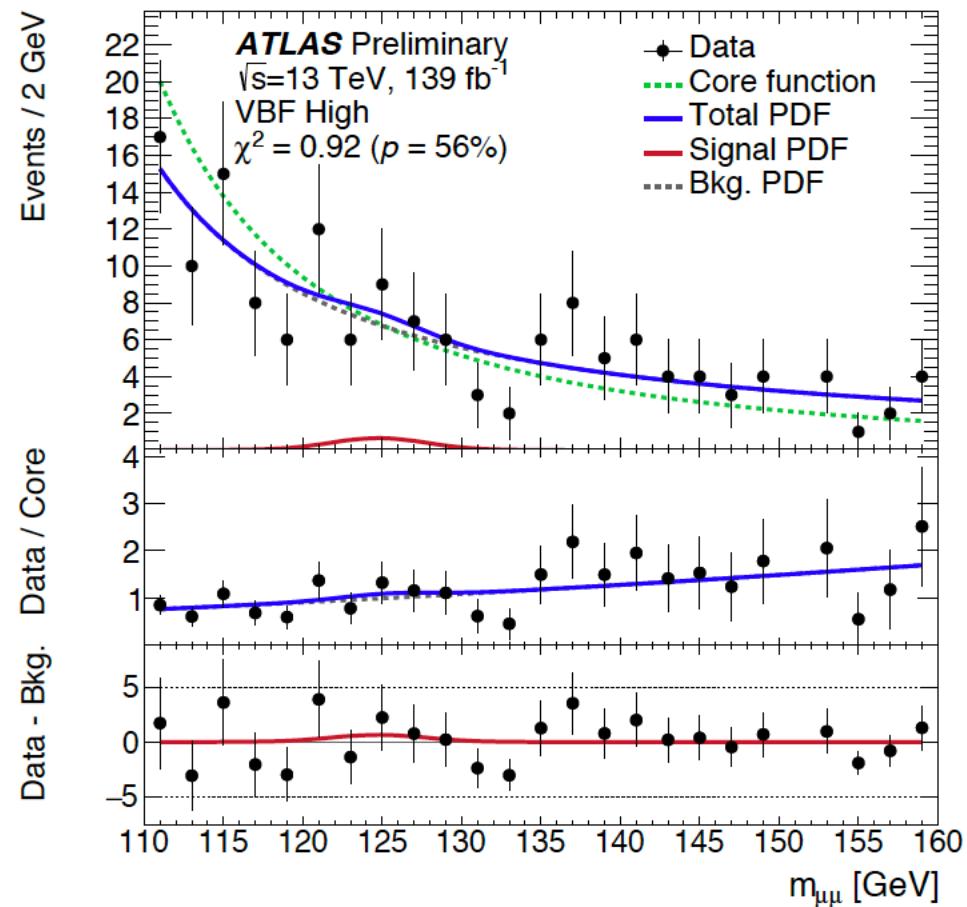
Selection	
	Primary vertex
Common	Two opposite-charge muons Muons: $ \eta < 2.7$, $p_T^{\text{lead}} > 27 \text{ GeV}$, $p_T^{\text{sublead}} > 15 \text{ GeV}$ No b -tagged jets
Z region	$76 < m_{\mu\mu} < 106 \text{ GeV}$
Sideband region	$110 < m_{\mu\mu} < 120 \text{ GeV}$ or $130 < m_{\mu\mu} < 180 \text{ GeV}$
Fit region	$110 < m_{\mu\mu} < 160 \text{ GeV}$
Jets	$p_T > 25 \text{ GeV}$ and $ \eta < 2.5$ or with $p_T > 30 \text{ GeV}$ and $2.5 < \eta < 4.5$

Category	0-jet	1-jet	VBF	2-jet $O_{\text{VBF}} < 0.60$
High	$O_{ggF}^0 \geq 0.75$	$O_{ggF}^1 \geq 0.78$	$O_{\text{VBF}} \geq 0.89$	$O_{ggF}^2 \geq 0.48$
Medium	$0.35 \leq O_{ggF}^0 < 0.75$	$0.38 \leq O_{ggF}^1 < 0.78$	$0.77 \leq O_{\text{VBF}} < 0.89$	$0.22 \leq O_{ggF}^2 < 0.48$
Low	$O_{ggF}^0 < 0.35$	$O_{ggF}^1 < 0.38$	$0.60 \leq O_{\text{VBF}} < 0.77$	$O_{ggF}^2 < 0.22$

$H \rightarrow \mu\mu$: Background function

Table 4: Selected empirical background functions in the different analysis categories together with the maximum values of the SS (in the 120–130 GeV mass range) normalised to the expected signal statistical error (δS) and to the SM predictions (S_{SM}) in %.

Category	Empirical Function	max(SS/ δS)[%]	max(SS/ S_{SM})[%]
0-jet High	Power0	10.6	14.7
0-jet Medium	Epoly2	0.51	1.3
0-jet Low	Power1	3.6	7.5
1-jet High	Epoly2	8.7	16.3
1-jet Medium	Epoly4	1.2	3.9
1-jet Low	Epoly3	-8.2	-33.2
2-jet High	Power1	6.1	12.1
2-jet Medium	Epoly3	-8.1	-19.8
2-jet Low	Epoly3	-2.5	-5.8
VBF High	Power1	14.6	26.5
VBF Medium	Epoly3	-11.6	-39.0
VBF Low	Epoly3	-18.5	-74.2

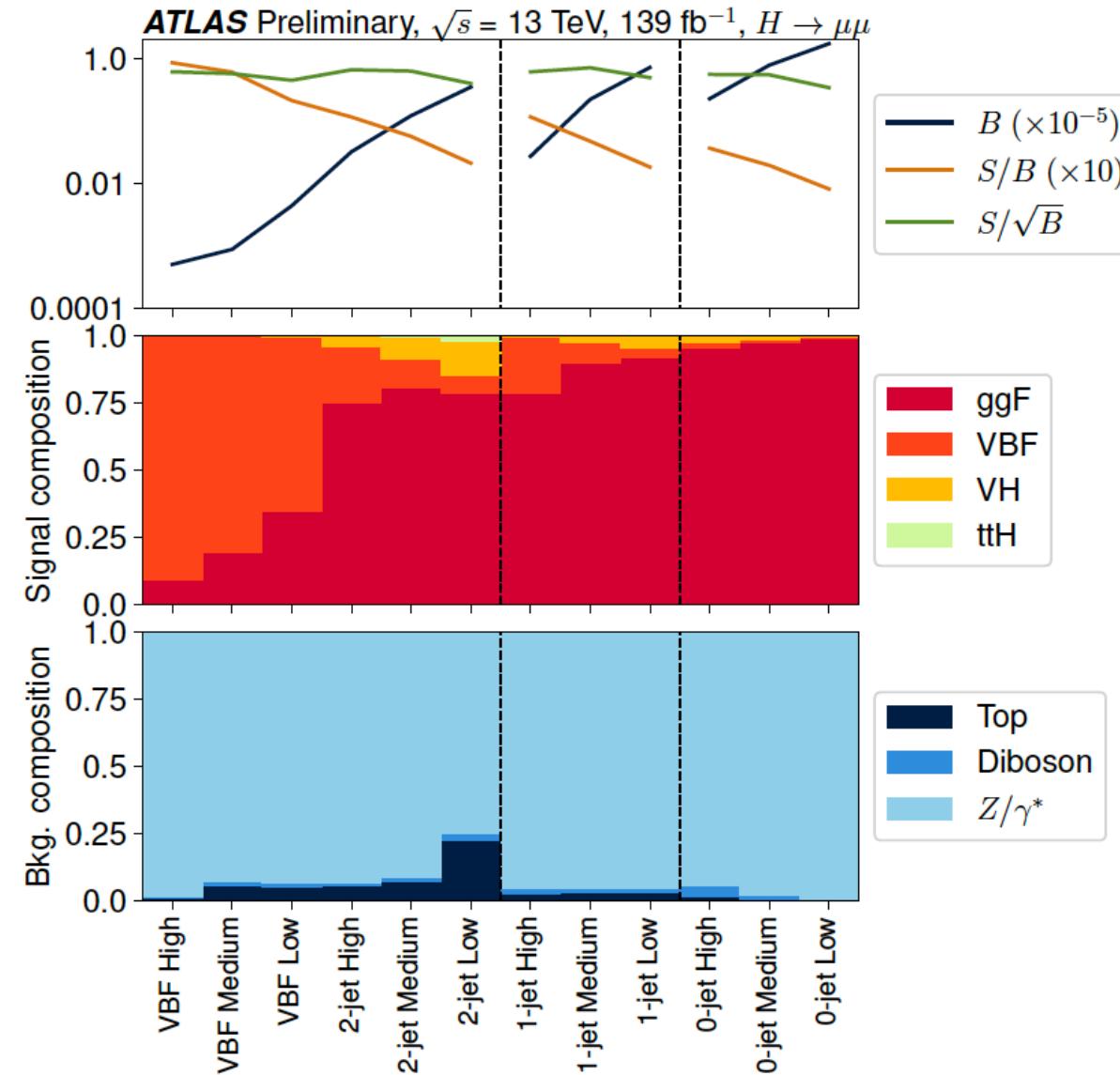


$H \rightarrow \mu\mu$: Yields

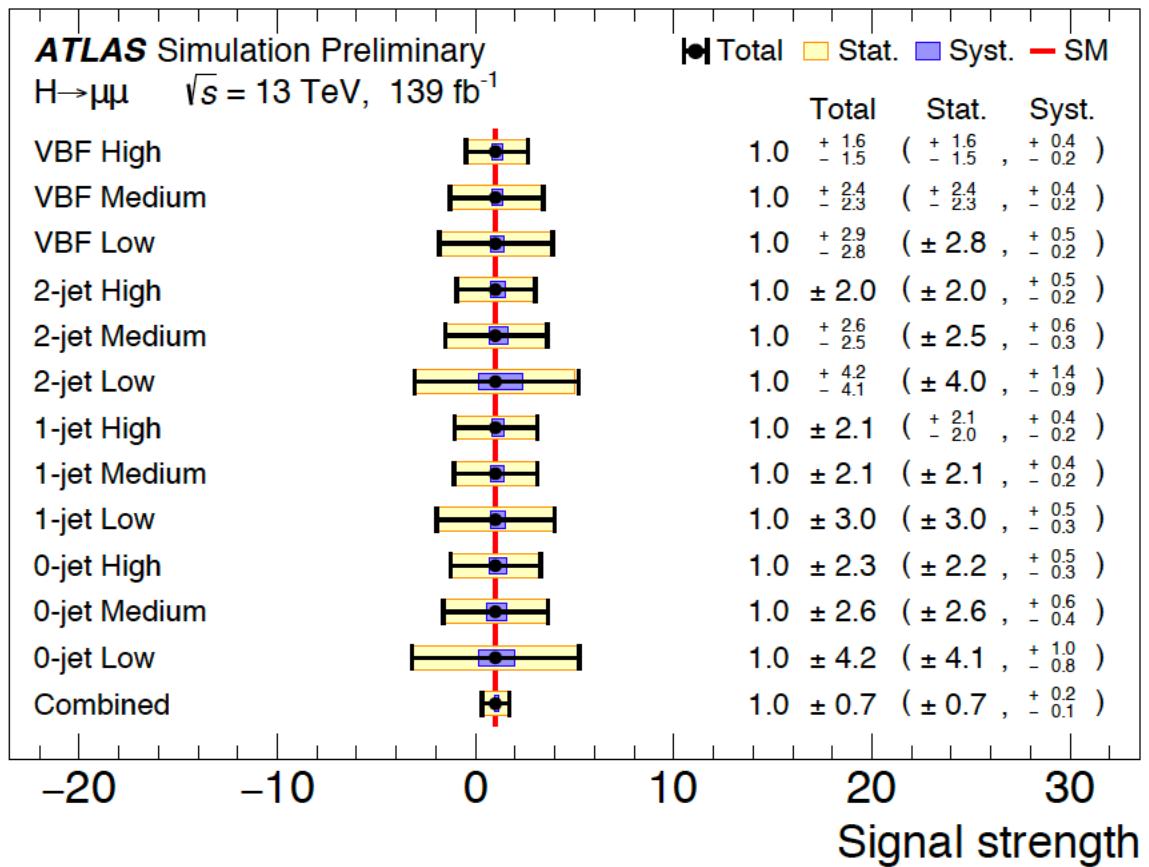
Table 5: Number of events observed in the $m_{\mu\mu} = 120\text{--}130\,\text{GeV}$ window in data, the number of signal events expected in the SM (S_{SM}), and events from signal (S) and background (B) as derived from the combined fit. In addition the observed number of signal events over square root of background events (S/\sqrt{B}) and the signal-to-background ratio (S/B) in % for each of the twelve BDT categories described in the text are displayed.

Category	Data	S_{SM}	S	B	S/\sqrt{B}	S/B [%]
VBF High	40	4.5	2.3	34	0.39	6.6
VBF Medium	109	5.5	2.8	100	0.28	2.8
VBF Low	450	9.6	4.9	420	0.24	1.2
2-jet High	3400	38	19	3440	0.33	0.6
2-jet Medium	13938	70	35	13910	0.30	0.3
2-jet Low	40747	75	38	40860	0.19	0.1
1-jet High	2885	32	16	2830	0.31	0.6
1-jet Medium	24919	107	54	24890	0.35	0.2
1-jet Low	77482	134	68	77670	0.24	0.1
0-jet High	24777	85	43	24740	0.27	0.2
0-jet Medium	85281	155	79	85000	0.27	0.1
0-jet Low	180478	144	73	180000	0.17	<0.1

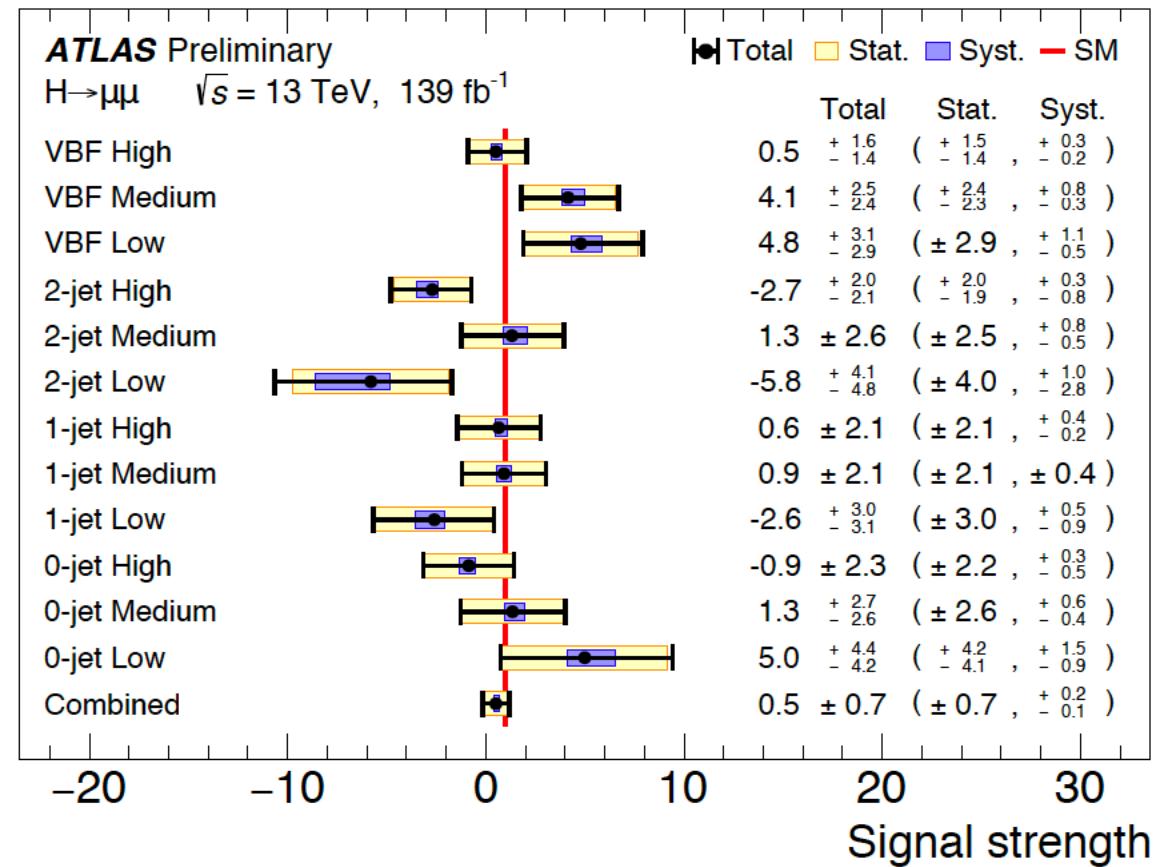
$H \rightarrow \mu\mu$: Composition of SRs



$H \rightarrow \mu\mu$: Results per region



Expected



Observed