Local hadron calibration with ATLAS

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Abstract.

The method of Local Hadron Calibration is used in ATLAS as one of the two major calibration schemes for the reconstruction of jets and missing transverse energy. The method starts from noise suppressed clusters and corrects them for non-compensation effects and for losses due to noise threshold and dead material. Jets are reconstructed using the calibrated clusters and are then corrected for out of cone effects. The performance of the corrections applied to the calorimeter clusters is tested with detailed GEANT4 information. Results obtained with this procedure are discussed both for single pion simulations and for di-jet simulations. The calibration scheme is validated on data, by comparing the calibrated cluster energy in data with Monte Carlo simulations. Preliminary results obtained with \( \sqrt{s} = 900 \) GeV collision data are presented. The agreement between data and Monte Carlo is within 5% for the final cluster scale.

1. Introduction

Precise measurement of the energies of jets is fundamental for many different physics analyses foreseen with the ATLAS detector [1]. In particular the jet energy scale uncertainty is one of the largest systematic errors on the measurement of the top quark mass and of the inclusive jet cross section, which are important steps towards new physics searches.

Jet calibration can be generally viewed as consisting of two phases. In the first phase the measured signal is corrected for detector effects and out of cone effects. This calibrates the measured jet to the particle level, which is defined as the corresponding jet obtained by running the same jet algorithm on the final state particles. In the second phase the jet energy is calibrated to the parton level.

The local hadron calibration is a complete approach to the first phase of jet calibration. In this scheme detector effects are corrected at cluster level, before any jet reconstruction. This provides a consistent calibration of all calorimeter signals, which can be used as input to missing transverse energy reconstruction as well. Clusters are obtained from calorimeter cells using a three dimensional topological algorithm, which suppresses noisy cells [2]. The energy of the input clusters is defined to be at the electromagnetic scale (EM) and includes compensation for sampling fraction losses optimized for electrons and photons. The local hadron calibration consists of four steps of corrections that are based on cluster shape variables, cluster energy and cluster pseudo-rapidity \( \eta = -\ln(\tan(\theta/2)) \), \( \theta \) being the angle from the beam axis) [3]:

(i) classification step: clusters are classified as stemming mainly from an electromagnetic or an
hadronic type of shower, each of the next three corrections differ for electromagnetic and for hadronic clusters;

(ii) hadronic weight step (W): clusters that are classified as hadronic receive a correction that recovers for invisible and escaped energy;

(iii) out of cluster step (OOC): clusters are corrected for the energy discarded by the clustering algorithm because of noise thresholds;

(iv) dead material step (DM): clusters are corrected for the energy lost outside the active calorimeter volumes.

The energy scale of jets reconstructed from local hadron calibrated clusters is still lower than the energy scale of jets from Monte Carlo final state particles, as shown in Figure 1. Cluster corrections cannot account for the so called out of cone effects, like energy lost by particle never reaching the calorimeter or jet-algorithm inefficiencies. In order to take into account these effects, dedicated jet level corrections, based on jet shape variables, jet energy and jet pseudo-rapidity have been developed. After this final calibration step the energy of the jets is correctly reconstructed with respect to the final state particle jets within less than 1% [4].

2. Local correction performance

A comparison to the particle jet level is not sufficient to evaluate the performance of the cluster corrections. In order to be able to disentangle effects due to the different calibration steps it is necessary to define a true cluster energy, for each of the cluster energy scales. This definition is possible using GEANT4 [5] shower simulations. In the ATLAS simulation framework GEANT4 information is organized in terms of so called calibration hits. A calibration hit can be seen as a true calorimeter cell or as true dead material deposit, depending on where the energy is released. The calibration hit energy is accessible for both active (liquid argon, scintillator) and inactive (absorber) material. For each reconstructed cluster the true cluster energy is then defined:

- at the hadronic scale as the sum of the energy of the calibration hits inside the cluster;
- at the out of cluster scale as the sum of the energy of the calibration hits near to the cluster, not included into any other cluster and deposited inside the active calorimeter regions;
- at the dead material scale as the sum of the energy of calibration hits near to the cluster, deposited in dead material regions;

The assignment of calibration hits to the out of cluster and dead material scale is performed via an algorithm that takes into account the proximity of the calibration hit to the cluster in \( \eta - \phi \) space and the energy of the cluster (\( \phi \) being the azimuthal angle measured around the
Figure 2. Linearity for the three cluster calibration correction steps with respect to true cluster energy, for single pion simulation. The hadronic weighting step $L_W$ is shown in blue, the out of cluster step $L_{OOC}$ in green and the dead material step $L_{DM}$ in red. The performance is shown for the central region.

Figure 3. Linearity for the three cluster calibration correction steps with respect to true cluster energy, for di-jet simulation. The hadronic weighting step $L_W$ is shown in blue, the out of cluster step $L_{OOC}$ in green and the dead material step $L_{DM}$ in red. The performance is shown for the central region.

beam axis). The linearity performance (L) of the cluster corrections can be studied based on the following quantities:

\[
L_W = \frac{R_W}{T_W} \quad L_{OOC} = \frac{R_{OOC} + T_W}{T_{OOC} + T_W} \quad L_{DM} = \frac{R_{DM} + T_{OOC}T_W}{T_{DM} + T_{OOC} + T_W}
\]

(1)

where $R_X$ is the reconstructed energy from correction X and $T_X$ is the energy that should have been reconstructed from correction X, as assigned by the calibration hit algorithm. In case of perfect calibration ($R_X = T_X$), the linearity terms in Equation 1 should be equal to unity. Deviation from this value are dependent on the reconstructed energy contribution $R_X$ under investigation (W or OOC or DM separately).

2.1. Single pion simulations
The local hadron calibration corrections are developed using single pion simulations [3]. In this type of events the reconstructed energy should match the initial energy of the pion, without any out of cone effects. At the same time all the clusters in the event belong to the same initial particle, without any ambiguities. For these reasons, single pion events represent the perfect benchmark for local cluster corrections.

Using the calibration hit true reference it is possible to study the linearity (L) of each correction separately, where the $R_X$ and $T_X$ terms of Equation 1 are calculated as a sum over all the clusters in the event. The performance for single pion simulations is shown in Figure 2 for the central region of the detector. All of the three cluster corrections perform very well, within residual non-linearities of few percent for low pion energies. This is because in the low energy regime the correlation between the lost and the deposited energy is more difficult to establish.

2.2. Di-jet simulations
The final goal of the local hadron calibration approach is the calibration of jets in high energy collisions. In order to study the performance of the cluster corrections in a typical collision event, $2 \rightarrow 2$ processes simulated with Pythia [6] have been used. In this case the terms $R_X$ and
T_{X} of Equation 1 are calculated as a sum over the clusters belonging to a jet, as chosen by the Anti-K_{T} algorithm with R=0.4 [7]. As shown in Figure 3 for the central region, the hadronic weight corrections perform very well for all energies, while the out of cluster (in green) and the dead material (red) corrections show a non linearity of up to 10 % for low jet energies. This is mainly due to the fact that the definition of the true out of cluster and dead material energy for clusters includes calibration hit energy due to lost particles, that do not contribute to the cluster formation. In order to remove this ambiguity, a new tool that correlates each calibration hit to the parent particle has been developed and will be used to refine the true cluster energy definition.

3. Validation on data

The first step towards the validation of the local hadron calibration on data is to compare the effect of the cluster corrections in data and Monte Carlo. For this purpose ATLAS data collected in December 2009 at a center of mass energy of $\sqrt{s} = 900$ GeV have been used [4]. Events are selected using the minimum bias trigger scintillators (MBTS), installed on both sides of the ATLAS detector and covering the pseudo-rapidity region $2.09 < |\eta| < 3.84$. Offline cuts on the MBTS hits and calorimeter timing (as detailed in [8]) are used to remove contamination from events produced by the beam halo, by the interaction of beam protons with the gas in the beam pipe or by cosmic muons. Only runs in which the calorimeter and the inner detector were fully operational and the solenoid was on have been considered. These criteria select 330810 events.

Data are compared to Monte Carlo (MC) simulations of non-diffractive, single and double diffractive processes in proton-proton collisions at a center of mass energy of $\sqrt{s} = 900$ GeV. Pythia with ATLAS MC09 tune [9] is used as generator, while the detector response is simulated.
As first step the energy of clusters at the electromagnetic scale has been compared between data and Monte Carlo. The ratio between the mean cluster energy in data and in MC for the whole pseudo-rapidity range is shown in Figure 4 for clusters with transverse energy larger than 500 MeV. The overall agreement is very good: ≈ 2% in the central region and ≈ 5% in the end-cap and forward region. Further studies are needed to understand the residual differences.

In order to validate the various calibration steps, for all clusters the ratio of the calibrated and the uncalibrated energy is considered. This procedure reduces the dependence on the absolute energy difference before calibration between data and Monte Carlo. The average of this ratio is shown versus pseudo-rapidity in Figure 5 for the hadronic weight corrections. The same study is shown in Figure 6 for clusters calibrated with hadronic and out of cluster corrections. Finally the same study is performed after hadronic weight and out of cluster and dead material corrections are applied to the clusters, as shown in Figure 7. Only clusters with a transverse energy larger than 500 MeV are considered. Since the selected minimum bias sample is dominated by low energy clusters, the corrections applied for energy lost outside clusters and in dead material are large with respect to the hadronic compensation weights. The ratio between data and Monte Carlo is shown at the bottom of Figures 5, 6 and 7. The value of the corrections is larger in data than in Monte Carlo simulations by ≈ 2% in the central region of the detector. This difference is likely due to incorrect noise description in the simulation, which is already under investigation. For the out of cluster and dead material corrections around $|\eta| = 3.1$ the data and

**Figure 5.** Mean of the ratio of the cluster energy calibrated with hadronic weights (W) and out of cluster corrections (OOC) over the energy before calibration in data (points) and Monte Carlo simulations (histogram), versus $\eta$. Only clusters with transverse energy larger than 500 MeV are considered. The lower plot shows the ratio of data over Monte Carlo simulations.

**Figure 6.** Mean of the ratio of the cluster energy calibrated with hadronic weights (W) and out of cluster corrections (OOC) over the energy before calibration in data (points) and Monte Carlo simulations (histogram), versus $\eta$. Only clusters with transverse energy larger than 500 MeV are considered. The lower plot shows the ratio of data over Monte Carlo simulations.

**Figure 7.** Mean of the ratio of the cluster energy calibrated with hadronic weights (W), out of cluster corrections (OOC) and dead material corrections (DM) over the energy before calibration in data (points) and Monte Carlo simulations (histogram), versus $\eta$. Only clusters with transverse energy larger than 500 MeV are considered. The lower plot shows the ratio of data over Monte Carlo simulation.
the simulation show a difference of $\approx 4\%$. This region corresponds to the transition between the end-cap and the forward calorimeter, where a large amount of dead material due to the forward calorimeter support structure is present. For this reason incorrect dead material description in the simulation is the likely cause of the disagreement, which can be evaluated and corrected with more data available.

4. Conclusions
The local hadron calibration is a complete method to calibrate the energy of jets to the particle jet level. It consists of a set of cluster corrections which are applied prior to the jet reconstruction and of jet level corrections dedicated to out of cone effects.

The cluster corrections have been discussed in detail. Their performance, in terms of linearity with respect to the true cluster energy, has been shown both for the single pion simulation case and for the di-jet simulation case. In both cases the linearity is near to unity for the hadronic weight corrections, while out of cluster and dead material corrections show a discrepancy of the order of few % for single pions and of 10 % for the di-jets. In order to understand this discrepancies a refined definition of the true cluster energy is in preparation, with the use of information on the origin of each true energy deposit in the simulation.

The validation of the cluster corrections on data has started using ATLAS data collected in December 2009 at a center of mass energy of $\sqrt{s} = 900$ GeV. Data have been compared to Monte Carlo simulations of non diffractive, single and double diffractive processes. For the uncalibrated scale the overall agreement is very good: $\approx 2\%$ in the central region and $\approx 5\%$ in the end-cap and forward region. The agreement for the ratio of the calibrated scale to the uncalibrated scale is very good: $\approx 2\%$ for most $\eta$ regions, and up to $\approx 4\%$ for the whole $\eta$ range.

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