

# Tests of Local Hadron Calibration Approaches in ATLAS Combined Beam Tests

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**Abstract.** Three ATLAS calorimeters in the region of the forward crack at  $|\eta| = 3.2$  in the nominal ATLAS setup and a typical section of the two barrel calorimeters at  $|\eta| = 0.45$  of ATLAS have been exposed to combined beam tests with single electrons and pions. Detailed shower shape studies of electrons and pions with comparisons to various Geant4 based simulations utilizing different physics lists are presented for the endcap beam test. The local hadron calibration approach as used in the full Atlas setup has been applied to the endcap beam test data. An extension of it using layer correlations has been tested with the barrel test beam data. Both methods utilize modular correction steps based on shower shape variables to correct for invisible energy inside the reconstructed clusters in the calorimeters (compensation) and for lost energy deposits outside of the reconstructed clusters (dead material and out-of-cluster deposits). Results for both methods and comparisons to Monte Carlo simulations are presented.

## 1. Introduction

ATLAS [1] is a multi purpose detector that operates at the Large Hadron Collider at CERN aimed at the study of proton-proton collisions at a nominal center of mass energy of 14 TeV. One of the main goals of the experiment is the discovery of the Higgs boson.

The ATLAS calorimeters are sampling, non-compensating devices designed to address the large dynamic energy range requirement going from 30 MeV up to 3 TeV and provide hermetic coverage from  $-4.9$  to  $+4.9$  in units of pseudorapidity  $\eta$ . The electromagnetic (*em*) parts feature liquid argon (LAr) calorimeters with lead as absorber material in the central and endcap regions and copper in the forward region. The hadronic part consists of a steel-scintillator Tile calorimeter in the central region, LAr-copper in the endcap and LAr-tungsten in the forward regions respectively.

In the past, performance studies for electrons and hadrons in beam tests have been carried out for individual setups of the electromagnetic and hadronic calorimeter modules. Two combined tests in 2004 of the ATLAS barrel and endcap regions closed this extensive program:

- The 2004 Combined Beam Test was done in the endcap region ( $\eta \sim 3.2$ ) in a particularly complex transition zone between the endcap and forward calorimeters.

- The 2004 Combined Beam Test in the barrel region ( $\eta \sim 0.45$ ) included a full slice of the ATLAS Barrel region, including the LAr and Tile calorimeters.

These setups were kept as close as technically possible to the ATLAS geometry, both with respect to the calorimeter modules, the support structure and the dead material distribution.

The goal of this study is a validation with combined beam tests data of the ATLAS strategy to use hadron calibration based on simulations to reconstruct the correct energy of hadrons.

## 2. Hadron calibration technique

The detection of particles that are subject to the strong interaction is more sophisticated than the detection of particles that develop electromagnetic showers only. There are several factors which are responsible for non-linearity and degradation of energy resolution of hadrons.

The ATLAS calorimeter system is non-compensating, i.e. it generates smaller signals per unit of incoming energy for hadrons than for electrons ( $e/h \sim 1.3$ ). Some energy losses (like binding energy losses in post-collision nuclear break-up) stay invisible and do not contribute to the signal. Additional imperfections in the reconstruction are imposed by energy deposits in the material outside of active zones of electromagnetic and hadronic calorimeters, i.e. in the dead material. These include cryostat walls, the magnetic coil, mechanical support structures, all material of the ATLAS Inner Detector and Muon System. Finally, some energy is deposited inside calorimeters but outside of any reconstructed object due to imperfect energy collection of the clustering algorithm.

In this study we consider two software compensation techniques to calibrate the detector response to hadrons: local hadron calibration (LHC) which is used in ATLAS, and layer correlation (LC). Both approaches rely on simulations, by establishing correlations between Monte Carlo truth energy deposits (energy in the dead material, invisible energy) with shower variables which can be measured in the experiment.

### 2.1. Local Hadron Calibration

The main goal of the local hadron calibration [2] is to provide jet algorithms with constituents — calibrated clusters with energies equal to their corresponding stable particle energies. The key feature of the approach is to factorize corrections in several sequential steps to disentangle detector effects of different types and to correct them independently.

The starting point of the calibration is the topological clustering [3] in the calorimeter cells which have been calibrated at the electromagnetic scale. Cluster shape variables are then used to classify clusters as having electromagnetic or hadronic origin. Hadronic clusters have smaller cell energy densities and larger depth in the calorimeter in comparison to electromagnetic ones. The hadron-like clusters are subject to a cell weighting procedure to compensate for the lower response of the calorimeter to hadronic energy deposits, while clusters classified as electromagnetic are kept at the original scale. In the next step out-of-cluster corrections are applied for the lost energy deposited in calorimeter cells outside of reconstructed clusters, i.e. in the tails of hadronic or electromagnetic showers rejected due to noise cuts. Finally dead material corrections are applied on the cluster level to account for energy deposits outside of active calorimeter volumes, e.g. in the cryostat, the magnetic coil and calorimeter inter-modular cracks.

### 2.2. Layer correlation method

The layer correlation technique [7] is an alternative approach to the standard ATLAS Local Hadron Calibration which has been used in the analysis of beam test data in the barrel region. It defines the total pion energy as the sum of clustered energy in 7 calorimeter layers of the combined electromagnetic and hadronic section. The event-by-event layer energy corrections

are derived as a function of a specific pair of linear combinations of layer energies which account most for the shower fluctuation.

The selection of such combinations is done using a principal component analysis. An event is regarded as a point in the 7-dimensional vector space of calorimeter layer energy deposits. Its coordinates can be expressed in a new basis of eigenvectors of the covariance matrix between these layers. Eigenvectors are ordered by decreasing eigenvalue, meaning that the projections along the first few eigenvectors contain most of the information on event-by-event longitudinal shower fluctuations. These projections are used as input to build two-dimensional lookup tables, containing compensation weights to correct for the non-linear response of the calorimeters to hadrons and weights to correct for energy losses in the dead material.

### 3. Analysis of beam test data in the endcap region

The beam test in the particularly difficult forward region  $2.5 < |\eta| < 4.0$  (the transition from the electromagnetic endcap calorimeter EMEC and hadronic endcap calorimeter HEC to the forward calorimeter FCal) was carried out in 2004 [4] in the CERN SPS H6 beam line.

The main elements of the setup are: beam instrumentation to measure the impact position and angle of beam particles, the liquid argon (LAr) cryostat with calorimeter modules and a tail-catcher to measure any leakage beyond the calorimeter modules. The load in the LAr cryostat consists of the inner section of one EMEC module (in  $\phi$  1/8 of the full EMEC wheel), eight front wheel HEC modules (8/32 of the full wheel), eight purpose-built rear wheel HEC modules and the FCal modules corresponding to the first 2 samplings of one quadrant.

In the two run periods more than 4000 data runs have been taken with electrons, pions or muons in the energy range  $6 \text{ GeV} \leq E \leq 200 \text{ GeV}$  with about 80 million triggers in total. Energy scans have been taken at a standard set of impact points. In addition, horizontal and vertical scans have been done at fixed particle energies.

To compare data with Monte Carlo (MC) expectation the simulation code Geant4 [5], version 9.2 has been used. From the physics lists for hadronic shower simulations available in Geant4 the physics list QGSP\_BERT and FTFP\_BERT have been used. Reconstruction has been done using standard ATLAS software: 3d topological clustering for the reconstruction of the energy response at *em* scale, and local hadron calibration for the calibration to the final hadronic scale.

#### 3.1. Energy response and shower shape studies.

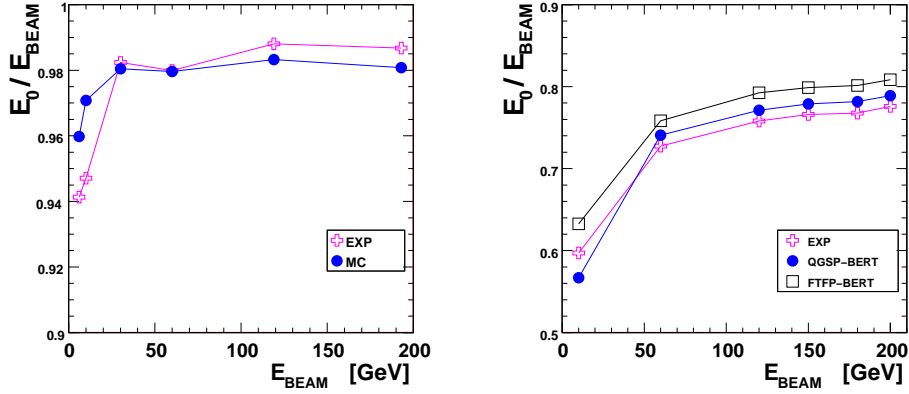
Evaluation of relevant calorimeter performance parameters like the energy dependence of the response, resolution and shower shape in experiment and MC is crucial for any simulation based hadron calibration scheme.

Figure 1 (left) shows the average ratio of reconstructed energy to the beam energy as a function of the beam energy for electrons in the endcap area. The response is well described by MC. The final *em* scale is at the level of 98% of the beam energy (for  $E > 50 \text{ GeV}$ ) due to energy lost in dead material in front of the active calorimeter.

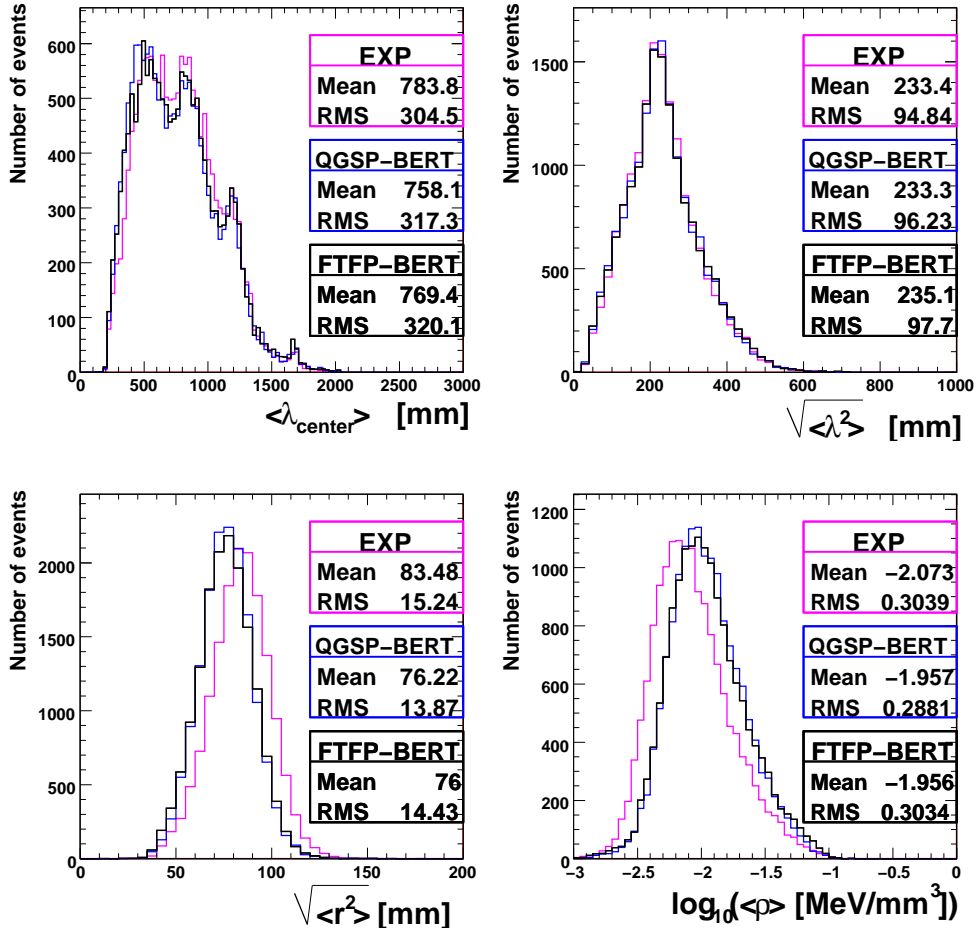
The response as function of energy has been studied for pions using energy deposits on electromagnetic scale (Fig.1, right). At the electromagnetic scale the energy is at the level of about 50-80% of the beam energy. This ratio increases with the beam energy due to the increasing electromagnetic fraction in hadronic showers. The expectations from simulation given by two physics lists are shown as well.

Additional studies show that the MC predicts a larger signal in the electromagnetic sections and a smaller one in the hadronic sections compared to the data. The FTFP\_BERT physics list describes the sharing of energy between longitudinal layers slightly better than the QGSP\_BERT list.

Several typical shower shape parameters, describing shower depth, length, width and average energy density, have been studied using charged pions at a fixed energy of 200 GeV (Fig. 2).



**Figure 1.** Energy response as a function of beam energy for electrons (left). Energy response at  $em$  scale as a function of beam energy for charged pions (right).



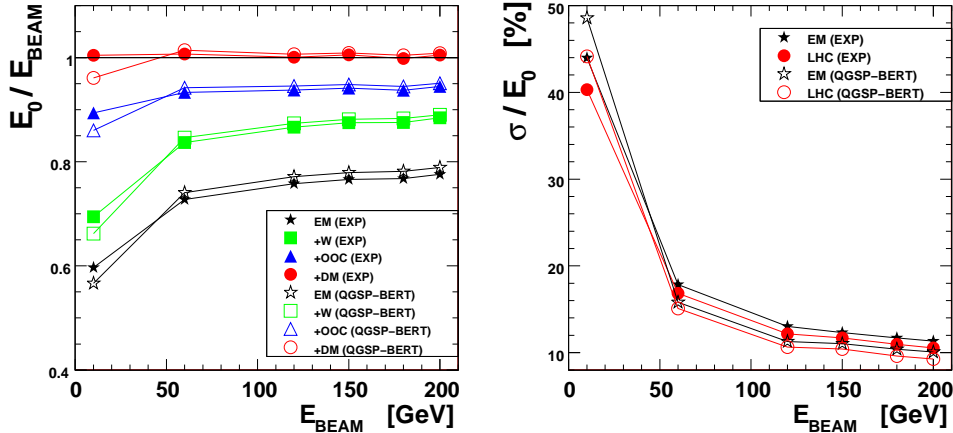
**Figure 2.** Shower shape parameters for 200 GeV charged pion: shower depth, length, width and energy density.

As results from the comparison of the simulations with the data we conclude:

- The total energy response is overestimated in MC: FTFP\_BERT predicts +4%, QGSP\_BERT predicts +2% more energy than the experimental data.
- Showers start earlier in MC, seen as larger energy deposition in electromagnetic calorimeter and smaller shower depth (FTFP\_BERT describes data slightly better than QGSP\_BERT).
- We observe more compact shower sizes in MC for both physics lists, seen as smaller shower width and larger average shower density.

### 3.2. Performance of local hadron calibration for pions.

The linearity in the endcap region as a function of pion energy after successively applying the correction steps is shown in Fig. 3 (left). Full markers indicate experimental data, while open markers show simulation results with the QGSP\_BERT physics list. Each correction step — weighting, out-of-cluster, dead material corrections — makes the response more linear. After the final step, at hadronic scale, the linearity in the data and simulation is recovered within 2%, except at low energies. The energy resolution at  $em$  scale and at hadronic scale as a function of energy is shown in Fig. 3 (right). The simulation in comparison to data predicts a better resolution by about 20%. The resolution is improving on the level 5-10% after applying the hadron calibration in both, data and MC. Poor energy resolution for 10 GeV charged pions is explained by the relatively large contribution of electronics noise in reconstructed clusters. The moderate improvement in the resolution could be explained by the usage of standard ATLAS calibration constants rather than beam test specific ones, not accounting for limited acceptance and difference in dead material description.



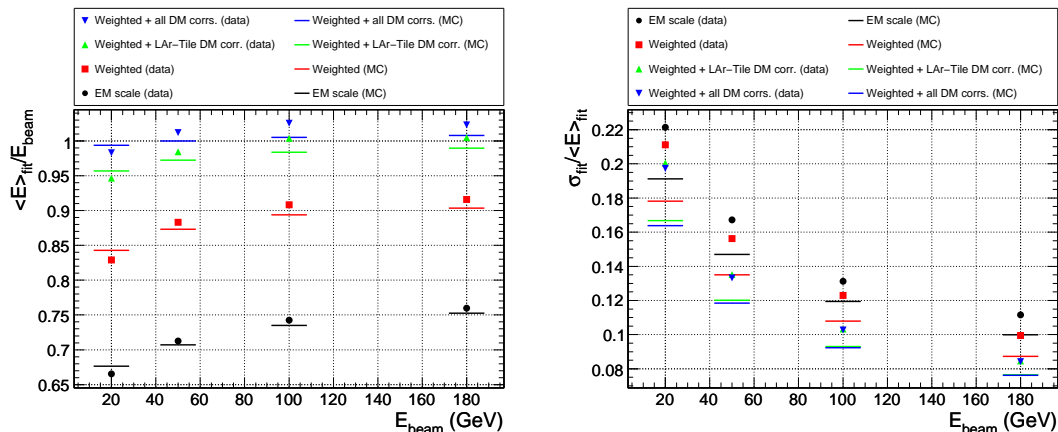
**Figure 3.** Energy dependence of the response for MC and data after each step of local hadron calibration (left). Energy resolution at  $em$  scale and after applying of LHC (right).

## 4. Analysis of beam test data in barrel region

The 2004 Barrel Combined Beam Test [6] was composed of a full slice of the ATLAS Barrel region, including the pixel detector, the silicon strip semiconductor tracker (SCT), the transition radiation tracker (TRT), the LAr and Tile calorimeters and the muon spectrometer. In addition, special beam-line detectors were installed to monitor the beam position and reject background events. The setup was exposed to beams of particles (pions, protons, electrons and muons) in the energy range 1 to 350 GeV in the CERN SPS H8 beam line. The calorimeters were positioned so that the beam impact angle corresponded to a pseudorapidity  $\eta = 0.45$  of the ATLAS detector.

#### 4.1. Linearity and resolution for the LC scheme

The performance for the fully corrected energy reconstruction is assessed in terms of linearity (Fig. 4, left) and the resolution (Fig. 4, right). The linearity and resolution are shown - first - at the electromagnetic scale - then - after applying the corrections: compensation weights, the LAr-Tile dead material correction, and finally after applying all corrections.



**Figure 4.** Linearity (left) and resolution (right) of reconstructed energy as a function of beam energy when successively applying the different parts of correction. Data (markers) and MC simulation (horizontal lines) are shown.

After all corrections, the linearity is recovered within 2% for beam energies above 50 GeV (3% for 20 GeV). The improvement in relative resolution when going from the electromagnetic scale to applying all corrections is about 17% to 20% for the data and 17% to 29% in simulation.

## 5. Conclusion

Two simulation based methods for the calibration of the calorimeter response to hadrons, local hadron calibration and layer correlation method, were studied with data of combined beam tests for the ATLAS endcap and barrel regions. Both methods were able to reconstruct the incoming pion energy within 3% in the energy range 20 – 200 GeV. The energy resolution is improved by about 20% in barrel region (LC method). In the endcap region (LHC method) it is improving by 10%, new beam test specific (rather than the ATLAS specific) correction constants have to be applied to reach the full performance.

## References

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