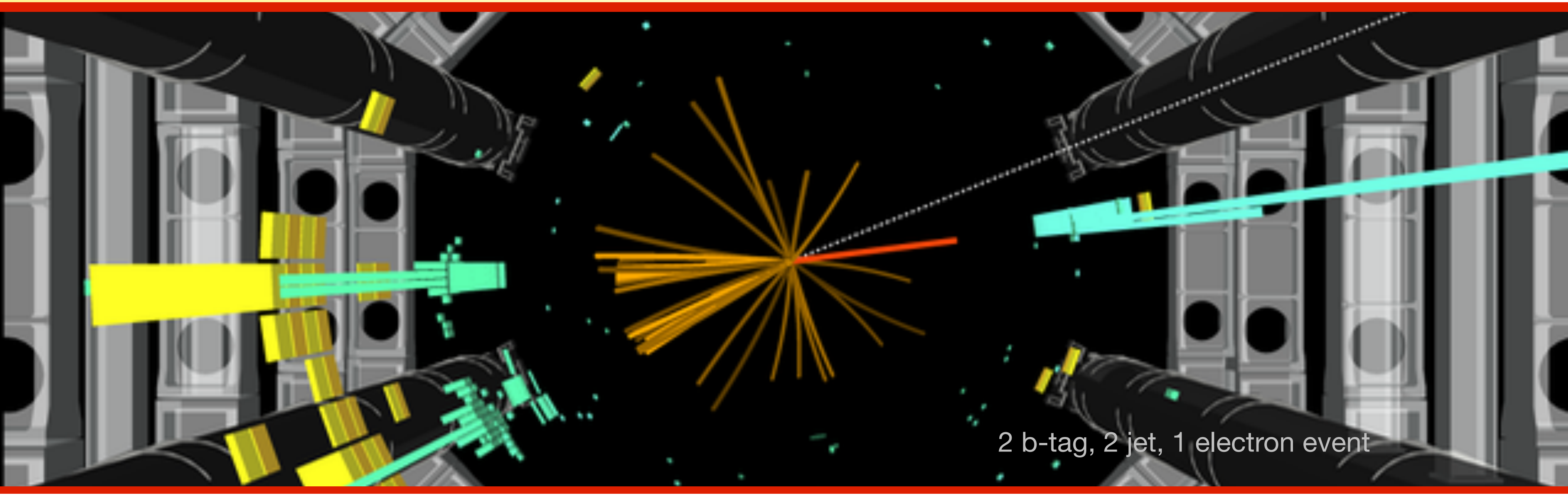
ATLAS results on Higgs decays to $b\bar{b}$ and $\mu\mu$

Aspen 2018
The Particle Frontier
30 March 2018



University of Glasgow

Aidan Robson
on behalf of the ATLAS Collaboration

ATLAS results on Higgs decays to $b\bar{b}$ and μμ

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- Motivation
- VH, H->bb
- ttH, H->bb
- H->μμ
- Prospects

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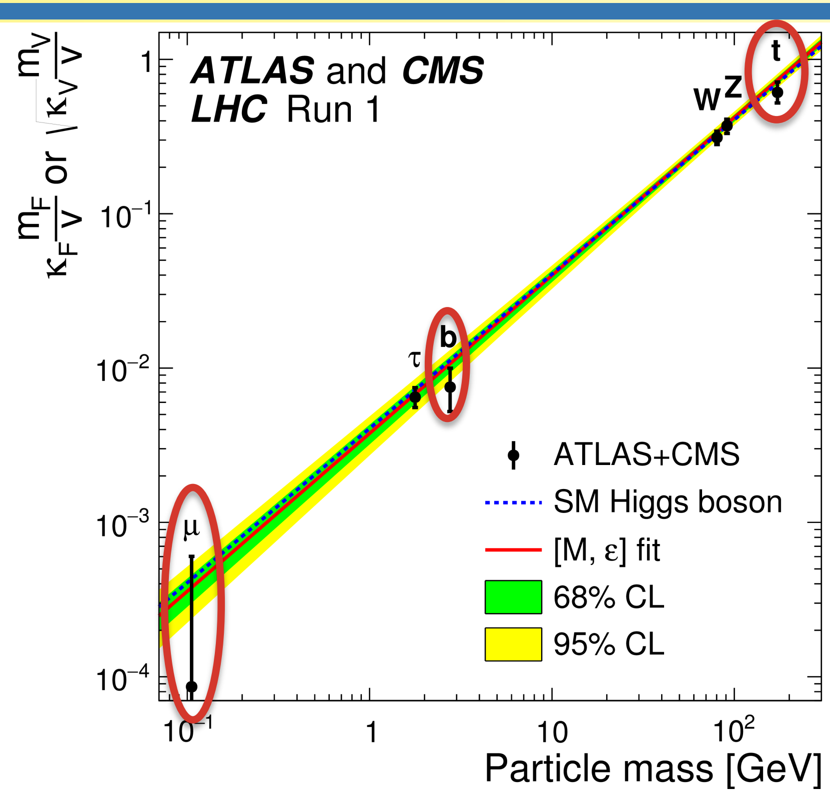
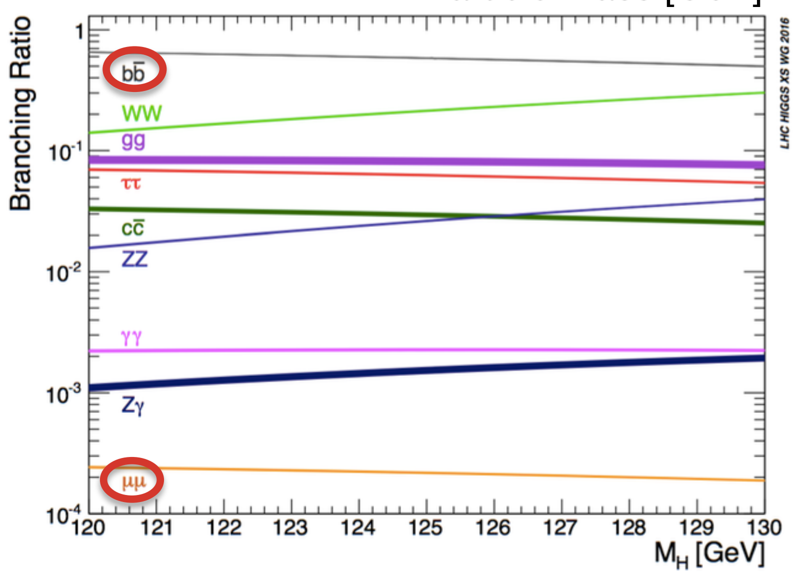
Motivations





- Higgs discovery: bosonic decay modes
- Direct measurement of couplings to 3[rd]-generation fermions more difficult
  - H->bb : an important missing piece
    – largest branching fraction (~58%)
    – direct probe of coupling to quarks
    – drives the uncertainty on the total decay width (and therefore the measurement of absolute couplings)

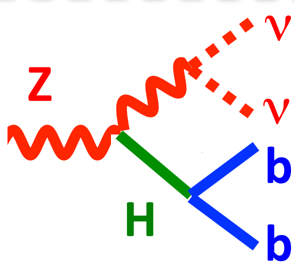
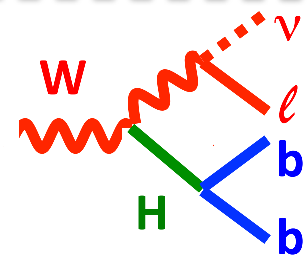
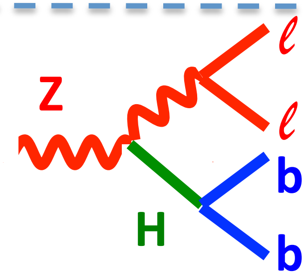
    Run 1 combined ATLAS+CMS:
    H->bb expected 3.7σ, measured 2.6σ
  - ttH : indirect measurement via gluon–gluon fusion production
  - H->ττ : not discussed here;
    5.9σ observation by CMS, Phys. Lett. B 779 (2018) 283
    4.5σ evidence by ATLAS JHEP 04 (2015) 117
- Couplings to 2[nd]-generation fermions much weaker -> test of Yukawa mechanism
  - H->μμ : very low branching fraction (~0.02%); could be enhanced by BSM

VH, H->bb signatures and selection

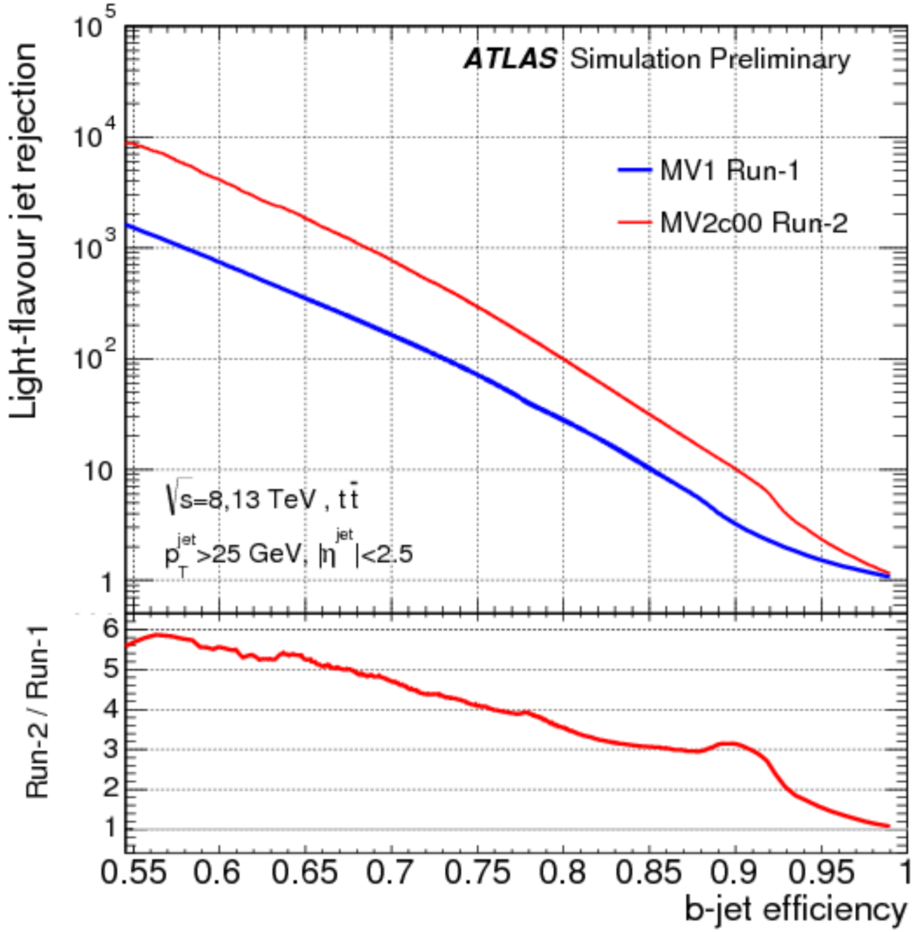
Capture events through 0-, 1-, and 2-charged lepton channels (e/μ)

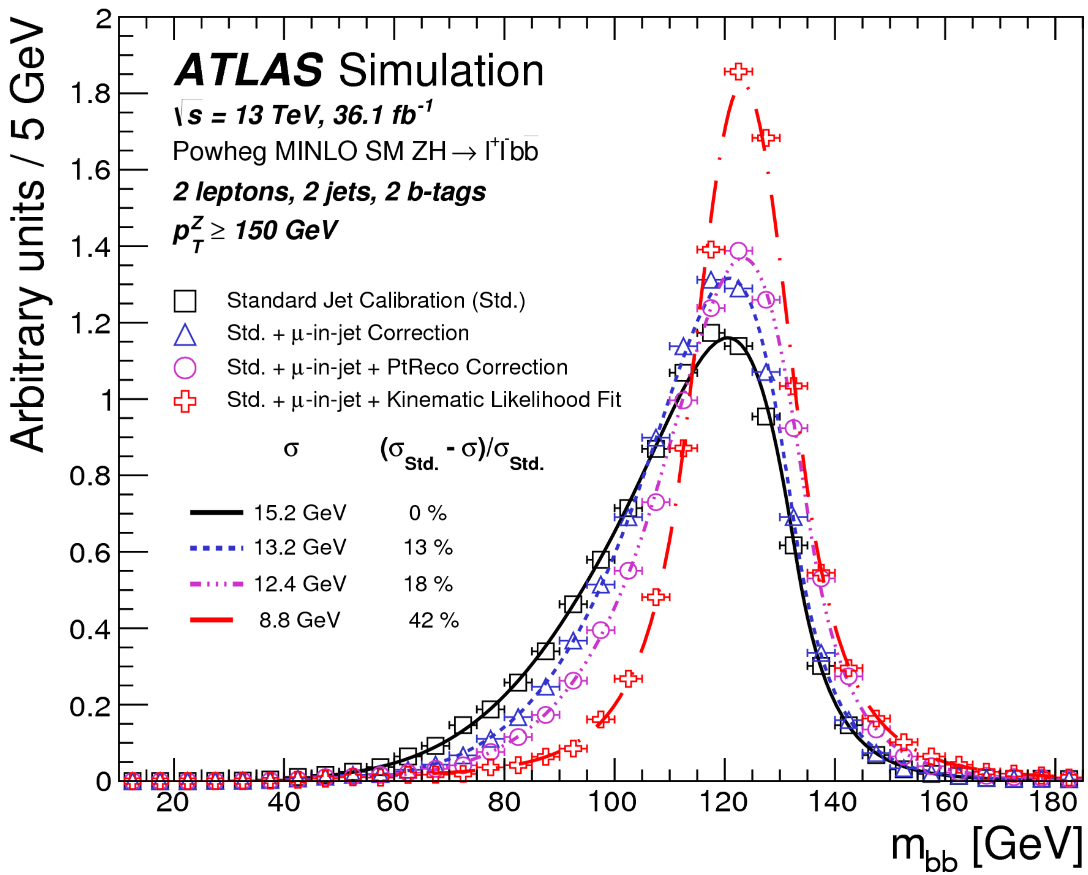
Tag b-jets for H reconstruction

Fit data to determine signal

0-lepton	1-lepton	2-lepton
		
MET > 150 GeV (+ multijet suppression)	p_T (V) > 150 GeV isolated lepton MET > 30 GeV (ele channel)	75<p_T (V)<150 GeV or p_T(V)>150 GeV 81<m(ℓℓ)<101GeV
Exactly 2 or 3 jets		2 or ≥3 jets
2 b-tagged jets with p_T>20 GeV, lead jet > 45 GeV		
Trigger based on single lepton and MET signatures		

Improvements





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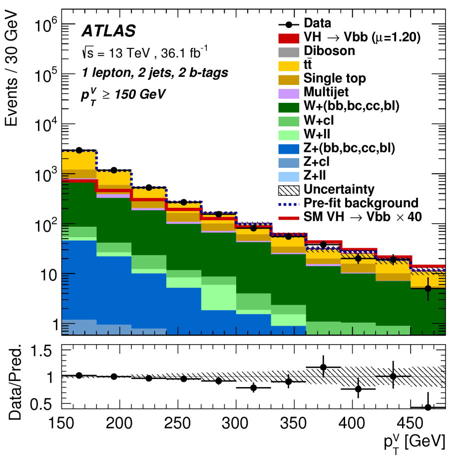
- *b*-tagging:
new innermost pixel layer (IBL) for Run 2
+ updated MVA algorithm
  –> significantly improves efficiency
  and c-jet rejection

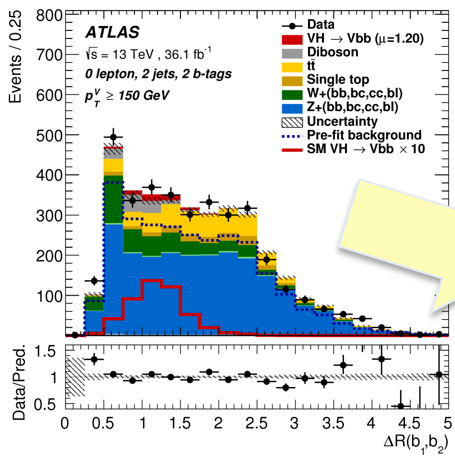
- m_{bb} corrections:
μ-in-jet, b-jet energy response correction, kinematic likelihood fit (2-lep)
–> m_{bb} resolution improved by 18–40%

VH, H->bb multivariate analysis

$p_T(V)$



$\Delta R(b_1,b_2)$



- Event-level variables including m_{bb} used in TMVA to train BDT for each signal channel and analysis region
- Likelihood fit applied across channels/regions to extract signal strength μ and normalisations of main backgrounds
- Shapes and relative normalisations across regions parametrised by nuisance parameters, constrained within allowed systematic uncertainties

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

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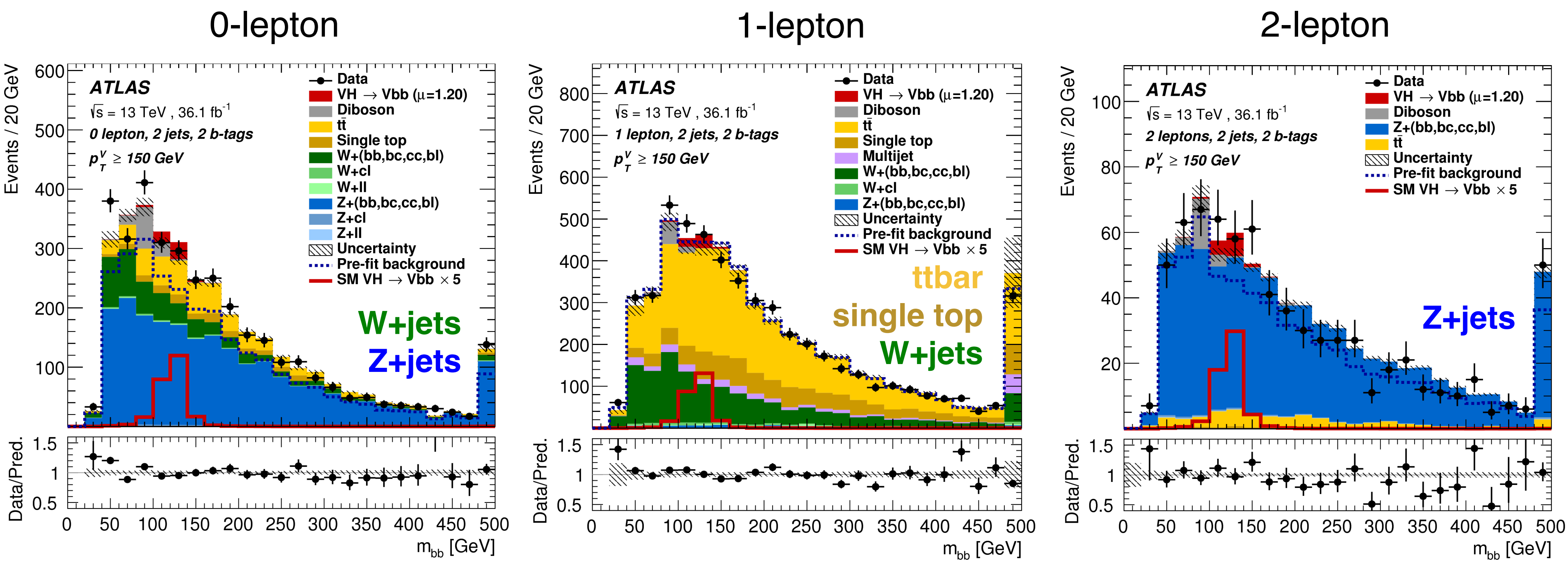
VH, H->bb backgrounds



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- Non-resonant backgrounds from **W+jets**, **Z+jets**, **ttbar**, and **single top**
- **W+jets** / **Z+jets** mainly suppressed by b-jet requirement (except **W**/**Z**+bb)
- **ttbar** mainly suppressed by N_{jet} requirement
- Resonant VZ, Z->bb backgrounds used to validate analysis procedure

VH, H->bb background strategy

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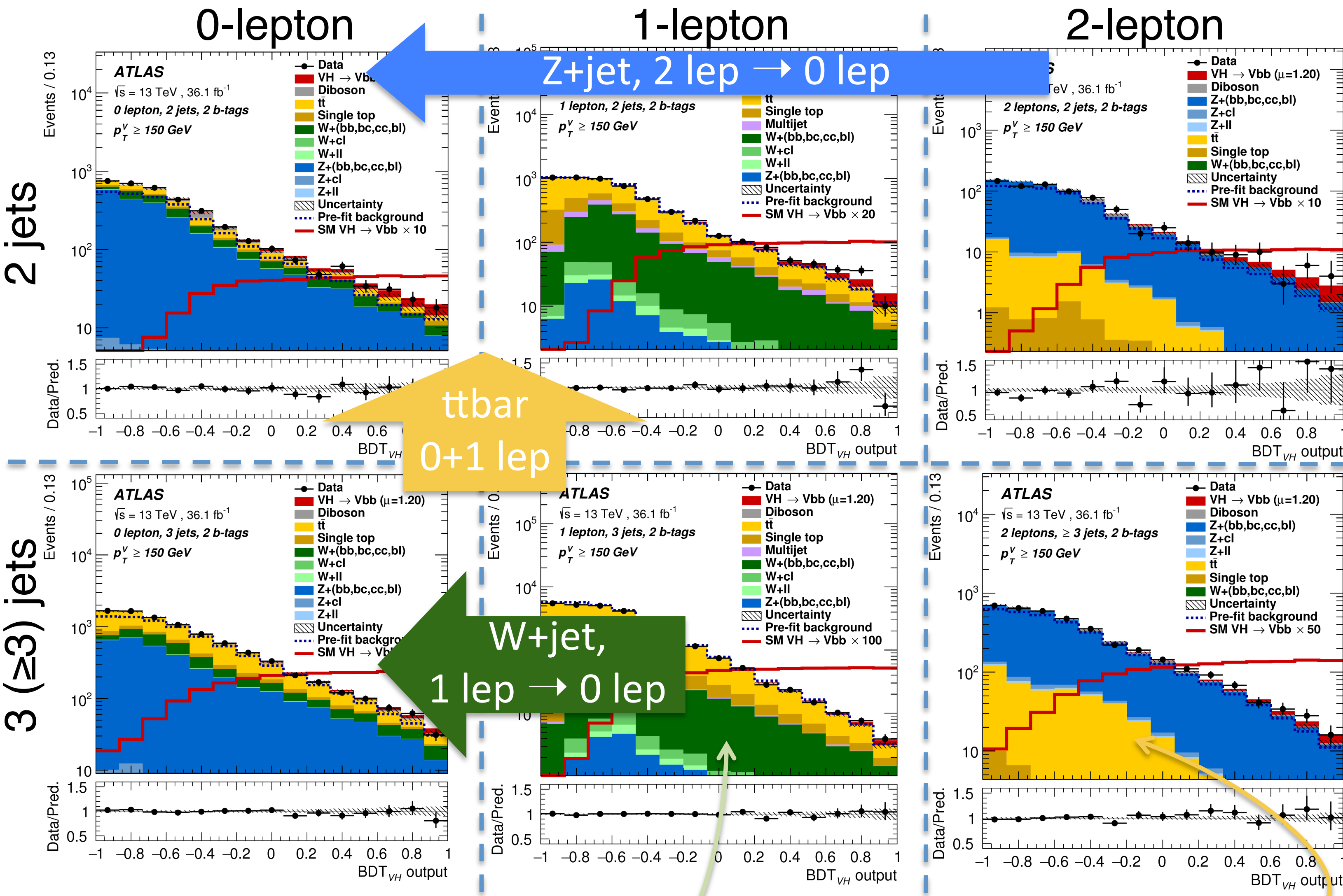


Z+jets: constrained in 2-lep extrapolated to 0-lep

W+jets: constrained in 1-lep with dedicated control region, extrap to 0-lep

ttbar:
– in 0-lep and 1-lep: constrained together by 3-jet region
– in 2-lep: constrained in a dedicated control region

Process	Normalisation
tt 0 & 1-lep	0.90±0.08
tt 2-lep 2-jet	0.97±0.09
tt 2-lep 3-jet	1.04±0.06
W+HF 2-jet	1.22±0.14
W+HF 3-jet	1.27±0.14
Z+HF 2-jet	1.30±0.10
Z+HF 3-jet	1.22+0.09

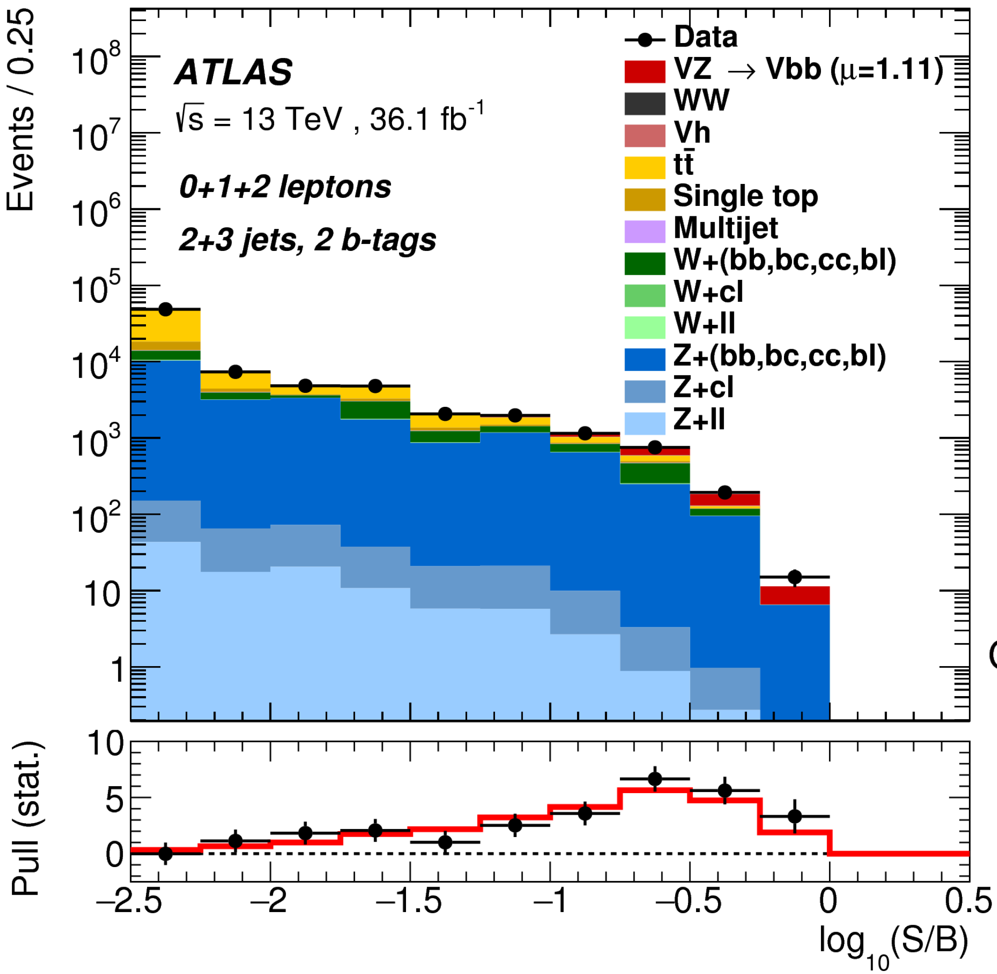
1-lep **W+jets control region**:
$m_{bb} < 75$GeV and $m_{top} > 225$ GeV
–> ~ 75-80% purity

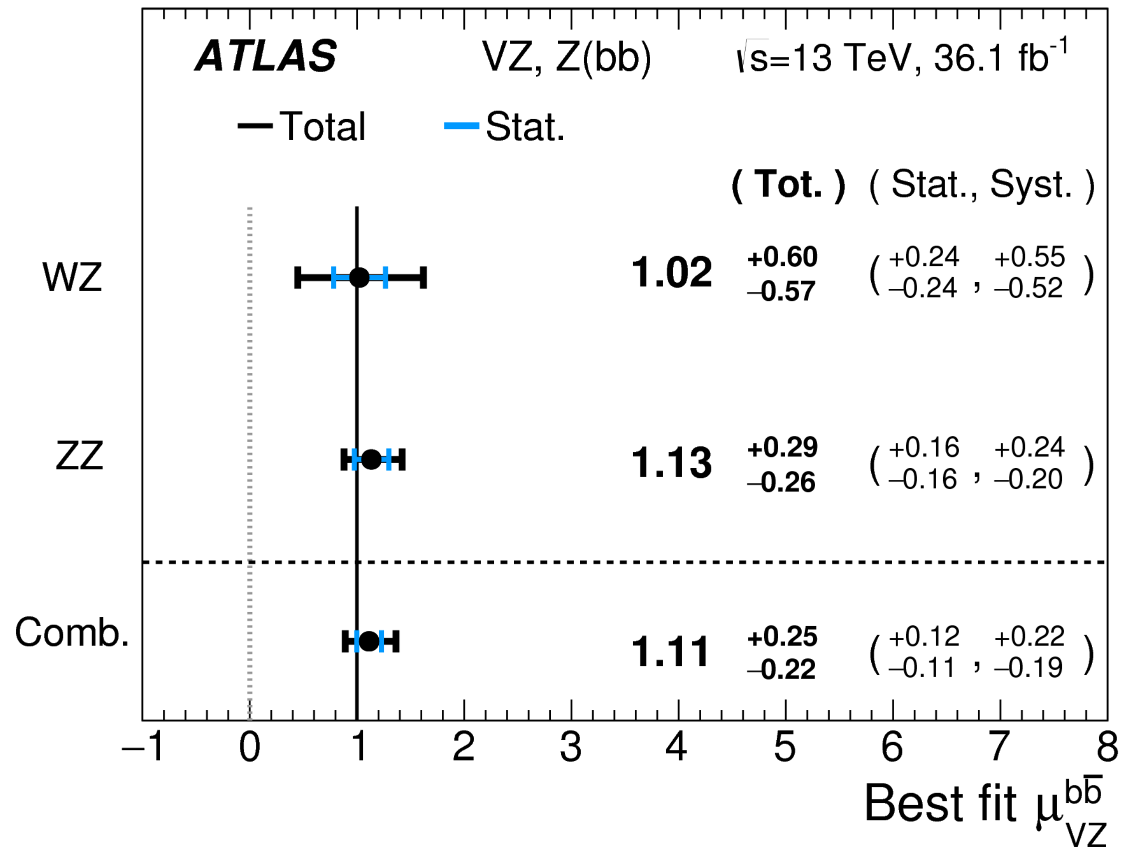
2-lep **ttbar control region**:
require eμ
–> > 99% purity

VZ, Z->bb validation

- Use same variables to train BDT_{VZ} with VZ, Z->bb as signal
  –> adapted for different mass, softer p_T spectrum

$$\mu = \frac{\sigma x Br}{(\sigma x Br)_{SM}}$$





- observe VZ, Z->bb with 5.8σ significance (5.3σ expected)
- validates BDT analysis

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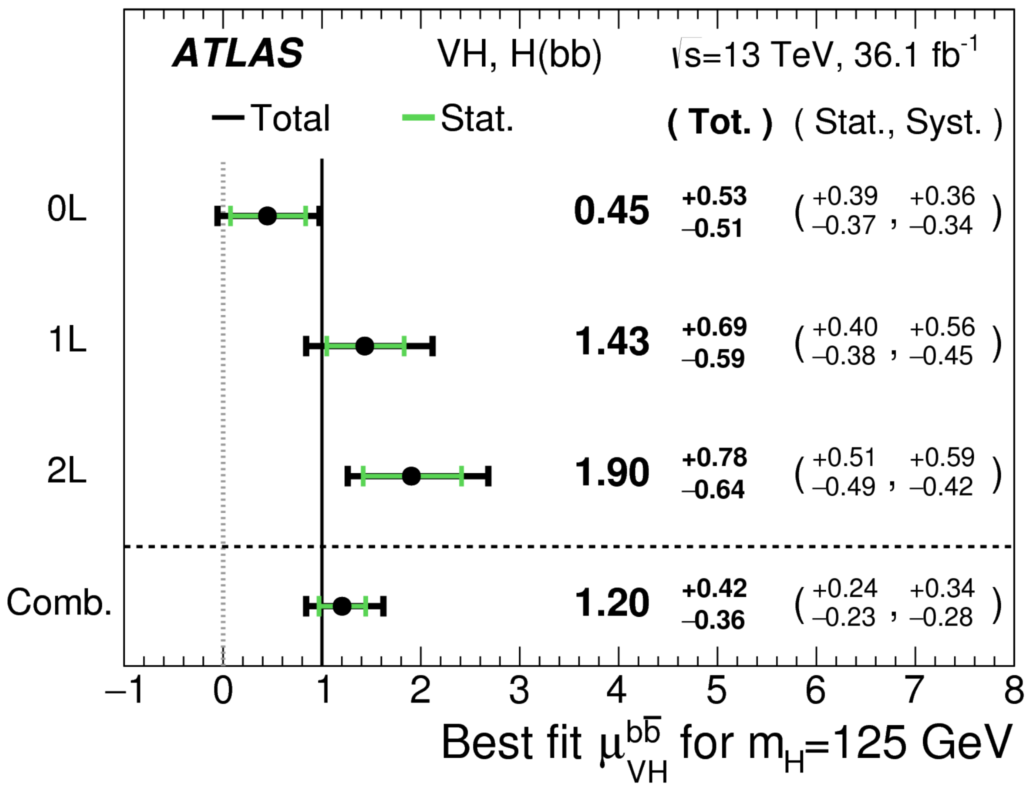
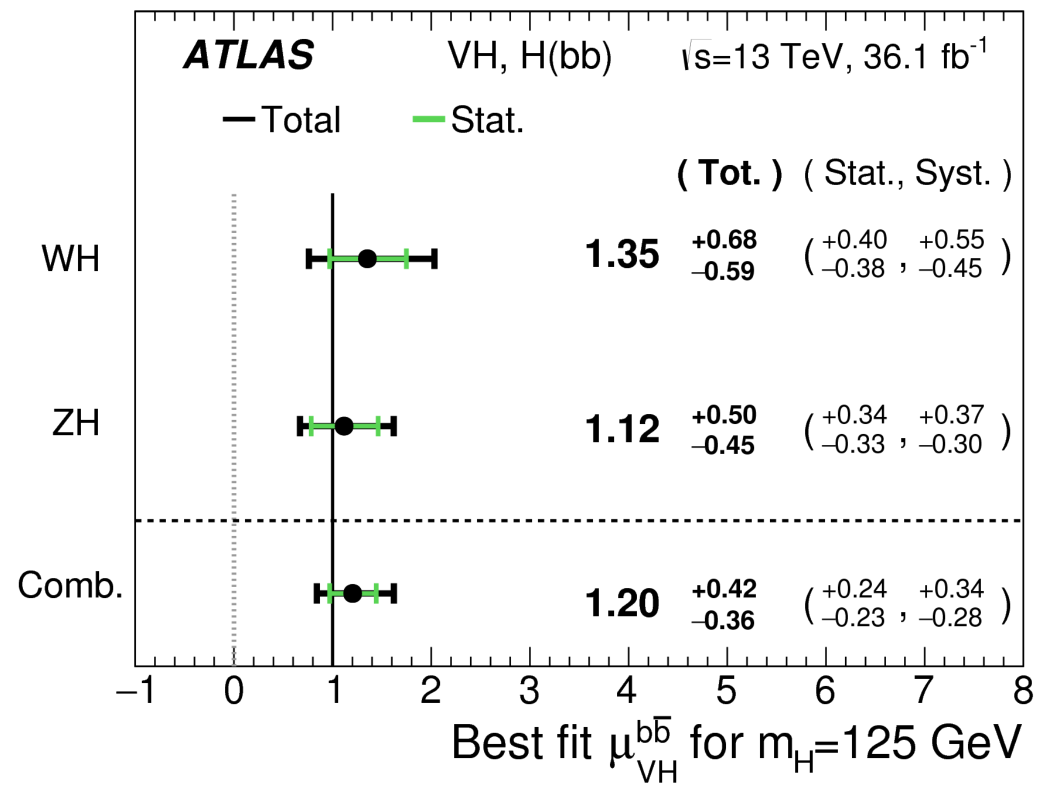
VH, H->bb results

- Observe VH,H->bb excess with 3.5σ significance (3.0σ expected)
- Evidence of VH(bb) !





- Consistent in WH and ZH; measure:

$\sigma(WH)\times Br(H\to bb) = 1.08\,^{+0.54}_{-0.47}$ pb

$\sigma(ZH)\times Br(H\to bb) = 0.57\,^{+0.26}_{-0.23}$ pb

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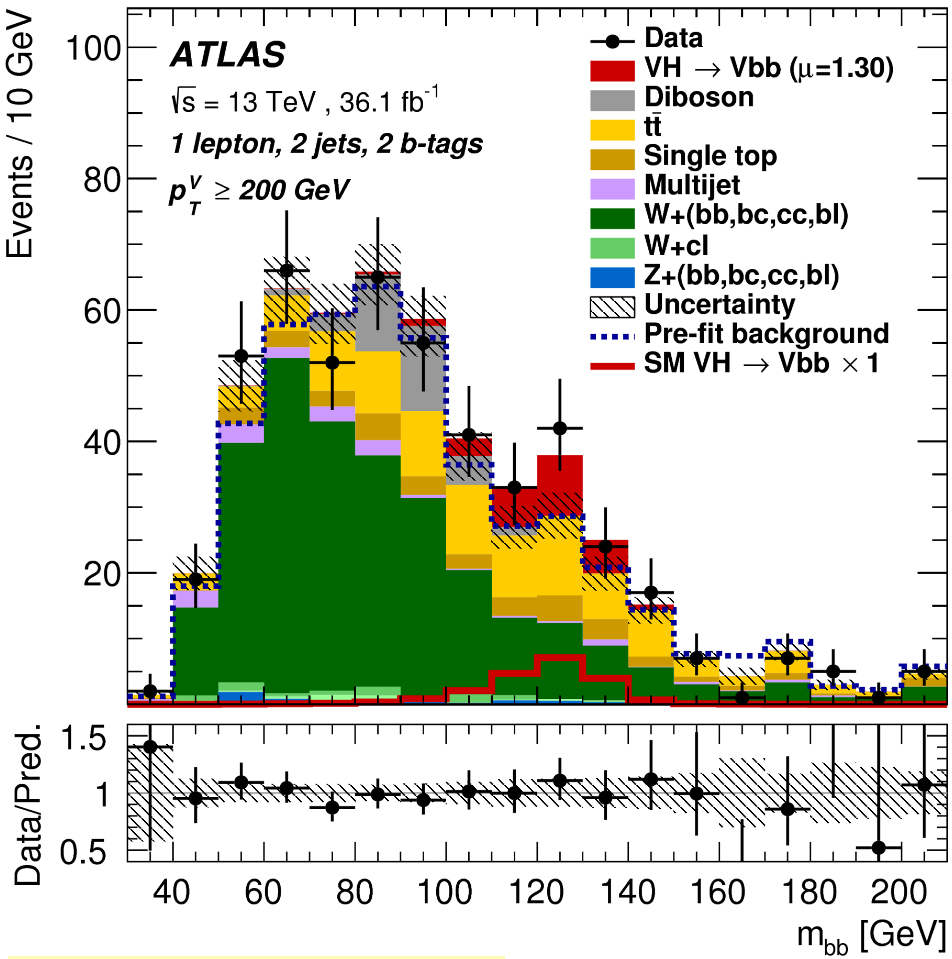
VH, H->bb validation

- Alternative approach as validation of BDT analysis: fit to m_{bb}
  + additional category $p_T(V) > 200$ GeV
  + additional cut on $\Delta R(b_1,b_2)$



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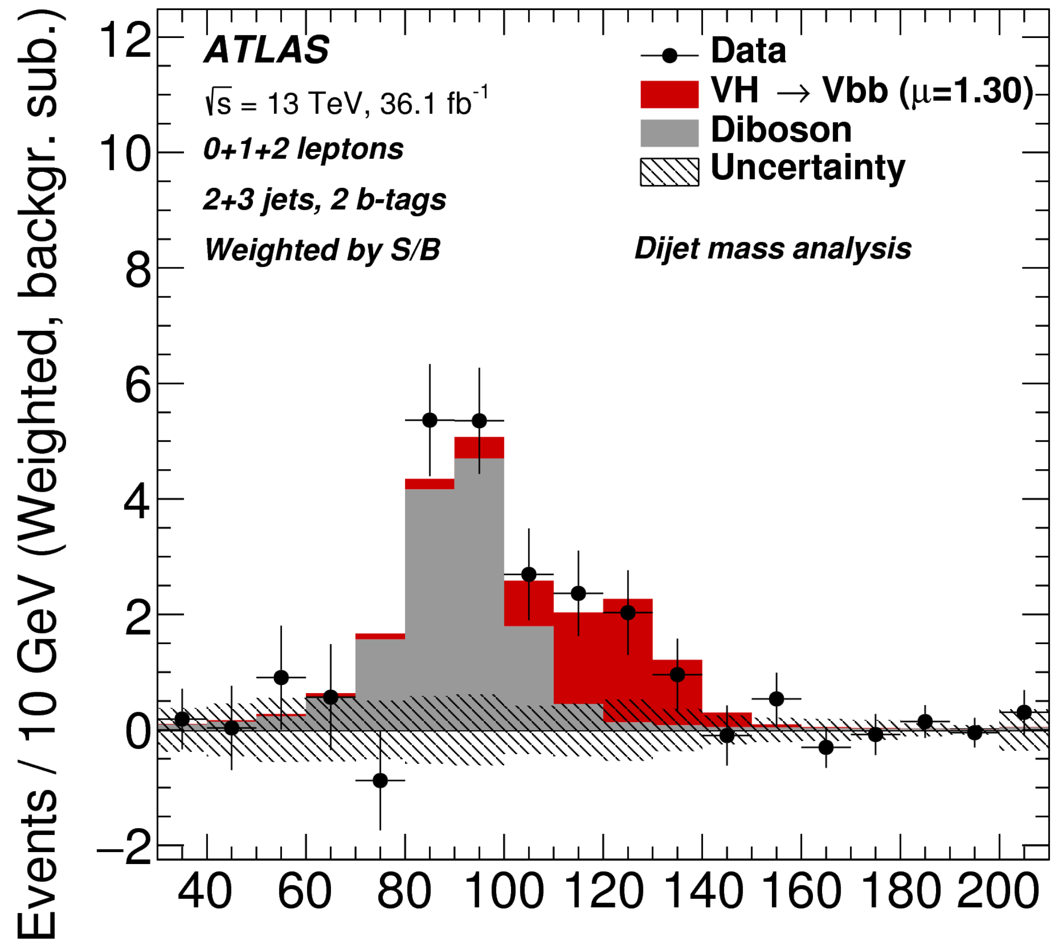
- Higgs signal strength $\mu=1.30^{+0.28}_{-0.27}$ (stat.)$^{+0.37}_{-0.29}$(sys)
- 3.5σ observed significance (2.8σ expected)
- consistent with BDT analysis



All analysis regions combined, weighted by their S/B, with all backgrounds except VZ subtracted

VH, H->bb dominant uncertainties

Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
$E_{\mathrm{T}}^{\mathrm{miss}}$		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

Systematic uncertainties are dominant:

- Background modelling – improved modelling needed, especially for extrapolation from control regions
- B-tagging calibration uncertainty – MC-to-data correction factors parametrised in p_T and η
- Signal modelling – variations in p_T(V), m_{bb} from changing QCD scale and PS tunes
- Monte Carlo statistics – few events with high p_T, 2 b-tags, and high BDT values (despite generator slicing / filtering)

–> prospects for improvement!

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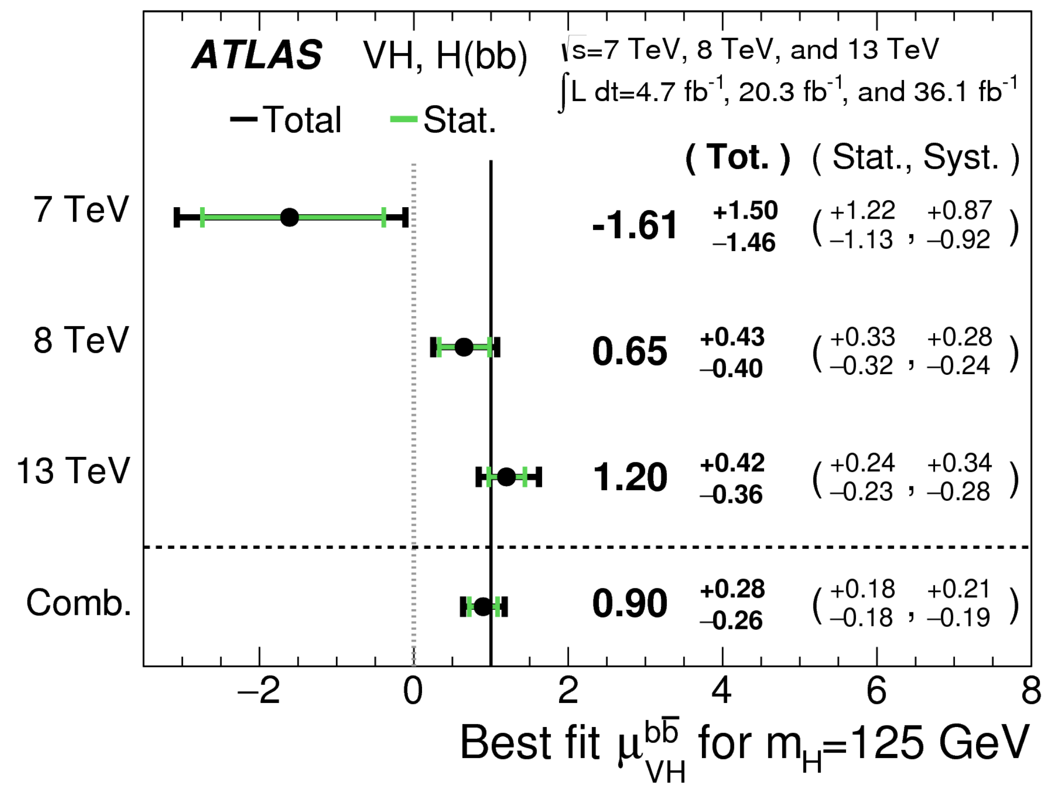
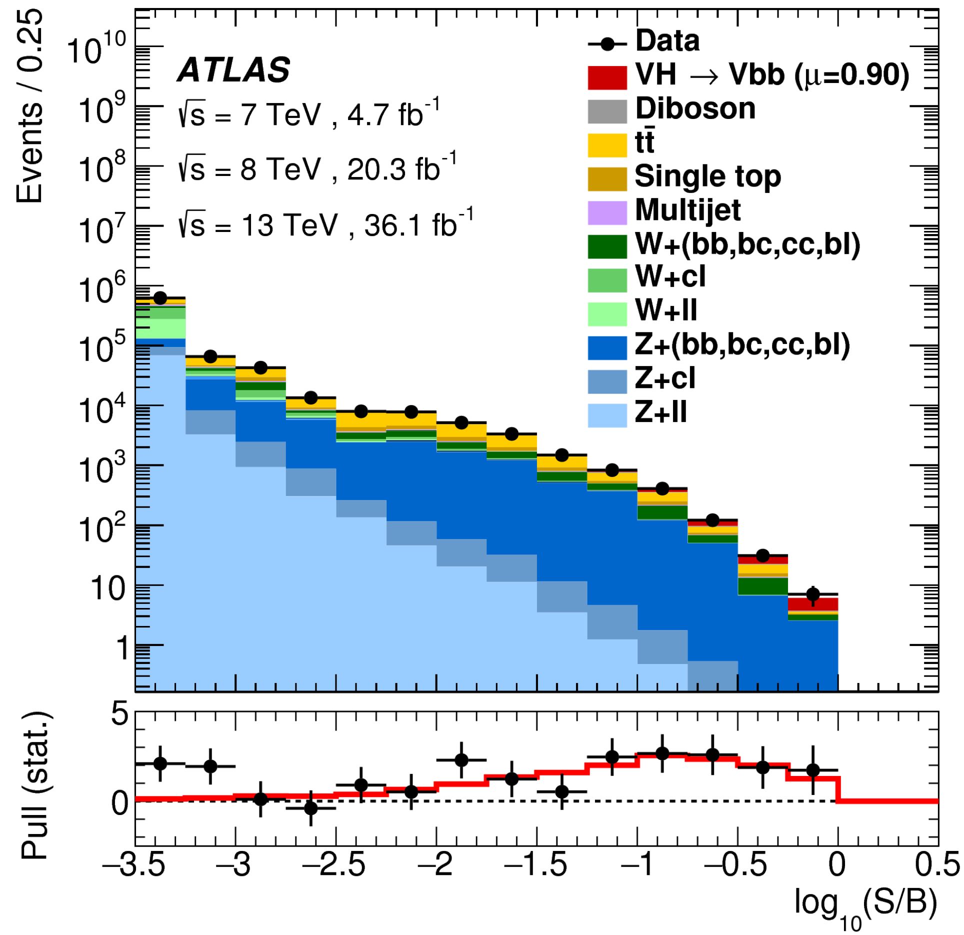
VH, H->bb combined results

- Combination with 7 & 8 TeV results from LHC Run 1
  – combined observed significance 3.6σ (4.0σ expected)





- consistent with Standard Model

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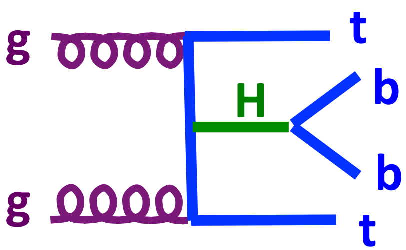
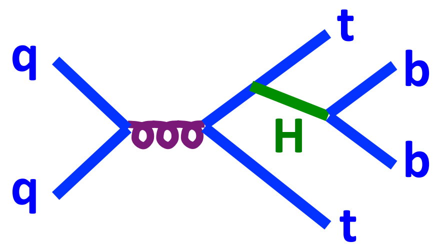
ttH, H->bb categorization

- ttH measurements target top-Yukawa coupling
- exploit large Br(H->bb) => ttH(bb) gives important contribution ttH measurement





- Categorized into sub-channels to increase sensitivity
  – number of leptons, number of jets, and b-tags corresponding to different working points:

	none	loose	medium	tight	very-tight
Efficiency	–	85%	77%	70%	60%
Discriminant value	1	2	3	4	5

2-lepton

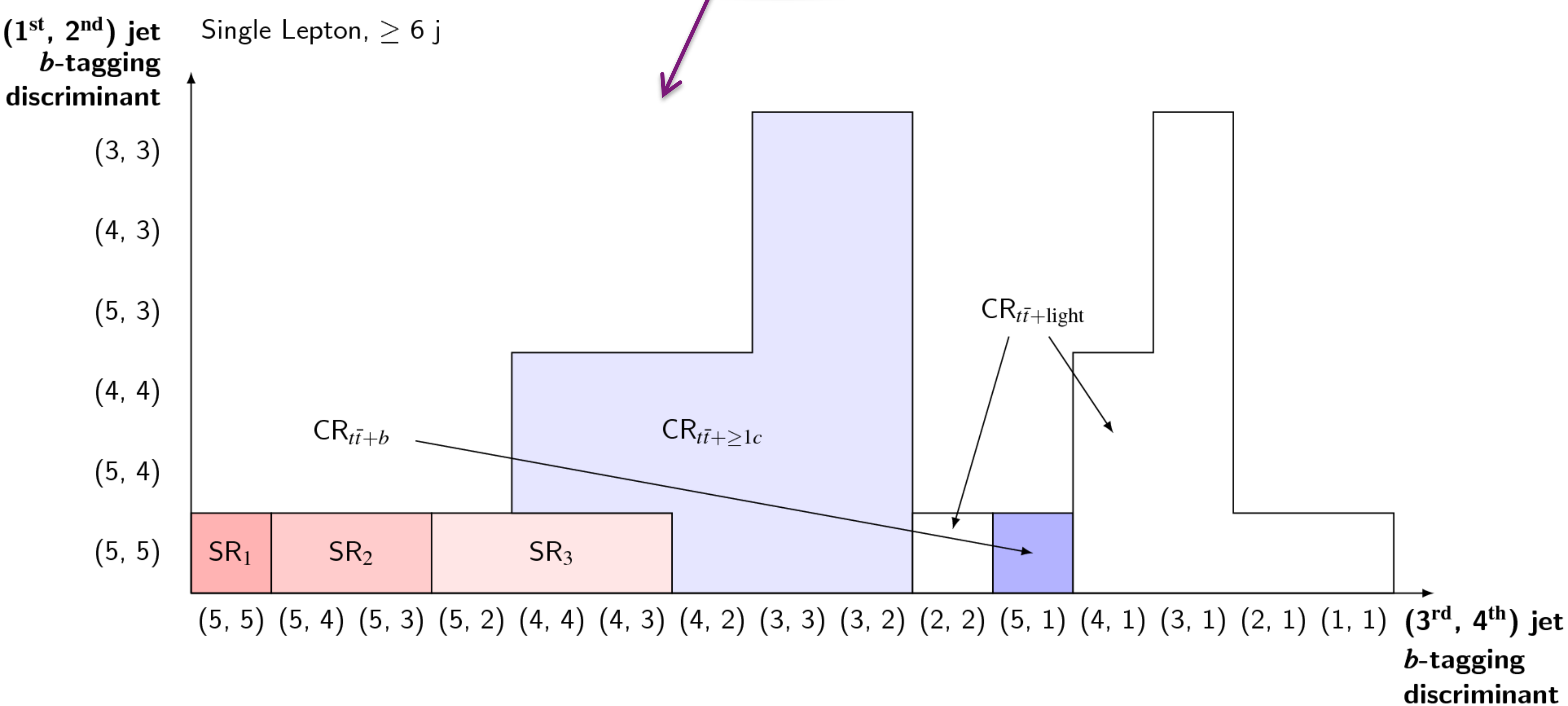
- Exactly two opposite-sign leptons, veto Z-candidates, no hadronic τ
- Require ≥3 jets and ≥2 medium b-tagged jets

1-lepton

- Exactly one lepton
- Resolved category:
  ≥5 jets & ≥2 very-tight or ≥3 medium b-tagged jets
- Boosted category:
  reconstruct Higgs and top decay products in two large R=1.0 jets, p_T(H)>200GeV, p_T(t)>250GeV

ttH, H->bb regions

- Regions constructed for 3 and ≥4 jets (2-lepton) and for 5 and ≥6 jets (1-lepton) (boosted channel is not categorized further)



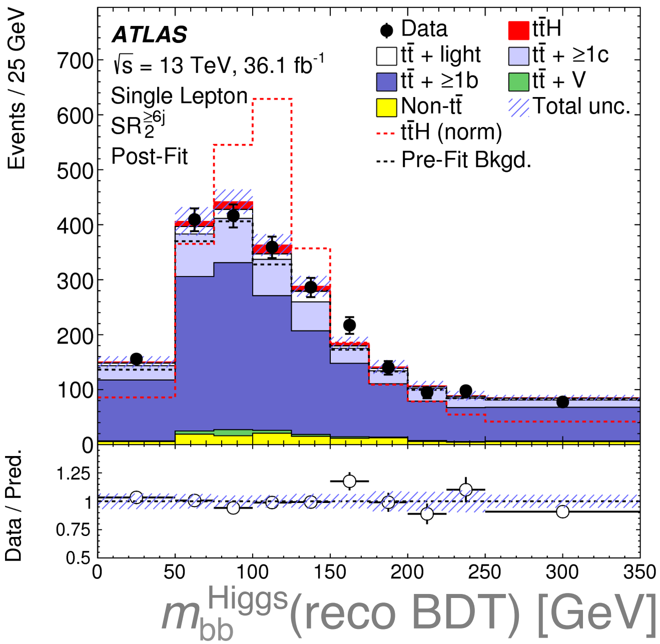
- Control regions for tt+b, tt+c and tt+light to constrain background systematics
- Highest signal purity is in 4 very-tight b-tag bins

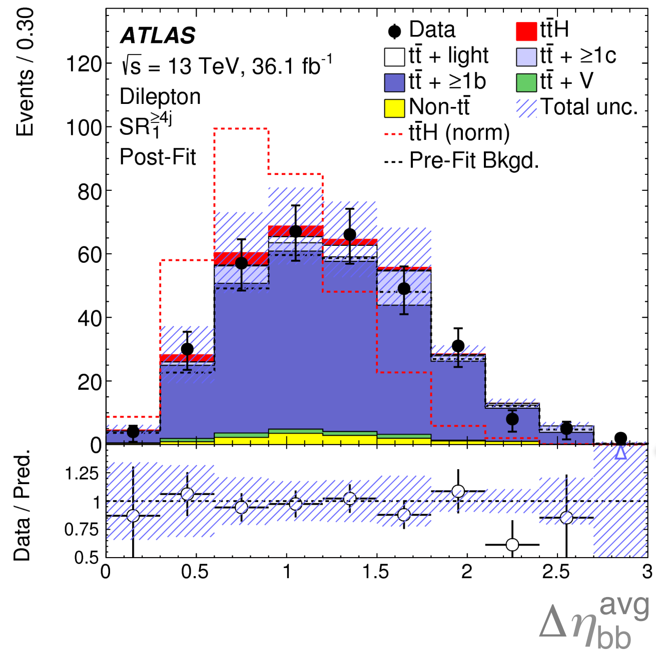
ttH, H->bb multivariate analysis

arXiv:1712.08895

- In signal regions, MVA techniques used to separate signal and background
- Reconstruction BDT (all resolved SRs)

  identify best assignment of jets to partons from ttH(bb)





discriminating variables e.g. m_{bb} $\Delta\eta_{bb}$

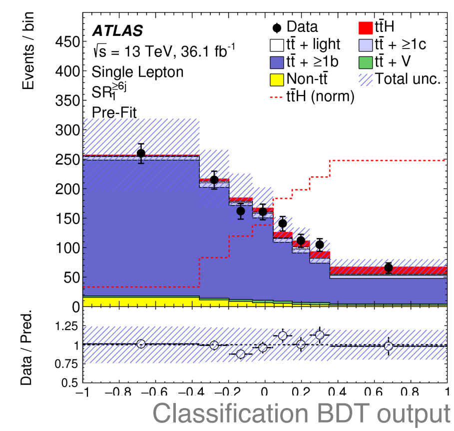
–> all inputs to classification BDT for sig/bck separation

- Likelihood discriminator (1-lep resolved SRs only)

  probability of signal/background based on PDFs for each

- Matrix Element ($SR^{\geq 6}$ only)

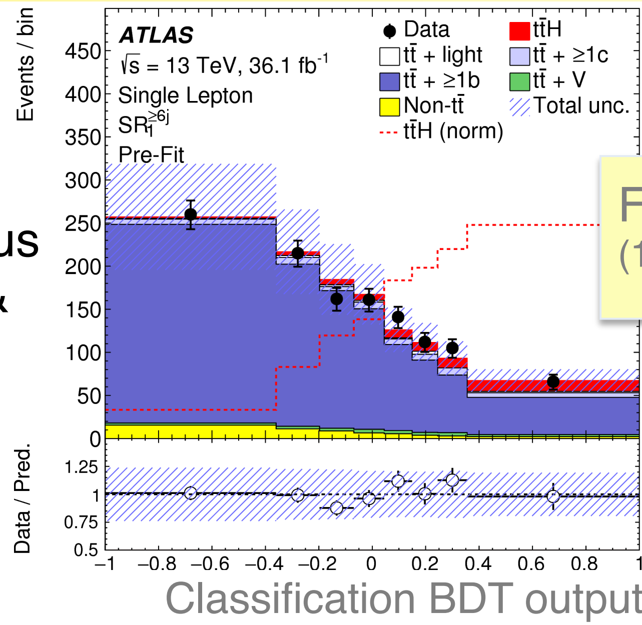
  likelihood estimation from ME method



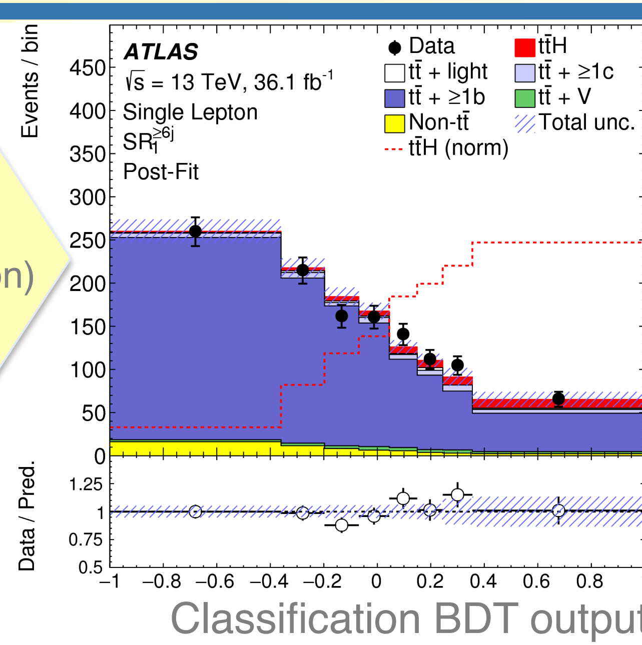
ttH, H->bb fit

arXiv:1712.08895

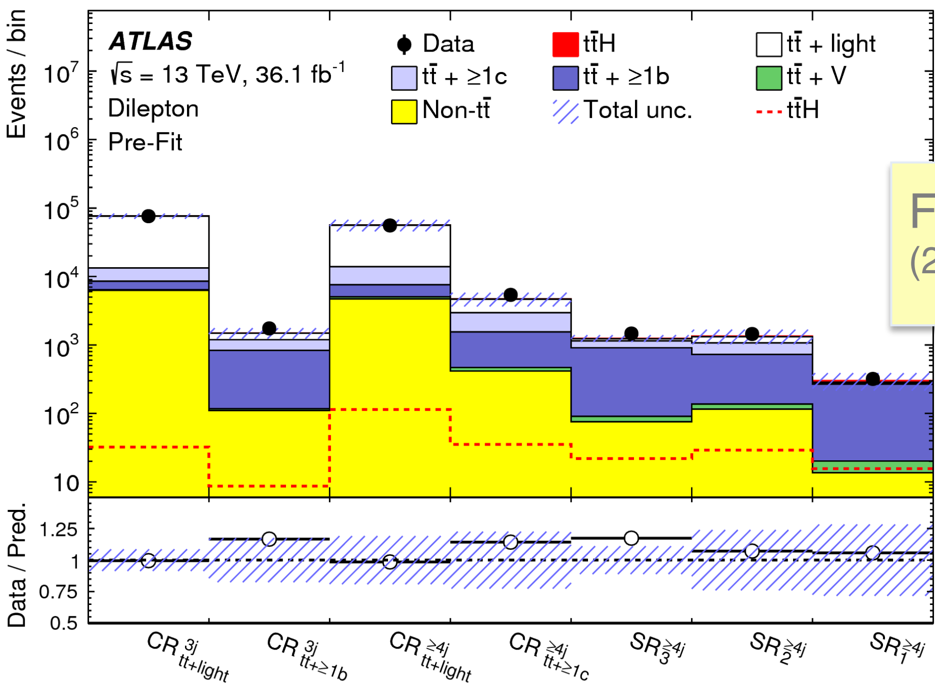
- Simultaneous fit to all SRs & CRs



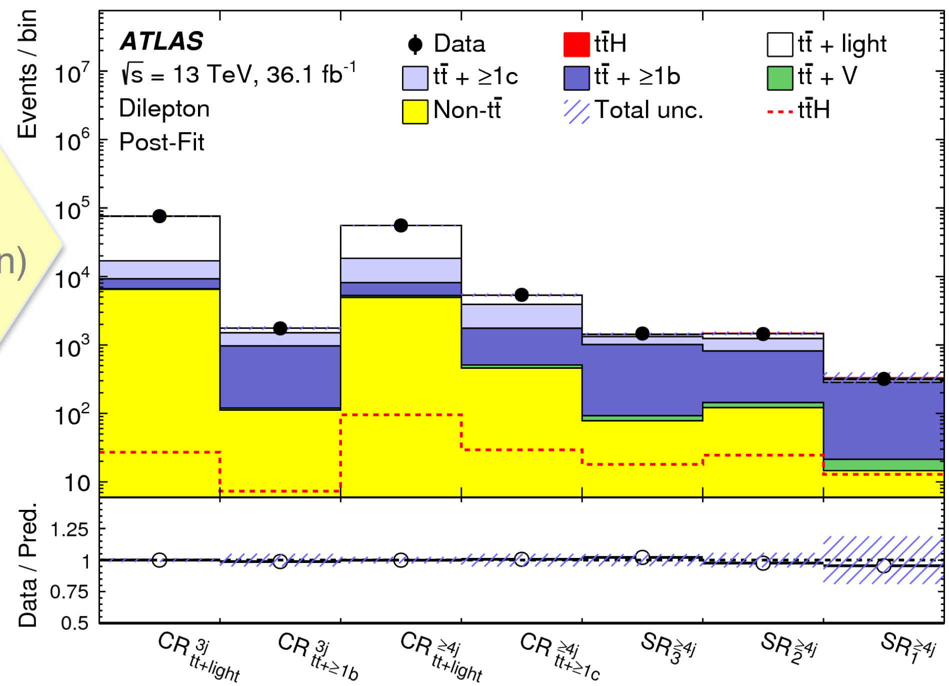
Fit
(1-lepton)



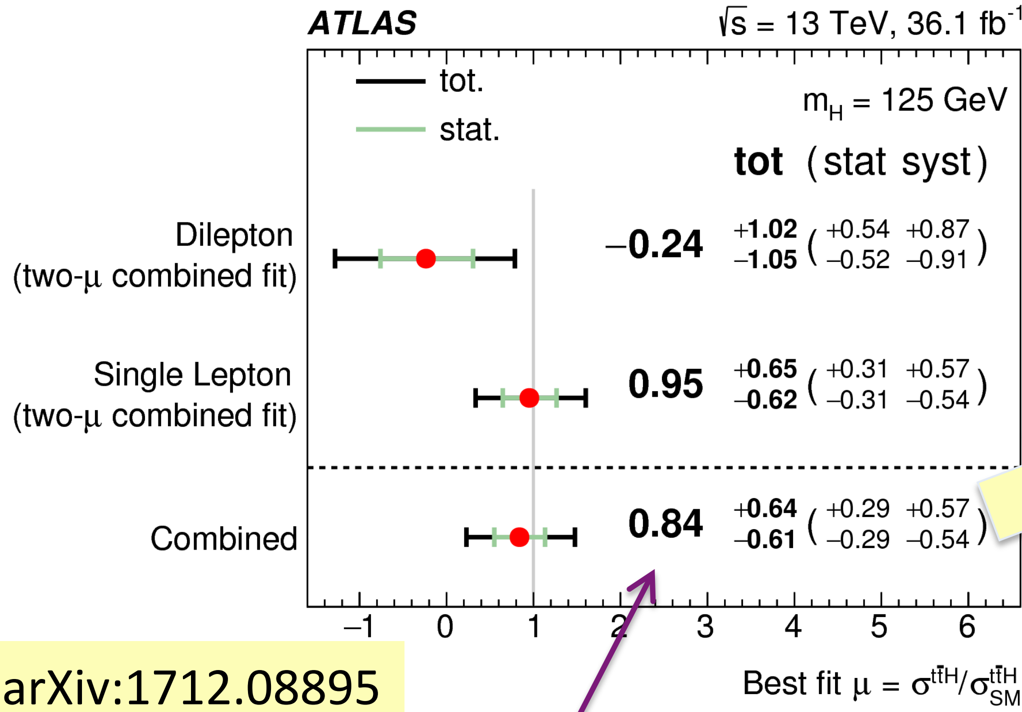
- tt+≥1b/c normalisation freely floating in the fit



Fit
(2-lepton)



ttH, H->bb results



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
Total statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61

- modelling of tt+hf background is limiting factor

arXiv:1712.08895 submitted to PRD

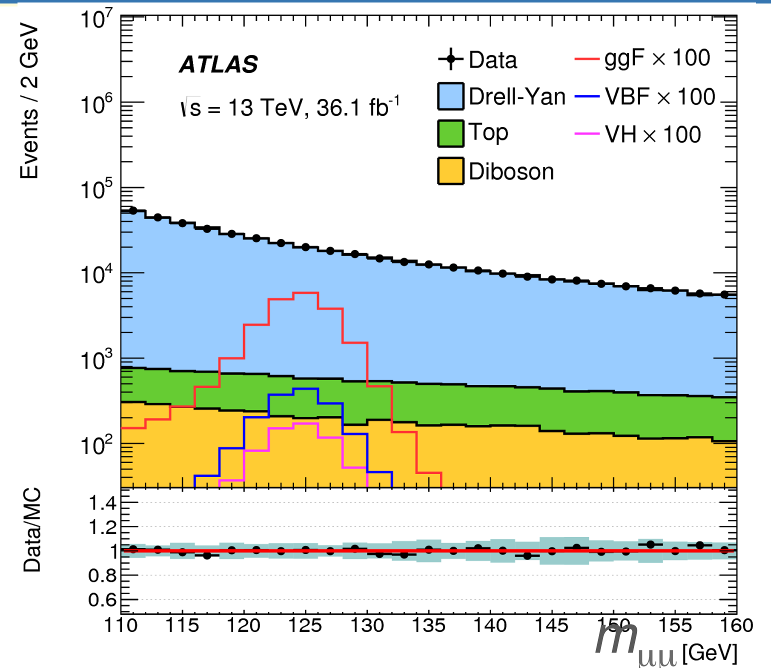
- ttH(bb) at 1.4σ observed (1.6σ expected)
- combine with ttH multilepton and subcategories of H->γγ and H->ZZ –> evidence for ttH production observed at 4.2σ

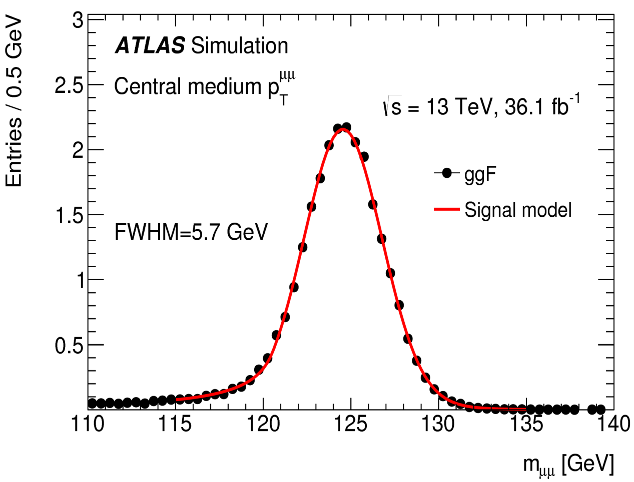
Channel	Best-fit μ		Significance	
	Observed	Expected	Observed	Expected
Multilepton	$1.6\,^{+0.5}_{-0.4}$	$1.0\,^{+0.4}_{-0.4}$	4.1σ	2.8σ
$H \to b\bar{b}$	$0.8\,^{+0.6}_{-0.6}$	$1.0\,^{+0.6}_{-0.6}$	1.4σ	1.6σ
$H \to \gamma\gamma$	$0.6\,^{+0.7}_{-0.6}$	$1.0\,^{+0.8}_{-0.6}$	0.9σ	1.7σ
$H \to 4\ell$	< 1.9	$1.0\,^{+3.2}_{-1.0}$	—	0.6σ
Combined	$1.2\,^{+0.3}_{-0.3}$	$1.0\,^{+0.3}_{-0.3}$	4.2σ	3.8σ

arXiv:1712.08891 submitted to PRD

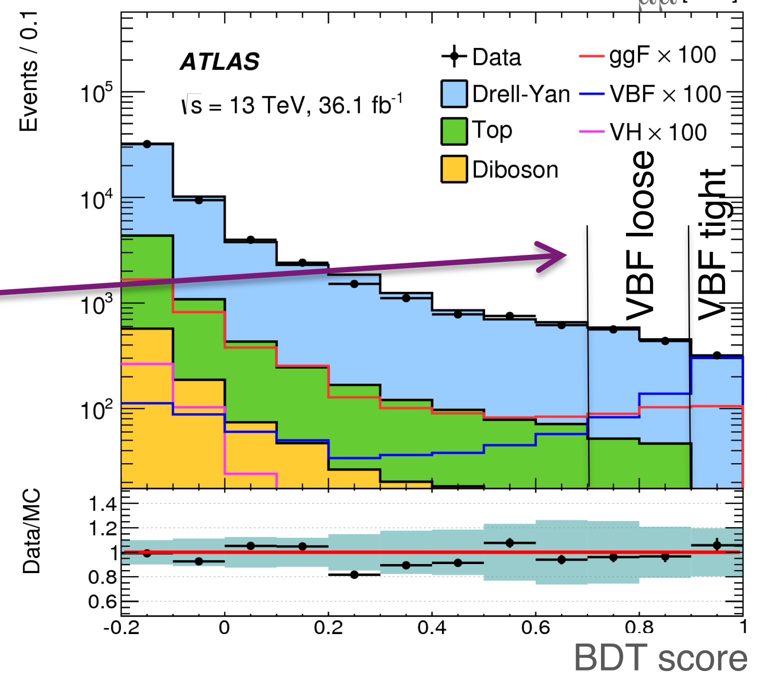
H->μμ

- Clean experimental signature
- Excellent mass resolution
- but small Br ~ 2.18×10^{-4}
  –> tiny signature buried under Drell-Yan
- Selection:
  two isolated muons with $p_T > 15$GeV
  MET < 80 GeV
  b-jet veto
  $110 < m_{\mu\mu} < 160$ GeV



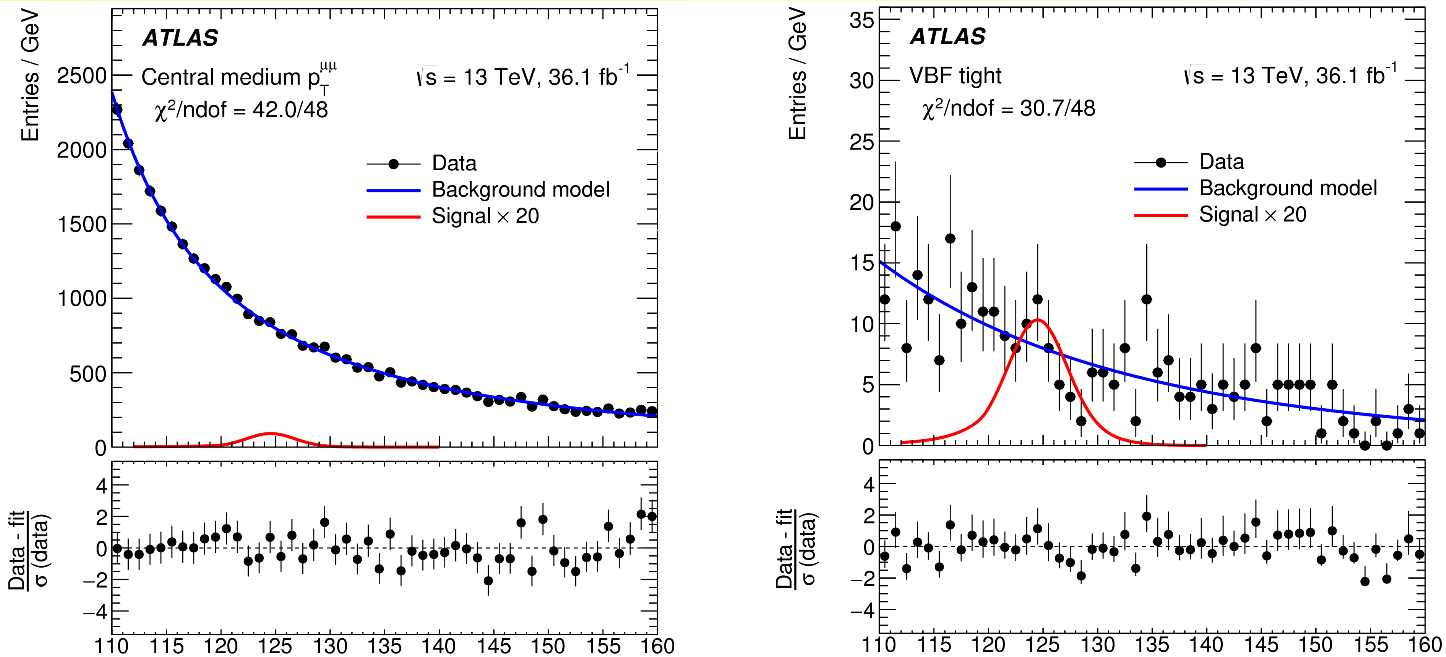


- Six gluon-gluon fusion categories based on η_μ and $p_T^{\mu\mu}$
- Two VBF categories with $N_{jets}\geq2$, selected by a BDT
- S/√B=0.37 in VBF tight region!



PRL 119 (2017) 051802

H->μμ results



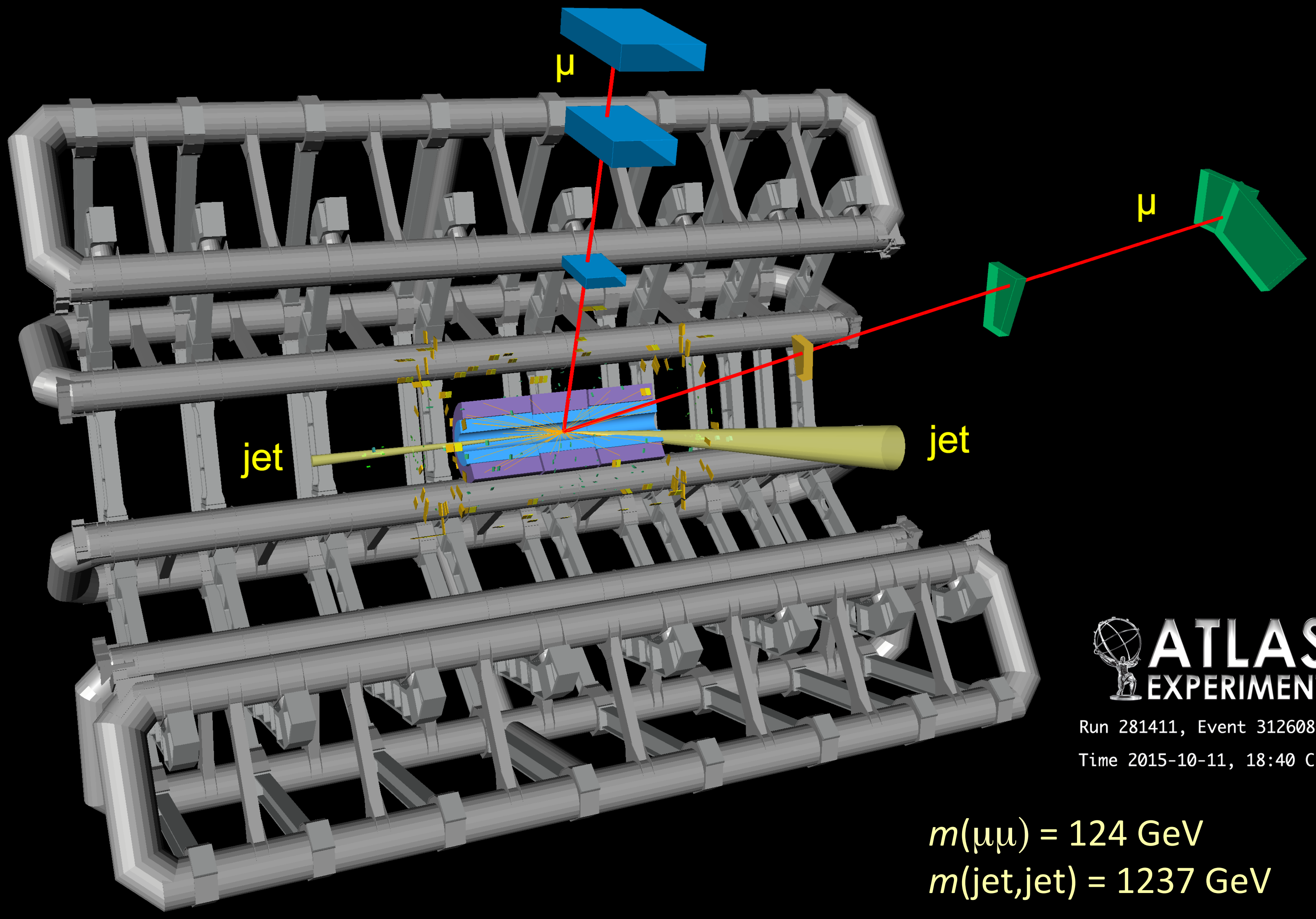
- Fit di-muon mass spectra:
  bump-hunt with parametrised background function
  (BW x Gauss + $\exp(A.m_{\mu\mu}) / m_{\mu\mu}^3$ fit to data in sidebands)
  simultaneous fit to observed $m_{\mu\mu}$ in all categories to extract signal strength

Dataset	Upper limit / SM (95%CL) observed (expected)	Signal strength
Run 2 (13 TeV)	3.0 (3.1)	–0.1 ± 1.5
Run 1 + Run 2 (7,8,13 TeV)	2.8 (2.9)	–0.1 ± 1.4

- Statistics-limited

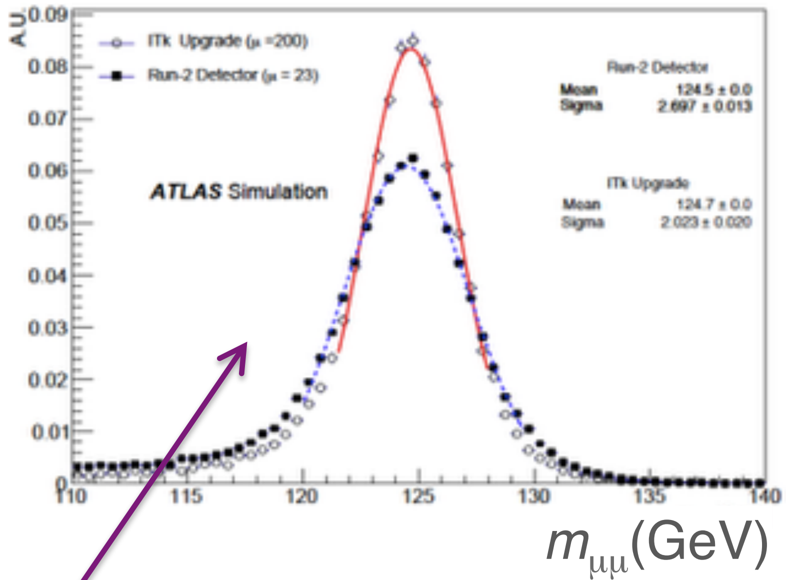
PRL 119 (2017) 051802

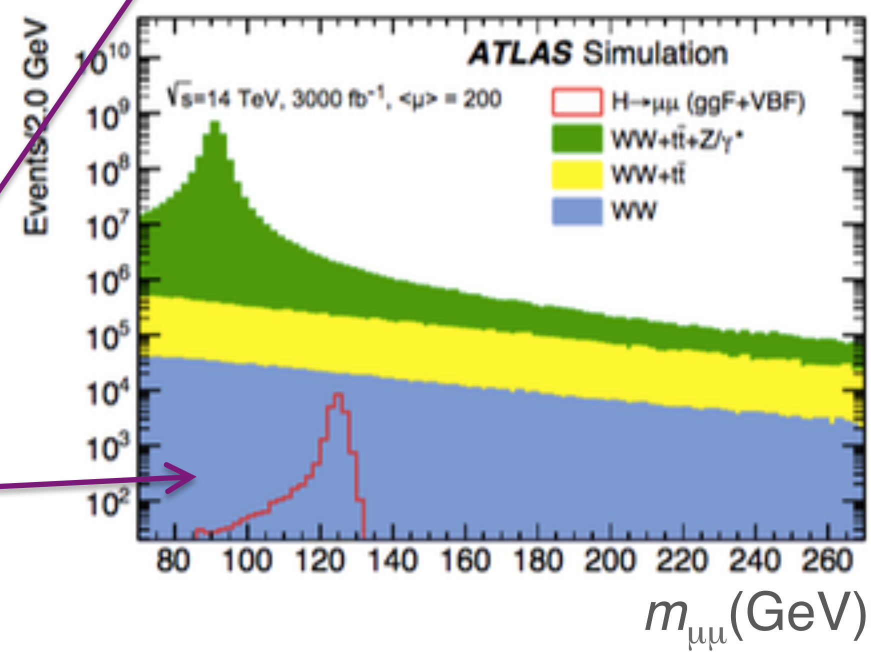
H->μμ candidate



Prospects

- All results shown with 36.1 fb^{-1} data at $\sqrt{s}$=13TeV
- Run 2 total expected to be 120–150 fb^{-1}
- VH,Hbb: published result is systematics-dominated – now working on background modelling, b-tagging, and MC stats in order to reach 5σ observation in Run 2. Beyond with HL-LHC: can study differential distributions
- ttH: working on background modelling, especially ttbb, towards 5σ observation in Run 2
- H$\mu\mu$: potential for combined ATLAS/CMS result to reach SM sensitivity with Run 2 data. HL-LHC: new ATLAS tracker layout –> 25% improvement in H$\mu\mu$ mass resolution; 8.6σ sensitivity estimated with 3000fb^{-1} (assuming <μ>=200)



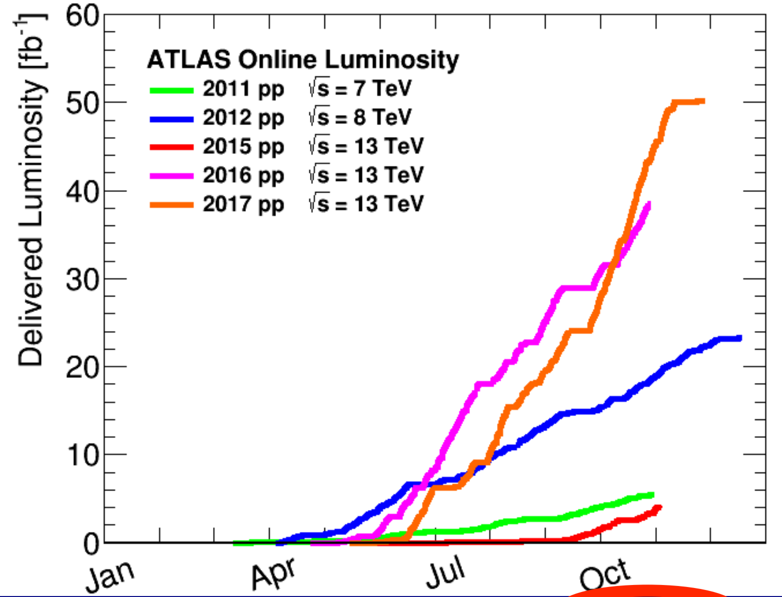


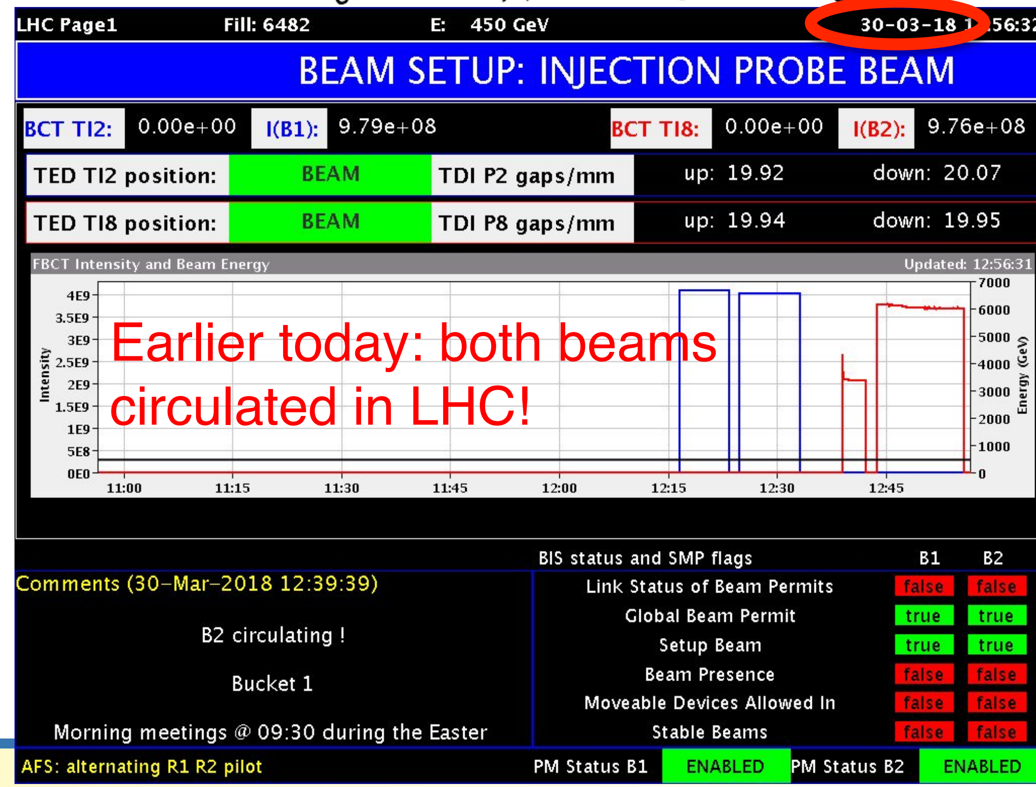
ATLAS muon upgrade TDR,
ATLAS-TDR-026 (2017)

Conclusions

- First LHC evidence for H->bb, in VH,H->bb at 3.6σ with 36.1fb^{-1} at $\sqrt{s}$=13TeV
  - signal strength uncertainty ~25–30%; consistent with SM
- First evidence for ttH production at 4.2σ with 36.1fb^{-1} at $\sqrt{s}$=13TeV;
  - ttH,H->bb contributes 1.4σ
- Search for H->$\mu\mu$ gives upper limit of 2.8 σ_{SM}xBr
  - potential for SM sensitivity with complete Run 2 dataset and ATLAS/CMS combination

–> Looking forward to 120–150 fb^{-1} !





Backups

VH generators

Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order	ace2.5cm
Signal						
$qq \to WH$ $\to \ell\nu b\bar{b}$	POWHEG-BOX v2 [19] + GOSAM [22] + MINLO [23,24]	NNPDF3.0NLO$^{(\star)}$ [20]	PYTHIA8.212 [13]	AZNLO [21]	NNLO(QCD)+ NLO(EW) [25,26,27,28,2	
$qq \to ZH$ $\to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	POWHEG-BOX v2 + GOSAM + MINLO	NNPDF3.0NLO$^{(\star)}$	PYTHIA8.212	AZNLO	NNLO(QCD)$^{(\dagger)}$+ NLO(EW)	
$gg \to ZH$ $\to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	POWHEG-BOX v2	NNPDF3.0NLO$^{(\star)}$	PYTHIA8.212	AZNLO	NLO+ NLL [32,33,34,35,36]	
Top quark						
$t\bar{t}$	POWHEG-BOX v2 [37]	NNPDF3.0NLO	PYTHIA8.212	A14 [38]	NNLO+NNLL [39]	
s-channel	POWHEG-BOX v1 [40]	CT10 [41]	PYTHIA6.428 [42]	P2012 [43]	NLO [44]	
t-channel	POWHEG-BOX v1 [40]	CT10f4	PYTHIA6.428	P2012	NLO [45]	
Wt	POWHEG-BOX v1 [46]	CT10	PYTHIA6.428	P2012	NLO [47]	
Vector boson + jets						
$W \to \ell\nu$	SHERPA 2.2.1 [16,48,49]	NNPDF3.0NNLO	SHERPA 2.2.1 [50,51]	Default	NNLO [52]	
$Z/\gamma^* \to \ell\ell$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NNLO	
$Z \to \nu\nu$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NNLO	
Diboson						
WW	SHERPA 2.1.1	CT10	SHERPA 2.1.1	Default	NLO	
WZ	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NLO	
ZZ	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NLO	

VH background systematics

$Z+$ 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)
Multi-jet (1-lepton)	
Normalisation	60 – 100% (2-jet), 100 – 400% (3-jet)
BDT template	S

V+jets normalisation / acceptance uncertainties from:

- –renorm & fact scales x0.5 and x2
- –CKKW merging scale 30->15GeV
- –parton shower/resum scale x0.5 and x2
- –difference with alternative ME (Madgraph5_aMC@NLO)

Shape distributions in m_{bb} and p_T^V dominated by Sherpa vs Madgraph

ttbar

Shape distributions in m_{bb} and p_T^V dominated by Sherpa vs Madgraph

VH background systematics

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%

VH signal systematics

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

Regions used in likelihood fit

Channel	SR/CR	Categories			
		$75\ \mathrm{GeV} < p_T^V < 150\ \mathrm{GeV}$		$p_T^V > 150\ \mathrm{GeV}$	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	BDT	BDT
1-lepton	SR	-	-	BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	W + HF CR	-	-	Yield	Yield
2-lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield	m_{bb}