Searching for $H \to b\bar{b}$ decays at ATLAS

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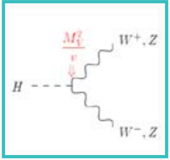
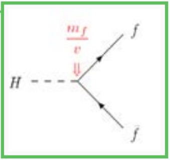
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \not{D} \psi + h.c.$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

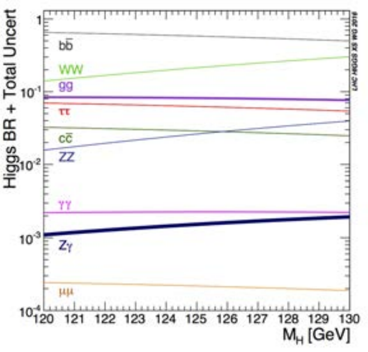


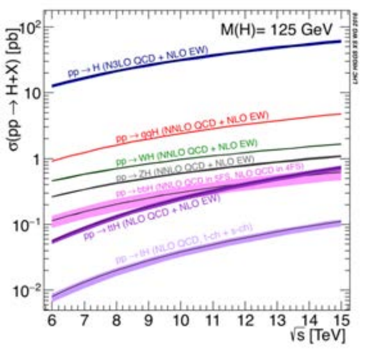


- In the SM, the Higgs mechanism provides masses to bosons and fermions
- Higgs discovery in 2012
  - ⇒ exploration of a whole new sector in the lagrangian !
- Obviously a major goal of the LHC programme

In the SM, all predictions fixed once Higgs mass is known

- Mass known at 2 per-mille level ! $m_H = 125.09 \pm 0.24\ \mathrm{GeV}$
- Very rich phenomenology at 125 GeV



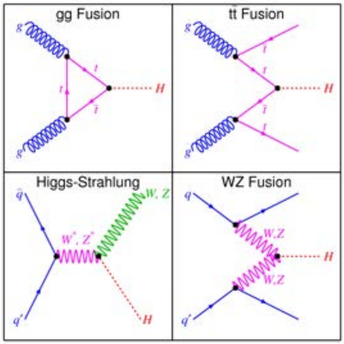


Consequence

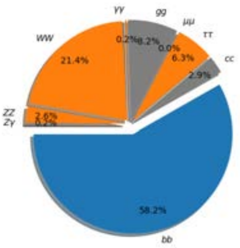
- Any deviation in couplings, spin/CP properties, differential distributions
- Would be a sign of new physics

$H \rightarrow bb$

- Important search on its own (coupling to b quark)
- Largest BR: $\sim 58\%$
- Drives the total width, thus measurements of absolute couplings
- Limits the amount of BSM decays allowed



Observed decays: $\sim 31\%$



Dominant decay: $\sim 58\%$

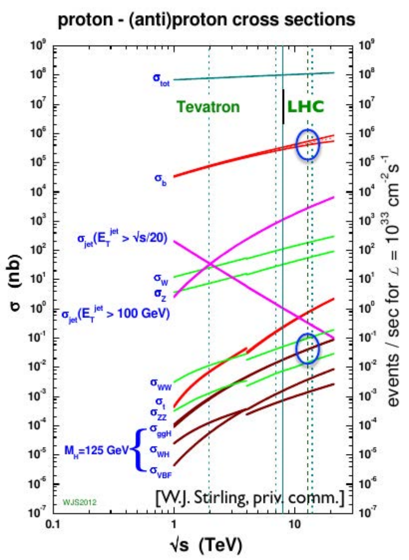
Where to look

ggF Need to go to highly boosted regime (CMS analysis)

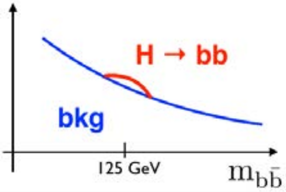
VBF Analysis "à la $H\gamma\gamma$". Also exploits VBF+γ topology

VH Most sensitive channel

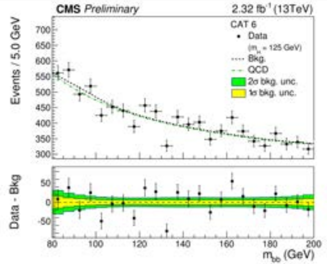
ttH Also important because of *ttH* production (direct coupling to top quark)



Very large production of *b*-jets at the LHC



- Inclusive production (2 *b*-jets in final state) overwhelmed by bkgs by many orders of magnitude
- Signatures of associated productions help reducing the bkgs
- But although S/B can be much better, it is never very large

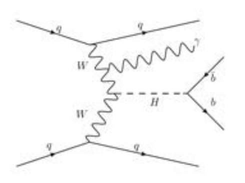


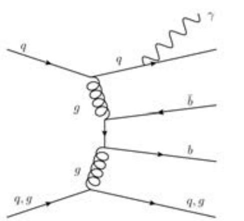
A difficult channel

- Like $H\gamma\gamma$, with poorer resolution
- Not so high-p_{T} jets, not so large multiplicity
- Difficult to even trigger !
- Only public analysis at 13 TeV: CMS (2.3 fb^{-1}). Upper limit 3.4×SM
- ATLAS: result in the VBF+γ topology

VBF+γ channel

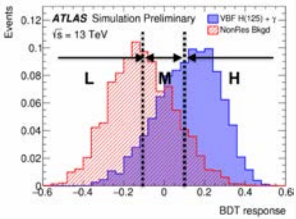
- Rare production (α_{QED} compared to VBF)
- Great at triggering and suppressing background
- Even more than you think: destructive interference

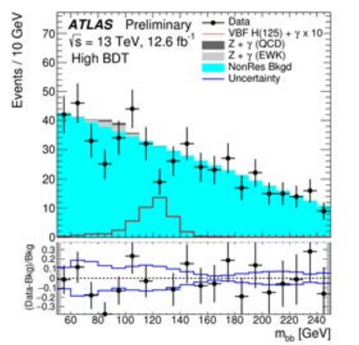




First analysis for ICHEP 2016

- ATLAS-CONF-2016-063 with 12.6 fb^{-1} of 13 TeV data
- BDT to create 3 categories, then fit m_{bb} in each of them
- Zbb as first signal to look for





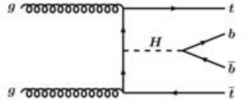
Results

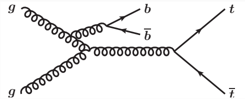
- Still rather low sensitivity
- Hugely dominated by data stat ⇒ hope for large datasets

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

$t\bar{t}H(bb)$ channel

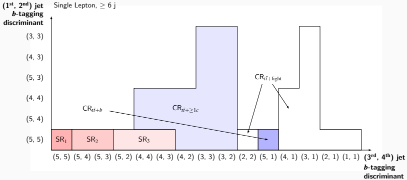
- Lower production (but not much lower) than $VH(bb)$
- Very busy topologies
- Combinatorics

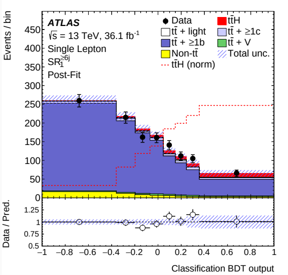




Analysis of 13 TeV data Phys. Rev. D 97 (2018) 072016

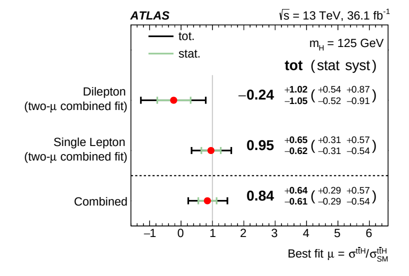
- Semi-leptonic and dileptonic $t\bar{t}$ decays
- Many jets and b-jets in final state
- Use of powerful ML techniques:
  - Reconstruction BDT to resolve the combinatorics: best matching of jets to W, top, Higgs
  - MEM and likelihood discriminant as intermediate variables
  - Final classification BDT to separate $t\bar{t}H$ from backgrounds
- Use of b-tagging distribution also very important
- Simultaneous fit of 9 SR and 10 CR, including a category with boosted Higgs

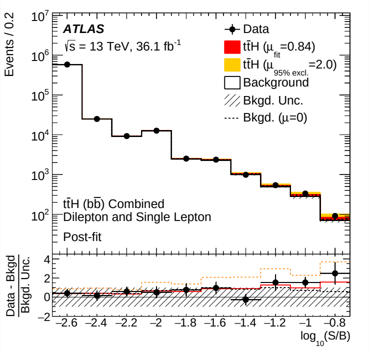




Results

- Compatible results between the single- and di-lepton channels
- Sensitivity 1.4σ (1.6σ exp)
  - Corresponds to a limit of 2.0$\times$SM
- Extreme sensitivity to $t\bar{t}+b\bar{b}$ modelling
- Also quite sensitive to b-tagging and jet energy scale

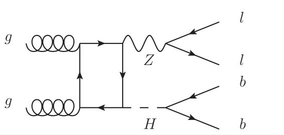


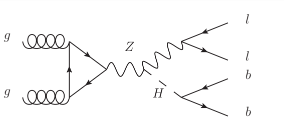


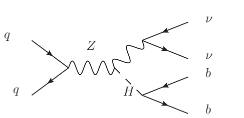
Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modeling	+0.46	−0.46
Background-model stat. unc.	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modeling	+0.22	−0.05
$t\bar{t}+\geq 1c$ modeling	+0.09	−0.11
JVT, pileup modeling	+0.03	−0.05
Other background modeling	+0.08	−0.08
$t\bar{t}$ + light modeling	+0.06	−0.03
Luminosity	+0.03	−0.02
Light lepton (e,μ) id., isolation, trigger	+0.03	−0.04
Total systematic uncertainty	+0.57	−0.54
$t\bar{t}+\geq 1b$ normalization	+0.09	−0.10
$t\bar{t}+\geq 1c$ normalization	+0.02	−0.03
Intrinsic statistical uncertainty	+0.21	−0.20
Total statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61

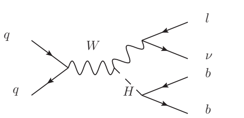
Processes

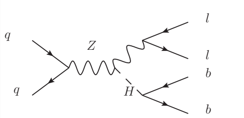
- *ZH* and *WH*
  - Leptonic decays for bkg rejection and trigger
  - 3 channels: 0, 1, 2 (charged) leptons
- *ZH* has *gg* induced diagrams
  - 10% of cross-section
  - p_{T} spectrum peaking around 140 GeV









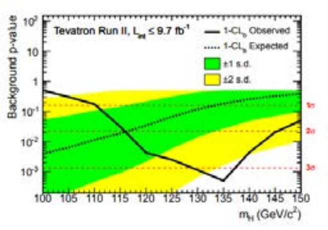


Previous results

Tevatron legacy: 3.1σ global, 2.8σ at 125 GeV (1.5 exp.)

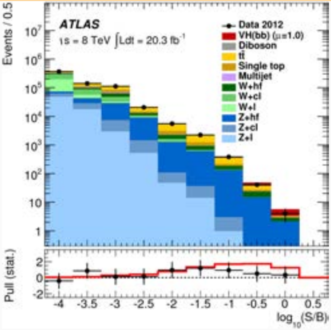
ATLAS and CMS Run 1: 1.4σ (2.6) / 2.1σ (2.5)

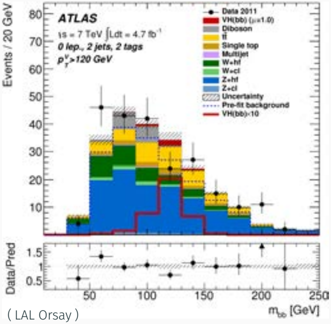
LHC combination: 2.6σ (3.7)

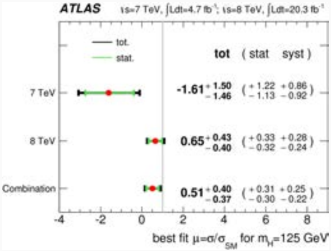


Final Run 1 analysis

- Result of major undertaking
- Highly optimized analysis, to squeeze as much sensitivity as possible (2.6σ exp)
- Introduction of BDTs, use of pseudo-continuous tagging
- Price: high complexity. 38 regions in MVA analysis, 92 regions in m_{bb} analysis (and almost 600 bins fitted)

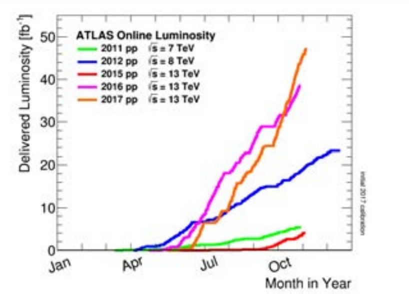






Machine and Physics

- Run 1: $\sim$ 5 + 20 fb^{-1} @ 7 and 8 TeV/ Run 2: 36 fb^{-1}
  - But higher pileup
- $\sqrt{s} = 13$ TeV: higher cross-section $\sim \times 2$
- Backgrounds increase as well: Z/W+jets $\times 1.7$, but $t\bar{t}$ $\times 3.3$



Towards Run 2 Results

General philosophy: Make the analysis simpler and more robust

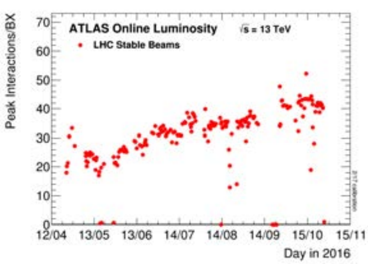
- Sacrifice little bit of sensitivity when it simplifies the analysis
- Keep BDTs, but remove difficult regions, and simplify the use of b-tagging
- Major item: background modelling and systematics

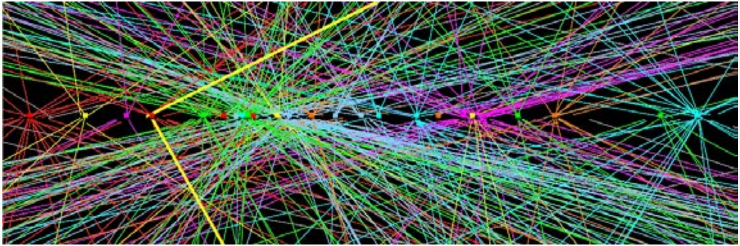
$\Rightarrow$ more solid analysis, larger integrated lumi: key to $3\,\sigma$?

- First result ICHEP 2016: ATLAS-CONF-2016-091
  - Expected sensitivity 1.9σ

Harsh conditions !

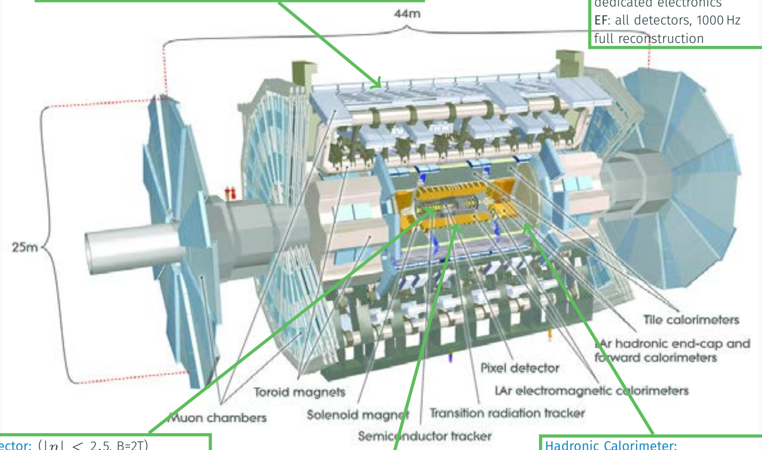
- Up to $\sim$ 40 PU interactions per event (routinely up to 60 in 2017...)
- Lot of work on reconstruction algorithms in ATLAS to reduce their PU dependence
- Especially jet reconstruction and b-tagging





Muon Spectrometer: ($|\eta| < 2.7$)
Air toroid with drift chambers,
Provides μ trigger and momentum measurement,
Resolution $< 10\%$ up to $p \sim 1\,\mathrm{TeV}$.

Trigger System:
3 levels
L1: calo and muons, 100 kHz
dedicated electronics
EF: all detectors, 1000 Hz
full reconstruction



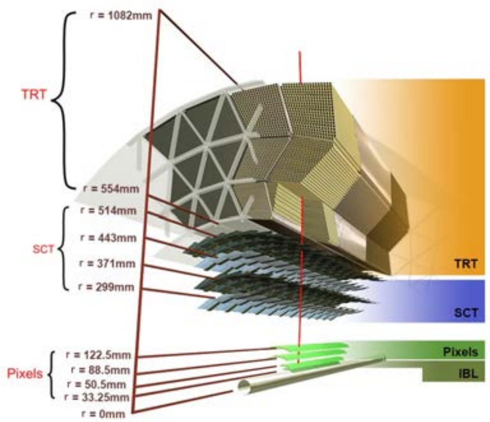
Inner Detector: ($|\eta| < 2.5$, B=2T)
Si Pixels, SCT, TRT
Precision tracking,
Vertex reconstruction,
e/π separation
$\sigma/p_T \sim 3.8\,10^{-4} p_T \oplus 0.015$

EM Calorimeter: ($|\eta| < 3.2$)
Pb-LAr, accordion structure
Provides trigger on e/γ,
Identification and measurement
$\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$

Hadronic Calorimeter:
Scint/Fe tiles in barrel ($|\eta| < 1.7$)
W/Cu-LAr in endcaps ($|\eta| < 4.9$)
Provides jet trigger and energy measurement,
$\sigma/E \sim 50\%/\sqrt{E} \oplus 3\%$
Hermetic coverage for MET

ATLAS Inner detector

- Made of 3 sub-detectors: Silicon Pixel, Silicon Strip and TRT
- New innermost layer IBL installed during LS1
  - Comes with a smaller, thinner beam pipe: $R = 3.3\,\text{cm}$
  - Smaller pixel size ($50 \times 250\,\mu\text{m}$)
  - More radiation hard
- b-tagging in general and $H(bb)$ in particular one of the main motivations for the upgrade !

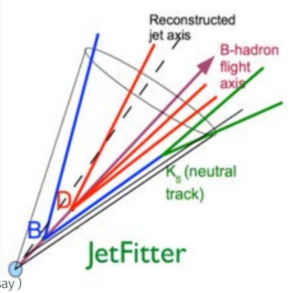


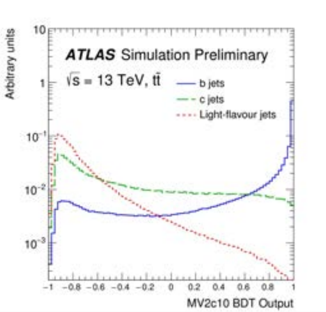
b-tagging

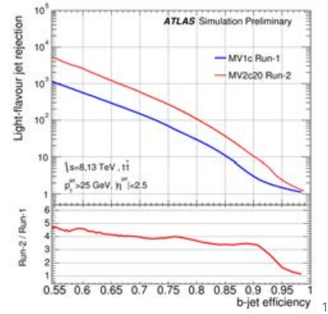
- Algorithms to identify jets from *b* hadrons
- Use track impact parameters, and reconstruction of secondary vertices

Run 2 performance

- Typical performance: 70%/8.2%/0.3% *b*/*c*/light efficiency
- Large improvement compared to Run 1, esp. on *c*-jet rejection
  - Tracking optimized for high-PU environments
  - Better algorithms + new IBL
- Makes it easier to use only events with 2 good *b*-tags



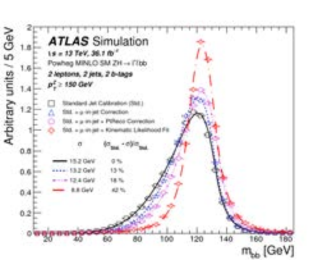




Mass resolution improvements

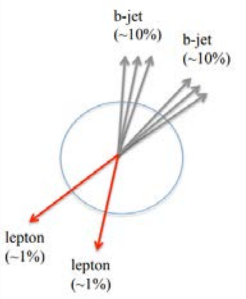
We have a pair of b-jets

- Add muons in the vicinity (semi-lep. decays)
- Simple average jet p_{T} correction. Accounts for neutrinos, and interplay of resolution and p_{T} spectrum effects.
- Improvement $\sim$ 18%



Kinematic Fit

- 2 leptons: final state fully reconstructed
- High resolution on leptons
- Constrain jet kinematics better: $\sum p_{\mathrm{T}}(\ell) = p_{\mathrm{T}}(bb)$ modulo intrinsic k_{T}
- Improvement $\sim$ 40%



Z+hf, W+hf

- Same final state as signal
- non-peaking
- Sherpa 2.2.1

Diboson WZ, ZZ

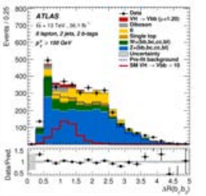
- Peaking at lower mass than the signal
- Larger cross-section
- Softer $p_{\mathrm{T}}(V)$ spectrum
- Sherpa 2.2.1

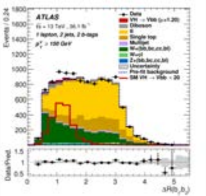
$t\bar{t}$, single-top

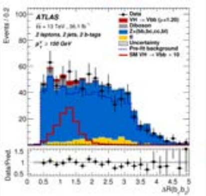
- 2 lepton: same final state as signal
- 0 and 1 leptons: additional jets, and/or missing leptons
- Powheg+Pythia

Multijet

- Very large cross-section and high rejection factors
- Channel-dependent
- Data-driven





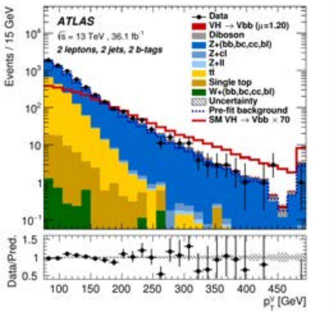


Conclusions

- m_{bb}, $\Delta R(b,b)$ very powerful variables
- Better S/B at higher $p_{\mathrm{T}}(V)$
- S/B depends on number of jets in the event
- Measurement of diboson process excellent validation of the analysis

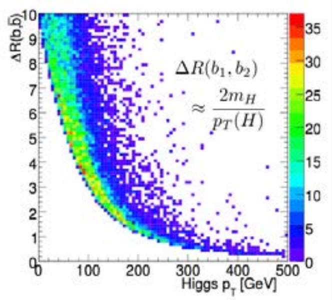
Improving S/B

- Much harder spectrum for signal than bkgs
- Going to high-p_{T} improves S/B
- Use it for event classification: $75 < p_{\mathrm{T}}(V) < 150$ GeV, $p_{\mathrm{T}}(V) > 150$ GeV
- Add it in our MVAs as well
- Need large bkg statistics in tails of distributions !



Topology

- $H \to b\bar{b}$ is a simple 2-body decay
- At high p_{T}, can cut hard on $\Delta R(b, b)$ with very high signal efficiency
- Helps reducing backgrounds significantly
  - Most prominently $t\bar{t}$



Z selection

- MET trigger
- MET>150 GeV
- Veto leptons p_{T}>7 GeV

Higgs candidate

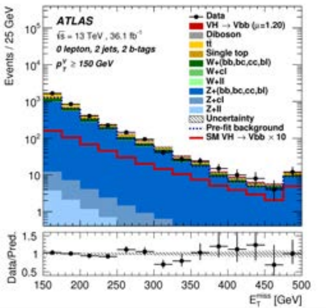
- 2 *b*-tagged jets. Leading p_{T}>45 GeV
- 1 additional jet max

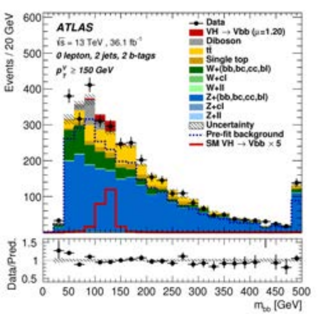
Anti-QCD

- Angular cuts

Signal Acceptance

- $\sim$20% of expected signal events are $WH(\tau\nu)$
- acceptance for *ggZH* 70% larger than for *qqZH*
  - Due to harder $p_{\mathrm{T}}(V)$ spectrum





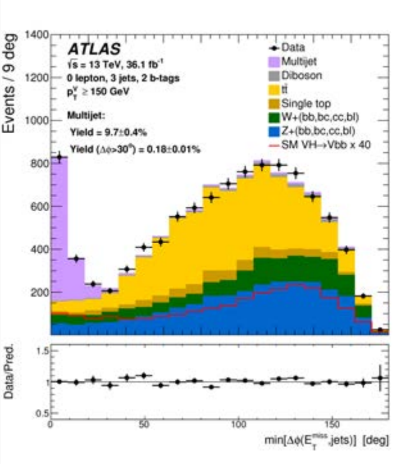
Multijet events

- Typically arise from jets with large fluctuations in their interaction
- MET aligned with jet
- Cuts on $\min(\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets}))$, $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, bb)$, $\Delta\phi(b1, b2)$ extremely efficient

$\Rightarrow$ Negligible remaining multijet contribution

Non-collisional backgrounds

- Usual backgrounds for hadronic final states
- Negligible when requiring 2 b-tags



W selection

- Single-electron or MET trigger
- Well identified, isolated electron (>27 GeV) or muon (>25 GeV)
- Veto additional leptons p_T>7 GeV
- $p_T(W) > 150$ GeV

Higgs candidate

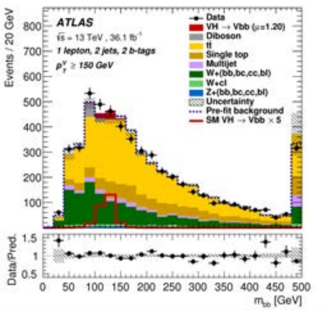
- 2 b-tagged jets. Leading p_T>45 GeV
- 1 additional jet max

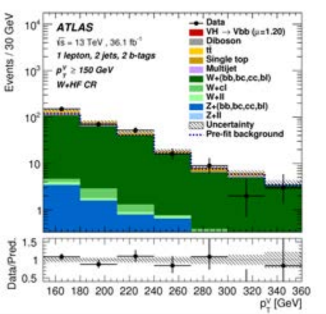
Anti-QCD

- MET>30 GeV in electron channel

W+hf control region

- $m_{bb} < 75$ GeV and $m_{top} > 225$ GeV
- >75% pure



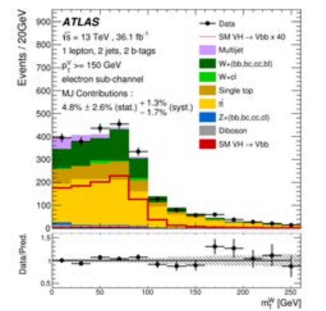


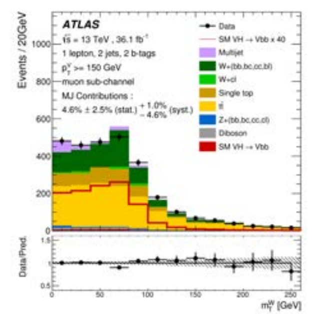
Multijet events

- From semi-lep decays, or from hadrons (electron channel)
- Reduced by tightening the lepton isolation and ID criteria
- Isolation tuned for the analysis (need tight isolation at high-p_{T})

Multijet estimation

- Separate in electron and muon events
- Templates from inverted isolation
- Corrected for bias in kinematics
- Normalization from fit to $m_T(W)$





Z selection

- Single-lepton triggers
- 2 electrons or muons. Leading p_{T}>27 GeV, sub-leading p_{T}>7 GeV
- Z mass: $81 < m_{\ell\ell} < 101$ GeV
- $75 < p_{\mathrm{T}}(Z) < 150$ GeV, or $p_{\mathrm{T}}(Z) > 150$ GeV

Higgs candidate

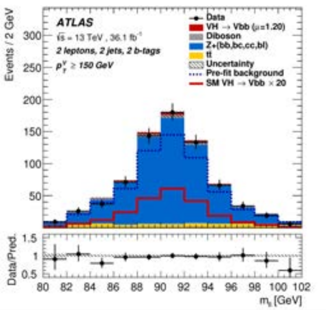
- 2 b-tagged jets. Leading p_{T}>45 GeV
- 0, or ≥ 1 additional jets

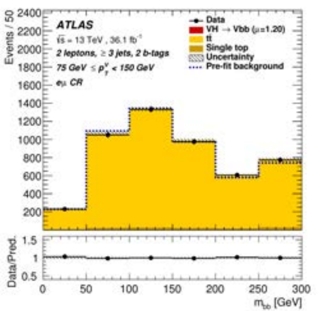
Top $e\mu$ control region

- Opposite-flavour events
- 99% pure

Signal Acceptance

- acceptance for $ggZH$ twice larger than for $qqZH$
  - Due to harder $p_{\mathrm{T}}(V)$ spectrum





MVA setup

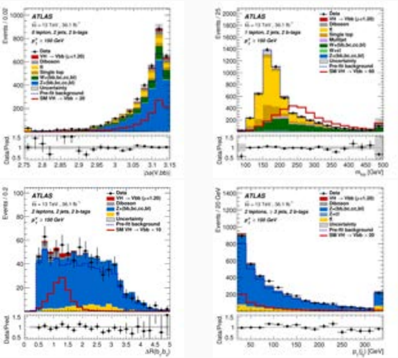
- Pretty standard BDT analysis
- Input variables and hyper-parameters tuned to yield best sensitivity

Variables

- Kinematic variables, some specific to 3-jet regions
- m_{bb}, $\Delta R(b, b)$ and $p_{\mathrm{T}}(V)$ most important ones
- Others depend on channel, e.g $m_{\ell\ell}$ in 2-lepton

Sensitivity

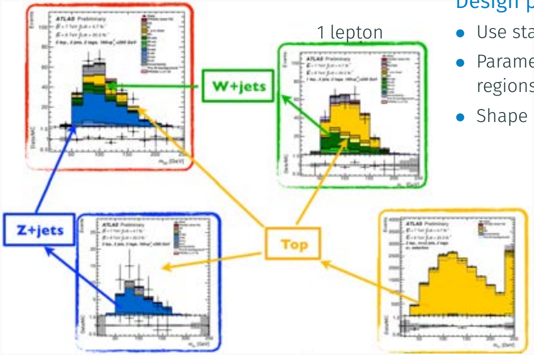
- Typically S/B from few % to few tens of % in high sensitivity bins



Philosophy

- Large backgrounds with many differences
- Bkg composition varies significantly over a large phase space
- Want to constrain modelling of bkg from data
  - Use as many regions as possible
- Much easier when cuts and phase space are similar among the channels
- Requires delicate understanding of the extrapolation from one region to another

0 lepton



2 leptons

e-μ region

Design principles

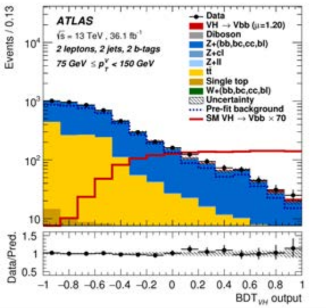
- Use state-of-the-art MC generators
- Parametrize extrapolation uncertainties across regions as uncertainties on ratios of yields
- Shape uncertainties on BDTs

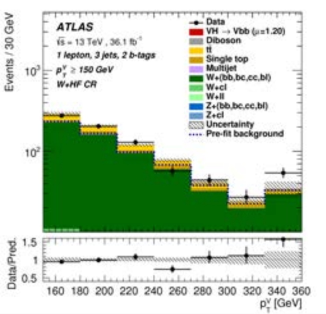
Principle

- Rely on MEPS@NLO (multi-jet merging at NLO) with up to 2 extra jets
- 2 lepton low $p_{\mathrm{T}}(V)$ can constrain Z normalizations, shapes
- 1 lepton Whf CR constrains W norm.

⇒ Normalization factors ~ 1.25

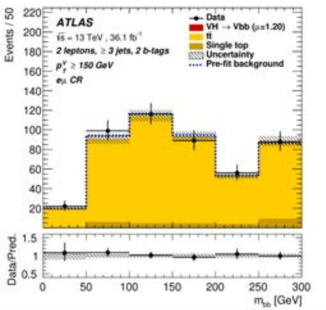
- Extrapolations to 0-lepton or 1-lepton SR needed
- Uncertainties on flavour composition
- BDT shapes: through m_{bb} and $p_{\mathrm{T}}(V)$ variations

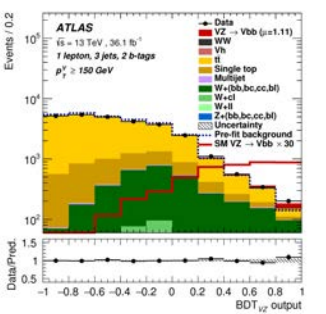




Principle

- 2 lepton vs 0/1 lepton: different phase space
- 2 lepton $e\mu$ and 0/1 lepton 3-jet regions very pure
- Normalization factors: $\sim$ 0.9 for 0/1 lepton, $\sim$ 1.0 for 2-lepton
- Uncertainties needed for extrapolation to 0/1 lepton 2-jet regions
- BDT shapes: through m_{bb} and $p_{\mathrm{T}}(V)$ variations





Multijet in 1 lepton

- Large shape and norm. effects on the data-driven estimate

Signal and Diboson

- No contraints from data
- Follow standard recipes for systematics
- Signal: Separate systematics on production (correlated with other channels in future Higgs combinations) from acceptance effects

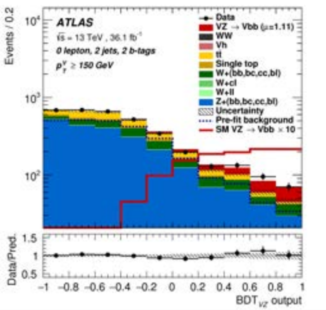
Signal	
Cross-section (scale)	0.7% (qq), 27% (gg)
Cross-section (PDF)	1.9% ($qq \to WH$), 1.6% ($qq \to ZH$), 5% (gg)
Branching ratio	1.7 %
Acceptance from scale variations (var.)	2.5 – 8.8% (Stewart–Tackmann jet binning method)
Acceptance from PS/UE var. for 2 or more jets	10 – 14% (depending on lepton channel)
Acceptance from PS/UE var. for 3 jets	13%
Acceptance from PDF+α_S var.	0.5 – 1.3%
m_{bb}, p_T^V, from scale var.	S
m_{bb}, p_T^V, from PS/UE var.	S
m_{bb}, p_T^V, from PDF+α_S var.	S
p_T^V from NLO EW correction	S

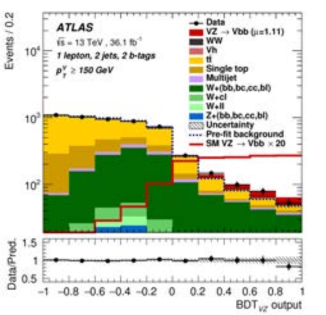
A must-have for *VHbb*

- Train the BDTs to look for $WZ + ZZ$ instead of VH
- Done before looking at VH
- Robust validation of background model and associated uncertainties
- Critical to convince ourselves we are ready to unblind !

Analysis strategy

- One main likelihood fit
- BDT in the 8 SR
- m_{bb} in the 4 top $e\mu$ CR
- Normalization in the 2 W+hf CR
- Systematics parametrized as nuisance parameters

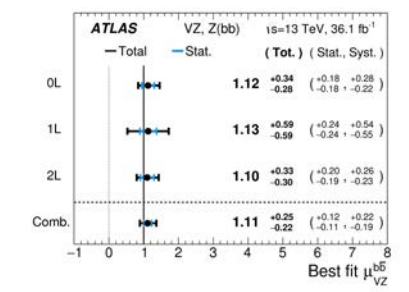


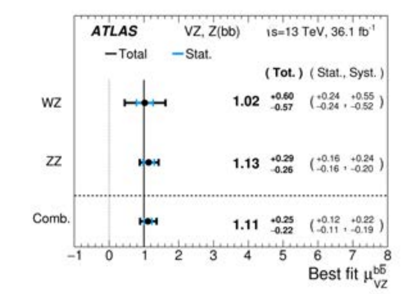


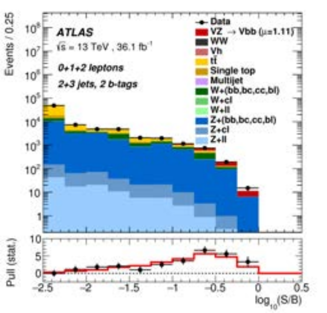
Results

- Clear observation: 5.8σ (5.3 exp.)
- Agreement with SM
- Excellent agreement between channels
- Much better sensitivity to *ZZ* than to *WZ*: combinatorics ; impact of low $p_{\mathrm{T}}(V)$ region

$\Rightarrow$ Ready to unblind *VH* !

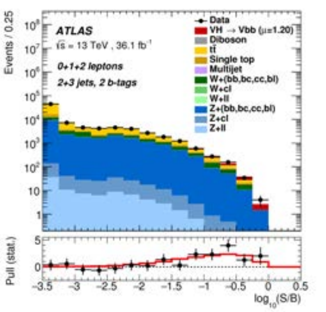


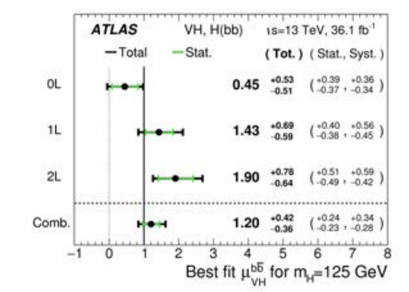


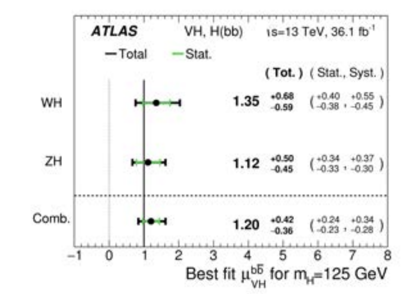


We have it !

- Evidence for *bb* decay at 3.5σ (3.0 exp.)
- Dominated by systematics
- Channels compatible at 10% level
- 2.4σ for *WH*, 2.6σ for *ZH*: *VHbb* most sensitive channel for *VH* production
- As cross-sections:
  - $\sigma(WH) \times \mathrm{B}(Hbb) = 1.08^{+0.54}_{-0.47}$ pb
  - $\sigma(ZH) \times \mathrm{B}(Hbb) = 0.57^{+0.26}_{-0.23}$ pb





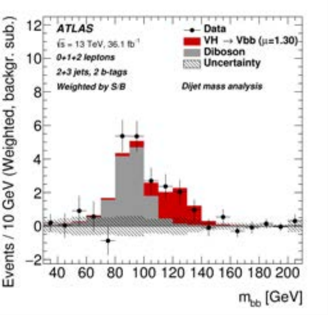


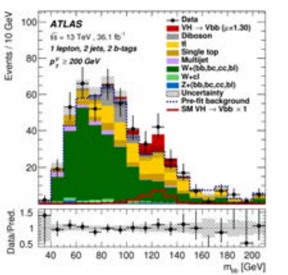
m_{bb} fit

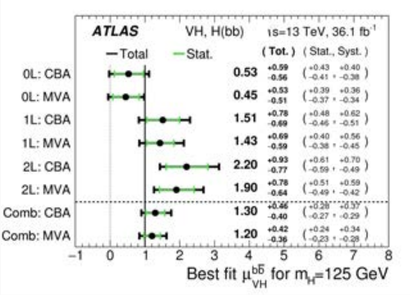
- Important cross-check to test robustness of result
- Cut $p_T(V) > 150$ GeV into $150 - 200$ and > 200 GeV
- Add simple cuts on: $\Delta R(b,b)$, $m_T(W)$ (1 lepton), E_T^{miss} significance (2 lepton)
- Then fit m_{bb} !

Results

- Evidence at 3.5σ (2.8σ exp.)
- Consistent with MVA in all channels







VHbb RESULTS: SYSTEMATICS

What limits us on the road to 5σ ?

b-tagging both *b* and *c* jet tagging corrections

- Will improve with time

Background modelling Z+hf, W+hf, $t\bar{t}$

- Better generators ?
- Understand better differences between generators
- Reduce uncertainties through specific SM measurements
- More data-driven approaches

Signal modelling dominated by PS/hadronization

- Needs better understanding of our MCs

MC stats never-ending race between data stat and MC stat

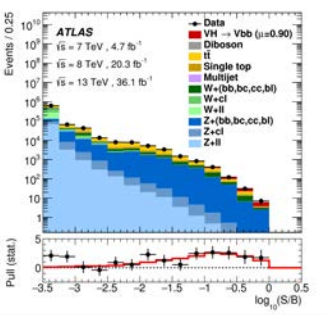
- Improve on MC filters
- Not easy in all cases, e.g $t\bar{t}$ phase space in 0/1-lepton
- Improve on MC generation speed

Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
E_T^{miss}		0.03
Leptons		0.01
b-tagging	*b*-jets	0.09
	c-jets	0.04
	light jets	0.04
	extrapolation	0.01
Pile-up		0.01
Luminosity		0.04
Theoretical and modelling uncertainties		
Signal		0.17
Floating normalisations		0.07
Z + jets		0.07
W + jets		0.07
$t\bar{t}$		0.07
Single top quark		0.08
Diboson		0.02
Multijet		0.02
MC statistical		0.13

Combination

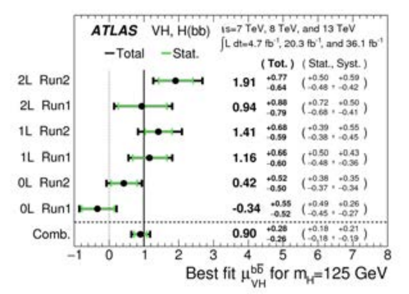
How to correlate systematics ?

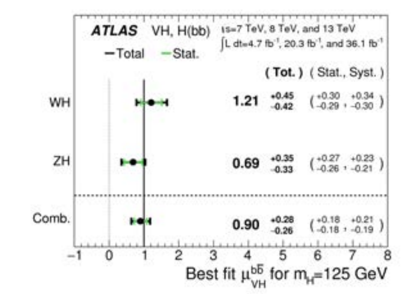
- Difficult to be sure in many cases (e.g *b*-tagging, when new detector / new algo ?)
- Correlate *b*-jet energy scale uncertainty, and Higgs production cross-sections
- Test that other correlations have little impact



Results

- Evidence at 3.6σ (4.0 exp.)
- Compatibility of the 6 measurements: 7%

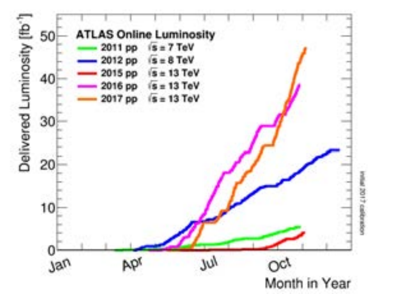




ATLAS EXPERIMENT

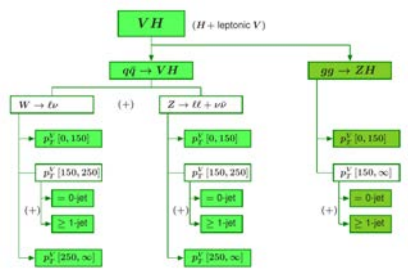
Next step: observation !

- 2017: more stat than 2016 !
- Without systematics, observation would be a no-brainer
- Hard work needed on MC stat generation, background modelling, *b*-tagging calibration



Signal Template Cross-sections (?)

- Standardized definition of fiducial regions for Higgs productions
- Fiducial definitions not too far from what can be achieved with differential measurements
- Allows easy combination of Higgs channels and across experiments
- Allows interpretation in EFT bases
- Goal for $VH(bb)$: $p_{\mathrm{T}}(V)$ measurement

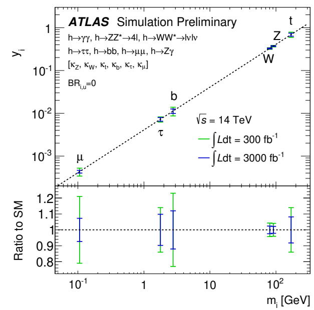


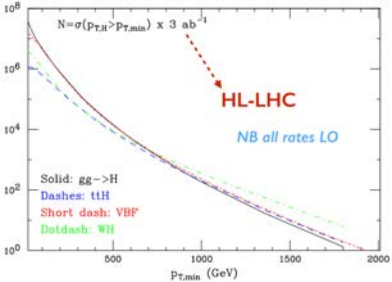
Couplings

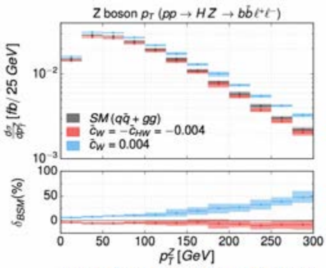
- Projections from ATLAS and CMS
- Coupling to *b*-quarks known in the 5–10% range ?
- Very much dependent on the systematics we can achieve

What for ?

- Deviations from New Physics can be mostly at high-p_T
- *VH* dominates total Higgs x-sec for $p_T(H) > 800$ GeV !
- Decent statistics expected even in this regime

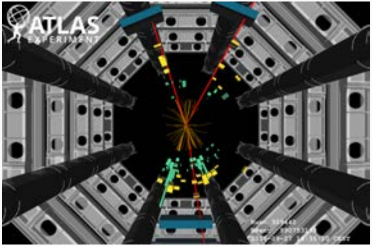


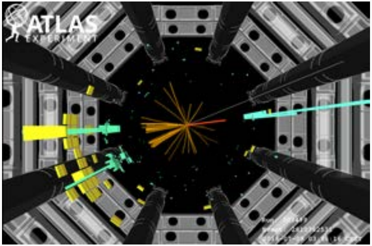




Mimasu, Sanz, Williams, arXiv:1512.02572v

- Evidence for Hbb decay at 3.6σ in ATLAS
  - arXiv:1708.03299
- Similar result by our CMS colleagues
  - arXiv:1709.07497
- Interesting to look in all production modes
  - As evidenced by the nice VBF+γ or $t\bar{t}H(bb)$ results
- Systematically limited in several channels
  - Adding more data will bring diminishing returns
  - Need to reduce systematics
- Next goals: observation and measurements !

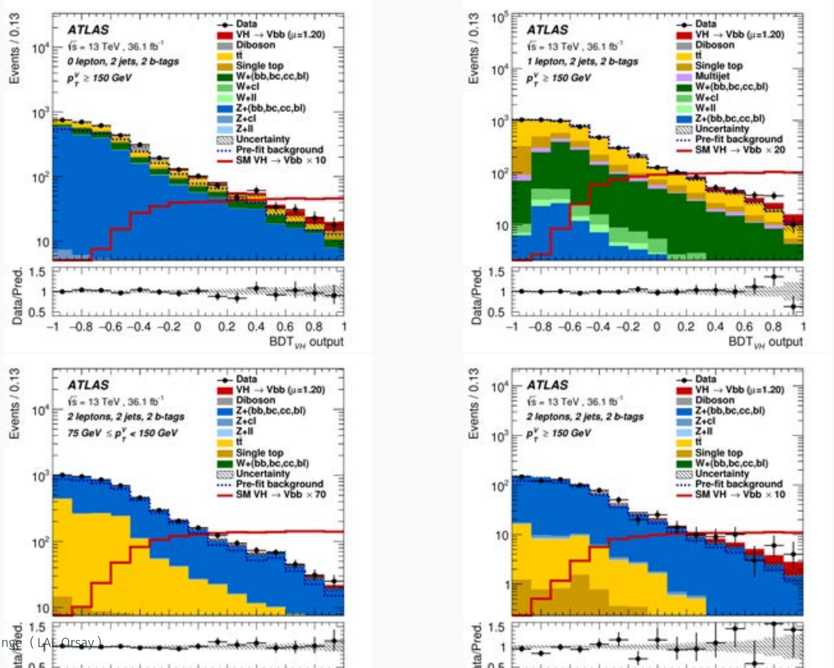




Supplementary Material

Signal regions	0-lepton		1-lepton		2-lepton			
	$p_T^V > 150$ GeV, 2-b-tag		$p_T^V > 150$ GeV, 2-b-tag		75 GeV $< p_T^V <$ 150 GeV, 2-b-tag		$p_T^V > 150$ GeV, 2-b-tag	
Sample	2-jet	3-jet	2-jet	3-jet	2-jet	≥3-jet	2-jet	≥3-jet
$Z + ll$	9.0 ± 5.1	15.5 ± 8.1	< 1	–	9.2 ± 5.4	35 ± 19	1.9 ± 1.1	16.4 ± 9.3
$Z + cl$	21.4 ± 7.7	42 ± 14	2.2 ± 0.1	4.2 ± 0.1	25.3 ± 9.5	105 ± 39	5.3 ± 1.9	46 ± 17
Z + HF	2198 ± 84	3270 ± 170	86.5 ± 6.1	186 ± 13	3449 ± 79	8270 ± 150	651 ± 20	3052 ± 66
$W + ll$	9.8 ± 5.6	17.9 ± 9.9	22 ± 10	47 ± 22	< 1	< 1	< 1	< 1
$W + cl$	19.9 ± 8.8	41 ± 18	70 ± 27	138 ± 53	< 1	< 1	< 1	< 1
W + HF	460 ± 51	1120 ± 120	1280 ± 160	3140 ± 420	3.0 ± 0.4	5.9 ± 0.7	< 1	2.2 ± 0.2
Single top quark	145 ± 22	536 ± 98	830 ± 120	3700 ± 670	53 ± 16	134 ± 46	5.9 ± 1.9	30 ± 10
$t\bar{t}$	463 ± 42	3390 ± 200	2650 ± 170	20640 ± 680	1453 ± 46	4904 ± 91	49.6 ± 2.9	430 ± 22
Diboson	116 ± 26	119 ± 36	79 ± 23	135 ± 47	73 ± 19	149 ± 32	24.4 ± 6.2	87 ± 19
Multi-jet e sub-ch.	–	–	102 ± 66	27 ± 68	–	–	–	–
Multi-jet μ sub-ch.	–	–	133 ± 99	90 ± 130	–	–	–	–
Total bkg.	3443 ± 57	8560 ± 91	5255 ± 80	28110 ± 170	5065 ± 66	13600 ± 110	738 ± 19	3664 ± 56
Signal (fit)	58 ± 17	60 ± 19	63 ± 19	65 ± 21	25.6 ± 7.8	46 ± 15	13.6 ± 4.1	35 ± 11
Data	3520	8634	5307	28168	5113	13640	724	3708

Control regions	1-lepton		2-lepton			
	$p_T^V > 150$ GeV, 2-tag		75 GeV $< p_T^V <$ 150 GeV, 2-tag		$p_T^V > 150$ GeV, 2-tag	
Sample	2-jet	3-jet	2-jet	≥3-jet	2-jet	≥3-jet
$Z + ll$	< 1	< 1	< 1	< 1	< 1	< 1
$Z + cl$	–	< 1	< 1	< 1	< 1	< 1
Z + HF	6.6 ± 0.7	19.3 ± 1.4	2.1 ± 0.2	2.8 ± 0.2	< 1	1.2 ± 0.1
$W + ll$	1.1 ± 0.1	2.9 ± 0.1	–	–	–	–
$W + cl$	2.6 ± 1.1	8.7 ± 3.7	–	–	–	–
W + HF	234 ± 21	594 ± 45	3.0 ± 0.3	2.7 ± 0.3	< 1	< 1
Single top quark	10.3 ± 2.8	40 ± 14	50 ± 15	127 ± 45	5.8 ± 1.8	27.9 ± 9.8
$t\bar{t}$	24.8 ± 7.8	107 ± 29	1437 ± 41	4852 ± 85	48.8 ± 3.8	431 ± 21
Diboson	5.6 ± 1.9	12.1 ± 4.2	–	< 1	–	–
Multi-jet e sub-ch.	8.2 ± 5.3	2.2 ± 5.6	–	–	–	–
Multi-jet μ sub-ch.	6.8 ± 5.1	3.7 ± 5.4	–	–	–	–
Total bkg.	300 ± 16	791 ± 27	1492 ± 37	4985 ± 68	55.2 ± 3.9	461 ± 19
Signal (fit)	< 1	1.2 ± 0.4	< 1	< 1	< 1	< 1
Data	302	790	1489	4967	50	470


ATLAS
√s = 13 TeV, 36.1 fb⁻¹
0 lepton, 2 jets, 2 b-tags
p_T^V ≥ 150 GeV
Data
VH → Vbb (μ=1.20)
Diboson
tt
Single top
W+(bb,bc,cc,bl)
W+cl
W+ll
Z+(bb,bc,cc,bl)
Z+cl
Z+ll
Uncertainty
Pre-fit background
SM VH → Vbb × 10
Events / 0.13
Data/Pred.
BDT_VH output
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
1 lepton, 2 jets, 2 b-tags
p_T^V ≥ 150 GeV
Data
VH → Vbb (μ=1.20)
Diboson
tt
Single top
Multijet
W+(bb,bc,cc,bl)
W+cl
W+ll
Z+(bb,bc,cc,bl)
Uncertainty
Pre-fit background
SM VH → Vbb × 20
Events / 0.13
Data/Pred.
BDT_VH output
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
2 leptons, 2 jets, 2 b-tags
75 GeV ≤ p_T^V < 150 GeV
Data
VH → Vbb (μ=1.20)
Diboson
Z+(bb,bc,cc,bl)
Z+cl
Z+ll
tt
Single top
W+(bb,bc,cc,bl)
Uncertainty
Pre-fit background
SM VH → Vbb × 70
Events / 0.13
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
2 leptons, 2 jets, 2 b-tags
p_T^V ≥ 150 GeV
Data
VH → Vbb (μ=1.20)
Diboson
Z+(bb,bc,cc,bl)
Z+cl
Z+ll
tt
Single top
W+(bb,bc,cc,bl)
Uncertainty
Pre-fit background
SM VH → Vbb × 10
Events / 0.13
Data/Pred.

Z + jets	
$Z+ll$ normalisation	18%
$Z+cl$ normalisation	23%
$Z+bb$ normalisation	Floating (2-jet, 3-jet)
$Z+bc$-to-$Z+bb$ ratio	30 – 40%
$Z+cc$-to-$Z+bb$ ratio	13 – 15%
$Z+bl$-to-$Z+bb$ ratio	20 – 25%
0-to-2 lepton ratio	7%
m_{bb}, p_T^V	S
W + jets	
$W+ll$ normalisation	32%
$W+cl$ normalisation	37%
$W+bb$ normalisation	Floating (2-jet, 3-jet)
$W+bl$-to-$W+bb$ ratio	26% (0-lepton) and 23% (1-lepton)
$W+bc$-to-$W+bb$ ratio	15% (0-lepton) and 30% (1-lepton)
$W+cc$-to-$W+bb$ ratio	10% (0-lepton) and 30% (1-lepton)
0-to-1 lepton ratio	5%
W + HF CR to SR ratio	10% (1-lepton)
m_{bb}, p_T^V	S

$t\bar{t}$ (all are uncorrelated between the 0+1 and 2-lepton channels)	
$t\bar{t}$ normalisation	Floating (0+1 lepton, 2-lepton 2-jet, 2-lepton 3-jet)
0-to-1 lepton ratio	8%
2-to-3-jet ratio	9% (0+1 lepton only)
W + HF CR to SR ratio	25%
m_{bb}, p_T^V	S
Single top quark	
Cross-section	4.6% (s-channel), 4.4% (t-channel), 6.2% (Wt)
Acceptance 2-jet	17% (t-channel), 35% (Wt)
Acceptance 3-jet	20% (t-channel), 41% (Wt)
m_{bb}, p_T^V	S (t-channel, Wt)

ZZ	
Normalisation	20%
0-to-2 lepton ratio	6%
Acceptance from scale variations (var.)	10 – 18% (Stewart–Tackmann jet binning method)
Acceptance from PS/UE var. for 2 or more jets	5.6% (0-lepton), 5.8% (2-lepton)
Acceptance from PS/UE var. for 3 jets	7.3% (0-lepton), 3.1% (2-lepton)
m_{bb}, p_T^V, from scale var.	S (correlated with WZ uncertainties)
m_{bb}, p_T^V, from PS/UE var.	S (correlated with WZ uncertainties)
m_{bb}, from matrix-element var.	S (correlated with WZ uncertainties)
WZ	
Normalisation	26%
0-to-1 lepton ratio	11%
Acceptance from scale var.	13 – 21% (Stewart–Tackmann jet binning method)
Acceptance from PS/UE var. for 2 or more jets	3.9%
Acceptance from PS/UE var. for 3 jets	11%
m_{bb}, p_T^V, from scale var.	S (correlated with ZZ uncertainties)
m_{bb}, p_T^V, from PS/UE var.	S (correlated with ZZ uncertainties)
m_{bb}, from matrix-element var.	S (correlated with ZZ uncertainties)
WW	
Normalisation	25%