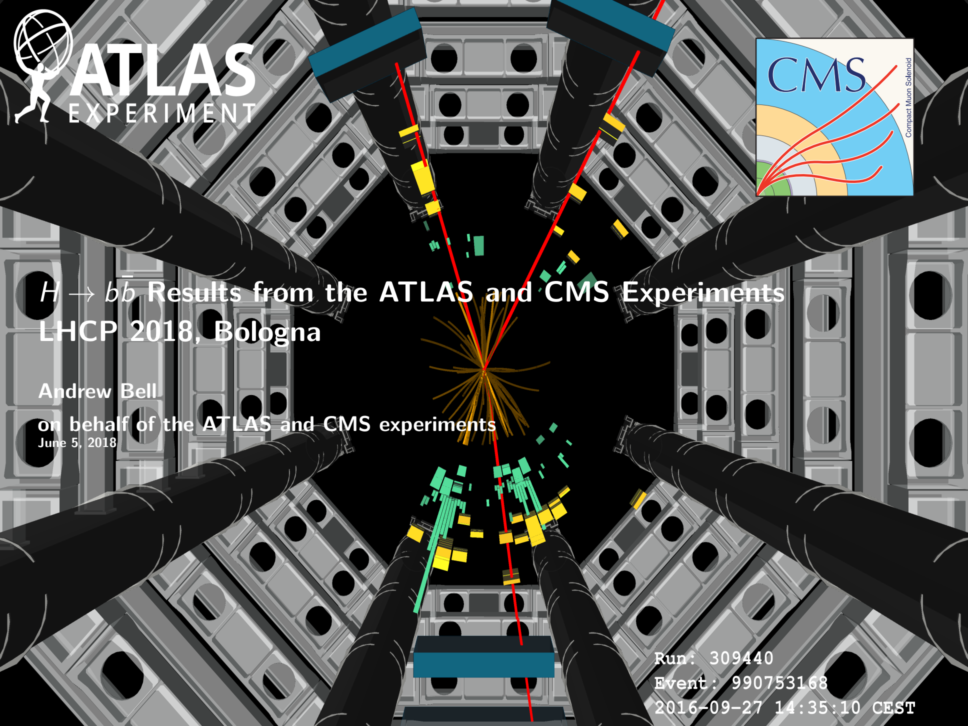
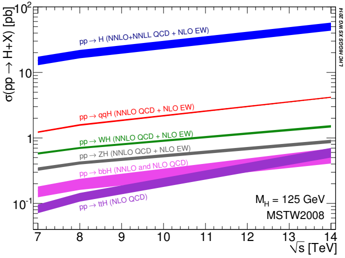
$H \to b\bar{b}$ Results from the ATLAS and CMS Experiments
LHCP 2018, Bologna

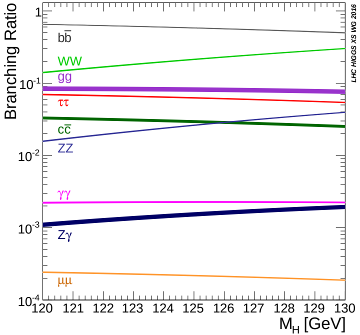
Andrew Bell
on behalf of the ATLAS and CMS experiments
June 5, 2018



Introduction and Overview

- Observation of the Higgs boson opened the door to a new section of the SM Lagrangian
  - Coupling to bosonic and leptonic sectors of the SM observed by ATLAS and CMS
- Direct coupling of the Higgs boson to $b\bar{b}$ is still to be observed:
  - ATLAS+CMS 7+8 TeV yields an observed (expected) significance of 2.6 (3.7) σ for $H \to b\bar{b}$
  - Very important to confirm the Yukawa coupling of the Higgs to the quark sector $\to$ **is this Higgs the SM Higgs?**
- With $m_H = 125$ GeV, $H \to b\bar{b}$ is predicted to be the largest decay mode ($\sim 58\%$)[1]:
  - Large QCD multijet background makes observation very challenging
- Current measurements leave room for BSM physics:
  - $H \to b\bar{b}$ drives the uncertainty on the total decay width
- Number of different Higgs production modes for exploring the $H \to b\bar{b}$ decay, but each has limitations

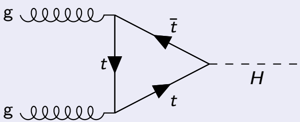




[1] LHCHXSWG

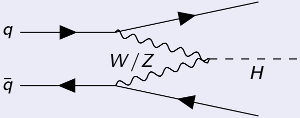
Higgs Production Modes

Gluon-gluon fusion (*ggF*)



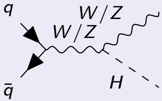
- Largest Higgs production mode at the LHC
- High multijet background $\rightarrow$ challenging S/B
- CMS search for boosted $H \rightarrow b\bar{b}$

Vector-boson fusion (VBF)



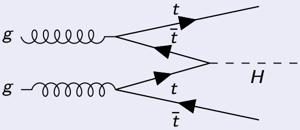
- Signature contains two VBF jets
- Large multijet background
- Can trigger using an additional photon to improve S/B (ATLAS-CONF-2016-063)

VH



- Associated production of Higgs with a vector boson ($V = W/Z$)
- Trigger on leptonic decays of V to improve S/B and reduce multijet contamination
- Main search channel for $H \rightarrow b\bar{b}$ at the LHC
- Recent Run-2 ATLAS and CMS results

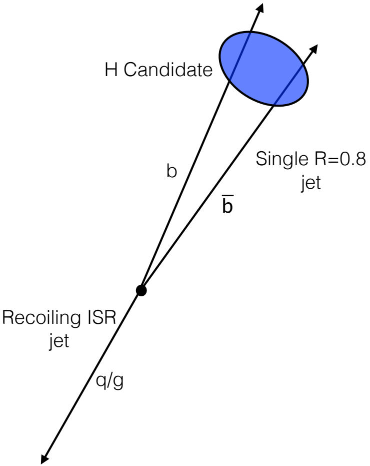
$t\bar{t}H$



- Use leptonic decays of top to trigger
- Combinatorics and $t\bar{t} + b\bar{b}$ background prove to be very challenging
- Dedicated ATLAS and CMS talks

Boosted $H \to b\bar{b}$ at CMS (1709.05543)

- Direct search for $gg \to H \to b\bar{b}$ events
- Background from QCD production of b-quarks has a cross-section 10^7 times larger
- For sufficient boost, b-jets merge into a single $R = 0.8$ jet (jet $p_{\mathrm{T}} > 450$ GeV)
- Use b-tagging to identify two b-hadrons within the large R jet:
  - Signal strength determined from maximum likelihood fit to the mass distribution
  - Simultaneous fit to $Z \to b\bar{b}$ and $H \to b\bar{b}$
- Observation of $Z \to b\bar{b}$ process (5.1 σ):
  - 1.5 σ significance for $H \to b\bar{b}$
  - Promising given the overwhelming QCD background
- Leading systematic uncertainties from Higgs p_{T} correction and jet energy scale



Process	Expected Significance	Observed Significance
$Z \to b\bar{b}$	5.8 σ	5.1 σ
$H \to b\bar{b}$	0.7 σ	1.5 σ

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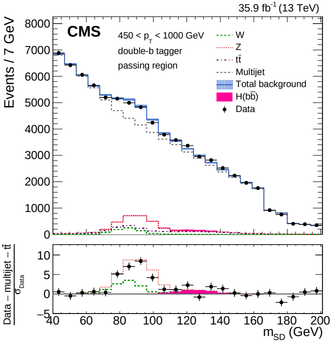
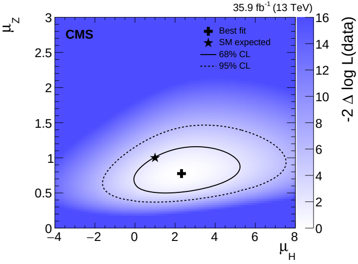
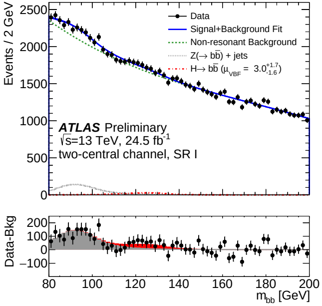
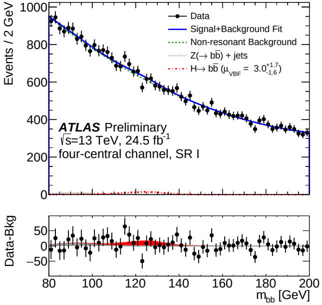




VBF $H \to b\bar{b}$ at ATLAS in Run-2 (NEW!)

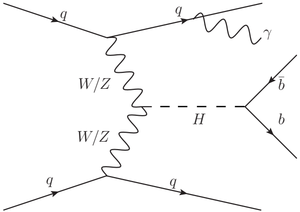
- Three analysis channels:
  - *Two-central* - at least one VBF jet with $3.2 < |\eta| < 4.4$, two b-tagged jets in central detector region
  - *Four-central* - VBF and b-tagged jets in central detector region
  - *Photon* - VBF within detector acceptance, b-tagged jets in central region, with an additional photon (next slide)
- Use a BDT discriminant to separate signal events from background:
  - Trained using a combination of 14 input variables (channel dependent)
    - $\rightarrow$ Mass agnostic
  - Divide BDT output into categories of sensitivity
  - Regions optimised for sensitivity to $H \to b\bar{b}$
- Likelihood fit to m_{bb} distribution in signal regions
- Analysis is sensitive to both inclusive and VBF $H \to b\bar{b}$ production



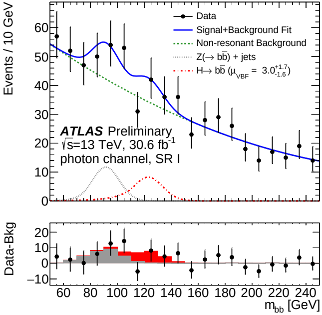


VBF+γ $H \to b\bar{b}$ at ATLAS

- Search for VBF, with an additional high p_{T} photon:
  - New analysis for Run-2
  - Provides a clean trigger signature
  - Greatly suppresses background processes (no photon radiation in gluon-gluon induced background)
- Require 2 VBF jets, 2 b-tagged jets, and 1 photon
- Previously published in ATLAS-CONF-2016-063:
  - Result updated for combination with VBF $H \to b\bar{b}$ analysis
- Use a BDT discriminant to separate signal events from background:
  - Trained using 9 input variables $\to$ mass agnostic
  - Divide BDT output into three categories of sensitivity (*low*, *medium*, *high*)

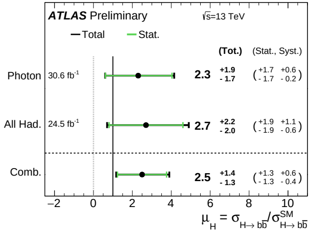


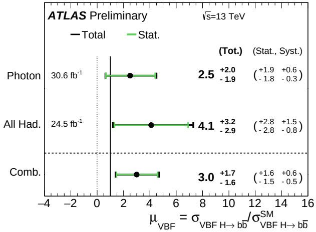
Example Feynman diagram



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

- Systematic uncertainties from non-resonant background modelling and signal modelling:
  - Dominant uncertainty from limited number of data events → will benefit from more luminosity
  - **Observed (expected) 95% CL upper limit for VBF $H \to b\bar{b}$ set at $5.9(3.0^{+1.3}_{-0.8})$ SM cross-section**





Earlier VBF Results

- Number of earlier Run-2 and Run-1 VBF results (without photon requirement)
  - Work underway to include full Run-2 datasets

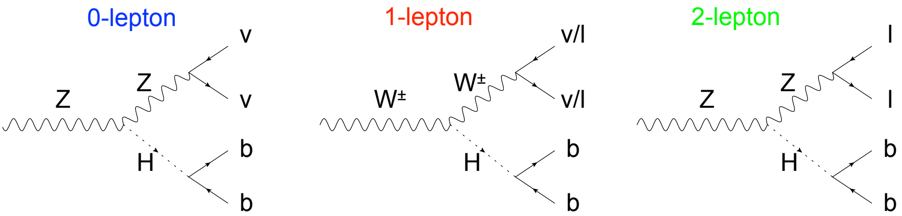
Analysis	Expected Limit	Observed Limit	Signal Strength	Reference
CMS Run-1	2.5	5.5	$2.8^{+1.6}_{-1.4}$	1506.01010
CMS Run-2 (2.32 fb^{-1})	5.0	3.0	$-3.7^{+2.4}_{-2.5}$	HIG-16-003
CMS Run-1+2	2.3	3.4	$1.3^{+1.2}_{-1.1}$	HIG-16-003
ATLAS Run-1	5.4	4.4	-0.8 ± 2.3	1606.02181

$VH(\to b\bar{b})$ Overview

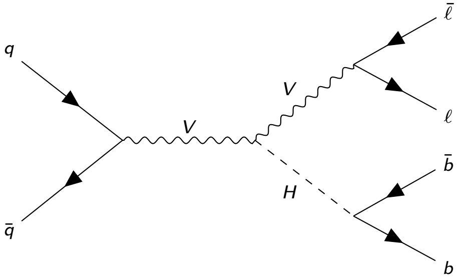
- $VH(\to b\bar{b})$ offers the best sensitivity to $H \to b\bar{b}$ at the LHC
- Leptonic decays of the vector boson ($V = W/Z$) provides a way to both trigger and reduce multijet background:
  - **Three channels: 0- ($Z \to \nu\bar{\nu}$), 1- ($W \to \ell\nu$) and 2-lepton ($Z \to \ell\bar{\ell}$)**
- Results have been published by ATLAS and CMS, using 2015+2016 datasets recorded at $\sqrt{s} = 13$ TeV (36.1 fb^{-1} and 35.9 fb^{-1}, respectively):

  $\to$ Will be the main focus of this talk

Analysis	Expected Significance	Observed Significance	Reference
Tevatron (D0 + CDF)	1.9	3.0	1207.6436
CMS (Run-1)	2.1	2.1	1310.3687
ATLAS (Run-1)	2.6	1.4	1409.6212
ATLAS+CMS (Run-1)	3.7	2.6	1606.02266



$VH(\to b\bar{b})$ Analysis Selections (ATLAS and CMS)



Vector Boson Selections

- In both analyses, channels divided by exact number of charged leptons
- 0-lepton also includes a number of anti-QCD cuts
- Only electrons or muons are considered

	0-lepton	1-lepton	2-lepton
ATLAS	$p_{\mathrm{T}}^{V} > 150$ GeV	$p_{\mathrm{T}}^{V} > 150$ GeV	$p_{\mathrm{T}}^{V} > 75$ GeV
CMS	$p_{\mathrm{T}}^{V} > 170$ GeV	$p_{\mathrm{T}}^{V} > 100$ GeV	$p_{\mathrm{T}}^{V} > 50$ GeV

Higgs Selection

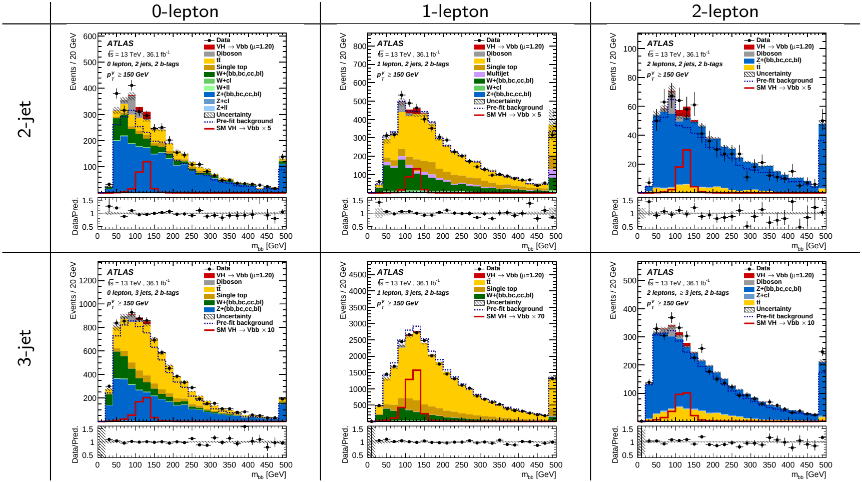
- Exactly 2 *b*-tagged jets:
  - ATLAS - MV2c10, 70% *b*-jet efficiency
  - CMS - CMVA, 50-75% *b*-jet efficiency
- 2-/3-jet analysis regions ($\geq$ 3-jets in 2-lepton channel)

Binned profile likelihood fit to a set of BDT discriminants

- Number of signal and control regions

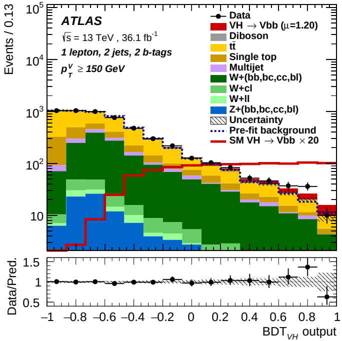
Backgrounds

- $t\bar{t}$ present in all channels
  - In 0- and 1-lepton, have missed an object (jet or lepton)
  - In 2-lepton, dileptonic $t\bar{t}$ contributes directly
- $Z+$jets dominant in 0- and 2-lepton channels
- $W+$jets significant in 0- and 1-lepton channels
- Smaller contributions from: Single top, multijet and diboson ($VZ(\rightarrow b\bar{b})$ used to validate analysis)



Multivariate analysis (ATLAS)

- m_{bb} is single most discriminating variable for $VH(\to b\bar{b})$ signal:
  - Construct BDT of several variables to boost sensitivity
  - m_{bb}, $\Delta R(b,b)$ and p_T^V most important variables



Example BDT output, 1-lepton, 2-jet

- Separate training for each signal region:
  - 8 signal regions
  - 2 $W+\mathrm{HF}$ CR[2] in 1-lepton
  - 4 top $e\mu$ CR in 2-lepton (m_{bb}) ($\sim$ 99% pure)

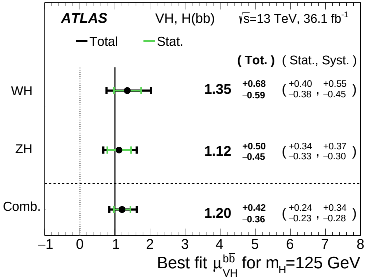
Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(\vec{b}_1, \vec{b}_2)$	×	×	×
$\lvert\Delta\eta(\vec{b}_1, \vec{b}_2)\rvert$	×		
$\Delta\phi(\vec{V}, \vec{bb})$	×	×	×
$\lvert\Delta\eta(\vec{V}, \vec{bb})\rvert$			×
m_{eff}	×		
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
m_{top}		×	
$\lvert\Delta Y(\vec{V}, \vec{bb})\rvert$		×	
	Only in 3-jet events		
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×

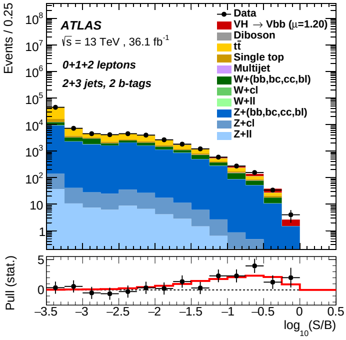
[2] $W+\mathrm{HF} = W+bb, W+bc, W+bl, W+cc$

Fitted μ_{VH} and significance (ATLAS)

- Results from fit $VH(\rightarrow b\bar{b})$ signal
- Top right: fitted signal strengths for WH/ZH
  - $\sim 75\%$ compatibility between WH/ZH
- Bottom right: Bins organised by S/B ratio
  - 3.5 (3.0) σ observed (expected) significance
  - Evidence of $VH(\rightarrow b\bar{b})$
  - Uncertainties dominated by systematic uncertainties

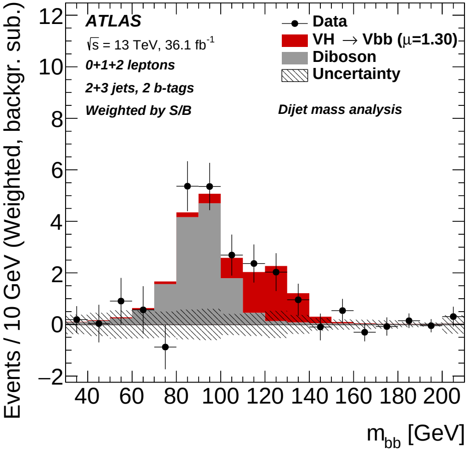
Dataset	p_0		Significance	
	Exp.	Obs.	Exp.	Obs.
0-lepton	4.2%	30%	1.7	0.5
1-lepton	3.5%	1.1%	1.8	2.3
2-lepton	3.1%	0.019%	1.9	3.6
Combined	0.12%	0.019%	3.0	3.5





Fitted μ_{VH} and significance (ATLAS)

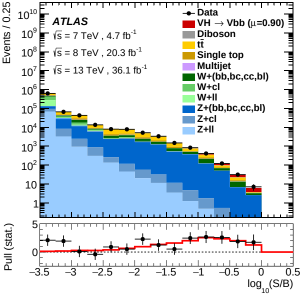
- m_{bb} distribution from dijet mass analysis
- Dijet mass analysis signal strength consistent with SM:
  - → $\mu_{VH} = 1.30^{+0.28}_{-0.27}(\text{stat.})^{+0.37}_{-0.29}(\text{syst.})$
  - From fit to m_{bb}, measure 3.5 (2.8) σ observed (expected) significance
  - Strong validation of BDT analysis, with visible $H \to b\bar{b}$ peak
  - More details in back-up



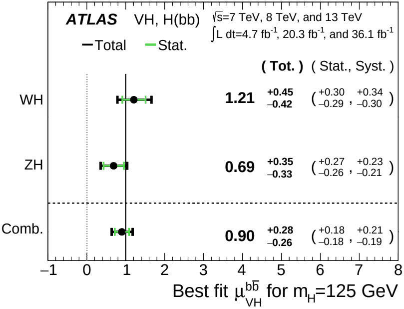
Combination with Run-1 results (ATLAS)

- Run-2 analysis combined with Run-1 result
- Decorrelation tests conducted for JES and *b*-tagging systematics:
  - Found to have negligible impact
  - Only signal and *b*-jet energy scale uncertainties correlated between Run-1 and Run-2

- Bins ordered by S/B for combined Run-1 + Run-2 *VH* fit (bottom left)
- Compare μ when fitting *WH* and *ZH* (bottom right):
  - 34% compatibility between *WH* and *ZH*
- **Final observed (expected) significance of** 3.6 (4.0) σ
- $\mu = 0.90 \pm 0.18(\mathrm{stat.})^{+0.21}_{-0.19}(\mathrm{syst.})$



S/B ordered plot for for combined Run-1 + Run-2 *VH* fit

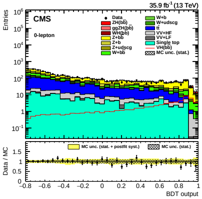


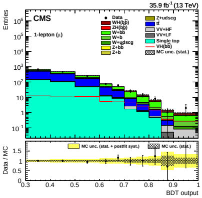
Fit 1 common signal strength and 2 decorrelated signal strengths for *WH*/*ZH*

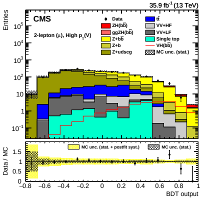
Multivariate Analysis (CMS)

- Similarly to ATLAS, CMS trains a BDT to improve signal sensitivity
- Train BDT on a combination of 22 variables (channel dependent)
- Example output for 0-lepton, 1-muon and 2-muon regions
- Cut on BDT output applied as part of event selection:
  - Target regions with increased S/B

Variable	Description	Channels
$M(\text{jj})$	dijet invariant mass	All
$p_T(\text{jj})$	dijet transverse momentum	All
$p_T(\text{j}_1)$, $p_T(\text{j}_2)$	transverse momentum of each jet	0- and 2-lepton
$\Delta R(\text{jj})$	distance in η–ϕ between jets	2-lepton
$\Delta\eta(\text{jj})$	difference in η between jets	0- and 2-lepton
$\Delta\phi(\text{jj})$	azimuthal angle between jets	0-lepton
$p_T(\text{V})$	vector boson transverse momentum	All
$\Delta\phi(\text{V},\text{jj})$	azimuthal angle between vector boson and dijet directions	All
$p_T(\text{jj})/p_T(\text{V})$	p_T ratio between dijet and vector boson	2-lepton
$M(\ell\ell)$	reconstructed Z boson mass	2-lepton
CMVA_{max}	value of CMVA discriminant for the jet with highest CMVA value	0- and 2-lepton
CMVA_{min}	value of CMVA discriminant for the jet with second highest CMVA value	All
CMVA_{add}	value of CMVA for the additional jet with highest CMVA value	0-lepton
p_T^{miss}	missing transverse momentum	1- and 2-lepton
$\Delta\phi(\vec{p}_T^{\text{miss}},\text{j})$	azimuthal angle between $\vec{p}_T^{\text{miss}}$ and closest jet ($p_T > 30\,\text{GeV}$)	0-lepton
$\Delta\phi(\vec{p}_T^{\text{miss}},\ell)$	azimuthal angle between $\vec{p}_T^{\text{miss}}$ and lepton	1-lepton
m_T	mass of lepton $\vec{p}_T + \vec{p}_T^{\text{miss}}$	1-lepton
m_{top}	reconstructed top quark mass	1-lepton
N_{aj}	number of additional jets	1- and 2-lepton
$p_T(\text{add})$	transverse momentum of leading additional jet	0-lepton
SA5	number of soft-track jets with $p_T > 5\,\text{GeV}$	All





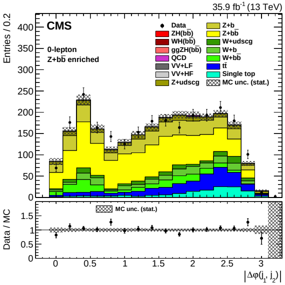


Backgrounds and Control Regions (CMS)

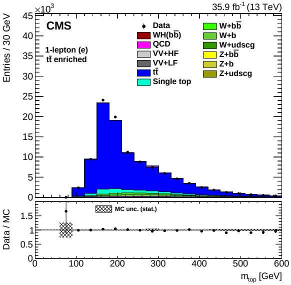
- Several background processes present in all channels:
  - $t\bar{t}$ in all channels
  - $Z+$jets in 0- and 2-lepton
  - $W+$jets in 0- and 1-lepton
  - Smaller contributions from single-top, multijet and diboson

- Dedicated control regions in each channel for (defined in back-up):
  - **0-lepton:** $t\bar{t}$, $Z+\mathrm{HF}$, $Z+\mathrm{LF}$
  - **1-lepton:** $t\bar{t}$, $W+\mathrm{HF}$, $W+\mathrm{LF}$
  - **2-lepton:** $t\bar{t}$, $Z+\mathrm{HF}$, $Z+\mathrm{LF}$

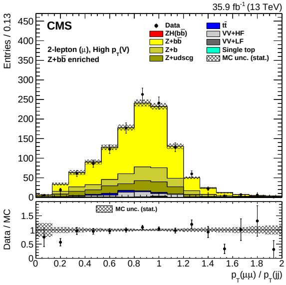
- Combine all SRs and CRs into a single maximum likelihood fit:
  - BDT discriminant output for SRs
  - Sub-leading jet b-tagging discriminant for CRs
- As in ATLAS analysis, use $VZ(\to b\bar{b})$ background as a validation (details in back-up)



0-lepton, $Z+\mathrm{HF}$ enriched CR



1-lepton, $t\bar{t}$ enriched CR

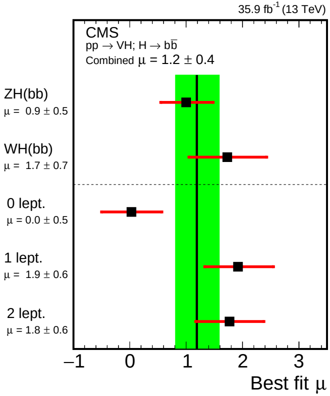


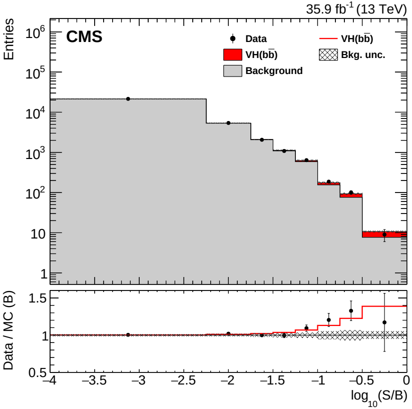
2-lepton, $Z+\mathrm{HF}$ enriched CR

$VH(\rightarrow b\bar{b})$ Results (CMS)

- Now look to extract $VH(\rightarrow b\bar{b})$ signal strength
- Observed signal strength $\mu_{VH} = 1.19^{+0.21}_{-0.20}(\text{stat.})^{+0.34}_{-0.32}(\text{syst.})$
- Corresponds to an observed (expected) significance of 3.3 (2.8) σ:
  - Evidence of $VH(\rightarrow b\bar{b})$
  - Uncertainties dominated by systematic uncertainties

Channels	Significance expected	Significance observed
0-lepton	1.5	0.0
1-lepton	1.5	3.2
2-lepton	1.8	3.1
Combined	2.8	3.3



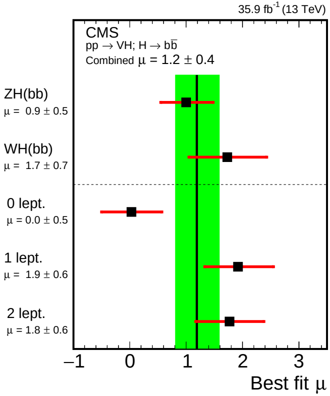


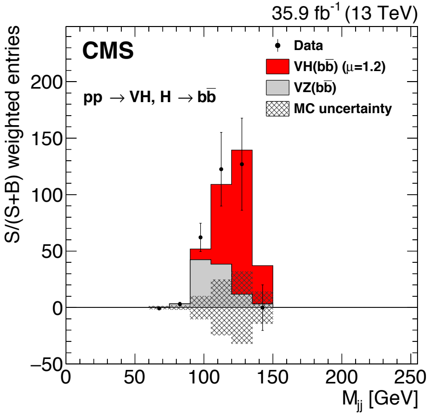
Bins organised by S/B ratio, combined *VH* fit to all channels

$VH(\to b\bar{b})$ Results (CMS)

- Now look to extract $VH(\to b\bar{b})$ signal strength
- Observed signal strength
  $\mu_{VH} = 1.19^{+0.21}_{-0.20}(\text{stat.})^{+0.34}_{-0.32}(\text{syst.})$
- Corresponds to an observed (expected) significance of 3.3 (2.8) σ:
  - Evidence of $VH(\to b\bar{b})$
  - Uncertainties dominated by systematic uncertainties

Channels	Significance expected	Significance observed
0-lepton	1.5	0.0
1-lepton	1.5	3.2
2-lepton	1.8	3.1
Combined	2.8	3.3





m_{bb} distribution for most sensitive region → visible $VH(\to b\bar{b})$ peak

Run-1 Combination (CMS)

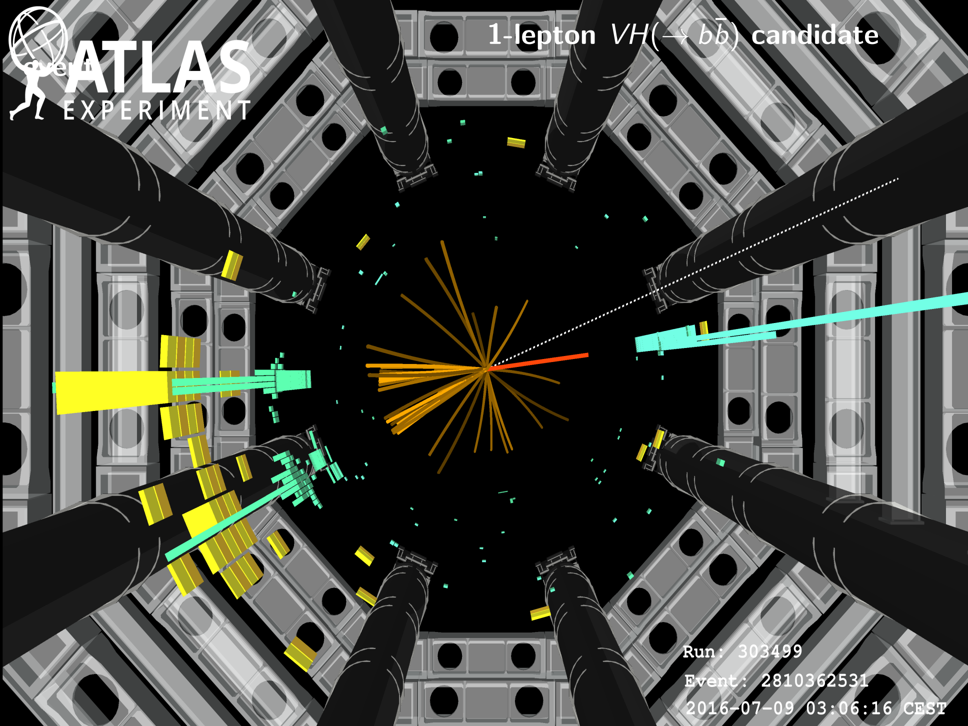
- Combined Run-2 $VH(\rightarrow b\bar{b})$ result with Run-1 measurement
- All uncertainties assumed to be uncorrelated, expect for signal uncertainties:
  - $\rightarrow$ Treating as uncorrelated has a negligible impact on signal significance

Data used	Significance expected	Significance observed	Signal strength observed
Run 1	2.5	2.1	$0.89^{+0.44}_{-0.42}$
Run 2	2.8	3.3	$1.19^{+0.40}_{-0.38}$
Combined	3.8	3.8	$1.06^{+0.31}_{-0.29}$

- **Final observed (expected) significance of** 3.8 (3.8) σ
- Combined signal strength:
  - $\mu_{VH}^{\text{CMS}} = 1.06^{+0.31}_{-0.29}$
- Similar precision to ATLAS measurement:
  - $\mu_{VH}^{\text{ATLAS}} = 0.90^{+0.28}_{-0.26}$

Conclusions

- The coupling of the Higgs boson to $b\bar{b}$ is still to be directly observed
- A number of very interesting results from ATLAS and CMS have helped to push us closer to observation:
  - Boosted CMS $H \to b\bar{b}$ + ISR jet observed 1.5 σ significance from background-only model
  - Updated VBF analysis by ATLAS has been able to set a limit of 5.9 times the SM cross-section
- Results using the 2015+2016 LHC datasets at $\sqrt{s} = 13$ TeV have given first **evidence** of $VH(\to b\bar{b})$ process at the LHC
- In combination with Run-1 data:
  - ATLAS measured a 3.6 (4.0) σ significance over the background only model
  - CMS measured a 3.8 (3.8) σ significance over the background only model
  - Uncertainties in both analyses are dominated by **systematic** uncertainties
- Results compatible between both analyses
- Analyses cross-checked using $VZ(\to b\bar{b})$ process $\to$ both ATLAS and CMS achieve observation of $VZ(\to b\bar{b})$
- Work ongoing to reach observation



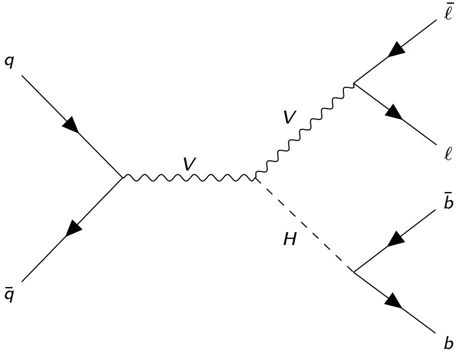
1-lepton $VH(\to b\bar{b})$ candidate
ATLAS
EXPERIMENT
Run: 303499
Event: 2810362531
2016-07-09 03:06:16 CEST

Back-up

Boosted $H \to b\bar{b}$ Systematic Uncertainties

Systematic source	W/Z	H
Integrated luminosity	2.5%	2.5%
Trigger efficiency	4%	4%
Pileup	<1%	<1%
$N_2^{1,\mathrm{DDT}}$ selection efficiency	4.3%	4.3%
Double-b tag	4% (Z)	4%
Jet energy scale / resolution	10/15%	10/15%
Jet mass scale (p_T)	0.4%/100 GeV (p_T)	0.4%/100 GeV (p_T)
Simulation sample size	2–25%	4–20% (ggF)
H p_T correction	—	30% (ggF)
NLO QCD corrections	10%	—
NLO EW corrections	15–35%	—
NLO EW W/Z decorrelation	5-15%	—

$VH(\rightarrow b\bar{b})$ Analysis Overview (ATLAS)



Vector Boson Selections

- 0-lepton:
  - Exactly 0 charged leptons
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV
  - Several anti-QCD cuts
- 1-lepton:
  - Exactly 1 charged lepton (e/μ)
  - $p_{\mathrm{T}}^{V} > 150$ GeV
- 2-lepton:
  - Exactly 2 charged leptons ($ee/\mu\mu$)
  - $m_{\ell\ell}$ compatible with m_Z
  - $p_{\mathrm{T}}^{V} > 75$ GeV

Higgs Selection

- Exactly 2 *b*-tagged jets (MV2c10, 70% *b*-jet efficiency)
- 2-/3-jet analysis regions ($\geq$ 3-jets in 2-lepton channel)

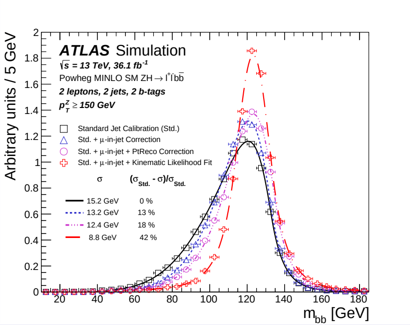
Binned profile likelihood fit to a set of BDT discriminants (Slide 11)

- Number of signal and control regions (Slide 29)

$VH(\to b\bar{b})$ Analysis Overview (ATLAS)

b-jet energy corrections

- Apply additional corrections to account for:
  - Muon-in-jet and b-jet energy response
  - In 2-lepton channel, use a kinematic likelihood fit (all objects are reconstructed)
- Improve m_{bb} resolution by $\sim 18\%$
- 42% improvement with kinematic fit in 2-lepton channel



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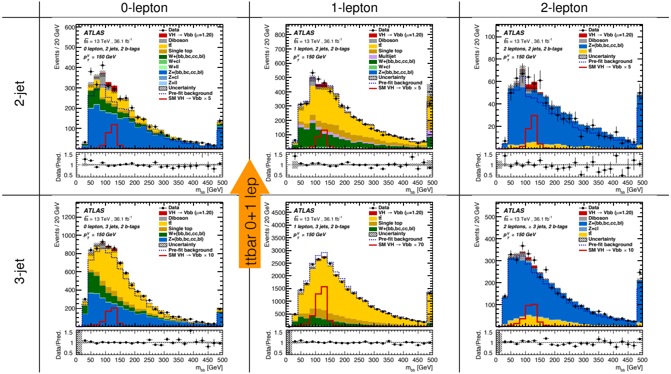
Fit model: Floating normalisations

- Overview of fit model concept
- 5 floating background normalisations for:
  - $t\bar{t}$ (0+1 lepton, 2-lepton 2-jet, 2-lepton 3+-jet)
  - $W+\mathrm{HF}$, $Z+\mathrm{HF}$ (2-jet, 3-jet)
- $t\bar{t}$ contribution is very different in 0- and 1-lepton to 2-lepton case:
  - In 0- and 1-lepton, have missed an object (jet or lepton) $\rightarrow$ one common floating normalisation
  - In 2-lepton, dileptonic $t\bar{t}$ contributes directly $\rightarrow$ top $e\mu$ CR can constrain normalisation in 2-/3+-jet
- Normalisation driven by a region, with appropriate extrapolation uncertainties



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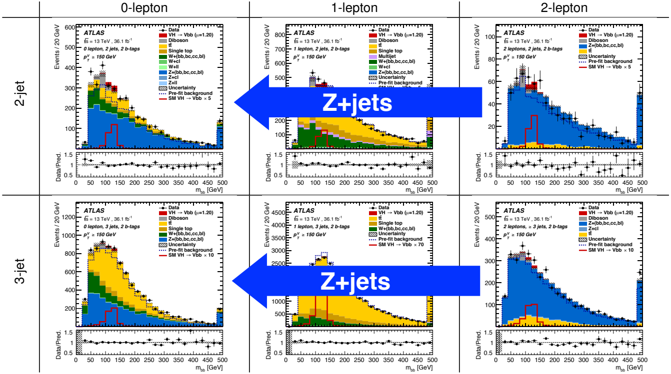

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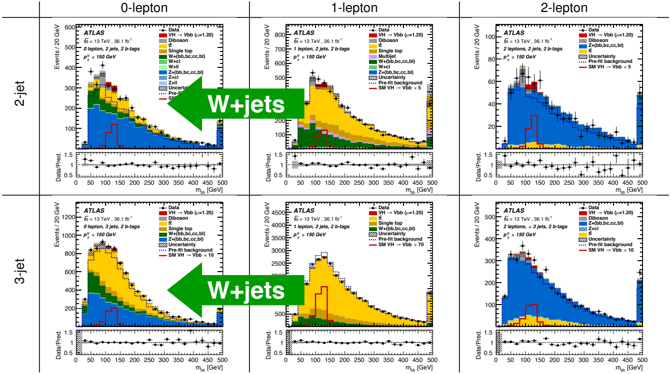


Fit model

- Binned maximum likelihood fit to extract signal significance and strength:
  - 8 signal regions
  - 2 $W + \mathrm{HF}$ CR[3] in 1-lepton (yield only) (m_{top}[4] > 225 GeV && $m_{bb} < 75$ GeV) ($\sim 75\%$ pure)
  - 4 top $e\mu$ CR in 2-lepton (m_{bb}) ($\sim 99\%$ pure)
  - 2-lepton channel includes > 3 jet multiplicities

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}

- Validation, diboson (back-up):
  - Retrain BDT to $VZ(\to b\bar{b})$ signal
- Validation, dijet mass analysis (back-up):
  - Additional split at $p_T^V > 200$ GeV
  - Tighter $\Delta R(b, b)$ selection applied
  - Fit to m_{bb} distribution

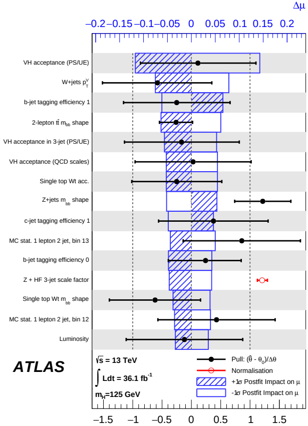
[3] $W + \mathrm{HF} = W + bb, W + bc, W + bl, W + cc$

[4] m_{top} is the invariant mass of the lepton, neutrino and jet with the lowest invariant mass

ATLAS: Ranking and Breakdown

- Middle shows numerical breakdown of uncertainties:
  - Systematically dominated
- Far right presents impact of systematic on μ, ordered by postfit impact
- Main contributions from:
  - Signal acceptance
  - $W+$jets p_T^V modelling (1-lepton)
  - b-tagging

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

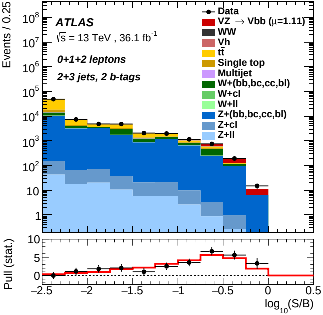


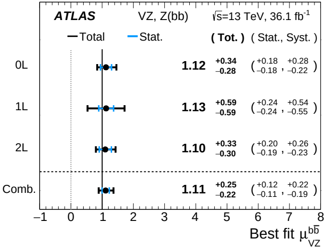
Validations of Fit: $VZ(\rightarrow b\bar{b})$ (ATLAS)

- Train BDT to select $VZ(\rightarrow b\bar{b})$ signal:
  - Otherwise identical setup and configuration as $VH(\rightarrow b\bar{b})$ fit
- Top right: Bins organised by S/B ratio, combined VZ fit to all channels

  $\rightarrow$ $\mu_{VZ} = 1.11^{+0.12}_{-0.11}(\text{stat.})^{+0.22}_{-0.19}(\text{syst.})$

  - 99% compatibility between channels
  - 5.8 (5.3) σ observed (expected) significance
  - Observation of $VZ(\rightarrow b\bar{b})$





Fit 1 common signal strength and 3 decorrelated signal strengths per channel

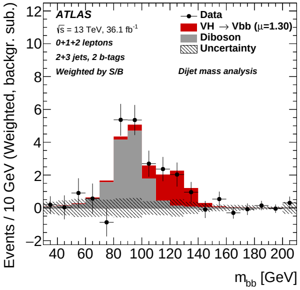
Validation of Fit: dijet mass analysis

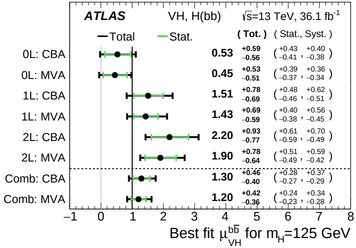
- Additional cross-check of fit using fit to m_{bb}
- Tightened event selection:
  - Additional region with split at $p_T^V = 200$ GeV
  - Merge $W+\mathrm{HF}$ CR into 1-lepton SR
- Top right shows background subtracted m_{bb} for all regions, from cut based fit
  - Each region weighted by Higgs S/B
- Dijet mass analysis signal strength consistent with SM:

  $\rightarrow$ $\mu_{VH} = 1.30^{+0.28}_{-0.27}(\mathrm{stat.})^{+0.37}_{-0.29}(\mathrm{syst.})$
  - 3.5 (2.8) σ observed (expected) significance
- Bottom right: Very consistent signal strengths from dijet mass and MVA fits

Channel			
Selection	0-lepton	1-lepton	2-lepton
m_T^W	-	< 120 GeV	-
$E_T^{miss}/\sqrt{S_T}$	-	-	$< 3.5\sqrt{\mathrm{GeV}}$

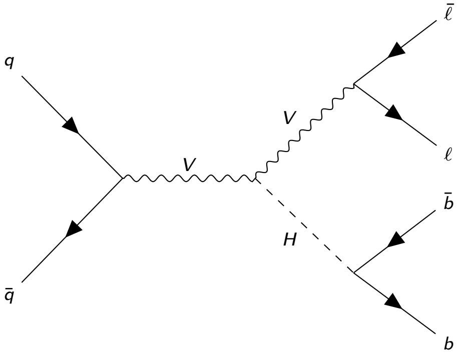
p_T^V regions			
p_T^V	(75, 150] GeV (2-lepton only)	(150, 200] GeV	(200, ∞) GeV
$\Delta R(\vec{b}_1, \vec{b}_2)$	<3.0	<1.8	<1.2





Cut based vs. MVA fit

$VH(\to b\bar{b})$ Analysis Overview (CMS)



- CMS analysis also targets leptonic decays of W/Z bosons

Vector Boson Selections

- 0-lepton:
  - Exactly 0 charged leptons
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 170$ GeV
  - Several anti-QCD cuts
- 1-lepton:
  - Exactly 1 charged lepton (e/μ)
  - $p_{\mathrm{T}}^{V} > 100$ GeV
- 2-lepton:
  - Exactly 2 charged leptons ($ee/\mu\mu$)
  - $m_{\ell\ell}$ compatible with m_Z
  - $p_{\mathrm{T}}^{V} > 50$ GeV

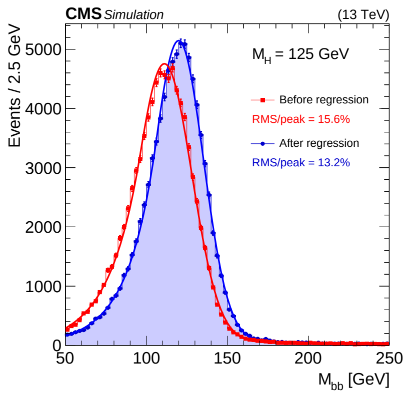
Higgs Selection

- Exactly 2 b-tagged jets (CMVA, 50-75% b-jet efficiency)
- 2-/3-jets ($\geq$ 3-jets in 2-lepton channel)

$VH(\to b\bar{b})$ Analysis Overview (CMS)

b-jet energy corrections

- Apply additional corrections using:
  - **Kinematics:** Jet p_{T}, energy, leading charged tracks, etc.
  - ***b*-jet specific:** soft lepton p_{T}, p_{T} of secondary vertex
- m_{bb} resolution improved by $\sim 10\%$



Vector Boson Selections

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  - Exactly 0 charged leptons
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 170$ GeV
  - Several anti-QCD cuts
- 1-lepton:
  - Exactly 1 charged lepton (e/μ)
  - $p_{\mathrm{T}}^{V} > 100$ GeV
- 2-lepton:
  - Exactly 2 charged leptons ($ee/\mu\mu$)
  - $m_{\ell\ell}$ compatible with m_Z
  - $p_{\mathrm{T}}^{V} > 50$ GeV

Higgs Selection

- Exactly 2 b-tagged jets (CMVA, 50-75% b-jet efficiency)
- 2-/3-jet analysis regions ($\geq$ 3-jets in 2-lepton channel)

Detailed CMS $VH(\to b\bar{b})$ Event Selection

Variable	0-lepton	1-lepton	2-lepton
$p_T(\mathrm{V})$	> 170	> 100	$[50, 150], > 150$
$M(\ell\ell)$	-	-	$[75, 105]$
	-	$(> 25, > 30)$	> 20
$p_T(j_1)$	> 60	> 25	> 20
$p_T(j_2)$	> 35	> 25	> 20
$p_T(\mathrm{jj})$	> 120	> 100	-
$M(\mathrm{jj})$	$[60, 160]$	$[90, 150]$	$[90, 150]$
$\mathrm{CMVA_{max}}$	> 0.9432	> 0.9432	> -0.5884
$\mathrm{CMVA_{min}}$	> -0.5884	> -0.5884	> -0.5884
N_{aj}	< 2	< 2	-
$N_{\mathrm{a}\ell}$	$= 0$	$= 0$	-
E_T^{miss}	> 170	-	-
Anti-QCD	Yes	-	-
$\Delta\phi(\mathrm{V,H})$	> 2.0	> 2.5	> 2.5
$\Delta\phi(E_T^{\mathrm{miss}}, E_T^{\mathrm{miss}}{}_{\mathrm{trk}})$	< 0.5	-	-
$\Delta\phi(E_T^{\mathrm{miss}}, \ell)$	-	< 2.0	-
Lepton Isolation	-	< 0.06	-
Event BDT	> -0.8	> 0.3	> -0.8

Detailed CMS $VH(\to b\bar{b})$ Control Region Selection

Variable	$t\bar{t}$	Z+LF	Z+HF
V Decay Category			
$p_T(j_1)$	> 60	> 60	> 60
$p_T(j_2)$	> 35	> 35	> 35
$p_T(\text{jj})$	> 120	> 120	> 120
E_T^{miss}	> 170	> 170	> 170
$\Delta\phi(\text{V,H})$	> 2	> 2	> 2
$N_{a\ell}$	≥ 1	$= 0$	$= 0$
N_{aj}	≥ 2	≤ 1	≤ 1
$M(\text{jj})$	–	–	$\notin [60 - 160]$
CMVA_{max}	> 0.4432	< 0.4432	> 0.9432
CMVA_{min}	> -0.5884	> -0.5884	> -0.5884
$\Delta\phi(\text{j}, E_T^{miss})$	–	> 0.5	> 0.5
$\Delta\phi(E_T^{miss}, E_{T\ \text{trk}}^{miss})$	–	< 0.5	< 0.5
$\min \Delta\phi(\text{j}, E_T^{miss})$	$< \pi/2$	–	–

0-lepton control region selections

Variable	$t\bar{t}$	W+LF	W+HF
$p_T(j_1)$	> 25	> 25	> 25
$p_T(j_2)$	> 25	> 25	> 25
$p_T(\text{jj})$	> 100	> 100	> 100
$p_T(\text{V})$	> 100	> 100	> 100
CMVA_{max}	> 0.9432	$[-0.5884, 0.4432]$	> 0.9432
N_{aj}	> 1	-	$= 0$
$N_{a\ell}$	$= 0$	$= 0$	$= 0$
METsig	-	> 2.0	> 2.0
$\Delta\phi(E_T^{miss}, \ell)$	< 2	< 2	< 2
$M(\text{jj})$	< 250	< 250	< 90 (low) or $[150, 250]$ (high)

1-lepton control region selections

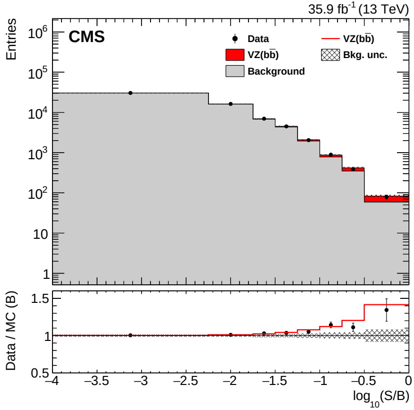
Variable	$t\bar{t}$	Z+LF	Z+HF
$p_T(\text{jj})$	> 100	> 100	-
$p_T(\text{V})$	$[50, 150], > 150$	$[50, 150], > 150$	$[50, 150], > 150$
CMVA_{max}	> 0.9432	< 0.9432	> 0.9432
CMVA_{min}	> -0.5884	< -0.5884	> -0.5884
N_{aj}	-	-	-
$N_{a\ell}$	-	-	-
E_T^{miss}	-	-	< 60
$\Delta\phi(\text{V,H})$	-	-	> 2.5
$M(\ell\ell)$	$\notin [0, 10], \notin [75, 120]$	$[75, 105]$	$[85, 97]$
$M(\text{jj})$	-	-	$\notin [90, 150]$

2-lepton control region selections

Validations of Fit: $VZ(\to b\bar{b})$ (CMS)

- Using equivalent analysis procedure, extract $VZ(\to b\bar{b})$ signal strength
- Modify m_{bb} cut and retrain BDTs
- Observed signal strength $\mu_{VZ} = 1.02^{+0.23}_{-0.22}$
- Corresponds to an observed (expected) significance of 5.0 (4.9) σ:
    - Observation of $VZ(\to b\bar{b})$

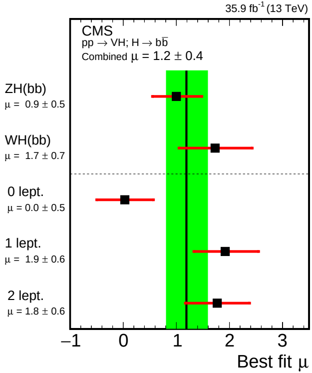
Channels	Significance expected	Significance observed	Signal strength observed
0-lepton	3.1	2.0	0.57 ± 0.32
1-lepton	2.6	3.7	1.67 ± 0.47
2-lepton	3.2	4.5	1.33 ± 0.34
Combined	4.9	5.0	1.02 ± 0.22



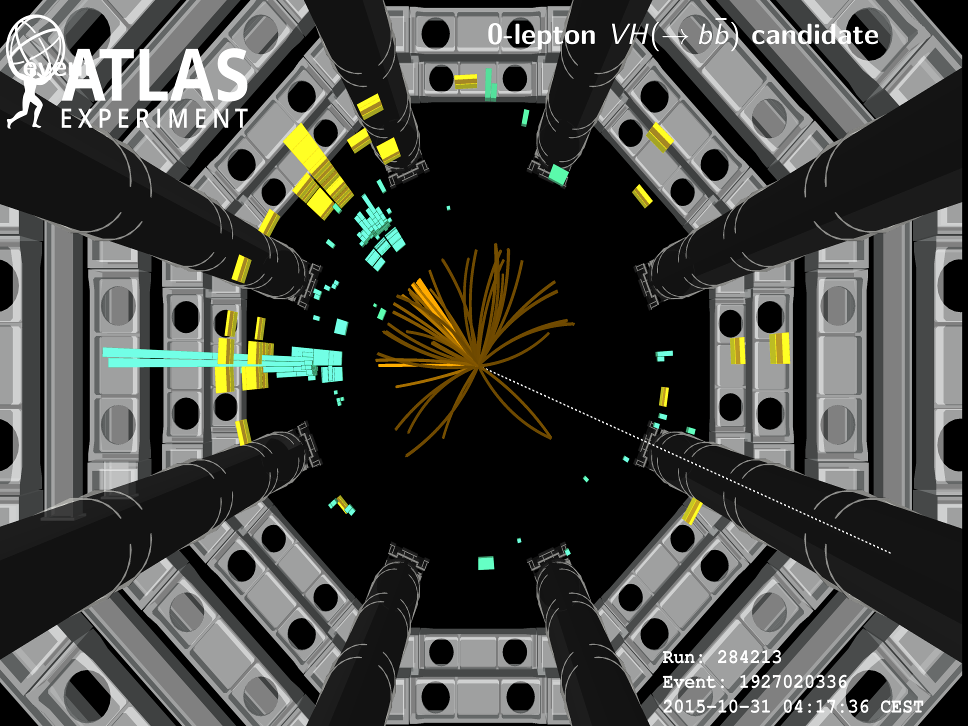
Bins organised by S/B ratio, combined VZ fit to all channels

Systematic Uncertainties (CMS)

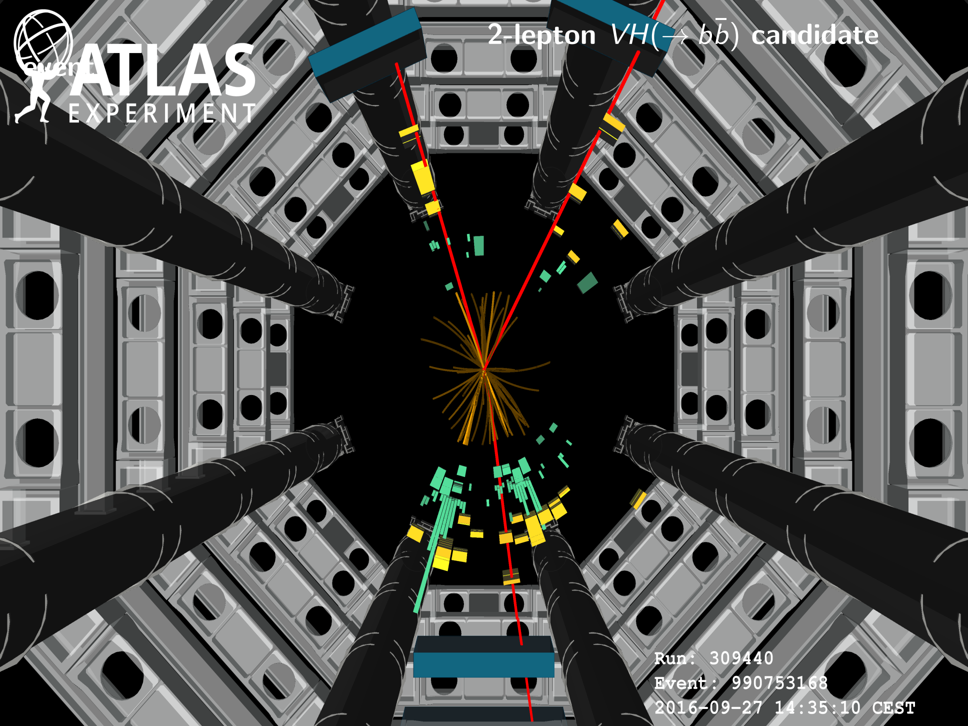
- Uncertainty in measured signal strength is dominated by systematic uncertainties
- Contributions from **experimental** systematic uncertainties:
  - Background scale factors
  - *b*-jet tagging related uncertainties
  - Jet energy scale
- Contributions from **MC and theory** uncertainties:
  - Limited number of simulated events
  - Signal and background modelling uncertainties



Source	Type	Individual contribution to the μ uncertainty (%)	Effect of removal to the μ uncertainty (%)
Scale factors ($t\bar{t}$, V+jets)	norm.	9.4	3.5
Size of simulated samples	shape	8.1	3.1
Simulated samples' modeling	shape	4.1	2.9
b tagging efficiency	shape	7.9	1.8
Jet energy scale	shape	4.2	1.8
Signal cross sections	norm.	5.3	1.1
Cross section uncertainties (single-top, VV)	norm.	4.7	1.1
Jet energy resolution	shape	5.6	0.9
b tagging mistag rate	shape	4.6	0.9
Integrated luminosity	norm.	2.2	0.9
Unclustered energy	shape	1.3	0.2
Lepton efficiency and trigger	norm.	1.9	0.1



ATLAS
EXPERIMENT
0-lepton $VH(\to b\bar{b})$ candidate
Run: 284213
Event: 1927020336
2015-10-31 04:17:36 CEST


ATLAS
EXPERIMENT
2-lepton $VH(\rightarrow b\bar{b})$ candidate
Run: 309440
Event: 990753168
2016-09-27 14:35:10 CEST