PREPARED FOR SUBMISSION TO JINST

CALORIMETRY FOR THE HIGH ENERGY FRONTIER

2-6 OCTOBER 2017

LYON (FRANCE)

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

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ABSTRACT: The Tile Calorimeter (TileCal) is the hadronic sampling calorimeter of the ATLAS experiment at the Large Hadron Collider (LHC). TileCal uses iron absorbers and scintillators as active material and it covers the central region $|\eta| < 1.7$. Jointly with the other sub-detectors it is designed for measurements of hadrons, jets, tau-particles and missing transverse energy. It also assists in muon identification. TileCal is regularly monitored and calibrated by several different calibration systems: a Cs radioactive source, a laser light system to check the PMT response, and a charge injection system (CIS) to check the front-end electronics. These calibration systems, in conjunction with data collected during proton-proton collisions, Minimum Bias (MB) events, provide extensive monitoring of the instrument and a means for equalizing the calorimeter response at each stage of the signal propagation. The performance of the calorimeter has been established with cosmic ray muons and the large sample of the proton-proton collisions and compared to Monte Carlo (MC) simulations. The response of high momentum isolated muons is also used to study the energy response at the electromagnetic scale, isolated hadrons are used as a probe of the hadronic response. The calorimeter time resolution is studied with multijet events. A description of the different TileCal calibration systems and the results on the calorimeter performance during the LHC Run 2 are presented. The results on the pile-up noise and response uniformity studies are also discussed.

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1 Introduction

The Tile Calorimeter (TileCal) is the central section of the hadronic calorimeter of the ATLAS experiment [1]. Tile Calorimeter [2] covers the $|\eta| < 1.7$ region of the detector. It consists of one barrel and two extended barrel sections and surrounds the Liquid Argon (LAr) barrel electromagnetic and endcap hadronic calorimeters, as seen in Figure 1. The Long Barrel (LB) and Extended Barrel (EB) sections roughly correspond to $|\eta| < 1.0$ and $|\eta| > 1.0$, respectively. The crack region between the TileCal LB and EB and the LAr electromagnetic barrel and hadronic endcap sections are covered with special cells made by scintillators (E-cells).

The TileCal provides important information for reconstruction of hadrons, jets, hadronic decays of

Figure 1. A cut-away diagram of the ATLAS inner detector and calorimeter. The Tile Calorimeter consists of one barrel and two extended barrel sections [3].

tau-leptons and missing transverse energy. This sampling calorimeter uses iron plates as absorber and scintillating tiles as active medium. The calorimeter readout is segmented into about 5000 cells (longitudinally and transversally), each of them being read by two photomultipliers (PMTs). Only a small number of cells are read by a single PMT. Tile cells and electronics are organised into 4 partitions, LBA and LBC for the A-side and C-side of the barrel region, and separate EBA and EBC partitions in the extended barrel region. Each partition is divided into 64 symmetric ϕ slices (modules), with 45 instrumented channels in LB modules and 32 channels in EB modules. Both

LB and EB have up to three layers: the A-layer being the closest to the beam axis, followed by the B(C) and D-layers. The η and radial structure of the TileCal cells is shown in Figure 2 (left). The E-cells appear in yellow. They cover the gap/crack region with $1.0 < |\eta| < 1.6$. They are partly closer to the beam axis than the A-layer cells and are exposed to high radiation.

The TileCal has three key elements: the optical part (scintillators and fibers), the PMTs and the read-out electronics. Figure 2 (right) shows a schematic of the assembly of these components. The light is produced in scintillating tiles, collected and routed by WLS fibers and converted into electric currents by the PMTs. Their signal is shaped and amplified with two gains. The sampling and the digitisation is realised by ADCs. Trigger signals are formed by an analogue sum of input signals and sent to the calorimeter trigger system, which also considers input from other calorimeters. During collisions, if an event is selected by the trigger system, the digitised signals are collected and processed by a Read-Out Driver. In parallel to this, integrators measure the integrated current from the PMTs.

Figure 2. The TileCal cell and scintillator structure, including the so-called E-cells (E1-E4) installed in the gap/crack region, which are highlighted in yellow (left). Schematic of the mechanical assembly and the optical readout of the TileCal (right) [3].

2 Calibration Systems

At each level of the TileCal signal reconstruction there is a dedicated calibration system to monitor the behaviour of the different detector components. Figure 3 shows the different calibration systems along with the paths followed by the signals from different sources. Fast readout is used for physics analyses of collision data. The reconstructed energy of each TileCal channel, $E(\text{GeV})$, is derived from the raw response, $A(\text{ADC})$ as follows, where the different C factors are calibration constants which will be explained in the next paragraphs:

$$E(\text{GeV}) = A(\text{ADC}) \cdot C_{\text{ADC} \rightarrow \text{pC}} \cdot C_{\text{pC} \rightarrow \text{GeV}} \cdot C_{\text{Cesium}} \cdot C_{\text{Laser}}. \quad (2.1)$$

The factors can evolve in time because of variations of PMTs high-voltage, PMTs stress induced by high light flux or optics ageing. The calibration systems are used to monitor the stability of these elements and provide corrections for each channel. While $C_{\text{pC} \rightarrow \text{GeV}}$ was fixed during dedicated test beam campaigns [4], the remaining calibration constants are provided by individual systems during the data taking:

Figure 3. Flow diagram of the readout signal path of the different TileCal calibration tools. In the text “Particles” are named “MB events”. The paths are partially overlapping, allowing for cross-checks and an easier identification of component failures [3].

- A moveable Cesium [5] radioactive γ -source to calibrate the optic components and the PMT gains. The channel response to the energy deposits is used to equalise the response of all the cells and maintain global response of the calorimeter at the electromagnetic scale. Deviation of measured Cesium signals from expected values, corrected for the Cesium decay curve, are interpreted as gain variations and translated into calibration constants (C_{Cesium}). The calibration scans are performed every few months, each scan takes about 8 hours during non-collision time. The measurement precision is better than 0.3%.
- Laser system [6] to monitor the PMTs and the electronic components. This system sends a controlled amount of light onto the photocathode of each PMT in the absence of collisions. Deviations of any channel response with respect to its reference response (at the time of the latest Cesium calibration) is then translated into a calibration constant: C_{Laser} . The Laser calibration runs are usually taken twice a week to monitor the individual PMT gain variations between the Cesium scans. Figure 4 shows the mean gain variation per cell type between end of May and end of October 2016, covering most of the 2016 proton-proton collisions data taking period. Laser pulses are also sent during empty bunch crossings of the LHC, with a frequency of 4 Hz (1 Hz) during Run 2 (Run 1). The laser system allows also to determine the timing of the signal respect to the proton collision timing.

Figure 4. Tile Calorimeter PMT gain variation map during 2016 pp collisions period obtained with the laser system. Long Barrel (left) and Extended Barrel (right) [3].

- Calibrations of digital gains and linearities with the charge injection system (CIS) [7]. The corresponding calibration runs are taken from daily to weekly, so $C_{\text{ADC} \rightarrow \text{pC}}$ conversion factors

can be regularly produced and applied to data. The overall stability of the calibration factor is at the level of 0.02% and usually less than 1% of the channels exhibit large fluctuations. CIS calibration constants are updated if the deviation from the previous measured value is above the CIS systematic error (0.7%).

- Monitoring of TileCal optics with the integrator system minimum bias (MB). Both the Minimum Bias and the Cesium systems measure the signal coming from scintillators and the variation in PMT response over time. Thus, they are expected to give similar results. The Laser system measures only the PMT gain drifts in time. The variations observed by the MB and Cesium systems are sensitive to PMT gain drift and scintillator irradiation (ageing). Thus, the difference between MB, or Cesium, and the Laser measurements can be interpreted as a loss of efficiency of the scintillators by irradiation damage. The cell probed in Figure 5 (left), A13, is the most irradiated cell in TileCal, excluding the E-cells. The MB system allows also to determine the variation of the LHC luminosity [8]. Figure 5 (right) shows the response variation measured by the MB and the Laser system for E-cells, covering the region $(1.2 < |\eta| < 1.3)$ as a function of time. The integrated luminosity evolution during the same period is also shown in the plot.

Figure 5. The relative response variation measured by the MB system, after the subtraction of the PMT gain drift component measured by the Laser system, as a function of the integrated charge collected in the cells in the gap/crack region in the EB, covering the region $(1.0 < |\eta| < 1.6)$ and in the cells in the inner layer of the EB, covering the region $(1.2 < |\eta| < 1.3)$, during the 2016 pp collisions data taking periods (left) and the Tile Calorimeter response variation in time measured by the MB and the Laser system for E-cells during 2016 pp collisions data taking periods (right) [3].

3 Performance

To maintain the smallest possible number of “dead” cells and to ensure the highest quality of the data, the front-end electronics, normally not accessible during data taking, is maintained yearly during detector openings. During the winter shutdown of 2016–2017, 48 out of 256 electronics “drawers” were opened and all the high and many of the low priority problems were fixed, leading to the 0.06% of “dead” cells after the end of the maintenance.

The ever-increasing instantaneous luminosity of the LHC led to the increase of the pile-up and hence to the increase of the noise levels, well above the pure electronics noise that stays below

20 MeV for most of the cells, while the pile-up noise reached 160 MeV for the inner layer of the calorimeter cells.

The cell signal timing is determined with a precision better than 1 ns using collision events (see Figure 6, left). The timing is initially set with splashes and tuned later with jets. The stability of the time settings during the data taking is monitored with the laser pulses in empty bunches of LHC abort gap, described above.

The ratio of energy deposited in TileCal to track momentum (E/p) for isolated charged hadrons in minimum bias events is used to evaluate calorimeter uniformity and linearity during data taking. The data and simulation do agree, showing linearity and uniformity in detector response. The dE/dx of minimum ionising particles show data and Monte Carlo (MC) agreement within 4% (see Figure 6, right). Muons from cosmic rays, beam halo and collisions are used to study in-situ the electromagnetic energy scale. A 1% (3%) response non-uniformity in η is seen in Tile Calorimeter Long (Extended) Barrel. The energy scale is set with a precision of 3%.

Figure 6. The cell time resolution in jet events as a function of the energy deposited in Long Barrel cells of the Tile Calorimeter (left) and calorimeter response to single isolated charged hadrons, characterised by energy over momentum (E/p), as a function of η (right) [3].

3.1 Monte Carlo developments

The response of the PMTs is not flat in the azimuthal angle difference between the energy deposition point and the center of the cell ($\Delta\phi$), but it shows a non-negligible dependence referred to as U-shape. The dependence of the response on $\Delta\phi$ was measured using $W \rightarrow \mu\nu$ events in the 2012 collisions data. The measurement is performed separately in the Long Barrel and in the Extended Barrels in each radial layer. The typical shape is shown in Figure 7 (left) for the Long Barrel. The U-shape has been implemented in the MC simulations and is expected to improve the light propagation performance in future official productions. Figure 7 (right) shows the comparison between simulations with and without U-shape for the layer A in the Long Barrel.

4 Conclusions

The hadronic Tile Calorimeter allows to measure jet energy and missing transverse energy in ATLAS experiment at the LHC. A set of calibration systems is used to monitor and calibrate the

Figure 7. Response dependence on the azimuthal angle difference between the muon track impact point and the center of the cell ($\Delta\phi$) measured in 2012 collisions data (left) and for MC (right). Look-up tables are prepared based on measurements in data and normalized as follows: First, average value for one PMT is set to 0.5. Second, the look-up tables are rescaled to have the same sampling fraction for 100 GeV electrons at $\eta = 0.35$ in the center of the cell as the simulations without the U-shape [3].

calorimeter response with better than 1% precision. The electromagnetic energy scale allows to achieve a great performance of Tile Calorimeter in LHC Run 2 with 3% precision.

Acknowledgments

This work is partially supported by the Spanish Ministry of Economy, Industry and Competitiveness and the European Regional Development Fund (ERDF), contract number FPA2015-65652-C4-2-R (MINECO/FEDER).

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