Validation of the ATLAS hadronic calibration with the LAr End-Cap beam tests data

Teresa Barillari
Max-Planck-Inst. fuer Physik Werner-Heisenberg-Institut, Foehringer Ring 6, D-80805 Muenchen, Germany
E-mail: barilla@mppmu.mpg.de

Abstract. The high granularity of the ATLAS calorimeter and the large number of expected particles per event require a clustering algorithm that is able to suppress noise and pile-up efficiently. Therefore the cluster reconstruction is the essential first step in the hadronic calibration. The identification of electromagnetic components within a hadronic cluster using cluster shape variables is the next step in the hadronic calibration procedure. Finally the energy density of individual cells is used to assign the proper weight to correct for the invisible energy deposits of hadrons due to the non-compensating nature of the ATLAS calorimeter and to correct for energy losses in material non instrumented with read-out.

The weighting scheme employs the energy density in individual cells. Therefore the validation of the monte carlo simulation, which is used to define the weighting parameters and energy correction algorithms, is an essential step in the hadronic calibration procedure.

Pion data, obtained in a beam test corresponding to the pseudorapidity region $2.5 < |\eta| < 4.0$ in ATLAS and in the energy range $40 \text{ GeV} \leq E \leq 200 \text{ GeV}$, have been compared with monte carlo simulations, using the full ATLAS hadronic calibration procedure.

1. Introduction
The primary goal of the ATLAS calorimeter is to measure the energy and the direction of the electrons, photons and jets. A good calorimeter performance is achieved by also having a good missing transverse energy and particle identification determination.

The beam tests [1] in the particularly difficult forward region $2.5 < |\eta| < 4.0$ (the transition from the electromagnetic end-cap calorimeter EMEC [2] and hadronic endcap calorimeter HEC [3] [4] to the forward calorimeter FCal [5]) was carried out in 2004 in the H6 beam-line at the CERN SPS which provides hadrons, electrons or muons in different energy range.

The beam test set-up has been chosen to be as close as possible to the final ATLAS detector, both with respect to the calorimeter modules, the support structures, and the dead material distribution. The set-up was also reproducing the ATLAS projective geometry but only at one $|\eta|$ point, and not over the entire $|\eta|$ region. The load in the liquid argon (LAr) cryostat [1] consisted of the inner section of the EMEC module, eight specially constructed front wheel HEC modules, eight purpose-built rear wheel HEC modules and the FCal modules. Limited by cryostat dimensions the depth of the rear wheel HEC modules was half of the ATLAS modules.

The goal of the study is to obtain the hadronic calibration in the forward region $2.5 < |\eta| < 4.0$, including corrections for dead material effects. The validation of the monte carlo (MC)
simulation in ATLAS using beam test data is an important step in the calibration studies. The default ATLAS hadronic calibration procedure is based on MC simulations.

In the following the initial studies done to validate the Geant4 monte carlo simulation using the ATLAS hadronic calibration procedure [6] with the 2004 EMEC-HEC-FCAL beam test data [1] are presented.

2. Data and monte carlo samples
During the beam tests more than 4000 runs have been taken with electrons, pions or muons in the energy range \(6 \text{ GeV} \leq E \leq 200 \text{ GeV}\). Energy scans have been taken at a standard set of impact points. The impact points used in the analysis here presented, point D and point H for the EMEC/HEC and FCal regions, correspond to \(\eta = 2.8\) and \(\eta = 3.65\) in ATLAS. Five pion runs in the energy range \(40 \text{ GeV} \leq E \leq 200 \text{ GeV}\) have been used to study the EMEC/HEC region and other five pion runs in the same energy range were used to test the FCal region. Six of these runs are negative pion data at 120, 180 and 200 GeV, and four are positive pion runs at 40 and 60 GeV. The beam test MC simulation used in the analysis consists of charged and neutral single pions obtained using Geant4 version 8.3 and the hadronic physics list QGSP_EMV. The default ATLAS hadronic calibration corrections, weights, dead material corrections etc., have been applied to the beam test monte carlo simulation.

3. Local hadronic calibration in ATLAS
The local hadronic calibration [6] [7] is one of the calibration approaches studied in the ATLAS collaboration. It consists of four main calibration steps. First the cluster are reconstructed in the calorimeters with an algorithm to optimize noise suppression and particle separation. Shower shape variables and other cluster characteristics are used to classify the clusters as hadronic or electromagnetic. The hadronic clusters are then subject to a cell weighting procedure to compensate the different response to hadrons compared to electrons. After the weighting, out-of-cluster corrections are applied to the clusters to correct for the energy deposited in the calorimeter but outside calibrated clusters. Finally the dead-material corrections are applied on both electromagnetic and and hadronic clusters to compensate for the energy losses in materials outside the calorimeter.

4. Performance of the hadronic calibration
The application of the ATLAS local hadronic calibration scheme to beam tests data, pions at 200 GeV in the EMEC/HEC region, is shown in figure 1. The reconstructed energy over the nominal beam energy \((E_{Reco}/E_\pi)\) distribution at electromagnetic scale (EM) is indicated in the figure by the open triangles and the dash-dotted line Gaussian fit. The reconstructed energy distribution after applying the weighting step is indicated by the open circles and its dotted line Gaussian fit. The full triangles and the dashed line Gaussian fit in the figure show the distribution obtained after adding the out-of-cluster correction (OOCC). The reconstructed energy after all corrections, included the dead material (DM) corrections, is shown by the full circles and the full line Gaussian fit. Figure 1 shows that the linearity \((E_{Mean}/E_\pi)\) computed as the mean of the Gaussian fitted to the energy distribution \((E_{Mean})\) divided by the pion beam energy \((E_\pi)\), improves at every step: at EM scale the linearity is 75.95%, after weighting it is 87.44%, after adding the OOCC the linearity is 90.98%, and after all corrections the \(E_{Mean}/E_\pi\) reaches a value of 99.92%. The resolution of the energy computed as \(\sigma/E_{Mean}\), at EM scale is 11.64%, after applying weighting the resolution gets to a value of 10.1%, after OOCC it is 10.0%, and after applying the DM correction the resolution is 9.9%. We see here that an improvement of the resolution is achieved after applying weighting corrections.
5. Linearity and resolution of data and simulation

The linearity in the EMEC/HEC region at EM scale and after all the calibration corrections for data and MC simulation is shown in figure 2 (left plot). The linearity values are given in table 1. The full circles in this figure indicate data at EM scale, open squares show the simulation results obtained with Geant4 QGSP_EMV also at EM scale, the full triangles and the open stars are here the data and the MC results obtained after calibration. This figure shows an overall agreement (within 3%) between data and monte carlo simulation.

The linearities values obtained in the FCal region for data and MC at EM scale and after all calibration corrections are given in table 1. The values in this table show that in the FCal region at higher beam energies the monte carlo has about 1% better linearity than the data. It should be emphasized here that the dead material in front of the FCal in the beam test set-up [1] is different than in ATLAS, this difference has not being corrected yet in the beam test monte carlo simulation.

The right plot in figure 2 shows the resolution obtained with data and monte carlo at EM scale and after the calibration corrections for the EMEC/HEC region. The resolution values are given in table 1. The symbols in this figure are the same as the ones used in the linearity plot. This plot shows that in the EMEC/HEC region the resolution improves after all calibration corrections, and the ATLAS hadronic calibration corrections are here working.
The resolution values obtained in the FCal region for data and MC at EM scale and after all calibration corrections are given in table 1. The values in this table show that in the FCal region, the resolution improves more in the data than in the Monte Carlo. The differences in the resolution values observed here, like in the linearity case, are due to the fact that the beam test analysis is using the default ATLAS calibration corrections. ATLAS is also using a Monte Carlo simulation, Geant4 QGSP, that doesn’t describe well the hadronic cascade model, Geant4 QGSP.BERTINI need to be used instead. Once the new beam test Monte Carlo simulation is available, with better weights, better beam tests DM corrections, and better hadronic cascade simulation, further improvements can be done for the whole hadronic calibration procedure.

Table 1. Linearities \((E_{\text{Mean}}/E_\pi)\) and resolutions \((\sigma/E_{\text{Mean}})\) values in percentage obtained in the EMEC/HEC (first 5 rows) and in the FCal (last 5 rows) regions for data and MC at EM scale and after calibration corrections (Calib.). \(E_\pi\) is the nominal beam energy. The uncertainties values here are the statistical errors from the Gaussian fits.

| \(E_\pi\) (GeV) | \(E^\text{Data}_{\text{Mean}}/E_\pi\) EM | \(E^\text{MC}_{\text{Mean}}/E_\pi\) EM | \(E^\text{Data}_{\text{Mean}}/E_\pi\) Calib. | \(E^\text{MC}_{\text{Mean}}/E_\pi\) Calib. |
|----------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 40             | 70.78 ± 0.24                    | 71.73 ± 0.14                   | 98.28 ± 0.32                   | 98.13 ± 0.18                   |
| 60             | 71.40 ± 0.40                    | 72.00 ± 0.11                   | 97.63 ± 0.52                   | 97.01 ± 0.15                   |
| 120            | 74.31 ± 0.08                    | 74.69 ± 0.10                   | 98.92 ± 0.09                   | 98.65 ± 0.11                   |
| 150            | 74.90 ± 0.08                    | 75.41 ± 0.10                   | 99.49 ± 0.09                   | 98.63 ± 0.10                   |
| 200            | 75.95 ± 0.07                    | 76.25 ± 0.10                   | 99.92 ± 0.08                   | 98.67 ± 0.11                   |

| \(E_\pi\) (GeV) | \(\sigma^\text{Data}/E_{\text{Mean}}\) EM | \(\sigma^\text{MC}/E_{\text{Mean}}\) EM | \(\sigma^\text{Data}/E_{\text{Mean}}\) Calib. | \(\sigma^\text{MC}/E_{\text{Mean}}\) Calib. |
|----------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 40             | 19.83 ± 0.26                    | 18.61 ± 0.15                   | 19.23 ± 0.25                   | 17.85 ± 0.15                   |
| 60             | 16.72 ± 0.48                    | 15.62 ± 0.13                   | 15.44 ± 0.47                   | 14.76 ± 0.12                   |
| 120            | 13.14 ± 0.09                    | 12.62 ± 0.10                   | 11.93 ± 0.08                   | 12.26 ± 0.10                   |
| 150            | 12.42 ± 0.09                    | 11.97 ± 0.10                   | 10.95 ± 0.08                   | 10.08 ± 0.09                   |
| 200            | 11.56 ± 0.08                    | 11.33 ± 0.11                   | 9.95 ± 0.07                    | 9.50 ± 0.10                    |

[1] Aderholz R et al., Performance of the ATLAS liquid argon endcap calorimeter in the pseudorapidity region 2.5 < |\(\eta\)| < 4.0 in beam tests, Preprint submitted to Elsevier Science
[2] ATLAS EM end-cap collaboration, Construction, assembly and tests of the ATLAS electromagnetic end-cap calorimeter, to be published in Nucl. Instr. and Meth. A
[3] Dowler B et al. Performance of the ATLAS hadronic end-cap calorimeter in beam tests 2002 Nucl. Instr. and Meth. A 482 p94
[4] Gingrich D M et al., Construction, assembly and testing of the ATLAS hadronic end-cap calorimeter 2007 JINST 2 P05005
[5] Artamonov A et al., The ATLAS forward calorimeter, 2008 Journal of Instrumentation JINST 3 P02010
[6] Bergeaas E, et al. 2008 Topological cluster classification and weighting ATLAS-LARG-2008-006 (Geneva, CERN)
[7] Menke S, Vivarelli I 2008 Detector Level Jet Corrections ATL-COM-PHYS-2008-095 (Geneva, CERN) p35