

## Readiness of the ATLAS liquid argon calorimeter for LHC collisions

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**Abstract** The ATLAS liquid argon calorimeter has been operating continuously since August 2006. At this time, only part of the calorimeter was readout, but since the beginning of 2008, all calorimeter cells have been connected to the ATLAS readout system in preparation for LHC collisions. This paper gives an overview of the liquid argon calorimeter performance measured in situ with random triggers, calibration data, cosmic muons, and LHC beam splash events. Results on the detector operation, timing perfor-

mance, electronics noise, and gain stability are presented. High energy deposits from radiative cosmic muons and beam splash events allow to check the intrinsic constant term of the energy resolution. The uniformity of the electromagnetic barrel calorimeter response along  $\eta$  (averaged over  $\phi$ ) is measured at the percent level using minimum ionizing cosmic muons. Finally, studies of electromagnetic showers from radiative muons have been used to cross-check the Monte Carlo simulation. The performance results obtained using the ATLAS readout, data acquisition, and reconstruction software indicate that the liquid argon calorimeter is well-prepared for collisions at the dawn of the LHC era.

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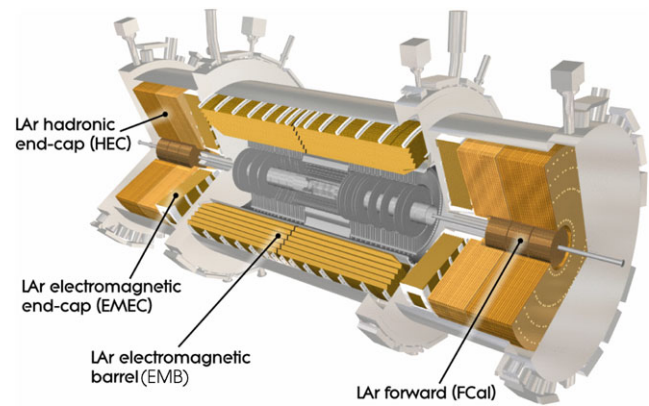
## 1 Introduction

Installation of the liquid argon (LAr) calorimeter in the ATLAS [1] experimental hall was completed in early 2008. Until recently, the expected performance of the LAr calorimeter was extrapolated from intensive testing of a few modules with electron and pion beams from 1998 to 2003 [2–10], and in 2004 of a complete ATLAS detector slice [11–13]. The 20 months separating the completion of the installation from the first LHC collisions have been used to commission the LAr calorimeter. This paper reviews the first in situ measurements of the electronics stability, the quality of the energy reconstruction, the calorimeter response uniformity and the agreement between data and the Monte Carlo simulation of electromagnetic shower shapes. The measurements are performed using calibration triggers, cosmic muons, and the first LHC beam events collected during this 20 months period. The results and the experience gained in the operation of the LAr calorimeter provide the foundation for a more rapid understanding of the experimental signatures of the first LHC collisions, involving electrons, photons, missing transverse energy ( $E_T^{\text{miss}}$ ), jets, and  $\tau$ s where the LAr calorimeter plays a central role.

This paper is organized as follows. Section 2 gives the present hardware status of the LAr calorimeter. Section 3 details the level of understanding of the ingredients entering the cell energy reconstruction: pedestals, noise, electronic gains, timing, and the quality of the signal pulse shape predictions. The current understanding of the first level trigger energy computation is also discussed. Section 4 describes the in situ performance of the electromagnetic LAr calorimeter using ionizing and radiating cosmic muons. Lastly, Sect. 5 draws the conclusions.

## 2 LAr calorimeter hardware status and data taking conditions

The LAr calorimeter is composed of electromagnetic and hadronic sub-detectors of which the main characteristics are described in Sect. 2.1. During the detector and electronics construction and installation, regular and stringent quality tests were performed, resulting in a fully functional LAr calorimeter. The operational stability of the cryostats since March 2008 is discussed in Sect. 2.2. The current status of the high voltage and the cell readout are discussed in Sects. 2.3 and 2.4 respectively. Finally, the general data taking conditions are given in Sect. 2.5. In ATLAS, the positive  $x$ -axis is defined as pointing from the interaction point to the center of the LHC ring, the positive  $y$ -axis is defined as pointing upwards, and the positive  $z$ -axis corresponds to protons running anti-clockwise. The polar angle  $\theta$  is measured from the beam axis ( $z$ -axis), the azimuthal angle  $\phi$  is measured in the transverse ( $xy$ )-plane, and the pseudorapidity is defined as  $\eta = -\ln \tan(\theta/2)$ .



**Fig. 1** Cut-away view of the LAr calorimeter, 17 m long (barrel + endcaps) and 4 m of diameter

### 2.1 Main characteristics of the LAr calorimeter

The LAr calorimeter [1], shown in Fig. 1, is composed of sampling detectors with full azimuthal symmetry, housed in one barrel and two endcap cryostats. More specifically, a highly granular electromagnetic (EM) calorimeter with accordion-shaped electrodes and lead absorbers in liquid argon covers the pseudorapidity range  $|\eta| < 3.2$ , and contains a barrel part (EMB [14],  $|\eta| < 1.475$ ) and an endcap part (EMEC [15],  $1.375 < |\eta| < 3.2$ ). For  $|\eta| < 1.8$ , a presampler (PS [15, 16]), consisting of an active LAr layer and installed directly in front of the EM calorimeters, provides a measurement of the energy lost upstream. Located behind the EMEC is a copper-liquid argon hadronic endcap calorimeter (HEC [17],  $1.5 < |\eta| < 3.2$ ), and a copper/tungsten-liquid argon forward calorimeter (FCal [18]) covers the region closest to the beam at  $3.1 < |\eta| < 4.9$ . An hadronic Tile calorimeter ( $|\eta| < 1.7$ ) surrounding the LAr cryostats completes the ATLAS calorimetry.

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, i.e. 97.2% of the full ATLAS calorimeter readout.

The relative energy resolution of the LAr calorimeter is usually parameterized by:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c, \quad (1)$$

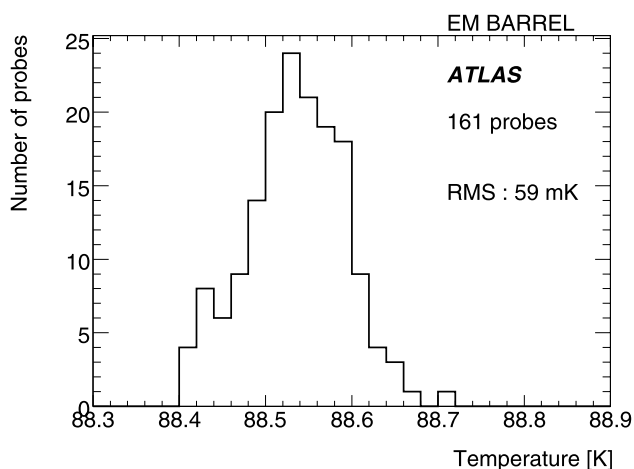
where ( $a$ ) is the stochastic term, ( $b$ ) the noise term and ( $c$ ) the constant term. The target values for these terms are respectively  $a \simeq 10\%$ ,  $b \simeq 170$  MeV (without pile-up) and  $c = 0.7\%$ .

### 2.2 Cryostat operation

Variations of the liquid argon temperature have a direct impact on the readout signal, and consequently on the energy

scale, partly through the effect on the argon density, but mostly through the effect on the ionization electron drift velocity in the LAr. Overall, a  $-2\%/K$  signal variation is expected [19]. The need to keep the corresponding contribution to the constant term of the energy resolution (1) negligible (i.e. well below 0.2%) imposes a temperature uniformity requirement of better than 100 mK in each cryostat. In the liquid,  $\sim 500$  temperature probes (PT100 platinum resistors) are fixed on the LAr detector components and read out every minute. In 2008–2009, installation activities in the ATLAS cavern prevented a stable cryostat temperature. A quiet period of ten days around the 2008 Christmas break, representative of what is expected during LHC collisions, allowed a check of the temperature stability in the absence of these external factors. The average dispersion (RMS) of the measurements of each temperature probe over this period is 1.6 mK (5 mK maximum), showing that no significant local temperature variation in time is observed in the three cryostats. Over this period, the temperature uniformity (RMS of all probes per cryostat) is illustrated for the barrel in Fig. 2 and gives 59 mK. Results for the two endcap cryostats are also in the range 50–70 mK, below the required level of 100 mK. The average cryostat temperatures are slightly different for the barrel (88.49 K) and the two endcaps (88.67 and 88.45 K) because they are independently regulated. An energy scale correction per cryostat will therefore be applied.

To measure the effects of possible out-gassing of calorimeter materials under irradiation, which has been minimized by careful screening of components, 30 purity monitors measuring the energy deposition of radioactive sources in the LAr are installed in each cryostat and read every 15 minutes. The contribution to the constant term of the energy resolution is negligible for a level of electronegative impurities below 1000 ppb  $O_2$  equivalent. All argon purity



**Fig. 2** Distribution of barrel cryostat probe temperatures averaged over a period of ten days

measurements over a period of two years are stable, in the range  $200 \pm 100$  ppb  $O_2$  equivalent, well below this requirement.

In summary, measurements of the liquid argon temperature and purity demonstrate that the stability of the operation of the three LAr cryostats is in the absence of proton beams within the required limits ensuring a negligible contribution to the energy resolution constant term.

### 2.3 High voltage status

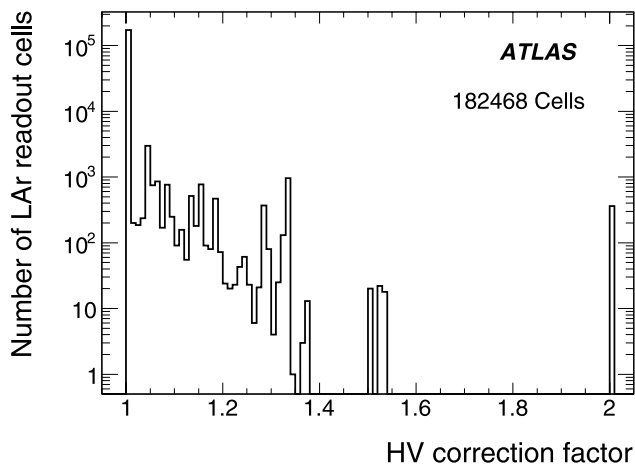
The electron/ion drift speed in the LAr gap depends on the electric field, typically 1 kV/mm. Sub-detector-specific high voltage (HV) settings are applied. In the EM barrel, the high voltage is constant along  $\eta$ , while in the EMEC, where the gap varies continuously with radius, it is adjusted in steps along  $\eta$ . The HV supply granularity is typically in sectors of  $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ . For redundancy, each side of an EM electrode, which is in the middle of the LAr gap, is powered separately. In the HEC, each sub-gap is serviced by one of four different HV lines, while for the FCal each of the four electrode groups forming a normal readout channel is served by an independent HV line.

For HV sectors with non-optimal behavior, solutions were implemented in order to recover the corresponding region. For example, in the EM calorimeter, faulty electrodes were connected to separate HV lines during the assembly phase at room temperature while, if the defect was identified during cryostat cold testing, the high voltage sector was divided into two in  $\phi$ , each connected separately. The effect of zero voltage on one side of an electrode was studied in beam tests proving that with offline corrections the energy can still be measured, with only a small loss in accuracy. Finally, for HV sectors with a permanent short-circuit, high voltage modules permitting large DC current draws of up to 3 mA (more than three orders of magnitude above the nominal limit) are used in order to operate the faulty sector at 1000 V or above.

As a result, 93.9% of readout cells are operating under nominal conditions and the rest sees a reduced high voltage. However, even with a reduced high voltage, signals can be well reconstructed by using a correction scale factor. Figure 3 shows the distribution of all HV correction factors for the EM, HEC and FCal cells as of the end of September 2009. Since the beginning of 2008, no changes have been observed. The largest correction occurs if one side of an EM electrode is not powered, and only half of the signal is collected. For the faulty cells, this correction factor is applied online at the energy reconstruction level. A similar correction is currently being implemented at the first level (L1) trigger.

In conclusion, since the beginning of 2008, all 182,468 readout cells are powered with high voltage, and no dead





**Fig. 3** High voltage correction factors for all LAr cells at the end of September 2009

region exists. Signals from regions with non-nominal high voltage are easily corrected and their impact on physics is negligible.

#### 2.4 Readout cell status

The cell signals are read out through 1524 Front-End Boards (FEBs [20, 21]) with 128 channels each, which sit inside front-end crates that are located around the periphery of the cryostats. The FEBs perform analog processing (amplification and shaping—except for the HEC where the amplification is done inside the cryostat), store the signal while waiting for the L1 trigger decision, and digitize the accepted signals. The FEBs also perform fast analog summing of cell signals in predefined projective “towers” for the L1 trigger.

The digitized signals are transmitted via optical fibers to the Readout Drivers (RODs) [22] located in the counting room 70 m away. The cell energy is reconstructed online in the ROD modules up to a nominal maximum L1 rate of 75 kHz. The cell and trigger tower energy reconstruction is described in detail in Sect. 3.

The response of the 182,468 readout cells is regularly monitored using 122 calibration boards [23] located in the front-end crates. These boards inject calibrated current pulses through high-precision resistors to simulate energy deposits in the calorimeters. At the end of September 2009, 1.3% of cells have problems. The majority of them, i.e. 1.2% of the total number of cells, are not read-out because they are connected to 17 non-functioning FEBs. On these FEBs, the active part (VCSEL) of the optical transmitter to the ROD has failed. This failure, occurring at a rate of two or three devices per month, is under intensive investigation and are expected to be fixed during the next LHC shutdown. The remaining 0.1% of cells with problems can be split in three sub-types: incurable cells, i.e. cells not responding to the input pulse (0.02%), or which are permanently (0.03%) or spo-

radically (0.07%) very noisy. The first two types are always masked in the event reconstruction (121 cells), while the sporadically very noisy cells, not yet well understood, are masked on an event by event basis. For cells which do not receive calibration signals (0.3%) average calibration constants computed among neighboring cells are used. For cells with non-nominal high voltage (6.1%) a software correction factor is applied. Both have very limited impact on the energy reconstruction.

In total, 180,128 cells, representing 98.7% of the total number of cells in the LAr calorimeter, are used for event reconstruction at the end of September 2009. The number of inactive cells (1.3%) is dominated by the cells lost due to faulty optical drivers (1.2%): apart from these, the number of inactive cells has been stable in time.

#### 2.5 Data taking conditions

The results presented here focus on the period starting in September 2008 when all the ATLAS sub-detectors were completed and integrated into the data acquisition. Apart from regular electronics calibration runs, two interesting types of data are used to commission the LAr calorimeter: the beam splash events and the cosmic muons. The first type corresponds to LHC events of September 10th 2008 when the first LHC beam hit the collimators located 200 m upstream of the ATLAS interaction point. A cascade of pions and muons parallel to the beam axis fired the beam related trigger, illuminated the whole ATLAS detector and deposited several PeV per event in the LAr calorimeter. The second type corresponds to long cosmic muon runs acquired on September–October 2008 and on June–July 2009 where more than 300 million events were recorded, corresponding to more than 500 TB of data.

For the LAr commissioning, L1 calorimeter triggers are used to record radiative energy losses from cosmic muons while the first level muon spectrometer and second level inner detector triggers are used to study pseudo-projective minimum ionizing muons. In most of the runs analyzed, the toroidal and solenoidal magnetic fields were at the nominal value.

### 3 Electronic performance and quality of cell energy reconstruction

The robustness of the LAr calorimeter energy reconstruction has been studied in detail using calibration and randomly triggered events, cosmic muons and beam splash events. Section 3.1 briefly describes the energy reconstruction method in the trigger towers and in the cells, as well as a validation study of the trigger. The time stability of the electronics is discussed in Sect. 3.2. The status of the electronics

timing for the first LHC collisions is presented in Sect. 3.3, and the quality of the LAr calorimeter energy reconstruction is assessed in Sect. 3.4.

### 3.1 Energy reconstruction in the LAr calorimeter

When charged particles cross the LAr gap between electrodes and absorbers, they ionize the liquid argon. Under the influence of the electric field, the ionization electrons drift towards the electrode inducing a current. The initial current is proportional to the energy deposited in the liquid argon. The calorimeter signals are then used to compute the energy per trigger tower or per cell as discussed in this section.

#### 3.1.1 Energy reconstruction at the first level calorimeter trigger

The timing requirements for the L1 trigger latency can only be met with fast analogue summing in coarse granularity. In the EM part, the pre-summation of analog signals per layer on the FEBs serves as input to tower builder boards where the final trigger tower signal sum and shaping is performed. In the HEC and FCal, the summation is performed on the FEBs and transmitted to tower driver boards where only shaping is done. The tower sizes are  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$  for  $|\eta| < 2.5$  and go up to  $\Delta\eta \times \Delta\phi = 0.4 \times 0.4$  for  $3.1 < |\eta| < 4.9$ . The analog trigger sum signals are sent to receiver modules in the service cavern. The main function of these modules is to compensate for the differences in energy calibration and signal attenuation over the long cables using programmable amplifier gains ( $g_R$ ). The outputs are sent to L1 trigger pre-processor boards which perform the sampling at 40 MHz and the digitization of five samples. At this stage, both the transverse energy and bunch crossing are determined using a finite impulse response filter, in order to maximize the signal-to-noise ratio and bunch crossing identification efficiency. During ATLAS operation, the output  $g_R A^{L1}$  of the filter, which uses optimal filtering, is passed to a look-up table where pedestal ( $P$  in ADC counts) subtraction, noise suppression and the conversion from ADC counts to transverse energy in GeV ( $F_{ADC \rightarrow GeV}^{L1}$ ) is performed in order to extract the final transverse energy value ( $E_T^{L1}$ ) for each trigger tower:

$$E_T^{L1} = F_{ADC \rightarrow GeV}^{L1} (g_R A^{L1} - g_R P). \quad (2)$$

Arrays (in  $\eta - \phi$ ) of these  $E_T^{L1}$  energies, merged with similar information coming from the Tile calorimeter, are subsequently used to trigger on electrons, photons, jets,  $\tau$ s and events with large missing transverse energy.

#### 3.1.2 Energy reconstruction at cell level

At the cell level, the treatment of the analog signal is also performed in the front-end electronics. After shaping, the

signal is sampled at 40 MHz and digitized if the event was selected by the L1 trigger. The reconstruction of the cell energy, performed in the ROD, is based on an optimal filtering algorithm applied to the samples  $s_j$  [24]. The amplitude  $A$ , in ADC counts, is computed as:

$$A = \sum_{j=1}^{N_{\text{samples}}} a_j (s_j - p), \quad (3)$$

where  $p$  is the ADC pedestal (Sect. 3.2.1). The Optimal Filtering Coefficients (OFCs)  $a_j$  are computed per cell from the predicted ionization pulse shape and the measured noise autocorrelation to minimize the noise and pile-up contributions to  $A$ . For cells with sufficient signal, the difference ( $\Delta t$  in ns) between the digitization time and the chosen phase is obtained from:

$$\Delta t = \frac{1}{A} \sum_{j=1}^{N_{\text{samples}}} b_j (s_j - p), \quad (4)$$

where  $b_j$  are time-OFCs. For a perfectly timed detector and in-time particles  $|\Delta t|$  must be close to zero, while larger values indicate the need for better timing or the presence of out-of-time particles in the event.

The default number of samples used for  $A$  and  $\Delta t$  computation is  $N_{\text{samples}} = 5$ , but for some specific analyses more samples, up to a maximum of 32, are recorded. Finally, including the relevant electronic calibration constants, the deposited energy (in MeV) is extracted with:

$$E_{\text{cell}} = F_{\mu A \rightarrow \text{MeV}} \times F_{\text{DAC} \rightarrow \mu A} \times \frac{1}{\frac{M_{\text{phys}}}{M_{\text{cali}}}} \times G \times A, \quad (5)$$

where the various constants are linked to the calibration system: the cell gain  $G$  (to cover energies ranging from a maximum of 3 TeV down to noise level, three linear gains are used: low, medium and high with ratios  $\sim 1/10/100$ ) is computed by injecting a known calibration signal and reconstructing the corresponding cell response; the factor  $1/\frac{M_{\text{phys}}}{M_{\text{cali}}}$  quantifies the ratio of response to a calibration pulse and an ionization pulse corresponding to the same input current; the factor  $F_{\text{DAC} \rightarrow \mu A}$  converts digital-to-analog converter (DAC) counts set on the calibration board to  $\mu A$ ; finally, the factor  $F_{\mu A \rightarrow \text{MeV}}$  is estimated from simulations and beam test results, and includes high voltage corrections for non-nominal settings (see Sect. 2.3). Note that the crosstalk bias in the finely segmented first layer of the electromagnetic calorimeter is corrected for in the gain  $G$  [4].

#### 3.1.3 Check of the first level tower trigger energy computation

The trigger decision is of utmost importance for ATLAS during LHC collisions since the data-taking rate is at maximum 200 Hz because of bandwidth limitations, i.e. a factor



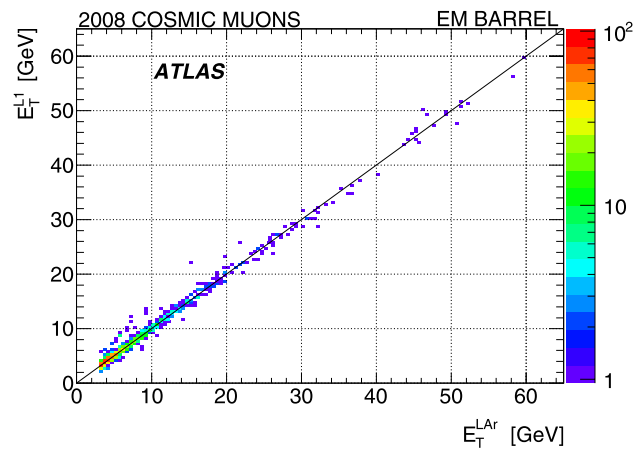
$2 \times 10^5$  smaller than the 40 MHz LHC clock. It is therefore important to check that no systematic bias is introduced in the computation of the L1 trigger energy and that the trigger energy resolution is not too degraded with respect to the offline reconstruction. In the following, this check is performed with the most granular part of the LAr calorimeter, the barrel part of the EM calorimeter, where 60 cell signals are summed per trigger tower.

Since cosmic muon events occur asynchronously with respect to the LHC clock, and the electronics for both the trigger and the standard readout is loaded with one set of filtering coefficients (corresponding to beam crossing), the reconstructed energy is biased by up to 10%, depending on the phase. For the study presented here,  $E_T^{L1}$  is recomputed offline by fitting a second-order polynomial to the three highest samples transmitted through the processors. The most critical part in the trigger energy computation is then to calibrate the individual receiver gains  $g_R$ . For that purpose, a common linearly increasing calibration pulse is sent to both the L1 trigger and the normal cell circuits: the inverse receiver gain  $1/g_R$  is obtained by fitting the correlation between the L1 calorimeter transverse energy ( $E_T^{L1}$ ) and the sum of cell transverse energies in the same trigger tower, later called *offline* trigger tower ( $E_T^{LA_r}$ ). In cosmic muon runs, receiver gains are set to 1.0 and are recomputed offline with dedicated calibration runs. As a cross check, the gain was also extracted using LHC beam splash event data which covers the full detector. In both cases, the L1 transverse energy is computed as in (2).

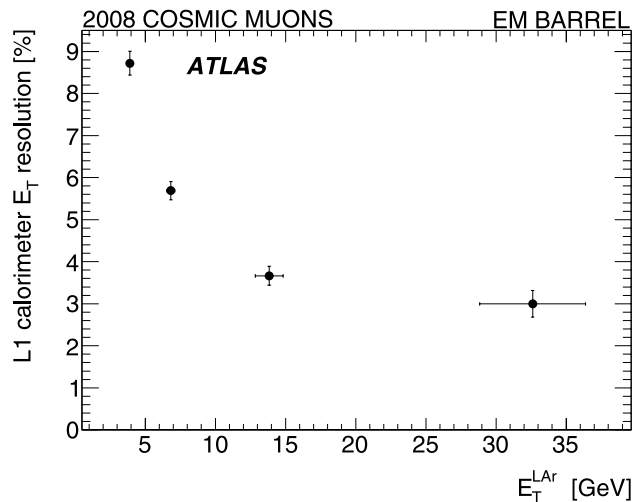
In the EM calorimeter, radiating cosmic muons may produce a local energy deposit of a few GeV, and fire the EM calorimeter trigger condition EM3 that requires a transverse energy greater than 3 GeV in a sum of four adjacent EM trigger towers. To mimic an electron coming from the interaction point, only those events that contain a track reconstructed with strict projectivity cuts are considered. Here, the L1 calorimeter transverse energy is computed using the gains determined with calibration runs. Figure 4 shows the correlation between  $E_T^{L1}$  and  $E_T^{LA_r}$ . Computing the ratio of  $E_T^{L1}$  and  $E_T^{LA_r}$  gives a Gaussian distribution with a mean of  $1.015 \pm 0.002$ , showing the very good correspondence between these two quantities, especially at low energy. This also shows that the trigger energy is well calibrated and almost unbiased with respect to the LAr readout.

Figure 5 shows the corresponding resolution computed as the relative difference of  $E_T^{L1}$  and  $E_T^{LA_r}$ . At low energy, the difference is dominated by electronic noise since the two readout paths have only part of their electronics in common. The ATLAS specification of 5% of L1 transverse energy resolution is reached for energies greater than 10 GeV. The L1 transverse energy resolution reaches around 3% at high energy.

As a crosscheck, a similar study was performed with gains computed from the beam splash events, without the



**Fig. 4** L1 transverse energy ( $E_T^{L1}$ ) computed with the receiver gains extracted from calibration runs versus the sum of cell transverse energies in the same trigger tower ( $E_T^{LA_r}$ )



**Fig. 5** Relative difference of  $E_T^{L1}$  and  $E_T^{LA_r}$  (L1 Calorimeter  $E_T$  resolution) as a function of  $E_T^{LA_r}$ . Strict projectivity cuts for the track pointing to the EM shower are applied. Horizontal error bars reflect the RMS of  $E_T^{LA_r}$  in each bin

projectivity cut. A slight degradation of the resolution is observed at high energy, but not at low energy where the noise dominates. Taking advantage of the higher statistics, it is possible to compute the 5 GeV “turn-on curve”, i.e. the relative efficiency for an offline trigger tower to meet the requirement  $E_T^{L1} \geq 5$  GeV as a function of  $E_T^{LA_r}$ . This is not the absolute efficiency as the calorimeter trigger condition EM3 is used to trigger the events. The efficiency is shown in Fig. 6, where a sharp variation around a  $E_T^{L1} = 5$  GeV energy threshold is observed.

These results give confidence that EM showers (electrons and photons) will be triggered efficiently in LHC events. After this study, the gains  $g_R$  were extracted from dedicated

calibration runs and loaded into the receivers to be used for the first LHC collisions.

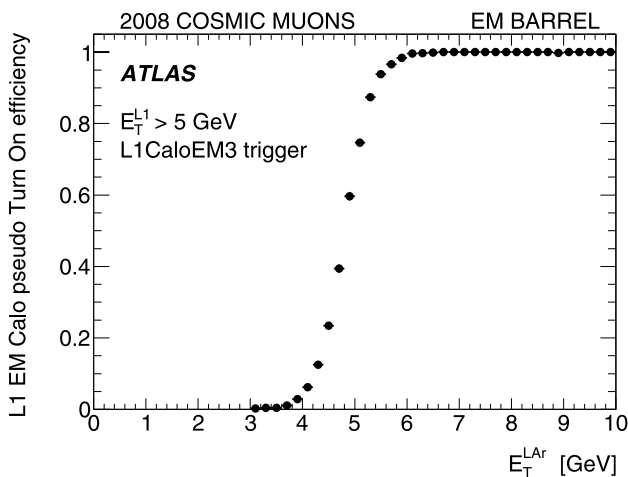
### 3.2 Electronic stability

Hundreds of millions of randomly triggered and calibration events can be used for a study of the stability of the properties of each readout channel, such as the pedestal, noise and gain. The first two quantities are computed for each cell as the mean (pedestal) of the signal samples  $s_j$  in ADC counts, and the width (noise) of the energy distribution. The gain is extracted by fitting the output pulse amplitudes against calibration pulses with increasing amplitudes.

#### 3.2.1 Pedestal

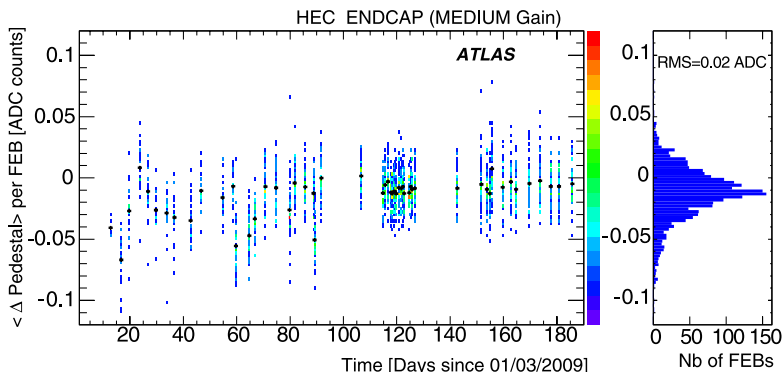
The stability of the pedestals is monitored by measuring variations with respect to a reference pedestal value for each cell. For each FEB, an average over the 128 channels is computed.

As an example, Fig. 7 illustrates the results for the 48 HEC FEBs over a period of six months in 2009. A slight drift



**Fig. 6** Turn-on curve efficiency for  $E_T^{L1} > 5$  GeV requirement obtained with events triggered by the EM3 L1 Calorimeter trigger

**Fig. 7** Average FEB pedestal variations in ADC counts, in medium gain, for the HEC during 6 months of data taking in 2009. The crosses indicate the mean value for each time slice



of the pedestal with time, uncorrelated with the FEB temperature and/or magnetic field configurations, is observed. Overall, the FEB pedestal variations follow a Gaussian distribution with a standard deviation of 0.02 ADC counts, i.e. below 2 MeV. The same checks have been performed on all other FEBs, and give typical variations of around 1 (0.1) MeV and 10 (1) MeV in the EM and FCal calorimeters respectively, in medium (high) gain. These variations are much lower for the EM and HEC or at the same level for the FCal than the numerical precision of the energy computation, which is 8 (1) MeV in medium (high) gain.

During the LHC running, it is foreseen to acquire pedestal and calibration runs between fills, thus it will be possible to correct for any small time dependence such as observed in Fig. 7. In the same spirit, random triggers collected during physics runs can be used to track any pedestal variations during an LHC fill.

#### 3.2.2 Noise

Figure 8 shows the noise measured in randomly triggered events at the cell level as a function of  $\eta$  for all layers of the LAr calorimeters. In all layers, a good agreement with the expected noise [1] is observed. Noise values are symmetric with respect to  $\eta = 0$  and uniformly in  $\phi$  within few percents. In the EM calorimeters, the noise ranges from 10 to 50 MeV, while it is typically a factor of 10 greater in the hadronic endcap and forward calorimeters where the granularity is 20 times coarser and the sampling fractions are lower. It should be noted that these results are obtained using five samples in (3) and (5), i.e. the noise is reduced by a factor varying from 1.5 to 1.8, depending on  $\eta$ , with respect to the single-sample noise value.

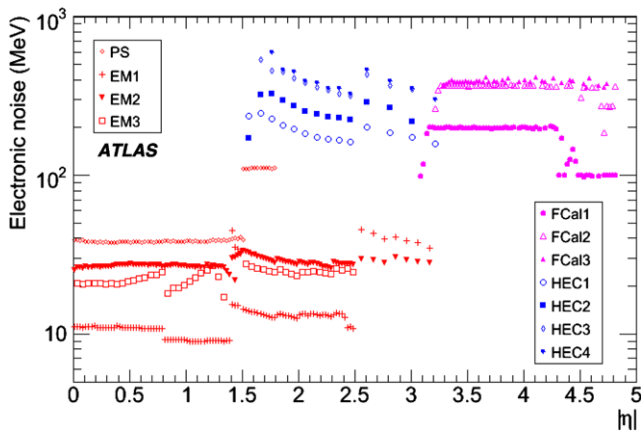
The coherent noise over the many cells used to measure electron and photon energies in the EM calorimeters should be kept below 5% [25] of the incoherent noise (i.e. the quadratic sum of all channel noise). For the second layer of the EM calorimeter, the contribution from the coherent noise has been estimated to 2%, by studying simultaneous increase of noise in a group of channels.

Systematic studies of noise stability have been pursued: all noise variations are typically within  $\pm 1$  keV, 0.1 MeV and 1 MeV for EM, HEC and FCal, respectively. No correlations with the FEB temperature and/or changes of magnetic field conditions have been observed.

### 3.2.3 Gain

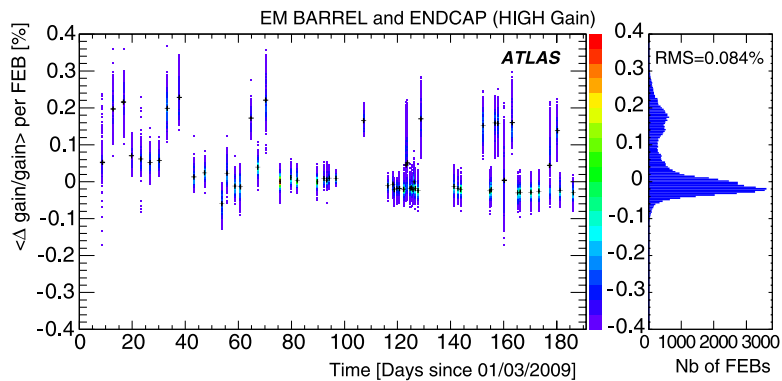
The calibration pulse is an exponential signal (controlled by two parameters,  $f_{\text{step}}$  and  $\tau_{\text{cali}}$ ) which emulates the triangular ionization signal. It is injected on the detector as close as possible to the electrodes, except for the FCal where it is applied at the base-plane of the front-end crates [18]. Thus, the analog cell response is treated by the FEBs in the same way as an ionization signal, but it is typically averaged over 100 triggers in the RODs and transmitted offline where the average signal peak height is computed. The cell gain is extracted as the inverse ratio of the response signal in ADC counts to the injected calibration signal in DAC counts.

The stability of the cell gain is monitored by looking at the relative gain difference averaged over 128 FEB channels. This is illustrated in Fig. 9 for the 1448 FEBs of the EM calorimeter, in high gain. All variations are within  $\pm 0.3\%$



**Fig. 8** Electronic noise ( $\sigma_{\text{noise}}$ ) in randomly triggered events at the EM scale in individual cells for each layer of the calorimeter as a function of  $|\eta|$ . Results are averaged over  $\phi$

**Fig. 9** Average FEB (high) gain variations during 6 months of 2009 data taking, in the EM part of the calorimeter. The crosses indicate the mean value for each time slice



and similar results are obtained for medium and low gains. An effect of 0.2% on the gains has recently been identified as coming from a particular setting of the FEBs. The two populations are most probably coming from this effect. Regular update of calibration database take account of the variations. Similar results are obtained for the HEC, and variations within  $\pm 0.1\%$  are measured for the FCal.

In conclusion, results presented for the pedestals, noise, and gains illustrate the stability of the LAr electronics over several months of data taking. Values are stored in the ATLAS calibration database and are used for online and offline reconstruction.

### 3.2.4 Global check with $E_T^{\text{miss}}$ variable

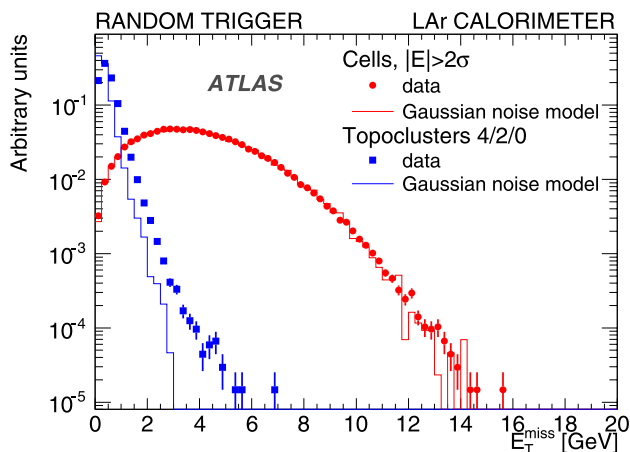
Another way to investigate the level of understanding of pedestals and noise in the LAr calorimeter is to compute global quantities in randomly triggered events with the calorimeter, such as the vector sum of transverse cell energies. The calorimetric missing transverse energy  $E_T^{\text{miss}}$  is defined as:

$$E_x^{\text{miss}} = - \sum_{i=1}^{N_{\text{cell}}} E_i \sin \theta_i \cos \phi_i,$$

$$E_y^{\text{miss}} = - \sum_{i=1}^{N_{\text{cell}}} E_i \sin \theta_i \sin \phi_i, \tag{6}$$

$$E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2},$$

where  $E_i$  is the cell energy,  $\theta_i$  its polar angle and  $\phi_i$  its azimuthal angle. Because of the high granularity of the LAr calorimeter, it is crucial to suppress noise contributions to  $E_T^{\text{miss}}$ , i.e. limit the number of cells,  $N_{\text{cell}}$ , used in the sum. In ATLAS, this is done with two methods: (i) a cell-based method in which only cells above a noise threshold of two standard deviations ( $|E_i| > 2\sigma_{\text{noise}}$ ) are kept; (ii) a cluster-based method which uses only cells belonging to three-dimensional topological clusters [26]. These clusters are built around  $|E_i| > 4\sigma_{\text{noise}}$  seeds by iteratively



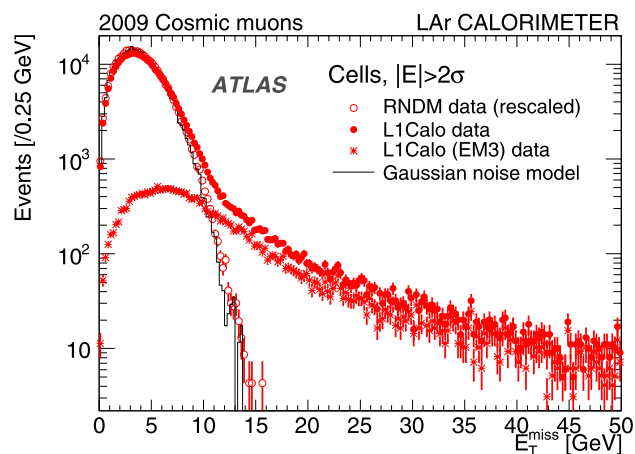
**Fig. 10**  $E_T^{\text{miss}}$  distribution with LAr calorimeter cells for 135,000 randomly triggered events in June 2009. The dots (squares) show the cell-based (cluster-based) methods in the data, and the histograms show the equivalent distributions for the Gaussian noise model (see text)

gathering neighboring cells with  $|E_i| > 2\sigma_{\text{noise}}$  and, in a final step, adding all direct neighbors of these accumulated secondary cells (Topocluster 4/2/0). In randomly triggered events, about 8500 and 500 LAr cells, respectively, are selected with these two noise-suppression methods.

The distributions of  $E_x^{\text{miss}}$  and  $E_y^{\text{miss}}$  should be Gaussian and centered on zero in randomly triggered events. The measurements are compared with a Gaussian noise model, where no pedestal shift or coherent noise is present, obtained by randomizing the cell energy according to a Gaussian model for the cell noise. For this  $E_T^{\text{miss}}$  computation, cells with very high noise (see Sect. 2.4) are removed from the computation.

Figure 10 shows the  $E_T^{\text{miss}}$  distributions for a randomly triggered data sample acquired in 15 hours. The two noise suppression methods are compared to the corresponding Gaussian noise model. For the cell-based method, a good agreement is observed between the data and the simple model. Because of the lower number of cells kept in the cluster-based method, a smaller noise contribution to  $E_T^{\text{miss}}$  is observed. The agreement between the data and the model is not as good as for the cell-based method, reflecting the higher sensitivity of the cluster-based method to the noise description. In both cases, no  $E_T^{\text{miss}}$  tails are present, reflecting the absence of large systematic pedestal shifts or abnormal noise.

Using  $E_T^{\text{miss}}$  it was possible to spot, in 2008, a high coherent noise due to the defective grounding of a barrel pre-sampler HV cable and sporadic noise in a few preamplifiers. These two problems were repaired prior to the 2009 runs. The time stability of  $E_T^{\text{miss}}$  is regularly monitored using randomly triggered events by observing the mean and width of the  $E_x^{\text{miss}}$  and  $E_y^{\text{miss}}$  distributions. With the cluster-based method, the variation of all quantities was measured to be



**Fig. 11**  $E_T^{\text{miss}}$  distribution with LAr calorimeter cells for 300,000 L1 calorimeter (L1Calo) triggers reconstructed with the cell-based method. Results for EM3 trigger conditions (Sect. 3.1.3) from the same run are superimposed on the same plot and the results from randomly triggered events are again overlaid (open symbols and histogram)

$\pm 0.1$  GeV over 1.5 months. This variation is small compared to the expected  $E_T^{\text{miss}}$  resolution ( $\simeq 5$  GeV for  $W \rightarrow e\nu$  events) and can be controlled further by more frequent updates of the calibration constants.

A similar analysis was performed with L1 calorimeter triggered events, corresponding to radiative energy losses from cosmic muons, from the same run as used above. The L1 calorimeter trigger (L1calo) triggers events when either the sum of adjacent trigger tower transverse energies is above 3 GeV in the EM calorimeter (EM3) or 5 GeV when summing EM and hadronic towers [27]. The results are illustrated in Fig. 11 for the cell-based noise suppression method. Most of these events are triggered by energy losses in the Tile calorimeter that do not spill in the LAr calorimeter, which therefore mainly records noise, leading to a  $E_T^{\text{miss}}$  distribution similar to the one obtained with random triggers. However, in few cases, events are triggered by the LAr calorimeter such as the EM3 trigger. The peak at 3 GeV is then shifted upwards to 6 GeV and the proportion of events with  $E_T^{\text{miss}}$  above 15 GeV is greatly enhanced.

### 3.3 LAr calorimeter timing

The energy reconstruction in each cell relies on the fact that in the standard (five samples) physics data acquisition mode, the third sample is located close to the signal maximum: this implies an alignment of the timing of all calorimeter cells to within a few ns.

Several parameters determine each cell timing: the first contribution comes from FEB internal delays which induce a cell timing variation of  $\pm 2$  ns within each FEB. This is accounted for when computing the optimal filtering coefficients. The second contribution concerns FEB to FEB variations due to different cable lengths to reach a given FEB:

this relative FEB timing can vary by up to  $\pm 10$  ns and can be corrected for by setting an adjustable delay on each FEB.

The study presented here aims at predicting (using calibration data and additional hardware inputs) and measuring (using cosmic muons and beam splash data) this relative FEB timing in order to derive timing alignment delays for each FEB.

### 3.3.1 Timing prediction

The time of the signal maximum is different in a calibration run ( $t_{\text{calib}}$ ) and in a physics run ( $t_{\text{phys}}$ ). The main contribution to this time is the delay  $T_0$  before the pulse starts to rise (the difference between the calibration and physics pulse widths is much smaller than this  $T_0$  delay variation). This delay is driven by cable lengths which are different in these two configurations and additional delays in physics runs because of the particle time of flight, and the Timing, Trigger and Control (TTC) system configurations.

In a calibration run, a signal is injected from the calibration board through the calibration cables, and is then read out through the physics signal cables. The value of the delay  $T_0^{\text{calib}}$  with respect to the signal injection can thus be computed for each FEB using the various cable lengths ( $L_{\text{calib}}, L_{\text{physics}}$ ) and signal propagation speeds ( $v_{\text{calib}}, v_{\text{physics}}$ ):

$$T_0^{\text{calib}} = \frac{L_{\text{calib}}}{v_{\text{calib}}} + \frac{L_{\text{physics}}}{v_{\text{physics}}}. \quad (7)$$

The above prediction is compared with the measured value in calibration runs. The measurement corresponds to the time at which the calibration pulse exceeds three standard deviations above the noise; it is found to agree with the prediction to within  $\pm 2$  ns, ignoring the variations within each FEB.

The time of the signal maximum  $t_{\text{calib}}$  is obtained by fitting the peak of the pulse of cells in a given FEB with a third order polynomial. As the cable length is a function of the cell position along the beam axis ( $z, \eta$ ), the cell times are averaged per FEBs in a given layer (except for the HEC where layers are mixed inside a FEB) and a given  $\eta$ -bin in order to align the FEBs in time.

The time of the ionization pulse in each cell can then be predicted from the calibration time using the following formula:

$$t_{\text{phys}} = t_{\text{calib}} - \frac{L_{\text{calib}}}{v_{\text{calib}}} + t_{\text{flight}} + \Delta t_{\text{TTC}}, \quad (8)$$

where  $t_{\text{calib}}$  was defined in the previous paragraph;  $t_{\text{flight}}$  is the time of flight of an incident particle from the interaction point to the cell, which varies from 5 ns for a presampler cell at  $\eta = 0$ , to 19 ns for a back cell in the HEC; and  $\Delta t_{\text{TTC}}$  is a global correction for the six partitions due to the cabling

of the TTC system which is needed to align all FEBs at the crate level. This predicted ionization pulse time is compared with the corresponding measurement in the next section.

### 3.3.2 Timing measurement

The ionization pulse time has been measured in beam splash and cosmic muon events. The time is reconstructed using optimal filtering coefficients. Since the arrival time of the particle is not known, one does not know in advance to which samples the time OFCs  $b_i$  should be applied (since these OFCs were computed for a particular set of samples around the pulse maximum). Therefore, an iterative procedure is used until the obtained  $\Delta t$  (see (4)) is less than 3 ns.

The time is then corrected for two effects: first, the time-of-flight difference between the beam splash or cosmic muon configurations and the collision configuration, and second, the asynchronicity of the beam splash and cosmic muon events, where arrival times vary with respect to the TTC clock.

The comparison between the measured and the predicted (8) ionization pulse time is shown in Fig. 12 for the C-side ( $\eta < 0$ ) of each LAr sub-detector.

This comparison is performed for each “slot” corresponding to a group of FEBs in a given layer and  $\eta$ -range, averaged over all calorimeter modules over  $\phi$ . As mentioned in the introduction, the relative timing of each group of FEBs varies by  $\pm 10$  ns due to the different corresponding cable lengths.

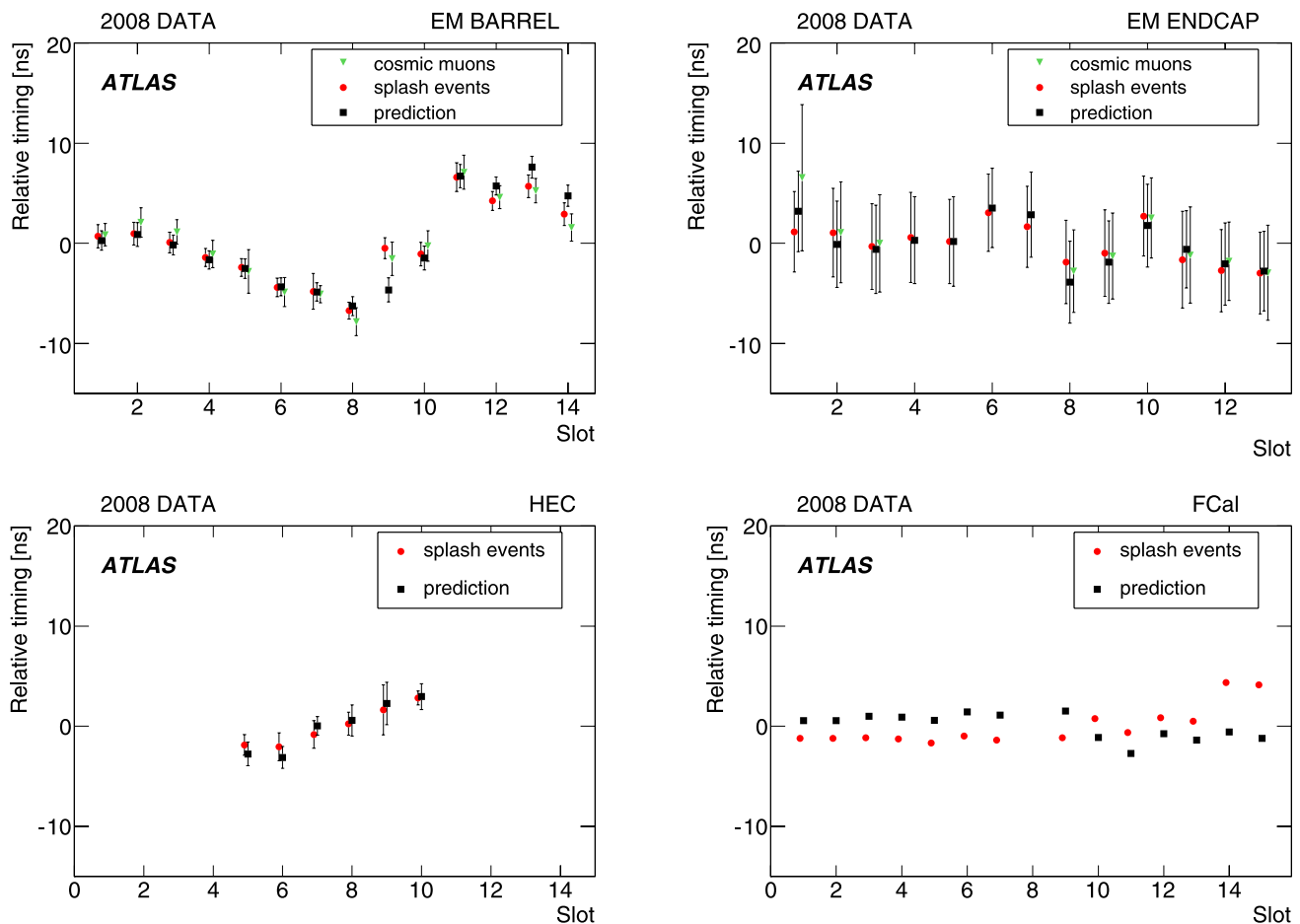
On the plots, the error bars correspond to the RMS of values for all modules in a slot: in the FCal, there is only one module per slot, so no error bars are shown (also note that slot 8 is empty in the FCal). In some regions, the cosmic data statistics was not sufficient to extract the time: the corresponding bins are thus empty. The agreement between the prediction and the two measurements is within  $\pm 2$  ns (and at worst  $\pm 5$  ns for two slots of the FCal).

Finally, a set of FEB timing alignment delays is obtained from these well understood measured relative times. These delays will be used at the LHC startup and updated once the phase between the beam and the machine clock will be measured and shown to be stable. The desired precision of  $\pm 1$  ns should be reached then.

## 3.4 Signal reconstruction studies and impact on intrinsic global energy resolution constant term

The main ingredient for accurate energy and time reconstruction of signals from LHC collisions is the prediction of the ionization signal shape, from which the optimal filtering coefficients used in (3) are computed. After recalling the basics of the method used to predict the shape in Sect. 3.4.1, an estimate of the signal prediction quality with three samples





**Fig. 12** Relative predicted and measured FEB times in the electromagnetic barrel (*top left*), electromagnetic endcap (*top right*), HEC (*bottom left*) and FCal (*bottom right*) calorimeters, for the C-side ( $\eta < 0$ ). The

$x$ -axis (“Slot”) corresponds to a group of FEBs in a given layer (or a group of layers in the HEC) and  $\eta$ -range. The *error bars* show the width of the distributions in each slot

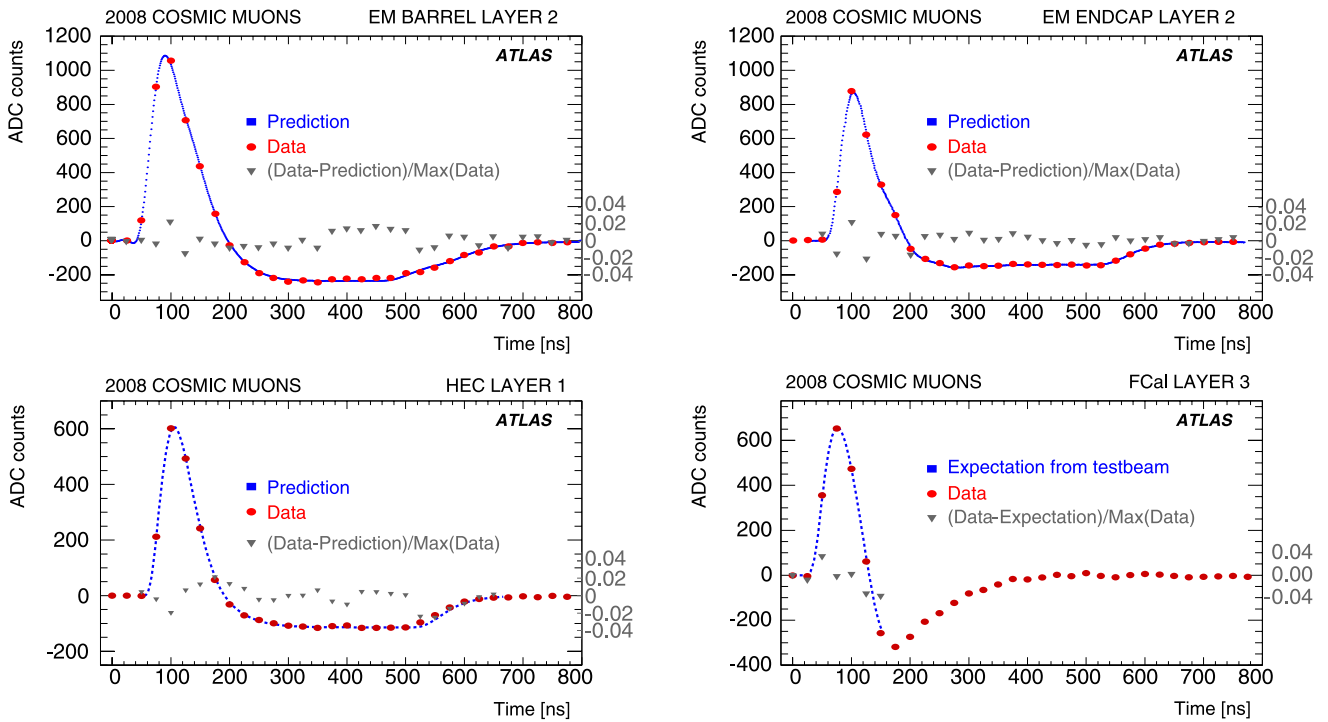
in the EM calorimeter is presented in Sect. 3.4.2. The full 32 samples shape prediction is used to determine the ionization electron drift time needed for the OFC computation in the EM calorimeter (Sect. 3.4.3). Finally, from these two studies an estimate of the main contributions to the constant term in the global energy resolution of the EM calorimeter is given in Sect. 3.4.4.

### 3.4.1 Prediction of the ionization pulse shape

The standard ATLAS method for prediction of the ionization pulse shape in the EM and the HEC relies on the calibration system. A precisely known calibration signal is sent through the same path as seen by the ionization pulses thus probing the actual electrical and readout properties of each calorimeter cell. In both the EM and the HEC, the calibration pulse properties are parameterized using two variables,  $f_{\text{step}}$  and  $\tau_{\text{cali}}$ , which have been measured for all calibration boards [23] and are routinely extracted from calibration signals [28].

The predicted ionization shapes are calculated from the calibration pulses by modeling each readout cell as a resonant  $RLC$  circuit, where  $C$  is the cell capacitance,  $L$  the inductive path of ionization signal, and  $R$  the contact resistance between the cell electrode and the readout line. The effective  $LC$  and  $RC$  have been estimated from a frequency analysis of the output calibration pulse shape [28]. They were also measured with a network analyzer during the long validation period of the three cryostats [29–31]. For the HEC, calibration pulses are transformed into ionization signal predictions using a semi-analytical model of the readout electronics, with a functional form with zeros and poles accounting for the cable and pre-amplifier transfer functions [32, 33]. The prediction of both the EM and HEC ionization pulses requires the knowledge of the electron drift time in liquid argon ( $T_{\text{drift}}$ ), which can be inferred from the calorimeter properties or directly measured from data (see Sect. 3.4.3).

To illustrate the good quality of the pulse shape prediction, radiating cosmic muons depositing few GeV in a cell



**Fig. 13** Typical pulse shapes, recorded during the cosmic ray campaign, for a given cell in the second layer for the barrel (top left) and the endcap (top right) of the EM calorimeter, as well as in the first layer

of the HEC (bottom left) and in the third layer of the FCal (bottom right). The relative difference between data and prediction is indicated by triangles on the right scale

have been used. Figure 13 shows a typical 32-sample pulse recorded in the barrel (top left) and the endcap (top right) of the EM calorimeter, as well as in the HEC (bottom left). In each case, the pulse shape prediction, scaled to the measured cell energy, agrees at the few percent level with the measured pulse.

As already mentioned, in the FCal the calibration pulse is injected at the base-plane of the front-end crates, and therefore the response to a calibration signal differs significantly from the response to an ionization pulse, preventing the use of methods described above. Instead, seven sample pulse shapes recorded during the beam test campaign [9, 10] have been averaged to obtain a normalized reference pulse shape for each layer. Figure 13 (bottom right) shows a typical example where the agreement between the reference pulse shape and the data is at the 4% level.

### 3.4.2 Quality of signal reconstruction in the EM calorimeter

Several PeV were deposited in the full calorimeter in LHC beam splash events. As an example, Fig. 14 shows the energy deposited in the second layer of the EM calorimeter. The structure in  $\phi$  reflects the material encountered by the particle flux before hitting the calorimeter, such as the endcap toroid. In this layer, a total of  $5 \times 10^5$  five sample signal shapes with at least 5 GeV of deposited energy were

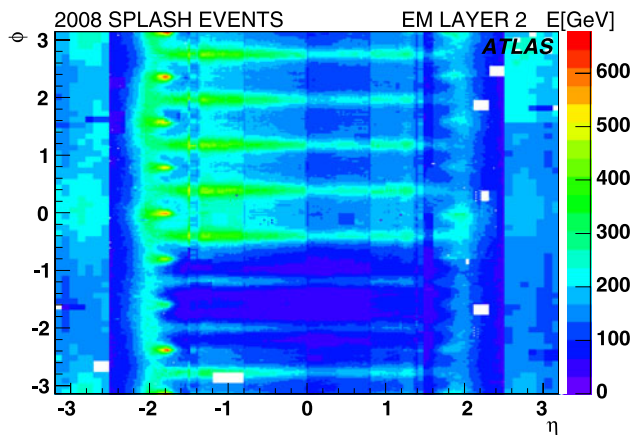
recorded. These events were used to estimate the quality of the pulse shape prediction for every cell.

For this purpose, a  $Q^2$ -estimator is defined as :

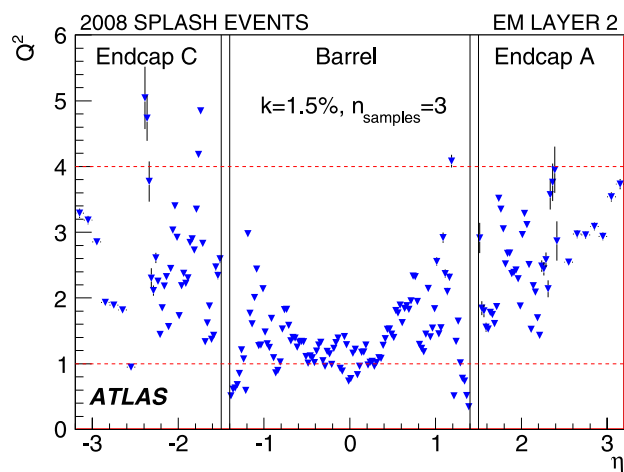
$$Q^2 = \frac{1}{N_{\text{dof}}} \sum_{j=1}^{N_{\text{samples}}} \frac{(s_j - Ag_j^{\text{phys}})^2}{\sigma_{\text{noise}}^2 + (kA)^2}, \tag{9}$$

where the amplitude  $A$  (3) is computed with a number of samples  $N_{\text{samples}} = 3$  (because the timing was not yet adjusted everywhere for the beam splash events, not all samples can be used),  $s_j$  is the amplitude of each sample  $j$ , in ADC counts,  $g_j^{\text{phys}}$  is the normalized predicted ionization shape and  $k$  is a factor quantifying the relative accuracy of the amplitude  $A$ . Assuming an accuracy of around 1%, with the 5 GeV energy cut applied one has  $\sigma_{\text{noise}}^2 < (kA)^2$ . In this regime, it is possible to fit a  $\chi^2$  function with 3 degree of freedom on the  $Q^2 \times N_{\text{dof}}$  distribution over cells in the central region (where the  $Q^2$  variation is small). Therefore,  $N_{\text{dof}} = 3$ . A given value of  $Q^2$  can be interpreted as a precision on the amplitude at the level  $kQ$ .

Figure 15 shows the  $Q^2$ -estimator in the second layer of the EM calorimeter averaged over  $\phi$ , assuming  $k = 1.5\%$  corresponding to  $Q^2 \sim 1$  for  $\eta \sim 0$ . The accuracy is degraded by at most a factor of  $\sim 2$  (i.e.  $Q^2 \sim 4$ ) in some endcap regions. This shows that these data can be described with a reasonable precision.



**Fig. 14** Total energy deposited in the LHC beam splash events in every cell of the EM calorimeter second layer. Empty bins are due to non functioning electronics

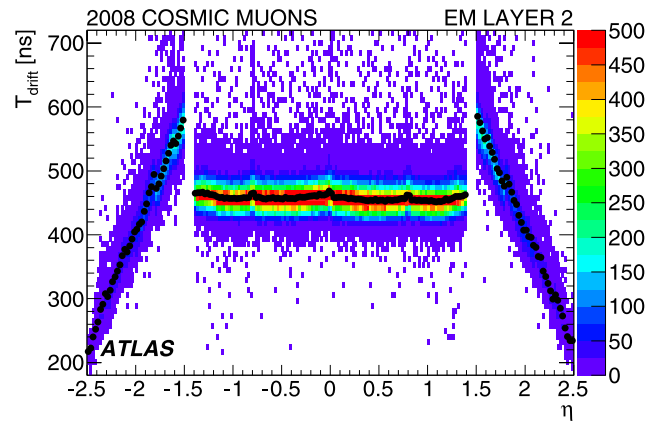


**Fig. 15** Estimator  $Q^2$  (defined in the text) as a function of  $\eta$  for  $5 \times 10^5$  pulse shapes with  $E > 5$  GeV in the EM calorimeter second layer cells.  $Q^2$  is defined in (9) with  $k = 1.5\%$

### 3.4.3 Ionization electron drift time measurement in the EM calorimeter

During the 2008 cosmic runs, half a million pulses with 32 samples were recorded in the EM calorimeter from cells in which at least 1 GeV was reconstructed. Given the good accuracy of the predicted signal undershoot (see Fig. 13), the drift time can be extracted from a fit to the measured signal [34].

Figure 16 shows the fitted drift time for all selected cells in the second layer using the standard pulse shape prediction method (Sect. 3.4.1). In the EMB, the drift time has also been measured with a method in which the shape is computed using a more analytical model and  $LC$  and  $RC$  extracted from network analyzer measurements [30]. The drift times extracted from the two methods are in excellent agreement, giving confidence in the results: a constant



**Fig. 16** Drift time measurement in the cells of the EM calorimeter second layer with  $E > 1$  GeV for the 2008 cosmic muon run. The dots correspond to drift time values averaged in  $\phi$

value around the expected 460 ns is obtained, except near the electrode edges ( $|\eta| = 0, 0.8$  and  $1.4$ ) where the electric field is lower. The decrease of the drift time in the EM endcap ( $1.5 < |\eta| < 2.5$ ) reflects the decrease of the gap size with  $|\eta|$ . Similar results are obtained for the first and third layers of the EM calorimeters.

### 3.4.4 Impact on the global energy resolution constant term of the EM calorimeter

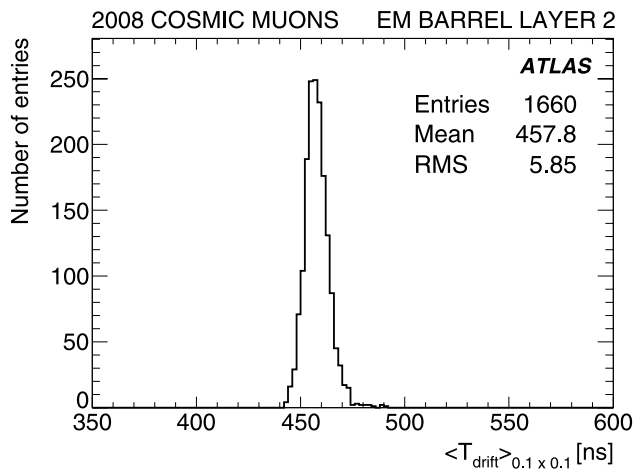
When five of the production EM calorimeter modules were tested individually in electron beams, the global constant term  $c$  of the energy resolution formula was measured to be  $c \sim 0.5\%$  in the EM barrel and  $0.7\%$  in the EM endcap [4]. The main contributors are the signal reconstruction accuracy, the LAr gap uniformity, and the electronics calibration system. The first two contributions  $c_{SR}$  and  $c_{gap}$  can be investigated using results presented in Sects. 3.4.2 and 3.4.3, considering only the second layer of the EM calorimeter where most of the electromagnetic shower energy is deposited.

From Fig. 15, one finds that  $\langle Q^2 \rangle \sim 1.4$  in the EM barrel and 2.6 in endcap, and hence  $\langle k \rangle = 1.8\%$  and  $2.4\%$  respectively. This corresponds to residuals between the predicted and measured pulses of 1 to 2% of the pulse amplitude (see Fig. 13 for illustration), for samples around the signal maximum. Similar residuals were obtained in the electron beam test analysis [28]. At this time, the contribution of the signal reconstruction to the constant term was estimated to be  $c_{SR} = 0.25\%$ . Given the measured accuracy with beam splash events, the beam test result seems to be reachable with LHC collisions.

The drift time measured in Sect. 3.4.3 is a function of the gap thickness ( $w_{gap}$ ) and the high voltage ( $V$ ):

$$T_{drift} \sim \frac{w_{gap}^{\alpha+1}}{V^\alpha} \quad (10)$$





**Fig. 17** Distribution of the local average drift time values in  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$  bins, for the middle layer of the EM barrel

where  $\alpha \simeq 0.3$  is empirically determined from measurements [19]. In the EM barrel, the electric field is constant, except in transition regions, and thus the drift time uniformity directly measures the LAr gap variations. To reduce statistical fluctuations, the measured drift time values are averaged over regions of  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ . The distribution of the average drift time is shown in Fig. 17 for the second layer of the EM barrel calorimeter.

The drift time uniformity, estimated as the ratio of the RMS of this distribution to its mean value, is  $1.28 \pm 0.03\%$ . Using the relation between the drift time and the gap from (10) and the fact that the signal amplitude is proportional to the initial ionization current ( $I \simeq \frac{\rho \cdot w_{\text{gap}}}{T_{\text{drift}}} \simeq w_{\text{gap}}^{-\alpha}$  where  $\rho$  is the linear density of charge), one can relate the relative variation of the drift time to the one of the amplitude applying a factor  $\alpha/(1 + \alpha)$  to the above result. Therefore, the drift time uniformity leads to a dispersion of response due to the barrel calorimeter gap variations of  $(0.29^{+0.05}_{-0.04})\%$  where the systematic uncertainties are included. This represents an upper bound on the corresponding constant term  $c_{\text{gap}}$ .

For comparison, during the EM calorimeter barrel module construction, the LAr gap thickness was measured, yielding an estimate of the constant term due to gap size variations of  $c_{\text{gap}} = 0.16\%$  [14]. The measurement of the gap size uniformity presented here takes into account further effects like deformations in the assembled wheels and possible systematic uncertainties from the in situ cosmic muon analysis.

#### 4 In situ EM calorimeter performance with cosmic muons

In the previous sections, we demonstrated the good performance of the electronics operation and the good understanding of the energy reconstruction. The cosmic ray events can

therefore now be used to validate the Monte Carlo simulation that will be used for the first collisions.

Two such analyses are presented in this section: the first study aims to investigate the electromagnetic barrel calorimeter uniformity using ionization signals from quasi-projective cosmic muons, and the second aims to reconstruct electromagnetic showers from radiative cosmic muons and to compare the measured shower shapes with simulation.

#### 4.1 Monte Carlo simulation

The ATLAS Monte Carlo [35, 36] simulates the interaction of particles produced during LHC collisions or from cosmic muons within the ATLAS sub-detectors. It is based on the Geant4 toolkit [37] that provides the physics lists, geometry description and tracking tools. For cosmic muons, the material between the ground level and the ATLAS cavern is also simulated, i.e. the overburden and the two access shafts. The simulated cosmic ray spectrum corresponds to what was measured at sea level [38]. Air showers are not simulated but have a negligible effect on the analyses presented here. In order to save CPU time, the generated events are filtered before entering the full Geant4 simulation by requiring that the particles cross a specific detector volume (in the following analyses, typically inner detector volumes).

An important use of the simulation, amongst many others, is to validate the selection criteria on shower-shape for high-level trigger and offline algorithms, as well as to derive the electron and photon energy calibrations.

It is important to note that, thanks to the digitization step of the calorimeter simulation which emulates the behavior of the electronics, the standard energy reconstruction procedure can be applied to the simulated events. The special procedure used for asynchronous cosmic muon data, which uses an iterative determination of the event time, is however not applied to the Monte Carlo data.

#### 4.2 Uniformity of the electromagnetic barrel calorimeter

##### 4.2.1 Goals and means of the analysis

Any non-uniformity in the response of the calorimeter has a direct impact on the constant term in the energy resolution (see Sect. 3.4.4); great care was taken during the construction to limit all sources of non-uniformity to the minimum achievable, aiming for a global constant term below 0.7%. The default ATLAS Monte Carlo simulation emulates the effect of the constant term, but for the present analysis, this emulation was turned off.

The uniformity of the calorimeter was measured for three barrel production modules using electrons during beam test campaigns [4]. Cosmic muons provide a unique opportunity to measure the calorimeter uniformity in situ over a larger

number of modules, unfortunately limited to the barrel calorimeter due to both the topology of the cosmic muon events and the choice of triggers. The scope of this analysis is nevertheless quite different than in the beam test. First, muons behave very differently from electrons: in most events, they deposit only a minimum ionization energy in the liquid argon and they are much less sensitive to upstream material. The result can therefore not be easily extrapolated to the electron and photon response. Second, the cosmic run statistics are limited, so uniformity cannot be studied with cell-level granularity. The goal of this cosmic muon analysis is rather to quantify the agreement between data and Monte Carlo, and to exclude the presence of any significant non-uniformity in the calorimeter response.

A previous uniformity analysis using cosmic muons [39] from 2006 and 2007 relied on the hadronic Tile calorimeter to trigger events and to measure the muon sample purity. For the 2008 data discussed here, both the muon spectrometer and inner detector were operating and were used for triggering and event selection. The data sample consists of filtered events requiring a reconstructed track in the inner detector with at least one hit in the silicon tracker. The tracks are also selected to be reasonably projective by requiring that their transverse ( $|d_0|$ ) and longitudinal ( $|z_0|$ ) impact parameters, with respect to the center of the coordinate system be smaller than 300 mm.

#### 4.2.2 Signal reconstruction

In the first step, a muon track is reconstructed in the inner detector. For that purpose, a dedicated algorithm looks for a single track crossing both the top and bottom hemispheres. This single track is then extrapolated both downward and upward into the calorimeter.

Around the two track impact positions in the calorimeter, a rectangle of cells (the cell road) is selected in the first and second layers (the signal to noise ratio for muons is too low in the third layer). The cells of the first layer have a size of  $\Delta\eta \times \Delta\phi = 0.003 \times 0.1$  and  $12 \times 3$  such cells are kept. Similarly, the cells of the second layer have a size of  $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ , and  $5 \times 5$  such cells are kept.

To reconstruct the energy of the selected cells, the muon timing is obtained via an iterative procedure that is usually only applied to cells with an ADC signal at least four times the noise level. Since most muons are minimum ionizing particles, the muon signal is small, typically 150 MeV is deposited in the most energetic cell in the second layer, only five times the noise, and many cells do not pass this threshold. Therefore, an alternative reconstruction is used in this analysis: in the first pass, the iteration threshold is lowered to zero so that the timing is computed for most of the cells. In the second pass, the timing of the most energetic cell determined in the first pass is applied to all the other cells of

the road. The cell energy is reconstructed at the electron energy scale and thus does not represent the true energy loss of the muon. Finally, clusters are formed in each layer to reconstruct the muon energy loss. The criteria used to decide on the cluster size are described below.

#### 4.2.3 Optimization of the uniformity measurement

In order to perform the most accurate evaluation of the calorimeter uniformity, the measurement granularity, the cluster size and the selection cuts have been optimized. The granularity chosen is a compromise between the need for high statistics (large binning) and the need for high precision. The cluster size optimizes the signal to noise ratio while the selection cuts reduce the biases while keeping high statistics.

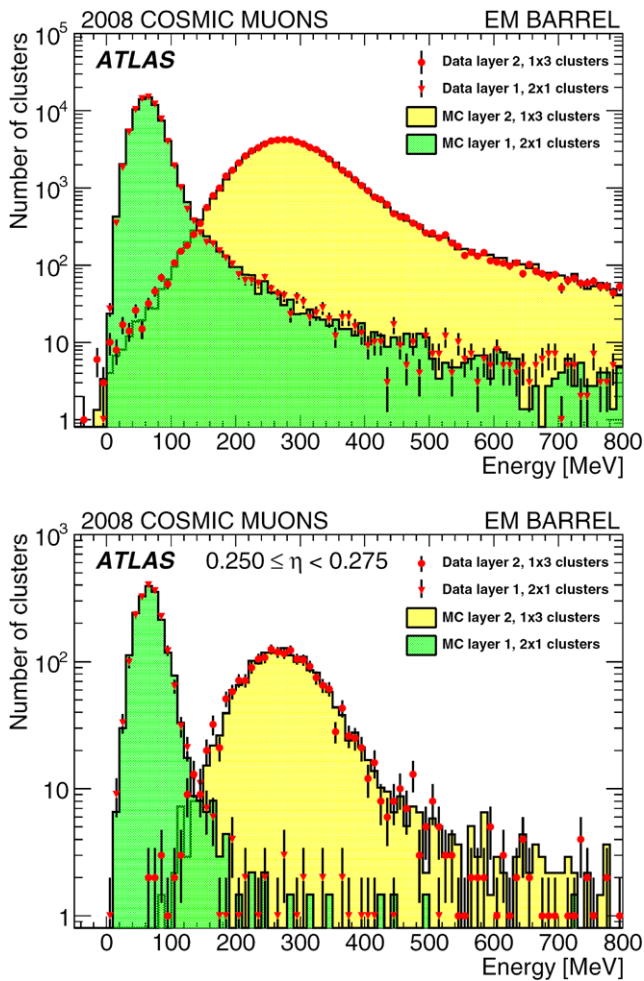
The binning is determined by requiring a minimum of 500 events per unit. In the  $\eta$  direction, this corresponds to bins of 0.025 (equal to the second layer cell width) up to  $|\eta| = 0.7$  and wider bins above.

In the first layer, the muon energy loss is measured using a  $\Delta\eta \times \Delta\phi = 2 \times 1$  (in first layer cell unit) cluster, which contains most of the deposited energy. Adding an additional cell brings more noise than signal. In the second layer, a  $1 \times 3$  (in second layer cell unit) cluster is used: it suffers less from noise than a  $3 \times 3$  cluster, but requires the removal of non-projective events which leak outside the cluster along the  $\eta$  direction.

This projectivity cut is based on the centrality of the muon in the second layer cell: when the muon passes close to the edge of the cell, a very small non-projectivity induces a large energy leakage into the neighboring cell. Therefore, for each second layer cell, eight bins corresponding to the eight first layer cells located in front of it were defined, and in each bin a cut is applied on the beam impact parameter  $z_0$  of the track, such that the muon is geometrically contained in the second layer cell. The remaining statistics after this projectivity cut is 76 k events in the data sample and 113 k events in the Monte Carlo sample. The events are mainly located under the cavern shafts leading to a coverage of around 20% of the full electromagnetic barrel calorimeter.

A comparison of the energy reconstructed in the first and second layers between data and Monte Carlo events is shown in Fig. 18. Because the muon energy loss is mostly  $\eta$ -dependent, both distributions are shown for all events (top), showing a large width due to the variation of the energy response over  $\eta$ , and for a single  $\eta$ -bin (bottom).

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 front layer and 1% in the second layer. Part of the difference comes from the slight difference in acceptance for data and Monte Carlo, as well as from the difference in energy reconstruction. This overall energy scale difference is corrected for in the MC in the rest of the study.

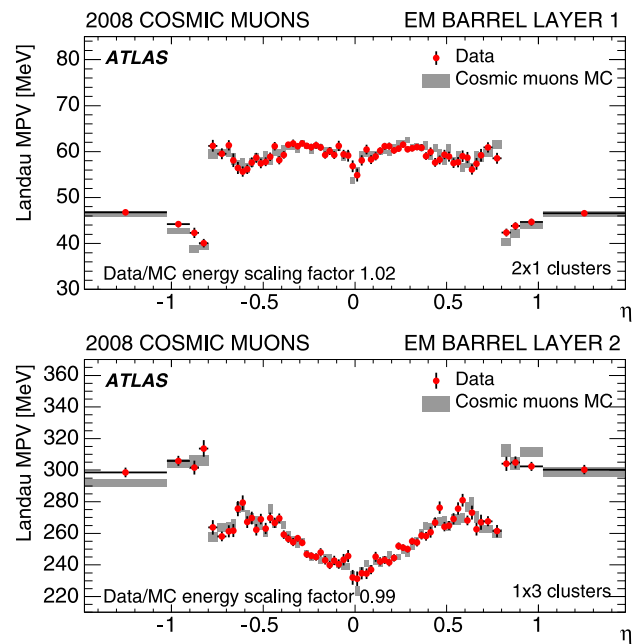


**Fig. 18** Energy in a  $2 \times 1$  cluster in the first layer (histogram for Monte Carlo and triangles for data) and in a  $1 \times 3$  cluster in the second layer (histogram for Monte Carlo and full circles for data) for all events (top) and a single  $\eta$ -bin (bottom)

#### 4.2.4 Calorimeter uniformity along $\eta$

Given the limited statistics of the projective cosmic muon data, the uniformity of the response in  $\eta$  cannot be estimated at the cell level. A natural choice of cell combination is to integrate clusters in  $\phi$  since the response should not vary along this direction due to the  $\phi$  symmetry of the calorimeter. The response along the  $\eta$  direction for cosmic muons depends on the variation of the amount of liquid argon seen by the muon. In particular, a transition occurs at  $|\eta| = 0.8$  where the lead thickness goes from 1.53 mm to 1.13 mm.

The estimation of the muon energy in each  $\eta$ -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. In particular, a 10% difference is observed between the width of the Gaussian expected from the electronic noise and the width of



**Fig. 19** Landau MPV as a function of  $\eta$  in the first (top) and second (bottom) layers for the data (red points) and Monte Carlo (grey bands)

the fitted Gaussian. Mostly this bias comes from remaining cluster non-containment effects which are found to be  $\eta$ -independent and thus do not produce any artificial non-uniformity. The most probable value (MPV) of the Landau distribution estimates the energy deposition.

Distributions of data and Monte Carlo MPVs along the  $\eta$  direction for the first and second layers are shown in Fig. 19.

In the first layer, the MPVs are roughly constant along  $\eta$ , except around  $\eta = 0$  where some cells are physically missing in the detector, and around  $|\eta| = 0.6$  where the cell depth is varying. In the second layer, the response follows a typical “V-shape” corresponding to the variation of the cell depth along  $\eta$  that rises up to  $|\eta| = 0.6$ . Again, the agreement between the data and Monte Carlo is very good, showing that the contribution of systematic effects due to the energy reconstruction method or the non-projectivity of the tracks is small.

The response uniformity  $U_{\text{meas}}$  is given by the RMS of the normalized differences between the data and Monte Carlo MPVs in each  $\eta$ -bin:

$$U_{\text{meas}} = \sqrt{\frac{\sum_{i=1}^{N_b} (U_{i,\text{meas}} - \langle U_{i,\text{meas}} \rangle)^2}{N_b}}, \quad (11)$$

with:

$$U_{i,\text{meas}} = \frac{\text{MPV}_{i,\text{Data}} - \text{MPV}_{i,\text{MC}}}{\text{MPV}_{i,\text{Data}}}, \quad (12)$$

where  $U_{i,\text{meas}}$  is averaged over  $\phi$ ,  $N_b$  is the number of bins in  $\eta$ , and  $\langle U_{i,\text{meas}} \rangle = 0$  since the global energy scale difference was corrected by rescaling the MC.

The measured uniformity should be compared to the expected uniformity  $U_{\text{exp}}$ , which is obtained similarly to (11) with  $U_{i,\text{exp}}$  given by:

$$U_{i,\text{exp}} = \frac{\text{MPV}_{i,\text{MC}}}{\text{MPV}_{i,\text{Data}}} \sqrt{U_{i,\text{Data}}^2 + U_{i,\text{MC}}^2} \quad (13)$$

with:

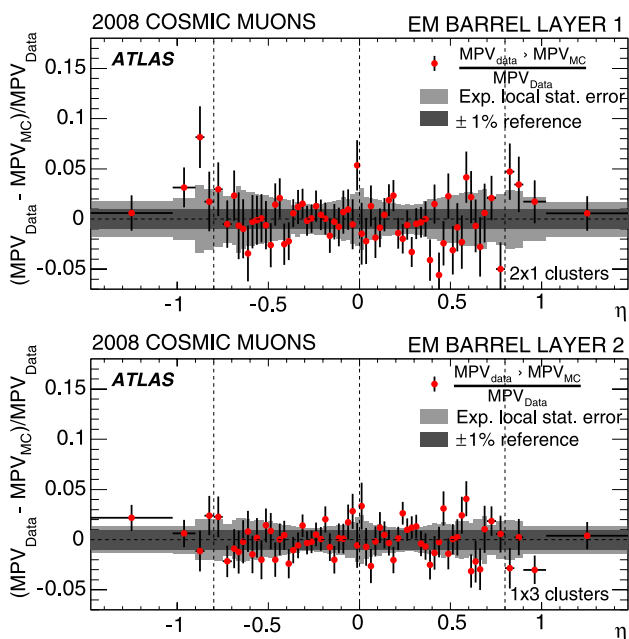
$$U_{i,\text{Data(MC)}} = \frac{\sigma(\text{MPV}_{i,\text{Data(MC)}})}{\text{MPV}_{i,\text{Data(MC)}}}, \quad (14)$$

where  $\sigma(\text{MPV}_{i,\text{Data(MC)}})$  is the statistical uncertainty on the measured Landau MPV. This uncertainty is due to the finite statistics of the data and Monte Carlo samples in each bin, the Landau dispersion of the ionization, and the electronic noise.

The measured uniformity  $U_{\text{meas}}$  should agree with the expected uniformity  $U_{\text{exp}}$  if the Monte Carlo simulation reproduces the data well: the key ingredients are the acceptance, the muon spectrum, and the energy reconstruction method. A significant departure of the measured uniformity from the expected one would be a measurement of additional non-uniformities  $U_{\Delta}$  ( $U_{\Delta}^2 = U_{\text{meas}}^2 - U_{\text{exp}}^2$ ).

The measured and expected uniformities for the two EM layers are shown in Fig. 20.

The fluctuations of the measured energies are large: the RMS of the corresponding distribution is  $2.4 \pm 0.2\%$  in the first layer and  $1.7 \pm 0.1\%$  in the second layer, showing that the statistical power of the analysis is limited given



**Fig. 20** Measured  $U_{i,\text{meas}}$  (red points) and expected  $U_{i,\text{exp}}$  (light grey band) cosmic muon energy dispersions as function of  $\eta$  for the first (top) and second (bottom) layers of the EM barrel. The dark grey band indicates a  $\pm 1\%$  strip for reference

the available data and Monte Carlo statistics. The fluctuations mostly remain within the limits of the band representing the expected values. The RMS of the latter distribution is 2.2% in the first layer and 1.6% in the second layer. This demonstrates that no significant additional non-uniformity ( $U_{\Delta}$ ) is present in the data. An upper limit is derived and yields  $U_{\Delta} < 1.7\%$  @ 95% CL in the first layer, and  $U_{\Delta} < 1.1\%$  @ 95% CL in the second layer.

The calorimeter response uniformity along  $\eta$  (averaged over  $\phi$ ) is thus consistent at the percent level with the Monte Carlo simulation and shows no significant non-uniformity.

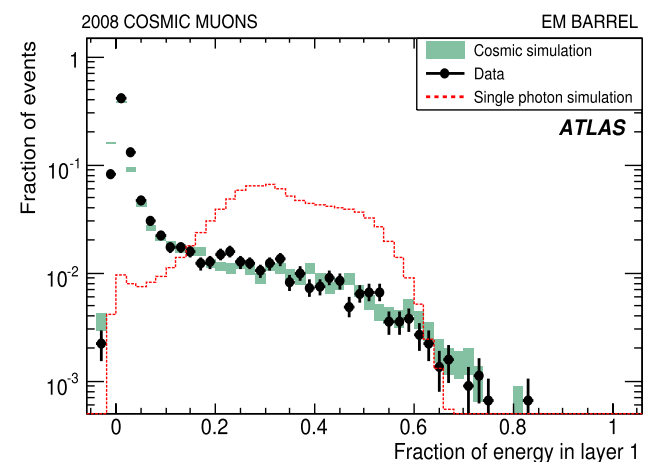
### 4.3 Electromagnetic shower studies

The second analysis aims at validating the Monte Carlo simulation of the distribution of some key calorimeter variables used in the ATLAS electron/photon identification. This is done using radiative cosmic muons that can give rise to electromagnetic showers in the calorimeter through bremsstrahlung or pair conversions.

#### 4.3.1 Selection of radiative muons

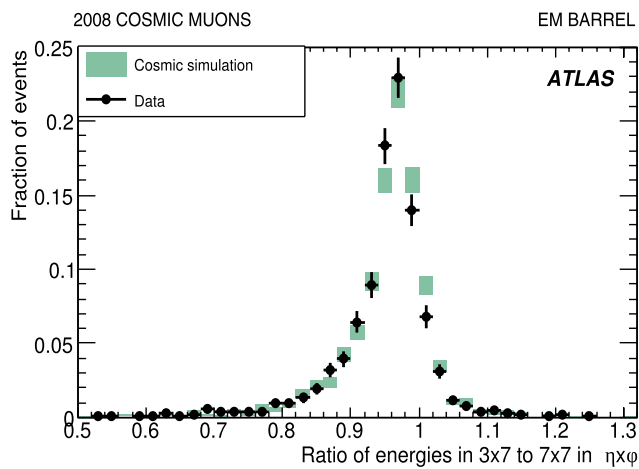
To increase the probability of the presence of a muon in the event, it is requested that at least one track has been reconstructed in the inner detector barrel with  $|d_0| < 220$  mm and  $p_T > 5$  GeV: these cuts ensure a similar acceptance for data and Monte Carlo.

A radiative energy loss is searched for in the electromagnetic barrel calorimeter by requiring a cluster with an energy greater than 5 GeV. Since the radiation can occur anywhere along the muon path, the corresponding shower is not always fully contained in the electromagnetic calorimeter: this is visible in Fig. 21 which shows the fraction of the cluster



**Fig. 21** Fraction of cluster energy deposited in the first layer of the electromagnetic barrel calorimeter for cosmic data (dots) and Monte Carlo (rectangles), as well as for simulated single photons of 5 GeV momentum from interaction vertex (red histogram)





**Fig. 22** Lateral shower containment in the second layer of the calorimeter given by the ratio of the energy deposited in a  $3 \times 7$  cluster to a  $7 \times 7$  cluster for radiative cosmic muon data (*dots*) and Monte Carlo simulation (*rectangles*)

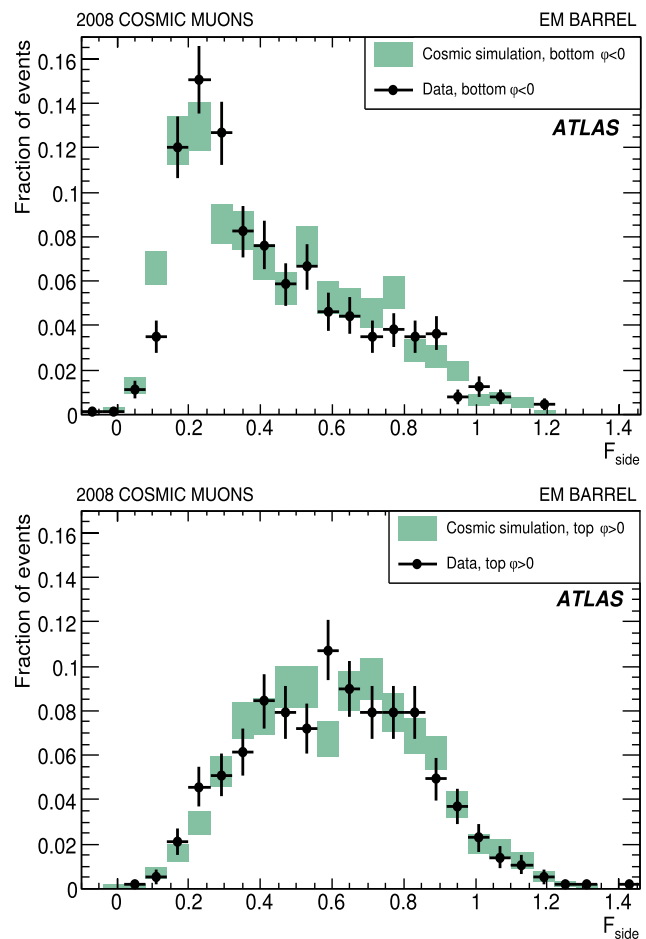
energy deposited in the first layer for simulated single photons from interaction vertex and for electromagnetic showers from radiating cosmic muons. This shows that the longitudinal shower development of the radiative photons is well reproduced by the Monte Carlo simulation, and that most of the radiating muons deposit very little energy in the first layer. To select “collision-like” showers, this fraction is requested to be greater than 0.1. A total of 1200 candidates remain in the data sample and 2161 in the Monte Carlo after this selection.

#### 4.3.2 Shower shape validation

Various shower shape distributions used for photon identification have been compared with the Monte Carlo simulation: Figs. 22 and 23 show two distributions of variables related to lateral shower containment in the first and second layers of the electromagnetic calorimeter.

Figure 22 shows the ratio of the energy deposited in a  $\Delta\eta \times \Delta\phi = 3 \times 7$  (in second layer cell unit) cluster to that in a  $7 \times 7$  cluster, in the second layer of the barrel calorimeter. In LHC collisions, this variable distinguishes electromagnetic showers, contained in 3 cells in  $\eta$ , from hadronic showers, leaking outside these 3 cells. The contribution from the noise explains that the ratio can be above 1.

Figure 23 shows the variable  $F_{\text{side}} = (E_{\pm 3} - E_{\pm 1})/E_{\pm 1}$  computed as the ratio of energy within seven central cells in the first layer ( $E_{\pm 3}$ ), outside a core of three central cells ( $E_{\pm 1}$ ), over energy in the three central cells: in LHC collisions, this variable typically separates photons, where little energy is deposited outside the core region, from  $\pi^0$ s, where the two photons produced by the  $\pi^0$  deposit some energy outside the core region. The agreement between the Monte Carlo simulation and the cosmic ray data is very good in



**Fig. 23** Lateral shower containment in the first layer for “collision-like” (*top panel*) or “reverse” (*bottom panel*) electromagnetic showers for radiative cosmic muon data (*dots*) and Monte Carlo simulation (*rectangles*). The definition of the  $F_{\text{side}}$  is given in the text

both the cases where the electromagnetic shower develops in the “collision-like” direction (in the bottom hemisphere) and the case where it develops in the backward direction (in the top hemisphere).

Within the statistics available from data, important calorimeter variables used in the electron/photon identification in ATLAS illustrate the good agreement between the Monte Carlo simulation and electromagnetic showers from radiative cosmic events in the calorimeter. These results, as well as the numerous comparisons done with beam test data [2–6], give confidence that robust photon and electron identification will be available for early data at the LHC.

## 5 Conclusions and perspectives

The liquid argon calorimeter has been installed, connected and fully readout since the beginning of 2008. Since then, much experience has been gained in operating the system.

Thanks to the very stable cryogenics and electronics operation over this period, first performance studies with the complete LAr calorimeter coverage have been done using several months of cosmic muon data and with LHC beam splash events from September 2008. These data provided a check of the first level trigger energy computation and the timing of the electronics. In the EM calorimeter, detailed studies of the signal shape predictions allow to check that, within the accuracy of the analysis, there is no extra contribution to the dominant contributions to the intrinsic constant term of the energy resolution. This indicates that the reach of a global constant term of 0.7% is achievable. The non-uniformity of the EM barrel calorimeter response to cosmic muons is consistent at the percent level with the simulated response. Finally, the electromagnetic shower profiles are in good agreement with the simulated ones, thus validating the Monte Carlo description. All these results allow for strong confidence in the readiness of the LAr calorimeter for the first LHC collisions.

The ultimate LAr calorimeter performance will be assessed with collision data: this is particularly true for the electromagnetic and hadronic energy scale computation in the ATLAS environment, which is needed for many ATLAS physics analyses.

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The ATLAS detector design and construction has taken about fifteen years, and our thoughts are with all our colleagues who sadly could not see its final realisation.

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