ATLAS search for the SM Higgs boson decaying to bb

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on behalf of the ATLAS Collaboration

Fundação para a Ciência e a Tecnologia
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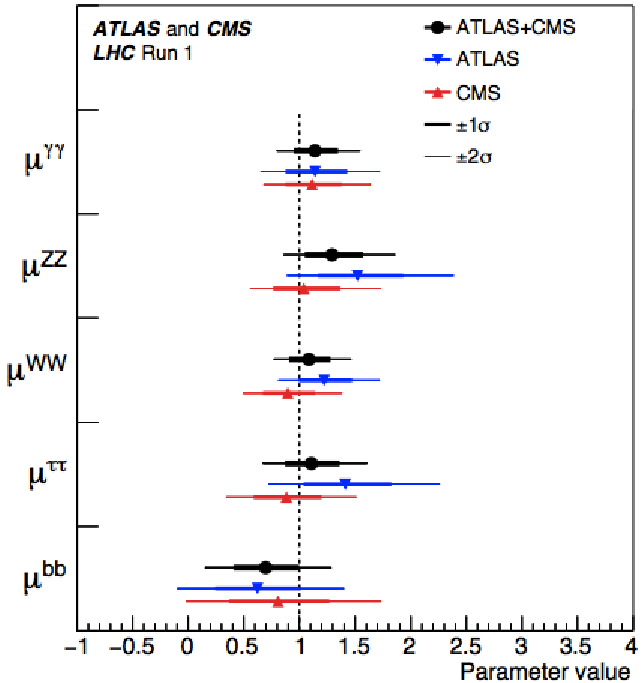
Motivation: why H→bb?

- Higgs boson observed & measured mainly in bosonic channels (γγ, WW, ZZ)
  - Compatible with SM
- H→bb: largest BR in the SM (~58%)
  - Constrain total width and measure absolute couplings
  - Probe the Higgs couplings to quarks
- Evidence of fermionic decays in Run 1:
  - H→ττ: 5.5σ (expected 5σ)
  - H→bb: 2.6σ (expected 3.7σ)
- Run 1 signal strength for H→bb:

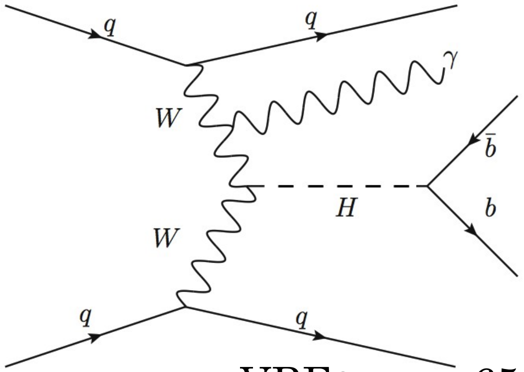
$$\mu_{bb}^{CMS+ATLAS} = 0.70^{+0.29}_{-0.27}$$

ATLAS+CMS Run 1 signal strength

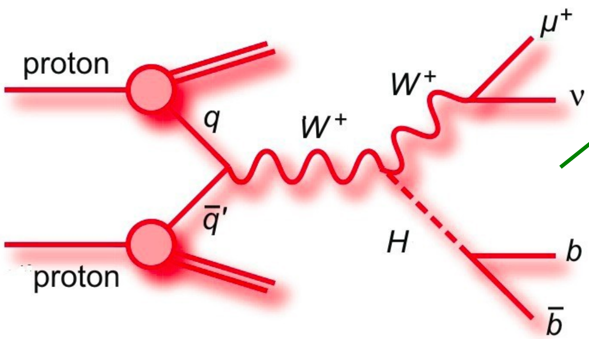


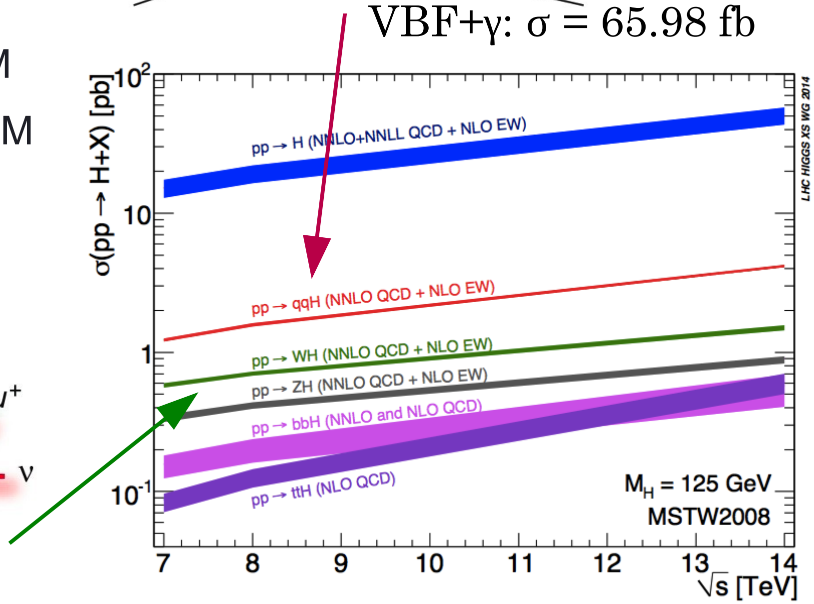
How?

- Explore non-dominant production modes
- Vector boson fusion + photon (VBF search)
  - Use photon to trigger
  - bbγjj non-resonant bckg. suppressed by ~10×
- Previous inclusive VBF (H→bb) limits:
  - ATLAS: obs/expect. upper limit : 4.4/5.4 × SM
  - CMS Run 1 obs/expect. upper limit: 5.5/2.5 × SM
  - CMS Run 2 (2015)
    - obs/expect. upper limit: 3.0/5.0 × SM
- Associated production with W or Z (VH search)
  - Trigger on e/μ from W/Z decay



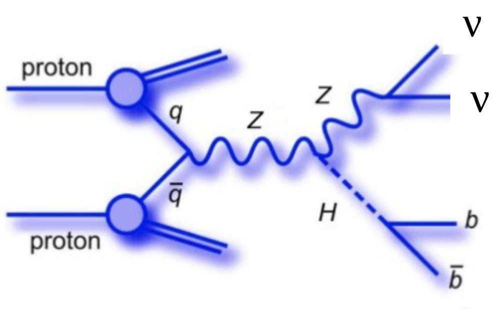
VBF+γ: σ = 65.98 fb

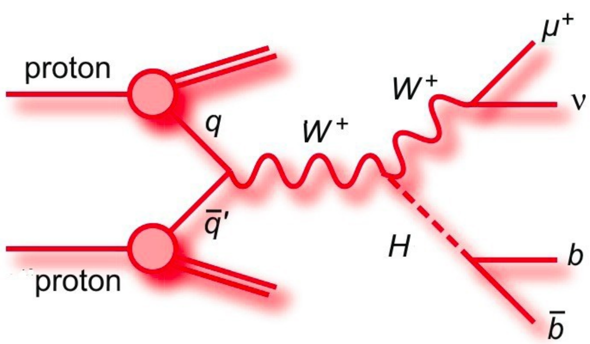


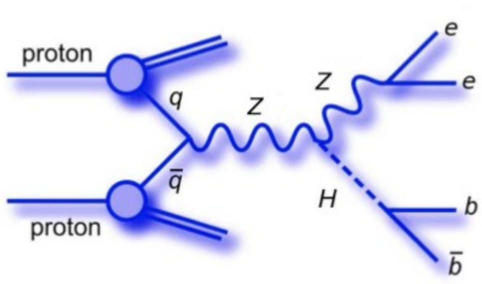


WH: σ = 1.373 pb
ZH: σ = 0.884 pb

VH searches: 3 channels





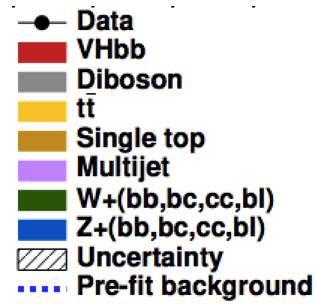


- 0-lepton:
  - E_T^{miss} > 150 GeV
- 1-lepton:
  - e/μ, p_T>25 GeV
  - Tight isolation
  - Missing E_T
  - p_T^V > 150 GeV
- 2-leptons:
  - Isolated ee, μμ
  - p_T^1>25 GeV, p_T^2>7 GeV
  - No missing E_T,
  - m_{ll} compatible with m_Z

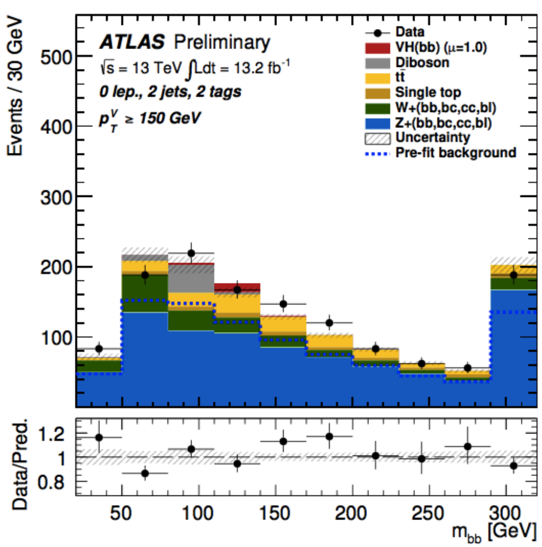
- Two jets
  - anti-kT with R=0.4
  - P_T^{j1}>45 GeV
  - p_T^{j2}>20 GeV
- Improved b-tagging with respect to Run 1:
  - Eff: 70%, light jet rejection: 380, charm rejection: 12
- Analysis categories:
  - 2/3 jets (0/1lepton)
  - 2/≥3jets (2lept.)
  - P_T^V </> 150 GeV (2lept)

Main backgrounds

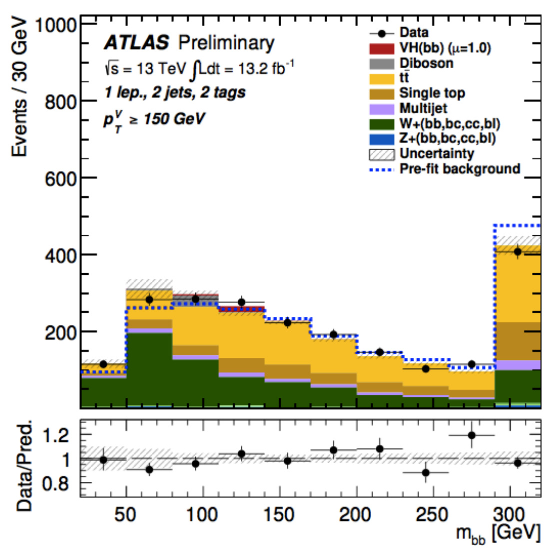
- Dominant backgrounds dependent on channel
  - Z+bjets dominates in 0, 2 lepton channels
  - Top quark and W+jets in 1 lepton channel
  - Multi-jet:
    - negligible in 0/2 lepton channels after anti-QCD cuts
    - Data-driven in 1 lepton channel



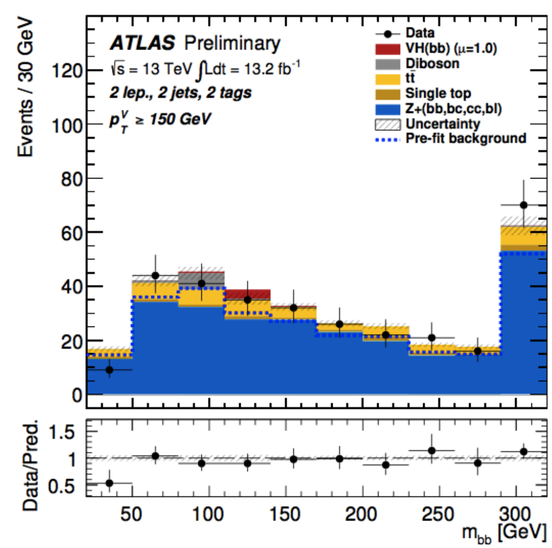
0 lepton



1 lepton

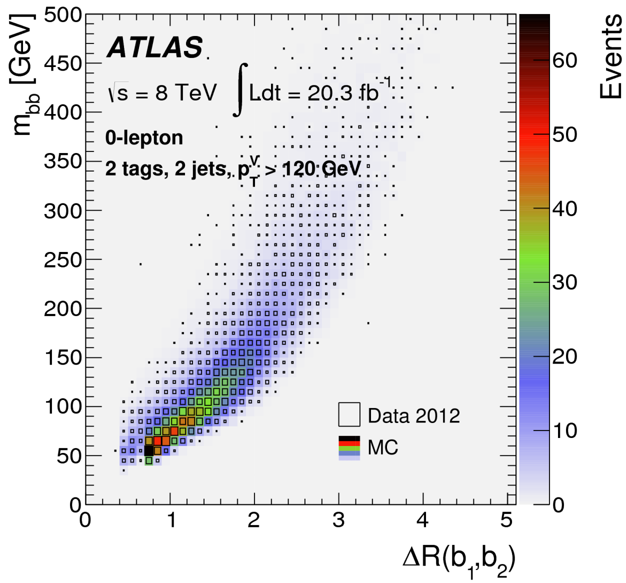


2 leptons



Multi-variate analysis

- Boosted decision tree (BDT)
  - Combine many different variables
  - Trained in 8 categories: 3 lepton, 2/3 jets, low/high p_T^V bin (2 lepton channel)
- Most discrimination from m_{bb} and $\Delta R(b_1,b_2)$



Variable	0-lepton	1-lepton	2-lepton
p_T^V		×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\|\Delta\eta(b_1, b_2)\|$	×		×
$\Delta\phi(V, bb)$	×	×	×
$\|\Delta\eta(V, bb)\|$			×
H_T	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
m_{ll}			×
m_{Top}		×	
$\|\Delta Y(V, H)\|$		×	
	Only in 3-jet events		
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×

- New in run 2: m_{Top}, $|\Delta Y(V,H)|$ → +7% in sensitivity

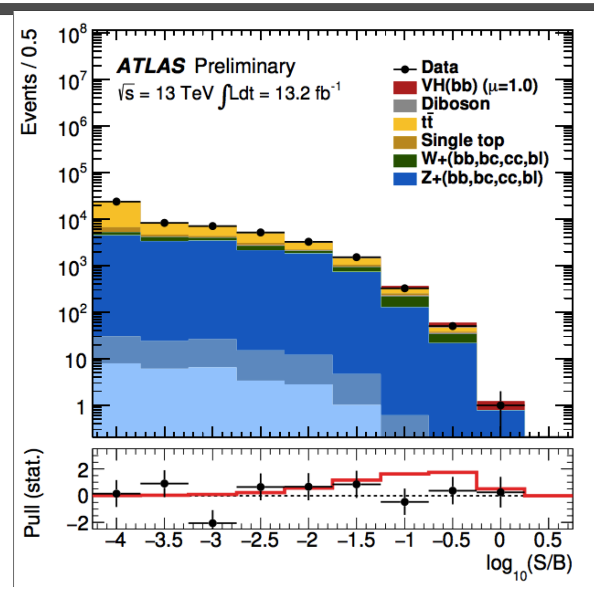
Combined fit

- Profiled likelihood fit to measure the signal strength

  Take into account all event categories

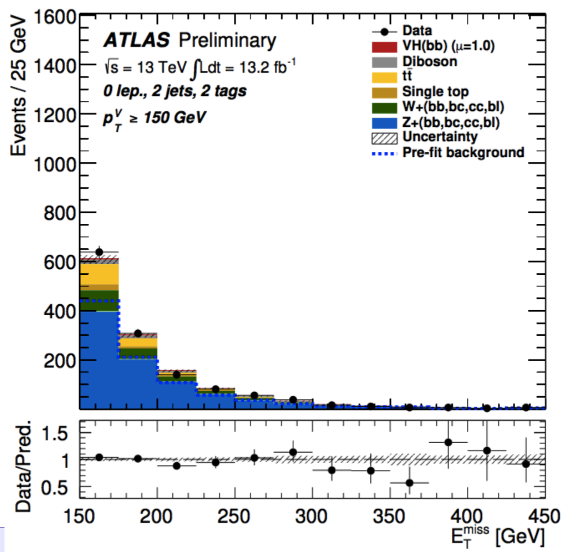
- Use BDT discriminant as input

- Post-fit distributions:



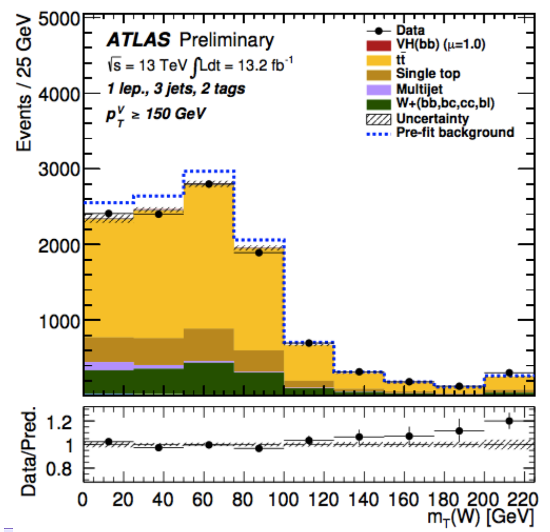
E_T^{miss}

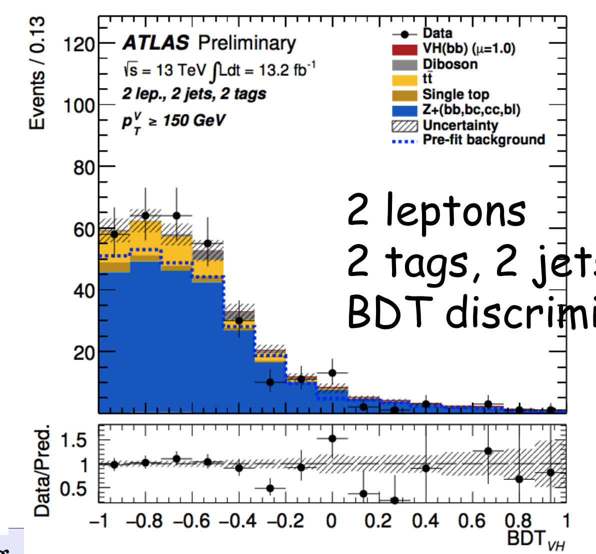
0 lep, 2jets, 2btags



W transverse mass

1 lep., 3jets, 2 btags





2 leptons
2 tags, 2 jets
BDT discriminant

Results H→bb in association with a W or Z

ATLAS-CONF-2016-091

- Combined signal strength with 13.2 fb^{-1} of pp collisions at $\sqrt{s}$= 13 TeV

$$\mu_{VH,\,H\rightarrow bb}=0.21^{+0.51}_{-0.50}$$

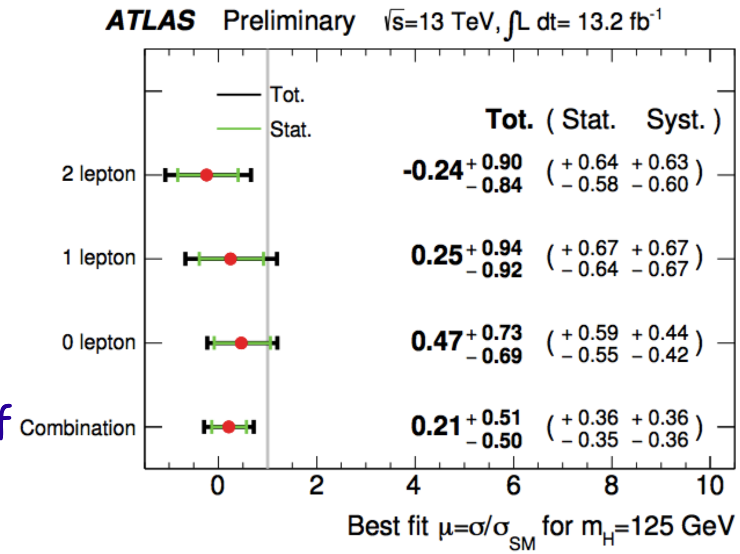
Systematic and statistical uncertainties of the same size

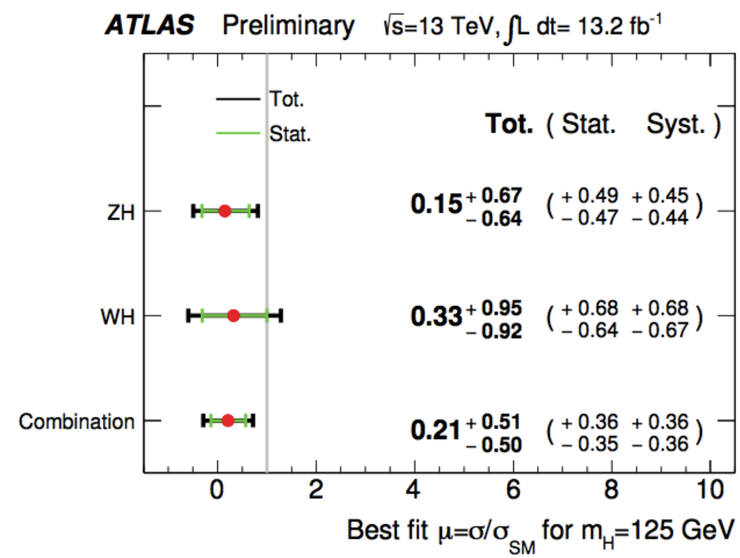
Dominant systematics from b-tagging and background normalization & modelling (W+jets, Z+jets, top)

- Fit cross checked with di-boson signal (WZ+ZZ with Z→bb)

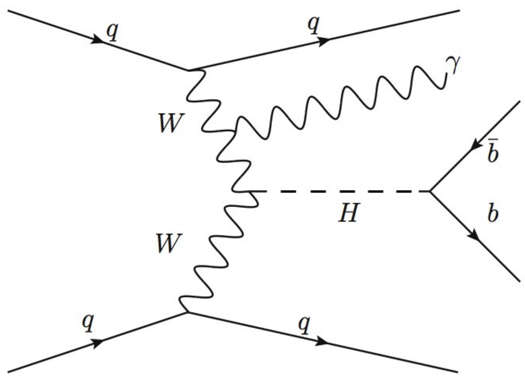
Observed significance: 3.2σ

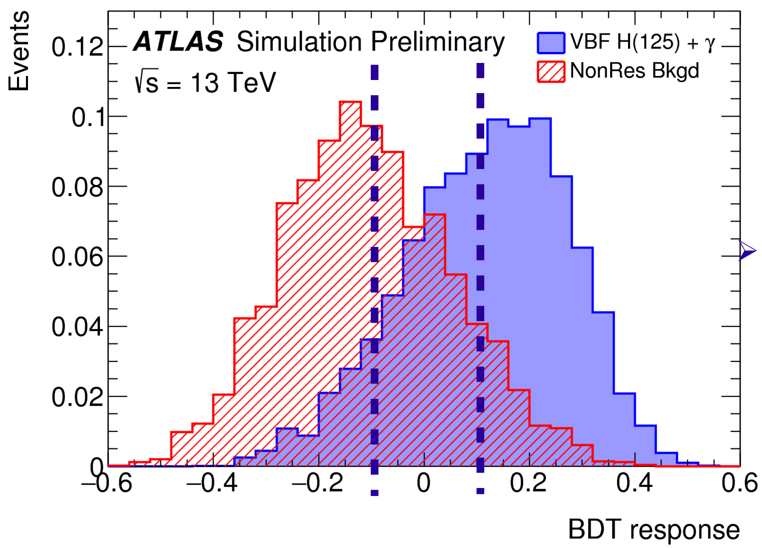
$$\mu_{VZ}=0.91\pm0.17(stat)^{+0.32}_{-0.23}(sys)$$





VBF+γ search





- Trigger:
  - L1 trigger: single photon (p_T > 25 GeV)
  - High level trigger: 4 jets p_T > 35 GeV, m_{jj} > 700 GeV
- Selection:
  - Tight ID photon, p_T > 30 GeV
  - 4 jets with p_T > 40 GeV
    - 2 central ($|\eta|$<2.5) b-tagged jets
    - p_T(bb system) > 80 GeV
    - Non b-tagged jets: m_{jj} > 800 GeV
- BDT discriminant
  - Built with variables uncorrelated to m_{bb}

$$\Delta R(jet,\gamma), m_{jj}, \Delta\eta_{jj}, H_T^{soft}, jet\ width, \gamma\ centrality, p_T^{balance}$$

  - Define 3 regions with different S/B
  - Fit m_{bb} in these 3 regions

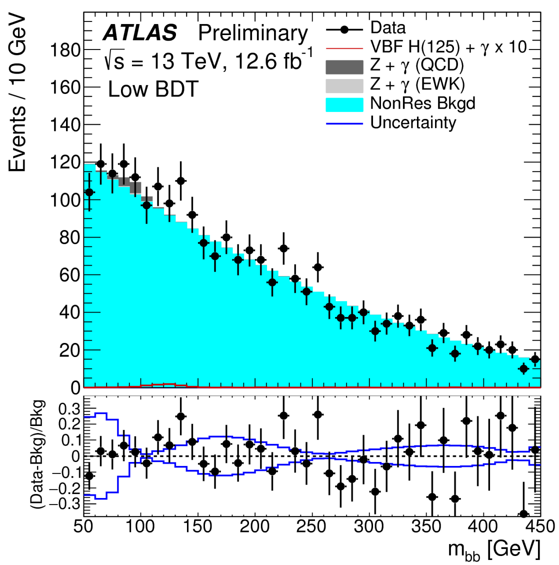
VBF+γ results

- Use a profile likelihood fit
- Non resonant background estimated with 2nd order polinomial fit in m_{bb} sideband
- Fit tested searching for $Z\to bb + \gamma$ production:
  - Expected 95% CL limit: $1.8^{+0.7}_{-0.5}$
  - Observed: 2.0

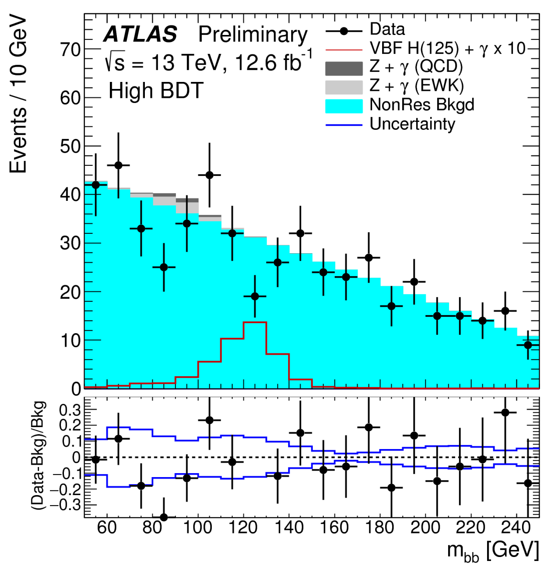
Result	$H(\to b\bar{b}) + \gamma jj$	$Z(\to b\bar{b}) + \gamma jj$
Expected significance	0.4	1.3
Expected p-value	0.4	0.1
Observed p-value	0.9	0.4
Expected limit	$6.0^{+2.3}_{-1.7}$	$1.8^{+0.7}_{-0.5}$
Observed limit	4.0	2.0
Observed signal strength μ	$-3.9^{+2.8}_{-2.7}$	0.3 ± 0.8

- Observed signal strength in the Higgs search:
  $\mu_{H,VBF+\gamma} = -3.9^{+2.8}_{-2.7}$
- Expected 95% CL limit:
  $6.0^{+2.3}_{-1.7}$
- Observed 95% CL limit:
  $4\times(\sigma\times BR)^{SM}$

- Low BDT score region:



- High BDT score region



Summary and conclusions

- The search for the Higgs decays to b-quarks is essential to probe the nature of the Higgs boson
  - Measure couplings to down-type quarks
  - Constraint total width

Presented very hot new ATLAS results on the search for H→bb

- In associated production with a W or a Z
  - 13.2 fb^{-1} of 13 TeV pp collisions
  - Expected (observed) significance: 1.92 (0.42)
  - Signal strength: $\mu_{VH,H\to bb}=0.21^{+0.51}_{-0.50}$

More details in poster 1115 (A. Buzatu): ATLAS VH(bb) Run II Search

- In vector boson fusion + photon production
  - 12.5 fb^{-1} of 13 TeV pp collisions
  - Expected (observed) 95% CL limit: $6^{+2.3}_{-1.7}$(4) times the SM expectation
  - Signal strength: $\mu_{H,VBF+\gamma}=-3.9^{+2.8}_{-2.7}$

First VBF+γ result!

Acknowledgements

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- OE, FCT-Portugal, CERN/FIS-NUC/0005/2015

Backup

Systematic uncertainties for VH analysis

- Signal

Signal	
Cross section (scale)	0.7% ($q\bar{q}$), 27% (gg)
Cross section (PDF)	1.9% ($q\bar{q} \to WH$), 1.6% ($q\bar{q} \to ZH$), 5% (gg)
Branching ratio	1.7 %
Acceptance (scale)	1.4%–5%
3-jet acceptance (scale)	1.4%–4.7%
p_T^V shape (scale)	S
Acceptance (PDF)	0.3%–0.7%
p_T^V shape (NLO EW correction)	S
Acceptance (parton shower)	4%–7.5%

- Simulated backgrounds:
  Normalisation, acceptance differences between regions, shapes
- Example for W+jets:

W+jets	
Wl normalisation	32%
Wcl normalisation	37%
Wbb normalisation	Floating
Wbl-to-Wbb ratio	17% (0-lepton) and 31% (1-lepton)
Wbc-to-Wbb ratio	42% (0-lepton) and 21% (1-lepton)
Wcc-to-Wbb ratio	17% (0-lepton) and 31% (1-lepton)
2-to-3 jet ratio	23%
0-to-1 lepton ratio	17%
p_T^V, m_{bb}	S

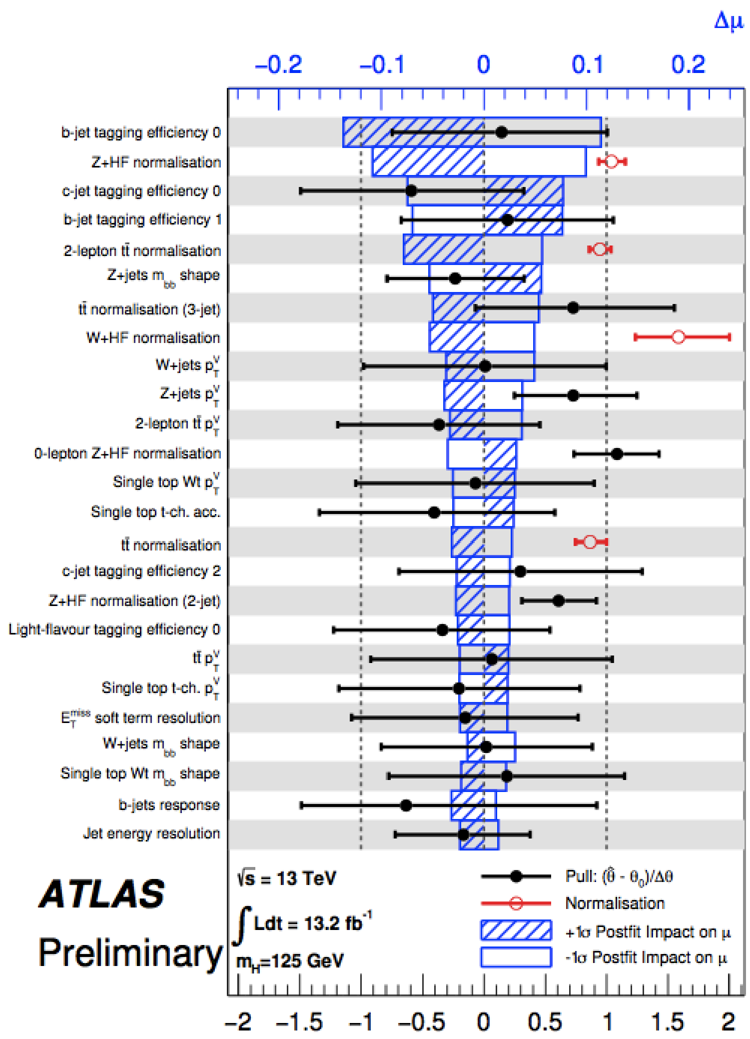
- Luminosity: 2.1% for 2015, 3.7% for 2016
- Jet energy scale, b-tagging:
  many sources → decomposed in uncorrelated components
- e, μ reconstruction, identification, trigger, energy/p_T scale: small impact

Uncertainties on simulated backgrounds (VH analysis)

Z+jets	
Zl normalisation	18%
Zcl normalisation	23%
Zbb normalisation	Floating
Zbc-to-Zbb ratio	14-27%
Zcc-to-Zbb ratio	7-31%
Zbl-to-Zbb ratio	15-38%
0-to-2 lepton ratio	26%
2-to-3 jet ratio	28% (0-lepton) and 25% (2-lepton)
p_T^V, m_{bb}	S
W+jets	
Wl normalisation	32%
Wcl normalisation	37%
Wbb normalisation	Floating
Wbl-to-Wbb ratio	17% (0-lepton) and 31% (1-lepton)
Wbc-to-Wbb ratio	42% (0-lepton) and 21% (1-lepton)
Wcc-to-Wbb ratio	17% (0-lepton) and 31% (1-lepton)
2-to-3 jet ratio	23%
0-to-1 lepton ratio	17%
p_T^V, m_{bb}	S
$t\bar{t}$ (all are decorrelated between the 0+1 and 2-lepton channels)	
$t\bar{t}$ normalisation	Floating
2-to-3-jet ratio	9% (0+1-lepton) and 24% (2-lepton)
p_T^V, m_{bb}	S

Single top	
Cross section	4.4% (s-channel), 4.6% (t-channel), 6% (Wt)
Acceptance 2-jet	16% (t-channel), 25% (Wt)
Acceptance 3-jet	19% (t-channel), 32% (Wt)
m_{bb}, p_T^V	S (p_T^V uncorrelated between 2 and 3-jet channels Wt)
ZZ	
Normalisation	20%
0-to-2 lepton ratio	30%
2-to-3 jet ratio	19 %
m_{bb}, p_T^V	S (correlated with WZ uncertainties)
WZ	
Normalisation	26%
2-to-3 jet ratio	14% (0-lepton) and 11% (1-lepton)
0-to-1 lepton ratio	12%
m_{bb}, p_T^V	S (correlated with ZZ uncertainties)
WW	
Normalisation	25%
Multi-jet	
Need final numbers	

Impact of the systematic uncertainties on signal strength for VH(bb) search



Run 2 VH(bb) selection

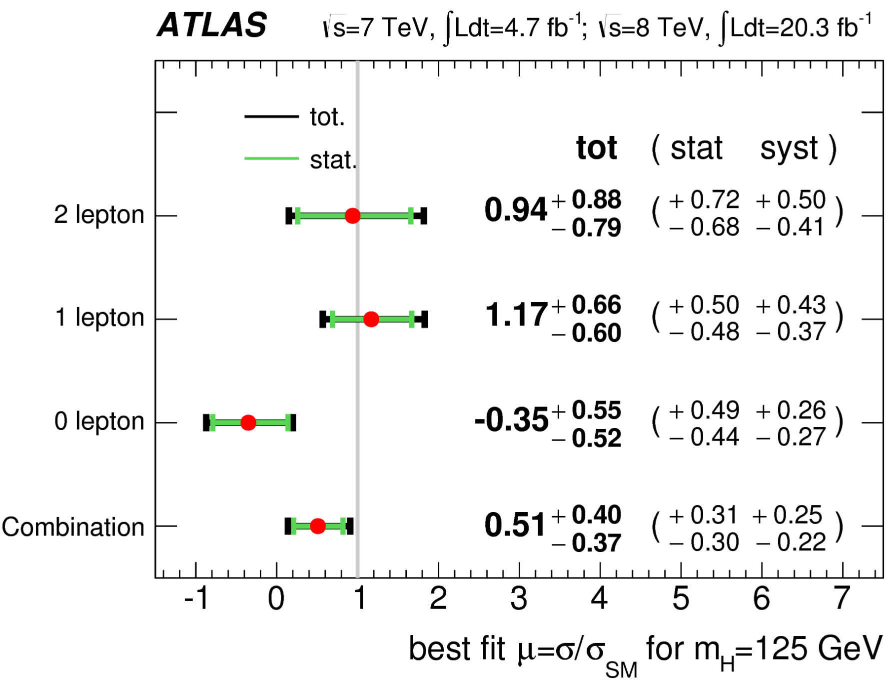
Selection	0-lepton	1-lepton	2-lepton
Trigger	E_T^{miss}	E_T^{miss} (μ sub-channel)	
		lowest unprescaled single lepton	
Leptons	0 loose lepton	1 tight lepton	2 loose leptons ($\geq$ 1 medium lepton)
Lepton pair	-	-	Same flavour opposite-charge for $\mu\mu$
E_T^{miss}	> 150 GeV	> 30 GeV (e sub-channel)	-
m_{ll}	-	-	$71 < m_{ll} < 121$ GeV
S_T	> 120 (2 jets), >150 GeV (3 jets)	-	-
Jets	$\geq$ 2 signal jets		
b-jets	2 b-tagged signal jets		
Leading jet p_T	> 45 GeV		
$\min\Delta\phi(E_T^{miss}, \text{jet})$	> 20°	-	-
$\Delta\phi(E_T^{miss}, h)$	> 120°	-	-
$\Delta\phi$(jet1,jet2)	< 140°	-	-
$\Delta\phi(E_T^{miss}, E_{T,trk}^{miss})$	< 90°	-	-
p_T^V regions	[0, 150] GeV (2-lepton), [150, ∞] GeV		

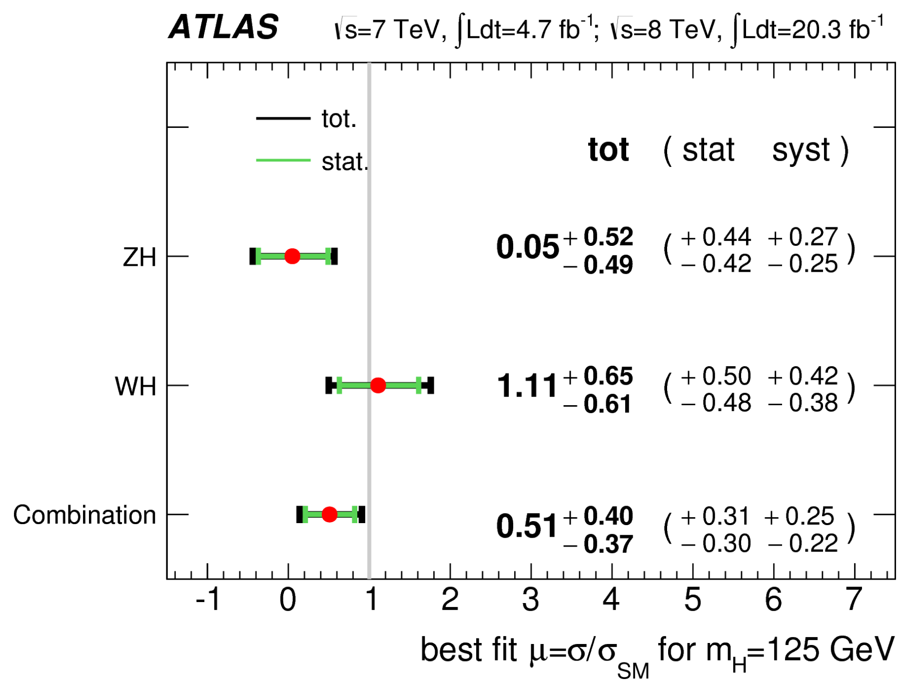
Table 1: Summary of the event selection in the 0-, 1- and 2-lepton channels.

Run 1 VH ($H \rightarrow bb$) results

- Expected (observed) significance: 2.6 (1.6) for a mass of 125.36 GeV

$$\mu = 0.52 \pm 0.32(stat) \pm 0.24(sys)$$





VBF systematics

Uncertainty source	Uncertainty $\Delta\mu$
Non-resonant background uncertainty in medium-BDT region	0.22
Non-resonant background uncertainty in high-BDT region	0.21
Non-resonant background uncertainty in low-BDT region	0.17
Parton shower uncertainty on $H + \gamma$ acceptance	0.16
QCD scale uncertainty on $H + \gamma$ cross section	0.13
Jet energy uncertainty from calibration across η	0.10
Jet energy uncertainty from flavour composition in calibration	0.09
Integrated luminosity uncertainty	0.08

VBF BDT variables

- $\Delta R(\text{jet}, \gamma)$: angular separation between one of the selected jets and the photon, with specific cases for the p_{T}-ordered jets j_1 and j_2, and for p_{T}-ordered b-jets b_1 and b_2;
- m_{jj}: invariant mass of the VBF-jet pair;
- $\Delta\eta_{jj}$: separation in η between the VBF jets;
- jet width for the VBF jets, sensitive to differences between quark and gluon jets [29];
- $p_{\mathrm{T}}^{\text{balance}}$: transverse-momentum balancing variable for the selected final state objects:

$$p_{\mathrm{T}}^{\text{balance}} = \frac{(p^{b_1} + p^{b_2} + p^{j_1} + p^{j_2} + p^{\gamma})_{\mathrm{T}}}{p_{\mathrm{T}}^{b_1} + p_{\mathrm{T}}^{b_2} + p_{\mathrm{T}}^{j_1} + p_{\mathrm{T}}^{j_2} + p_{\mathrm{T}}^{\gamma}} \tag{1}$$

  For signal events produced via electroweak processes, where there is minimal QCD radiation, the final state objects should be more balanced than in the background. For non-resonant multijetback-ground, where additional radiation is more likely and more final state objects are expected, the final state should be more unbalanced than in the signal electroweak process.

- centrality of the photon with respect to the VBF jets:

$$\text{centrality}(\gamma) = \left| \frac{y_{\gamma} - \frac{y_{j_1} + y_{j_2}}{2}}{y_{j_1} - y_{j_2}} \right| \tag{2}$$

- $H_{\mathrm{T}}^{\text{soft}}$: scalar p_{T} sum over the track-jets with $p_{\mathrm{T}} > 7$ GeV. The track-jets used to calculate $H_{\mathrm{T}}^{\text{soft}}$ are

- Search for a CP-odd Higgs boson $A \rightarrow Zh \rightarrow Zbb$ with 3.2 fb^{-1} of pp collisions at 13 TeV: