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Calibration and Performance of the ATLAS Tile Calorimeter during the LHC Run 2

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Summary. — The Tile Calorimeter (TileCal) covers the central part of the ATLAS experiment and provides important information for the reconstruction of hadrons, jets, hadronic decays of tau leptons and missing transverse energy. This sampling hadronic calorimeter uses steel plates as the absorber and scintillating tiles as the active medium. The TileCal calibration system comprises radioactive Cesium sources, lasers, charge injection elements and an integrator-based readout system. Combined information from all systems allows for monitoring and equalizing the calorimeter response at each stage of the signal production, from scintillation light to digitisation. The performance of the calorimeter is established with the large sample of the proton-proton collisions. A description of the different TileCal calibration systems and the results of the calorimeter performance during the LHC Run 2 are presented.

1. – Introduction

ATLAS [1] is a multi-purpose detector designed to reconstruct events from colliding protons and lead ions at the Large Hadron Collider. The Tile Calorimeter (TileCal) [2] is a central hadronic calorimeter ($|\eta| < 1.7$) in the ATLAS experiment. It is a sampling calorimeter using steel as an absorber and scintillating tiles as an active medium. Its main purpose is to provide important information for reconstruction of hadrons, jets, hadronic decays of tau leptons and missing transverse momentum. The calorimeter is divided into a central long barrel (LB) and two extended barrels (EB). The transverse segmentation is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in the first two radial layers and 0.2×0.1 in the outermost layer. The majority of cells are read out by two photomultiplier tubes (PMTs), only a small number of cells are read by a single PMT. TileCal has more than 5000 cells and approximately 10000 PMTs.

2. – Energy reconstruction and calibration of the calorimeter

The signal from the PMTs is shaped and amplified using two gains (1:64) and sampled every 25 ns. The signal amplitude (A) and time (t) are reconstructed using the optimal filtering algorithm [3]. The measured amplitude is multiplied by different calibration

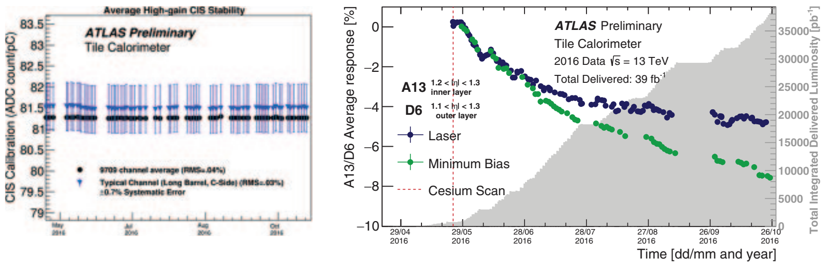

Fig. 1. – Left: The average of the CIS calibration constants for high-gain channels during 2016. Right: Variation of the response to the minimum bias (green) and the laser (blue) calibration for A13 cells with respect to reference cell D6 during 2016. Figures are taken from [6].

factors to obtain the channel energy in GeV:

$$E[\text{GeV}] = A[\text{ADC}] \times C_{\text{ADC}\rightarrow\text{pC}} \times C_{\text{laser}} \times C_{\text{Cs}} \times C_{\text{pC}\rightarrow\text{GeV}}, \quad (1)$$

where $C_{\text{ADC}\rightarrow\text{pC}}$, C_{laser} and C_{Cs} are factors derived by the dedicated calibration systems as described below. The last factor, $C_{\text{pC}\rightarrow\text{GeV}}$, sets the global electromagnetic scale (derived during test beams using electrons).

The conversion from ADC counts to pC, $C_{\text{ADC}\rightarrow\text{pC}}$, is measured using a charge injection system (CIS). The factor $C_{\text{ADC}\rightarrow\text{pC}}$ is determined by comparing a known injected charge with the response of the readout electronics. Typical uncertainty is 0.7% per channel. The overall stability of the calibration factor appears to be at the level of 0.02% (fig. 1, left). The CIS system is also used to monitor the front-end electronics and correct for non-linearities. The laser system [4] sends light pulses of adjustable intensity to each PMT to measure the individual PMT gain variation. Precision of the measurement is better than 0.5% for each channel. The laser calibration is typically taken together with the CIS calibration twice per week. The cesium (Cs) calibration system [5], which circulates a radioactive γ-source (^{137}Cs) through all cells, is used to monitor scintillators and PMTs and to equalize the readout response of the cells. The Cs signal is readout by slow integrators. Precision of the measurement is better than 0.5% for each channel.

In addition, the minimum bias system measures the detector response to soft parton interactions, so-called minimum bias events, using the slow integrator readout. It is used for monitoring of the instantaneous luminosity in ATLAS. The response of the minimum bias system together with results from laser calibration system is shown in fig. 1 (right). Both the cesium and the minimum bias systems measure the signal coming from scintillators and they are both expected to have the same variation in response over time, whereas the laser system monitors the gain stability of each PMT. The down-drifts of the PMT gains coincide with the collision periods, while up-drifts are observed during machine development periods, where no collisions occur. The difference between the minimum bias and the laser results is interpreted as an effect of the scintillators ageing due to irradiation.

3. – Performance of the calorimeter

A good description of the cell energy distribution and of the noise in the calorimeter is crucial for construction of topological clusters which are used for jets and missing trasverse momentum reconstruction. The total noise per cell in the calorimeter comes from two sources. First, there is the electronic noise which is measured in dedicated

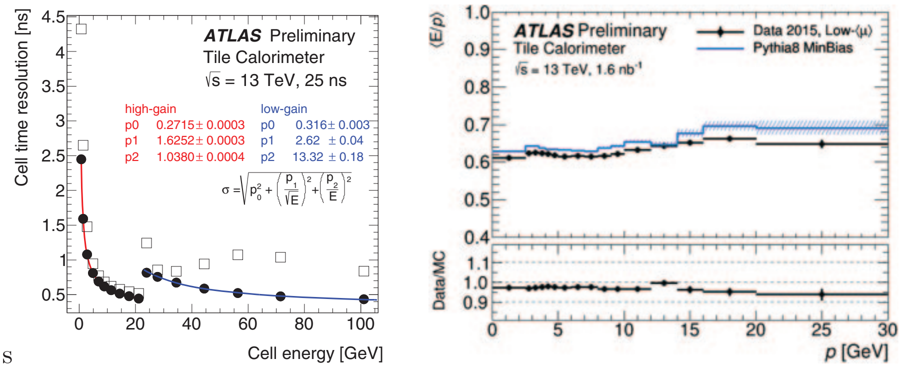

Fig. 2. – Left: The cell time resolution in jet events as a function of the energy deposited in cells. The closed circles correspond to Gaussian σ, the open squares indicate the RMS of the underlying time distributions. Right: Average energy-over-momentum ratio E/p as a function of the momentum of the track for isolated hadrons using 2015 data. Figures are taken from [7].

runs with no signal in the detector. Second, there is the contribution from pile-up which originates from multiple interactions occuring at the same bunch crossing or from the minimum bias events from previous/following bunch crossings. The pile-up contribution is the dominant effect under the LHC Run 2 conditions. Thus the largest noise values are in the regions with the highest exposure, *e.g.*, the noise in the cells in the innermost layer in the barrel region is about 150 MeV for the average number of interactions per bunch crossing of 30.

The reconstructed time in all TileCal cells/channels is monitored in physics and laser calibration data recorded during the proton-proton collisions runs. Cells associated with jets are used for the timing studies in collisions data to minimise the effect of the pile-up contamination in the sample. The cell time resolution in jet events as a function of the energy deposited in cells is shown in fig. 2 (left). The time resolution of the TileCal is better than 1 ns for energy deposits in a cell larger than a few GeV.

The validation of the reconstruction and calibration methods of the TileCal is done using isolated charged hadrons during LHC Run 2. The calorimeter response to the isolated charged hadrons is characterised by the mean of the energy-to-momentum ratio (E/p), where E is the cluster energy measured in the TileCal and p is the momentum of the associated track measured in the Inner Tracker. The mean value of E/p is approximatelly 0.6, reflecting the non-compensation of the calorimeter, as shown in fig. 2 (right). The agreement between the data and Monte Carlo simulations is about 4% which is at the level of the electromagnetic scale uncertainty of the TileCal as determined from studies of isolated particles and in test beam.

4. – Conclusions

The TileCal performance is very stable during the LHC Run 2. Together with other ATLAS subdetectors it contributes to the excellent measurement of jets, tau leptons and missing transverse momentum. The powerful calibration system, with a precision better than 1% for each of the individual calibration system, guarantees a good stability of the calorimeter response in time. The results of the *in situ* measurements in LHC Run 2 are in agreement with the electromagnetic energy scale uncertainty of 4% as observed in previous studies and in test beam.

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