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## Performance of the ATLAS Tile Calorimeter in LHC Run-2

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**ABSTRACT:** The Tile Calorimeter (TileCal) is a sampling hadronic calorimeter covering the central region of the ATLAS experiment, with steel as absorber and plastic scintillators as active medium. The scintillators are read out by wavelength shifting fibres to photomultiplier tubes (PMTs at the back of each wedge-shaped calorimeter module). The analogue signals from the PMTs are amplified, shaped, and digitized on the detector every 25 ns, and stored on detector in digital pipeline buffers until a trigger decision is received. The data are then read out to the off-detector systems for further processing. The TileCal employs several calibration systems that, together with the collected collision data, provide the basis for response equalization and monitoring at each stage of the readout path; from scintillation light production to energy and time reconstruction. Furthermore, the calorimeter performance has been established with test beam data, cosmic ray muons and large samples of proton-proton collision data. During LHC Run-2, high-momentum isolated muons have been used to study and validate the electromagnetic scale, while hadronic response has been probed with isolated hadrons. The calorimeter time resolution has been studied with multi-jet events. We present and summarize results of the calorimeter calibration and performance.

**KEYWORDS:** Calorimeter methods; Calorimeters; Detector alignment and calibration methods (lasers, sources, particle-beams); Performance of High Energy Physics Detectors

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## 1 Introduction

In high energy physics experiments, hadronic calorimeters are crucial in identification of hadronic jets and measurement of their energy and direction. They also provide information for triggers and participate in the measurement of the missing transverse momentum carried by non-interacting particles.

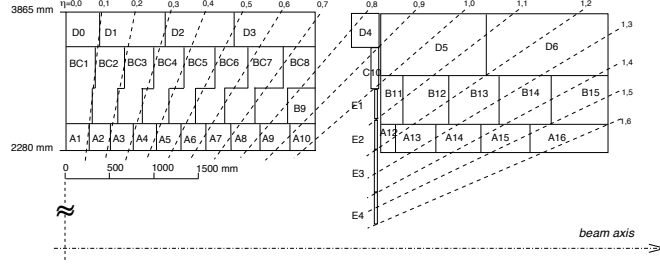
The barrel portion of the hadronic calorimeter employed by ATLAS [1], one of the two general-purpose experiments at the Large Hadron Collider (LHC), is called the Tile Calorimeter (TileCal) [2]. Two cylinders limit its volume. The inner (outer) has a radius equal to 2.28 (4.23) m. The central barrel covers pseudorapidities<sup>1</sup> up to  $|\eta| < 1.0$ . The extended barrel part provides a coverage of the region  $0.8 < |\eta| < 1.7$ . It is a sampling calorimeter that uses steel absorber and scintillating plastic tiles as active material. When a charged particle passes through the scintillating tiles, ultraviolet light is emitted and collected at radial edges of each tile. The light is then transported via wavelength shifting fibers to Photomultiplier Tubes (PMT) located in a steel girder at the back of each barrel module.

The frontend electronics is divided along the  $z$ -axis (the beams axis) into four partitions, two long barrels (LBA and LBC) and two extended barrels (EBA and EBC). Each TileCal partition consists of 64 modules of equal azimuthal width  $\Delta\phi = 0.1$ . The cell layout of half long central barrel and extended barrel modules is shown in figure 1 for  $z > 0$ . A mirroring of those in the other direction in  $z$  defines the four partitions of the calorimeter. In each module a three-dimensional cell structure is defined by grouping several optical fibres connected to the same PMT. The longitudinal sampling layers, denoted A, BC and D have a granularity  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$  in the two innermost layers and  $\Delta\eta \times \Delta\phi = 0.2 \times 0.1$  in the outermost one.

Most TileCal cells are read out by two PMTs, accounting for 9856 readout channels in total corresponding to 5182 cells. The PMT output is a shaped current pulse read out at two gains, high and low. The ratio between the high gain and the low gain amplification is 64.

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<sup>1</sup>ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the  $z$ -axis along the beam pipe. The  $x$ -axis points from the IP to the centre of the LHC ring, and the  $y$ -axis points upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$ -axis. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ .



**Figure 1.** Segmentation in depth and  $\eta$  of the modules in half long central and extended barrel [1].

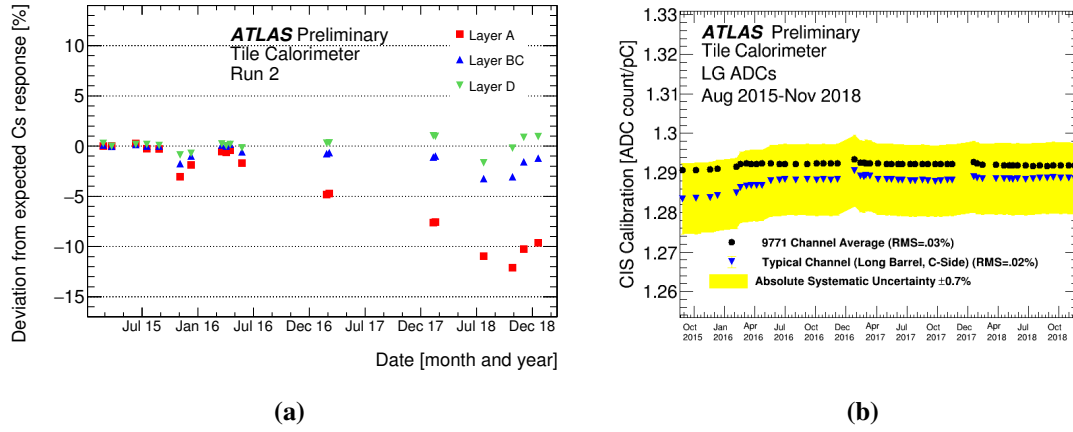
## 2 Calibration systems

At each level of the TileCal signal reconstruction, there is a dedicated calibration system to monitor the behavior of the different detector components. The reconstructed energy of each TileCal channel,  $E$  [GeV], is derived from the raw response,  $A$  [ADC], as follows:

$$E \text{ [GeV]} = A \text{ [ADC]} \cdot C_{\text{pC} \rightarrow \text{GeV}} \cdot C_{\text{TileSize}} \cdot C_{\text{Cs}} \cdot C_{\text{Las}} \cdot C_{\text{ADC} \rightarrow \text{pC}} \quad (2.1)$$

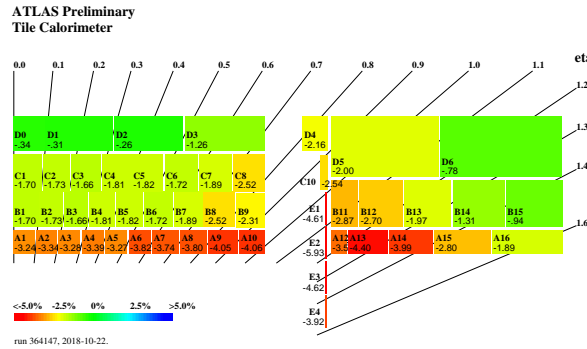
The  $C$  factors are calibration constants which can evolve in time because of variations in PMT high-voltage, stress induced on the PMTs by high light flux or aging of scintillators due to radiation damage. The calibration systems are used to monitor the stability of these factors and provide corrections for each channel. The electromagnetic scale calibration constant  $C_{\text{pC} \rightarrow \text{GeV}}$ , converting the electric charge (in pC) received from the PMT to the energy deposited in the TileCal cell, was fixed during dedicated test beam campaigns. Additional correction,  $C_{\text{TileSize}}$ , was applied to address the different size of tiles in different layers. The remaining calibration constants are provided by individual systems during the ATLAS operations: i) moveable Cesium radioactive  $\gamma$ -source to calibrate the optic components and the PMTs; ii) Laser system to monitor the PMTs and the electronic components; iii) Charge Injection System (CIS) to calibrate digital gains and linearities; iv) integrator Minimum Bias (MB) system to monitor beam conditions and the TileCal optics.

**Cesium calibration.** The Cesium calibration system employs three radioactive sources that can be moved using a hydraulic system to scan all TileCal cells. Each  $^{137}\text{Cs}$   $\gamma$ -source emits 0.662 MeV photons to illuminate the scintillators. The signal is collected through a special readout that integrates over 10 ms the analog PMT signals [3]. This system is used to calibrate the optical components of the calorimeter as well as the PMTs. The channel response to the energy deposits is used to equalize the response of all the cells and maintain global response of the calorimeter at the electromagnetic scale. A deviation of measured Cesium signals from expected values, corrected for the Cesium decay activity, is interpreted as cell light collection and PMT gain variations and translated into calibration constants,  $C_{\text{Cs}}$ . The deviation of  $C_{\text{Cs}}$  calibration constant from 1 (in %) during full Run-2 is shown in figure 2a. The precision of the system is of the order of 0.3%. Cesium calibration scans were spaced by one to three months up to 2015. During 2016 the frequency was reduced, and scans were taken only at the beginning and end of the proton-proton collisions period. The frequency of the Cesium calibration is not sufficient to track fast drifts of the PMT responses. The Laser system is used between two Cesium scans to correct for this.



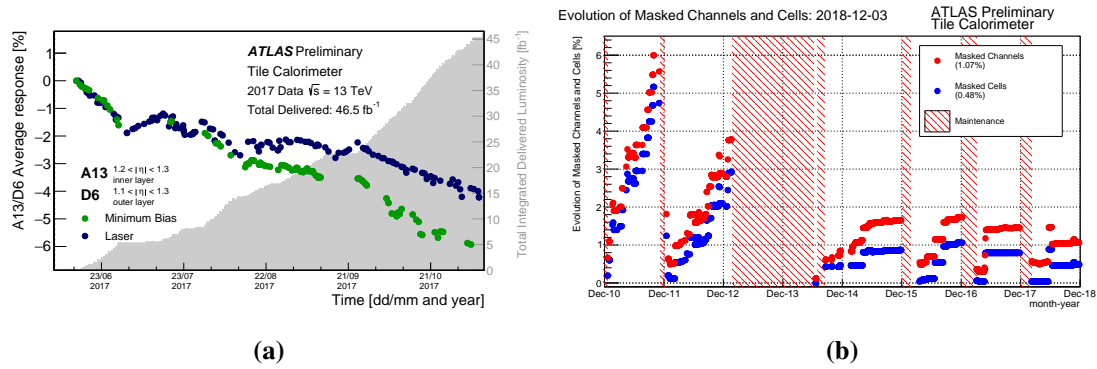
**Figure 2.** a) The variation in the TileCal cell response during Run-2 measured by Cesium system. b) The CIS calibration constant averages of all channels for calibration runs spanning Run-2 [4].

**Laser calibration.** The gain stability of each PMT is measured using a Laser calibration system [3] that sends a controlled amount of light onto the photocathode of each PMT in the absence of collisions. Deviations in a channel's response with respect to its nominal value (at the time of the latest Cesium calibration) is translated into a calibration constant:  $C_{Las}$ . The Laser calibration runs are taken daily to monitor the individual PMT gain variations between Cesium scans. The precision on the gain variation is better than 0.5% per channel. Figure 3 shows the mean gain variation per cell type observed during full proton-proton data taking period in 2018. Due to photocathode degradation the observed down-drift mostly affects cells at the inner radius, which are the cells with higher current. Laser pulses are also sent during empty bunch crossings of the LHC to monitor the time calibration.



electronic response. A linear fit to the mean reconstructed signal (in ADC counts) as a function of the injected charge yields the calibration constant. The corresponding calibration runs are taken daily. The overall stability of the calibration factor is at the level of 0.03% as shown in figure 2b and usually less than 1% of the channels exhibit large fluctuations.

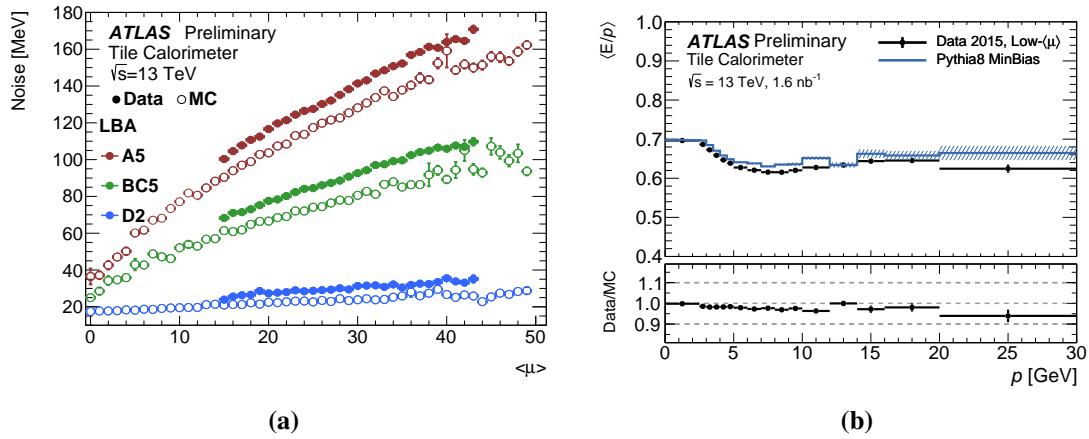
**Minimum Bias system.** Proton-proton collisions at the LHC are dominated by soft parton interactions, so-called Minimum Bias events. The PMT currents caused by MB events are integrated using the same integrator readout as in Cesium system with a time window of 10 ms. Data produced by the integrator are continuously recorded during collisions. They are used to monitor the stability of the full optical chain providing an independent cross-check of the Cesium calibration [3]. Figure 4 shows the variations in the response of the most highly irradiated regular cells observed by MB and Laser systems during the 2017 data taking period. The difference between Minimum Bias and Laser is interpreted as an effect of the scintillators' irradiation. The correction factors measured with the Minimum Bias system are applied during absence of Cesium calibration. This allows us to account for optical effects that are not corrected by the Laser calibration.



**Figure 4.** a) Variations in the response to Minimum Bias and Laser for cells in the inner layer of the extended barrel as functions of time during the 2017 data taking period. b) The percentage of masked cells and channels as functions of time from December 2010 to December 2018 [4].

### 3 Performance

**Detector status and data quality.** Performance of the TileCal is monitored online during data-taking. Additional detailed offline monitoring is performed within two days after each stable run and the calibration constants are corrected if needed. The cells or readout channels with severe problems that can affect the physics measurements are masked. If the problem is considered intolerable, then the affected data are not used in physics analyses. The TileCal achieved 100% data quality efficiency in 2015, 99.3% in 2016, 99.4% in 2017 and 100% in 2018. The evolution of the fraction of masked cells and channels in the TileCal from the beginning of ATLAS operations in 2010 is shown in figure 4b. The shaded regions correspond to maintenance periods, when the front-end electronics could be accessed and repaired. Regular maintenance helped to keep the fraction of masked cells below 1%.



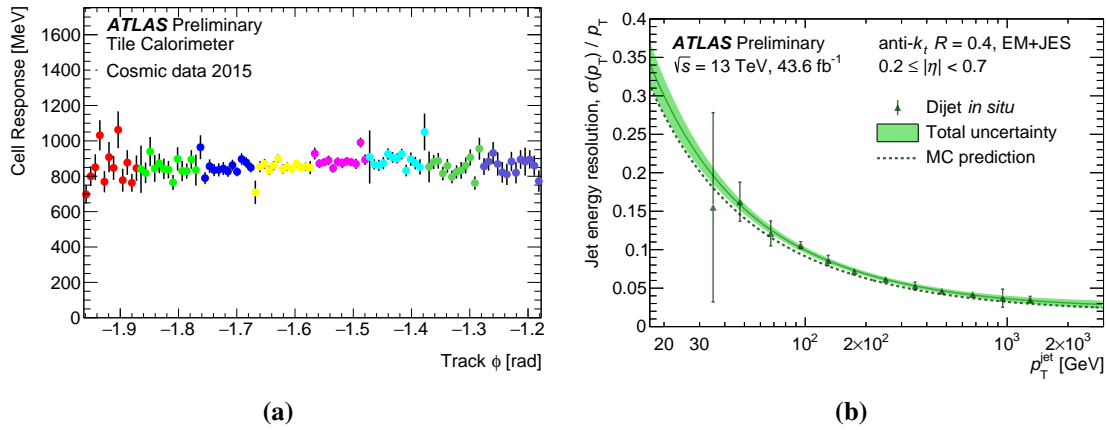
**Figure 5.** a) Total noise measured in the TileCal cells in data and MC as functions of  $\langle\mu\rangle$  [4]. b) The TileCal response to single isolated charged hadrons as a function of momentum [5].

**Noise.** Measurement of noise is essential for energy reconstruction of physics objects using the Tile Calorimeter. Noise in the TileCal consists of two components: electronics and pile-up noise. Electronics noise is defined as the width of the gaussian fit to the reconstructed cell energy distributions obtained in special runs without collisions. Pile-up noise arises from multiple interactions occurring in the same bunch crossing or from collisions in previous/following bunch crossings. It contributes to the signal response and to the widening of the cell energy distribution, increasing with the average number of interactions per bunch crossing  $\langle\mu\rangle$ . Figure 5a shows the increase of the total noise, defined as the standard deviation of the cell energy distribution, as a function of  $\langle\mu\rangle$ .

**Single particle, muon response and jet performance.** The ratio  $E/p$  is used to check the response of the calorimeter exploiting isolated tracks produced in Minimum Bias events [3]. The Inner Detector [1] allows a precise determination of low value momenta ( $p$ ). The quantity  $E$  is the energy of the shower deposited in the calorimeter by the particle measured at EM scale. In order to ensure that a large fraction of the tracks reach and deposit their energy in the TileCal, cuts limiting the energy deposited in electromagnetic calorimeter are applied. The  $E/p$  is used to evaluate calorimeter uniformity and linearity during data taking. Figure 5b shows the mean  $E/p$  as the function of track momentum measured in data and in MC simulation. The data agree with simulation within 5%, showing uniformity in detector response.

The interaction of muons with the detector material is well understood, so response to their passage can be predicted reliably. Therefore, muons from cosmic rays are used to study in-situ the electromagnetic energy scale and inter-calibrate the detector cells. Figure 6a shows the mean energy deposited by cosmic muon in the TileCal cells. Eight central-bottom modules are shown. The response uniformity across  $\phi$  is within few percents.

One of the main uses of the Tile Calorimeter is the measurement of jet energy and missing transverse energy. Figure 6b shows the relative jet energy resolution as a function of jet momentum in 2017 data and Monte Carlo. The jet energy resolution is better than 10% at momentum above 100 GeV. The energy resolution constant term agrees with the expected value of 3% [2].



**Figure 6.** a) Response of the TileCal to cosmic muons entering at different azimuth angle  $\phi$  in the center region of the calorimeter. Eight central-bottom modules are shown with different colors [4]. b) The relative jet energy resolution as a function of jet momentum in 2017 data and Monte Carlo [6].

## 4 Conclusion

The Tile Calorimeter is an important component of the ATLAS detector at the LHC. It performed very well during Run-2. Several calibration systems are used in conjunction: Cesium, Laser, Charge Injection and Minimum Bias. They allow the electromagnetic scale to remain within the required precision of about 1% providing an efficient monitoring and corrections of minute instabilities of the Tile Calorimeter cells response. Thanks to regular maintenance, the fraction of inefficient cells is kept below 1%. Performance of the TileCal is studied using charged hadrons and cosmic muons.

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