Single Hadron Response Measurement in ATLAS

Pavel Starovoitov on behalf of the ATLAS Collaboration
Deutsches Elektronen-Synchrotron (DESY), Notkestraße 85, 22607 Hamburg, Germany
E-mail: Pavel.Starovoitov@desy.de

Abstract. Single hadron response measurement in minimum bias proton-proton collisions at a center of mass energy of $\sqrt{s} = 7$ TeV are presented. Together with test-beam results, these measurement form the basis to evaluate the calorimeter energy response uncertainty of jets at high transverse momenta. The single hadrons response is measured in the momentum range of 0.5 to about 20 GeV in-situ, by comparing the calorimeter response of all energy deposits in a cone around an isolated track with the more precisely measured track momenta. The agreement between data and Monte Carlo simulation is on the level of a few percent. Using kaon and $\Lambda$ particles, the calorimeter response of identified pions, proton and anti-proton is studied. The MC simulation describes the energy response of pions and protons well, but differences are observed for anti-protons. It is discussed how the jet calorimeter response uncertainty and its correlation between transverse momentum bins is determined from these measurements.

1. Introduction

Hadron jets are the dominant physics objects produced in high-energy proton-proton collisions at the Large Hadron Collider (LHC) at CERN. They are the key ingredient of many physics analyses from the di-jet cross-section to the top quark measurements as well as for searches for new phenomena with jets in the final state. The uncertainty on the jet energy scale (JES) is the largest source of detector-related systematic uncertainty. It is thus the subject of an extensive and detailed study.

The jet energy measured by the calorimeter is corrected for calorimeter non-compensation and energy loss in dead material. The corresponding jet energy scale correction factor is referred to as the JES. The JES is derived from Monte Carlo (MC) simulations by comparing the calorimeter energy of an isolated reconstructed jet to that of the particle jet that points to it.

The uncertainty on the calorimeter energy response is a significant component of the total uncertainty on the JES. It is derived by convolving the measured uncertainty on the single charged hadron energy response and the estimated uncertainty on the neutral particle energy response with the expected particle spectrum within a jet.

The calorimeter response to single isolated charged hadrons, and the accuracy of its Monte Carlo simulation description, can be evaluated from the ratio of the calorimeter energy $E$ to the associated isolated track momentum $p$. The aim of the measurement is to estimate the systematic uncertainty on jet calorimeter response and therefore the focus is on data-to-MC comparison. The ratio $E/p$ is measured using proton-proton collisions at centre-of-mass energies of $\sqrt{s} = 7$ TeV over a wide range of track momenta in the central region of the calorimeter. Possible additional uncertainties introduced by certain particle species are addressed by measuring the response to hadrons identified through the reconstruction of known short-lived particles.
A sample of about 20 million non-diffractive proton-proton collision events at $\sqrt{s} = 7$ TeV are generated using Pythia 6.421 [1] with the ATLAS minimum bias tune 1 (AMBT1) [2]. For isolated, high-momentum ($p_T > 15$ GeV) tracks the MC sample has ~ 60% of the number of events containing a track with $p_T > 15$ GeV than in the data. All the events are run through a full detector simulation [3] based on Geant4 [4]. The Geant4 physics model used is QGSP_BERT [5]. The reconstruction and analysis software used for the MC simulation is the same as for the data.

2. The ATLAS detector

The ATLAS detector covers almost the whole solid angle around the collision point with layers of tracking detectors, calorimeters and muon chambers and is described in detail in Ref. [6]. Here, the features relevant for this analysis are summarised.

The inner detector (ID) is immersed in a 2 T axial magnetic field and provides tracking for charged particles with $|\eta| < 2.5$. The ID consists of a silicon pixel tracker and silicon microstrip tracker (SCT) covering $|\eta| < 2.5$ and a transition radiation tracker (TRT) covering $|\eta| < 2.0$.

The calorimeter system covers $|\eta| < 4.9$, using a variety of technologies. High granularity liquid-argon (LAr) electromagnetic (EM) sampling calorimeters, with excellent performance in terms of energy and position resolution, cover $|\eta| < 3.2$. They use accordion shaped electrodes and lead absorbers and consist of a barrel (EMB, $|\eta| < 1.475$) and an end-cap (EMEC, $1.375 < |\eta| < 3.2$). They are longitudinally segmented in depth into three layers, with a pre-sampler behind the solenoid. For $|\eta| < 1.7$ hadronic calorimetry is provided by a sampling calorimeter made of iron and scintillating tiles (TileCal). TileCal comprises a large barrel ($|\eta| < 0.8$) and two smaller extended barrel cylinders ($0.8 < |\eta| < 1.7$). It is segmented longitudinally into three layers, with a total thickness of about eight interaction lengths at $\eta = 0$. The hadronic end-cap calorimeters (HEC, covering $1.5 < |\eta| < 3.2$) are LAr sampling calorimeters with copper absorbers. The copper/tungsten-LAr forward calorimeters (FCal) provide both electromagnetic and hadronic energy measurements and extend the coverage to $|\eta| < 4.9$.

3. Calorimeter response to charged hadrons

For every selected event, each track candidate is extrapolated to the second longitudinal layer of the EM calorimeter. A track is defined as isolated if its impact point has a distance $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} > 0.4$ from all other track candidate impact points. Events are required to have at least one reconstructed vertex with at least four associated tracks.

The isolated tracks must also have a transverse momentum of $p_T > 500$ MeV, a minimum of one hit in the pixel detector and six hits in the SCT, and small transverse and longitudinal impact parameters computed with respect to the primary vertex, $|d_0| < 1.5$ mm and $|z_0| \sin \theta < 1.5$ mm. The above requirements ensure a good quality of the track and reduce contributions from fake tracks to a negligible level.

The sum of the energy deposits in layers of calorimeter cells associated to a selected track is computed using topological clusters [7] at the electromagnetic (EM) scale, i.e., without applying any correction for the calorimeter non-compensation or for energy loss in dead material. The purpose of the topological clustering algorithm is to identify areas of connected energy deposits in the calorimeter, based on the significance of the energy deposits in cells with respect to the expected noise level. Topological clusters are formed around cells with energy $|E_{\text{cell}}| > 4\sigma_{\text{noise}}$ ("seeds"), where $\sigma_{\text{noise}}$ is the RMS of that cell noise. Then, iteratively, the cluster is expanded by adding all neighbouring cells with $|E_{\text{cell}}| > 2\sigma_{\text{noise}}$. Finally, the cells surrounding the resulting cluster are added, regardless of their energy. The $\eta - \phi$ position of a cluster $i$ in a given calorimeter layer $j$, $(\eta_{cl}^i, \phi_{cl}^i)$ is computed as the energy-weighted position of the cells in layer $j$ belonging to the cluster.
The position of the track \( k \) extrapolated to the layer \( j \) is \((\eta^{kj}_{tr}, \phi^{kj}_{tr})\). The energy of a cluster in the layer \( j \) \((E_j)\) is associated to the track if:

\[
\sqrt{(\eta^{kj}_{tr} - \eta^{ij}_{cl})^2 + (\phi^{kj}_{tr} - \phi^{ij}_{cl})^2} < R_{coll}.
\]

The parameter \( R_{coll} \) is set to 0.2 based on a trade-off between maximising the particle shower containment and minimising the background contribution coming from neutral particles produced close to the track. Roughly 90% of the shower energy is collected in a cone of such size.

The energy \( E \) associated to a track is computed as the sum of the associated energy deposits in all layers, \( E = \sum_j E_j \), and the ratio \( E/p \) is formed with the reconstructed track momentum. Note that because of calorimeter noise fluctuations, \( E \) (and therefore \( E/p \)) can assume negative values.

### 3.1. \( E/p \) distributions

The \( E/p \) distribution in the one representative region of \( \eta \) and track momentum is shown in Figure 1a. The large number of entries with \( E/p = 0 \) corresponds to isolated tracks that have no associated cluster in the calorimeter. Several effects may be responsible for this:

- Particles can interact hadronically before reaching the calorimeter (in the ID, cryostat or solenoid magnet). Such particles can change their direction, or produce a large number of low momentum secondary particles.
- A cluster is created only if a seed is found. Hadrons with low momentum and an extended shower topology sometimes do not have a single cell energy deposit large enough to seed a topological cluster.

The cases where the calorimeter response is compatible with zero have been further studied. The probability that the calorimeter response is suppressed by noise threshold requirements, \( P(E = 0) \), is shown in Figure 2a as a function of the amount of material (in nuclear interaction lengths) in front of the active volume in the central \((|\eta| < 1.0)\) calorimeter region. When the hadron passes through more material, the probability that no energy is associated to the track increases.

Figure 1: (a) The \( E/p \) distribution for isolated tracks with an impact point in the region \(|\eta| < 0.6\) and with a momentum in the range \(2.2 \leq p < 2.8 \text{ GeV}\). (b) The same as (a) for background [8].
Figure 2: (a) Probability to measure a calorimeter response consistent with zero $P(E = 0)$ as a function of the amount of material in nuclear interaction lengths in front of active volume of the calorimeter for $|\eta| < 1.0$. (b) $P(E = 0)$ as a function of track momentum for $|\eta| < 0.6$ [9].

Figure 2b shows $P(E = 0)$ as a function of the track momentum in the central region of the calorimeter ($|\eta| < 0.6$). In this region, the dead material in front of the calorimeter is approximately constant. The probability decreases with increasing track momentum. In general, $P(E = 0)$ is well predicted by the MC simulation.

3.2. Background
The energy measured inside the cone of $\Delta R < R_{\text{coll}} = 0.2$ centered around the track impact point may be contaminated by energy deposits from the showers of close-by particles produced in the proton-proton collision. The track isolation requirement suppresses possible shower contamination from charged particles. There is no obvious way to suppress shower contamination from photons, mostly produced in $\pi^0 \rightarrow \gamma\gamma$ decays, and neutral hadrons. The neutral particle background contribution to the $E/p$ measurement in the MC simulation depends on the event generator settings of the parameters governing non-perturbative QCD processes and on the modelling of the calorimeter response to low momentum neutral particles, and it is therefore difficult to model correctly.

The background subtraction relies on the assumption that the EM energy from photons and neutral hadrons is independent of the energy deposited by the selected track. Charged hadrons are selected that behave like minimum ionising particles in the EM calorimeter and start their shower in the hadronic calorimeter (late-showering hadrons). Excluding a narrow region around the late-showering hadron track, the remaining EM energy is mainly due to showers from neutral particles.

Late-showering hadrons are selected by requiring a small amount of EM energy in a cone
Figure 3: $\langle E/p \rangle$ at $\sqrt{s} = 7$ TeV as a function of the track momentum for (a) $|\eta| < 0.6$ and (b) $0.6 \leq |\eta| < 1.1$. The black markers represent the collision data, while the green rectangles represent the MC prediction, with the vertical width showing its statistical uncertainty. The lower panes show the ratio of the MC simulation prediction to collision data. The grey band indicates the size of the systematic uncertainty on the measurement. The dotted lines are placed at $\pm 5\%$ of unity and at unity [9].

of $\Delta R < 0.1$, $E_{\text{EM}}^{0.1} < 1.1$ GeV, and a large HAD energy fraction, $E_{\text{HAD}}^{0.1}/p > 0.4$. The background is measured in the EM calorimeter in an annulus around the late-showering charged hadrons. The mean of the background distribution over many events in a given momentum and pseudorapidity bin estimates the energy deposition of photons and neutral hadrons showering in the EM calorimeter:

$$\langle E/p \rangle_{\text{BG}} = \left\langle \frac{E_{\text{EM}}^{0.2} - E_{\text{EM}}^{0.1}}{p} \right\rangle.$$  \hspace{1cm} (2)

where $E_{\text{EM}}^{0.2}$ is the EM energy in a cone of $\Delta R < 0.2$. The background $E/p$ distribution in the one representative region of $\eta$ and track momentum is shown in Figure 1b.

The background contribution from neutral hadrons depositing their energy in the hadronic calorimeter was estimated with a similar technique applied to different hadronic calorimeter layers and found to be negligibly small.

3.3. Results

The single charged hadron response is defined as

$$\langle E/p \rangle = \langle E/p \rangle_{\text{raw}} - \frac{4}{3} \langle E/p \rangle_{\text{BG}}$$ \hspace{1cm} (3)

where $\langle E/p \rangle_{\text{raw}}$ is the mean value of the $E/p$ distribution before background subtraction.

The background is rescaled by the factor of 4/3, which is the ratio of the area of the full $\Delta R < 0.2$ cone to that of an annulus with $0.1 \leq \Delta R < 0.2$, to take into account the background contribution in $E_{\text{HAD}}^{0.1}$, since the background is only measured in this annulus. A uniform energy density of the background in the $\Delta R < 0.2$ cone is assumed.

Several systematic uncertainties on the measurement are estimated. Each is taken to be completely correlated between all pseudorapidity and momentum bins in the $\langle E/p \rangle$
measurement. The dependence of $\langle E/p \rangle$ on the track selection requirements has been estimated by varying the number of silicon tracker hits required and the impact parameter selection with respect to the primary vertex within reasonable ranges. The MC-to-data ratio of $\langle E/p \rangle$ was found to be almost unaffected by variations in the track selection. The maximum variation found in the ratio (0.5%) is taken as a systematic uncertainty. The uncertainty on the momentum scale $p$ as measured by the inner detector is negligibly small for $p < 5$ GeV. For $p > 5$ GeV, a conservative 1% uncertainty has been assumed on the momentum scale. The 1% difference between the background estimate described in and the alternative one is taken as a systematic uncertainty.

The mean $E/p$ value after background subtraction is evaluated in bins of momentum and pseudorapidity. Figure 3 shows $\langle E/p \rangle$ as a function of the track momentum, in two different $|\eta|$ bins up to $|\eta| = 1.1$, at $\sqrt{s} = 7$ TeV. The lower parts of the figures present the ratio of MC simulation to data. The maximum momentum that can be probed with the data considered is approximately 30 GeV. The agreement between data and MC simulation is within $\sim 2\%$ for particles with momenta in the 1–10 GeV range, and it is around 5% for momenta in the 10–30 GeV range. Below 1 GeV, where tracks are just at the kinematic threshold of entering the calorimeter volume, large differences of $\sim 10\%$ or more between data and MC simulation are visible. However, due to the low absolute calorimeter response to very low momentum particles, these differences are not critical for the JES determination.

4. Calorimeter response to identified hadrons
The extrapolation of the previous single particle response studies into the environment of a jet requires understanding of two additional effects. A jet includes a variety of hadrons that may differ from the inclusive sample of isolated hadrons. Therefore, measuring the average response to different species of particles is valuable to ensure that the Monte Carlo correctly models all aspects of the jet shower. Additionally, the hadrons in a jet are not isolated. Threshold effects and hadronic shower widths affect the calorimeter response to the multi-hadron system.

Single hadrons are identified using decays of $K_S$ (for positive and negative pions), $\Lambda$ (for protons), and $\bar{\Lambda}$ (for anti-protons) particles. These single hadrons are required to be isolated from all other charged particles in the event. Single pions will have manifestly lower energy response distributions from those of anti-protons, because of the eventual annihilation of the anti-proton. By identifying and isolating single pions, single protons, and single anti-protons, the effects of hadronic interactions and annihilation can be separated at low to moderate energies, where they are most important.

Figure 4 shows the difference in response between $\pi^-$ and $\bar{p}$ in the central ($|\eta| < 0.6$) pseudorapidity bins as a function of available energy ($E_a$). The difference shows a $\sim 30\% \times \langle E/p \rangle$ disagreement between data and MC simulation for $E_a < 3$ GeV, though they are consistent for $E_a > 4$ GeV. At these low available energies, the anti-proton response should be dominated by the annihilation and the subsequent shower. The difference indicates large contributions from processes not well-modelled by GEANT4.

When the mother particle is highly boosted, the decay products are more collimated. For track momenta of $\sim 2$–6 GeV from $K_S$ decays, the range of opening angles of the decay products allows a measurement of calorimeter response as more tightly collimated pairs of pions are selected. There are two related effects probed by such a measurement. Energy deposited in the calorimeter may fall below the thresholds for reconstruction and be neglected as consistent with noise. As two showers overlap, the addition of energies that might have individually been below threshold can produce a signal above these noise thresholds.

The ratio $E/p$ as calculated here for a single pion should increase as another particle approaches it and more of the second particle’s energy is included in the calorimeter energy, $E$. As shown in Figure 5, the response does not vary with separation for large extrapolated
Figure 4: The difference in \( \langle E/p \rangle \) between \( \pi^+ (\pi^-) \) from \( K_S \) candidates and \( p (\bar{p}) \) from \( \Lambda (\bar{\Lambda}) \) candidates in tracks with (a) \(|\eta| < 0.6\) [9].

Figure 5: \( \langle E/p \rangle \) for pions as a function of the extrapolated distance between that pion and a pion of the opposite sign. In all cases the pions are daughters of a reconstructed \( K_S \) candidate and are required to be isolated from all tracks in the event except the other daughter of the decay. The response is shown for low energy \( (2.2 \leq E_a < 2.8 \text{ GeV}) \) (a) \( \pi^+ \) and (b) \( \pi^- \) in the central pseudorapidity bin \(|\eta| < 0.6\). The MC simulation has no tracks passing the selection in the smallest bin (smallest two bins) of opening distance for \( \pi^+ (\pi^-) \) [9].

distances, where the single pion is isolated.

5. Calorimeter jet energy scale uncertainty

The jet energy scale calibration corrects the measured jet energy for several effects, including calorimeter non-compensation and energy loss in dead material. The calibration itself is derived from MC simulation. The calorimeter uncertainty on the JES is calculated from the uncertainty on the energy response of all particles contributing to a jet. Within the MC simulation, the energy contribution of each individual particle to a given jet can be separated. The convolution of the uncertainty on the single particle energy response with the MC jet particle composition
is then used to calculate the calorimeter uncertainty on the jet energy scale.

The calorimeter JES uncertainty is derived for the well-understood central region of the calorimeter. The main reasons for the restriction to the central calorimeter region are the smaller amount of material in front of the calorimeter and the existence of combined test beam measurements with a setup very similar to the final ATLAS configuration. Therefore, the calorimeter JES uncertainty is only evaluated using the single particle response for $|\eta| < 0.8$.

The numerical evaluation of the uncertainty on the jet energy scale is performed with Monte Carlo pseudo-experiments. In each pseudo-experiment, the jet energy scale is calculated after randomly changing the Monte Carlo single particle energy response within the appropriate uncertainty range given by the measured data/MC ratio. The final uncertainty on the jet energy scale is then given by the spread of the distribution of the jet energy scale over all pseudo-experiments. Within each pseudo-experiment, all randomly changed parameters are kept fixed, such that the energy response correlations are properly taken into account.

The uncertainties on the particle energy response functions entering the calculation are taken from the in-situ $E/p$ measurements, ATLAS combined test beam (CTB) measurements [10] and Geant4 Monte Carlo predictions.

When the single charged hadron response from $E/p$ is used to assess the uncertainty on the jet energy scale, further systematic uncertainties that might affect the propagation of the response to the jet have to be taken into account. The probability to find $E/p = 0$ is strongly correlated to the amount of upstream material and hence a good measure of the $E/p$ acceptance. A fully correlated (in $p$ and $\eta$) 28% uncertainty is derived from the maximal observed difference between data and MC simulation in this probability. Given an amount of energy released in the calorimeter, the energy collected in the topological clusters may differ from the energy released in the calorimeter, depending on how isolated the energy deposit is. This can introduce a bias in the particle response in a jet with respect to the response measured for isolated hadrons. A conservative systematic uncertainty has been computed by comparing the results of the $\langle E/p \rangle$ measurement obtained using topoclusters to those obtained by repeating the measurement using all calorimeter cells in a cone of size $\Delta R < 0.2$. The double ratio of data/MC cluster response to data/MC cell response is used to estimate the uncertainty. The relevant result for the central calorimeter region is presented in Figure 6, showing discrepancies of $\sim 5\%$ at low $p$ that disappear within the statistical uncertainties for $p > 10$ GeV.

Statistically consistent results were found for the $E/p$ data to Monte Carlo ratio for calorimeter energy measured in $\Delta R < 0.3$. Hence no additional uncertainty is assumed due to the out-of-cone $\Delta R > 0.2$ energy deposits.

The $E/p$ measurements only cover the response of charged hadronic particles with momenta less than $\sim 20$ GeV. However, depending on the jet momentum, on average between 35% and 90% of the energy in jets is carried by particles that are not measured in situ using the isolated track analysis (mostly photons from $\pi^0$ decays, neutral hadrons and high momentum charged hadrons). Hence, the uncertainty on the energy response to these particles is needed in order to obtain the total calorimeter uncertainty on the jet energy scale.

In 2004, an ATLAS Combined Test Beam (CTB) program was carried out at CERN. A “slice” of the ATLAS detector composed of the final versions of all sub-detectors in the barrel region was exposed to Super Proton Synchrotron (SPS) test beams. The layout of the sub-detectors was designed to be as close to that of ATLAS as possible. The setup was used to measure the combined calorimeter response to single charged pions of energies between 20 and 350 GeV for pseudorapidity values of 0.20, 0.25, 0.35, 0.45, 0.55 and 0.65 [10, 11, 12]. From the measurements in Ref. [10], the ratio of data to MC simulation predictions is used to supplement the in-situ $E/p$ measurements with a larger energy range.

For single particle momenta above 400 GeV no direct measurements in a test beam or in situ exist. Therefore an additional uncertainty of 10% is added in quadrature to that of the 350 GeV
Figure 6: Ratio of the $\langle E/p \rangle$ measurement obtained with topological clusters to that obtained using all calorimeter cells in (a) the central ($|\eta| < 0.6$) and (b) forward ($0.6 \leq |\eta| < 1.1$) regions. The inset shows the ratio of the MC prediction to data [9].

measurement uncertainty in order to cover possible effects from calorimeter non-linearities at high energy densities and longitudinal leakage [13].

The absolute electromagnetic energy scale in ATLAS has been established using $Z \rightarrow ee$ decays for the electromagnetic LAr calorimeters and using the energy loss of minimum ionising muons in the TileCal. For the bulk of the electromagnetic LAr barrel calorimeter, the uncertainty on the cell energy measurement is 1.5%, and for the LAr presampler the uncertainty is 5% [14]. For the TileCal, the scale uncertainty is 3% [15]. This uncertainty does not affect charged particles with $E/p$ measured in situ, but needs to be considered for all other particles contributing to jets.

Test beam measurements of protons [10, 11, 12, 13] and $E/p$ measurements for identified pions and protons have shown that the agreement between data and MC simulation for protons is similar to the data to MC agreement for charged pions. Hence no additional uncertainty for charged baryons is assumed.

No test beam measurements for neutral hadronic particles have been carried out. Moreover, the GEANT4 models have large uncertainties. On average 10–12% of the jet energy is carried by neutral hadrons, mostly $K_s$, $K_L$ and neutrons. Most of the $K_s$ decay to pions before they reach the calorimeter. Hence the $E/p$ and CTB measurements can be used for $K_s$.

For neutrons and anti-neutrons GEANT4 studies comparing alternative GEANT4 hadronic physics models to the ATLAS-default hadronic physics model QGSP_BERT [5] show that the (anti-)neutron to (anti-)proton response ratio is determined at the 10% level for particle momenta below 3 GeV and at the 5% level for higher momenta. Hence the (anti-)neutron response can be related to the sufficiently well simulated (anti-)proton response with these additional uncertainties.

The individual components of the calorimeter uncertainty on the jet energy scale together with its expected shift are summarised in Figure 7 for anti-$k_t$ [17] jets with $R = 0.6$ in the pseudorapidity range $|\eta| < 0.8$. No single component is dominant and depending on the jet momentum several components contribute at approximately the same level to the total uncertainty. The envelope of the shift and uncertainty on the calorimeter JES is taken as the
Figure 7: Expected total shift (black dots) and uncertainty (light blue band) on the relative calorimeter jet response with respect to the MC simulation for jets reconstructed with the anti-\( k_t \) jet algorithm (\( R = 0.6 \)) in the range \(|\eta| < 0.3\) as function of the jet transverse momentum \([9]\). The \(x\)-axis is the jet transverse momentum calibrated from the EM scale to the hadronic scale using an MC-based JES calibration factor \([16]\).

6. Conclusions

The average calorimeter response to isolated hadrons with respect to the track momentum \(\langle E/p \rangle\) has been measured in minimum bias events \(\sqrt{s} = 7\) TeV. A background from neutral hadrons of 4–8% is subtracted from data and Monte Carlo with a systematic uncertainty of below 1%. After the background has been removed, the agreement between data and Monte Carlo simulation is within 2% for particles with momenta up to 10 GeV and is around 5% for momenta in the 10–30 GeV range, where the statistical uncertainty dominates the total uncertainty.

The calorimeter response of identified single charged hadrons has been measured using short-lived particle decays. A good agreement between data measured at \(\sqrt{s} = 7\) TeV and the Monte Carlo simulation is found for charged pions and protons. However, a disagreement of up to 10% is found between the Monte Carlo simulation and data for the difference of responses to low momentum anti-pions and anti-protons \(\langle (E/p)_{\pi^-} \rangle - \langle E/p \rangle_{\bar{p}}\). This difference is attributed to the poor modelling of the anti-proton response in the Monte Carlo simulation.

The ATLAS calorimeter jet energy scale uncertainty has been determined for the well understood central detector region by propagating the energy response uncertainty of all particles contributing to a jet. For charged hadron momenta below 20 GeV, the single charged hadron response has been used, while for higher momenta, the response measured in the ATLAS combined test beam has been included. For the response to neutral pions \(\pi^0 \rightarrow \gamma\gamma\), the uncertainty on the electromagnetic calorimeter energy scale is dominant, while for all other neutral hadrons an additional uncertainty due to the limited knowledge of the calorimeter response has been incorporated.
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