Jet measurements in ATLAS

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Abstract. The reconstruction of jets generated in the proton-proton collisions at the Large Hadron Collider (LHC) at a center of mass energy of $\sqrt{s} = 7$ TeV with the ATLAS detector is discussed. Beginning with a brief review of the calorimeter signal definitions relevant for jet finding, and the use of reconstructed charged particle tracks, the jet reconstruction strategy is described in some detail. Emphasis is put on the jet energy scale (JES) calibration strategy applied for first data, which is based on a short sequence of data driven and simulation based calibrations and corrections to restore the measured jet energy to particle level. The level of understanding of the signal patterns entering the JES corrections is shown for selected variables in comparisons to simulations. The present systematic uncertainties on the JES, which can be as low as 2% for central jets, are presented and analyzed with respect to the individual fractional contributions entering their determination. Some characteristic jet reconstruction performance and selected results from the first year of jet physics with ATLAS in a newly accessible kinematic domain are shown in conclusion.

1. Introduction

The ATLAS experiment [1] at the Large Hadron Collider (LHC) commenced its first successful year of proton physics running at $\sqrt{s} = 7$ TeV in early November 2010. A total of about 45 fb$^{-1}$ of proton-proton (pp) collision data were recorded, with instantaneous luminosities peaking at approximately $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$, thus generating up to about 3.5 pp collisions per LHC bunch crossing on average.

Collimated bundles of particles (jets) in the final state of a pp collision are not only produced by the hadronization of high energy partons emerging from the hardest scattering process, but also by initial and final state (gluon) radiation associated with this scattering, and in the softer multiple parton interactions in both the underlying event and the possible additional pp collisions in the same proton bunch crossing (pile-up). Any of these jets with transverse momentum ($p_T$) of more than a few GeV leave significant signals in the ATLAS detector system and are reconstructed for the characterization and measurement of the actual final state. The quality of this reconstruction and the calibration strategies applied in its context are discussed in this note, together with selected examples of the reconstruction performance and jet physics measurements. The discussion of the jet calibration strategies is intentionally restricted to the methods applied in the default ATLAS jet reconstruction for the 2010 pp data, which has been used for all published jet reconstruction performance evaluations, jet physics analysis and searches for new physics so far. Specifically, contributions to this workshop describing some of these results include in-situ jet energy scale validations [2], inclusive jet and di-jet cross sections [3], jets in $t\bar{t}$ final states [4] and jets in searches for new physics [5].
The structure of this note is as follows. In Section 2, the ATLAS experiment is briefly described. The detector signals used for the reconstruction of particle jets and other physics objects are discussed in Section 3, while the jet reconstruction and calibration sequences are presented in Section 4. The determination the systematic jet energy scale uncertainties and their fractional contributions are shown in Section 5, while some results from jet physics sensitive to the jet reconstruction quality are discussed in Section 6. This note concludes with a brief summary and outlook in Section 7.

2. The ATLAS experiment
The ATLAS collaboration designed, built and now operates one of two multi-purpose experiments at the LHC. Its detector system features the inner detector (ID) tracking system closest to the collision vertex in radius, which provides charged particle track reconstruction for pseudorapidities $|\eta| < 2.5$ in a solenoid field of 2 T. The ID contains from inside out a silicon pixel detector, a silicon strip detector for high precision track and vertex reconstruction, and a transition radiation detector featuring a large number of straw tubes arranged in a large number of planes (from 73 central up to 160 in the end cap) for large radius tracking.

The ID is surrounded by electromagnetic calorimetry covering $|\eta| < 3.2$, featuring liquid argon calorimeters with lead absorbers folded into an accordion ($|\eta| < 1.4$) or a "Spanish fan" shape ($1.4 < |\eta| < 3.2$). These calorimeters provide high precision reconstruction for electrons and photons without any azimuthal discontinuities. The readout geometry of these devices is projective with respect to the nominal collision vertex in ATLAS, and highly segmented, with up to three longitudinal layers and a typical radial granularity in $\eta$ and azimuth ($\phi$) of $\Delta \eta \times \Delta \phi = 0.025 \times 0.025$. The depth of the electromagnetic calorimeters is between 22 – 26 radiation length ($X_0$) and up to 1.5 hadronic interaction length ($\lambda$). The total number of readout channels is about 170,000.

Hadronic calorimetry in the central region of ATLAS is provided by a scintillator tile/iron calorimeter surrounding the electromagnetic calorimetry with coverage up to about $|\eta| < 1.7$. The typical readout granularity is $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ in three longitudinal layers. Liquid argon/copper calorimetry featuring a parallel plate absorber structure with four longitudinal segments and the same projective granularity covers 1.5 < $|\eta|$ < 3.2 at both ends of the central calorimeters. The gap between these end-cap calorimeters and the LHC beam line is closed by three modules of forward calorimeters at both ends of the detector, covering 3.2 < $|\eta|$ < 4.9. All forward calorimeters are high density liquid argon devices with a large number of tubular electrodes arranged parallel to the beam line. The modules closest to the collision vertex feature a copper absorber, while the modules behind it have a tungsten absorber. Overall, ATLAS calorimetry provides nearly continuous hadronic coverage of at least 10 $\lambda$ within $|\eta| < 4.9$, with a total of nearly 190,000 independently read out cells. The ATLAS calorimeters are non-compensating, with a typical $e/\pi$ signal ratio of about 1.3.

The ATLAS calorimeters are surrounded by a muon spectrometer covering $|\eta| < 2.7$ and featuring muon chambers in an air core toroid magnetic field, which allows high precision reconstruction of all three components of the muon momentum. The overall dimensions of the experiment including the muon system are about 46 m long and 23 m high, at a total weight of approximately 7,000 t. A comprehensive overview of all detector systems can be found in Ref. [1].

3. Input signals
The most important detectors for jet reconstruction in ATLAS are the calorimeters. The performance of the individual systems has been evaluated in extensive test beam programs for the various modules, see e.g. Refs. [6–10], and in-situ, see for example Refs. [11, 12].
3.1. Calorimeter towers and cluster

The about 190,000 cell signals collected in each recorded collision event by the ATLAS calorimeters are reconstructed on a basic electromagnetic energy scale, which has been determined for each module in the system using electron test beam and simulations. The cell signals are further collected into calorimeter towers or topological cell clusters. In case of calorimeter towers, the event energy flow is projected onto a regular \( \Delta \eta \times \Delta \phi = 0.1 \times 0.1 \) grid within the detector acceptance \((-\pi < \phi \leq \pi, -5 < \eta < 5)\). The cell signal contribution to a tower in this grid\(^1\) is determined by the overlap of the cell area in \((\eta, \phi)\) space with the tower. If a projective cell is smaller than or equal to the tower bin size, its energy \(E_{\text{cell}}\) is added in full to the energy in the tower it overlaps. Larger projective cells contribute \(w_{\text{cell}}E_{\text{cell}}\) to any tower they overlap, with the geometrical weight \(w_{\text{cell}} < 1\) reflecting the sharing of \(E_{\text{cell}}\) according to the fraction of area shared between tower and cell. Non-projective cells like the ones in the forward calorimeters can be smaller than the tower, yet distribute their energy among several bins with \(w_{\text{cell}}\) depending on the projection of the actual cell front face onto the tower grid.

Topological cell clusters \([14]\) are three dimensional signal objects formed from cells following significant spatial energy flow patterns in the calorimeters. The main motivation is the attempt to reconstruct individual particle showers in the calorimeter, or at least provide a measure highly correlated with the spatial energy flow in the event even if particle bundles are too collimated (like in jets) to distinguish individual showers within the calorimeter readout granularity. Figure 1 from Ref. \([13]\) indicates this correlation between the multiplicities in particle flow and clusters.

The cluster algorithm starts from cells whose signal is more than \(4\sigma_{\text{noise}}\), around which signals from directly neighboring cells are collected in all three dimensions. If any of these signal is more than \(2\sigma_{\text{noise}},\) its neighbors are collected as well, independent of their signal significance. Finally, the collected cluster is split if it contains more than one local signal maximum. This clustering approach produces ”energy blobs” around significant signals in the calorimeter, which can cross sub-system boundaries and provide shape and location information. The algorithm also acts as a noise suppression tool, as cells with insignificant signals away from seeds are not included into any topological cluster and dropped from jet and other physics object reconstruction which uses

\(^1\) The direction \((\eta_{\text{cell}}, \phi_{\text{cell}})\) of the cell is defined by the nominal collision vertex and the cell location.
Figure 2. The average isolation of topological cell clusters in jets, for electromagnetic and hadronic clusters, as a function of the cluster energy on electromagnetic scale. Full simulations using Pythia [15] are compared to data (from Ref. [16]).

3.2. Calorimeter energy scales

As already mentioned above, the calorimeter cell signal $E_{cell}$ in ATLAS is reconstructed on the basic electromagnetic energy scale. Calorimeter towers contain sums of possibly weighted cell signals, meaning the tower energy $E_{tower}$ is also reconstructed on this basic scale. In addition, each tower has a direction $(\eta_{tower}, \phi_{tower})$ which is defined by its bin center in the $(\eta, \phi)$ grid. From this a massless four-momentum $(E_{tower}, \vec{p}_{tower})$, with $E_{tower} = |\vec{p}_{tower}|$, is constructed for input to jet finding and other further reconstruction. Topological cell clusters provide additional information outside of their total energy on electromagnetic scale, which is the sum of cell signals $E_{cell}$ in the cluster. Their location and shape hints to the origin of the signal, which for high density clusters located more or less completely in the electromagnetic calorimeter is very likely an electron or photon. Larger clusters and/or clusters located deep inside the calorimeters are likely of hadronic origin. These features provide a basis for a local hadronic calibration, where the cluster context defines the calibration and correction functions for both electromagnetic and hadronic clusters. For hadronic clusters, a non-compensation correction is applied to each cell of the cluster (a cell signal weighting approach), depending on the cluster location, energy, and the cell signal density. Additional corrections are then applied to recover out-of-cluster signal losses and local energy loss in nearby inactive material. The last two are also applied to electromagnetic clusters, with different parameters reflecting the differences in the underlying shower developments. Like towers, clusters are represented by a massless four-momentum, either on electromagnetic or hadronic energy scale.

All corrections and calibrations are derived independent from each other using detailed single particle simulations based on the Geant4 toolkit [17, 18]. Each correction uses only cluster observables not depending on any other correction, and, even though the effects of e.g. a poor response (large $e/h$) and the amount of energy lost outside of clusters or in inactive material are correlated in a particular hadronic shower, the correction functions and parameters at cluster...
level are not. It should also be noted that all calibrations and corrections exploit the available knowledge of the relation between deposited energy and signal in the detector simulation, and are not results of numerical fits.

The completely simulation based determination of the calibrations and corrections for the local hadronic energy scale requires good modeling of the observable parameters used in the various procedures. For example, the out-of-cluster corrections derived for single particles are topology dependent, as energy lost for one cluster may generate a signal in a nearby cluster. To scale this correction for a jet environment, the spatial cluster isolation is explicitly measured and used in this correction. Figure 2 from Ref. [16] shows a comparison of the average isolation of clusters in jets as a function of the cluster energy. Simulations follow the data very well with this complex observable.

![Figure 3](image.png)

**Figure 3.** The spectrum of the charged track $p_T$ ratio $f_{\text{track}}$, as described in the text, in comparison of data with simulations (left). The scaling of $f_{\text{track}}$ with jet $p_T$ is shown in the right figure, again for data and simulations (taken from Ref. [16]).

### 3.3. Reconstructed tracks

In addition to the calorimeter signals, ATLAS also uses tracks to reconstruct jets, which provide independent detection of jet activity and measurements of jet properties like width. Tracks pointing to calorimeter jets can also be used to refine jet calibration. As for calorimeter signals, good modeling of basic track properties is essential. One of the characteristic parameters considered for calibration refinement is the ratio of charged particle transverse momentum ($p_T^{\text{track}}$) to the total measured $p_T$ from the calorimeter, $f_{\text{track}} = p_T^{\text{track}} / p_T$, depicted in Fig. 3. Simulations reproduce the $f_{\text{track}}$ spectrum and scaling of the average $f_{\text{track}}$ with $p_T$ very well.

### 4. Jet reconstruction and calibration

The ATLAS jet reconstruction implementation supports calorimeter towers and clusters, and reconstructed tracks, as input signals, in addition to simulated particles from physics generators. The corresponding software is designed to allow use of all jet finding strategies of interest on any of these inputs, with only a few input specific tools like those for jet calibration to be configured. The jet algorithm suite provided by FastJet [19] and the infrared safe seedless cone algorithm SISCone [20] are used within this framework. The present default jet definition used by ATLAS...
Figure 4. The number of constituents in wide central jets reconstructed with the ATLAS calorimeters (top left from calorimeter towers, top right from topological cell clusters). The scaling of the average number of tracks pointing to the cluster jets as function of jet $p_T$ is shown at the bottom (left, including tracks with $p_T > 500$ MeV, right for tracks with $p_T > 1$ GeV). Data is shown in comparison to simulations (from Ref. [16]).

is the anti-$k_T$ algorithm [21] with full four-momentum recombination ("$E$-scheme") and two jet sizes, $R = 0.4$ and $R = 0.6$.

4.1. Jet formation
The jet reconstruction sequence starts with a list of calorimeter towers, topological cell clusters, reconstructed tracks, or generated particles. In the case of clusters and towers, all objects with $E_{\text{cluster}} < 0$ or $E_{\text{tower}} < 0$ are rejected\(^2\), to ensure meaningful four-momentum algebra during jet formation. In the present default configuration, the calorimeter signals enter jet finding at the electromagnetic energy scale - the use of locally calibrated clusters is under commissioning.

\(^2\) Intentionally, negative energy tower and cluster signals are not generally removed from the calorimeter signal; rather, they are used to e.g. monitor noise characteristics.
The configured jet clustering algorithm of choice is then applied to the selected (now physically meaningful) input objects, forming jets with links back to their constituents. This allows the measurement of shapes and other jet characteristics, and the analysis of jet substructure. The number of constituents forming a jet naturally depends not only on its particular fragmentation, but also on the input signal definition in case of jets reconstructed with the calorimeter (calorimeter jets), and the track selection cuts for tracks in jets, see Fig. 4 from Ref [16].

4.2. Jet calibration

The present calibration scheme for calorimeter jets in ATLAS establishes a flat response to jets within the full coverage of the calorimeters. The approach features few correction levels, thus limiting the algorithm biases and reducing sensitivity to modeling details in the simulation. It is based on the electromagnetic energy scale signal of jets, given by (example for cluster jets, similar for towers):

\[
(E_{em}, \vec{p}_{em})_{jet} = \sum_{i=1}^{N_{jet}} (E_{em}, \vec{p}_{em})_{cluster,i} \quad \text{with} \quad E_{em} > 0 \quad \text{for all} \quad i
\]

\(E_{em}\) and \(\vec{p}_{em}\) are the energy and momentum reconstructed on the electromagnetic energy scale, for jets and clusters. \(N_{jet}\) is the number of clusters forming the jet. The jet level calibration sequence then is

(1) Pile-up correction (derived from data) As already mentioned, with increasing LHC luminosity the number of additional \(pp\) collisions in same bunch crossing as the triggered hard scattering increases, thus adding energy to the event. These extra collisions are completely incoherent with the hard scatter and each other, and the added energies are mostly from soft QCD processes similar to those measured in minimum bias events. They give rise to a transverse energy density \(\rho_T(N_{PV}, \eta) = \langle E_T \rangle (N_{PV}, \eta) / (\Delta \eta \times \Delta \phi)\), which is measured on the electromagnetic energy scale with minimum bias events taken at the same
luminosities. \( N_{PV} \) is the number of reconstructed primary vertices in the event, and as such a measure of the number of additional collisions. The corrected jet momentum for a jet with reconstructed direction \( \eta_{\text{jet}} \) is then

\[
(E_{\text{em}+\text{PU}}, \vec{p}_{\text{em}+\text{PU}})_{\text{jet}} = \left( E_{\text{em}} - \Delta E_T(N_{PV}, \eta_{\text{jet}}) \cosh \eta_{\text{jet}}, (1 - \Delta E_T(N_{PV}, \eta_{\text{jet}}) \cosh \eta_{\text{jet}}/E_{\text{em}}) \cdot \vec{p}_{\text{em}} \right)_{\text{jet}},
\]

with \( \Delta E_T(N_{PV}, \eta_{\text{jet}}) = \rho_T(N_{PV}, \eta_{\text{jet}}) \cdot A_{\text{jet}}^{\phi} \) and the jet area \( A_{\text{jet}}^{\phi} \) measured in \( (\eta, \phi) \) space. Figure 5 (left) shows the average amount of pile-up energy for anti-\( k_T \) jets with \( R = 0.6 \) with the 2010 LHC beam conditions.

(2) Event vertex correction (from data) Calorimeter jets are reconstructed from clusters or towers located in the nominal geometry reference frame of ATLAS, with the central vertex defining the experiment center assumed to be located at \( \vec{x}_{\text{center}} = (0,0,0,0) \). On the other hand, not only is the LHC beam spot systematically shifted with respect to \( \vec{x}_{\text{center}} \), the actual primary event vertex \( \vec{x}_{PV} \) is also reconstructed by the ID. The momentum \( \vec{p}_{\text{em}+\text{PU}} \) of each calorimeter jet, and of all clusters forming this jet, is corrected for the change of directions induced by this vertex shift \( (\vec{p}_{\text{em}+\text{PU}} \rightarrow \vec{p}_{\text{em}+\text{PU}+\text{PV}}) \), while the jet energy is unchanged. The new jet four momentum is then \( (E_{\text{em}+\text{PU}}, \vec{p}_{\text{em}+\text{PU}+\text{PV}}) \).

(3) Response correction (from simulations) The paramount correction in the present scheme is the response correction, where signal inefficiencies due to the non-compensation, signal definition, crack regions in the calorimeters, energy losses in inactive material, and the charged particle energy losses due to the magnetic solenoid field in front of the calorimeter are corrected. The correction is determined using QCD di-jet events generated by Pythia and processed through the full simulation of the ATLAS detector to model detector signals. The simulated calorimeter jets are matched with “true” generated particle jets built with the same anti-\( k_T \) algorithm configuration. The total energy of the particle jets \( E_{\text{jet}}^{\text{true}} \) is then compared to the reconstructed matched jet energy \( E_{\text{em}+\text{PU}, j} \) (see item (1) above) in regions defined by the reconstructed jet direction \( \eta_{\text{jet}} \) and as function of \( E_{\text{jet}}^{\text{true}} \) and denoted as response \( R_{\text{em}}(E_{\text{jet}}^{\text{true}}, \eta_{\text{jet}}) = \langle E_{\text{em}+\text{PU}, j}/E_{\text{jet}}^{\text{true}} \rangle(E_{\text{jet}}^{\text{true}}, \eta_{\text{jet}}) \). Applying the numerical inversion technique described in Ref. [24] allows to change from a truth energy to a measured energy parametrization, i.e. \( R_{\text{em}}(E_{\text{jet}}^{\text{true}}, \eta_{\text{jet}}) \rightarrow R_{\text{em}}(E_{\text{em}+\text{PU}, j}, \eta_{\text{jet}}) \) while maintaining the shape of the response function and avoiding calorimeter energy resolution biases. The response correction is applied as follows:

\[
(E_{\text{em}+\text{PU}+\text{R}}, \vec{p}_{\text{em}+\text{PU}+\text{PV}+\text{R}})_{\text{jet}} = (E_{\text{em}+\text{PU}}, \vec{p}_{\text{em}+\text{PU}+\text{PV}})_{\text{jet}} \times R_{\text{em}}^{-1}(E_{\text{em}+\text{PU}, j}, \eta_{\text{jet}}).
\]

The response corrections can be significant, as indicated in Fig. 5 (right). It decreases for more forward going jets, as expected from the increasing jet energies (at a fixed \( p_T \)) in this region.

(4) Direction correction (from simulations) The direction \( \eta_{\text{jet}} \) of jets close to poorly instrumented regions of the ATLAS calorimeters, like transitions between calorimeter modules and cracks between cryostat vessels, is often biased with respect to the true jet direction, i.e. depending on the shape of the problem region it may be pulled forward towards the beam or pulled back towards the central region. The corresponding small shifts in \( \eta \) have been computed using simulations and are used for a direction correction \( \Delta \eta_{\text{jet}}(E_{\text{em}+\text{PU}}, \eta_{\text{jet}}) \), parametrized as a function of the jet energy and the original jet direction (no vertex correction applied). This correction works only on the jet momentum and leaves the energy unchanged:

\[
(E_{\text{em}+\text{JES}}, \vec{p}_{\text{em}+\text{JES}})_{\text{jet}} = (E_{\text{em}+\text{PU}+\text{R}}, \vec{p}_{\text{em}+\text{PU}+\text{PV}+\text{R}} \otimes \Delta \eta_{\text{jet}}(E_{\text{em}+\text{PU}}, \eta_{\text{jet}}))
\].
Figure 6. Single charged hadron response measured by the average calorimeter response over the track momentum $\langle E/p \rangle$, as function of $p$ (left, Ref. [25]). The upper right figure from Ref. [23] shows the total (fractional) systematic jet energy scale uncertainty for central jets ($0.3 \leq |\eta_{\text{jet}}| < 0.8$) and the contributing error sources as function of the jet $p_T$, while the lower right figure shows the same for forward jets ($3.6 \leq |\eta_{\text{jet}}| < 4.5$).

5. Systematic jet energy scale uncertainty

The systematic jet energy scale uncertainty for the present default jet calibration sequence is determined by the model dependence of the calibration functions and the precision of the data driven corrections. While the careful evaluation of the pile-up correction shows little systematic uncertainty in this procedure, the response correction receives contributions from multiple sources. These include physics modeling, detector simulation (geometry and signal modeling), uncertainties related to the actual beam spot location, and uncertainties related to observed differences between experimental and simulated response. A careful analysis of this last aspect includes the determination of the uncertainty of the charged hadron response from isolated tracks in collision events with momentum $2 < p < 20$ GeV, the uncertainty related to the response to higher momentum ($20 < p < 350$ GeV) charged hadrons from test beams, the basic electromagnetic scale uncertainty from $Z \rightarrow e^+ e^-$ in $pp$ collisions, and estimates of response uncertainties for neutral hadrons of all energies, and all hadrons with $p > 400$ GeV (all summarized in Ref. [25]). Additional contributions to the systematic jet energy scale uncertainty arise from threshold effects in the cell clustering algorithm, and the intercalibration in $\eta$ with di-jet events [26], especially for regions beyond the tracking acceptance ($|\eta| < 2.5$). Figure 6 shows the excellent understanding of the single charged hadron response in ATLAS, with systematic
Figure 7. The average jet width $\langle w_{\text{jet}} \rangle$ as function the jet $p_T$, measured by the ATLAS calorimeters using Eq.(2), for anti-$k_T$ jets with $R = 0.6$ and $p_T > 20 \text{ GeV}$ (left). The observed disagreement with simulations based on pre-LHC collision modeling parameters for parton showering, radiation and soft QCD is confirmed by the average distance between the two hardest charged tracks measured in the ID pointing to these jet, as seen in the right figure (both figures from Ref. [16]).

uncertainties determined from the comparison with simulations of less than 2% for $p < 10 \text{ GeV}$ and less than 5% for $10 < p < 20 \text{ GeV}$. The same figure also shows that this is the dominating uncertainty for central jets with $p_T > 100 \text{ GeV}$. The $\eta$ intercalibration introduces the largest fractional errors for forward jets with $p_T < 100 \text{ GeV}$, at similar jet energies. Additional in-situ evaluations of jet energy scale uncertainties and extrapolation techniques are discussed in Ref. [2].

6. Observations from jet reconstruction

Even with the relatively small collision data sample collected by ATLAS in 2010 it is possible to demonstrate very good jet reconstruction performance. As discussed in the previous section, the systematic jet energy scale uncertainty is between about 2 − 4% in the central region. The measurement of other jet features like width and shape are well understood as well. For example, the calorimeter measurement of the jet width $w_{\text{jet}}$, defined as

$$ w_{\text{jet}} = \frac{1}{E_{\text{T,jet}}} \sum_{i=1}^{N_c} r_i \times E_{\text{T,i}}, \text{ with } E_{\text{T,jet}} = \sum_{i=1}^{N_c} E_{\text{T,i}} \text{ and } r_i = \sqrt{(\phi_i - \phi_{\text{jet}})^2 + (\eta_i - \eta_{\text{jet}})^2}, \quad (2) $$

with $N_c$ being the number of clusters in the jet, indicates wider jets in data than in early\(^3\) jet modeling. This is confirmed by a complementary width measurement from the ID, the distance $\Delta R(\text{trk}_1, \text{trk}_2)$ between the two hardest tracks $\text{trk}_1, \text{trk}_2$ pointing to the jet, see Fig. 7 from Ref. [16].

The jet reconstruction and calibration approach presented here is appropriate for many physics analysis, see Refs. [3–5] for examples shown at this workshop. Other precise QCD measurements performed by ATLAS with the 2010 data include jet topologies and shapes, both\(^3\) No soft QCD tuning to actual LHC data yet in the model.
of which also provide input to tuning the soft QCD modeling parameters. Figure 8 from Ref. [27] shows the unfolded jet shape measurement in terms of the energy containment fraction $\Psi(r)$, which is the fraction of jet energy contained inside a cone of $r = 0.3$ around the jet axis, as function of the jet $p_T$. The shape indicates a changing mixture of quark and gluon initiated jets in the final state with increasing jet $p_T$, convoluted with perturbative QCD effects from the running strong coupling, as expected from similar studies at the Tevatron [28].

A precise measurement sensitive to QCD dynamics, in particular concerning jet production by additional parton emission, is the angular de-correlation between the two leading jets, which has first been done at the Tevatron [29] and is also available from ATLAS in Ref. [30], see Fig. 8. The increasing azimuthal de-correlation with increasing number of jets in the events is well modeled by Pythia.

![Figure 8](image-url)

**Figure 8.** The fraction of jet energy outside a cone of $r = 0.3$ around the jet axis, measured in terms of the relative energy containment $\Psi(r)$, as function of the jet $p_T$ (left, from Ref. [27]). The azimuthal distance between the two leading jets in events with $n_{jets} \geq 2$ to 5 is shown in the right figure from Ref. [30], which indicates increasing de-correlation with increasing number of additional jets.

7. Conclusion and outlook

During 2010, the first year of $pp$ collisions at $\sqrt{s} = 7$ TeV in LHC, ATLAS collected a large amount of data for studying jet properties, Standard Model jet physics, and jet topologies as search tools for new physics. A very good jet reconstruction performance, even with a simplified calibration model (the present default), has been achieved with systematic jet energy scale uncertainties as low as 2% for central jets. Early measurements of jet shapes helped improving the modeling of parton showers and radiation in the new kinematic domain now accessible. Due to the precision achieved in jet reconstruction, measurements of inclusive jet and di-jet cross sections, and angular de-correlation, among others, in this high energy domain provided important tests of the Standard Model and thus a solid base for background determinations for searches with jets in the final state. Further improvements presently under commissioning include dynamic hadronic calibration, which improves the jet energy resolution and is useful for jet substructure analysis, e.g. to understand sub-jet calibrations in jets from boosted heavy particle decays.
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