Search for the bb decay of the Standard Model Higgs boson in ATLAS

Higgs Hunting, 26th July 2013

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On behalf of the ATLAS Collaboration
Introduction

Full 2011 (4.7 fb\(^{-1}\) @ 7 TeV) and 2012 (20.3 fb\(^{-1}\) @ 8 TeV)

ATLAS-CONF-2013-079

talk outline:
- Event Selection
- Background Modeling
- Diboson fit results
- Higgs fit results
- \(ttH, H \to bb\) summary

See Inês Ochoa talk for more on details about the VH analysis
Analysis strategy

Events categorised by $V p_T$ to boost sensitivity

Additional categories used to determine backgrounds

- number of leptons (0, 1, 2)
- number of jets (2, 3)
- number of b-tagged jets (1, 2)
- $p_T$ bins (at 0, 90, 120, 160, 200 GeV intervals)

The main backgrounds are determined in the following regions

<table>
<thead>
<tr>
<th>Lepton</th>
<th>$p_T$ Bins</th>
<th>Signal</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Event Selections - 2 lepton

Trigger - single and di-lepton
Leptons - 1 medium and 1 loose leptons
Missing Transverse Momentum < 60 GeV
Mass cut on Z boson - $83 < m_{ll} < 99$ reduce $tt$

boson $p_T^V$ is vector sum of the two leptons

Analysis Selections of Jets

- $p_T > 20$ GeV & $|\eta| < 2.5$
- at least 2 jets
- leading jet $p_T > 45$ GeV
- 2 b-tagged jets (70% efficiency each jet, event efficiency is ~50%)

3 types of lepton identification increasing in purity

- **Loose**
  - $p_T > 10$ GeV
  - electrons $|\eta| < 2.47$ & muons $|\eta| < 2.7$
  - impact parameter
  - basic quality requirements
  - track isolation

- **Medium**
  - $p_T > 25$ GeV
  - electrons - additional track quality and the shower shape
  - muons - $|\eta| < 2.5$

- **Tight**
  - tighter track isolation
  - calorimeter isolation
  - electrons - more stringent quality requirements
Event Selections - 1 lepton

Trigger - single lepton or Missing E_T (20% increase for muons)

Leptons - 1 tight and no loose leptons

Missing Transverse Momentum > 25 GeV

Transverse Mass < 120 GeV \[ \text{select W} \]

Transverse Mass > 40 GeV \[ \text{reduce multijet} \]

Veto jets - \( p_T > 30 \text{ GeV} \& |\eta| > 2.5 \) \[ \text{reduce tt} \]

\( \text{boson } p_T^V \) is magnitude of the vector sum of the lepton and Missing E_T

Analysis Selections of Jets

- \( p_T > 20 \text{ GeV} \& |\eta| < 2.5 \)
- at least 2 jets
- leading jet \( p_T > 45 \text{ GeV} \)
- 2 b-tagged jets (70% efficiency each jet, event efficiency is \( \sim 50\%) \)

\[ m_T^W = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos(\phi^\ell - \phi^{\text{miss}}))} \]

3 types of lepton identification increasing in purity

- Loose
  - \( p_T > 10 \text{ GeV} \)
  - electrons \( |\eta| < 2.47 \) & muons \( |\eta| < 2.7 \)
  - impact parameter
  - basic quality requirements
  - track isolation

- Medium
  - \( p_T > 25 \text{ GeV} \)
  - electrons - additional track quality and the shower shape
  - muons - \( |\eta| < 2.5 \)

- Tight
  - tighter track isolation
  - calorimeter isolation
  - electrons - more stringent quality requirements
Event Selections - 0 lepton

Trigger - Missing $E_T$
Leptons - no loose leptons

Missing Transverse Momentum $> 120$ GeV
Track-based Missing Transverse Momentum $p_T^{\text{miss}} > 30$ GeV

$$\Delta \phi (E_T^{\text{miss}}, p_T^{\text{miss}}) < \pi/2$$
$$\min[\Delta \phi (E_T^{\text{miss}}, \text{jet})] > 1.5$$
$$\Delta \phi (E_T^{\text{miss}}, b\bar{b}) > 2.8$$

reduce multijet to $< 1\%$
Veto jets - $p_T > 30$ GeV & $|\eta| > 2.5$ reduce $t\bar{t}$

boson $p_T^V$ is Missing $E_T$

Analysis Selections of Jets

- $p_T > 20$ GeV & $|\eta| < 2.5$
- at least 2 jets
- leading jet $p_T > 45$ GeV
- 2 b-tagged jets (70% efficiency each jet, event efficiency is $\sim 50\%$)

fully efficient for $E_T^{\text{miss}} > 160$ GeV
B-tagging and $m_{bb}$ mass resolution

Jet Reconstruction

- **Anti-$k_t$** $R=0.4$
- Pile-up correction jet-area based
- Calibrated using $p_T$ and $\eta$ dependent factors
- Corrections applied for muons in jet
- B-tagging is neural network-based
  - inputs: 3 different b-tagging methods
  - efficiency: 70% for b, ~20% for c, ~0.6% for light
  - ~2% precision achieved in the calibration analysis (intermediate $p_T$ region)
Further Optimisations

\( \Delta R(b, b) \) optimisations
- \( \Rightarrow \) max cuts reduces background
- \( \Rightarrow \) min cuts reduces V+jets background

1 lepton channel
- \( \Rightarrow \) Missing \( E_T \) cut increase at highest bin
- \( \Rightarrow \) Min Transverse Mass cut removed in higher bins

<table>
<thead>
<tr>
<th>All Channels</th>
<th>( p_T^V ) [GeV]</th>
<th>0-90</th>
<th>90-120</th>
<th>120-160</th>
<th>160-200</th>
<th>&gt;200</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta R(b, b) )</td>
<td>( 0.7-3.4 )</td>
<td>( 0.7-3.0 )</td>
<td>( 0.7-2.3 )</td>
<td>( 0.7-1.8 )</td>
<td>( &lt;1.4 )</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1-lepton</th>
<th>( E_{\text{miss}}^T ) [GeV]</th>
<th>( &gt;25 )</th>
<th>( &gt;50 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_W^T ) [GeV]</td>
<td>( 40-120 )</td>
<td>( &lt;120 )</td>
<td></td>
</tr>
</tbody>
</table>

After object ID and kinematic selection, the main discriminator is \( m_{bb} \)
tt Background

Normalisation determined by fit to data

Mismodeling $p_T$
- PowHeg predicts too hard a $p_T$ distribution
- correction applied at generator level

Systematic uncertainties
- 3-to-2 jet ratio: 5%
- $m_{bb}$ shape: 5%
- top $p_T$ correction
- c jet efficiency at high $p_T^V$

1 lepton, 3 jets, 2 tags

2 lepton, tt control
V+jets Background

Normalisation determined by fit to data
Mismodeling of $\Delta\phi(j,j)$:
  • 0 b-tag control
  • subtract from data all other background (except Z+jets)
  • divide by MC Z+jets
  • linear parametrisation
  • $p_T^V$ distributions are affected
  • treated as uncorrelated
    • W+jets and Z+jets
    • no. of b jets
    • no. of jet

Systematics uncertainties:
  • flavour composition
  • 3-to-2 jet ratio
  • $m_{bb}$ shape
  • $p_T^V$
Systematics

Experimental systematic uncertainties
- lepton reconstruction and PID
- Jet Energy Scale
- B-tagging
- Missing \( E_T \)
- Multijet background:
  - normalisation uncertainties 100% for the 0- and 2-lepton channels
  - 1 lepton freely floating in global fit, independently of no. of jets and tags
  - \( p_T^V \)
- Luminosity: 2.8% for 2012, 1.8% for the 2011
- Pile-up

Simulated background systematic uncertainties
- single top
  - \( \sigma \): 4-7%
  - 3-to-2 jet ratio: 5-15%
  - \( p_T^V \) shape: 5%
  - \( m_{bb} \) shape: 5-10%
- diboson
  - \( \sigma \): 5-7%
  - 3-jet to 2-jet ratios
  - \( p_T^V \): 5-60%

Signal systematic uncertainties
- cross sections: 5-7%, calculated at NNLO in QCD, applying electroweak corrections at NLO
- NLO EW corrections: ~2%, differential cross sections applied as function of \( p_T^V \) on the LO WH and ZH signals (pythia8)
- Higgs boson BR to bb: 3.3% for \( m_H = 125 \text{ GeV} \)
- **Signal Acceptance: 10% comparing pythia8, pythia6 and herwig**
The fit also adjusts the shapes of the dijet mass distributions within the constraints from the systematic uncertainties:

- **Multijet**: determined in data before final fit
- **Diboson, single top, V+light**: Normalisation constrained by theoretical uncertainties
- **tt, Vb, Vcl**: Normalisation completely determined by fit to data

### Table: Global Fit

<table>
<thead>
<tr>
<th>Lepton Configuration</th>
<th>Multijet</th>
<th>Diboson, Single Top, V+light</th>
<th>tt, Vb, Vcl</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 lepton × 3 pT bins</td>
<td>admixture</td>
<td>admixture</td>
<td></td>
</tr>
<tr>
<td>1 lepton × 5 pT bins</td>
<td>W+c</td>
<td>Top</td>
<td></td>
</tr>
<tr>
<td>2 lepton × 5 pT bins</td>
<td>Z+c</td>
<td>Z+b</td>
<td>Top</td>
</tr>
</tbody>
</table>

### Diagrams:

- **Top**
- **W+jets**
- **Z+jets**

**Norm.**

**Shape**

**Norm.**
Post-fit $m_{bb}$ distributions

2 jets 2 tags, highest $p_T^V$ bin (> 200 GeV)

Good agreement between data and signal+background expectation

After global fit, uncertainties on the background and signal yields are 3% and 12% (Before fit, 10-13% and 13-14%)

Dominant systematic uncertainties include:

- $tt$ modeling ($m_{bb}$ shape, 2-3-jet ratio, $p_T^V$)
- Tagging efficiency for $c$ jets
- Multijet normalisation 1 lepton
- Signal acceptance

rest of $p_T^V$ bins in backups
Fitting Cross Check - Diboson

Diboson decay, VZ, Z→bb
- very similar decay signature
- softer $p_T$ spectrum & lower $m_{bb}$
- cross section ~5 times larger

Fit to diboson peak, fixing Higgs peak to SM expectation

Fit summary for each channel and both years

\[ \mu_{VZ} = 0.9 \pm 0.2 \] agrees with SM expectation of 1, corresponds to 4.8σ observed significance (5.1σ expected)

20% uncertainties with run 1 dataset
Limits

Cross section upper limits, normalised to the SM Higgs boson production cross section

Observed (expected) limits for $m_H = 125$ GeV:
- 7 TeV: 2.0 (3.3) x SM
- 8 TeV: 1.9 (1.3) x SM
- Combined: 1.4 (1.3) x SM

No significant excess is observed

This expected limit represents a 35% improvement in the analysis sensitivity
Fit to Higgs Cross Section

Fit summary for each channel and both years

**ATLAS Prelim.**

\[ m_H = 125 \text{ GeV} \]

** signal strength parameter: \[ \mu = \frac{\sigma_{\text{meas}}}{\sigma_{\text{SM}}} \]**

The fitted value of the signal strength parameter is:

\[ \mu = 0.2 \pm 0.5\text{(stat.)} \pm 0.4\text{(syst.)} \]
ttH

2011 (4.7 fb\(^{-1}\) @ 7 TeV)
ATLAS-CONF-2012-135

*tt* semileptonic decay: \(ttH \rightarrow Wb Wb bb \rightarrow l\nu bb bb\)

**Selections**

- single lepton trigger
- High jet multiplicity: 4 b-jets + 2 jets
  - \(p_T > 25\) GeV
  - \(|\eta| < 2.5\)
  - b-tagging - 70% efficiency
- 1 isolated high \(p_T\) lepton
  - electron \(p_T > 25\) GeV
  - muon \(p_T > 20\) GeV
- high missing \(E_T\)
  - \(e\) channel: missing \(E_T > 30\) GeV, \(m_T > 30\) GeV
  - \(\mu\) channel: missing \(E_T > 20\) GeV, missing \(E_T + m_T > 60\) GeV
**ttH fit distributions**

- **Signal categories:**
  - 5 or ≥ 6 jets; 3 or ≥ 4 b-jets

- **Background categories:**
  - 4 jets; 0 or 1 or ≥ 2 b-jets
  - 5 or 6 jets; 2 b-tags

After selections; fit to data constraining systematics

Main background: tt

Main systematics: b/c tagging, tt modeling

*pre-fit*

*post-fit*
ttH results

Cross section upper limits, normalised to the SM Higgs boson production cross section

Observed (expected) limits for $m_H = 125$ GeV:

- $13.1\ (10.5) \times \text{SM}$

No significant excess is observed
Conclusions

- Results on the search for VH, H to bb on full 2011 and 2012 data
- Results on the search for ttH, H to bb on 2011 data
- 35\% gain in significance on top of the luminosity:
  - ΔR(b,b) optimisation
  - background modeling
  - experimental systematics
- Fit to diboson peak consistent with SM expectation.
- No significant excess is observed.
- Observed (expected) limit for m_H = 125 GeV is 1.4 (1.3) xSM @ 95\% CL
- The corresponding limit expected in the absence of signal is 1.3.
- The ratio of the measured Higgs-boson production strength to the SM expectation is found to be μ = 0.2 ± 0.5(stat.) ± 0.4(syst.)
- ttH, Observed (expected) limit for m_H = 125 GeV is 13.1 (10.5) xSM @ 95\% CL
Backups
### Signal Acceptance

<table>
<thead>
<tr>
<th>(W/Z)(H → b¯b)</th>
<th>Cross-section × BR [fb]</th>
<th>$m_H = 125$ at 7 TeV</th>
<th>Acceptance [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0-lepton</td>
</tr>
<tr>
<td>$Z \rightarrow \ell\ell$</td>
<td>12.3</td>
<td>0.0</td>
<td>0.7</td>
</tr>
<tr>
<td>$W \rightarrow \ell\nu$</td>
<td>107.1</td>
<td>0.2</td>
<td>3.5</td>
</tr>
<tr>
<td>$Z \rightarrow \nu\nu$</td>
<td>36.4</td>
<td>2.2</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(W/Z)(H → b¯b)</th>
<th>Cross-section × BR [fb]</th>
<th>$m_H = 125$ at 8 TeV</th>
<th>Acceptance [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0-lepton</td>
</tr>
<tr>
<td>$Z \rightarrow \ell\ell$</td>
<td>15.3</td>
<td>0.0</td>
<td>0.9</td>
</tr>
<tr>
<td>$W \rightarrow \ell\nu$</td>
<td>130.2</td>
<td>0.2</td>
<td>3.3</td>
</tr>
<tr>
<td>$Z \rightarrow \nu\nu$</td>
<td>45.5</td>
<td>2.5</td>
<td>-</td>
</tr>
</tbody>
</table>
Model of the Fit

Likelihood of Poisson probabilities:

\[ L(\mu, \theta) = \prod_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \prod_{k=1}^{M} \frac{u_k^{m_k}}{m_k!} e^{-u_k} \]

signal and background parameterisations:

\[ s_i = s_{tot} \int_{\text{bin } i} f_s(x; \theta_s) \, dx \quad b_i = b_{tot} \int_{\text{bin } i} f_b(x; \theta_b) \, dx \]

test hypothesised values of \( \mu \) with a test statistics:

\[ \Lambda(\mu) = \frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta})} \]
7 and 8 TeV Limits

\[ \text{ATLAS Preliminary} \]
\[ \sqrt{s} = 7 \text{ TeV} \quad \int \text{Ldt} = 4.7 \text{ fb}^{-1} \]
\[ \text{ATLAS Preliminary} \]
\[ \sqrt{s} = 8 \text{ TeV} \quad \int \text{Ldt} = 20.3 \text{ fb}^{-1} \]
2 jet, 2 tag fitted numbers of signal and background events and the observed numbers of events

<table>
<thead>
<tr>
<th>Process</th>
<th>0-lepton</th>
<th>1-lepton</th>
<th>2-lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>120-160</td>
<td>160-200</td>
<td>&gt;200</td>
</tr>
<tr>
<td>$Z \rightarrow \nu\nu$</td>
<td>1.6</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>$Z \rightarrow \ell\ell$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>$W \rightarrow \ell\nu$</td>
<td>0.4</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>VH total</td>
<td>2.0</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>VH expected</td>
<td>11</td>
<td>5.8</td>
<td>6.1</td>
</tr>
<tr>
<td>Top</td>
<td>159</td>
<td>33</td>
<td>8</td>
</tr>
<tr>
<td>W+c, light</td>
<td>22</td>
<td>5.5</td>
<td>2.8</td>
</tr>
<tr>
<td>W+b</td>
<td>30</td>
<td>10</td>
<td>6.1</td>
</tr>
<tr>
<td>Z+c, light</td>
<td>24</td>
<td>8.1</td>
<td>5.2</td>
</tr>
<tr>
<td>Z+b</td>
<td>226</td>
<td>71</td>
<td>39</td>
</tr>
<tr>
<td>WW</td>
<td>0.5</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>VZ</td>
<td>26</td>
<td>11</td>
<td>10.3</td>
</tr>
<tr>
<td>Multijet</td>
<td>4.8</td>
<td>1.1</td>
<td>0.7</td>
</tr>
<tr>
<td>Total Bkg.</td>
<td>491</td>
<td>141</td>
<td>72</td>
</tr>
<tr>
<td>Data</td>
<td>502</td>
<td>143</td>
<td>90</td>
</tr>
<tr>
<td>$S/B$</td>
<td>0.004</td>
<td>0.008</td>
<td>0.02</td>
</tr>
</tbody>
</table>
3 jet, 2 tag fitted numbers of signal and background events and the observed numbers of events

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>120-160</td>
<td>160-200</td>
<td>&gt;200</td>
</tr>
<tr>
<td>$Z \rightarrow \nu \nu$</td>
<td>0.4</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>$Z \rightarrow \ell \ell$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>$W \rightarrow \ell \nu$</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>VH total</td>
<td>0.5</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>VH expected</td>
<td>2.7</td>
<td>1.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Top</td>
<td>169</td>
<td>44</td>
<td>13</td>
</tr>
<tr>
<td>W+c, light</td>
<td>7.2</td>
<td>2.2</td>
<td>1.3</td>
</tr>
<tr>
<td>W+b</td>
<td>12</td>
<td>4.7</td>
<td>3.3</td>
</tr>
<tr>
<td>Z+c, light</td>
<td>6.3</td>
<td>2.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Z+b</td>
<td>59</td>
<td>26</td>
<td>17</td>
</tr>
<tr>
<td>WW</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>VZ</td>
<td>3.7</td>
<td>1.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Multijet</td>
<td>3.1</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Total Bkg.</td>
<td>260</td>
<td>82</td>
<td>40</td>
</tr>
<tr>
<td>Data</td>
<td>287</td>
<td>59</td>
<td>40</td>
</tr>
<tr>
<td>$S/B$</td>
<td>0.002</td>
<td>0.004</td>
<td>0.009</td>
</tr>
</tbody>
</table>
0 lepton, 2 jet 2 tag
1 lepton, 2 jet 2 tag
2 lepton, 2 jet 2 tag

**ATLAS Preliminary**

1. $\sqrt{s} = 7$ TeV, $L_{int} = 4.7$ fb$^{-1}$
2. $\sqrt{s} = 8$ TeV, $L_{int} = 20.3$ fb$^{-1}$

2 lepton, 2 jets, 2 tags, $p_T < 90$ GeV

![Graph](image_url)

$\frac{\text{Events}}{\text{Data/MC}}$ vs $m_{bb}$ [GeV]
0 lepton, 3 jet 2 tag
1 lepton, 3 jet 2 tag
2 lepton, 3 jet 2 tag
ttH Signal
ttH Backgrounds