Jet substructure measurements sensitive to soft QCD with the ATLAS detector

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Overview
Introduction

Study of energy flow within the body of hadronic jets
  ▶ Useful in identification of boosted heavy particles
  ▶ Important probe of perturbative QCD and also sensitive to soft QCD effects

Three recent ATLAS results on substructure measurements sensitive to soft QCD:

1. Measurement of the $k_T$ splitting scales in $Z \to ll$ events in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

2. A measurement of the soft-drop jet mass in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
   (Submitted to PRL) ▶ arXiv:1711.08341

3. Measurement of colour flow using jet-pull observables in $t\bar{t}$ events with the ATLAS experiment at $\sqrt{s} = 13$ TeV ▶ ATLAS-CONF-2017-069
The ATLAS Experiment

- General purpose detector with multi-layer detection chambers
- Charge particle tracks reconstructed in **Inner Detector (ID)**
- Hadronic jets reconstructed from **topological clusters** of energy deposits in calorimeter cells
  - Sequence of calibrations applied to correct jet to hadron level
Overview of jet reconstruction algorithms

- Cluster any set of four-momenta (charged tracks, calorimeter energy deposits) into collimated “jets”
- ATLAS uses infra-red- and collinear-safe sequential recombination algorithms
  ▶ Iteratively combine pair with min. $d_{ij}$ until $d_{ib} < d_{ij}$
  - $d_{ij} = \min(p_{T,i}^n, p_{T,j}^n) \times \frac{\Delta R_{ij}^2}{R^2}$; $d_{ib} = p_{T,i}^n$

$k_T$ ($n=2$)
- Softest pair of constituents clustered first
- Follows IR and collinear splittings

anti-$k_T$ ($n=-2$)
- Hardest constituent clustered with closest neighbour
- Regularly shaped jets

Cambridge-Aachen ($n=0$)
- Closest pair of constituents clustered first
- Mimics angular-ordered parton showers
ATLAS measurement of $k_T$ splitting scales in $Z \rightarrow ll$ events
$k_T$ splitting scales

- $\sqrt{d_0} = p_T$ of final jet
- $\sqrt{d_1} = \min(p_{T,1}, p_{T,2}) \times \frac{\Delta R_{12}}{R}$, etc.
- Small $\sqrt{d_k} \Rightarrow$ soft/collinear splitting
- Large $\sqrt{d_k} \Rightarrow$ hard splitting

- $k_T$ clustering sequence run in reverse
- $d_{ij} = \min(p_{T,i}, p_{T,j}) \times \frac{\Delta R_{ij}^2}{R^2}$; $d_{ib} = p_{T,i}^n$
- Splitting scale $\sqrt{d_k} = \min(\sqrt{d_{ij}}, \sqrt{d_{ib}})$ for $k^{th}$ iteration step
Overview of measurement

- Measurement of $k_T$ splitting scale in $Z+\text{jets}$ events with charged particle tracks at $\sqrt{s} = 8 \text{ TeV}$
- $Z \rightarrow ll$ events provides clean environment
- Smaller experimental uncertainties from charged tracks compared to calorimeter clusters
- Separate measurements for $R = 0.4$ and $R = 1.0$ jet radius parameters
  - Different sensitivity to hadronisation and underlying event
- Iterative Bayesian Unfolding of measured distributions based on Sherpa LO predictions
- Results also extrapolated to include neutral particles
Uncertainties

- Modelling uncertainties are dominant
- Experimental uncertainties are mostly related to track reconstruction and measurement
- Larger uncertainties in charged+neutral results due to sensitivity to hadronisation model
  - Mostly affects small values of $\sqrt{d_k}$ (soft and collinear regime)
Unfolded distributions

R=0.4 $\mu\mu$ channel; charged-only

R=1.0 $ee$ channel; charged+neutral

Large discrepancies to both NLO MEPS and NNLO predictions at low values of $\sqrt{d_k}$
- Estimated modelling uncertainties mostly dominated by perturbative QCD
- Results can be used for generator tuning for non-perturbative effects

NLO Sherpa+OpenLoops (MEPS@NLO) describes data better in high $\sqrt{d_k}$ tail compared to Powheg(DYNNLO)+Pythia8 NNLO (NNLOPS) predictions
ATLAS measurement of the soft-drop jet mass
Soft-drop algorithm

- Cluster input constituents with Cambridge-Aachen algorithm
- Apply **soft-drop** criterion at each step of clustering sequence, in reverse order
  \[
  \min\left(\frac{p_{T,1}p_{T,2}}{p_{T,1}+p_{T,2}}\right) > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R}\right)^\beta
  \]
- Remove softer of two branches if criterion not satisfied
- Higher $z_{\text{cut}} \Rightarrow$ more energy removed by algorithm
- $\beta$: Tunes sensitivity to wide-angle radiation

- Jet substructure calculations beyond leading log accuracy problematic due to non-global logarithms (NGLs)
  - Related to particles radiating out of and then into jet
- **Soft drop** grooming makes jet substructure insensitive to NGLs
  - Removes energy in jet related to soft QCD processes and pile-up
Overview of measurement

- Measurement of soft-drop jet mass for anti-$k_T$ $R=0.8$ jets built from topological calorimeter-cell clusters at $\sqrt{s} = 13$ TeV
- Events with dijet topologies selected
  $\Rightarrow p_{T,1}/p_{T,2} < 1.5$ for two leading jets
- Distribution of $\log_{10}(\rho^2)$ studied for $\beta = 0, 1, 2$
  - Dimensionless mass parameter $\rho = \frac{m_{\text{softdrop}}}{p_{\text{ungroomed}}}$
- Iterative Bayesian unfolding applied simultaneously to $\log_{10}(\rho^2)$ and jet $p_T$ distributions using Pythia LO predictions
- Three distinct regions:
  - **Non-perturbative region** $\log_{10}(\rho^2) < -3.7$ (soft and collinear emissions)
  - **Resummation region** $-3.7 < \log_{10}(\rho^2) < -1.7$ (resummation dominates)
  - **Fixed-order region** $\log_{10}(\rho^2) < -3.7$ (wide-angle hard gluon emissions)
Uncertainties

- QCD modelling uncertainty dominant in non-perturbative regime
- Experimental uncertainties on energy scale of calorimeter clusters dominate in perturbative region
Unfolded distributions

Distributions normalised to $\sigma_{resum}$

Largest difference between Monte Carlo and analytic predictions in non-perturbative regime

- Effect larger for higher $\beta$ (smaller fraction of soft energy removed)

NLO+NLL calculation included non-perturbative corrections $\Rightarrow$ better agreement at low $\log_{10}(\rho^2)$

Good agreement between data and analytic calculations in resummation and fixed-order regions
ATLAS measurement of colour flow using jet-pull observables in $t\bar{t}$ events
Jet pull observables

Coloured partons

Jet algorithm \rightarrow \text{DGLAP evolution}

Jets of colour singlet hadrons

- Colour connections between high-$p_T$ particles affects structure of emitted radiation
- Colour flow in QCD is poorly constrained by current data
- **Jet pull angle** $\theta_P$ measures colour connection between jets
  - $\theta_P \sim 0$ for colour connected jets
  - Uniform distribution when no colour connection exists

Jet pull vector

$$\vec{P} = \sum_{i \in J} \frac{|\Delta r_i| \cdot p_T^i}{p_T} \Delta \vec{r}_i$$
Overview of measurement

- Jet pull angle measured in $t\bar{t}$ events at $\sqrt{s} = 13$ TeV for:
  - Jets originating from colour singlet W (colour connected)
  - $b$-jets coming from the two top quarks (no colour connection)
- Magnitude of pull vector also measured
- Calculation based on charged particle tracks to improve spatial resolution of measurement
- Dominant uncertainty in measurement from $t\bar{t}$ modelling
- Largest experimental uncertainty comes from $b$-tagging
- Iterative Bayesian unfolding with predictions from Powheg+Pythia8 simulations

<table>
<thead>
<tr>
<th>Target colour flow</th>
<th>Signal colour flow</th>
<th>Spurious colour flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(j_1$ and $j_2$ are colour connected)</td>
<td>$(j_1$ and $j_2$ are not colour connected)</td>
</tr>
<tr>
<td><strong>Jet assignment</strong></td>
<td>$j_1^W$: leading $p_T$ non-$b$-tagged jet</td>
<td>$j_1^b$: leading $p_T$ $b$-tagged jet</td>
</tr>
<tr>
<td></td>
<td>$j_2^W$: 2\textsuperscript{nd} leading $p_T$ non-$b$-tagged jet</td>
<td>$j_2^b$: 2\textsuperscript{nd} leading $p_T$ $b$-tagged jet</td>
</tr>
<tr>
<td><strong>Observables</strong></td>
<td>$\theta_P (j_1^W, j_2^W)$: “forward pull-angle”</td>
<td>$\theta_P (j_1^b, j_2^b)$: “forward di-$b$-jet-pull angle”</td>
</tr>
<tr>
<td></td>
<td>$\theta_P (j_2^W, j_1^W)$: “backward pull-angle”</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>\vec{P}(j_1^W)</td>
</tr>
</tbody>
</table>
Various hadronisation models tested (Pythia6, Pythia8, Herwig7, Sherpa)
  ▶ All predict smaller jet pull (stronger colour flow effect) than data
Signal jet pull modelled best by Powheg+Herwig7; but spurious jet pull modelled poorly
Pythia6 describes data better than Pythia 8
  ▶ Differences between the two models not limited to hadronisation
Comparison to exotic colour-flow model

- “Colour flip” model tested replacing colour singlet $W$ with a colour octet
- Both pull angle and pull vector able to discriminate such exotic colour flow from Standard Model
- Data agrees better with SM predictions
Summary

- Presented three recent ATLAS measurements of substructure observables sensitive to soft QCD
  - $k_T$ splitting scales for charged track jets in $Z \rightarrow ll +$jets events
  - Soft-drop jet mass in dijet events
  - Jet-pull observables in $t\bar{t}$ events
- Results can constrain both analytic calculations in perturbative regime and soft hadronic activity in non-perturbative region
- Useful for tuning of MC simulation of non-perturbative QCD
Backup slides
ATLAS measurement of $k_T$ splitting scales in $Z \rightarrow ll$ events
## Signal and background yields

<table>
<thead>
<tr>
<th>Process</th>
<th>$Z \rightarrow e^+e^-$</th>
<th>$Z \rightarrow \mu^+\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Events</td>
<td>Contribution [%]</td>
</tr>
<tr>
<td>QCD $Z + \text{jets}$</td>
<td>5 090 000</td>
<td>98.93 %</td>
</tr>
<tr>
<td>Multijet</td>
<td>42 000</td>
<td>0.81 %</td>
</tr>
<tr>
<td>Electroweak $Z + \text{jets}$</td>
<td>5 350</td>
<td>0.10 %</td>
</tr>
<tr>
<td>Top quarks</td>
<td>6 190</td>
<td>0.12 %</td>
</tr>
<tr>
<td>$W(W)$</td>
<td>1 100</td>
<td>0.02 %</td>
</tr>
<tr>
<td>$Z \rightarrow \tau^+\tau^-$</td>
<td>1 100</td>
<td>0.02 %</td>
</tr>
<tr>
<td>Total expected</td>
<td>5 150 000</td>
<td>100.00 %</td>
</tr>
<tr>
<td>Total observed</td>
<td>5 196 858</td>
<td></td>
</tr>
</tbody>
</table>
ATLAS measurement of the soft-drop jet mass
Unfolded $\log_{10}(\rho^2)$ across $p_T$
ATLAS measurement of colour flow using jet-pull observables in $t\bar{t}$ events
## Signal and background yields

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>1 026 000 ± 95 000</td>
</tr>
<tr>
<td>$t\bar{t}V$</td>
<td>3270 ± 250</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>1700 ± 100</td>
</tr>
<tr>
<td>Single-top</td>
<td>48 400 ± 5500</td>
</tr>
<tr>
<td>Diboson</td>
<td>1440 ± 220</td>
</tr>
<tr>
<td>$W + \text{jets}$</td>
<td>27 700 ± 4700</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>8300 ± 1400</td>
</tr>
<tr>
<td>NP/Fake leptons</td>
<td>53 000 ± 30 000</td>
</tr>
<tr>
<td><strong>Total Expected</strong></td>
<td>1 170 000 ± 100 000</td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td>1 153 003</td>
</tr>
</tbody>
</table>
### Uncertainties

<table>
<thead>
<tr>
<th>$\Delta \theta_P \left( j_1^W, j_2^W \right) , [%]$</th>
<th>$\theta_P \left( j_1^W, j_2^W \right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$0.0 - 0.21$</td>
</tr>
<tr>
<td>Hadronisation</td>
<td>0.63</td>
</tr>
<tr>
<td>Generator</td>
<td>0.37</td>
</tr>
<tr>
<td>Colour Reconnection</td>
<td>0.11</td>
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<tr>
<td>$b$-Tagging</td>
<td>0.35</td>
</tr>
<tr>
<td>Non-Closure</td>
<td>0.25</td>
</tr>
<tr>
<td>ISR / FSR</td>
<td>0.32</td>
</tr>
<tr>
<td>Other</td>
<td>0.25</td>
</tr>
<tr>
<td>JER</td>
<td>0.12</td>
</tr>
<tr>
<td>JES</td>
<td>0.13</td>
</tr>
<tr>
<td>Tracks</td>
<td>0.09</td>
</tr>
<tr>
<td>Syst.</td>
<td>0.97</td>
</tr>
<tr>
<td>Stat.</td>
<td>0.22</td>
</tr>
<tr>
<td>Total</td>
<td>0.99</td>
</tr>
</tbody>
</table>