Response of single isolated hadrons in the ATLAS calorimeter

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Abstract. Data produced in proton-proton collisions at a center-of-mass energy of \( \sqrt{s} = 900 \) GeV collected by the ATLAS experiment at CERN are used to select isolated tracks and to probe the calorimeter response associated to them. The ratio \( E/P \) between the energy \( E \) deposited in the calorimeter around the track impact point, and the track momentum \( P \) is measured over a wide rapidity range for particles with momentum range from 0.5 to 10 GeV/c. The average measured \( E/P \) is compared to the predictions of the Monte Carlo simulation.

1. Introduction
The ATLAS detector is a large collider detector built to be used for LHC collisions at CERN. It consists of inner detector combining different tracking subsystems, sampling calorimeters and muon spectrometer.

Single isolated tracks can be used to assess the calorimeter response to single particles by comparing the track momentum to the energy measured in a cone around the track. For the particle momenta produced in 900 GeV proton-proton collisions, the track momentum measurement is precise and accurate. The transverse momentum resolution of the inner detector to charged track is 0.05\% \( P_T \) [GeV/c] \( \pm \) 1\%. In the central region the typical energy resolution of the ATLAS calorimeter to jets is about 50\%/\( \sqrt{E} \) [GeV] \( \pm \) 3\%. The ratio \( E/P \) is an observable that allows to assess the calorimeter response to hadrons.

The basic idea of the analysis is to associate a calorimeter energy deposit to an isolated track and compare the energy in the calorimeter to the track momentum as measured by the inner detector. A cone of a given size is used around the extrapolated impact point of the track at the calorimeter entrance, and the energy which is deposited in the cone is measured. However, there are two sources of contamination that must be accounted for when comparing to the single particle energy deposit. First, the shower associated to a track can be superimposed with showers associated to other close-by tracks. This contamination can be largely reduced with an isolation cut on the track, such that a track is accepted for analysis only if it is far enough from any other track. A track is accepted for the analysis only if the track under study is far enough from any other track. Second, isolated tracks can be accompanied by neutral particles whose energy deposit can overlap to that of the charged particle. There is no obvious way to eliminate this contamination. Its contribution to the final result has been estimated in Sec. 4 and Sec. 7.
2. Event and track selection

All the events have been collected in the LHC commissioning period of December 2009. The runs considered for the analysis have been selected requiring that the Pixel and Silicon Microstrip tracker (SCT) detectors, the ATLAS solenoid and the ATLAS calorimeters were operational.

Events have been triggered with the requirement of at least 1 hit on either side of the Minimum Bias Trigger Scintillators, which cover the pseudo-rapidity range, $2.09 < |\eta| < 3.84$ and are located in front of the end-cap electromagnetic calorimeters. Collision candidate events have been selected by requiring the presence of one reconstructed vertex with at least two tracks associated to it.

For each event, a search for isolated tracks is performed. For each track candidate $i$, its $\eta - \phi$ position is extrapolated to the second longitudinal layer of the electromagnetic calorimeter ($\eta_{EM2}^i, \phi_{EM2}^i$). Then, for each of the other track candidates $j$, the extrapolated position ($\eta_{EM2}^j, \phi_{EM2}^j$) is also computed. If

$$\Delta R_{ij} = \sqrt{(\eta_{EM2}^i - \eta_{EM2}^j)^2 + (\phi_{EM2}^i - \phi_{EM2}^j)^2} > 0.4$$

(1)

for all $j$, then the track candidate is defined to be isolated and it is processed further in the analysis.

The following selection has been applied on the resulting isolated track candidates:

- a transverse track momentum of $P_T > 500$ MeV/c.
- at least 1 hit in the Pixel detector and 6 hits in the SCT.
- the transverse and longitudinal impact parameters computed with respect to the primary vertex, $|d_0| < 1.5$ mm, $|z_0| \sin \theta < 1.5$ mm.

This selection is the same as that applied in [2]. In this study tracks with absolute value of pseudo-rapidity smaller than 2.3 have been used.

3. Monte Carlo simulation

The Monte Carlo (MC) simulation used in this paper consists of a sample of about one million events of proton-proton collisions at $\sqrt{s} = 900$ GeV produced by non-diffractive processes. The event generation was done with Pythia [5] 6.4.21. The phenomenological model to describe proton-proton collisions was tuned to reproduce minimum bias and underlying event data at a center-of-mass energy range between 200 GeV and 1.96 TeV. The ATLAS detector simulation software based on GEANT4 [3] has been used to process the generated events.

4. Definition of the $E/P$ Observable

The sum of the energy deposits in all the calorimeter longitudinal layers associated to a track ($E$) is the observable that will be compared to the track momentum $P$. It is computed making use of topological clusters at the electromagnetic scale, i.e., without applying any correction for the calorimeter non-compensation and for the energy loss in dead material. The purpose of the topological clustering algorithm is to identify areas of connected energy deposits in the calorimeter and suppress the noise based on the significance of the energy deposits in cells with respect to the expected noise level. A topological cluster is initiated by cells with an energy deposit $|E_{cell}| > 4\sigma_{noise}$, where $\sigma_{noise}$ comes from the Gaussian fit of the electronic noise in the cell. Then, iteratively, the cluster expands adding all neighboring cells with $|E_{cell}| > 2\sigma_{noise}$.

1 The ATLAS reference system is a cartesian right-handed coordinate system, with the nominal collision point at the origin. The anti-clockwise beam direction defines the positive $z$-axis, while the positive $x$ axis is defined as pointing from the nominal interaction point to the center of the LHC ring. $\phi$ is the polar angle with respect to the $x$ axis, $\theta$ is the azimuthal angle with respect to the $z$ axis. The pseudo-rapidity is defined as $\eta = -\ln \tan \theta/2$. 
Finally, the cells surrounding the resulting cluster are added, regardless of their energy. The $\eta - \phi$ position of a cluster in a given longitudinal calorimeter layer is computed as the energy-weighted position of the cells in the layer.

For each longitudinal layer, the layer cluster energy $E_j$ is associated to the good track $k$, if the distance between the extrapolated track position $\eta_{tr}^{kj}$, $\phi_{tr}^{kj}$ (obtained using the direction of the track at the impact point on the calorimeter) and the cluster position is smaller than a given value $R_{coll}$. That is, if

$$\sqrt{(\eta_{tr}^{kj} - \eta_{ij}^{cl})^2 + (\phi_{tr}^{kj} - \phi_{ij}^{cl})^2} < R_{coll}$$

then the cluster energy in the layer $E_j$ is associated to the track. Subsequently the cluster energies in all the calorimeter layers is summed

$$E = \sum_j E_j$$

The parameter $R_{coll}$ has been chosen based on a trade-off between maximizing the particle shower containment and minimizing the background contribution coming from neutral particles produced close to the track.

Fig. 1 shows the comparison of the arithmetic mean value $\langle E/P \rangle$ as a function of the size of $R_{coll}$. The momentum and pseudo-rapidity spectra of the single pions have been weighted such to reproduce those of the charged particles in the non-diffractive minimum bias sample. The energy associated to a track in the minimum bias sample is equivalent to the single pion energy, provided that $R_{coll}$ is small enough. The $(E/P)$ ratios start to differ for collection cone opening angles larger than $\Delta R = 0.2$, which correspond to a radial shower containment of about 90%. A cone of $R_{coll} = 0.2$ is chosen as the best compromise between shower containment and background contribution.

5. The $E/P$ Distribution
As an example the $E/P$ distribution for tracks with momentum in the range from 1.2 to 1.8 GeV/c is shown in Fig. 2. The simulation reproduces the data well.
The large number of entries with $E/P = 0$ corresponds to isolated tracks that have no cluster associated in the calorimeter. The following effects are responsible for that:

- Particles can undergo hadronic interactions in the material in front of the calorimeter. This can happen in the inner detector volume, in the cryostat or in the solenoid placed in front of the calorimeter. Such particles can change their direction, or produce a large number of low momentum particles emerging from the hadronic interaction.
- As discussed in Sec. 4, a cluster is created only if a seed cell 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 compatible with noise, $P(E = 0)$, is defined as follows: the noise width ($\sigma$) is determined by finding, in the negative energy tail, the bin that contains $1/\sqrt{e}$ times fewer events than the bin at $E/P = 0$. $P(E = 0)$ is then obtained as the ratio of the number of events with $E/P < \sigma$ to the total number of events ($N_{tot}$) in the $E/P$ distribution.

$$P(E = 0) = \frac{N(E/P < \sigma)}{N_{tot}} \quad (4)$$

Fig. 3(a) shows the probability $P(E = 0)$ as a function of the amount of material in nuclear interaction lengths in front of active volume of the calorimeter in $0.0 < \eta < 1.0$ region (a). $P(E = 0)$ as a function of track momentum (b).

$P(E = 0)$ decreases with increasing track momentum. It is important to notice that, in general, the number of tracks with no clusters associated in the calorimeter as well as the $P(E = 0)$ probability are well predicted by the MC simulations.
6. Results as a Function of $P$ and of $\eta$

The isolated tracks have been classified in bins of momentum and of pseudo–rapidity of the impact point extrapolated to the second longitudinal layer of the electromagnetic calorimeter. For each $P$ and $\eta$ bin, the estimator that was chosen to perform the comparison is the mean value, $\langle E/P \rangle$.

Fig. 4 shows $\langle E/P \rangle$ as a function of $P$ regardless of the pseudo–rapidity of the impact point of the track. The black dots represent the data. The green shaded area corresponds to the MC prediction. The lower part of the figure shows the ratio between MC and data. The range that can be probed with the available statistics is approximately 500 MeV/c < $P$ < 10 GeV/c. In general, the agreement between MC and data is very good. The ratio between MC and data is fluctuating around one, with a maximum deviation that is well within 5%.

The dependence of $\langle E/P \rangle$ on $\eta$ is shown in Fig. 5. In this case, all tracks in a given $P$ range have been used. The region where the worst agreement between data and MC is found is the one around $\eta = 1.7$, where the MC is higher than the data. This is the transition region between the Barrel and Endcap EM calorimeters, where numerous services for the calorimeters and the inner detector are present.

7. Systematics

The following possible systematics have been evaluated:

- Track selection: the specifics of how isolated tracks are selected can have a systematic influence on the average value $\langle E/P \rangle$. The uncertainty on $\langle E/P \rangle$ due to the applied track selection was evaluated changing it within reasonable margins. The maximum variation of the $\langle E/P \rangle$ due to the track selection is in general of the same order as the statistical error, and it is below 0.01 (1.5%) for all bins. Detailed studies showed that the uncertainty of the response due to the track selection is small and well under control.

- Background contamination: the shower associated to a track can be contaminated by energy deposits from neutral particles. If the Monte Carlo modeling of the neutral component of the non–diffractive events is wrong, the contamination can be different for MC and data.
Figure 5. Average $\langle E/P \rangle$ as a function of $\eta$ for tracks with momentum $0.5 \text{ GeV}/c < P < 2.0 \text{ GeV}/c$ (left) and $2 \text{ GeV}/c < P < 15 \text{ GeV}/c$ (right).

In this analysis, the background contamination was estimated both using the MC simulation and a data-driven background procedure [4], finding consistent results. We obtained a neutral particle contamination of $(2.5 \pm 1.5)\%$ to the energy deposit associated to a track of momentum $P$. This affects the absolute $E/P$ measurement, but, since the contamination is small, even assuming a significant difference in data and MC with respect to this component, it would negligibly affect the agreement between data and MC. No additional uncertainty associated to the background contamination was therefore considered.

8. Conclusions
The data from proton–proton collisions at $\sqrt{s} = 900 \text{ GeV}$ collected by the ATLAS experiment have been used to compare the single track calorimeter response to the MC simulation predictions. Overall, an agreement within 5% on $\langle E/P \rangle$ has been found for particle momenta between $0.5 \text{ MeV}/c$ and $10 \text{ GeV}/c$, and for a particle pseudo-rapidity range from -2.3 to 2.3. Such a level of understanding of the ATLAS detector in the early stage of the experiment is encouraging and demonstrates the accurate description of dead material before the calorimeter and of the noise in the MC.

References
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