Hadron response and shower development in the ATLAS calorimeters

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Abstract. The response of the ATLAS Calorimeters to hadrons in the energy range between 2 to 350 GeV produced at CERN’s Super Proton Synchrotron (SPS) H8 test-beam line has been measured. The article summarizes the results obtained from the combined test-beam, during which a full slice of the ATLAS detector was exposed to the beam. Results are also presented from a dedicated standalone hadron Tile Calorimeter test-beam where this sub-detector had a special configuration to allow measurements of the longitudinal development of pion and proton induced showers up to 20 nuclear interaction lengths. Data results are compared to GEANT4 simulations using several hadronic interaction models.

1. Introduction

ATLAS is a multi-purpose detector built at the LHC collider at CERN. It consists of inner detector combining different tracking subsystems, sampling calorimeters and muon spectrometer. The ATLAS calorimeter system is divided into electromagnetic and hadronic sections. The electromagnetic calorimeter is lead-liquid argon (LAr) sampling detector with a fine granularity. In the central region the hadronic calorimeter is an iron-scintillator (Tile) sampling calorimeter. In this region the energy resolution for jets is about $50%/\sqrt{E} \text{ [GeV]} \pm 3\%$. [1]

The energy for each calorimeter cell is reconstructed from digitized samples of the signal from each readout channel. The results presented in this paper are at the electromagnetic energy scale, i.e. no correction for non-compensation of the calorimeters or dead material energy losses are applied.

2. Monte Carlo Simulation

The simulation of the calorimeter modules was performed within the ATLAS software framework using the GEANT4 simulation toolkit [2]. Within the GEANT4 several models can be used to simulate the interaction of particles with matter. A “physics list” is a consistent collection of models that covers the interaction of all particles in the whole energy range from thermal energies to several TeV range. At high energies the Quark-Gluon String (QGS) and Fritiof (FTF) fragmentation models are used. In the intermediate energy region Bertini (BERT) intra-nuclear cascade model is applied. The Precompound (P) model is used at lower energies. Detector response simulation includes the emulation of Birks’ law [3] and the simulation of the incoherent noise.
3. H8 beam line at the SPS at CERN
The H8 test-beam line at the SPS accelerator at CERN was instrumented with a set of beam detectors: scintillator trigger counters, wire chambers measuring the lateral coordinates of the beam particles and a helium filled Cherenkov counter. In order not to bias the calorimeter response, whenever possible, only minimal use of the calorimeter itself was made for particle identification. The signal in the scintillator counters was required to be compatible with single particle response. Events in the beam halo were rejected. A detailed description of all cuts used in the analysis can be found in [4], [5] and [6].

4. The combined test-beam measurements
The combined test-beam was an important step towards improving our understanding of the ATLAS detector. The drawing in Fig. 1 shows a simplified view of the detector setup in the combined test-beam. The transition radiation tracker (TRT) is used for particle identification. The electromagnetic (EM) calorimeter placed inside the cryostat and the hadronic Tile calorimeter (TileCal) located behind the EM section are shown. The beam energy ranged between 2 to 350 GeV. Data are compared to GEANT4 simulation version 9.1.

4.1. Pion response and resolution
A topological clustering algorithm [7] is applied to group neighboring cells into clusters and suppress the noise based on cell signal significance compared to the expected noise. The total energy response is defined as a sum of energies of all clusters.

The mean energy response and the energy resolution as a function of the beam momentum is presented in Fig. 2. The pion response (see Fig. 2 left) in the data is best described by the QGSP_BERT physics list. The data are described within 5% below 10 GeV and within 1% for higher momenta. The response for the QGSP physics list is about 5 - 10% lower than the one measured in the data. The Fritiof model is about 2 - 3% too low at high pion momenta, but 2–5% too high at low pion momenta. As in the case of the QGSP model adding the Bertini cascade increases the energy response, which is in better agreement with the data at high energy (+1%), but worse at low energies (5 - 10%). In general the Monte Carlo simulation predicts a better resolution than the one measured in the data (see Fig. 2 right). The resolution in the simulation is better by 10% below 10 GeV and about 5% at higher momenta. At high momenta adding the cascade model to the QGSP or FTFP models makes the resolution better which is in worse agreement with the data. However, the QGSP model gives a too broad resolution (by 5 - 10%) for pion momenta between 100 and 180 GeV. The QGSP_BERT model predicts a resolution that is lower by 5 - 10% than in the data for all pion momenta.

The response of the calorimeter to pions of 320 and 350 GeV energy as a function of pseudorapidity of beam impact point is shown in Fig. 3. The relative difference between MC and data results ($\Delta E_{\text{Comb}}$) is shown in the bottom part of the plots. The sum of the energies measured in the electromagnetic and hadronic calorimeters ($E_{\text{Comb}}$) is used. The MC simulation has the tendency to overestimate the response of the calorimeter. The response of the detector is uniform for data and MC across the calorimeter.
Figure 2. Mean energy (left) and resolution (right) for pions at beam momenta $P_{\text{beam}}$ between 2 and 180 GeV. Only statistical uncertainties are shown. The yellow band indicates the uncertainty due to the particle identification cuts.

Figure 3. Calorimeter response as a function of pseudorapidity of beam incident point. The uncertainty includes statistical and systematic errors. QGSP_BERT physics list is used.

Figure 4. Mean energy fraction in the core of the shower as a function of beam momentum. The yellow band indicates the uncertainty due to the particle identification cuts.
4.2. Shower lateral spread

In order to study radial shower development we define the fraction of energy in narrow cone around the beam direction:

$$E_{core} = \Sigma_{\text{cells with } d\phi, d\eta < 0.1} E_{\text{cell}} / \Sigma_{\text{cells with } d\phi, d\eta < 0.3} E_{\text{cell}}$$

The dependence of $E_{core}$ on the beam momentum is shown in Fig. 4. The QGSP model produces showers which are too narrow for all pion momenta. The mean fraction is about 5% too high. The Fritiof model gives the same result for the beam momenta below 10 GeV, but produces showers that are a bit wider for high pion momenta (4%). Adding the Bertini cascade makes the shower wider for both the QGSP and the Fritiof models. In general, the shape of the data distribution is well described by these models.

5. The Tile Calorimeter standalone test-beam measurements

The layout of the Tile Calorimeter modules in the H8 test-beam line area is shown in Fig. 5. It consists of two Barrel Modules and two Extended Barrel modules. The beam impinges from the side (90°) of the middle located Barrel Module, perpendicularly to the scintillating tiles. The direction of the beam is defined to be the $z$-axis.

The Cherenkov counter is used to discriminate pions from protons event-by-event. At 20 GeV only negative beam was available. Electron and muon rejection has been done using calorimeter information. The resulting biases on the measurements are studied and they are found to be negligible. Data are compared to GEANT4 simulation version 9.3. No cut is applied on the cell energies.

5.1. Longitudinal shower profiles of pion and proton induced showers

The special test-beam configuration of the calorimeter modules made it possible to measure shower longitudinal profiles up to 20 nuclear interaction lengths ($\lambda$).

The measured longitudinal profiles of pion and proton induced showers are presented in Fig. 6. The measurements extend up to 20 $\lambda$ in depth. On average, hadron showers quickly deposit their energy and reach the maximum of the mean energy deposition within the first few nuclear interaction lengths in depth. The average energy deposition then exponentially decreases towards the end of the shower and is lower by approximately four orders of magnitudes at 20 $\lambda$.

The longitudinal profiles of pion induced showers obtained with MC simulation are compared to the measured data in Fig. 7. The distributions in the figure show that the simulation predicts shorter showers compared to the data for both pion (left plot) and proton (right plot) induced showers. The latter is worse described.

5.2. Impact of longitudinal leakage on the energy resolution

The large depth of the calorimeter in the test-beam allowed to study the influence of longitudinal leakage on the energy resolution. The depth dependence of the TileCal energy resolution is shown in Fig. 8 for pions. The resolution for the calorimeter having depth of 10.9 $\lambda$ is used as reference. In the left plot the resolution is defined as the ratio of the RMS spread and the mean of the total energy distribution, while in the right plot the resolution is defined as the ratio of the standard

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1 We use throughout this analysis an effective nuclear interaction length for the Tile calorimeter $\lambda = 20.55$ cm, calculated using the known fraction of materials used in the detector construction and their nuclear interaction lengths.
deviation $\sigma$ and the peak of a Gaussian fit to the total energy distribution in the range $-2\sigma$ to $2\sigma$ around the peak value. The worsening of the resolution (with the decrease of calorimeter depth) defined as RMS/mean ratio is significantly more than for the one defined as $\sigma$/peak ratio, since the first one takes into account the low energy tails in the total energy distribution caused by longitudinal leakage.
Figure 8. Dependence of the TileCal energy resolution on the depth of the calorimeter for pions at different energies. The resolution is defined as RMS/mean of the total energy distribution in the left plot and in the right one it is defined as \( \frac{\sigma}{\text{peak}} \) of a Gaussian fit to the distribution in the range \(-2\sigma\) to \(2\sigma\) around the peak value. The vertical dashed lines denote the length of the hadronic and the full ATLAS calorimeter at \( \eta = 0 \).

Summary and Conclusions

The response of the ATLAS barrel calorimeters has been studied for hadrons within the energy range of 2 to 350 GeV in test-beam setup. Longitudinal profiles of pion and proton induced showers have been measured up to a depth of 20 nuclear interaction lengths.

The experimental data have been compared with the results of GEANT4 simulation, using FTFP and QGSP physics lists, as well as extensions with the Bertini intra-nuclear cascade model. The energy response of the ATLAS calorimeters to hadrons is described by the simulation within 5% in the energy range between 2 – 350 GeV, while the energy resolution is described with about 10% accuracy. Neither of those physics lists is able to satisfactorily reproduce the longitudinal and lateral developments of pion and proton induced showers in the whole energy range although the addition of the intra-nuclear cascade improves the description of data by the simulation.

References

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