Understanding Jet Structure and Constituents: Track Jets and Jet Shapes at the ATLAS Detector

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*On behalf of the ATLAS Collaboration*

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Overview

- ATLAS and the Large Hadron Collider
- Prologue: Jets and their properties
- Jet Reconstruction and definitions
  - Calorimeter-based: topological clustering, associated tracks
  - Inner Detector-based: apply jet algorithm to tracks
- Data-Simulation comparison of jet constituents
  - Constituent multiplicity
  - Jet shapes
- Track-based jet measurements
  - Inclusive cross section
  - Charged particle fragmentation w.r.t. charged particle jets
The LHC and ATLAS

- Large Hadron Collider: p-p, Pb-Pb
- 2010-2011: 7 TeV CM energy, maximum luminosity: $1-2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- Ultimately: 14 TeV CM energy, max. lumi. $\sim 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

ATLAS
- 45m long, 25m diameter, 7000 tons
- 3-level trigger: reduce design beam-crossing rate of 40 MHz to $\sim 200$ Hz recorded
Data Collected So Far

ATLAS uptime and data quality excellent
- >94% for all subsystems

Luminosity increasing rapidly
- Note log scale!

Moving steadily to goal of 1 fb$^{-1}$ collected through 2011
ATLAS Subdetectors

- **ATLAS Calorimeters**
  - Electromagnetic: Pb + Liquid Ar
    - Separate jets, e/γ
  - Hadronic
    - Central: Fe + scintillating tiles
    - Forward: Cu/W + Liquid Ar
  - Coverage: $|\eta| < 4.9$

- **ATLAS Inner Detector**
  - 3 silicon pixel layers
  - 4 double-sided silicon strip layers
  - Transition Radiation Tracker
  - 2.0 T solenoid magnet
  - Coverage: $|\eta| < 2.5$
  - $\sigma/pT \sim 3.8 \times 10^{-4}$ pT (GeV) $\oplus$ 0.015

And, of course, ATLAS got its name from the large toroidal magnetic field for the muon system... Not used for this talk!
Triggers (in this talk)

- **Minimum Bias Trigger Scintillator (MBTS)**
  - Polystyrene structures mounted on endcap calorimeter cryostat
  - 2 cm thick, $Z = 3.6m$
  - Acceptance: $2.09 < |\eta| < 3.48$

- Most plots in this talk triggered with 1 MBTS hit
  - ~100% efficiency for events with jets

- Jet and EM triggers based on sliding tower jet-finding in calorimeter
  - Jet shape plots use lowest-threshold jet trigger, which is 100% efficient for applicable jet momenta ($p_T > 60$ GeV)

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ATLAS Preliminary
\(s = 7\) TeV, Data 2010

**Level 1 Trigger Rates**

![Graph](https://example.com/graph.png)
Prologue: Jets and their Properties

- ATLAS jet measurements
  - Inclusive jet cross-section (see talk – A. Alonso)
  - New di-jet resonance limit (see talk – H. Peng)
- Major uncertainty: jet energy scale
- Pileup will impact every ATLAS measurement
  - Continuum from very soft interactions to dijets
- Need to verify modeling of QCD and soft physics that produces jet structure
- This talk: our knowledge so far, measurements to improve it...

![Graph showing jet measurement data]
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Jet Reconstruction: Calorimeter

- **Main constituent algorithm: topological clusters**
  - Seed with cells with signal $4\sigma$ above noise
  - Extend with adjacent (3D) cells $2\sigma$ above noise
  - Add one final “layer” of cells above noise
- **Apply anti-$k_T$ jet algorithm** ($R=0.6, 0.4$)
  - Cone-like
  - Infrared safe – JHEP 04 (2008) 063
- **Association of tracks with jet:**
  - Select good-quality tracks (next slide)
  - Associate track with jet if: $\Delta R(\text{Track, Jet}) < R_{\text{Jet}}$
Jet Reconstruction: Tracks

- **Select good-quality tracks:**
  - $p_T > 500$ MeV, $|\eta| < 2.5$
  - Impact parameter requirements w.r.t. primary vertex
    - $|d_0| < 1.5$ mm, $|z_0 \sin \theta| < 1.5$ mm
  - Silicon hit requirements
    - Analysis: 6 SCT hits, innermost pixel hit + outer pixel or inner SCT hit
    - Calorimeter matching: 6 SCT hits, any pixel hit
- **Anti-$k_T$ jet algorithm ($R=0.6$, 0.4) applied to selected tracks**
  - Track jet analysis requirements: jet $p_T > 4$ GeV, $|\eta| < 0.57$
- **Complement to calorimeter jet measurements**
  - Independent systematic errors
  - Very low momentum – emergence of jets from soft collisions
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    - N.B. Not corrected for detector effects
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Constituent Multiplicity

- Sensitive to soft particle modeling

Clusters

Tracks - $p_T > 0.5$ GeV

Tracks - $p_T > 1.0$ GeV
Jet Shapes

- \( \rho(r) = \langle \frac{1}{r} \frac{dp_T}{dr} \rangle_{\text{jets}} = \frac{1}{A N_{\text{jet}} \sum_{\text{jets}}} p_T(r - \Delta r/2, r + \Delta r/2) \)

- Shape depends on event generator, but generally good agreement
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Charged Particle Jet Measurements

- **Charged particle jets**: apply anti-$k_T$ algorithm to all charged primary particles with $p_T > 500$ MeV
  - No direct comparison to pQCD
  - Can compare to Monte Carlo generators
- **Inclusive cross section measurement**
  - Correction method: bayesian iterative unfolding
  - Systematic uncertainties, $R = 0.6$:

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<thead>
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<tbody>
<tr>
<td>Tracking efficiency</td>
<td>$+4%$ $-4%$</td>
<td>$+7%$ $-7%$</td>
<td>$+8%$ $-7%$</td>
<td>$+8%$ $-8%$</td>
<td>$+9%$ $-8%$</td>
</tr>
<tr>
<td>Fragmentation/ U.E.</td>
<td>$+2%$ $-1%$</td>
<td>$+0.4%$ $-3%$</td>
<td>$+2%$ $-0.0%$</td>
<td>$+2%$ $-1%$</td>
<td>$+5%$ $-11%$</td>
</tr>
<tr>
<td>High $p_T$ tracks</td>
<td>negligible</td>
<td>negligible</td>
<td>$+0.1%$ $-0.7%$</td>
<td>$+1%$ $-4%$</td>
<td>$+6%$ $-10%$</td>
</tr>
<tr>
<td>Unmatched reconstructed jets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\pm 1.0%$</td>
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<tr>
<td>Mismodelling in $\phi$</td>
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<td></td>
<td></td>
<td></td>
<td>$\pm 1.6%$</td>
</tr>
<tr>
<td>Luminosity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\pm 11%$</td>
</tr>
</tbody>
</table>
Inclusive cross section

- Cross-section best modeled by Phojet
- Disagrees with Pythia
Fragmentation measurement

- $z$ correction uses simple bin-by-bin factors from simulation
- Systematic uncertainties
  - Track-finding efficiency
  - Event generator tuning
$z = \frac{\vec{p}_{\text{track}} \cdot \vec{p}_{\text{jet}}}{|\vec{p}_{\text{jet}}|}$

- Impacted by jet fragmentation, underlying event
- Best described by AMBT1 Tune of Pythia

\[4 \text{ GeV} < p_{T,\text{Jet}} < 6 \text{ GeV}\]

\[10 \text{ GeV} < p_{T,\text{Jet}} < 15 \text{ GeV}\]
Conclusions

- **First ATLAS measurements and studies of jet constituents done**
  - Number of constituents in fair agreement, improves with $p_T > 1$ GeV
  - Jet shapes – good agreement
  - Charged particle jet momentum – Pythia prediction too high at low end
  - Charged particle jet $z$ – AMBT1 tune good, suggests further tuning
- **Studies so far give confidence in jet measurements, further measurements and refinements planned...**
- **Foundations being laid for years of exciting discoveries ahead!**
Charged Fraction

\[ f_{\text{track}} = \frac{\Sigma p_{T,\text{track}}}{p_{T,\text{jet}}} \]

- Good between simulated events and data!
- \( f_{\text{track}} > 1 \) mostly due to calorimeter fluctuating low
More on Unfolding

- Inclusive charged particle jet cross section determined from track jet distributions using Bayesian Iterative unfolding
- Corrects for:
  - Jet-finding efficiency
  - Reconstructed track jets not matched to charged particle jets
  - Bin-to-bin migration of reconstructed jets due to tracking efficiency and resolution smearing
  - Corrections determined from migrations in simulated sample

- Correction of z done with simple correction factors in bins of jet $p_T$ – correction factors vary slowly with $p_T$

S. Zenz, ISMD 2010
Tests of Unfolding

- Unfolding validated with toy samples
  - Simulated MC tracks smeared
- Also tested with fully-simulated MC pseudodata
  - Produce response matrix with Pythia 6 main sample
  - Apply to reconstructed track jets in fully-simulated Pythia 8 sample – quite different truth distribution from Pythia 6
  - Compare unfolded result to original Pythia 8 truth
  - Agrees within uncertainties that are correlated between samples
$R = 0.6 \ z$ distributions (1)

$\int Ldt = 370 \mu b^{-1}$

*ATLAS* Preliminary

anti-$k_t$ Charged Particle Jets $R=0.6$

$4 \text{ GeV} < p_{T,\text{Jet}} < 6 \text{ GeV}$

$6 \text{ GeV} < p_{T,\text{Jet}} < 10 \text{ GeV}$
$R = 0.6 \, z$ distributions (2)

\[ \int \text{d}t = 370 \, \mu\text{b}^{-1} \]

**ATLAS** Preliminary
anti-$k_t$ Charged Particle Jets $R=0.6$

\[ 10 \, \text{GeV} < p_{T,\text{Jet}} < 15 \, \text{GeV} \]

\[ 15 \, \text{GeV} < p_{T,\text{Jet}} < 24 \, \text{GeV} \]

22 September 2010

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R = 0.4 $z$ distributions (1)

$\int L dt = 370 \mu b^{-1}$

**ATLAS Preliminary**

anti-$k_t$ Charged Particle Jets $R=0.4$

$4 \text{ GeV} < p_{T,\text{Jet}} < 6 \text{ GeV}$

$6 \text{ GeV} < p_{T,\text{Jet}} < 10 \text{ GeV}$

22 September 2010

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$R = 0.4$ z distributions (2)

10 GeV $< p_{T,\text{Jet}} < 15$ GeV

15 GeV $< p_{T,\text{Jet}} < 24$ GeV

ATLAS Preliminary
anti-$k_t$ Charged Particle Jets $R=0.4$
Raw track multiplicity in track jets
Anti-\(k_T\) Jet Algorithm

- Anti-\(k_T\) algorithm is related to \(k_T\) – operates by iteratively combining constituent pairs with smallest “distance” \(d\)
  - Difference with \(k_T\) is in the exponent in the definition of “distance”
  - Shown recently to be **infrared safe** – JHEP 04 (2008) 063
  - Results are **cone-like**: well-contained inside radius \(D\) in \((y,\phi)\) space and thus approximately contained inside radius \(D\) in \((\eta,\phi)\) space
- Algorithm: make a list of distances between constituents \(d_{ij}\) and distances to beam axis \(d_{iB}\) (defined below), proceed iteratively:
  - If smallest value is a \(d_{ij}\), replace them on the list with their sum
  - If smallest value is a \(d_{iB}\), call it a jet and remove it from the list
  - Continue until the list is empty

\[
d_{i,j} = \min(p_{T,i}^{-2}, p_{T,j}^{-2}) \frac{[\Delta R_y(i, j)]^2}{D^2}
\]

\[
d_{iB} = p_{T,i}^{-2}
\]