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Performance and calibration of the ATLAS Tile Calorimeter

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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 the wavelength shifting fibres coupled to the photomultiplier tubes (PMTs). The analogue signals from the PMTs are amplified, shaped, digitized by sampling the signal every 25 ns and stored on detector until a trigger decision is received. The TileCal front-end electronics reads out the signals produced by about 10000 channels measuring energies ranging from about 30 MeV to about 2 TeV. Each stage of the signal production from scintillation light to the signal reconstruction is monitored and calibrated. 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. A summary of the performance results from the two methods is presented.

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1. Introduction

The Tile Calorimeter (TileCal) is a sub-system of the ATLAS detector at the LHC whose main task is to measure energy of hadrons and jets created in the proton collisions [1]. It is mechanically divided into three major parts: one Long Barrel (LB) at the central area of the collision point $|\eta| < 1.0$, and two Extended Barrels (EB) in the forward regions $0.8 < |\eta| < 1.7$[1]. Each TileCal barrel consists of 64 modules along the azimuthal ϕ direction. At each module, light from the scintillating tiles is collected by wavelength shifting (WLS) fibres which run radially along the module. A cell is defined by bundling a set of fibres onto two photomultiplier tubes (PMTs).

Measurement in the TileCal may degrade due to different factors: radiation damage, scintillator aging, etc.; therefore, it is important to monitor its condition to ensure stable and reliable measurements. In these proceedings, we evaluate different TileCal calibration systems and its performance using isolated muons and hadrons produced in proton-proton collisions from LHC Run 2.

2. Calibration Systems

After energy deposition by particles inside a TileCal cell, the associated channel yields a signal amplitude A that is proportional to the deposited energy. A series of calibrations is performed to convert the amplitude to the particle energy, which follows the equation:

$$E\,[\mathrm{GeV}] = \frac{A\,[\mathrm{ADC}]}{C_{\mathrm{pC}\to\mathrm{GeV}} \cdot C_{\mathrm{ADC}\to\mathrm{pC}} \cdot C_{\mathrm{Cs}} \cdot C_{\mathrm{Las}}}\,, \tag{1}$$

where each constant C_i in the denominator corresponds to a calibration constant that is derived from separate calibration procedure. The first constant $C_{\mathrm{pC}\to\mathrm{GeV}}$ is the electromagnetic scale calibration constant used to convert calorimeter signals (in electric charge pC) to reconstructed energy (in GeV), and is derived from test beam campaigns. The other three constants are calculated from separate calibration systems: **Cesium** and **Minimum Bias** systems to provide C_{Cs}, **Laser** system to provide C_{Las}, and **Charge Injection** system to provide $C_{\mathrm{ADC}\to\mathrm{pC}}$.

The different calibration systems measure response drifts caused by different sources. For example, the Cesium and Minimum Bias systems are sensitive to scintillator and PMT degradation, while the Laser system is sensitive only to scintillator aging [2]. Effects from these different sources can be disentangled by comparing the response drift with the Cesium and Minimum Bias systems versus the Laser system. Figure 1 shows the variation of the average calorimeter response to Laser, Cesium, and Minimum Bias calibrations over time for one of the cells most exposed to the flux of particles originating from the interaction point. For the cell, the total response drift is approximately 16% as measured by Cesium system and is attributed to scintillator and PMT degradation. Approximately half of that effect is contributed by the PMT drift as measured by the Laser system, leaving the other half to the scintillator aging.

[1]ATLAS uses spherical coordinates to describe particle's trajectory from the collision point where θ and ϕ are the polar and azimuthal angle. Pseudorapidity η is a measure of forwardness relative to the detector and is formulated as $-\ln(\tan\frac{\theta}{2})$.

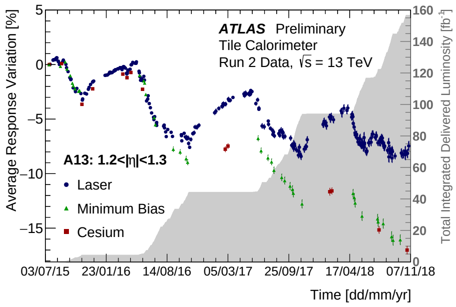

Figure 1: Variation of the average response to Laser, Cesium, and Minimum Bias calibrations for one of the cells most exposed to the flux of particles originating from the interaction point as a function of time [3].

3. Performance with single muons and hadrons

Muons produced in proton-proton collisions are used to probe the TileCal cell response. The probability density function of the deposited energy deposited over the path length $\Delta E/\Delta x$ of the muons inside the cells follows the Landau function [4]. Therefore, we define the calorimeter cell response to muons as the truncated mean of the $\Delta E/\Delta x$ distribution, with the truncation removing the highest 1% of the distribution. It is useful to take the ratio R of the truncated mean between data and Monte Carlo (MC) simulation because many systematic uncertainty sources, e.g momentum spread, incident angle spread, and pile-up[2] cancel out. The distribution of R across the TileCal azimuthal ϕ-modules is fitted using a Gaussian likelihood

$$\mathcal{L}_c = \prod_{m=1}^{64} \frac{1}{\sqrt{2\pi}\sqrt{\sigma_{c,m}^2 + s_c^2}} \exp\left[-\frac{1}{2}\frac{\left(R_{c,m} - \mu_c\right)^2}{\sigma_{c,m}^2 + s_c^2}\right], \tag{2}$$

where the product runs over the 64 ϕ-modules. The $R_{c,m}$ and $\sigma_{c,m}$ are the observed double ratio and its statistical uncertainty, respectively, for cell c and module m. At maximum likelihood, $\hat{\mu}_c$ and $\hat{s}_c$ represent the average response ratio and the non-uniformity across ϕ-modules. Figure 2 shows the R distribution over the ϕ-modules for a reference cell. The $\hat{\mu}_c$ values for every cell are plotted into the TileCal schematic as shown in Figure 3. All cells reported a data-MC response ratio close to one considering the non-uniformity over modules and uncertainty of the fit.

Hadrons deposit higher energy in the hadronic calorimeter compared to muons which allows the study of calorimeter response at higher energies. The hadrons were identified by matching the energy deposition in a TileCal cell to a track coming from a hard scatter primary vertex. To reduce the contribution from neutral particles and muons, the events are required to have at least 70% of the total energy deposited in the TileCal.

Energy response to hadrons is evaluated in the form of deposited energy divided by the associated track momentum E/p. Figure 4 shows the E/p distribution evaluated in low pile-up data ($\langle\mu\rangle \approx 2$). The distribution shows good agreement between data and MC with mean data-MC ratio close to one even in the higher energy range probed by isolated hadrons.

[2]Pile-up is any tracks and subsequent objects that are not associated with a hard scatter primary vertex. The number of primary vertices per bunch crossing, denoted $\langle\mu\rangle$, is commonly used as the measure of pile-up intensity of an event.

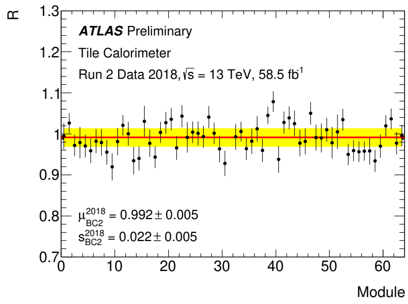

Figure 2: Ratio of the truncated mean of $\Delta E/\Delta x$ between data and simulation R as a function of the Tile Calorimeter module for a reference cell using single isolated muons from proton-proton collision. The red line (yellow band) represents $\hat{\mu}_c$ ($\hat{s}_c$) [5].

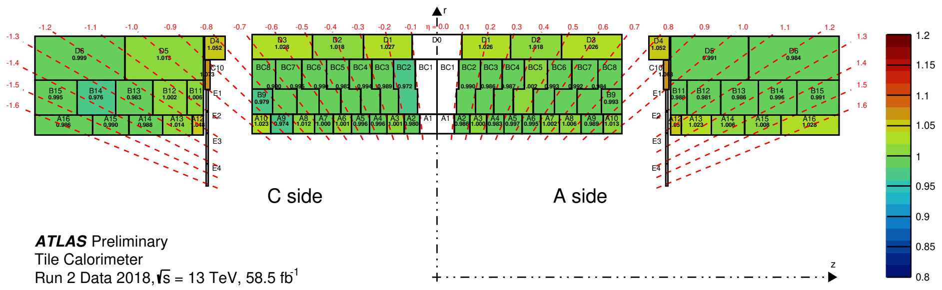

Figure 3: The TileCal cell map showing the average response ratio $\hat{\mu}_c$ obtained from the likelihood fit for each cell. The figure in full resolution can be found in Ref. [5].

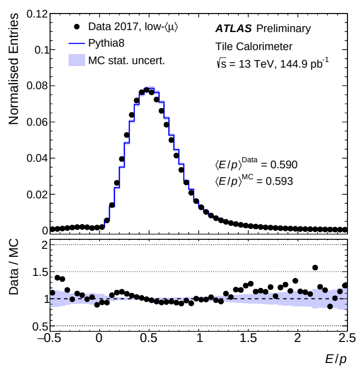

Figure 4: Calorimeter response represented by deposited energy over momentum E/p probed by single isolated hadrons in low pile-up data ($\langle\mu\rangle \approx 2$) [5]. The lower panel shows the data-MC ratio of each bin.

4. Conclusions

By studying the calorimeter response drift from expected value, the effects of radiation and aging of the ATLAS TileCal optics are measured. To evaluate the performance more thoroughly, two in-situ analyses using isolated muons and hadrons produced in proton-proton collisions of the LHC Run 2 are performed. The two independent studies both reported good data-MC agreement which validates the correction by the calibration systems.

References

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[2] ATLAS Collaboration, *Operation and performance of the ATLAS Tile Calorimeter in Run 1*, Eur. Phys. J. C (2018) 78:987.

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[4] Landau, L., *On the energy loss of fast particles by ionization*, J. Phys. (USSR, 1944) 8:201-205.

[5] ATLAS Collaboration, *Approved Tile Calorimeter Plots*, 2022. https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileSingleParticleResponse.