Evidence for the H to bb decay in VH production with the ATLAS detector

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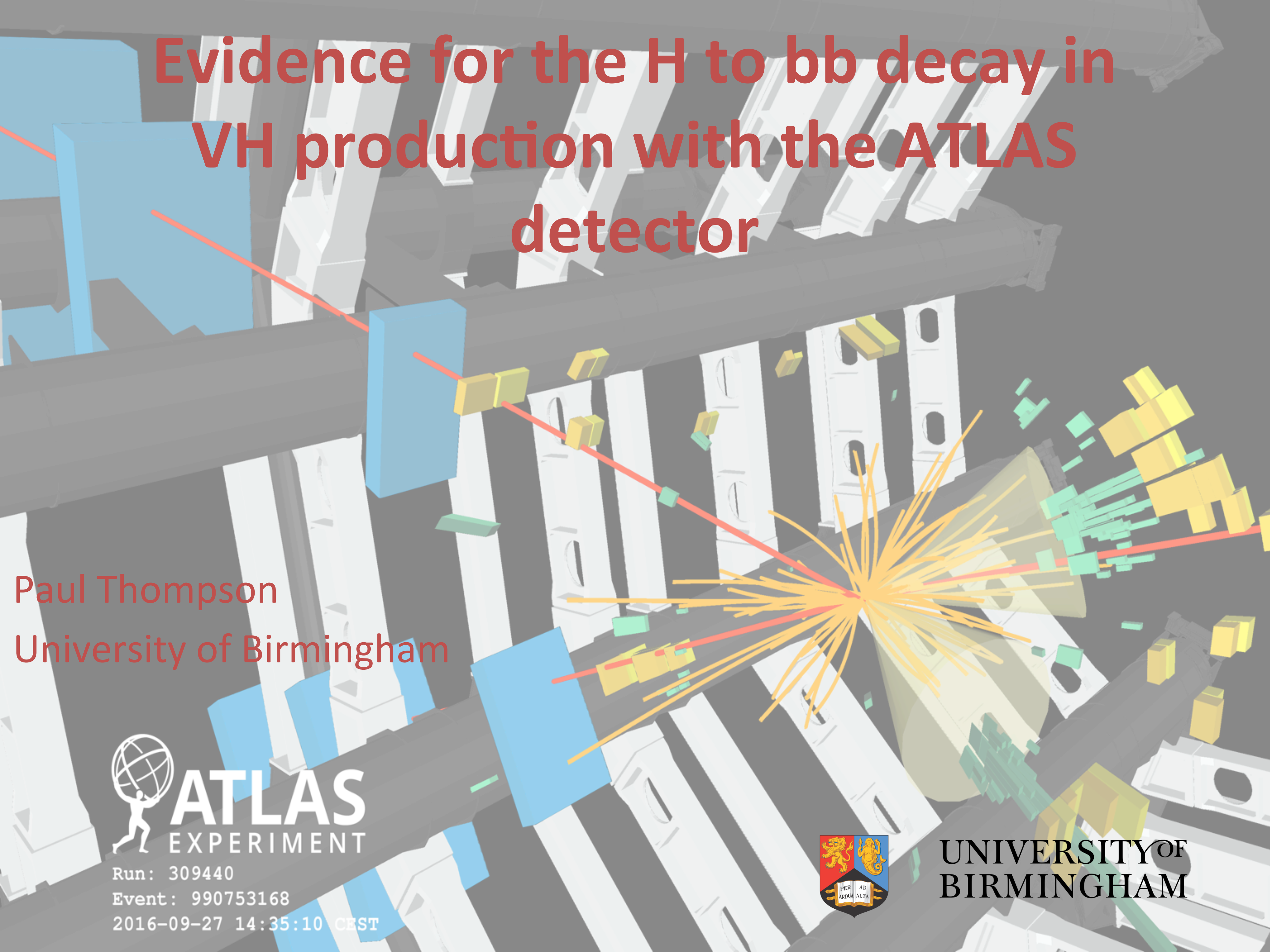


UNIVERSITY OF BIRMINGHAM

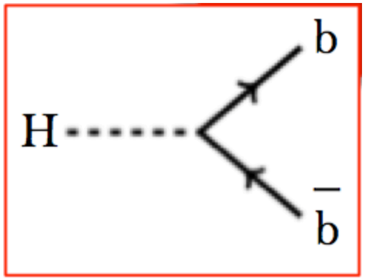
Searches for Higgs Bosons in the VH(bb) Channel at ATLAS

Paul Thompson
University of Birmingham

Birmingham PP Seminar
15th October 2014

- Recent final results on the search in the VH(bb) channel at ATLAS in LHC Run 1
- Prospects for search in LHC Run 2 ->Today the measurement!
- Using the same final state to probe physics Beyond the Standard Model (BSM)

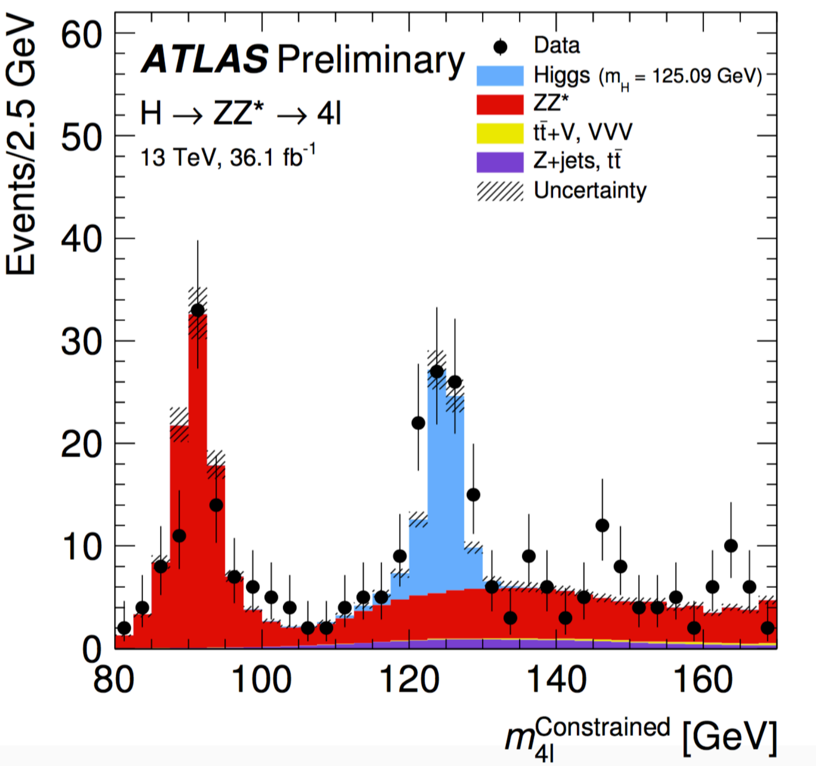
Outline

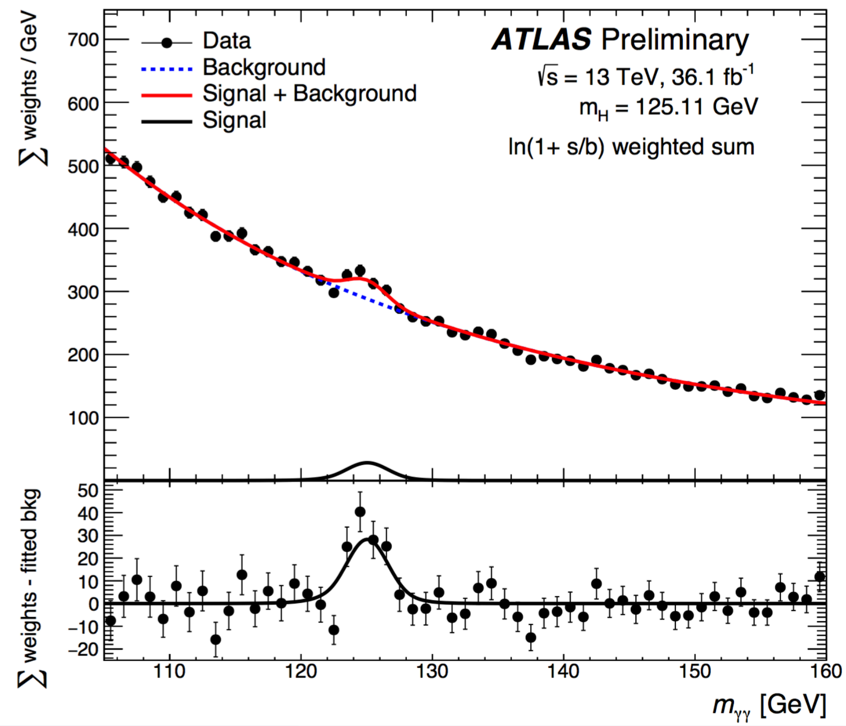


- Standard Model Higgs production at the LHC and the role and challenges of H→bb
- What features enable H to bb searches at the LHC?
  - First ATLAS sensitivity studies ~20 years ago predicted marginal sensitivity using 30fb^{-1} of 14 TeV data
  - Due to LHC and ATLAS detector performance and understanding
  - Analysis techniques
- Presentation of latest Run 2 analysis and results
  - Combination with Run 1
- Using the Higgs as a probe of physics beyond the Standard Model
- Outlook/Summary

Standard Model Higgs

- Higgs Boson discovered in Run 1 (7,8 TeV) of LHC 5 years ago. Initial measurements in line with Standard Model (SM) predictions. Opened up way to explore new sector of SM Lagrangian.
- Measurements at Run 2 (13 TeV) increase precision in e.g. H→4 leptons and H→γγ continue to be in line with SM. Look at the signal strength $\mu = \frac{\sigma \times \mathrm{BR}}{(\sigma \times \mathrm{BR})_{\mathrm{SM}}}$



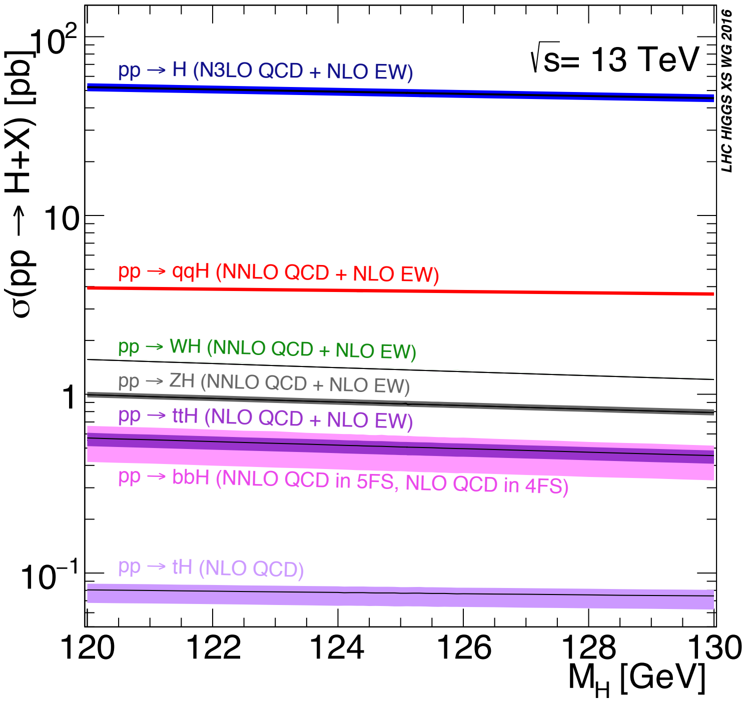


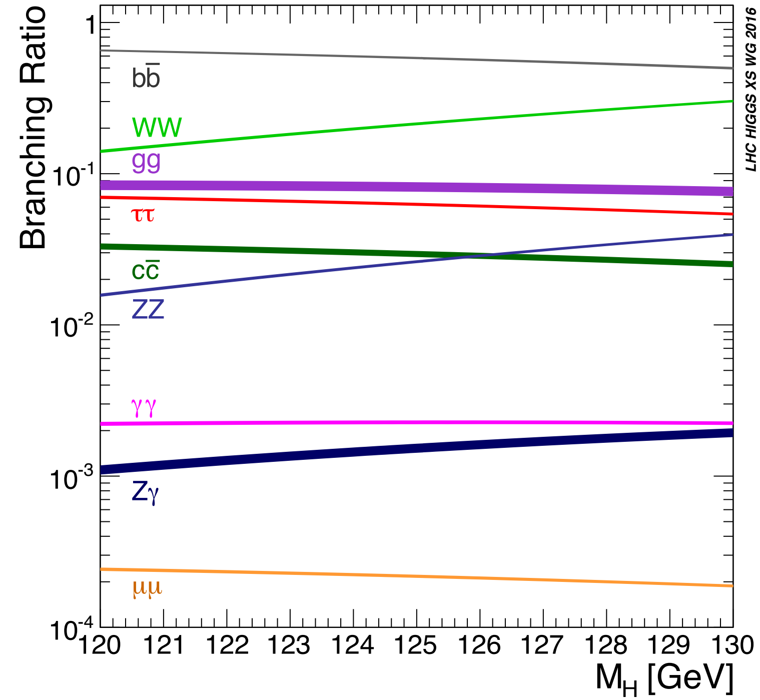
- Global signal strength: $\mu = 1.28^{+0.18}_{-0.17}(\mathrm{stat.})^{+0.08}_{-0.06}(\mathrm{exp.})^{+0.08}_{-0.06}(\mathrm{th.}) = 1.28^{+0.21}_{-0.19}$

- Global signal strength: $\mu = 0.99^{+0.12}_{-0.11}(\mathrm{stat})^{+0.06}_{-0.05}(\mathrm{exp.})^{+0.06}_{-0.05}(\mathrm{th.}) = 0.99 \pm 0.14$

Standard Model Higgs

- In the SM all predictions fixed once mass is known



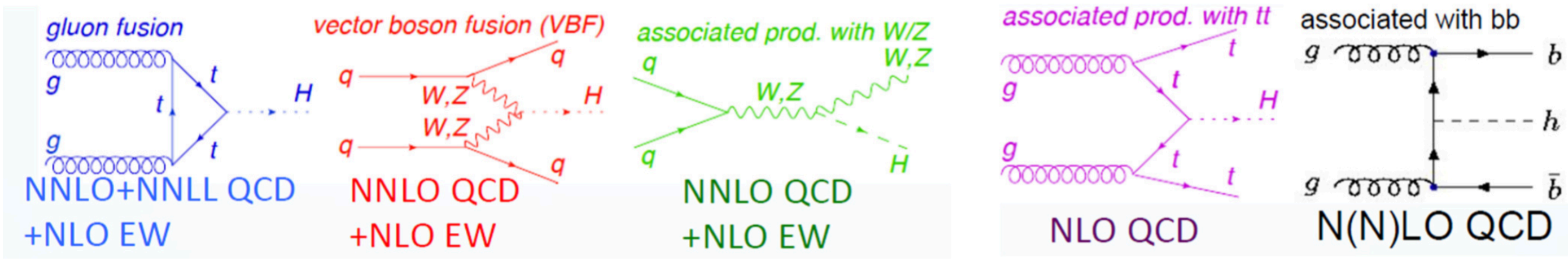


- Look for deviations in
  - Coupling strengths to other particles
  - Spin/CP properties
  - Differential distributions
- Differences would be a sign of new physics
- We know SM does not describe dark matter, mass hierarchy etc

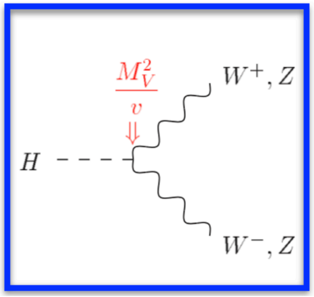
ATLAS+CMS Run I	125.09 ± 0.24 GeV
ATLAS Run 2*	124.98 ± 0.28 GeV
CMS Run 2*	125.26 ± 0.21 GeV

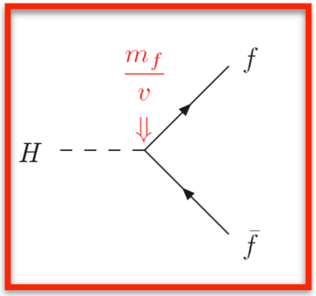
*preliminary

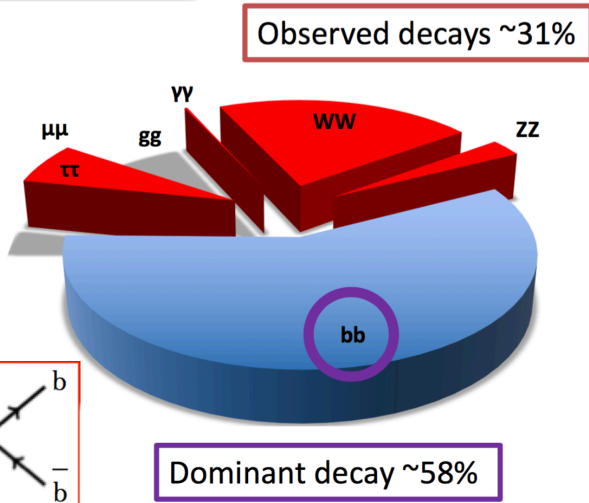
Picture Today

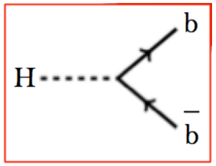


- Established production modes
  - Gluon fusion
  - Vector Boson Fusion
  - ttH (summer 2017)
- Established decay modes
  - To bosons: H→ZZ, H→WW, H→γγ
  - To fermions: H→ττ (ATLAS+CMS Run 1, CMS Run 2)
- Most of Higgs decays undetected
- Higgs → bb important part of understanding
  - Direct probe of coupling to fermions (down type quarks)
  - Drives uncertainty on total decay width
  - The more Higgs decays we see the less space there is for undetected/invisible decays

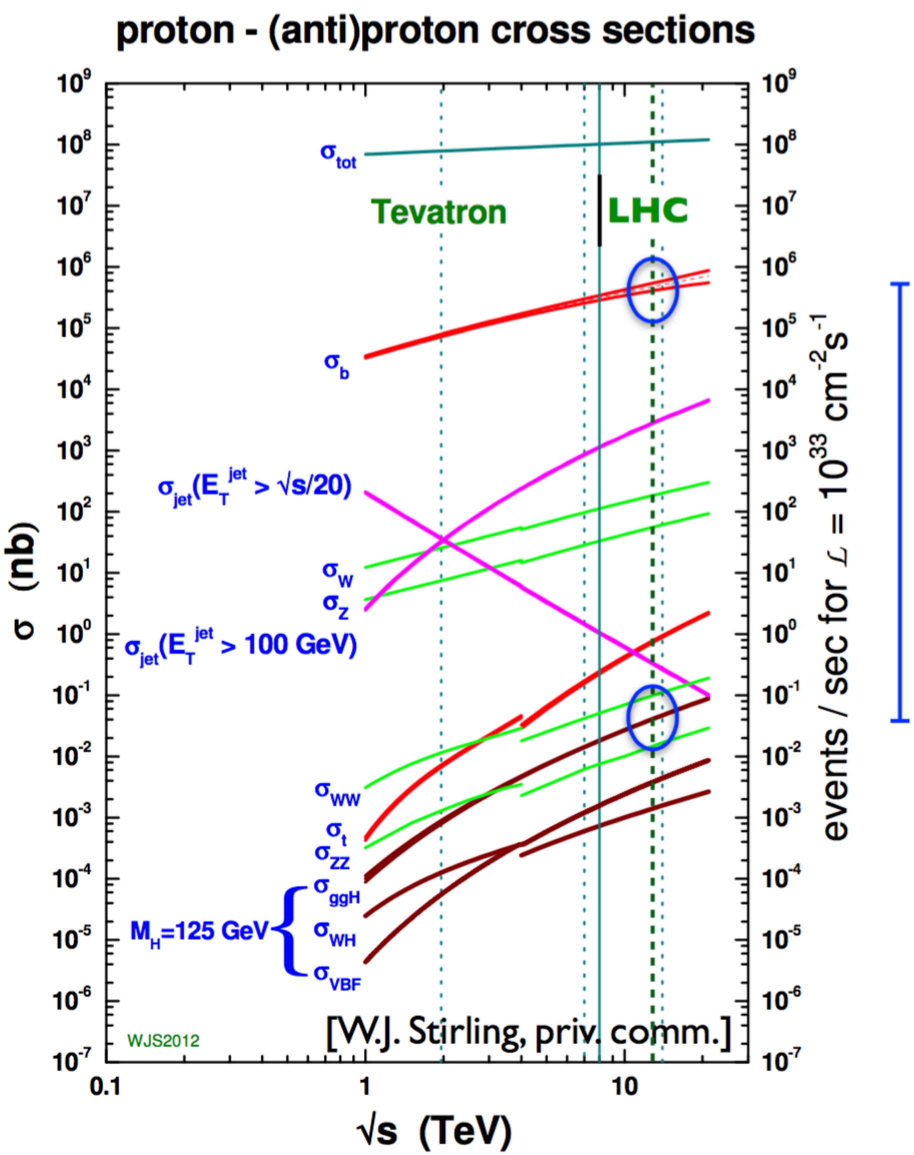






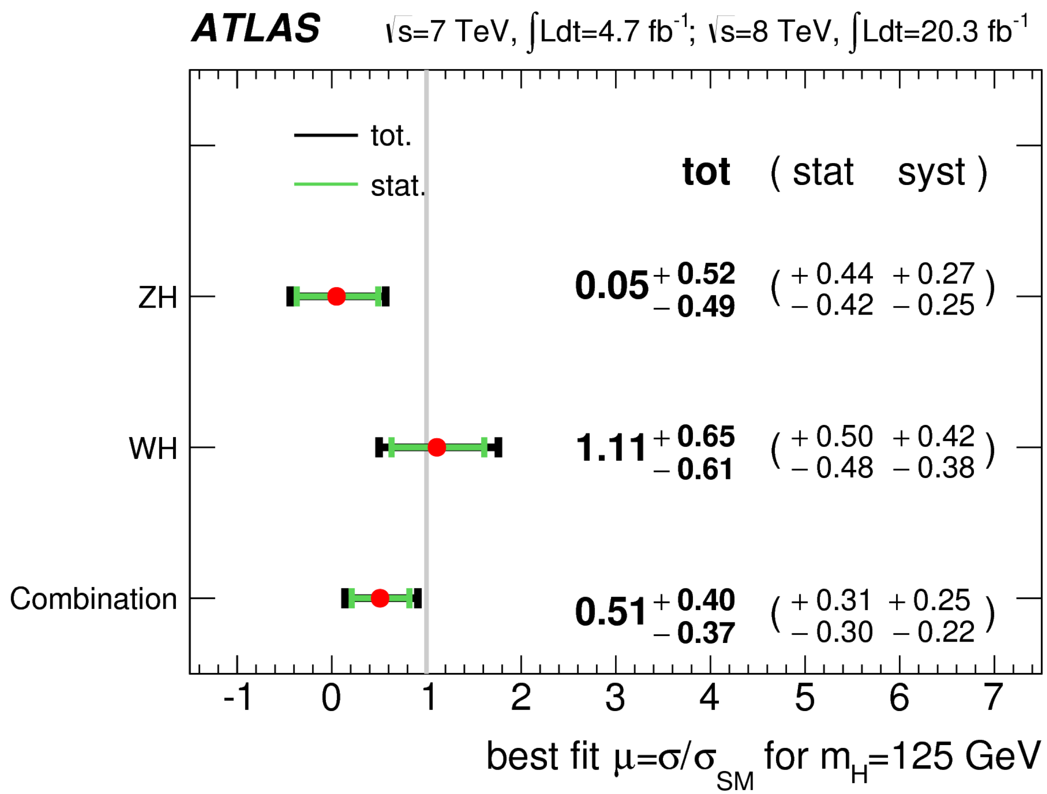


Detecting H→bb



- Jets containing b jets are produced in copious amounts at the LHC
- Inclusive H→bb is difficult, multijet cross section g→bb is overwhelming (10^7 larger!). Triggering possible at high p_T^H although still low S/B.
- For the associated production mode VH the W or Z bosons can help with triggering the event and with background suppression
- Main production mode for H→bb

Previous H→bb Results



[1] Phys. Rev. Lett. **109** (2012) 071804

[2] JHEP01(2015)069

[3] Eur.Phys.J. C75(5), 212 (2015) + twiki

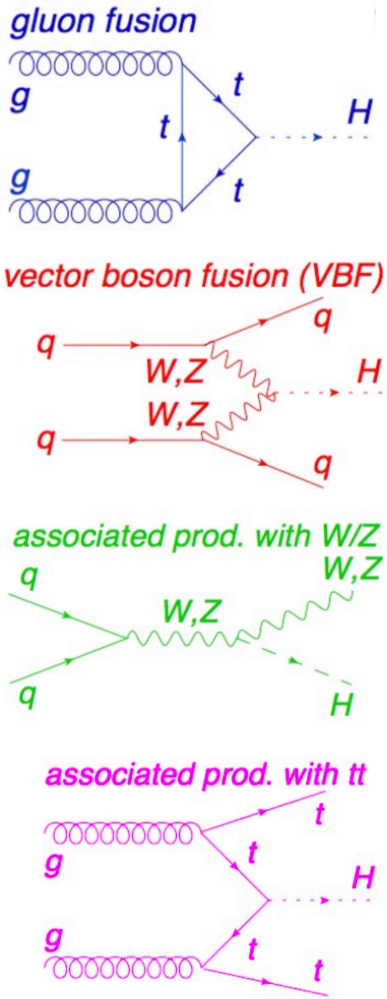
[4] JHEP08(2016)045

- CDF+D0 [1] 2.8σ observed for 1.5σ expected
- ATLAS Run 1 [2] signal strength shown for separate production modes and combination. Observed significance of 1.4σ for 2.6σ expected.
- CMS Run 1 [3] 2.1σ observed for 2.5σ expected
- ATLAS+CMS Run 1 [4] combination 2.6σ observed for 3.7σ expected
- H→bb becomes an LHC Run 2 measurement…

Looking for H→bb

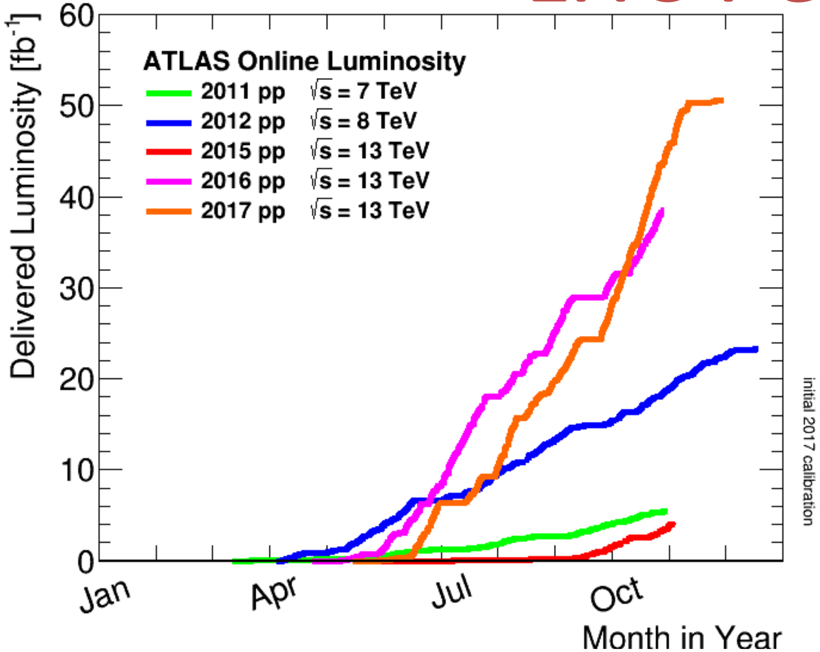
ATLAS Run 2 H→bb results

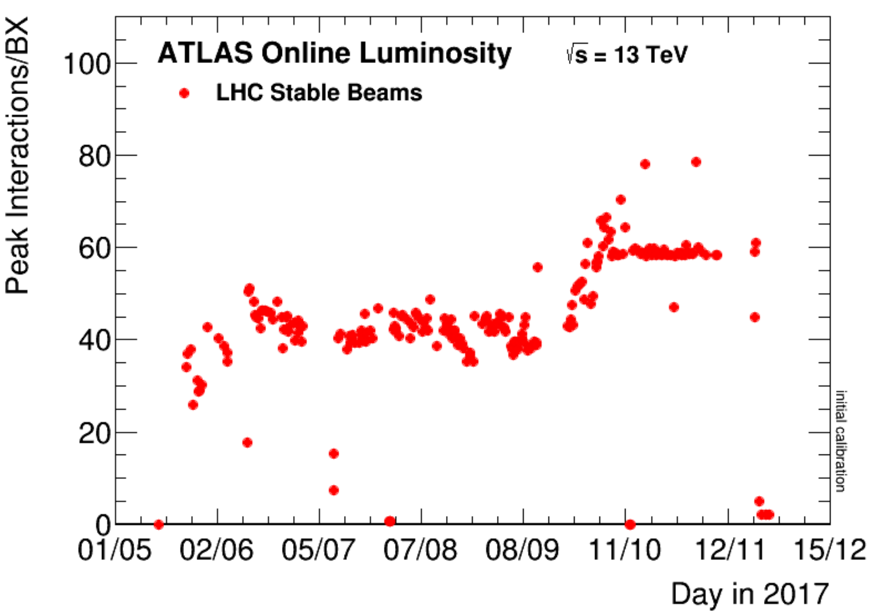
Channel	Number of Events for 36.1 fb^{-1} m_H = 125 GeV
ggH, H(bb)	~920k
VBF H, H(bb) ATLAS-CONF-2016-063	~78k
VH, H(bb) (V=W, Z) ATLAS-CONF-2017-041	~47k
ttH, H(bb) ATLAS-CONF-2016-080	~11k



- Inclusive H→bb is difficult. Can use jet substructure techniques at p_T^H> 450 GeV
- VBF also large multijet background. Additional γ can help, similar sensitivity, higher S/B
- VH main production mode for H→bb. Focus here on VH, H(bb) result released for EPS 2017 conference (now accepted for publication)
- ttH. Leptonic signatures for trigger but challenging combinatorics and difficult tt+bb background

LHC Performance



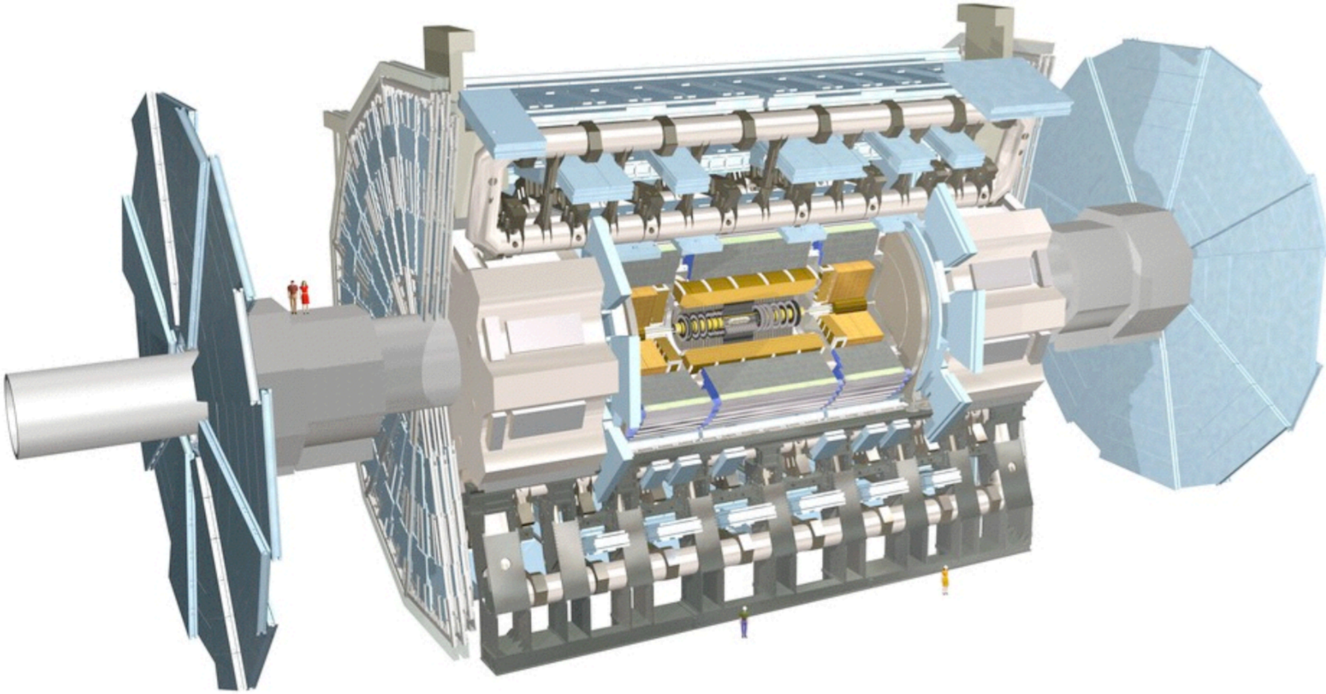


- Run 1 @7,8 TeV delivered 29 fb^{-1}
- Run 2 @13 TeV delivered 4 fb^{-1} in 2015 and 38 fb^{-1} in 2016
- 2017 pp data taking just finished. Around 46 fb^{-1} pp data for analysis

Excellent LHC performance brings higher pile-up and rates!

- Many optimisations performed in ATLAS to try to eliminate any degradation due to pile-up
- Crucial for this analysis to reduce effects of pile-up on jet resolution and missing transverse energy (MET) trigger/ measurements and on the tracking and b-jet tagging performance

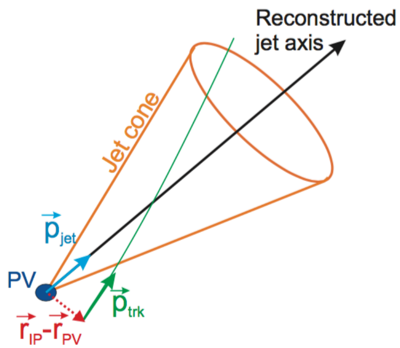
The ATLAS Detector



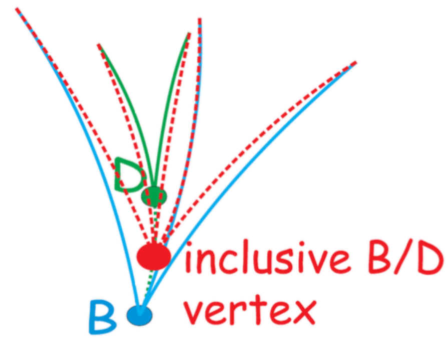
Most Important components for H→bb:

- Silicon tracking: Run 2 upgrades included insertable B-Layer close to interaction region. Revised tracking and pixel clustering algorithms. Overall improvements of factor 2 in impact parameter resolution.
- Jet energy scale uncertainty from calorimeters understood to within 1.5% in central and high p_T region
- Trigger rate at L1 increased from 75kHz to 100KHz and Higher level trigger from 400 to 1000 Hz. Also keeping MET trigger thresholds as low as possible

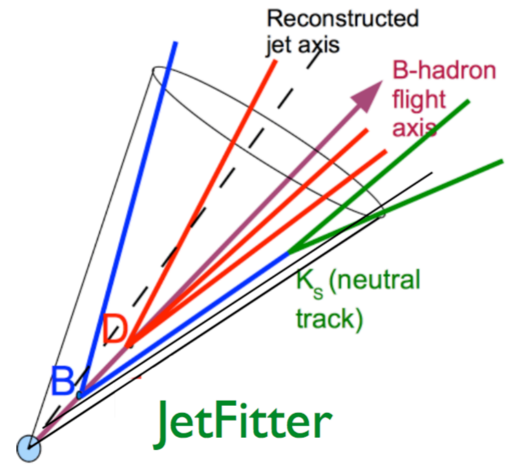
B-tagging



IP based (IP3D)



One vertex (SV1)



JetFitter

MV2c10

b-jet efficiency	light jet mistag rate	c-jet mistag
85%	3%	~33%
77%	0.7%	~16%
70%	0.3%	~8%
50%	<0.1%	~2.9%

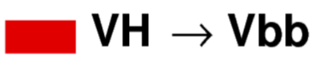
(nominal MC, ttbar events, p_T>20 GeV)

- Combine the various different taggers using a BDT to give a single discriminant
- Optimisations performed for both 2015 and 2016 data. Focus was on improving high p_T performance and increasing c-jet rejection.
- Light jet and c-jet rejection factors improved by factors 2 and 2.5 compared with Run 1.
- c-jet calibration 10% for p_T 40-80 GeV using W decays in ttbar events
- Analysis uses 70% b-jet efficiency
- b-jet calibration 2% p_T 50-100 GeV

MC Samples

Increasingly we use NLO MC programs, NNLO PDFs, normalised to highest order calculations

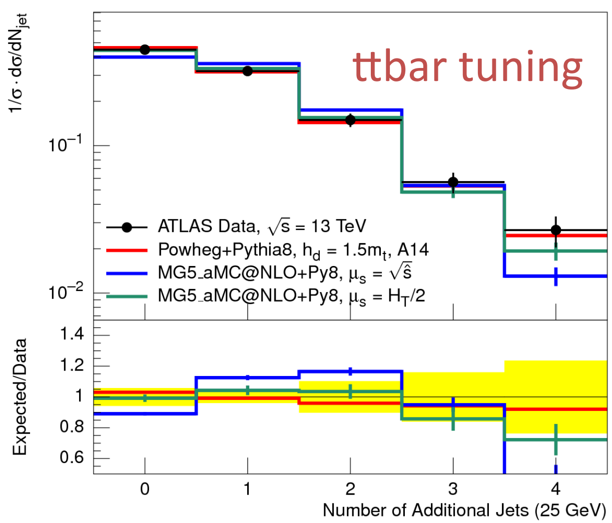
Process	ME generator	ME PDF	PS and Hadronization	UE model tune	Cross-section order	ace2.5cm
Signal						
$qq \to WH \to \ell\nu bb$	POWHEG-BOX v2 + GOSAM + MINLO	NNPDF3.0NLO$^{(\star)}$	PYTHIA8.212	AZNLO	NNLO(QCD)+ NLO(EW)	
$qq \to ZH \to \nu\nu bb/\ell\ell bb$	POWHEG-BOX v2 + GOSAM + MINLO	NNPDF3.0NLO$^{(\star)}$	PYTHIA8.212	AZNLO	NNLO(QCD)$^{(\dagger)}$+ NLO(EW)	
$gg \to ZH \to \nu\nu bb/\ell\ell bb$	POWHEG-BOX v2	NNPDF3.0NLO$^{(\star)}$	PYTHIA8.212	AZNLO	NLO(QCD)+ NLL(QCD)	
Top-quark						
$t\bar{t}$	POWHEG-BOX v2	NNPDF3.0NLO	PYTHIA8.212	A14	NNLO+NNLL	
t-channel	POWHEG-BOX v1	CT10f4	PYTHIA6.428	P2012	NLO	
s-channel	POWHEG-BOX v2	CT10	PYTHIA6.428	P2012	NLO	
Wt	POWHEG-BOX v2	CT10	PYTHIA6.428	P2012	NLO	
Vector boson + jets						
$W \to \ell\nu$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NNLO	
$Z/\gamma* \to \ell\ell$	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	

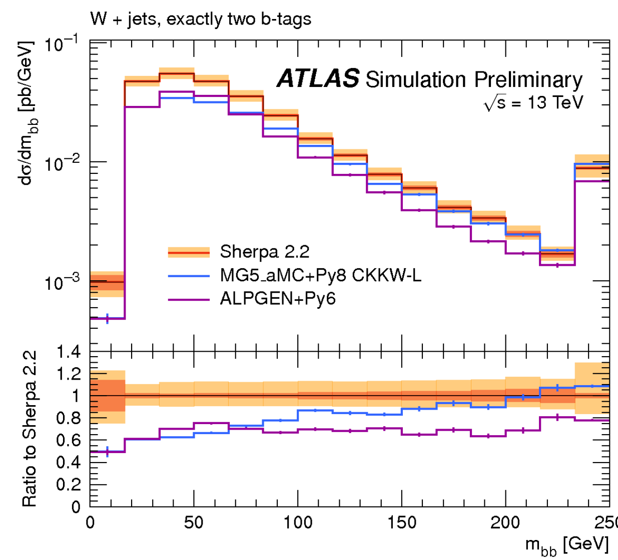


MC Samples (aside)

Increasingly we use NLO MC programs, NNLO PDFs, normalised to highest order calculations

- E.g. Sherpa V+jets uses MEPS@NLO up to 2 jets at NLO and up to 4 jets at LO
- *Improved precision* introduces new issues e.g. longer *processing time, negative* and *large* event weights from NLO method
- In order to populate backgrounds in most sensitive regions need to slice in P_T^V, H_T etc..
- For systematic uncertainties write to MC event files, where possible, weights for factorisation/renormalisation scale variations, PDF eigenvectors, α_S variations etc.
- MC studies benefit from dedicated efforts to improve understanding of physics modelling
- Produce ~annual notes on status of MC models studies (top, V+jets, multiboson, multijet) for feedback from experts e.g. at ATLAS-CMS MC workshop. https://twiki.cern.ch/twiki/bin/view/AtlasPublic/MCPublicResults



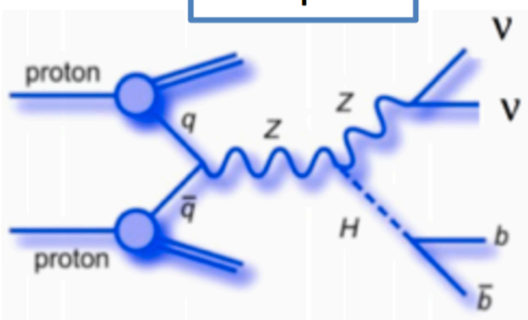


W+jets NLO vs LO

VH→bb Backgrounds

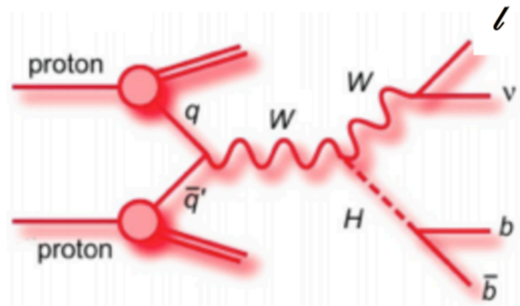
Analysis is divided into different V decays (n charged leptons) each with different backgrounds

0-Lepton



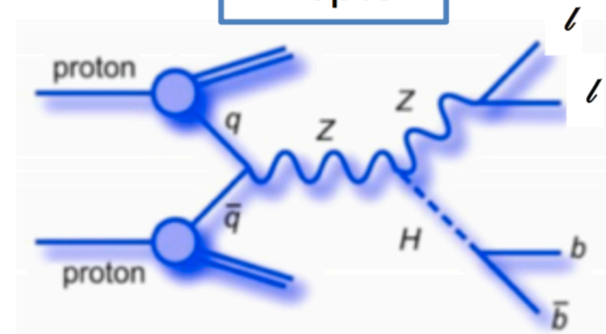
High Missing transverse momentum for trigger and reduce QCD multijets

1-Lepton



Tight lepton identification and high pTW to reduce multijets

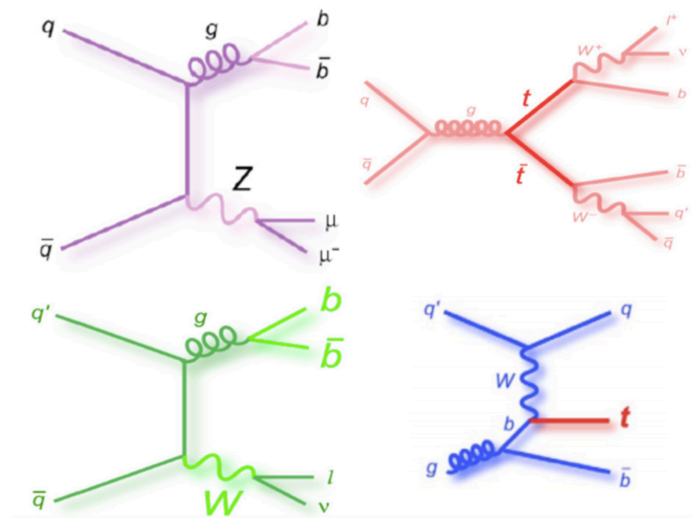
2-Lepton



Two opposite sign leptons and Z mass window

Dominant backgrounds:

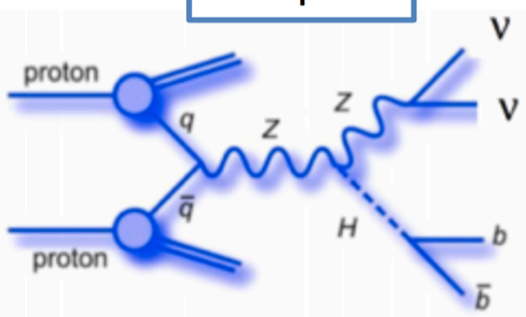
- Z/W+heavy flavour jets
- Top (ttbar and single top), particularly at higher jet multiplicity
- QCD multijet
- Diboson VZ with Z→bb and V=W,Z.
  Z resonance is used as "Standard Model Candle" to validate VH analysis



VH→bb Analysis Cuts

Analysis is divided into different V decays (n charged leptons) each with different backgrounds

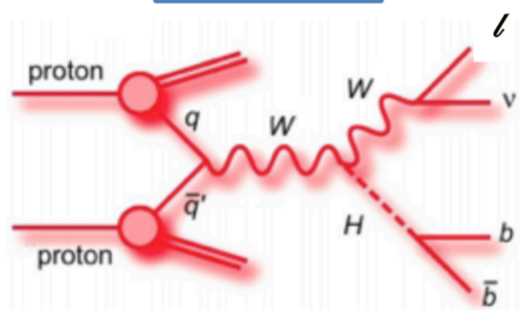
0-Lepton



High *missing transverse momentum* for trigger and reduce *QCD multijet*

Additional criteria to reduce multijet

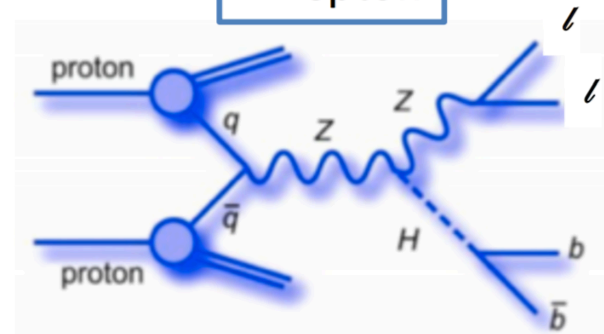
1-Lepton



Tight *lepton identification* and high p_T^W to reduce multijet

MET>30 GeV in electron channel
Muon channel triggered by MET trigger

2-Lepton



Two *opposite sign* leptons and *Z mass window*

Jets are: Anti-kT radius 0.4, pT>20 GeV(30 GeV) for |eta|<2.5(4.5): require 2 central

Exactly 2 or 3 jets, MET, p_T^W> 150 GeV

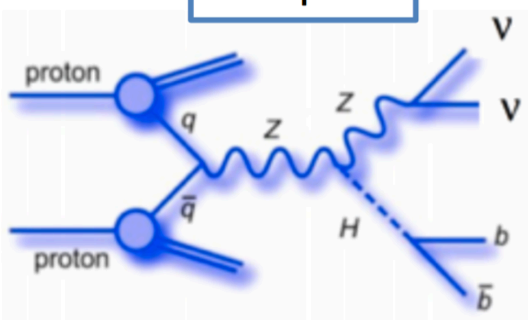
2 or >=3 jets, p_T^V> 75 GeV

- 2 b-tagged central jets with p_T > 45, 20 GeV

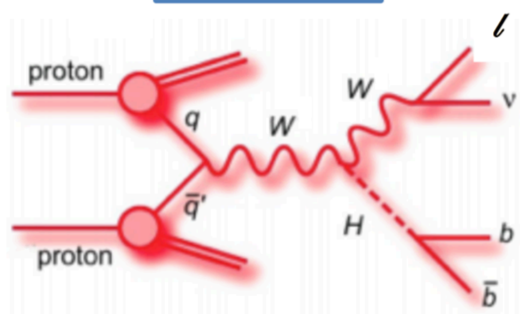
VH→bb Event Displays

Analysis is divided into different V decays(n charged leptons) each with different backgrounds

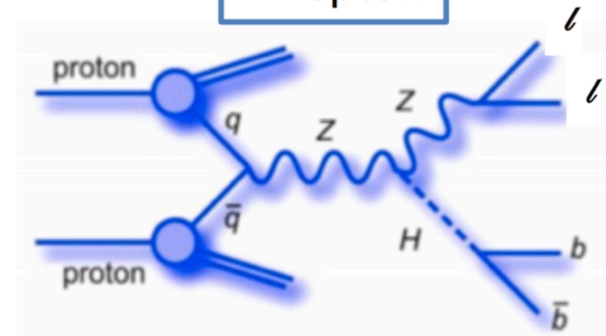
0-Lepton

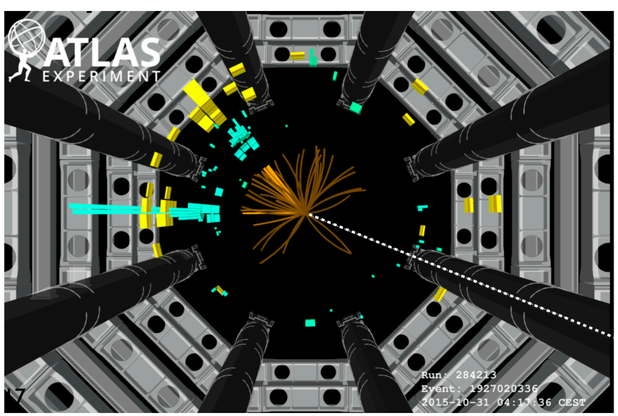


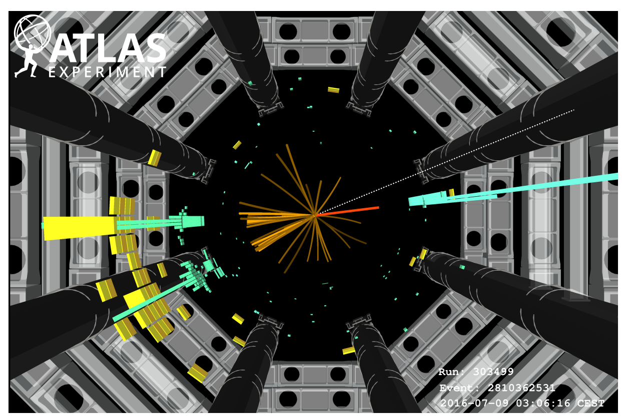
1-Lepton

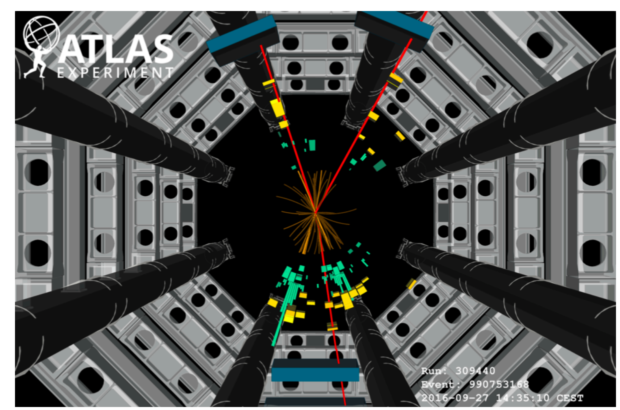


2-Lepton



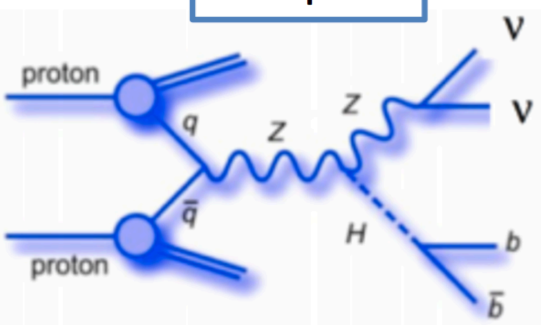






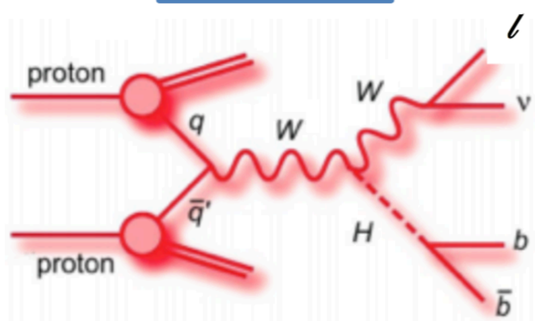
VH→bb Backgrounds(after selection)

0-Lepton



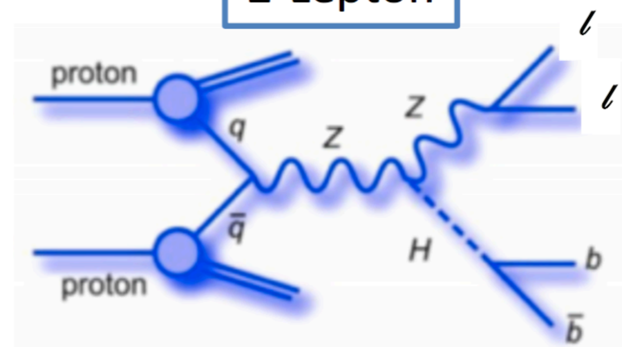
Z+hf, W+hf, ttbar

1-Lepton

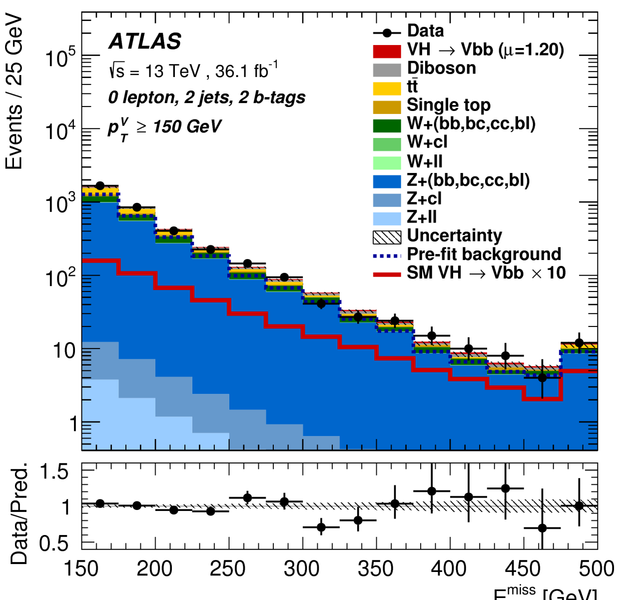


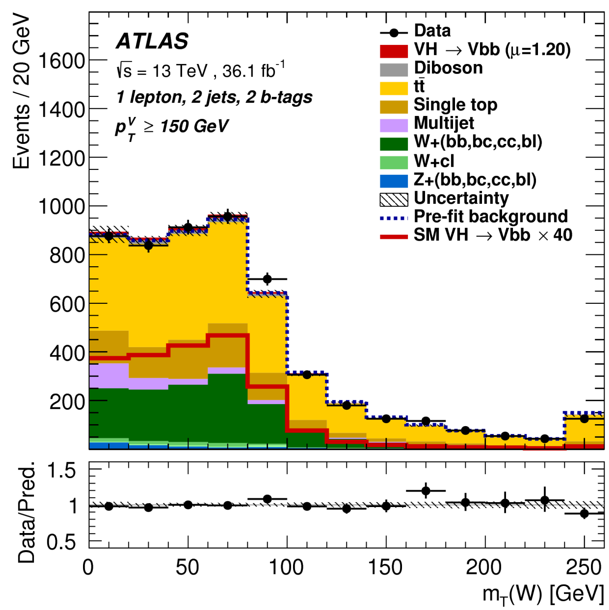
W+hf, ttbar, single-top

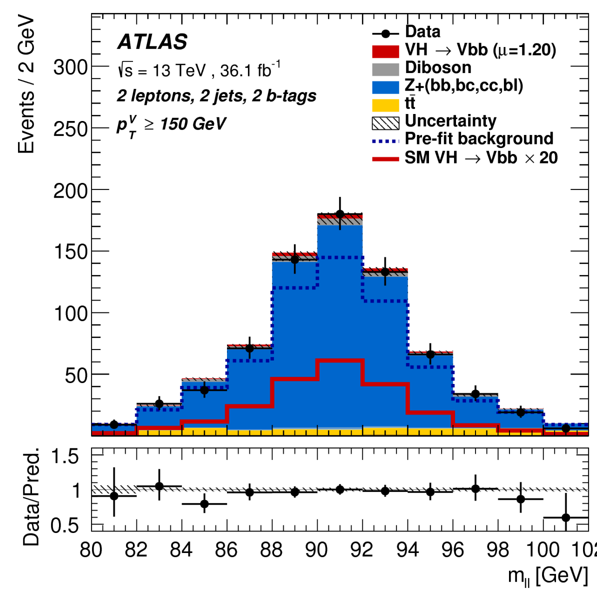
2-Lepton



Z+hf, ttbar

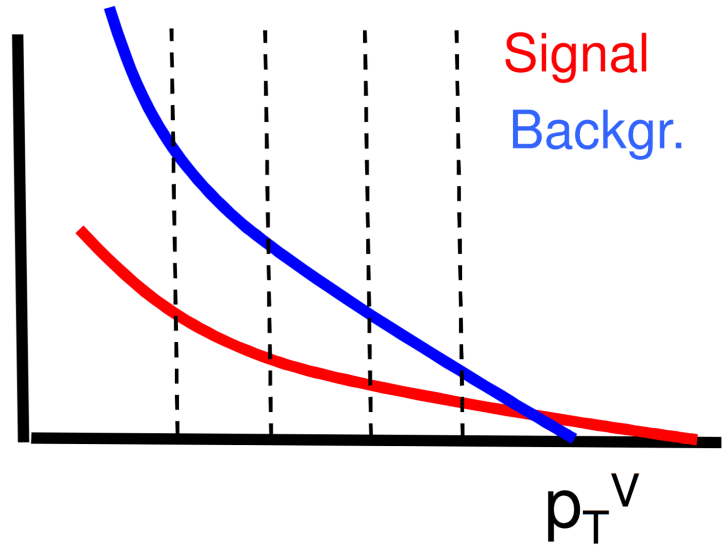






H→bb Analysis Strategy

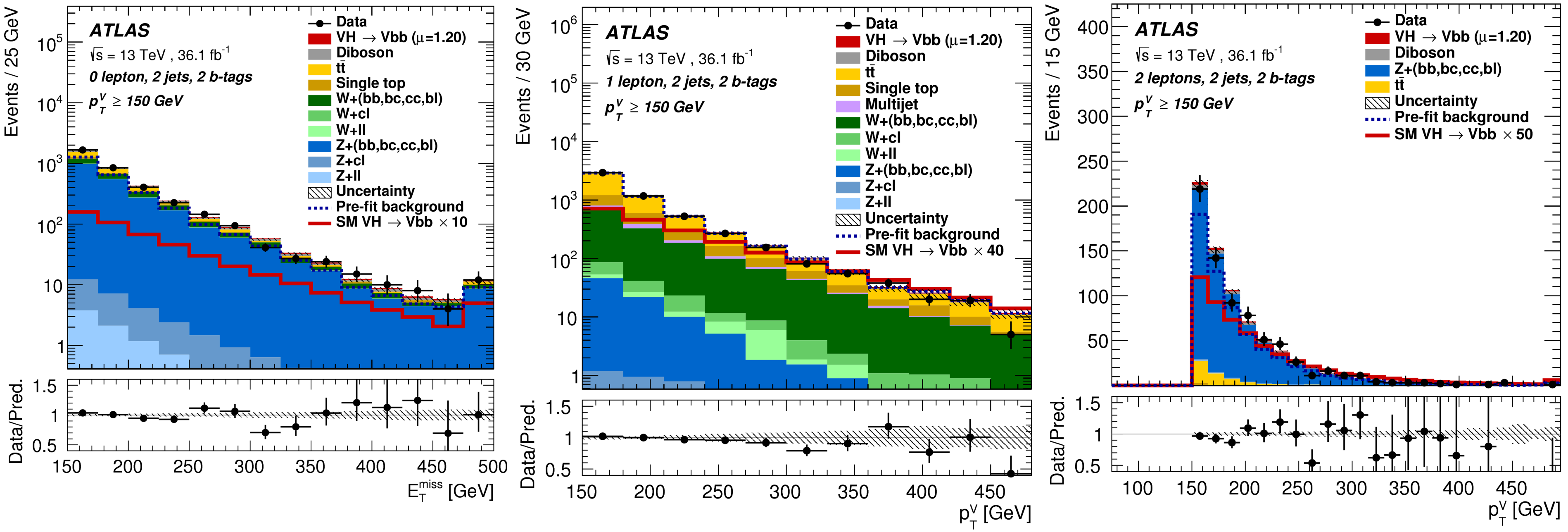
- For best sensitivity use loose selection with multivariate techniques (MVA) to reduce backgrounds ("nominal analysis")
- "Dijet mass" analysis (aka "cut based") using m_{bb} as discriminant with extra background suppressing cuts as a cross check
- Both analyses: Improve m_{bb} resolution to increase sensitivity and separate from VZ
- Both Analyses: exploit signal/background differences vs p_T^V and jet multiplicity



Control backgrounds across different lepton channels

- W+jets. Define control region (CR) at low m_{bb} and high m_{top}
- Z+jets: Clean control regions in 2 lepton data to evaluate MC modelling uncertainties
- Top: control regions at higher jet multiplicities, shape uncertainties from MC. Top CR in 2 lepton using opposite sign e-μ events.
- Multijet: Normalisations and shapes obtained from data. Difficult to control, reduce to negligible levels where possible.

Low/High pTV



Exploit the Signal and Background differences a a function of p_T^H / p_T^V / MET

- Use p_T^V categorisation. For 2 lepton nominal analysis, additional 75 < p_T^V < 150 GeV, else > 150 GeV
- Used as input variable to multivariate analysis
- Additional p_T^V > 200 GeV bin for dijet analysis
- Technicalities - requires sufficient MC stats at high p_T^V, use p_T^V slicing/filtering

Signal Event Efficiency

Signal Efficiencies for different production modes and lepton categories:

MVA analysis For b-tag eff. of 70%

Run 2

$m_H = 125$ GeV at $\sqrt{s} = 13$ TeV				
Process	Cross-section × BR [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$qq \to (Z \to \ell\ell)(H \to b\bar{b})$	29.9	< 0.1	< 0.1	7.0
$gg \to (Z \to \ell\ell)(H \to b\bar{b})$	4.8	< 0.1	< 0.1	15.7
$qq \to (W \to \ell\nu)(H \to b\bar{b})$	269.0	0.2	1.0	–
$qq \to (Z \to \nu\nu)(H \to b\bar{b})$	89.1	1.9	–	–
$gg \to (Z \to \nu\nu)(H \to b\bar{b})$	14.3	3.5	–	–

Similar event yields/sensitivity for all lepton channels

How does it compare to Run 1?

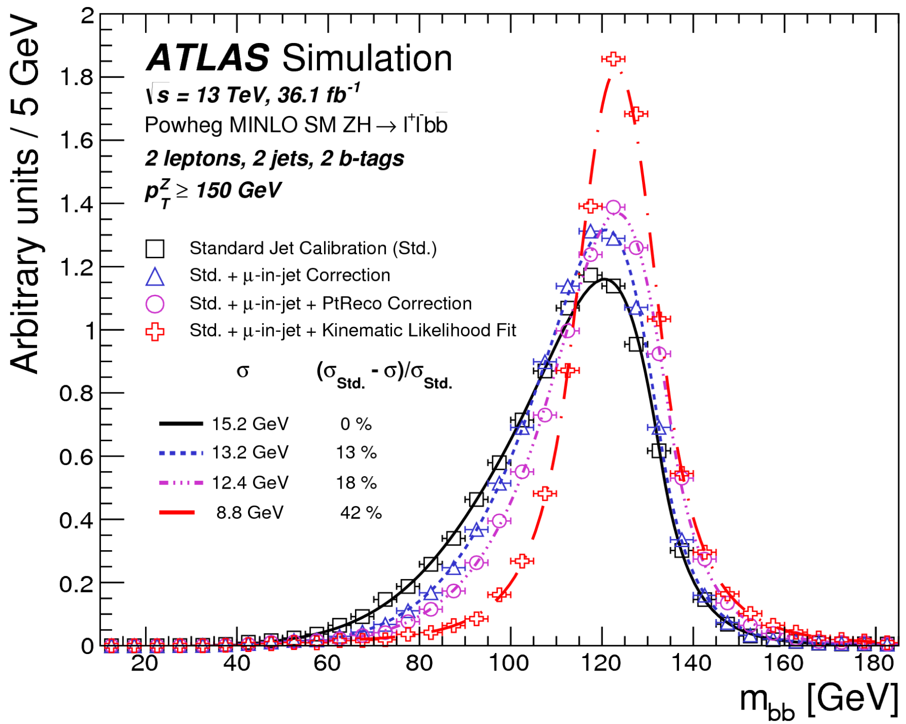
Run 1

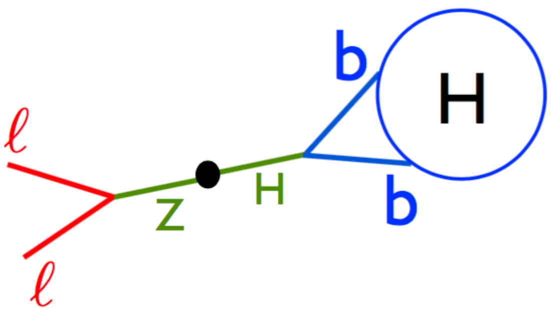
$m_H = 125\,\text{GeV}$ at $\sqrt{s} = 8\text{TeV}$				
Process	Cross section × BR [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$q\bar{q} \to (Z \to \ell\ell)(H \to b\bar{b})$	14.9	–	1.3 (1.1)	13.4 (10.9)
$gg \to (Z \to \ell\ell)(H \to b\bar{b})$	1.3	–	0.9 (0.7)	10.5 (8.1)
$q\bar{q} \to (W \to \ell\nu)(H \to b\bar{b})$	131.7	0.3 (0.3)	4.2 (3.7)	–
$q\bar{q} \to (Z \to \nu\nu)(H \to b\bar{b})$	44.2	4.0 (3.8)	–	–
$gg \to (Z \to \nu\nu)(H \to b\bar{b})$	3.8	5.5 (5.0)	–	–

MVA (cut based) analysis for b-tag eff. of 80%

Generally lower (taking b-tag eff into account) – tighter trigger conditions due to higher pile-up, analyses start at higher pTV (better sensitivity, background modelling)
Benefit from increased cross section (especially gg→ZH) and COM p_T^V boost

m_{bb} Reconstruction



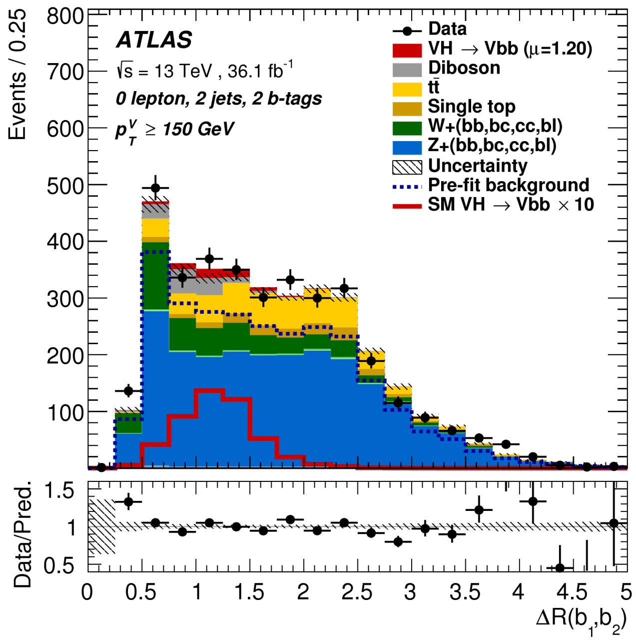


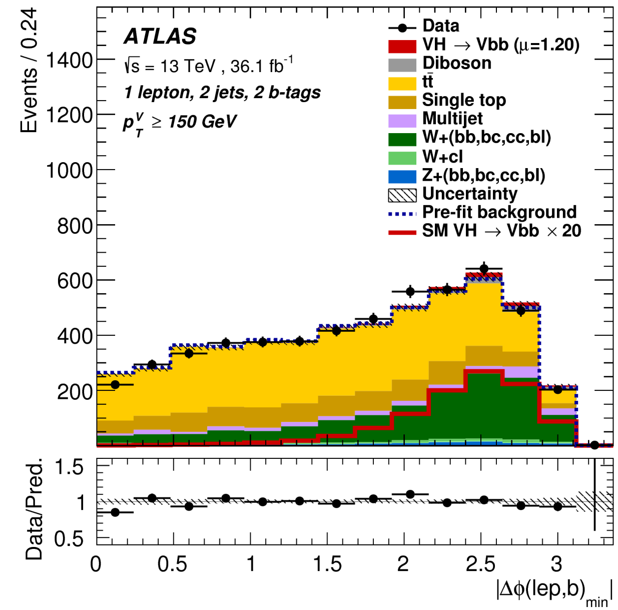
$$\vec{p}_{T,b\bar{b}} = \sum_{\ell} \vec{p}_{T,\ell}$$

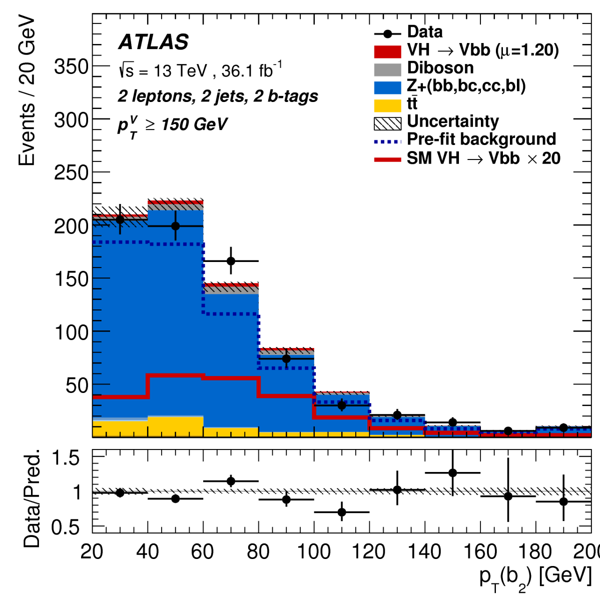
- Start from standard jet Calibration (topological clusters + sequential corrections including 2 corrections for pile-up)
- Add any close by muons from semi-leptonic decays to the jet
- Apply a "PtReco" correction as function of p_T of jet to obtain "true" pT
- In 2 lepton events additional constraint that no real energy imbalance in event. Apply kinematic Likelihood Fit using parameterisations of lepton and jet resolutions

Multivariate Analysis

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







- As Run 1, use Boosted Decision Tree (BDT)
- 17 input variables used to various degrees by channels
- BDT inputs include m_{bb} for all channels
- Train per channel in 2/3 jet categories and low/high p_T^V for 2 lepton, for VH and VZ as signal
- Check BDT inputs are well modelled by MC models

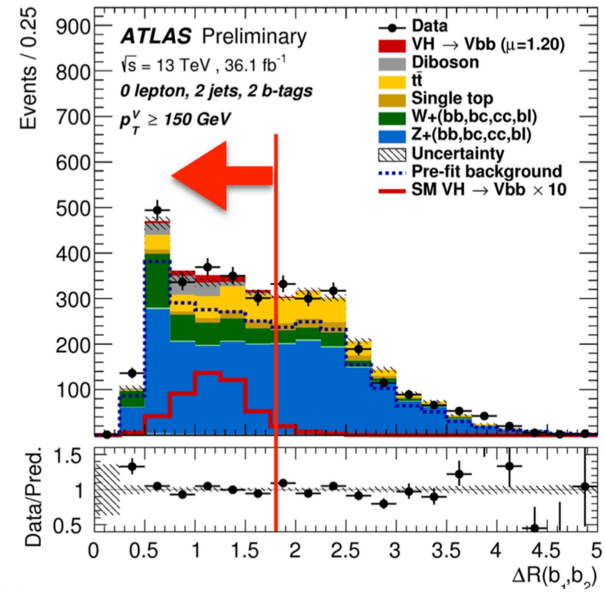
m_{bb} Analysis

$\Delta R(\mathrm{b}_1, \mathrm{b}_2)$

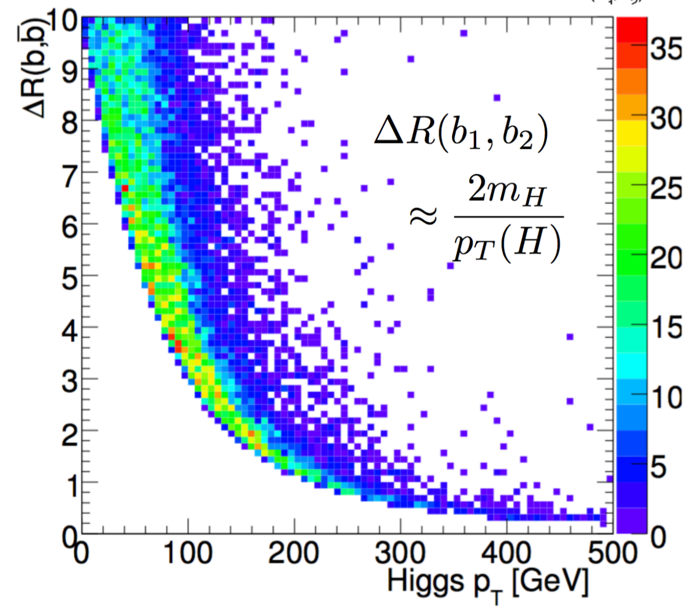
Additional selection criteria w.r.t. nominal MVA

	Channel		
Selection	0-lepton	1-lepton	2-lepton
m_{T}^{W}	-	< 120 GeV	-
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{S_{\mathrm{T}}}$	-	-	$< 3.5\sqrt{\mathrm{GeV}}$

	p_{T}^{V} regions		
p_{T}^{V}	[75, 150] GeV (2-lepton only)	[150, 200] GeV	[200, ∞] GeV
$\Delta R(b_1, b_2)$	<3.0	<1.8	<1.2



- Exploit p_T variation of S/B
- Additional category for $p_T^V > 200$ GeV
- Require smaller ΔR(b1,b2) for increasing p_T^V
- Highly efficient for signal and suppresses e.g. ttbar background
- Note: at around pT>400 GeV the 2 radius=0.4 jets start to merge



H→bb Analysis Regions

Simultaneous *likelihood fit* to discriminating variables in all analysis regions to extract:

- Signal strength μ
- *Normalisation* of 3 main backgrounds (ttbar and Z/W+HF freely floating)
- *Shapes* and *relative normalisations* between regions parameterised by *nuisance parameters* constrained within allowed systematic uncertainties (priors)

Channel	SR/CR	Categories			
		2 b-tagged jets			
		$75\ \text{GeV} < p_T^V < 150\ \text{GeV}$		$p_T^V > 150\ \text{GeV}$	
		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}

Nominal:
8 Signal Regions
6 Control Regions

Cut Based:

14 Signal Regions
4 Control Regions

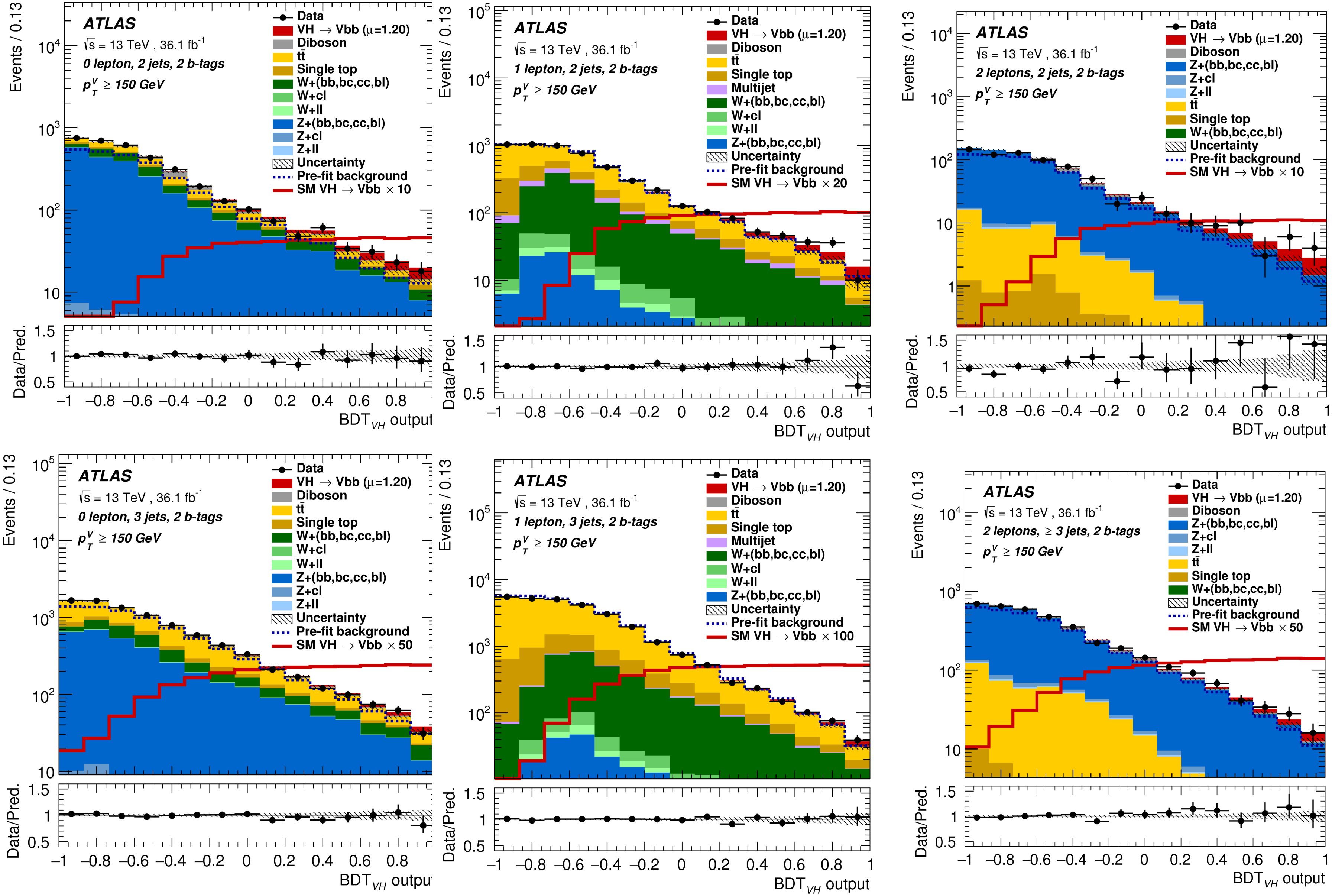
Channel	SR/CR	Categories					
		2 b-tagged jets					
		$75\ \text{GeV} < p_T^V < 150\ \text{GeV}$		$150\ \text{GeV} < p_T^V < 200\ \text{GeV}$		$p_T^V > 200\ \text{GeV}$	
		2 jets	3 jets	2 jets	3 jets	2 jets	3 jets
0 lepton	SR	-	-	m_{bb}	m_{bb}	m_{bb}	m_{bb}
1 lepton	SR plus W+HF CR	-	-	m_{bb}	m_{bb}	m_{bb}	m_{bb}
2 lepton	SR	m_{bb}	m_{bb}	m_{bb}	m_{bb}	m_{bb}	m_{bb}
2 lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield*	$m_{bb}{}^{\dagger}$	Yield*	$m_{bb}{}^{\dagger}$

Background Estimation

0-Lepton | 1-Lepton | 2-Lepton

2-jet

3-jet

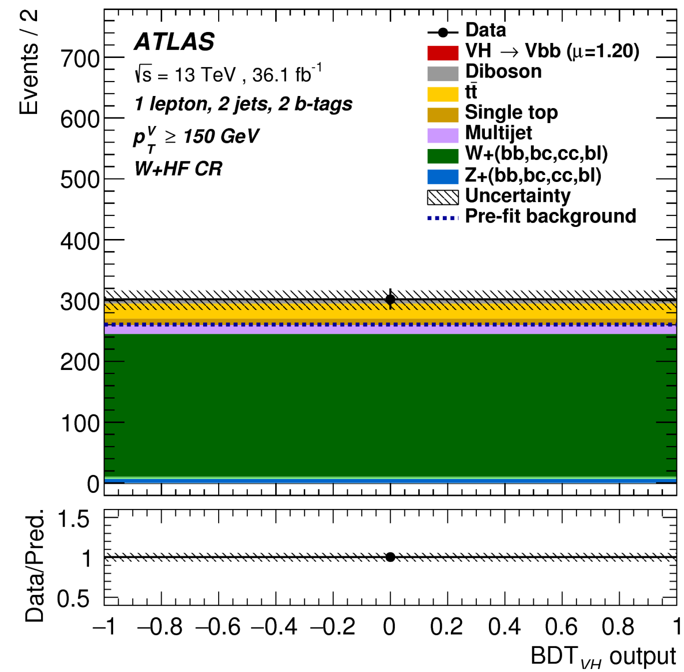


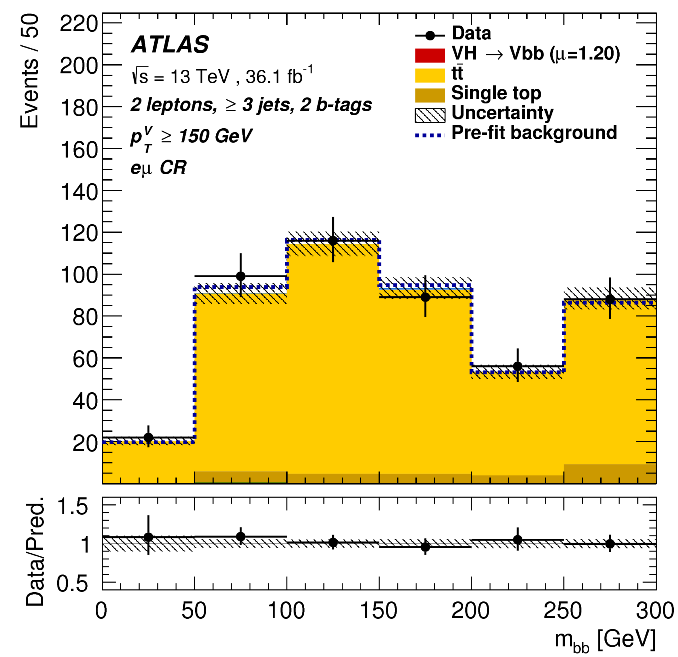
Control Regions

Dedicated control regions to better isolate backgrounds

Control Region	**W+HF**	**ttbar**
Channel	1 lepton	2 lepton
Selection	m_{bb} < 75 GeV, m_{top}>225 GeV	Require e-μ
purity	75-80%	>99%
Fit observable	yield	m_{bb}

- W+HF use yield only
- m_{bb} used in 2 lepton ttbar CR to control systematics on shape
- Due to different regions of phase space probed ttbar model in the 2 lepton channel is decorrelated from the 0 and 1 lepton
- Use MC modelling variations as uncertainty on extrapolation from CR to signal region





W/Z Background Model

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%
p_T^V, m_{bb}	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)
p_T^V, m_{bb}	S

Free floating uncertainties:

Process	Normalisation factor
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

Data suggest need for better theoretical understanding

Modelling uncertainties from MC/data studies:

Extrapolation to 0-lepton

Extrapolation from W+HF to SR

ttbar Background Model

Free floating uncertainties

Process	Normalisation factor
$t\bar{t}$ 0- and 1-lepton	0.90 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	0.97 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	1.04 ± 0.06

Theory agrees with data within errors

$t\bar{t}$ (all are decorrelated 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%
p_T^V, m_{bb}	S

Extrapolation uncertainties analogous to W/Z

Impact of Systematics on μ

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

Limiting factors
- Signal modelling
- Monte Carlo statistics
- Flavour tagging
- Background modelling

Systematically Limited

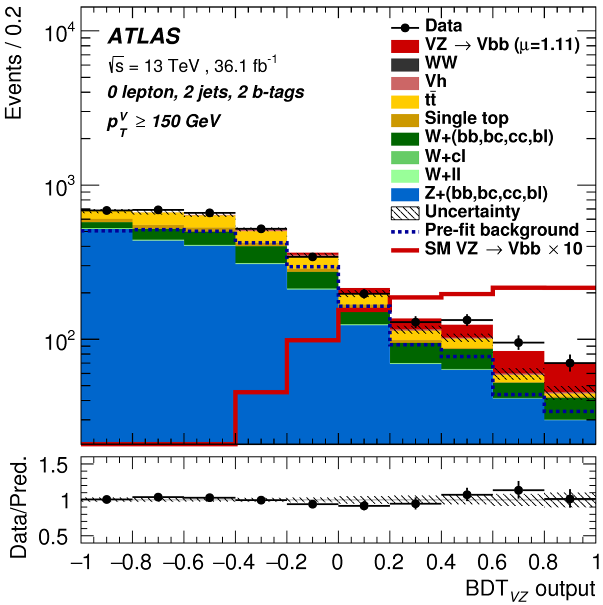
Signal modelling dominated by extrapolation from high p_T^V to full phase space and showering Pythia 8 vs Herwig 7. Doesn't affect significance

Monte Carlo Stats in spite of pTV slicing

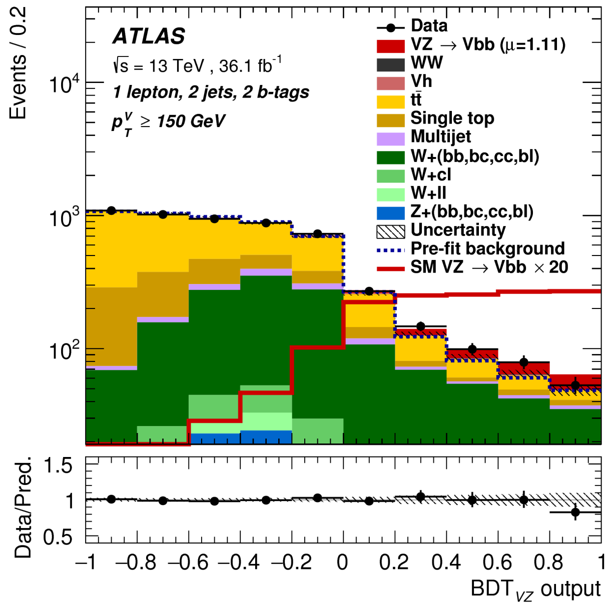
Backgrounds(data+MC): all contribute similar level

VZbb BDT Analysis

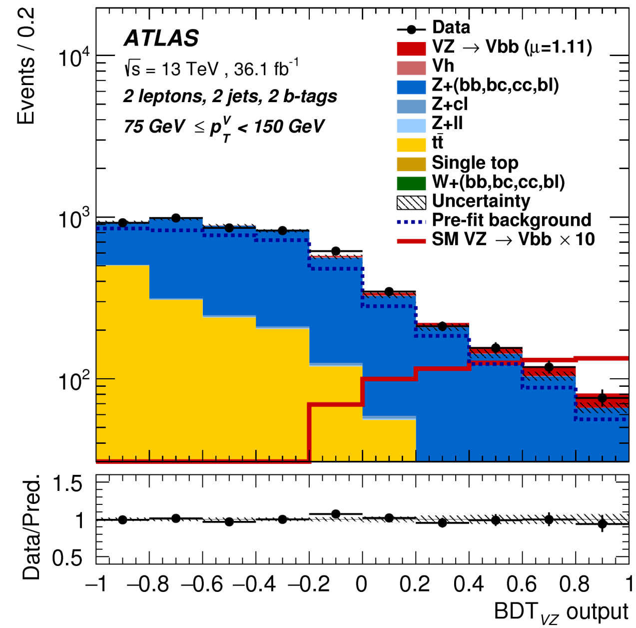
0-lepton, 2-jet, p_T^V>150 GeV



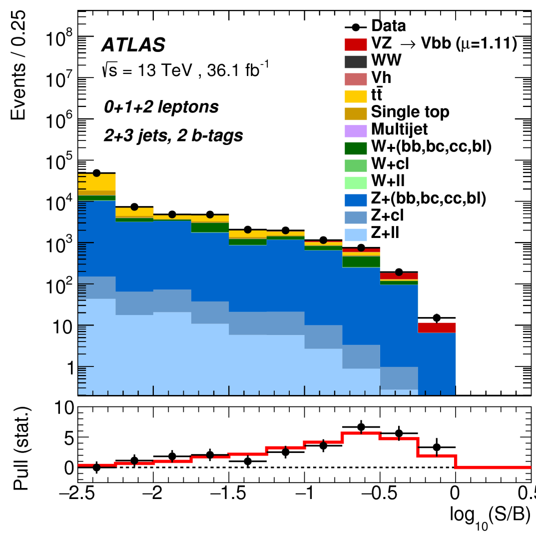
1-lepton, 2-jet, p_T^V>150 GeV



2-lepton, 2-jet, p_T^V>150 GeV

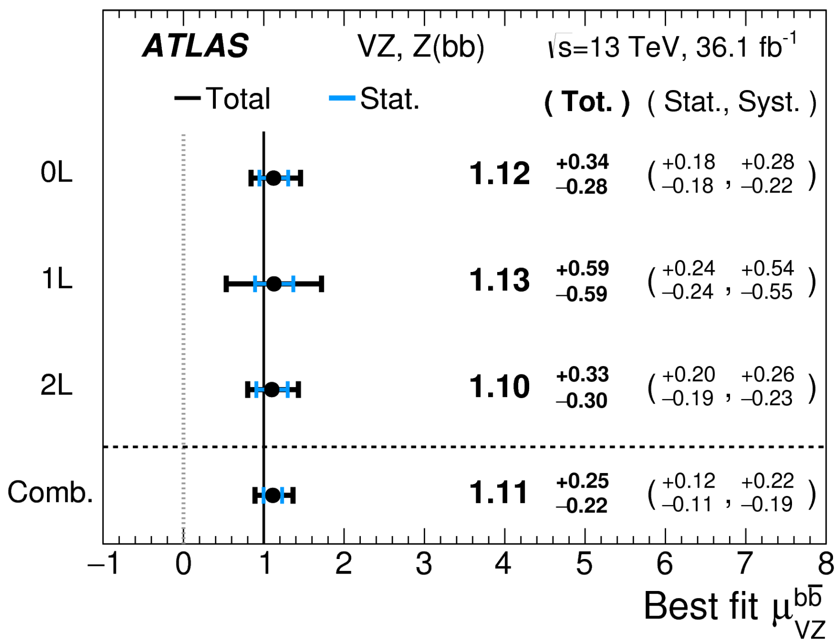


Final discriminants from all regions plotted as function of $\log_{10}(S/B)$

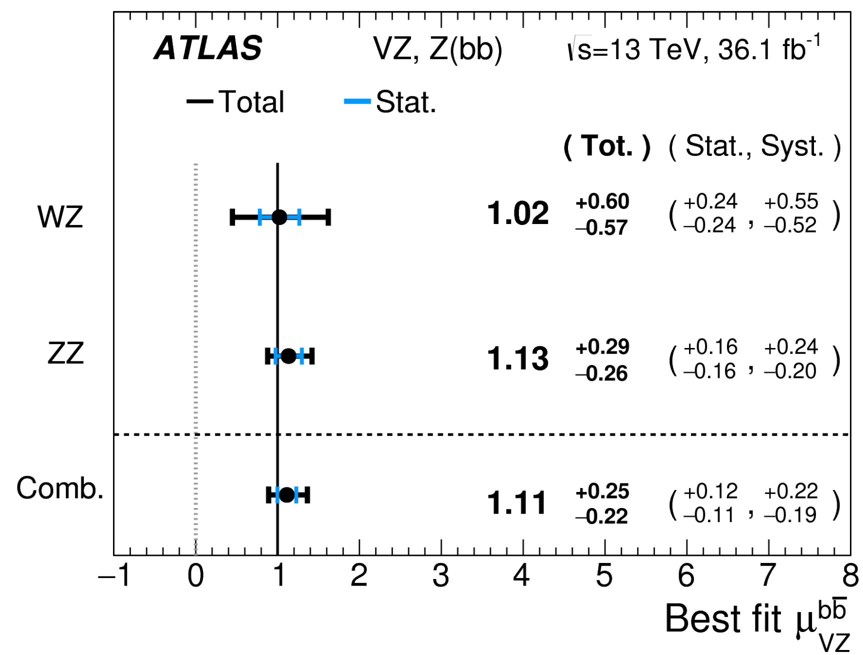


VZ Analysis Results

Fitted signal strength for 0,1,2 lepton analyses



Fitted signal strength for W/ZH processes



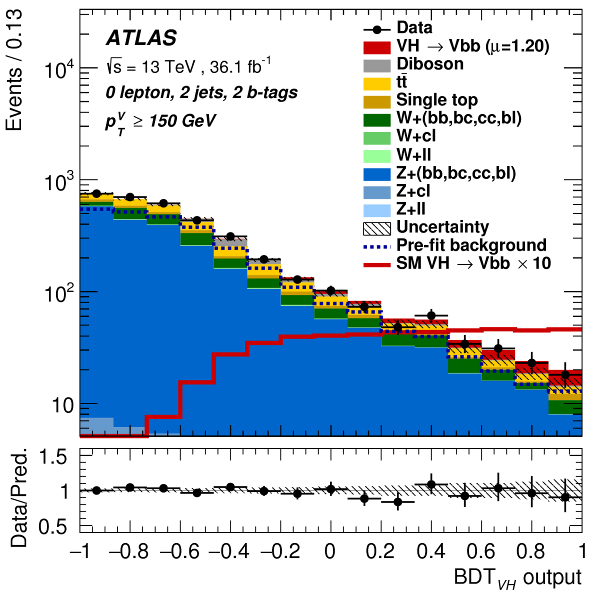
Compatibility ~100%

Significance:
5.8σ observed
5.3σ expected

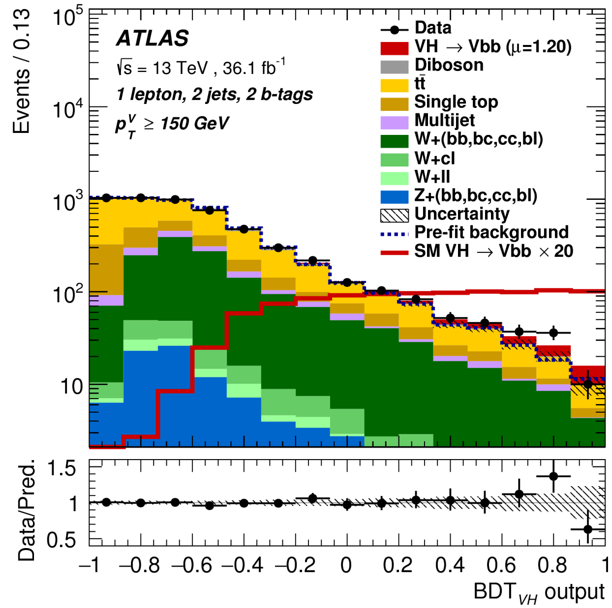
Now we have validated the analysis with known SM process let's look at VH…

VH BDT Analysis

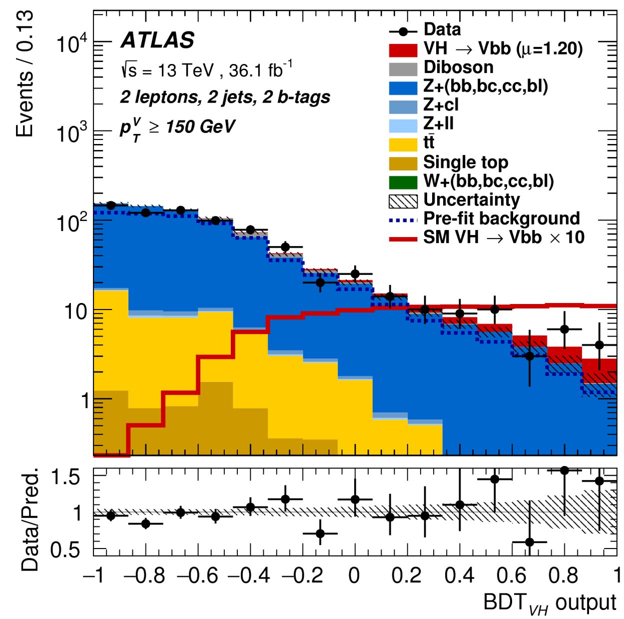
0-lepton, 2-jet, p_T^V>150 GeV



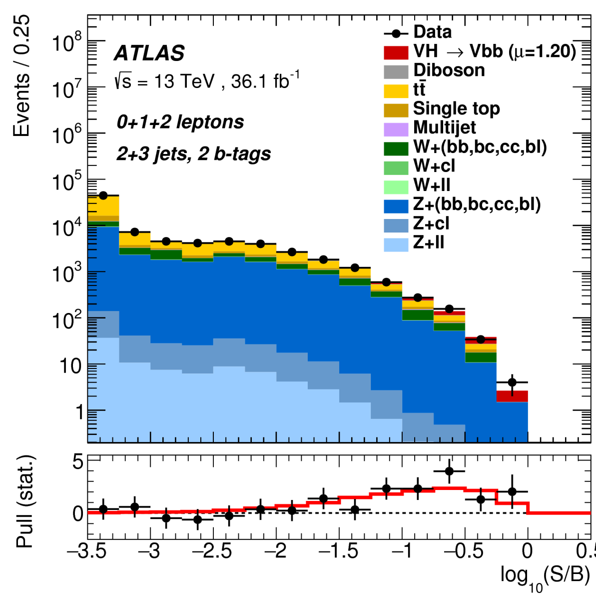
1-lepton, 2-jet, p_T^V>150 GeV



2-lepton, 2-jet, p_T^V>150 GeV

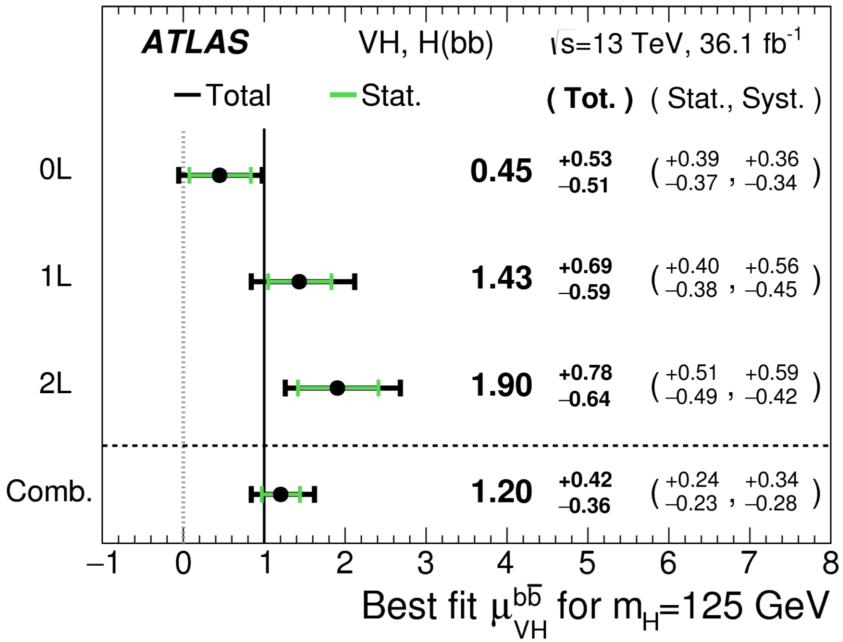


Final discriminants from all regions plotted as function of $\log_{10}(S/B)$

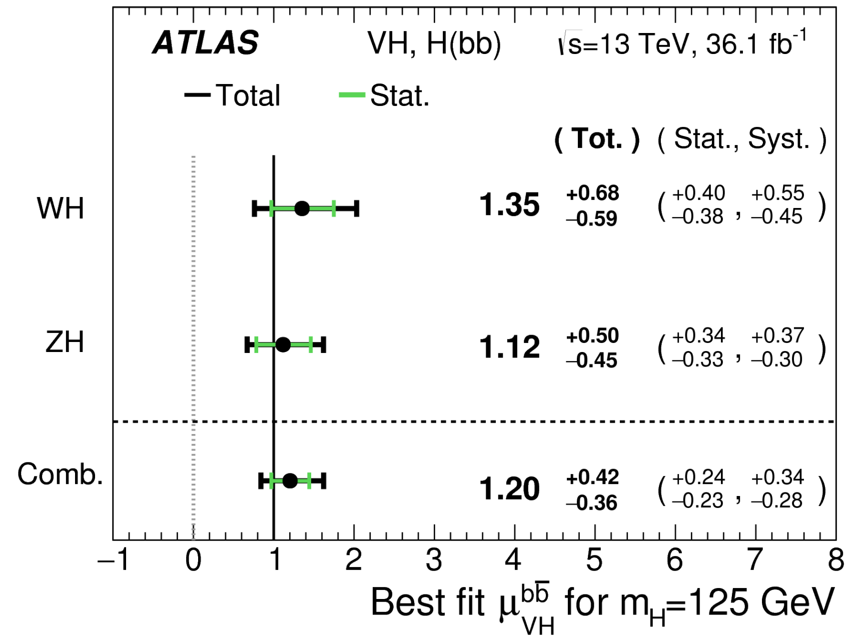


VH Analysis Results

Fitted signal strength for 0,1,2 lepton analyses



Fitted signal strength for W/ZH processes

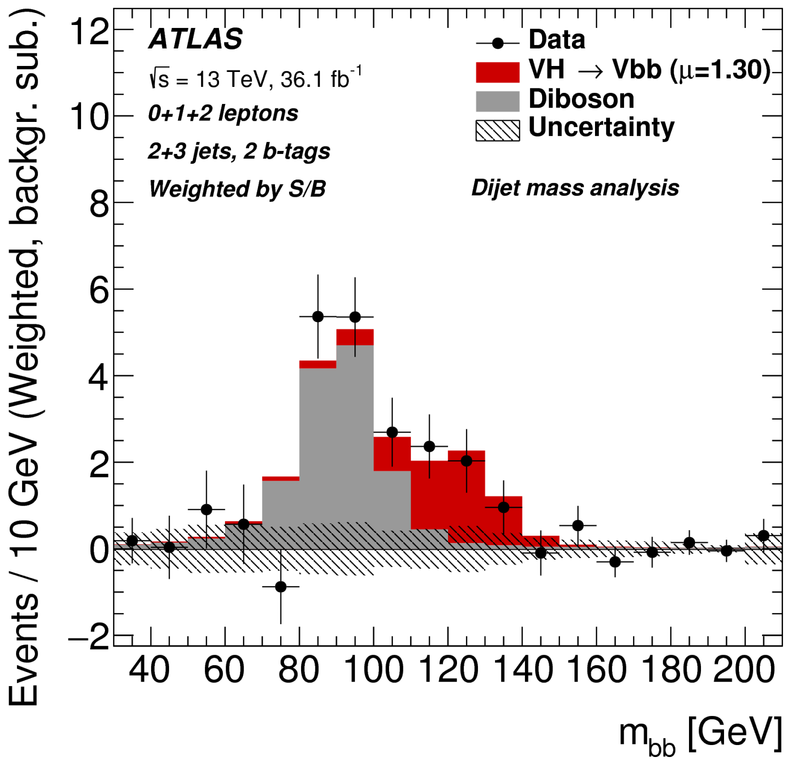


Significance:
Observed 3.5σ
Expected 3.0σ

- 3.5σ evidence for VH, H→bb
- Within 1σ of SM

Dijet-mass Analysis

- A fit to the m_{bb} observable is applied in 18 analysis regions
- Background subtracted (except diboson) m_{bb} distribution.
- Entries weighted by S/B. Background stat. and sys. uncertainty band shown



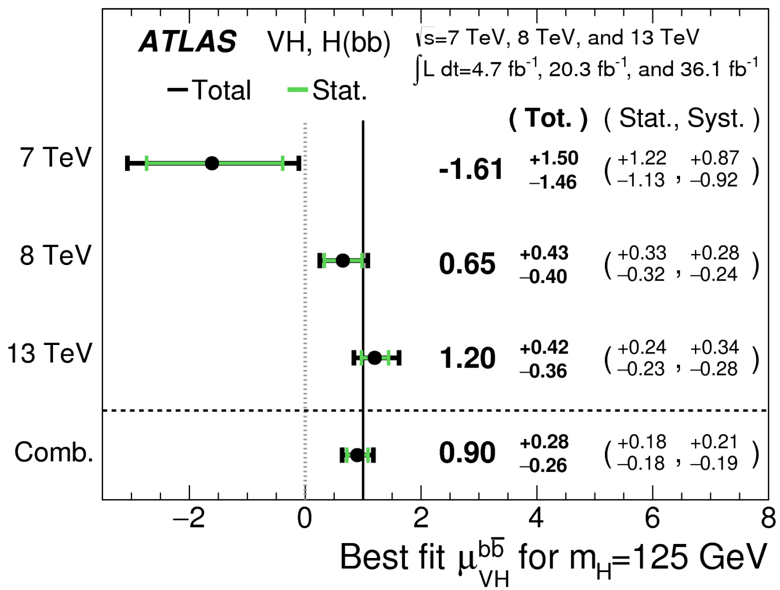
Significance:
3.5σ observed
2.8σ expected

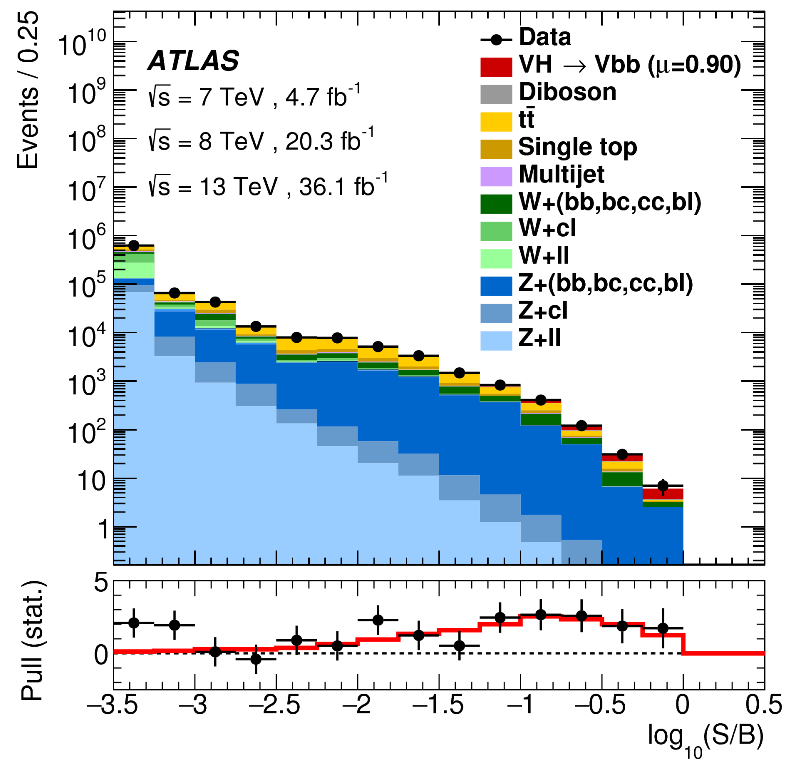
- Important validation of BDT analysis

Signal strength: $\mu=1.30^{+046}_{-0.40}$ (tot.) $^{+0.28}_{-0.27}$ (stat.) $^{+0.37}_{-0.29}$ (syst.)

Run 1 + 2 Combination

- The Run-2 BDT VH, H → bb analysis is combined with the corresponding Run-1 analysis.
- Signal uncertainties and b-jet energy scale uncertainties are correlated across years. The impact of correlations in other uncertainties was cross-checked and found to be negligible.



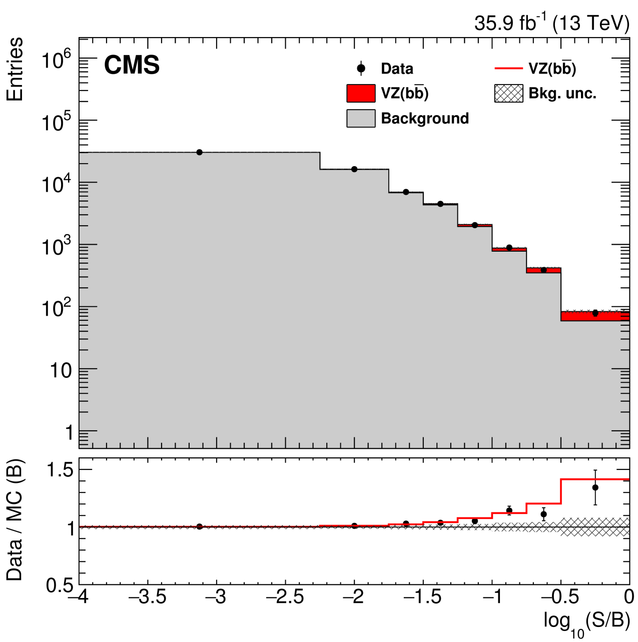


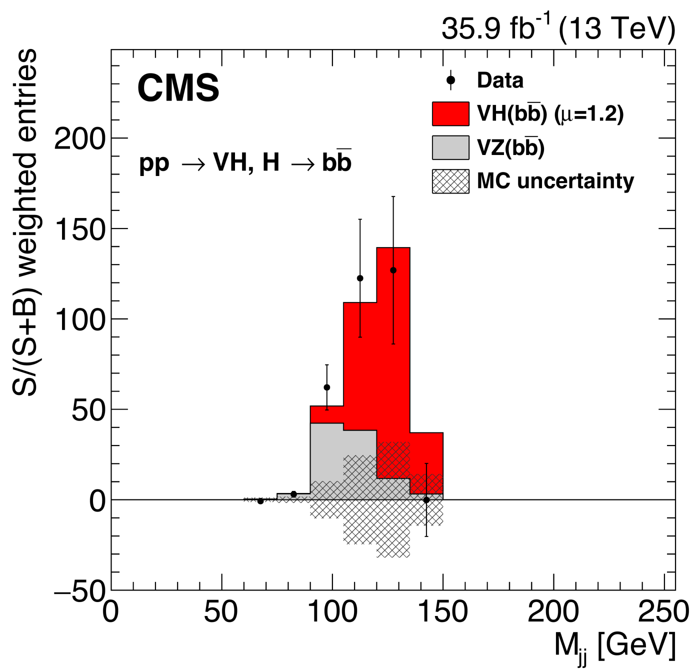
Significance:
Observed 3.6σ
Expected 4.0σ

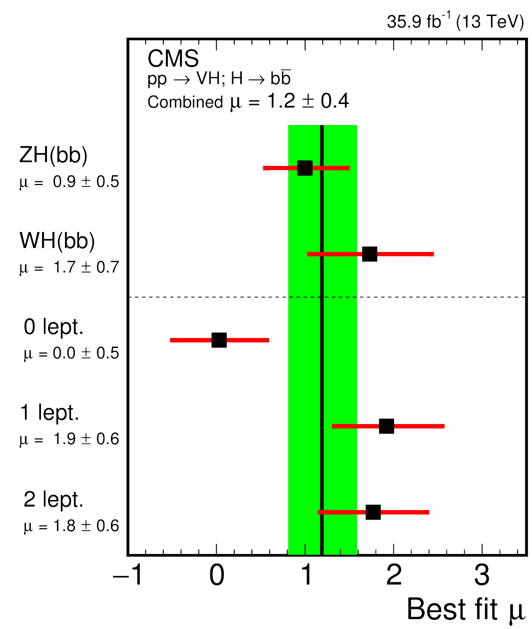
CMS VHbb Results

- CMS Result on similarly sized dataset and kinematic region was submitted in September
  https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-16-044
- Sensitivity similar: significance 2.8 expected and observed 3.3, which is signal strength: 1.2 ± 0.4
- Combined with Run-1 gives significance of 3.8 (3.8) expected (observed), and signal strength:

$$1.06^{+0.31}_{-0.29}$$







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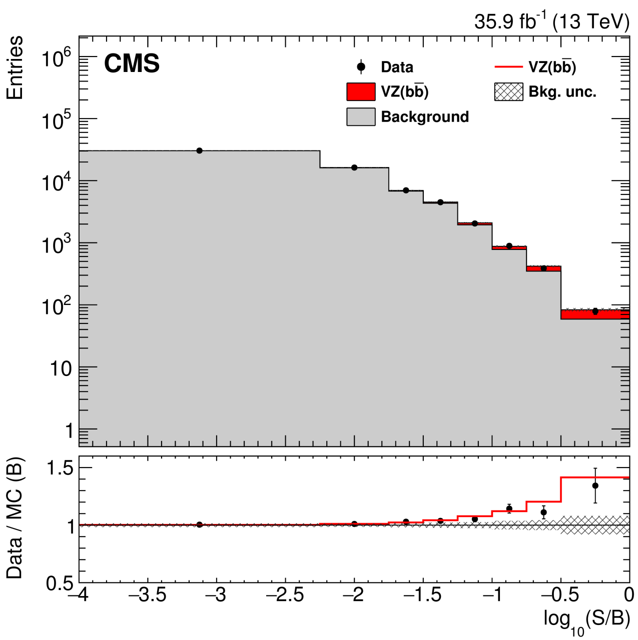
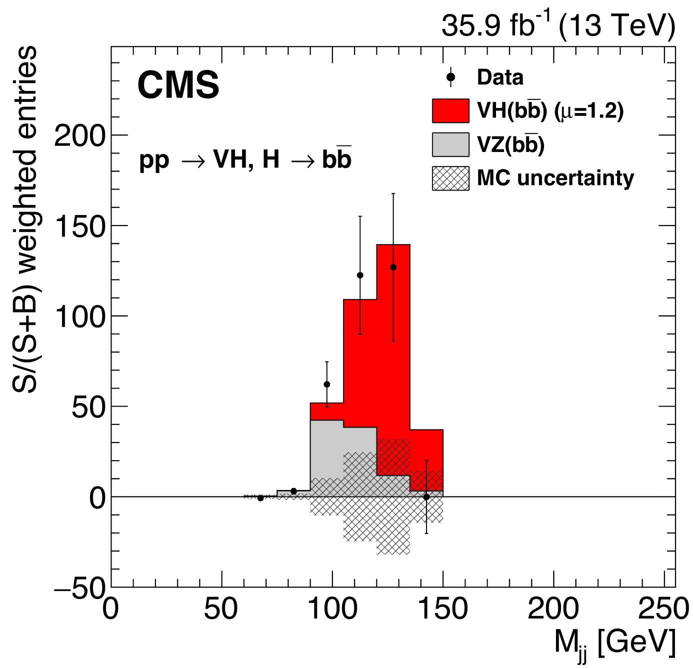
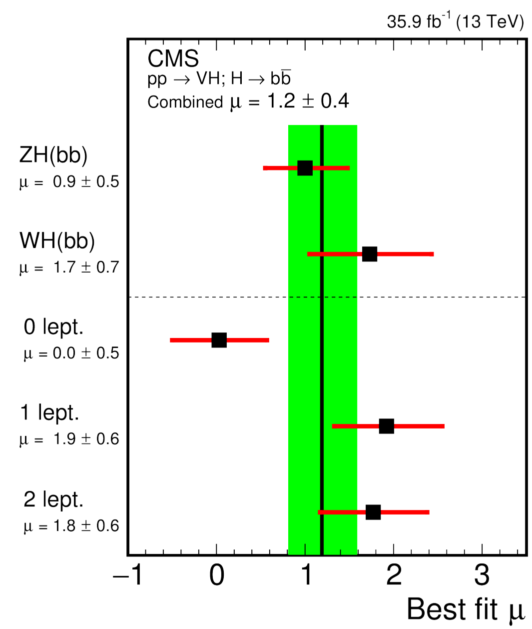


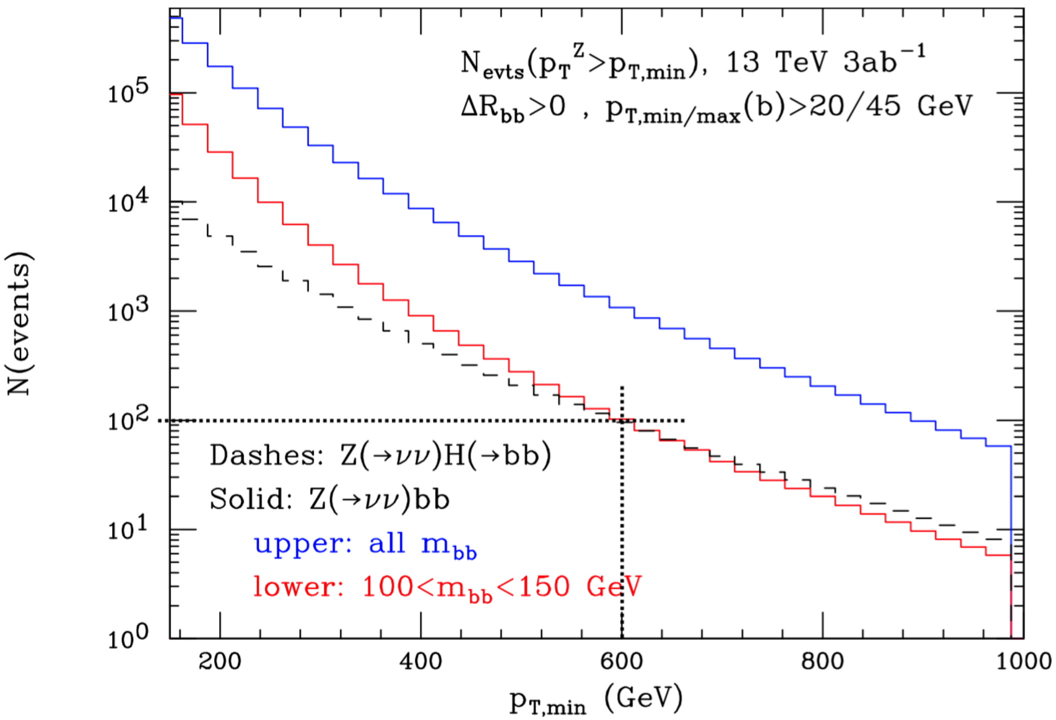




Outlook (VHbb Run 2)

- Now have VHbb evidence will process 2017 data and try to establish observation (the race is on!) . Analysis will become increasingly systematically limited, focus on systematics, turning measurements into "template cross sections".
- Background modelling uncertainties will benefit from more data. All backgrounds similar importance: can try to improve MC modelling limited ones e.g. Single top uncertainty dominated by Wt overlap with ttbar
- Continue the impressive detector/calibration performance. Mitigate effects of increased pile-up.
- Large signal uncertainties. Reduce part of these by measuring the visible cross sections, p_T^V bins? For the future m(VH) distribution (sensitive to new physics)
- Update combinations e.g. with ttH(bb)
- Gains from deep machine learning? Although now signal is established cut based may give similar performance.
- Sub-structure techniques? Still too early?
- New ideas, techniques…?
- And think more about the future with 3000 fb^{-1} pb data...

VHbb and HL-LHC



- The focus will be on H->bb at high pT. The fact we didn't see new physics at the LHC turn-on means it is hiding at larger scales
- The increase in *precision* means we want to increase our *sensitivity* to the new physics
- "Back of the envelope" calculations from M. Mangano
- Using full HL-LHC data and boosted "fat-jets" with 2 b-subjets

at $p_T > 150$ GeV: $B = 10^5$ $S = 10^4$ => $\delta = \sqrt{B}/S \sim 3\%$

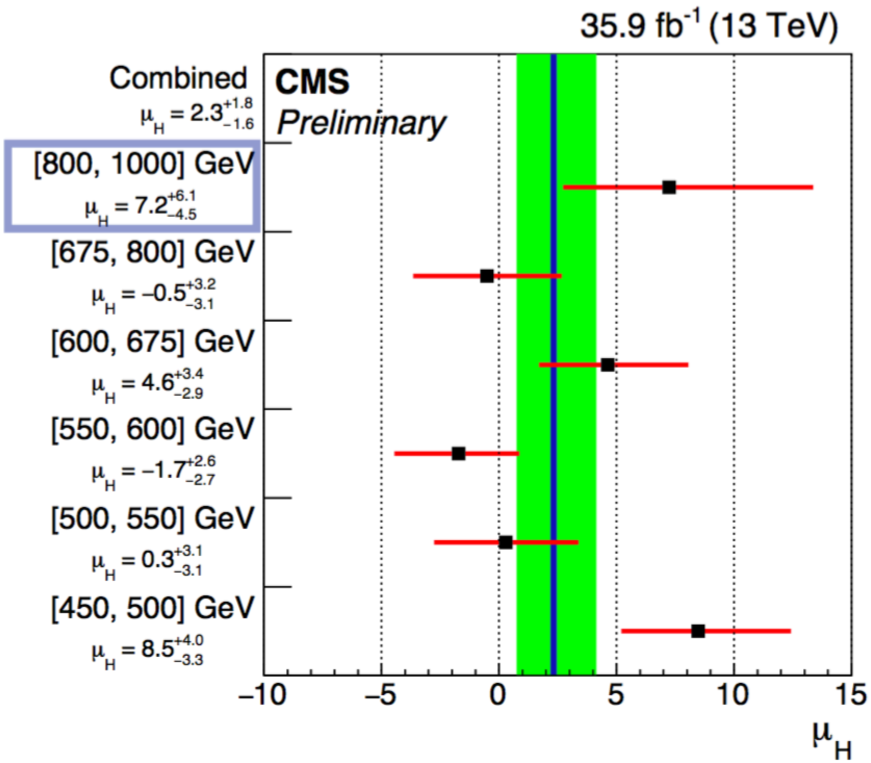
at $p_T > 600$ GeV: $B = 10^2$ $S = 10^2$ => $\delta = \sqrt{B}/S \sim 10\%$

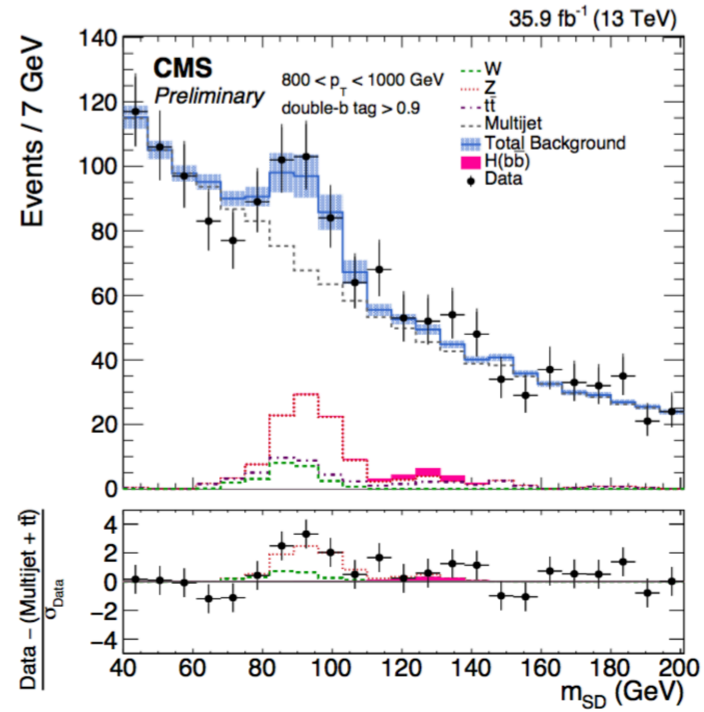
$$\delta \sim (p_{T,min}/\Lambda)^2 \Rightarrow \Lambda \sim p_{T,min}/\sqrt{\delta} \Rightarrow$$

$$\Lambda_{600}/\Lambda_{150} = 600/150 * \sqrt{(3\% / 10\%)} \sim 2.3$$

Looking for deviations from SM across the pT spectrum

CMS Inclusive H->bb





- Looking inclusively at H->bb, signal production mainly ggF. Background is QCD di-b-jets
- Look in the high pTbb (>450 GeV) region for better S/B where the boost merges the 2-bjets
- Use large radius “fat-jet” and the soft-drop mass which aims to reduce effects of pile-up
- First observation 5.1(5.8) observed(expected) significance for Z->bb
- The Higgs significance is 1.5(0.8) observed (expected)
- Note: Quite some trouble to repeat their H cross section predictions (details in the paper limited). On-going discussions so let’s see what comes in the publication

Summary

- 3.6σ evidence (4.0σ expected) has been presented for Higgs boson decays to b-quarks and for its production in association with a vector boson
- Important milestone on the way to observation, that demonstrates we understand the ingredients to reliably extract a H → bb signal!
- Within the present ~25-30% uncertainty on μ, the Standard Model (SM) holds
- Assuming the SM production rate, results consistent with the Yukawa coupling to b-quarks in the SM
- Measurement also establishes the VH production process
- The first step of a longer journey in Run 2 and beyond

Back-up

Event Selection

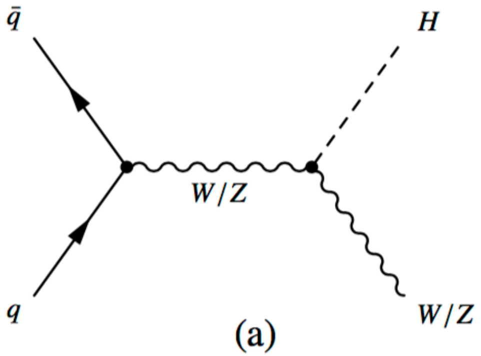
Selection	0-lepton	1-lepton		2-lepton
		e sub-channel	μ sub-channel	
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton
Leptons	0 loose lepton	1 tight electron $p_{\mathrm{T}} > 27$ GeV	1 medium muon $p_{\mathrm{T}} > 25$ GeV	2 loose leptons ≥ 1 lepton with $p_{\mathrm{T}} > 27$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV		-
$m_{\ell\ell}$	-	-		81 GeV $< m_{\ell\ell} <$ 101 GeV
Jets	Exactly 2 or 3 jets			Exactly 2 or ≥ 3 jets
b-jets	exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
H_{T}	> 120 (2 jets), >150 GeV (3 jets)	-		-
$\min\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet})$	$> 20°$ (2 jets), $> 30°$ (3 jets)	-		-
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, bb)$	$> 120°$	-		-
$\Delta\phi(b_1, b_2)$	$< 140°$	-		-
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, E_{\mathrm{T,trk}}^{\mathrm{miss}})$	$< 90°$	-		-
p_{T}^{V} regions	> 150 GeV			[75, 150] GeV, > 150 GeV
Signal Region	✓	$m_{bb} \geq 75$ GeV or $m_{\mathrm{top}} \leq 225$ GeV		Same flavour leptons opposite-sign charge ($\mu\mu$ sub-channel)
Control Region	-	$m_{bb} < 75$ GeV and $m_{\mathrm{top}} > 225$ GeV		Different flavour leptons

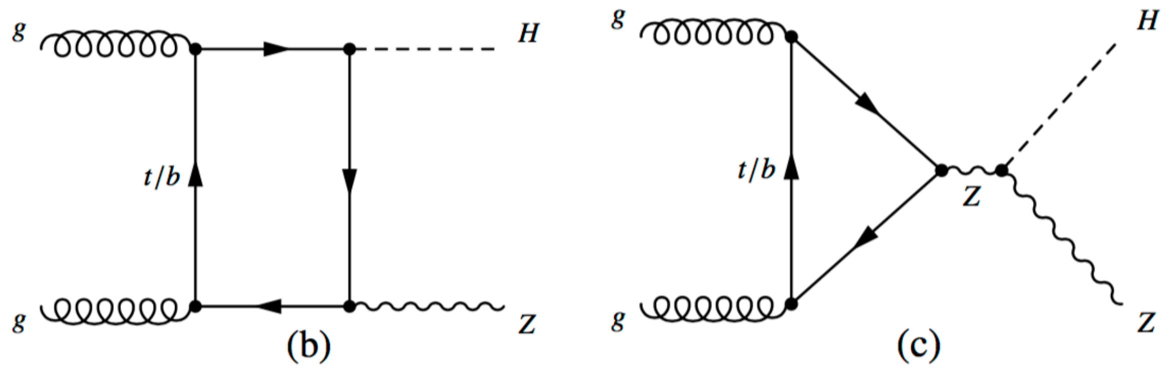
Signal and Background Fit Model

- Extrapolation uncertainties across fit regions parameterised in terms of ratio of yields
- Determine uncertainties of V+jets on 2 most important, largely independent, variables p_T^V and m_{bb} and propagate to BDT distributions.
- Both yield ratios and shape uncertainties evaluated using detailed MC studies or data to MC comparisons in control regions.
- Typically scale/factorisation variations, matrix element/parton shower matching variation, PDF+α_S, comparison to alternative generator with different matrix element or merging scheme

- Run 2 analysis: Attempt to *simplify* and increase *robustness* of analysis (low number of regions and BDT bins, reduced non b-jet contribution) essential to avoid "overconstraining" systematic uncertainties in profile likelihood fit

ggZH

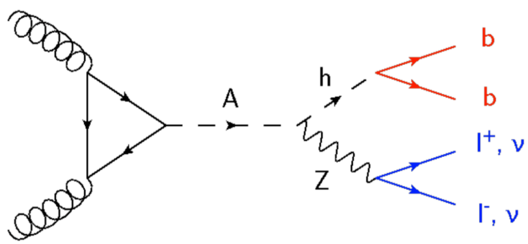




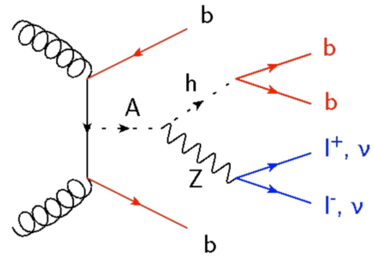
"VHbb" BSM searches (in 2 slides)

- Search for resonances decaying into vector boson + Higgs Zh or Wh (ATLAS-CONF-2017-055)
- 2 Higgs doublet models: extension of SM with additional doublet and 5 higgs h, H, H^+,H^-,A
- Appears in extensions such as SUSY, axion models, baryogenesis

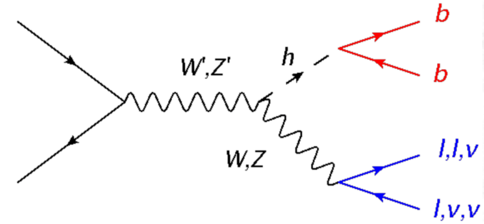
Gluon Fusion - A

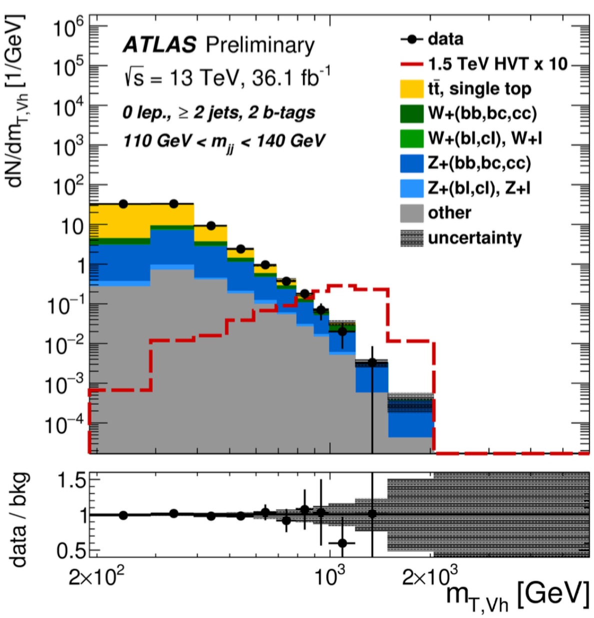


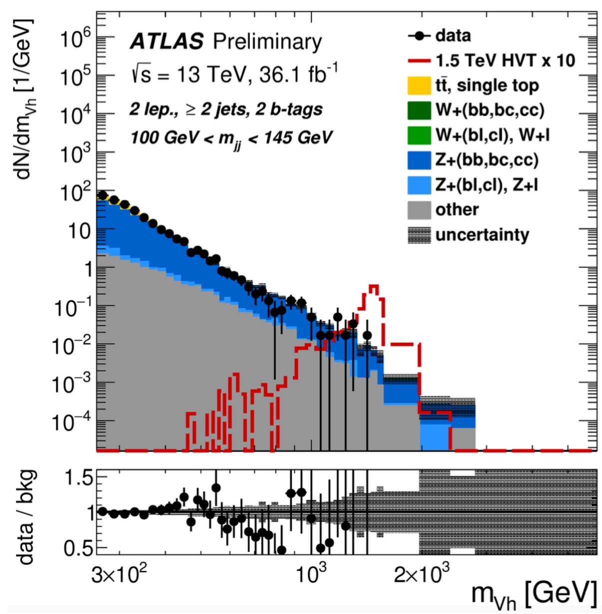
bbA



Heavy Vector Triplets
W',Z' production





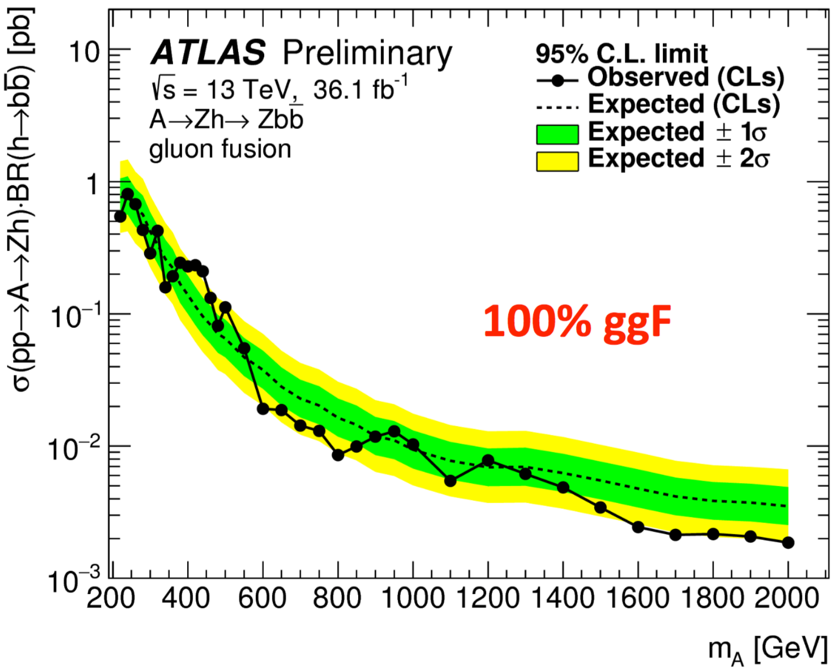


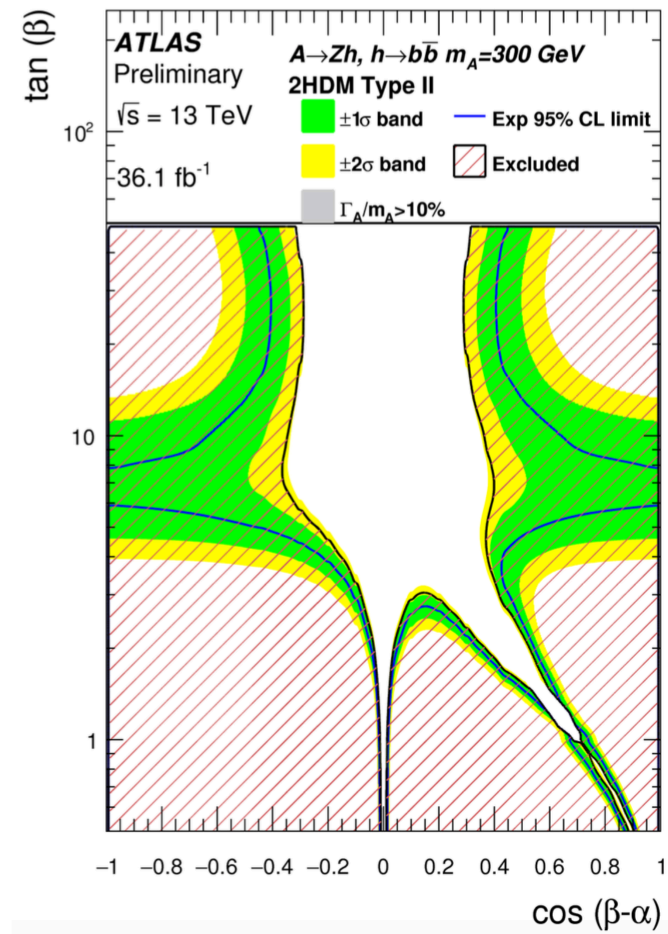
- Several extensions to SM predict heavy vector bosons
- HVT: simplified model with additional SU(2) triplet W'^+,W'^-,Z'

- **Resolved** & **merged** categories
- **3 channels** based on V decays
  - 0-/2-lepton (A, Z'), 1-lepton (W')
- **b-tag categories:**
  - 1-/2-tag used for A and V'
  - 3+ tag used for A (sensitive to bbA)
- **Select dijet/jet mH window to reduce bkgds**
  - Fit m(Vh) or mT(Vh) spectra

Semi-Leptonic VH: A→Zh

- 0-/2-lepton combined limits presented separately for ggF and bbA production
- Mild excess at m_A= 440 GeV
  - arises mostly from 3+ b-tag region in 2-lepton channel
  - local (global) significance: 3.6 (2.4) std. dev.





- 2D limits as a function of tanβ/cos(β-α)
  - tanβ — ratio of vevs for each Higgs doublet
  - α — mixing angle between the 2 CP-even states
- SM alignment limit cos(β-α)=0. Similar limits to combined H couplings fit.