Jet Substructure Measurements Sensitive to Soft QCD effects with the ATLAS Detector

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Two recent ATLAS measurements of substructure observables sensitive to soft QCD effects:

**Measurement of the $k_t$ splitting scales in $Z \rightarrow \ell\ell$ events in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector**

Constrain and tune MC generators (hard perturbative modeling and soft hadronic activity)

arXiv:1704.01530  STDM-2015-14 Published in JHEP08 (2017) 026

**A measurement of the soft-drop jet mass in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector**

Perturbative region: constrain calcs
Non-perturbative: constrain MC generators

Jet Reconstruction for Substructure

- Both measurements use **iterative recombination** jet reconstruction procedures to identify different types of jets, whose histories contain information useful to identify their substructure.

- The inputs to jet reconstruction algorithm are the four-momenta of either **charged particle tracks**, **clusters of energy** in the calorimeter, or **truth particles**.

1. Make a list of input four momenta, and define all possible pairs.

2. Find the smallest $d_{ij}$ of all pairs, and combine that pair.

3. Repeat.

$$d_{ij} = \min \left( k_{T_i}^n, k_{T_j}^n \right) dR_{ij}$$

- If $n=2$: choose the harder $k_T$ in the pair
- If $n=0$: ignore the $k_T$
- If $n=-2$: choose the softer $k_T$ in the pair

Different $n$ = different smallest $d_{ij}$
Jet algorithms refresher

\( kT \ (d_{ij} \propto p_T^2) \)

soft + close

\( \text{CA} \ (d_{ij} \propto p_T^0) \)

close

\( \text{anti-}kT \ (d_{ij} \propto \frac{1}{p_T^2}) \)

hard + close
Jet algorithms refresher

\( kT \ (d_{ij} \propto p_T^2) \)
- soft + close

\( \text{CA} \ (d_{ij} \propto p_T^0) \)
- close

\( \text{anti-}kT \ (d_{ij} \propto \frac{1}{p_T^2}) \)
- hard + close
Jet algorithms refresher

\[ \text{kT (} d_{ij} \propto p_T^2 \text{)} \]
soft + close

\[ \text{CA (} d_{ij} \propto p_T^0 \text{)} \]
close

\[ \text{anti-kT (} d_{ij} \propto \frac{1}{p_T^2} \text{)} \]
hard + close
Jet algorithms refresher

\[ kT \ (d_{ij} \propto p_T^2) \]
soft\+close

\[ \text{CA} \ (d_{ij} \propto p_T^0) \]
close

\[ \text{anti-}kT \ (d_{ij} \propto \frac{1}{p_T^2}) \]
hard\+close
Jet algorithms refresher

- kT (\(d_{ij} \propto p_T^2\))
  - soft + close

- CA (\(d_{ij} \propto p_T^0\))
  - close

- anti-kT (\(d_{ij} \propto \frac{1}{p_T^2}\))
  - hard + close
Jet algorithms refresher

- $kT \ (d_{ij} \propto p_T^2)$
  - soft+close

- CA \ ($d_{ij} \propto p_T^0$)
  - close

- anti-$kT$ \ ($d_{ij} \propto \frac{1}{p_T^2}$)
  - hard+close
Jet algorithms refresher

\[ kT \left( d_{ij} \propto p_T^2 \right) \]
soft + close

\[ CA \left( d_{ij} \propto p_T^0 \right) \]
close

\[ \text{anti-}kT \left( d_{ij} \propto \frac{1}{p_T^2} \right) \]
hard + close
Jet algorithms refresher

\[ kT \ (d_{ij} \propto p_T^2) \]  
**soft+close**

\[ CA \ (d_{ij} \propto p_T^0) \]  
**close**

\[ \text{anti-}kT \ (d_{ij} \propto \frac{1}{p_T^2}) \]  
**hard+close**
Jet algorithms refresher

$kT$ \( (d_{ij} \propto p_T^2) \)  
soft + close

$CA$ \( (d_{ij} \propto p_T^0) \)  
close

$anti-kT$ \( (d_{ij} \propto \frac{1}{p_T^2}) \)  
hard + close

The final jet
Jet algorithms refresher

- $kT$ ( $d_{ij} \propto p_T^2$ )
  - soft + close

- CA ( $d_{ij} \propto p_T^0$ )
  - close

- anti-$kT$ ( $d_{ij} \propto \frac{1}{p_T^2}$ )
  - hard + close

Back up one step
Jet algorithms refresher

\[ kT \quad (d_{ij} \propto p_T^2) \quad \text{soft+close} \]

\[ \text{CA} \quad (d_{ij} \propto p_T^0) \quad \text{close} \]

\[ \text{anti-}kT \quad (d_{ij} \propto \frac{1}{p_T^2}) \quad \text{hard+close} \]

Back up one step
Jet algorithms refresher

$kT \ (d_{ij} \propto p_T^2)\quad CA \ (d_{ij} \propto p_T^0)\quad anti-kT \ (d_{ij} \propto \frac{1}{p_T^2})$

soft + close\quad close\quad hard + close

The penultimate stage in the jet clustering epitomizes the difference between the algorithms: if there is hard underlying structure then kT and CA have the ability to spot it.
Measurement of the $k_t$ splitting scales in $Z \rightarrow \ell\ell$ events in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector
Measurement uses \(k_t\) algorithm (soft+close first = hard+wide last) with tracks as input.

\[
\sqrt{d_{ij}} = \min (k_{T_i}^2, k_{T_j}^2) \, dR_{(ij)}
\]

\[
\begin{align*}
\sqrt{d_0} &= p_T \\
\sqrt{d_1} &= p_{T_2} \times dR_{(1,2)} \\
\sqrt{d_2} &= \min(p_{T_i}, p_{T_j}) \times dR_{(i,j)} \\
\sqrt{d_3} &= \min(p_{T_i}, p_{T_j}) \times dR_{(i,j)}
\end{align*}
\]

= final track-jet \(p_T\)

Note that soft / collinear splittings have low values of \(\sqrt{d_i}\)
Run 18 TeV dataset: 20.2/fb
Aim to select $Z_{\ell\ell} +$jets events at high purity, examine splitting scales in jets. Track-jets are used to reduce uncertainties.

<table>
<thead>
<tr>
<th>Process</th>
<th>$Z \rightarrow e^+e^-$</th>
<th>$Z \rightarrow \mu^+\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD $Z +$jets</td>
<td>5 090 000 events</td>
<td>7 220 000 events</td>
</tr>
<tr>
<td>Multijet</td>
<td>42 000 events</td>
<td>25 000 events</td>
</tr>
<tr>
<td>Electroweak $Z +$jets</td>
<td>5 350 events</td>
<td>7 340 events</td>
</tr>
<tr>
<td>Top quarks</td>
<td>6 190 events</td>
<td>8 440 events</td>
</tr>
<tr>
<td>$W(W)$</td>
<td>1 100 events</td>
<td>1 460 events</td>
</tr>
<tr>
<td>$Z \rightarrow \tau^+\tau^-$</td>
<td>1 100 events</td>
<td>1 700 events</td>
</tr>
<tr>
<td>Total expected</td>
<td>5 150 000 events</td>
<td>7 260 000 events</td>
</tr>
<tr>
<td>Total observed</td>
<td>5 196 858 events</td>
<td>7 349 195 events</td>
</tr>
</tbody>
</table>

~12M events in data with ~99% purity.

Iterative Bayes unfolding to particle-level applied to data-background.
Unfolded Data v. Calculations

Fixed order calculations not really helping for very low masses

ATLAS

$\sqrt{s} = 8$ TeV, 20.2 fb$^{-1}$

$Z \rightarrow e^+e^-$, $R = 0.4$

**LEADING EIGHT SPLITTING SCALES MEASURED**

Data (2012)

MEPS@NLO

NNLOPS

Measurement of the $k_t$ splitting scales in $Z \rightarrow \ell\ell$ events in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

arXiv:1704.01530  STDM-2015-14 Published in JHEP08 (2017) 026
A measurement of the soft-drop jet mass in pp collisions at \( \sqrt{s} = 13 \) TeV with the ATLAS detector
Soft Drop Jet Mass

Measurement uses CA algorithm $R=0.8$ with calibrated energy clusters as inputs.

$$\min(p_{Ti}, p_{Tj}) / (p_{Ti} + p_{Tj}) > 10\% \left( \frac{dR_{ij}}{R} \right)^\beta$$

Larger values of $\beta$: more likely to pass criteria: less radiation removed.

When algorithm terminates, mass of resulting ‘groomed’ jet $m$ is used. The $p_T$ of the ungroomed jet is then used in the denominator of the soft drop mass variable:

$$\log_{10} \left( \frac{m}{p_T} \right)^2$$
Event Selection

Run 2 13 TeV dataset : 32.9/fb

Aim is to select dijet events (high-$p_T$ ensures full trigger efficiency), and examine the soft drop masses of the jets.

Trigger:
Dijet trigger 600 GeV

Offline selection:
Two anti-$k_t$ $R=0.8$ jets, the leading one with $p_{T1}>600$ GeV, second with $p_{T2}>\frac{2}{3} p_{T1}$, $\eta<1.5$

anti-$k_t$ $R=0.8$ jets used for event selection, then the constituents are reclustered with CA $R=0.8$. 
**Soft Drop Jet Mass Measurement**

\( \beta = 0 \): more soft radiation removed

\( \beta = 2 \): less soft radiation removed

**ATLAS**
\( \sqrt{s} = 13 \text{ TeV}, 32.9 \text{ fb}^{-1} \)
anti-\( k_t, R = 0.8, p_T^{\text{lead}} > 600 \text{ GeV} \)
Soft drop \( \beta = 0, z_{\text{cut}} = 0.1 \)

\( \beta = 2, z_{\text{cut}} = 0.1 \)

A measurement of the soft-drop jet mass in pp collisions at \( \sqrt{s} = 13 \text{ TeV} \) with the ATLAS detector

Data v. Calculations

Iterative Bayesian unfolding to particle-level applied to data.

NP effects are expected to be large
Largest uncertainty is QCD modeling 10-20%, biggest where NP effects a problem.

Cluster Energy Scale is largest at low values (few clusters)

NP effects are expected to be large
Summary

Two recent ATLAS measurements of substructure observables sensitive to soft QCD effects:

Measurement of the $k_t$ splitting scales in $Z \rightarrow \ell\ell$ events in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

Constrain and tune MC generators (hard perturbative modeling and soft hadronic activity)

A measurement of the soft-drop jet mass in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

Perturbative region: constrain calcs
Non-perturbative: constrain MC generators

Soft drop mass shows particular promise for looking in detail at soft QCD.

..thank you for your attention.
ADDITIONAL MATERIAL
kT splitting event selection

• **Trigger:**
  • Opposite-charge electron or muon pair targeting $Z_{ll}$

• **Offline selection:**
  • Tracks: $p_T>400$ MeV, $\eta<2.5$, $\geq 1$ pixel, $\geq 5$ SCT, $\chi^2<3$, $d_0<1$ mm, $z_0 \sin<0.6$ mm
  • Electrons: must be Isolated, $p_T>25$ GeV, $\eta<2.47$ (excluding 1.37-1.52)
  • Muons: (combined) must be $p_T>25$ GeV, $\eta<2.4$,
  • Isolation: ($p_T$ in dr$<0.2 < 10\%$ pT muon and $p_T$ in dr$<0.2 < 13\%$ pT electron
  • $Z_{ll}$ mass: 71-111 GeV
Analysis Sample

~5M signal events with ~99% purity.

Z+jets normalised to NNLO prediction ([PhysRevD.69.094008](http://journals.aps.org/prd/abstract/10.1103/PhysRevD.69.094008))

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<th>$Z \rightarrow e^+e^-$ Contribution [%]</th>
<th>$Z \rightarrow \mu^+\mu^-$ Events</th>
<th>$Z \rightarrow \mu^+\mu^-$ Contribution [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD $Z + \text{jets}$</td>
<td>5,090,000</td>
<td>98.93 %</td>
<td>7,220,000</td>
<td>99.40 %</td>
</tr>
<tr>
<td>Multijet</td>
<td>42,000</td>
<td>0.81 %</td>
<td>25,000</td>
<td>0.34 %</td>
</tr>
<tr>
<td>Electroweak $Z + \text{jets}$</td>
<td>5,350</td>
<td>0.10 %</td>
<td>7,340</td>
<td>0.10 %</td>
</tr>
<tr>
<td>Top quarks</td>
<td>6,190</td>
<td>0.12 %</td>
<td>8,440</td>
<td>0.12 %</td>
</tr>
<tr>
<td>$W(W)$</td>
<td>110</td>
<td>0.02 %</td>
<td>1,460</td>
<td>0.02 %</td>
</tr>
<tr>
<td>$Z \rightarrow \tau^+\tau^-$</td>
<td>110</td>
<td>0.02 %</td>
<td>1,700</td>
<td>0.02 %</td>
</tr>
<tr>
<td>Total expected</td>
<td>5,150,000</td>
<td>100.00 %</td>
<td>7,260,000</td>
<td>100.00 %</td>
</tr>
<tr>
<td>Total observed</td>
<td>5,196,858</td>
<td></td>
<td>7,349,195</td>
<td></td>
</tr>
</tbody>
</table>

Estimated from data


Iterative Bayesian unfolding to particle-level applied to background-subtracted data.
Data v. Calculations

MEPS@NLO: SHERPA v2.2.1, 2(4) partons at N(LO) (Comix and OpenLoops) PDF: NNPDF3.0nnlo

NNLOPS: POWHEG-BOX (DY@NNLOPS and MiNLO) (showering by Pythia 8.185, monash tune) PDF: PDF4LHC15nnlo

**ATLAS**

$\sqrt{s} = 8$ TeV, 20.2 fb$^{-1}$

$Z \rightarrow e^+e^-$, $R = 0.4$

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Measurement of the $k_t$ splitting scales in $Z \rightarrow \ell\ell$ events in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector
Uncertainties

3-10% uncertainty over most of range
Steeper rise (to ~15%) for subleading splitting scales

**ATLAS**

$\sqrt{s} = 8$ TeV, 20.2 fb$^{-1}$

$Z \rightarrow e^+e^-$, $R = 0.4$

- Total uncertainty
- Unfolding
- Experimental
- Data statistics
- MC statistics

Steeper rise (to ~15%) for subleading splitting scales

Total: Includes 1.9% luminosity

Closure, number of iterations, prior.

Tracking, pileup, event selection

Measurement of the $k_t$ splitting scales in $Z \rightarrow \ell\ell$ events in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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