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The ATLAS calorimeters provide precision measurements of electrons, photons, jets and missing transverse energy produced in the LHC proton-proton collisions. High granularity liquid-argon electromagnetic and hadronic sampling calorimeters are used. An iron-scintillator hadronic calorimeter surrounds the liquid-argon detectors. Results assessing the calorimeter performance obtained using cosmic ray muons are presented. The non-uniformity of the barrel electromagnetic calorimeter response is consistent at the percent level with the simulated response. The response uniformity of the hadronic calorimeter layers is at the level of 4%. The determination of the global energy scale was performed in the hadronic calorimeter with an uncertainty of ±4%.

Workshop on Discovery Physics at the LHC-KRUGER2010
Kruger National Park, Mpumalanga, South Africa
December 05 – 10, 20

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1.Introduction

The calorimeters of the ATLAS experiment [1] at LHC [2] consist of four sampling detectors with full azimuthal symmetry and coverage around the beam axis. The calorimeters closest to the beam-line are housed in three cryostats filled with liquid-argon (LAr), one barrel and two end-caps [2]. More specifically, a highly granular electromagnetic (EM) calorimeter with accordion-shaped electrodes and lead absorbers covers the pseudo rapidity range $|\eta| < 3.2$, and contains a barrel part (EMB [3], $|\eta| < 1.475$) and an end cap part (EMEC [4], $1.375 < |\eta| < 3.2$). For $|\eta| < 1.8$, a pre sampler (PS [4, 5]), consisting of an active LAr layer and installed directly in front of the EM calorimeter, provides a measurement of the energy lost upstream. Located behind the EMEC is a copper-liquid argon hadronic end cap calorimeter (HEC [6], $1.5 < |\eta| < 3.2$), and a copper/tungsten-liquid argon forward calorimeter (FCal [7]) covers the region closest to the beam at $3.1 < |\eta| < 4.9$. All the LAr detectors are segmented transversally and divided in three or four layers in depth, and correspond to a total of 182,468 readout cells.

The hadronic tile calorimeter (TileCal) [1], surrounding the LAr cryostats, is a sampling plastic-scintillator/iron detector, covering the region $|\eta| < 1.7$. It is divided into three cylindrical sections, referred to as the long barrel (LB) and extended barrels (EB). Each of the three sections is composed of 64 azimuthal segments, referred to as modules, subtending $\Delta\phi = 2\pi/64 \cong 0.0982$. The TileCal plates, made of iron or scintillating material, are placed perpendicular to the colliding beam axis and are radially staggered in depth. Two sides of the scintillating tiles are read out by wave-length shifting (WLS) fibers into two separate PMTs. By the grouping of WLS fibers to specific PMTs, the modules are segmented in z and in radial depth. Three radial segments (A, BC, D) are obtained in the LB and EB. The resulting typical cell dimensions are approximately $\Delta\eta\times\Delta\phi = 0.1 \times 0.1$ (0.2×0.1 in the last layer). TileCal comprises in total 5182 readout cells.

The uniformity of the calorimeters was determined from intensive testing of modules with electron and pion beams [8, 9]. The cosmic ray muon data collected in 2008 allowed to determine the calorimeter response uniformity in-situ. The EM calorimeter results are reported in Section 2. The uniformity of the TileCal compartments and the determination of the scale used to reconstruct the jet energy are discussed in Section 3. The conclusions are drawn in Section 4.

2.In-situ EM calorimeter performance with cosmic ray muons

The investigation of the electromagnetic barrel calorimeter uniformity using ionization signals from quasi-projective cosmic ray muons is presented in this section. Any non-uniformity in the response of the calorimeter has a direct impact on the constant term in the energy resolution; great care was taken during the construction of the detector to limit all sources of non-uniformity to the minimum achievable, aiming for a global constant term below 0.7%. The uniformity of the calorimeter was measured for three barrel production modules using electrons during beam test campaigns [8].

The cosmic ray muon Monte Carlo (MC) simulation, event selection and the calorimeter signal reconstruction are discussed in Ref. [10]. A comparison of the energy reconstructed in the first and second layers between data and Monte Carlo events is shown in Figure 1. The agreement between the data and Monte Carlo distributions is very good, both for the shape and for the absolute energy scale which differs by only 2% in the first layer and 1% in the second layer. This overall energy scale difference is corrected for in the MC in the rest of the study.
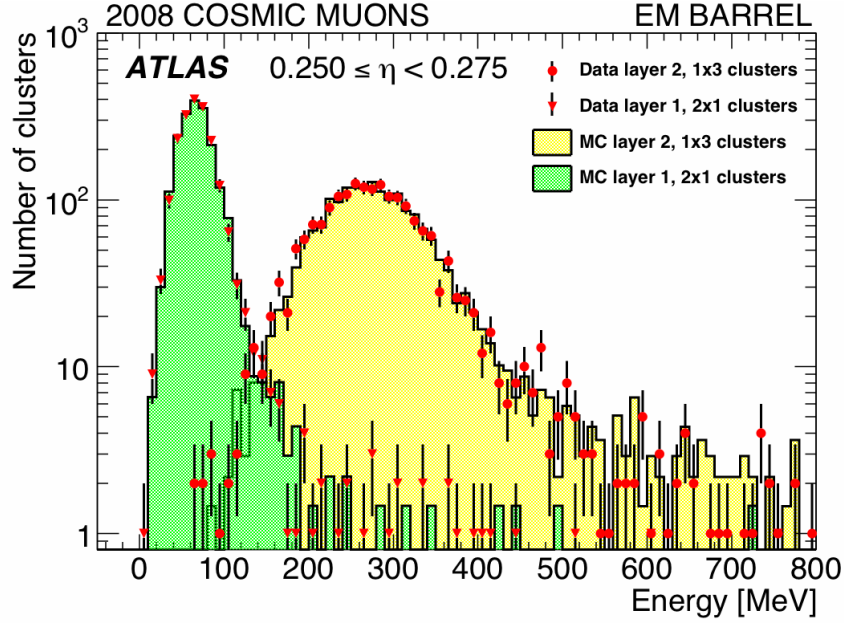
Figure 1: Energy in a 2×1 cluster [10] in the first layer of the EM barrel (histogram for Monte Carlo and triangles for data) and in a 1×3 cluster in the second layer (histogram for Monte Carlo and full circles for data) for all events
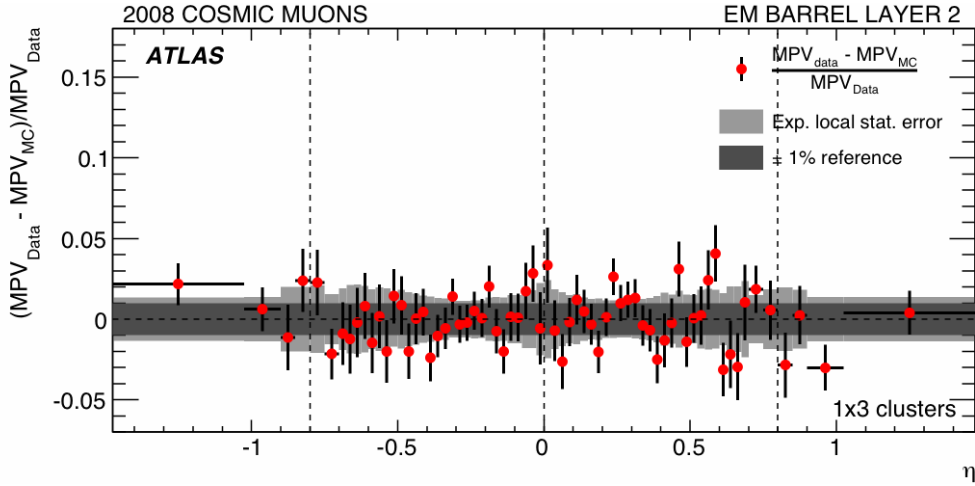

Figure 2: Measured $U_{i,meas}$ (red points) and expected U_{exp} (light grey band) cosmic ray muon energy dispersions as function of η for the second layer of the EM barrel. The dark grey band indicates a $\pm 1\%$ strip for reference.

      Given the limited statistics of the projective cosmic ray muon data, the uniformity of the response in η cannot be estimated at the cell level. A natural choice of cell combination is to integrate clusters in ϕ since the response should not vary along this direction due to the ϕ symmetry of the calorimeter. The estimation of the muon energy in each η-bin is done with a fit of the cluster energy distribution using a Landau function convoluted with a Gaussian. The Landau function accounts for fluctuations of the energy deposition in the ionization process and the Gaussian accounts for the electronic noise and possible remaining fluctuations. The most probable value (MPV) of the Landau distribution estimates the energy deposition.

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The normalized differences between the data and Monte Carlo MPVs in each η-bin i, $U_{i,meas}$ are reported in Fig. 2. They are compared to the expected bin uniformity $U_{i,exp}$ which includes only statistical uncertainty on the Landau MPV's. The response uniformity U_{meas} is given by the RMS of the normalized differences between the data and Monte Carlo MPVs in each η-bin. It should be compared to the expected uniformity, U_{exp}, which is obtained similarly [10]. A significant departure of the measured uniformity from the expected one would be a measurement of additional non uniformities $U_{\Delta}\left(U_{\Delta}^2 = U_{meas}^2 - U_{exp}^2\right)$. An upper limit is derived and yields U_{Δ} < 1.7% @ 95% CL in the first layer and U_{Δ} < 1.1% @ 95% CL in the second layer. The calorimeter response uniformity along η (averaged over ϕ) is thus consistent at the percent level with the Monte Carlo simulation and shows no significant non uniformity

3.In-situ TileCal calibration with cosmic ray muons

The response of the TileCal was studied comparing the ratio between the energy deposited in a calorimeter cell (dE) and the length of the path of the track in the cell (dx) obtained using experimental and simulated data. The event simulation and selection and the calorimeter signal reconstruction are reported in Ref. [11]. The estimator of the muon response for each TileCal cell was defined as the mean $\langle dE/dx \rangle_t$, of the dE/dx distribution truncated to the lower region containing 99% of events.

3.1Cell uniformity

Cosmic rays data were used to check the uniformity of the cell response obtained using a movable radioactive ^{137}Cs source [12]. The experimental and simulated distributions of the truncated mean of the cells of a given layer were determined. The selection criteria, especially the requirement of 100 events per cell, limit the number of measured cells to the values shown in Table 1, but still a quite representative fraction of 23% of the total cells is considered. The statistical population for the simulated and real data used for this study is identical. The observed spread is the combination of different factors: statistical fluctuations, systematic errors due to the inherent limitations of measuring the cell response with the dE/dx of cosmic ray muons, and the spread in the cell equalization.

The Monte Carlo simulation has no variation in the quality of the optical components of the calorimeter or in the channel signal shape. Such variations are present in the data but it is difficult to disentangle between the spread due to them or to the statistical fluctuations from an underlying systematic due to the measurement method. As shown in Table 1 the MC RMS in every layer is compatible with that of data. This indicates that cells are well inter calibrated within layers.

Layer	Number of cells	Fraction of Cells [%]	RMS (MeV/mm)	
			Data	MC
A	352	18	0.060	0.049
BC	421	22	0.046	0.043
D	316	38	0.052	0.048

Table 1: Uniformity at the cell level for individual radial compartments. The listed values represent the RMS of the distributions of the truncated mean *dE/dx* obtained using experimental and simulated data. The number of cells considered and the fraction of the total that they represent are also shown.

3.2 Layer inter calibration

The results discussed in Section 3.1 show that the cells are reasonably inter calibrated within a given layer. In order to check the layer uniformity, the truncated mean of a single *dE/dx* distribution for all cells in a given layer was determined. This approach allows one to estimate systematic effects [11]. The results are displayed in Fig. 3, the error bars representing the total uncertainty based on the quadratic sum of the statistical and systematic uncertainties. The differences in the cosmic ray muon response among individual layers are present even after correcting for the residual dependencies on the path length, momentum, impact angle, impact point, by considering the ratio of data over Monte Carlo. The resulting values are strongly correlated; therefore the maximum difference of 4% between the individual measurements with the cosmic ray muon data indicates the layer response discrepancy.
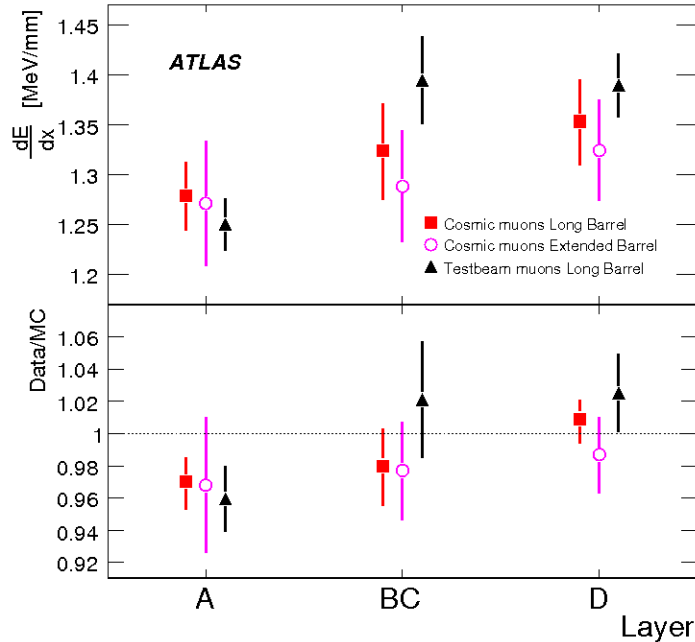

Figure 3: The truncated mean of the *dE/dx* for cosmic ray and testbeam muons shown per radial compartment and, at the bottom, compared to Monte Carlo. For the cosmic ray muon data, the results were obtained for modules at the bottom part of the calorimeter. The error bars shown combine in quadrature both the statistical and the systematic uncertainties, considering only the diagonal terms of the error matrix.

3.3 Validation of the EM scale from Test Beam

The TileCal EM energy scale used for the jet energy measurement was established at test beams after the photomultiplier gain equalization obtained with the Cs source. The numerical value for the EM scale was measured using electron beams. The last step was to reproduce the above PMT gain equalization on the full set of the Tile Calorimeter modules in the ATLAS environment and to transfer via the Cs response the EM scale factor as defined in the test beam.

The goodness of the procedure can be checked using the cosmic rays measurements. To reduce the systematic error due to the simulation of the calorimeter muon response, the ratio of the truncated means obtained using experimental and simulated cosmic rays data were compared to the corresponding ratios obtained using muons at test beams [11]. As reported in Fig. 3 and Table 2 the EM scale measured with cosmic ray muons relative to that determined at testbeam in the long barrel, amounts to 1.01, 0.96 and 0.98 for the A, BC and D layers respectively. The errors include statistical and systematic uncertainties. Since the global

uncertainties per layer are at most 4 %, these values are consistent with 1.0, showing that, within the precision limits of the analysis, the propagation of the EM scale from testbeam to ATLAS was performed successfully.

Layer	A	BC	D
$\dfrac{(Data/MC)_{\text{ Cosmic Rays}}}{(Data/MC)_{\text{ Test Beam}}}$	1.01±0.03	0.96±0.04	0.98±0.03

Table 2: Double ratios of the truncated mean of *dE/dx* obtained using experimental and simulated cosmic ray and test beam data. The systematic uncertainty corresponds to the diagonal terms of the error matrix.

4.Conclusions

The non uniformity of the EM barrel calorimeter response to cosmic ray muons is consistent at the percent level with the simulated response. This indicates that a constant term equal to 0.7% can be obtained in the expression of the electron energy resolution.

The cell response uniformity in TileCal, as measured with muon tracks, is at level of 2-3%. The EM scale is consistent with the value set at test beam with an uncertainty equal to 4%.

In the future the measurements of Z decays into two electrons, in the case of LAr, and of isolated muons, in the case of TileCal, would allow for the determination of the calorimeter uniformity and EM scale.

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