Identification of boosted hadronically decaying particles with jet substructure in ATLAS Run-2

Jason Veatch
University of Göttingen
(AG Lai)

on behalf of the ATLAS collaboration
Introduction

• Large-R jets played a major role in ATLAS Run-1
  • Analyses pushed into more boosted regimes
• Many new developments in Run-2
  • New jet reconstruction methods
  • Improved heavy resonance tagging
• Wide range of uses in ATLAS analyses
  • Many more uses of boosted topologies in Run-2
Developments related to large-R jets
Alternative jet definitions

• Multi-dimensional optimization of jet algorithms
  • Input objects and grooming techniques
Alternative jet definitions

- Multi-dimensional optimization of jet algorithms
- Input objects and grooming techniques
- Differences in jet observables

ATLAS Simulation Preliminary
\( \sqrt{s} = 13 \text{ TeV}, \langle \mu \rangle = 21.1, \text{ W jets} \)

- Trimmed
  - \( f_{\text{cut}} = 5\%, R_{\text{sub}} = 0.1 \)
  - \( f_{\text{cut}} = 5\%, R_{\text{sub}} = 0.2 \)
  - \( f_{\text{cut}} = 5\%, R_{\text{sub}} = 0.3 \)

\( |\eta|^{\text{Truth}} < 1.2 \)
\( 300 < p_{T}^{\text{Truth}} < 500 \text{ GeV} \)
anti-\( k_{T}^{1.0} \) LCTopo

ATLAS Simulation Preliminary
\( \sqrt{s} = 13 \text{ TeV}, \langle \mu \rangle = 21.1, \text{ W jets} \)

- SoftDrop
  - \( z_{\text{cut}} = 0.1, \beta = 0.0 \)
  - \( z_{\text{cut}} = 0.1, \beta = 1.0 \)
  - \( z_{\text{cut}} = 0.1, \beta = 2.0 \)

\( |\eta|^{\text{Truth}} < 1.2 \)
\( 300 < p_{T}^{\text{Truth}} < 500 \text{ GeV} \)
anti-\( k_{T}^{1.0} \) LCTopo
Alternative jet definitions

- Multi-dimensional optimization of jet algorithms
- Input objects and grooming techniques
- Background rejection
Alternative jet definitions

- Multi-dimensional optimization of jet algorithms
- Input objects and grooming techniques
- Pileup mitigation
  - $W$ mass, width and $D_2$ measured vs $\langle \mu \rangle$
  - Constituent-level pileup mitigation already works well

---

ATL-PHYS-PUB-2017-020
Alternative jet definitions

- Comparison of 5 different optimized configurations
- Calibrations derived and applied

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Soft Drop</th>
<th>Pruning</th>
<th>Trimming</th>
<th>Reclustering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constit Sub + SoftKiller</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft Drop</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>z_{cut} = 0.1, \beta = 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pruning</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>z_{cut} = 0.15, R_{cut} = 0.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trimming</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R_{sub} = 0.1, f_{cut} = 9%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reclustering</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LCTopo</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trimming</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R_{sub} = 0.2, f_{cut} = 5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EMTopo</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reclustering</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R = 0.4, f_{cut} = 5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Alternative jet definitions

- Comparison of 5 different optimized configurations
- Tagging performance comparisons
- Trade-off between mass and substructure tagging
- Current grooming optimal for mass+D\textsubscript{2} tagging
- Soft-drop optimal for mass-only tagging
Reclustered jets

- Use calibrated $R = 0.4$ jets to build large-$R$ jets
Reclustered jets

- Use calibrated $R = 0.4$ jets to build large-$R$ jets
- Improved resolution
Reclustered jets

- Use calibrated $R = 0.4$ jets to build large-$R$ jets
- Improved resolution
- Lower systematic uncertainties
- Propagated from $R = 0.4$ jets
Reclustered jets

- Use calibrated $R = 0.4$ jets to build large-$R$ jets
- Improved resolution
- Lower systematic uncertainties
- Propagated from $R = 0.4$ jets
- Used in many ATLAS analyses

<table>
<thead>
<tr>
<th>Type</th>
<th>Reference</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUSY multijet</td>
<td>JHEP12 (2017) 034</td>
<td>1.0</td>
</tr>
<tr>
<td>SUSY multi b-jet</td>
<td>arXiv:1711.01901</td>
<td>0.8</td>
</tr>
<tr>
<td>SUSY stop 0 lep</td>
<td>JHEP 12 (2017) 085</td>
<td>0.8 and 1.2</td>
</tr>
<tr>
<td>SUSY stop 1 lep</td>
<td>arXiv:1711.11520</td>
<td>$R \leq 3.0$ (variable)</td>
</tr>
<tr>
<td>VLT pairs 1 lep</td>
<td>JHEP 08 (2017) 052</td>
<td>1.0</td>
</tr>
<tr>
<td>tt resonances</td>
<td>ATLAS-CONF-2016-104</td>
<td>1.0</td>
</tr>
</tbody>
</table>

ATLAS-CONF-2017-062
Track-CaloClusters

- Novel jet inputs using tracker and calorimeter
  - Shorthand: TCC
  - Calorimeter granularity is too coarse for boosted objects
  - Tracks included for their much better angular resolution
Track-CaloClusters

- Novel jet inputs using tracker and calorimeter
  - Tracks matched to topological clusters
  - Position from tracks and energy from clusters
  - Combined TCC: contain a cluster and $\geq 1$ good track(s)
Track-CaloClusters

- Novel jet inputs using tracker and calorimeter
- Improved performance compared to standard jets
- New pileup suppression possible - under study
- Used in ongoing ATLAS analyses
Measuring large-R jet response with in-situ techniques

- In-situ methods used to derive large-R jet uncertainties
- Jet Energy Scale: Jet balance method
Measuring large-R jet response with in-situ techniques

- In-situ methods used to derive large-R jet uncertainties
- Jet Energy Scale: Jet balance method
Measuring large-R jet response with in-situ techniques

- In-situ methods used to derive large-R jet uncertainties
- Jet Energy Scale: Jet balance method
- Jet Mass Scale: Forward folding and $R_{\text{trk}}$ methods

$$R_{\text{trk}} = \frac{\left( \frac{p_T^{\text{calo}}}{p_T^{\text{track}}} \right)^{\text{data}}}{\left( \frac{p_T^{\text{calo}}}{p_T^{\text{track}}} \right)^{\text{MC}}}.$$
Measuring large-R jet response with in-situ techniques

- In-situ methods used to derive large-R jet uncertainties
  - Jet Energy Scale: Jet balance method
  - Jet Mass Scale: Forward folding and $R_{\text{trk}}$ methods
Measuring large-R jet response with in-situ techniques

- In-situ methods used to derive large-R jet uncertainties
- Jet Energy Scale: Jet balance method
- Jet Mass Scale: Forward folding and R_{trk} methods
- Combined uncertainties constrained to < 5%
Tagging heavy resonances
W tagging

- Identify large-R jets as boosted hadronic W decays
W tagging

- Identify large-R jets as boosted hadronic W decays
- Comparison of three different tagging techniques
  - Mass/$D_2$
  - In-situ comparisons show good modeling in data
W tagging

- Identify large-R jets as boosted hadronic W decays
- Comparison of three different tagging techniques
  - Mass/D$_2$, BDT, DNN
- In-situ comparisons show good modeling in data
W tagging

- Identify large-R jets as boosted hadronic W decays
- Comparison of three different tagging techniques
  - Mass/$D_2$, BDT, DNN
- In-situ comparisons show good modeling in data
- BDT and DNN give improved performance
W tagging

- Identify large-R jets as boosted hadronic W decays
- Comparison of three different tagging techniques
  - Mass/D², BDT, DNN
  - In-situ comparisons show good modeling in data
- BDT and DNN give improved performance
- Used in many ATLAS analyses

<table>
<thead>
<tr>
<th>Process</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>VV→lvqq</td>
<td>JHEP 03 (2018) 042</td>
</tr>
</tbody>
</table>
Top quark tagging

- Identify large-R jets as boosted hadronic top decays
- Comparison of six different tagging techniques
  - Mass/$\tau_{32}(/\text{split}_{12})$, BDT, DNN, shower deconstruction, HTT
  - In-situ comparisons show good modeling in data
Top quark tagging

- Identify large-R jets as boosted hadronic top decays
- Comparison of six different tagging techniques
  - Mass/τ_{32}/(split_{12}), BDT, DNN, shower deconstruction, HTT
  - In-situ comparisons show good modeling in data
- BDT and DNN give the best performance
Top quark tagging

- Identify large-R jets as boosted hadronic top decays
- Comparison of six different tagging techniques
  - Mass/\(\tau_{32}/\text{split}_{12}\), BDT, DNN, shower deconstruction, HTT
  - In-situ comparisons show good modeling in data
- BDT and DNN give the best performance
- Used in ongoing and published ATLAS analyses

\[ \text{tt diff xsec} \quad \text{arXiv:1801.02052} \]
H→bb tagging

- Identify large-R jets as boosted H→bb decays
H\rightarrow bb tagging

- Identify large-R jets as boosted H\rightarrow bb decays
- Match b-tagged R = 0.2 track jets to large-R jet
- Higgs mass requirement
- Use D_2 to identify 2-prong decay
H→bb tagging

- Identify large-R jets as boosted H→bb decays
  - Match b-tagged R = 0.2 track jets to large-R jet
  - Higgs mass requirement
  - Use D_2 to identify 2-prong decay
- Used in many ATLAS analyses

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DM + H→bb</td>
<td>JHEP12 (2017) 034</td>
</tr>
</tbody>
</table>
Improved $H \rightarrow bb$ tagging

- Additional techniques to improve $H \rightarrow bb$ tagging
  - Variable-R track jets
Improved $H \rightarrow bb$ tagging

- Additional techniques to improve $H \rightarrow bb$ tagging
  - Variable-R track jets
  - Exclusive $kt$ calorimeter subjets
Improved $H\rightarrow bb$ tagging

- Additional techniques to improve $H\rightarrow bb$ tagging
  - Variable-R track jets
  - Exclusive kt calorimeter subjets
  - Center of mass subject reconstruction

ATL-PHYS-PUB-2017-010
Improved $H \rightarrow bb$ tagging

- Additional techniques to improve $H \rightarrow bb$ tagging
  - Variable-R track jets
  - Exclusive $k_t$ calorimeter subjets
  - Center of mass subjet reconstruction
- Improvements in tagging performance
Improved $H \rightarrow bb$ tagging

- Additional techniques to improve $H \rightarrow bb$ tagging
  - Variable-R track jets
  - Exclusive $kt$ calorimeter subjets
  - Center of mass subject reconstruction
- Improvements in tagging performance
- Search for further improvements continues…
Conclusions and Outlook

• Many new developments related to large-R jets
  • Improved large-R jet modeling and reconstruction
  • Techniques to identify heavy resonances
• Development continues as analyses rely more on boosted techniques to push limits to higher mass points
• Boosted topologies will become even more important with higher energy collisions
• Many more improvements on the way…
Thank you for your attention
Backup slides
Measuring large-R jet response with in-situ techniques

- Comparison of $R_{\text{trk}}$ and forward folding results
Measuring large-R jet response with in-situ techniques
H→bb tagging

- Comparison of cut levels

**ATLAS Simulation Preliminary**

MV2c10 b-tagging at 77% WP

- $p_T^{\text{jet}}>250$ GeV, $|\eta^\text{true}|<2.0$
- $p_T^{\text{true}}>5$ GeV, $|\eta^\text{true}|<2.5$

Truth Higgs Acceptance

- Baseline selection
- 1 b-tag, Loose $m^{\text{calo}}_{\text{jet}}$ window
- 2 b-tags, No $m^{\text{calo}}_{\text{jet}}$ selection
- 2 b-tags, Loose $m^{\text{calo}}_{\text{jet}}$ window
- 2 b-tags, Tight $m^{\text{calo}}_{\text{jet}}$ window, D_{q} sel.

Truth Higgs $p_T$ [GeV]

Multi-jet rejection

- 1 b-tag, Loose $m^{\text{calo}}_{\text{jet}}$ window
- 2 b-tags, No $m^{\text{calo}}_{\text{jet}}$ selection
- 2 b-tags, Loose $m^{\text{calo}}_{\text{jet}}$ window
- 2 b-tags, Tight $m^{\text{calo}}_{\text{jet}}$ window, D_{q} sel.

$p_T$ [GeV]
Improved $H \rightarrow b\bar{b}$ tagging

**ATLAS**

Simulation Preliminary

- $76 \text{ GeV} < m_{\text{jet}} < 146 \text{ GeV}$
- $250 \text{ GeV} < p_{T,\text{jet}} < 400 \text{ GeV}$
- double $b$-tagging

**ATLAS**

Simulation Preliminary

- $76 \text{ GeV} < m_{\text{jet}} < 146 \text{ GeV}$
- $1500 \text{ GeV} < p_{T,\text{jet}} < 2000 \text{ GeV}$
- double $b$-tagging