First measurement of jets and missing transverse energy with the ATLAS calorimeter at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV

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First measurement of jets and missing transverse energy with the ATLAS calorimeter at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV

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Abstract.

In December 2009, ATLAS recorded the first proton-proton collisions delivered by the LHC at a center-of-mass energy of $\sqrt{s} = 900$ GeV, and at $\sqrt{s} = 7$ TeV beginning in March 2010. We report on the first measurements of the kinematic distributions of jets and missing transverse energy at both center-of-mass regimes. These data also provide the opportunity to test the inputs to jet reconstruction and the jet calibration schemes available in ATLAS. Basic jet properties such as the number of associated charged particles, the longitudinal and radial shower topology in jets, and the transverse energy profiles of jets are compared to Monte Carlo simulation of the full detector response. We show that the basic inputs to jet reconstruction and calibration are generally well modeled by these simulations and that discrepancies will help to guide future Monte Carlo tunings and detector response descriptions.

1. Introduction

The ATLAS detector is a multi-purpose detector at the Large Hadron Collider (LHC) at CERN designed to conduct both precision Standard Model measurements as well search for signatures of physics beyond the Standard Model [1]. The collisions delivered in December 2009 at $\sqrt{s} = 900$ GeV, and at $\sqrt{s} = 7$ TeV shortly thereafter in March 2010, provide the opportunity to study the kinematics and properties of jets, as well as to conduct missing transverse energy measurements with the ATLAS calorimeters. Precise measurements of the charged particle content (measured with the Inner Detector tracking system) and energy distributions within jets at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV lend insight into the process of jet production and internal jet structure at higher center-of-mass energies and their modeling by a Monte Carlo (MC) simulation based on phenomenological models of non-diffractive processes, including a full simulation of the detector response.

2. The ATLAS calorimeters

The ATLAS calorimeter is a non-compensating sampling calorimeter built of multiple sub-detectors with several different designs. The central calorimeter system consists of a liquid argon (LAr) electromagnetic (EM) calorimeter ($|\eta| < 1.475$), and a scintillating tile (Tile) hadronic calorimeter.

1 The pseudo-rapidity is defined as $\eta = -\ln(\tan(\theta/2))$, where the polar angle $\theta$ is taken with respect to the positive $z$ direction. The anti-clockwise beam direction defines the positive $z$-axis, with the $x$-axis pointing to the
calorimeter ($|\eta| < 1.7$). The Tile calorimeter is divided into a barrel region ($|\eta| < 1.03$) and an extended barrel region, with space for services in between. The end-cap calorimeter is comprised of LAr EM and hadronic calorimeters ($1.375 < |\eta| < 3.2$ and $1.5 < |\eta| < 3.2$, respectively). A third LAr calorimeter sub-detector covers the very forward region ($3.1 < |\eta| < 4.9$), with the end-cap and forward calorimeters housed in the same cryostat. All calorimeter sub-detectors are segmented in depth to allow for measuring the longitudinal shower development.

The calibration schemes developed in ATLAS aim to correct for the non-compensation of hadronic energy deposits and to improve the jet energy resolution. A good description by the Monte Carlo simulation of the properties of jets used by the calibrations helps to reduce the systematic uncertainties in the jet energy scale. This is of key importance for many ATLAS analyses, and is a central topic of these studies.

3. Event selection and jet reconstruction

3.1. Event trigger and selection

Data collected with the tracking detectors and calorimeters fully operational and the solenoid at its full magnetic field strength are compared to a sample of fully simulated non-diffractive pp collisions (“minimum bias”) and di-jet events generated with the PYTHIA [2] event generator program at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV. For both data and MC, events are selected by requiring at least one hit on both sides of the minimum bias trigger scintillators (MBTS), located inside the inner cavity in front of the end-cap cryostats, and cover the pseudo-rapidity range $2.09 < |\eta| < 3.84$. Additional offline timing criteria are applied to reject beam background events. The simulated events are generated with a tuned set of parameters [3], and simulated using a full GEANT4 [4] simulation of the ATLAS detector. Only non-diffractive processes are considered since single and double diffractive contributions and softer collisions have been shown to be negligible for the version of PYTHIA used for these studies. The same trigger and event selection criteria are applied to the MC as to the data.

3.2. Jet reconstruction and track selection

Jets are constructed using the infrared and collinear-safe anti-$k_t$ jet algorithm [5] with a distance parameter of $R = \sqrt{\Delta y^2 + \Delta \phi^2} = 0.6$. The inputs to the jet algorithm in both data and Monte Carlo simulation are either noise suppressed by requiring at least one hit on both sides of the minimum bias trigger scintillators (MBTS), located inside the inner cavity in front of the end-cap cryostats, and cover the pseudo-rapidity range $2.09 < |\eta| < 3.84$. Additional offline timing criteria are applied to reject beam background events. The simulated events are generated with a tuned set of parameters [3], and simulated using a full GEANT4 [4] simulation of the ATLAS detector. Only non-diffractive processes are considered since single and double diffractive contributions and softer collisions have been shown to be negligible for the version of PYTHIA used for these studies. The same trigger and event selection criteria are applied to the MC as to the data.

At $\sqrt{s} = 900$ GeV, no calibrations are applied to jets to compensate for differences in the calorimeter hadronic and electromagnetic responses [7]. In this case, only jets with transverse momenta $p_T^{\text{EMScale}} > 7$ GeV and pseudo-rapidity in the range $|\eta^{\text{jet}}| < 2.6$ are considered. Additional quality criteria are also applied to ensure that jets are not produced by single noisy calorimeter cells or problematic detector regions [8]. At $\sqrt{s} = 7$ TeV [9], an average jet energy scale correction is derived in the MC simulation and applied to each jet as a function of $p_T^{\text{EMScale}}$ and $|y^{\text{jet}}|$, resulting in jets with a uniform response and an average jet energy scale uncertainty of about $\pm 7\%$ [10, 11].

center of the LHC ring. Rapidity is defined as $y = 0.5 \times \ln[(E + p_z)/(E - p_z)]$, where $E$ denotes the energy and $p_z$ is the component of the momentum along the beam direction.

2 The effect of the jet mass is very small and pseudo-rapidity ($\eta$) is used instead of rapidity ($y$) in order to maintain the desired geometrical interpretation. Only in the jet finding procedure and in the detailed studies of the jet internal profile presented in Section 6 are rapidity units employed.
To measure the charged particle content of jets, tracks within the acceptance of the ATLAS Inner Detector are used with at least seven hits in the silicon detectors, transverse momenta of \( p_T > 500 \) MeV, pseudo-rapidity \(|\eta| < 2.5\) and a small impact parameter with respect to the primary vertex in the event \([12,13]\).

### 4. First observation of jets and measurements of missing transverse energy

The basic kinematic distributions of jets provide the first opportunity to compare the response predicted by the MC simulation to the data sample of pp collisions collected at two center-of-mass energies. Figure 1 shows the jet \( p_T^{\text{EMScale}} \) distribution above 7 GeV in data and MC simulation at \( \sqrt{s} = 900 \) GeV. Figure 2 shows the same measurement performed at \( \sqrt{s} = 7 \) TeV for jets with \( p_T^{\text{jet}} > 30 \) GeV where a simple MC calibration scheme described in Section 3.2 is used to calibrate the jets \([10,13]\). In both cases, the MC simulation is normalized to the number of jets in data. The same convention is used for the \( \Delta \phi \) distributions for di-jet events, measuring the azimuthal separation between jets, at \( \sqrt{s} = 900 \) GeV (Figure 3) and \( \sqrt{s} = 7 \) TeV (Figure 4). These distributions indicate a good agreement between data and the MC simulation suggesting that the detector response and topology of di-jet events are well-modeled in both cases.

![Figure 1](image1.png)

**Figure 1.** Jet transverse momentum distribution at \( \sqrt{s} = 900 \) GeV.

![Figure 2](image2.png)

**Figure 2.** Jet transverse momentum distribution at \( \sqrt{s} = 7 \) TeV.

The missing transverse energy \( (E_T^{\text{miss}})^3 \) depends crucially on the response of the calorimeter to both isolated objects such as jets as well as soft unclustered energy deposits, which are often very difficult to model. In soft pp collisions, such as those that dominate the sample described here, no true \( E_T^{\text{miss}} \) is expected. We observe that the shape of the \( E_T^{\text{miss}} \) spectrum and the tails of the distribution are well reflected in the MC simulation at both \( \sqrt{s} = 900 \) GeV (Figure 5) and \( \sqrt{s} = 7 \) TeV (Figure 6), indicating that the response of the calorimeter to soft diffuse energy depositions is well described.

The performance of the \( E_T^{\text{miss}} \) measurements and the agreement between data and MC simulations can be quantitatively assessed by evaluating the transverse components separately as a function of the total transverse energy of the event, \( \sum E_T = \sum_{j=1}^{N_{\text{cell}}} E_j \sin \theta_j \), as shown in Figure 7. In this case, the resolution is expected to increase as \( \sqrt{\sum E_T} \). Fits to both the data and the MC show a reasonable agreement at \( \sqrt{s} = 7 \) TeV, and similarly good performance is observed at \( \sqrt{s} = 900 \) GeV (not shown) \([14,15]\). The result of this fit as a function of \( \sum E_T \)

\[
E_T^{\text{miss}} = \sqrt{(E_T^{\text{miss}})^2 + (E_0^{\text{miss}})^2}.
\]

\(^3\) The \( E_T^{\text{miss}} \) is defined using \( E_T^{\text{miss}} = -\sum_{j=1}^{N_{\text{cell}}} E_j \sin \theta_j \cos \phi_j \).
yields $\sigma(E^\text{miss}_x, E^\text{miss}_y) = 0.41 \times \sqrt{\sum E_T \text{ GeV}}$ in data and $\sigma(E^\text{miss}_x, E^\text{miss}_y) = 0.43 \times \sqrt{\sum E_T \text{ GeV}}$ in the MC simulation, when reconstructed at the EM scale. Both scale factors have negligible statistical uncertainty. The less than 5% difference in these resolution curves is likely due to imperfections in the PYTHIA physics modeling, and remains to be further understood.
5. Jet reconstruction and calibration schemes

ATLAS has adopted diverse approaches to calibrating jet energies to the hadronic scale and currently has four methods under study. These methods offer different levels of complexity and different sensitivities to systematic effects, yet all aim to establish a uniform jet energy scale and to reduce fluctuations in the measurement, thus improving the jet energy resolution. These schemes are described in detail in Refs. [12, 13], while in this section we discuss the properties of jets and clusters which form the basis of these calibrations: longitudinal energy deposition by layer, cell energy density, and topological cluster properties.

Figure 8 shows the fractional jet $p_T$ resolution as a function of the $p_T$ of the matched particle jet as calculated using a Monte Carlo simulation of proton-proton collisions at $\sqrt{s} = 10$ TeV and for jets calibrated with the four different calibrations. The first (“EM+JES”) uses a simple $p_T$ and $\eta$-dependent calibration scheme, and is used presently to calibrate jets in the $\sqrt{s} = 7$ TeV data. This simple approach does not obtain the ultimate resolution achievable by applying more sophisticated methods. The second method (global sequential calibration, or “GS”) uses the fraction of the jet energy deposited in each of the longitudinal layers while the third method (global cell weighting, or “GCW”) uses the distribution of cell energy densities inside jets to apply calibration weights. The last calibration (local cluster weighting, or “LCW”) uses properties of topological clusters to classify and apply a weight to the clusters in jets themselves, and thereby bring the jet energy to the hadronic scale.

The reliance of the latter three calibration schemes on jet constituent properties to apply the calibration weights requires a detailed understanding of those properties. Several comparisons are made between data and predictions from MC simulation. At $\sqrt{s} = 900$ GeV, Figure 9 compares the layer energy fraction for the second layer of the EM barrel (the deepest layer of barrel the EM calorimeter), Figure 10 compares the cell energy densities in the same layer, and Figure 11 compares the cluster energy before and after weighting to the same ratio predicted from MC simulation. In all cases, deviations from the MC simulation predictions are much less than 5%, and are encouraging steps towards the successful commissioning of jet calibration in ATLAS and establishing a jet energy scale uncertainty for the different calibration schemes. Similar results are obtained at $\sqrt{s} = 7$ TeV [13].

6. Jet properties and internal structure

Several studies are performed of the properties of jets which can lend insight into the response of the calorimeter to the details of the hadronic shower, such as the charged particle distributions within jets and the longitudinal and transverse structure of jets.
expected, the track multiplicity increases with increasing average track multiplicity at low \( p_T \). Nevertheless, the data prefer a smaller and angular distributions in jets are well modeled, and that the response of the ATLAS detector is well described by the predictions from the MC simulation, suggesting that the track momentum of soft underlying event and pile-up contributions within the jet calibration procedure.

Studies of the internal structure of jets at colliders in terms of jet shapes [16] or transverse energy profiles have demonstrated their sensitivity to a proper understanding of the jet fragmentation process, the detector response to low energy particles, and the accurate treatment of soft underlying event and pile-up contributions within the jet calibration procedure.

The transverse size of the jet can be characterized in terms of the jet width \( w_{\text{jet}} \), defined as the weighted average distance of the jet constituents to the jet direction,

\[
w_{\text{jet}} = \frac{\sum (r \times E_T^{\text{constituent}})}{\sum E_T^{\text{constituent}}},
\]

where \( r = \sqrt{(\phi^{\text{constituent}} - \phi^{\text{jet}})^2 + (\eta^{\text{constituent}} - \eta^{\text{jet}})^2} \), \( E_T^{\text{constituent}} \) is the transverse energy of the jet constituent, and the sum runs over the constituents associated to the jet by the jet algorithm. Figure 13 presents the measured jet width distribution for jets within \( |\eta| < 2.6 \) at \( \sqrt{s} = 900 \text{ GeV} \) while Figure 14 shows its dependence on \( p_T^{\text{jet}} \) at \( \sqrt{s} = 7 \text{ TeV} \). The shapes of the width distributions are well described by the predictions from the non-diffractive MC simulation, although the data at both \( \sqrt{s} = 900 \text{ GeV} \) and \( \sqrt{s} = 7 \text{ TeV} \) favor slightly wider jets in the central \( \eta \) ranges, particularly in the region \( 0.6 < |\eta| < 1.9 \). This discrepancy persists over a large range in jet transverse momentum, suggesting that improvements in the description of soft processes and the hard jet fragmentation are needed, which are likely to address the discrepancy together with potential improvements in the jet energy calibration.

Studies of the internal structure of jets at colliders in terms of jet shapes [16] or transverse energy profiles have demonstrated their sensitivity to a proper understanding of the jet fragmentation process, the detector response to low energy particles, and the accurate treatment of soft underlying event and pile-up contributions within the jet calibration procedure.

The differential jet profile is defined as the average jet transverse momentum that lies inside an annulus of inner radius \( r - \Delta r/2 \) and outer radius \( r + \Delta r/2 \) around the jet axis:

\[
\langle \frac{1}{(2\pi r)^{\text{jets}}} \frac{d^2 p_T}{dr} \rangle_{\text{jets}} = \frac{1}{A N_{\text{jet}}} \sum_{\text{jets}} p_T(r - \Delta r/2, r + \Delta r/2), \ 0 \leq r \leq R,
\]

where \( p_T \) is the scalar sum of the transverse momentum of jet constituents in a given annulus with area \( A \), \( N_{\text{jet}} \) is the number of jets, \( R = 0.6 \), and \( \Delta r = 0.1 \) is used. Figure 15 shows
the measured jet profiles using calorimeter towers for jets in different jet rapidity regions up to $|y_{\text{jet}}| = 2.6$. The jet profiles present the expected shape with a prominent peak at low $r$ which indicates that the majority of the jet momentum is concentrated in the core of the jet. However, much like the jet width, the data favor slightly wider jets than predicted from the MC simulation.

**Figure 12.** Number of tracks in jets with $|\eta| < 1.9$ vs. jet $p_T$ at $\sqrt{s} = 900$ GeV.

**Figure 13.** Jet width for jets with $|\eta| < 2.6$ at $\sqrt{s} = 900$ GeV and $p_T > 7$ GeV.

**Figure 14.** Mean jet width vs. jet $p_T$ at $\sqrt{s} = 7$ TeV for jets with $|\eta| < 2.8$.

**Figure 15.** Measured jet profiles at $\sqrt{s} = 7$ TeV using calorimeter towers for jets with $p_T^{\text{jet}} > 7$ GeV in different $|y_{\text{jet}}|$ regions.
7. Conclusions
Preliminary results have been shown on the first observation and measurements of jets and missing transverse energy in the ATLAS calorimeters at both $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV. A reasonable agreement is found in basic kinematic distributions of jets. Various jet properties have been studied in the data that characterize or impact the jet reconstruction and calibration and compared to Monte Carlo simulations of the full ATLAS detector. A slightly higher soft activity is found around jets in the data, even though this effect is smaller as the $p_T$ of the jet considered increases. This effect is also observable in the transverse profile of the jet, which points to wider jets in the data than in the Monte Carlo simulation. The measured distributions of charged tracks inside the jets also indicates a small excess in data compared to the Monte Carlo simulation. Such differences could be attributed to deficiencies on the current understanding of the detector response, the noise description, or the modeling of soft hadronic activity and fragmentation processes in the Monte Carlo simulations. A better agreement is found in the energies deposited in the different longitudinal segments of the calorimeter. These results will be considered in the future tuning of the Monte Carlo generators for ATLAS. The inputs to the different calibration schemes have also been shown to be in reasonable agreement in the data and the Monte Carlo simulation. Certain corrections that are part of the different calibration schemes have been validated directly in the data showing also good agreement. These are encouraging steps towards the successful commissioning of jet calibration in ATLAS and establishing a jet energy scale uncertainty for the different calibration schemes.

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