Commissioning of the ATLAS Tile Hadronic Calorimeter with cosmic muons, single beams and first collisions

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Abstract. Until December 2009 the ATLAS detector has undergone a long period of commissioning with cosmic rays. The LHC collider delivered to the ATLAS detector brief periods of single beams and from December 2009 months of proton-proton collisions at different center of mass energy (900 GeV, 2.36 TeV and 7 TeV). The focus of these running periods was to commission the ATLAS detector for the 2010 collision run during which physics results were expected. In this paper, we will show how the data from cosmic muons, from single beam events and early collisions has been used to commission and to calibrate the ATLAS Tile Hadronic Calorimeter.

1. The Tile Hadron Calorimeter
The ATLAS Tile Calorimeter (TileCal) [1] is the barrel hadronic calorimeter of the ATLAS experiment [2] at the CERN Large Hadron Collider [3]. A cut-away drawing of the calorimeters and the inner detector is shown in Fig.1. The main goal of TileCal is the precise measurements of hadrons, jets, taus and the missing transverse energy ($E_T^{miss}$).

TileCal is a sampling calorimeter made of iron plates as absorber and plastic scintillator as active material. It is divided into three cylindrical sections, whose axes coincide with the colliding beam axis ($z$ axis). The cylindrical sections are referred to as the long barrel (LB) and extended barrels (EB).

Each of the three sections is composed of 64 azimuthal segments, referred to as modules, subtending $\Delta \phi = 2\pi/64 \simeq 0.1$ . Radially, TileCal extends from an inner radius of 2.28 m to an outer radius of 4.25 m. In the direction perpendicular to the beam axis the calorimeter is composed of 3 radial layers. The typical cell dimensions are $\Delta \phi_{cell} \times \Delta \eta_{cell} = 0.1 \times 0.1 \ (0.1 \times 0.2$ in the last radial layer). This segmentation defines a quasi-projective tower structure covering the region $|\eta| < 1.7$. The deviations from perfect projectivity are small compared to the typical angular extent of hadronic jets.

A schematic drawing of a module is given in Fig.2. The TileCal plates made of iron and scintillating material, are placed perpendicular to the colliding beam axis and are radially staggered in depth.
2. Calorimeter response to cosmic muons

Since the interaction of muons with matter is well understood and well modeled, cosmic rays measurements were used to provide information about the response of the detector.

The cosmic ray events used in this analysis have been collected with the ATLAS experiment between September and October 2008. The selection of the events relies on the RPC and TGC systems of the Muon Spectrometer [4]. The analysis is based on a total of about 1M triggered events. The tracks are reconstructed using the Inner Detector system [5] information and are extrapolated through the volume of the calorimeters taking into account of material and magnetic field. The track path length $d_x$ is then evaluated as the distance between the entrance and the exit points for every cell crossed by the muon.

The events are required to have a reconstructed track in the Inner Detector with at least 8 hits in the Pixel and SCT systems. The tracking requirement introduce some cut-off in the distributions of transverse and longitudinal impact parameters. These are $|d_0| < 380$ mm and $|z_0| < 800$ mm respectively. The events are further required to have the track momentum in the window $10 \text{ GeV} < p < 30 \text{ GeV}$. The lower limit was applied to minimize effects of multiple scattering. The upper cut restricts the muon radiative energy losses which otherwise cause considerable fluctuations in the deposited energy. A small fraction of events has the cell response compatible with the pedestal level although the cells should be hit by the muon. This happens because the particle actually crosses a neighboring cell and it is consistent with the expected deviation from a linear muon trajectory due to multiple scattering. In order to remove this effect, only tracks that are well within a module were selectected by applying the cuts $|\Delta \phi_{\text{in}}| = |\phi_{\text{cell}} - \phi_{\text{in}}| < 0.045$ and $|\Delta \phi_{\text{out}}| = |\phi_{\text{cell}} - \phi_{\text{out}}| < 0.045$, where $\phi_{\text{in}}$($\phi_{\text{out}}$) is the azimuthal angle of the entrance (exit) point of the muon trajectory in the cell. In order to remove residual noise contribution, a low cut $dE_{\text{cut}} = 60 \text{MeV}$ was applied on the measured cell energy $dE$. Deposits of energy in a short path have a larger variation of the sampling fraction. In order to limit this effect only tracks with path length $dz > 200$ mm were considered. The energy deposited by a muon track with a trajectory close to the vertical direction is badly measured in TileCal due to the strong sampling fraction variation caused by the vertical orientation of the scintillating tiles. To ensure more stable results, tracks are required to have a minimum cell path $z$ component. The cut $z = |z_{\text{in}} - z_{\text{out}}| > 6$cm was applied, where $z_{\text{in}}$ and $z_{\text{out}}$ are the
crossing points at the z cell surfaces.

Figure 3. On the left the response of the barrel module BC cells as a function of track path length is shown. A linear fit to the corresponding distribution of mean values is superimposed. The excess of events around the track path length of 840 mm (radial size of the BC cells of the barrel module) is a purely statistical effect, since most of the cosmic ray muons enter the calorimeter at small zenith angle. On the right the distribution of the truncated mean $dE/dx$ per cell, shown for the radial layer D for data and MC.

Figure 4. Uniformity of the A layer cell response to cosmic muons, expressed in terms of normalised truncated mean of $dE/dx$, as a function of azimuthal angle $\phi$ (left) and the pseudorapidity $\eta$ (right).

At energies in the range between 10 GeV and 30 GeV the dominant energy loss process
is ionization and the energy lost is essentially proportional to the track path length (Fig. 3-left). The response of the detector was then studied determining the ratio between the energy deposited in a calorimeter cell \((dE)\) and the length of the path of the track in the cell \((dx)\). Our estimator for the muon response is the truncated mean of \(dE/dx\), defined as the mean in which 1% of the events in the high-energy tails of the distribution are removed. This quantity is less affected by the higher energy loss processes (bremsstrahlung, \(\delta\)-rays...) that can cause fluctuations on the mean \(dE/dx\).

The uniformity of the cell response in the layer D is shown in Fig. 3-right. The cells considered are required to have at least 100 selected muon deposits. For the D layer 316 cells fullfill this requirement and represent 38% of the total number of cells in this layer. The distribution is compared with Monte Carlo (MC) simulated cosmic events. Since the MC shows an RMS compatible with that of data, it indicates that cells are well intercalibrated within the layer. Fig. 4 shows the cell response, expressed in terms of truncated mean of \(dE/dx\), as a function of \(\phi\) and \(\eta\) for the layer A cells. The \(dE/dx\) values are normalized on the average \(dE/dx\) of all the cells of the layer. Data and MC show similar pattern and the dispersion of the data points is below 3% for the explored range.

3. Timing calibration with "splash" events
To allow for optimal reconstruction of the energy deposited in the calorimeter the timing of the readout channels must be adjusted with a precision of \(\sim 1\) ns. These time offsets can be measured using the laser calibration system. The timing precision for channels in the same module achieved with laser is 0.6 ns for 99% of the Tile Calorimeter readout channels.

The inter-partition timing and global timing with respect to the rest of ATLAS were coarsely set using cosmic-ray data and more accurately using the so called "splash" events. In these events the LHC proton beam hits a completely closed collimator placed on the beam line 140 m away from ATLAS interaction point. The effect is that \(O(10^5)\) particles (mainly muons) arrive simultaneously in the ATLAS detector, depositing in TileCal a total energy of \(\sim 10^3\) TeV.

Fig. 5 (a) shows the cell time measured in beam splash events, averaged over the full range of the azimuthal angle \(\phi\) for all cells with the same \(z\)-coordinate of ATLAS (along the beam axis). The visible discontinuities at \(z = 0\) and \(z = \pm 3000\) mm for the 2008 data are due to the uncorrected time differences between the four TileCal partitions. These were calculated using the 2008 data and adjusted for the 2009 running period. After the muon time-of-flight corrections (b), the timing shows an almost flat distribution within 2 ns in each partition, confirming a good intercalibration between modules with the laser system. In 2009, the TOF-corrected timing distribution (c) shows an timing intercalibration between the partitions of \(\pm 5\) ns. In preparation for the 2010 run, the 2009 single beam results were used to provide the offsets for all cells and, as is shown in Fig. 5 (d) for the 2010 single beam results, all remaining non-uniformities were corrected for. The spread of the TileCal cell timing distribution at the start of the 7 TeV collisions is of order 0.5 ns 1.

4. Calorimeter performance in collision events
In November 2009 the Large Hadron Collision entered a tuning phase to reach the optimal operating conditions. From November 2009 up to now the center of mass energy of the proton-proton collisions was increased from 900 GeV, corresponding to protons colliding at the injection energy, to 2.36 TeV and finally up to 7 TeV. In Fig.6 the cell response spectrum is shown for collision events at different \(\sqrt{s}\). The same distribution for MC simulated events at \(\sqrt{s} = 7\) TeV is shown for comparison. The events were triggered using the MBTS system (Minimum Bias Trigger Scintillators) [1] both in data and MC. In order to compare the signal spectrum with the

1 This value takes into account 97% of the TileCal channels.
Figure 5. Timing of TileCal signals recorded with single beam data in September 2008 (a and b), November 2009 (c) and February 2010 (d). The time is averaged over the full range of the azimuthal angle $\phi$ for all cells with the same $z$-coordinate (along beam axis), shown separately for the three radial layers. Corrections for the muon time-of-flight along the $z$ axis are applied in the b), c) and d) figures, but not on the top left (a).

noise the distribution resulting from random triggered events are also shown. The results show that the MC provides a good description of the response spectrum both for noise and signal regions. The response as a function of $\eta$ is shown in Fig.7. In order to suppress the noise only the cells with a signal $> 500$ MeV are used. The agreement is within 2% in the central region, while is worse at large eta ($\eta > 1.2$) where also the statistics is poorer.

References
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Figure 6. Energy response of the TileCal cells. The distributions from collision data at 7 TeV, 2.36 TeV, and 0.9 TeV are superimposed with non-diffractive minimum bias Pythia MC and randomly triggered events.

Figure 7. Transverse Energy ($E_T$) of TileCal cell as a function of eta in collision candidate events at $\sqrt{s} = 7$ TeV. Only cells with transverse energy above 500 MeV are considered. Nondiffractive minimum bias Pythia MC events with the same energy cut are superimposed with the collision candidate events. The cut is chosen at 500 MeV in order to have negligible electronic noise contribution.