Jet measurements, and subjet structure for boosted hadronic objects

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Motivation

- Jet production at the LHC is the dominant high transverse-momentum process.
- Testing ground for our understanding of perturbative QCD in a new kinematic regime.
- Hard QCD processes are a background for many new physics models including boosted heavy objects.

- A jet is a composite object; more information available than only its 4-vector.
- Internal structure of jets provides crucial discrimination against backgrounds for searches involving boosted massive particles.

[F. Kraus]
Jet Reconstruction

- 3D noise suppressed clusters of calorimeter cells, fed as input to jet algorithms:
  
  → **anti-k$_t$** $R=0.4$, 0.6
  
  → Cambridge-Aachen $R=1.2$, **anti-k$_t$** $R=1.0$ for substructure studies (large-$R$ jets)

- Jet calibration restores the measured jet energy to the particle-level jet energy scale (JES), on average. Main source of uncertainty for many measurements.

- Reduced uncertainty in 2011 thanks to in-situ measurements (Z+jet: ATLAS-CONF-2012-053)

Jet Trigger

- ATLAS trigger selects jets using the **anti-k$_t$** algorithm (as of 2011)

- 3 successive levels to cope with the large data input rate
Inclusive jet cross section

- 2010 data. Spans jet $p_T$ from 20 GeV to 1.5 TeV, wide rapidity coverage of $|y| < 4.4$
- Anti-$k_t$ jet $R=0.4$ and $R=0.6$

- Good agreement with NLO fixed order calculations (with non-perturbative corrections)
- POWHEG interfaced to different parton showers (PS) MC shows some deviations
  - indication of some uncertainty coming from different PS approximations.
High mass dijet cross section

- Full 2011 dataset: 4.8 fb^{-1}
- Spans dijet system mass from 260 GeV to 4.6 TeV, \( y^* = |y_1 - y_2|/2 < 2.5 \)

- Overall good agreement with both NLOJET++ and POWHEG + PS
- Largest disagreement at very high \( m_{12} \) and \( y^* \)
Flavour composition of dijet events

- Two flavour discriminating variables constructed from kinematic properties of secondary vertices found in jets → MC based template for light, charm and beauty flavour state of jets.
  - Flavour dijet fractions extracted from a multidimensional fit to the data.

- Predictions for light-beauty fraction lower than measured value at high $p_T$

- Asymmetry in the number of leading and subleading beauty jets: $A_b = \frac{N_{SL}^b}{N_{L}^b} - 1$
  Poor description by Pythia.

ATLAS jet and substructure measurements

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ICHEP 2012, Melbourne, July 4-11 2012
Event shapes at large momentum transfer

- Event shapes characterize the event energy flow → probes and tests the multi-jet topologies through the use of hadronic jets.

- Selected events are required to have \( \frac{1}{2} H_{T,2} = \frac{1}{2} (p_{T,jet_1} + p_{T,jet_2}) > 250 \text{ GeV} \)

- Six observables studied, fully unfolded back to particle level. Shown here:
  - \( y_{23} = p_{T,jet_3}^2 / H_{T,2}^2 \)
  - **Aplanarity** (~ amount of transverse momentum w.r.t. the plane formed by the two hardest jets)

- \( y_{23} \) well described by 2 → 2 MC (Pythia, Herwig++)

- Herwig++ predicts more planar events

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**ICHEP 2012, Melbourne, July 4-11 2012**

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Boosted Hadronic Objects

- **Boosted production of heavy particles** (e.g.: top, Higgs, W) → collimated decay products at high $p_T$
  - Decay is best captured by a single **large-R jet** (anti-$k_t$ R=1.0, Cambridge-Aachen R=1.2)

- QCD jets (induced by a single light quark/gluon) are an important background for searches involving boosted objects
  - Extensively studied with 2010 data:
    - *Jet mass and substructure of inclusive jets*, arXiv:1203.4606, JHEP.
    - *Jet fragmentation and transverse profile*: arXiv:1109.5816, EPJC.

- Wide variety of new jet substructure techniques studied with 2011 data and compared to LO and NLO+PS predictions at the reconstructed level
  - **Jet grooming techniques**: Trimming, Mass-drop filtering, pruning
  - **Substructure observables**: Mass, $k_t$ splitting scales, N-subjettiness
Large-R jets performance

- **Jet grooming** algorithms remove extraneous constituents in a jet → reveals the jet internal hard structure.

- An asset for large-R jets: mitigates the underlying event and pile up contributions (see ATLAS-CONF-2012-066).

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**Jet mass** (left) and first \( k_t \) splitting scale (right) for anti-\( k_t \) R=1.0 jets with trimming applied, in inclusive QCD dijet events.

Good description by POWHEG in both cases, even in the tails.
Large-R jets performance

- Grooming preserves jet mass for jets with real hard substructure (e.g. boosted hadronic top decay) → enhanced signal discrimination

- Qualitative effect of trimming in $t\bar{t}$ events, in data. Standard (resolved) semi-leptonic $t\bar{t}$ selection. **Jet mass** for the leading-$p_T$ anti-$k_T$ R=1.0 jet (with $p_T > 350$ GeV)

Well contained boosted tops better resolved with trimmed jets. Increased discrimination between jets encompassing one, two or three partons.
Properties of boosted jets

- Analysis performed using the 2010 dataset using high $p_T$ standard (R=0.6) and large-R (R=1.0) anti-$k_t$ jets.

- Several jet shapes measured and unfolded back to particle level. Shown here:

  - **Width** ($p_T$ weighted average of the distances between the jet's constituents and its axis)

  - **Angularity**, for massive R=0.6 jets (measure of the symmetry in the energy flow inside a jet)
    Peak and maximum value positions from direct calculations
Jets @ $\sqrt{s} = 8$ TeV

- Inclusive jet $p_T$ (left) and dijet mass (right) spectrum for $pp$ collisions at $\sqrt{s} = 8$ TeV for anti-$k_t$ $R=0.4$ jets.

- Comparison with $\sqrt{s} = 7$ TeV 2011 data and to Pythia 6 (Pythia 8) MC predictions at $\sqrt{s} = 7$ TeV ($\sqrt{s} = 8$ TeV).

→ lower center of mass energy in 2011; therefore, lower cross section.
Conclusion

- ATLAS has performed many precision measurements to test perturbative QCD predictions in a previously unexplored kinematic regime. Discussed here:
  - Inclusive jet and dijet differential cross sections
  - Flavour composition of dijet events
  - Event shapes at high momentum transfer

  → overall good data/theory agreement

- Gaining confidence in our understanding of jet substructure techniques with the ATLAS detector
  - Jet mass, shapes, substructure observables measured in 2010 and 2011 data.
  - Exhaustive number of new jet *grooming* algorithms tested.

  → Already used in current searches involving boosted particles production. Will become a key handle on background processes for many searches in 2012 and beyond.
Backup Slides
Jets @ $\sqrt{s} = 8$ TeV

Jet 1:
- $p_T = 1.96$ TeV
- $\eta = -0.07$, $\phi = -2.68$

Jet 2:
- $p_T = 1.65$ TeV
- $\eta = 0.17$, $\phi = 0.48$

Missing $E_T = 318$ GeV,
- $\phi = 0.43$

Sum $E_T = 3.81$ TeV

- High mass central dijet event collected in April 2012.
  Invariant dijet mass of 3.62 TeV
Inclusive and dijet cross sections of $b$-jets

- Measurement of jets containing a $b$-hadron, in 2010 data. Comparison with pQCD predictions.

- Cross check between two experimental methods for $b$-tagging in the inclusive measurement: displaced vertices and muon tagging in jets.

- $b$-JES and $b$-jet tagging efficiency are the main sources of systematic uncertainty.

\[ \text{arXiv:1109.6833, EPJC} \]
ATLAS jet and substructure measurements

Large-R jets performance

- Jet grooming algorithms removes extraneous constituents in a jet → reveals the jet internal hard structure.

- An asset for large-R jets: mitigates the underlying event and pile up contributions.

\begin{itemize}
  \item Average jet mass as a function of the number of reconstructed vertices in fully simulated events for jets emanating from light quarks and boosted top quarks.
  \item Much reduced pile up dependence after trimming.
  \item Increased separation power.
\end{itemize}

Large-R jets performance

- Jet mass (upper row) and first $k_t$ splitting scale (bottom row) for anti-$k_t$ $R=1.0$ jets with and without trimming applied, in inclusive QCD dijet events.

- Good description by POWHEG in both cases, even in the tails.

- Jet mass scale validated in situ by comparing to jets built out of tracks from the inner detector. Systematic uncertainty estimated at $\sim 4\%-8\%$
Jet mass and substructure

- Analysis performed using 2010 dataset using high $p_T$ large-$R$ jets. Only one primary reconstructed vertex was allowed → no pile-up

- Jet mass shapes relatively well modelled
  - Pythia predictions → softer spectrum
  - Herwig++ predictions → harder spectrum
  - Substructure variables are better reproduced by MC predictions than mass.

N-subjettiness measures the degree of resemblance of a jet with an N subjet configuration. $\sqrt{d_{12}}$ is the first $k_t$ splitting scale; measures the hard substructure inside a jet.
Jet mass and substructure

- Analysis performed using 2010 dataset using high $p_T$ large-$R$ jets. Only one primary reconstructed vertex was allowed → no pile-up

- *Split & Filtering* procedure identifies hard splittings in a jet's clustering history and filters out the remaining soft components
  - improves significantly the MC/Data agreement.