ATLAS Searches for Resonances Decaying to Boson Pairs
EPS-HEP 2019

Roland Jansky, on behalf of the ATLAS experiment
University of Geneva

11th July 2019
Jets at the Energy Frontier

- LHC: $\sqrt{s} = 13$ TeV.
- Common background for all presented analyses: QCD multi-jet production, $t\bar{t}$, $(W/Z+\text{jets})$. 

$m=8.12$ TeV dijet event
jet $p_T=3.79$ TeV
Jets at the Energy Frontier

- LHC: $\sqrt{s} = 13$ TeV.
- Common background for all presented analyses: QCD multi-jet production, $t\bar{t}$, ($W/Z$+jets).

$m=8.12$ TeV dijet event
jet $p_T=3.79$ TeV

something new?

proton

proton
Targeting all-hadronic final states and high masses:

- Search for bump in dijet invariant mass spectrum, where both jets are identified as $W$- or $Z$-bosons.
- Using new jet reconstruction input and optimized tagger.

\[
p_1 (1 - x)^{p_2 - \xi} x^{p_3}, \quad x = m_{jj}/\sqrt{s}.
\]

arXiv:1906.08589 (submitted to JHEP)
Improved Jet Substructure Reconstruction

- **New techniques**: combining tracker and calorimeter information on fundamental level.

- **TrackCaloClusters** improve jet substructure resolution at high $p_T$ by factor two.

- **Boosting sensitivity** of ATLAS searches on full LHC Run 2 data set.

---

**ATL-PHYS-PUB-2017-015**

![Graph showing jet $D_2$ resolution with ATLAS Simulation conditions: $\sqrt{s} = 13$ TeV, anti-$k_T$ R=1.0, WZ → qqqq, $|\eta|^{jet}<2.0$, $p_T^{jet}>200$ GeV.]
**Results:** no excesses. Quoting limits for spin-0 radion, spin-1 Heavy Vector Triplet (HVT) $W'/Z'$, spin-2 Randall-Sundrum graviton.

- Biggest improvement at intermediate masses.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>5.72</td>
<td>5.75</td>
<td>4.286</td>
</tr>
<tr>
<td>3.0</td>
<td>1.86</td>
<td>2.85</td>
<td>0.415</td>
</tr>
<tr>
<td>4.0</td>
<td>1.98</td>
<td>2.34</td>
<td>0.040</td>
</tr>
<tr>
<td>5.0</td>
<td>1.98</td>
<td>2.02</td>
<td>0.006</td>
</tr>
</tbody>
</table>
Heavy Resonance Combination

- **Combination** of different individual results powerful to narrow-down BSM physics.
- Allows probing **individual couplings** and larger phase-spaces.

Search for HH→bbbb in VBF Production

- Resonant production in BSM scenarios.
  - Narrow or broad width.

- Non-resonant production also of interest.
  - Via the Higgs self coupling $\lambda$, vector-boson coupling $c_V$, divector-boson coupling $c_{2V}$.
  - Deviation of these from the SM could enhance this final state.

- First search in this production state.

ATLAS-CONF-2019-030
Search for HH→bbbb: Trigger

- Events selected with combination of 4 b-jet triggers.
  - Jet $E_T$ thresholds as low as 35 GeV.
  - b-jet trigger efficiency measured in data → Simulation corrected.
Search for HH\(\rightarrow\)bbbb: Kinematics

- Kinematics between four b-jets main discriminant.
  - Mass of two \(H\) candidates used to create **signal**, **validation**, and **sideband** region.
  - Latter two used for background modelling: multijet normalisation leading uncertainty.

**SM Non-resonant Signal**

\[\bar{s} = 13\ \text{TeV}, \ 126\ \text{fb}^{-1}\]

**Multijet Background**

\[\bar{s} = 13\ \text{TeV}, \ 126\ \text{fb}^{-1}\]
Search for $HH \rightarrow bbbb$: Energy Regression

- Mass resolution of 2-b-jet system critical.
  - $b$-jet energy regression:
    - Using Boosted Decision Tree to further correct jet energy for effects like out of cone leakage and semi-leptonic $B$-decays.
  - Gain topology dependent:
    - $t\bar{t}$ $\sim 10\%$
    - 600 GeV signal $\sim 25\%$

![Graph showing ATLAS Simulation with $\sqrt{s} = 13$ TeV and $m_H = 600$ GeV.](image)

$\frac{\sigma_r/\mu_r}{\sigma_n/\mu_n} \approx 0.75$

$m_{2b}$ [GeV]
• **Results:** no excesses. Quoting limits for spin-0 narrow- and broad-resonances.
• Currently, statistically limited, especially at high masses.
**Results:** no excesses. Quoting limits for spin-0 narrow- and broad-resonances.

Currently, statistically limited, especially at high masses.
• First result on full Run 2 dataset targeting $VV$.
• Results: no deviations from SM expectations observed. Limits on models (e.g. HVT model B excluded up to 3.8 TeV).
• Combination of calorimeter and tracker information $\Rightarrow$ superior jet substructure performance for ATLAS.
• Combination of individual final states allows refined results and study of individual couplings.

• First ever result on $HH \Rightarrow bbbb$ via vector boson fusion production.
• Results: no deviations from SM expectations observed. Limits on narrow and broad resonances, as well as Higgs di-vector-boson coupling $c_{2V}$.
• b-jet energy regression $\Rightarrow$ increase jet energy resolution and boost sensitivity of the result.
Search for $HH\rightarrow bbbb$: Trigger

**ATLAS Preliminary**

$\sqrt{s}=13$ TeV

Data 2018

Offline $b$-tagging efficiency 70%

- Online 77% operating point
- Online 70% operating point
- Online 60% operating point
- Online 50% operating point
- Online 40% operating point

Efficiency w.r.t. Offline $b$-tagging

Mean Number of Interactions per Crossing
## Search for HH → bbb: Full Selections

### Signal topology

<table>
<thead>
<tr>
<th>Condition</th>
<th>Requirements</th>
</tr>
</thead>
</table>
| $m_{4b} < 1250$ | $\min \left[ \frac{0.360 \text{ GeV}}{m_{4b}} - 0.5 \right] < \Delta R^{\text{lead}}_{bb} < \frac{553}{m_{4b}} + 0.475$  
  \[ \frac{235}{m_{4b}} < \Delta R^{\text{subl}}_{bb} < \frac{875}{m_{4b}} + 0.35 \] |
| $m_{4b} \geq 1250$ | $\Delta R^{\text{lead}}_{bb} < 1$  
  \[ \Delta R^{\text{subl}}_{bb} < 1 \] |

Pairs with minimum

\[
D_{HH} = \sqrt{(m_{2b}^{\text{lead}})^2 + (m_{2b}^{\text{subl}})^2} \sin \left( \tan^{-1} \left( \frac{m_{2b}^{\text{lead}}}{m_{2b}^{\text{subl}}} \right) \right) - \tan^{-1} \left( \frac{116.5}{122.7} \right)
\]

### VBF topology

<table>
<thead>
<tr>
<th>Condition</th>
<th>Requirements</th>
</tr>
</thead>
</table>
| At least two jets with $p_T > 30$, $|\eta| > 2.0$ | Two highest-$p_T$ jets with opposite sign $\eta$  
  \[ \Delta \eta^\text{VBF}_{jj} > 5.0 \text{ and } m^\text{VBF}_{jj} > 1000 \text{ GeV} \] |

### Background rejection

<table>
<thead>
<tr>
<th>Component</th>
<th>Requirements</th>
</tr>
</thead>
</table>
| Multijet | $\Delta \eta_{HH} < 1.5$  
  $\Sigma p_T^i < 60 \text{ GeV}$, where $i = b$-jets and VBF-jets  
  $p_T^{\text{lead}} > 0.5m_{4b} - 103$  
  $p_T^{\text{subl}} > 0.33m_{4b} - 73$ |
| $t\bar{t}$ | $X_{WT} = \left( \frac{m_{W} - 80.4}{0.1m_{W}} \right)^2 + \left( \frac{m_{t} - 172.5}{0.1m_{t}} \right)^2 > 1.5$ |
Table 2: Upper limits at 95% CL for SM non-resonant $HH$ production via VBF in fb. Uncertainties related to the branching ratio of the $H \rightarrow b\bar{b}$ decay are not considered.

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>$-2\sigma$</th>
<th>$-1\sigma$</th>
<th>Expected</th>
<th>$+1\sigma$</th>
<th>$+2\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ [fb]</td>
<td>1600</td>
<td>500</td>
<td>700</td>
<td>1000</td>
<td>1400</td>
<td>2100</td>
</tr>
<tr>
<td>Source</td>
<td>$m_X = 300$ GeV</td>
<td>Source</td>
<td>$m_X = 800$ GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------------</td>
<td>----------------</td>
<td>-----------------------------</td>
<td>-----------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multijet normalisation</td>
<td>46%</td>
<td>Multijet modelling</td>
<td>37%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multijet kinematic reweighting</td>
<td>29%</td>
<td>Jet energy resolution</td>
<td>18%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>27%</td>
<td>Jet energy scale</td>
<td>17%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multijet modelling</td>
<td>16%</td>
<td>Multijet kinematic reweighting</td>
<td>12%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>9%</td>
<td>$t\bar{t}$ modelling</td>
<td>7%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$ modelling</td>
<td>7%</td>
<td>Multijet normalisation</td>
<td>7%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>64%</td>
<td>Total systematic uncertainty</td>
<td>53%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>77%</td>
<td>Statistical uncertainty</td>
<td>85%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
WW/ZZ/WZ Resonances: Boosted Dijets

Run: 299584
Event: 563621388
2016-05-20 08:26:49 CEST
M(JJ)=2.40 TeV

R. Jansky - ATLAS Searches for Resonances Decaying to Boson Pairs