A Search for pp → hh → 4b with ATLAS

On 19.5 fb⁻¹ of √s = 8 TeV data collected by ATLAS in 2012

IoP 2015, Manchester
Rebecca Falla
Motivation

The discovery of the Higgs boson in 2012 has opened up many new searches
Higgs boson can be used as a tool for discovery

Many new physics models predict significant rates of Higgs boson pair production at high invariant mass
Resonant: KK Graviton $G^* \rightarrow hh$, extended Higgs sector $H \rightarrow hh$...
Non-resonant: New coloured scalars, direct $ttH$ vertices...

$\text{BR}(H \rightarrow bb) \sim 57\%$
Pair of Higgs bosons decays to 4b jets $\sim \frac{1}{3}$ of the time

Distinctive topology from boosted pairs of b-jets
Greatly reduces backgrounds
Negligible ambiguity in reconstructing Higgs boson decays
Overview of Analysis

Event Selection:
- 4 b-tagged jets that form two boosted dijet systems
- Require $m_{dijet} \sim m_h$

Backgrounds:
- Multijet QCD 90%
- TTbar 10%
- Z + jets <1%

Search:
- For resonant Higgs boson pair production look for bumps in $m_{4j}$ spectrum
- For non-resonant Higgs boson pair production, do simple event counting
Event Selection

1. 4 b-tagged Anti-K$_T$ R = 0.4 jets:
   1. $p_T > 40$ GeV, $|\eta| < 2.5$
   2. B-tagging with 70% efficiency

2. 2 Dijets:
   1. $p_T > 150$ and 200 GeV
   2. $\Delta R(jet, jet) < 1.5$

3. Cuts dependent on the reconstructed $m_{4j}$

4. Top Rejection Criteria

5. Both dijet masses $\sim m_H$

---

Low mass inefficiency due to $4^{th}$ jet $p_T < 40$ GeV

High mass inefficiency due to boost of each Higgs boson causing the b-quarks ending up too close together to resolve into two b-tagged jets

---

Bulk RS, $k/M_{Planck} = 1.0$

ATLAS Work in Progress

$\sqrt{s} = 8$ TeV

Acceptance x Efficiency

4 b-jets
2 dijets
MDC
$t\bar{t}$ Veto
Signal Region

$M_{4j}$ [GeV]
Data-Driven Multijet Background Model

Multijet model = 2-tag data
- Passes basic kinematic cuts & top rejection criteria
- Only one dijet is required to be double b-tagged
- Gives a 98% pure multijet sample

Normalisation and shape of model controlled and tested in $m_{12}$-$m_{34}$ plane
Regions defined by a circle centred on (124,115) with radius 58 GeV

Sideband Region
Sets normalisation of multijet bkgd
2-tag kinematics reweighted to 4-tag data in sideband

Control Region
Used to test the kinematic reweighting and normalization done within the sideband
Testing in Control Region

Test normalisation of multijet prediction in control region

<table>
<thead>
<tr>
<th></th>
<th>Sideband</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reweighted QCD</td>
<td>907 ± 3</td>
<td>789 ± 3</td>
</tr>
<tr>
<td>ttbar MC</td>
<td>25.5 ± 0.3</td>
<td>57.5 ± 0.4</td>
</tr>
<tr>
<td>Z + jets MC</td>
<td>14 ± 1</td>
<td>20 ± 1</td>
</tr>
<tr>
<td>Total Background</td>
<td>946 ± 3</td>
<td>867 ± 3</td>
</tr>
<tr>
<td>Data</td>
<td>952 (± 31)</td>
<td>852 (± 30)</td>
</tr>
</tbody>
</table>

ATLAS Work in Progress

- Errors here are stat. only
- Agreement in control region is within statistical error
Multijet Model Cross Checks

Multijet model tested by repeating the reweighting using different region definitions and b-tagging weights

Test of kinematics used to reweight 2→4 tag
  – Use “low mass” and “high mass” enhanced sideband region

Test of 2-tag model
  – Use lower and higher b-tagging requirements on 2-tag sample

Test for signal contamination
  – Use a larger signal ellipse to eliminate signal contamination in control region

All tests showed good agreement, an uncertainty of 6% on normalisation was assigned
Data Driven TTbar Normalisation

- Define a ttbar enhanced control region from data events that pass full selection but fail the ttbar veto (TTCR)
- Multijet in this region is modelled by 2-tag sample also failing ttbar veto and scaled by $\mu_{QCD}$

$\text{ttbar yield in } hh \text{ signal region is then given by:}$

$$N_{tt}^{Bkg} = \frac{\epsilon^2}{1 - \epsilon^2} \times N_{tt}^{CR}$$
Data Driven TTbar Normalisation

- Define a $t\bar{t}$ enhanced control region from data events that pass full selection but fail the $t\bar{t}$ veto (TTCR).
- Multijet in this region is modelled by 2-tag sample also failing $t\bar{t}$ veto and scaled by $\mu_{QCD}$.

The $t\bar{t}$ yield in $hh$ signal region is then given by:

$$N_{t\bar{t}}^{Bkg} = \frac{\epsilon^2}{1 - \epsilon^2} \times N_{t\bar{t}}^{CR}$$

**Per dijet efficiency to pass $t\bar{t}$ veto**
- Measured in data using semi-leptonic control region (SLCR).
- Measure $\epsilon = 0.527 \pm 0.03$ (stat) $\pm 0.053$ (sys.)

**$t\bar{t}$ yield in TTCR**
- Determined by subtracting multijet contribution.

Method has two assumptions which are tested in MC to 10% closure:
- Dijet efficiencies uncorrelated
- $\epsilon$ in SLCR same as $\epsilon$ in signal

- Gives $N_{t\bar{t}} = 5.2 \pm 2.6$ events (error driven by stat in TTCR)
Systematics Overview

Affecting only background:
- Multijet normalisation uncertainty ± 6%.
- Multijet shape uncertainty.
- ttbar normalisation uncertainty ± 50%.
- ttbar shape uncertainty.

Affecting only signal:
- Luminosity ± 2.8%.
- B-tagging scale factor uncertainties.
- Jet energy scale uncertainties.
- Jet energy resolution uncertainty.
- Signal Modelling 1%
Final Background Prediction

Sample | Events in hh Region
--- | ---
Multijet | 81.4 ± 4.9
TTbar | 5.2 ± 2.6
Z + jets | 0.4 ± 0.2
Total Bkgd | 87.0 ± 5.6

ATLAS Work in Progress
Expected Limits

Resonant:
For a Bulk R-S Kaluza Klein Graviton we are expected to exclude
500 < \( m_G < 700 \) GeV

Non-Resonant SM HH:
Expected exclusion of \( 200^{+80}_{-60} \) fb which corresponds to \( \mu = \frac{\sigma}{\sigma_{SM}} = 57^{+23}_{-18} \)
Excluded $m_{G^*}$ from 590 - 710 GeV

Have improved on analysis Strategy since then:

- Kinematic cuts based on the reconstructed $m_{4j}$
- Kinematic fit using $m_{dijet} = m_H$ constraint
- Lower high $p_T$ b-tagging scale factor uncertainties
A search for $pp \rightarrow hh \rightarrow 4b$ on ATLAS 2012 data is being performed.

Data driven methods have been used to estimate the dominant backgrounds.

Multiple cross checks have shown the analysis method to be robust.

Large improvements in sensitivity have been made since the 2014 note: ATLAS-CONF-2014-005.
Thanks for Listening!
BACKUP SLIDES
Multijet Normalisation Scale Factor - $\mu_{QCD}$

$$\mu_{QCD} = \frac{N_{QCD}^{4\text{-tag}}}{N_{QCD}^{2\text{-tag}}} = \frac{N_{data}^{4\text{-tag}} - N_{tt}^{4\text{-tag}} - N_{Z+jets}^{4\text{-tag}}}{N_{data}^{2\text{-tag}} - N_{tt}^{2\text{-tag}} - N_{Z+jets}^{2\text{-tag}}}$$

This is worked out in the sideband
Data & Triggers

• Data: JetEtMiss stream 2012 periods B-L 19.5 fb⁻¹

• Using OR of 5 unprescaled triggers:
  – EF_2b35_loose_j145_j35_a4tchad
  – EF_b45_medium_4j45_a4tchad_L2FS
  – EF_b45_medium_j145_j45_a4tchad_HT500
  – EF_4j80_a4tchad_L2FS
  – EF_j360_a4tchad

Signal trigger efficiency > 99% for all $m_{G^{*}}$

MC modelling of triggers validated against Data in bootstrap study for $Z \rightarrow bb$ analysis (ATL-COM-PHYS-2013-606)
TTbar Veto (1)

- TTbar decays to bWbW ~100% of time
- Selected ttbar jets in analysis are mostly bc bc

“Extra jets” in the event used to reconstruct $m_W$ and $m_t$ by combining with dijets:
  - $m_W =$ mass of least b-like jet in dijet and extra jet.
  - $m_t =$ mass of dijet and extra jet.
TTbar Veto (2)

Reject event if any dijet-extra jet combination satisfies $X_{tt} < 3.2$

$$X_{tt} = \sqrt{\left(\frac{m_W - 80.4}{\sigma_{m_W}}\right)^2 + \left(\frac{m_t - 172.5}{\sigma_{m_t}}\right)^2}$$

Where $\sigma_X = 0.1 m_X$

Rejects ~60% of ttbar whilst keeping ~90% of signal!

- Extra jet conditions: $p_T > 30$ GeV, $|\eta| < 2.5$, $\Delta R$ w.r.t dijet < 1.5
- Note that many signal events do not have extra jets and so pass this veto automatically