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The ATLAS Tile Hadronic Calorimeter performance in the LHC collision era

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Abstract

The Tile Calorimeter (TileCal), the central section of the hadronic calorimeter of the ATLAS experiment, is a key detector component to detect hadrons, jets and taus and to measure the missing transverse energy. Due to the very good muon signal to noise ratio it assists the spectrometer in the identification and reconstruction of muons. TileCal is built of steel and scintillating tiles coupled to optical fibers and read out by photomultipliers. The calorimeter is equipped with systems that allow to monitor and to calibrate each stage of the readout system exploiting different signal sources: laser light, charge injection and a radioactive source. The performance of the calorimeter has been measured and monitored using calibration data, cosmic muons, LHC single beam and collision events. The results reported here assess the performance of the calibration systems, absolute energy scale, the energy and timing uniformity as well as the calorimeter performance with single hadrons. The results obtained demonstrate a good understanding of the detector and prove that its performance is within the design expectations.

1. Introduction

The ATLAS experiment [1] is successfully taking data from cosmic muons, single beams and proton-proton collisions since the startup of the LHC in September 2008, and in less than two years has already surpassed 2 fb\(^{-1}\) of collected integrated luminosity running at 7 TeV of center-of-mass energy [2] (Figure 1). The ATLAS detector is equipped with an inhomogenous hadronic calorimeter, the Tile Calorimeter (TileCal) [3], for the measurement of showers produced by heavy particles from LHC’s proton-proton collisions. TileCal is a sampling calorimeter made of scintillating tiles as active medium and steel plates as absorbers. It is divided into four partitions, two barrel and two extended barrel, covering in total a pseudorapidity range of \(|\eta| < 1.7\) and is segmented into 64 modules along the azimuth \(\phi\). Wavelength shifting fibers collect the light generated in the tiles and carry it to photomultipliers. Each photomultiplier receives signal from multiple tiles which are grouped in cells of different size depending on their pseudorapidity and depth. Three layers are defined and the dimensions of cells are optimized to obtain a structure of projective towers, see Figure 2). 5184 cells are read with double or single readout, the latter in case of special cells, for a total of 9856 channels and corresponding to a segmentation of the calorimeter of \(\Delta\eta \times \Delta\phi = 0.1 \times 0.1\) in the first two layers and 0.2 \(\times\) 0.1 in the last layer.

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The signal properties for each channel are reconstructed with an online weighting algorithm, the Optimal Filtering (OF) method [4], which computes the signal amplitude and time combining seven sequential digitized and weighted signals, taking as reference the pulse shape from \( \pi \)'s produced at the testbeam shown in Figure 3. The noise, measured in pedestal runs and with random triggered events, is modeled using a double gaussian description for the cell noise probability distribution (Figure 4).

To date, two maintenance periods have allowed intervention to the accessible parts of the calorimeter, i.e. mainly the electronics, in order to recover cells which were masked during data taking because of different problems, while detailed calibration runs are taken whenever data taking is suspended for long enough time. Before the maintenance period of winter 2010, 3.8% of the cells were unusable, while in May 2011 five full modules are off, corresponding to 2.1% of cells, and in total 2.4% of the cells are masked (see Figure 5).

2. Calibration System

TileCal has three calibration systems [3] used to derive the value for the energy measured in each channel \( E_{ch} \) from the signal amplitude in ADC counts \( A \) as measured with the OF method:

\[
E_{ch} = A \cdot C_{ADC\rightarrow pC} \cdot C_{pC\rightarrow GeV} \cdot C_{Cs} \cdot C_{laser}. \tag{1}
\]

The factor \( C_{pC\rightarrow GeV} \) comes from the calibration during testbeam of 11% of modules [5], using beams of high energy electrons to set the electromagnetic energy scale to 1.05 pC/GeV, while all the other terms are derived from the three
Figure 3: Reference pulse shape for the OF method, taken from testbeam data with pions for High Gain and Low Gain channels. Recent studies showed that the pulse shape is the same for any type of particle and has been also rederived from collisions.

calibration systems (see the scheme in Figure 6).

The Charge Injection System (CIS) allows to calibrate the front-end electronics gain by injecting a signal of known amplitude and phase into the front-end electronics. In this way the factor $C_{ADC \rightarrow pC}$, converting ADC counts in a charge, is extracted. Periodical calibration runs are regularly taken and show a very good stability in time, e.g. in 2010 the average difference was 0.04% and the single channel RMS spread was 0.07%. The Laser System, equipped with a laser located outside the ATLAS cavern, monitors the photomultipliers (PMTs) gain stability and linearity by sending light to the PMTs through optical fibers. Over a period of 40 days, the average gain variation is in general below 1%. The Cesium System (Cs) [6] is designed to let a Cesium-137 source pass through all calorimeter cells thanks to an hydraulic system. Three sources of similar activity are used, two for the extended barrel partitions and one for the central barrel partitions. Cesium scans provide measurements of single cell response with a precision of about 0.3%.

3. Timing

Accurate timing is important for the signal reconstruction performance, where the desired precision to which the signal arrival time (position of the peak in terms of signal shape) has to be known is 1 ns. Also intercalibration of cells within modules and partitions is a relevant issue. Figure 7 shows the results obtained with single beam studies in 2008 and 2010. In 2008 the cells times were synchronized with the laser system using a reference channel for each partition and then validated with cosmic muons [7], obtaining a precision on the intercalibration of 2 ns per partition but the four of them were disaligned in time with a difference of up to 10 ns for adjacent partitions. When LHC started running it provided single beams impacting on a closed collimator placed at about 140 m from the nominal collision point in the center of the ATLAS detector. The impact produced a huge number of very energetic particles reaching the detector parallel to the beam axis (“splash events”), which deposited a large amount of energy in the whole TileCal. Using 2008 splash events allowed to study the time intercalibration (Figure 7, left) and correct it to get the final result validated with 2010 splash events (Figure 7, right). The precision reached in the cells intercalibration is better than 1 ns. Furthermore, studies on clusters of energy used to reconstruct high momentum jets (“topoclusters” defined by ATLAS calorimeters energy clustering algorithm) show an RMS below 1 ns for the distribution of the time of cells forming the topocluster (Figure 8).
Figure 4: Defining the energy deposited in the cell as $E$ and the effective noise constant as $\sigma_{\text{eff}}$, the variable $E/\sigma_{\text{eff}}$ represents the significance level of energy deposit being compatible with noise in data, in units of gaussian sigmas. Noise modeled with a single gaussian model (red squares) does not result in a gaussian description of the tails after $4\sigma$, worsening the performance of the ATLAS calorimeter’s energy clustering algorithm. It has been observed that a double gaussian model (blue triangles) gives instead the expected gaussian behaviour (fit) obtained also with MonteCarlo simulation (black circles).

4. Performance

4.1. Performance with cosmic muons

Even before the startup of the LHC, cosmic muons allowed to validate the EM scale obtained at the testbeam, test the uniformity of the detector response and intercalibrate the time of the cells. The difference between the time offsets as measured with cosmic muons and with 2008 single beam splash events shows an agreement at the level of 1 ns, thus confirming the goodness of the analysis (Figure 9 left). The comparison between cosmic data and MonteCarlo prediction (Figure 9 right) and between testbeam muons and cosmic muons is used to validate the EM scale and shows that the propagation from testbeam to ATLAS was successful. In Figure 10 the uniformity of the response of cells of BC layer is shown as a function of pseudorapidity $\eta$ and azimuth angle $\phi$, for data and MonteCarlo prediction. A global uniformity within 3% is observed for all the layers.

4.2. Performance with collision data

The LHC began to run in 2009 providing collisions at $\sqrt{s} = 900$ GeV center-of-mass energy, later switching to 2.36 TeV and finally operating at 7 TeV. Figure 11 shows the distribution of energy deposition in TileCal from Minimum Bias events for the three different $\sqrt{s}$ points. The uniformity of cell response to first collisions at center-of-mass energy of 7 TeV is shown in Figure 12.

Some studies have been performed to analyse the response to single pions showering in TileCal. Isolated tracks of momentum $p$ are required to behave as minimum ionizing particles (mips) in the Electromagnetic LAr calorimeter in front of TileCal, to be sure their whole energy $E$ is deposited in the hadronic calorimeter. The mean value of the consequently defined $E/p$ ratio is shown in Figure 13 compared to MonteCarlo prediction, proving that a good agreement is obtained.

5. Conclusions

These first years of data taking and detector operation showed how well the ATLAS experiment and TileCal are performing as expected from design goals. The calibration systems for TileCal are efficiently monitoring the...
Figure 5: Left: two dimensional \((\eta, \phi)\) map showing the amount of cells masked per tower, each tower being composed by three cells in the three layers A, B/C, D. Right: evolution in time of the percentage of masked cells, red bands represent maintenance periods.

Figure 6: Scheme of the calibration systems and signal reconstruction process in TileCal. Signal is collected from tiles to photomultipliers through wavelength shifting fibers, then the photomultiplier output is shaped with a passive shaping circuit and amplified separately in High and Low Gain (HG and LG) branches, in proportion 64:1. HG and LG signals are then sampled at the LHC bunch-crossing frequency (40 MHz) and digitized. If a first level trigger “accept” command is received, the data are sent to ReadOut Driver Boards (RODs) outside the experimental hall.

calorimeter performance and its response, uniform within 2-3\% in \(\eta\) and \(\phi\), is observed to be stable in time. The energy scale uncertainty, which was successfully extrapolated from testbeam to ATLAS, is conservatively considered to be 4\%. The time synchronization between cells is well below 1 ns and has been verified with single beam and cosmic muons. A lot of studies, old analyses and new ones, are going on to maintain these achievements and to go further in understanding the behavior of this amazing device to the exciting physics happening now at the LHC.

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Figure 7: Time of cells, averaged over $\phi$. Different layers are shown in different color and style. On the left, studies with 2008 single beam splash events showed discontinuities between the four TileCal partitions, which were then corrected as shown in the 2010 analogous study, on the right, where a precision of better than 1 ns is reached.
Figure 8: Cell time distribution (in Low Gain) for cells belonging to topoclusters of reconstructed jets with $p_T > 20$ GeV.

Figure 9: Left: difference between time offsets from 2008 test beam and cosmic muons analysis. Right: muon energy loss per path length $dE/dx$ as a function of momentum of the track (measured in the Inner Detector).
Figure 10: Normalized truncated mean \( \frac{dE/dx}{<dE/dx>} \) as a function of \( \eta \) (left) and \( \phi \) (right), for data (black, full dots) and MC (red, open circles), showing the uniformity of the response to cosmic muons. Dotted lines delimit a \( \pm 3\% \) variation from unity.

Figure 11: Energy deposition in TileCal cells for different \( \sqrt{s} \) values, Minimum Bias MonteCarlo (\( \sqrt{s} = 7 \) TeV) and random triggered events.
Figure 12: Average energy deposition in TileCal cells as a function of $\eta$ (left) and $\phi$ (right), for data and MonteCarlo.

Figure 13: Mean value of the ratio between energy deposited in TileCal and track momentum (measured by the Inner Detector) as a function of $\eta$ (left) and $\phi$ (right), for isolated pions showering in TileCal.