dE/dx measurement in the ATLAS Pixel Detector and its use for particle identification

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Abstract

The ATLAS Pixel detector is able to provide a measurement of the specific energy loss dE/dx for tracks from proton-proton collisions at high centre of mass. In this note we present a study of how this information can be used to identify the particle species for non relativistic particles. The study uses data recorded in the $\sqrt{s} = 7$ TeV proton-proton collisions during the 2010 run period and Monte Carlo simulation samples with corresponding conditions. The ionization losses of each track are measured in the Pixel Detector and the probability for a particle to match a given mass hypothesis is calculated. This allows to study the efficiency for particle identification and the mistag fractions from other particles of different masses. The mass measurements for the charged Kaon and proton agree with the PDG values and are seen to be stable throughout the 2010 data taking period. The use of this method to detect and measure hypothetical high-mass non-relativistic particles is also described.
1 Introduction

The ATLAS Pixel Detector [1, 2] consists of 1744 silicon pixel modules, arranged in three concentric barrel layers and two endcaps of three disks each. It provides on average three measurement points for charged tracks with $|\eta|$ up to 2.5 using $\approx 82$ million pixels of typical size $50 \mu m \times 400 \mu m$. The direction defined by the shorter pitch is the local $x$-coordinate on the module and corresponds to the high precision position measurement in the $R\phi$ plane. The direction defined by the longer pitch is the local $y$-coordinate and is oriented approximately along the $z$ direction in the barrel and along $R$ in the end-caps. Hits in a pixel are read out if the signal exceeds a tunable threshold, which was set at 3.5 ke during the 2010 run. Under these conditions, after masking few noisy channels, the noise rate probability is $\approx 10^{-10}$ per LHC clock cycle (the time window for the signal to be recorded has been varied from 5 LHC clock cycles at the beginning of the 2010 run to 1 LHC clock cycle at the end). The charge collected in each pixel is measured with 8-bit dynamic range using the Time over Threshold (ToT) technique: the width of the discriminator output signal of each pixel is measured checking the number of 25 ns clock cycles during which the signal is above threshold. The constant feedback current design used in the ATLAS pixel amplifier makes the ToT a sub-linear function of the charge. The ToT gives therefore precise information about the ionization losses of charged particles crossing pixel modules.

The purpose of this note is to explain how the ionization loss information can be used to measure the charge-to-mass ratio of particles in a limited region of phase space.

In Section 2 the data and Monte Carlo sets used in this note are defined. In Section 3.1 the ionization measurement and the factors limiting its precise determination are presented and discussed. In that section the cuts to define the clusters to be used in the $dE/dx$ calculations are also defined and justified. In Section 3.2 the actual $dE/dx$ measurement is described. In Section 4 the particle identification (PID) probability is calculated for low momentum hadrons and the mass spectrum are studied for light hadrons, deuterons and hypothetical stable heavy mass particles. The conclusions of the study are summarized in Section 5.

2 Data Samples, Event selection and Tracking reconstruction

The data used in this analysis consist of about 12 million events recorded by the ATLAS experiment at $\sqrt{s} = 7$ TeV, using the first $\approx 190 \mu b^{-1}$ of proton-proton collisions provided by the LHC; the maximum instantaneous luminosity was approximately $1.9 \times 10^{27} \text{cm}^{-2}\text{s}^{-1}$. These events come from an online selection that contains minimum-bias and diffractive triggers, those used in the ATLAS measurement of charged-hadron distributions [3]. During this data-taking period the solenoid magnet was on and the Inner Detector was working with more than 97% of the Pixel detector, 99% of the SCT and 98% of the TRT operational.

Tracks are reconstructed offline within the full acceptance range $|\eta| < 2.5$ of the Inner Detector [4,5]. Track candidates are reconstructed by requiring a minimum number of silicon hits and then extrapolated to include measurements in the TRT. In these data, tracks satisfying $p_T > 100$ MeV and $|d_0| < 100$ mm are reconstructed, where $d_0$ is the transverse impact parameter with respect to the primary vertex. To increase the efficiency for the lowest momentum tracks ($100 < p_T < 200$ MeV) looser cuts on the fit quality are imposed. This is possible once all the hits associated with higher momentum tracks have been used.

Additional cuts are applied to reject tracks with mis-measured $p_T$ or fakes. A minimum number of 2/4/6 SCT hits per track is required depending on the transverse momentum of the track, $p_T < 200$, $200 < p_T < 300$ or $p_T > 300$ MeV, respectively. A track-fit $\chi^2$ probability larger than 0.01 for $p_T > 10$ GeV cut is applied to remove tracks with mis-measured $p_T$ due to nuclear interactions or some residual mis-alignment.
Applying the previous selection cuts a sample of $3.2 \times 10^8$ tracks is selected.

The same requirements on events and tracks were imposed on a sample of 5 million non-diffractive minimum-bias MC events. All the events are then reconstructed and analysed by the same program chain used for the data. The distribution of the longitudinal position of the primary vertex in the simulated sample was reweighed to make it consistent with the data [3].

Finally, eight samples of $\approx 100k$ events each, have been reconstructed throughout the 2010 p-p data taking period. These are used to assess the stability of the measurement over time and over five orders of magnitude variation in instantaneous luminosity (see Sec. 4.3 for details).

3 Pixel $dE/dx$

3.1 Charge Collection in Clusters

A minimum ionizing particle (MIP) crossing a silicon pixel sensor will generate $\approx 80$ electron-hole pairs per micrometer of thickness. This charge is measured with 8-bit accuracy using the ToT method [2] provided it is above threshold ($3.5$ ke in the data we are considering in this note). The calibration of the detector is such that a MIP crossing the 250 $\mu$m sensor thickness at normal incidence will give a ToT count of 30, while the overflow is at 255. Each pixel diode will then measure a charge ranging from $3.5$ ke to $170$ ke. All the Pixel read-out channels are calibrated and equalized within 2%, which is significantly below the intrinsic accuracy on the ionization loss for a MIP. This procedure is repeated as frequently as required to guarantee stable operation. The charge collection efficiency is uniform over the sensor area with the exception of dead areas ($\approx 3\%$) most of which are due to non operational Pixel modules. The fraction of individual dead pixel is only a few per mille.

In LHC collisions the charge generated by one track crossing the Pixel detector is rarely contained in just one pixel. Neighboring pixels are then joined together to form clusters and the charge of the cluster is calculated summing up the charges of all pixels after calibration correction. The charge contained in a cluster is the quantity relevant for the $dE/dx$ measurement.

The Pixel detector charge measurement can be biased for various reasons:

(a) some charge may be lost if it is below the $3.5$ ke threshold

(b) some charge may be lost because it goes out of the detector active area (e.g. the cluster is at the boundary of a module or of a dead region).

(c) some charge may be lost because the ToT counter of a given pixel exceeds 255. In this very rare case the charge information on this pixel is lost.

while (a) and (c) are unavoidable biases, (b) can be removed by fiducial volume cuts.

In order to exclude all the reducible biases indicated, the local position of the cluster is constrained not to be at the edge of the module or in the ganged region, i.e. the $\approx 1$mm region along $x$ between two facing read-out chips where continuous sensitivity is obtained connecting two pixel sensors to one electronics channel. The different orientation of the modules relative to the magnetic field in the barrel and in the endcap sections of the detector requires to take into account the Lorentz angle effects in the implementation of these geometrical cuts. Figure 1 shows the dependence of the most probable value of the cluster charge on $\alpha$, where $\alpha$ is the spatial incident angle calculated versus the normal to module surface. It shows a good agreement between data and simulation down to $\cos \alpha = 0.16$. Clusters associated with tracks shallower than this limiting value (only a 0.4% of the sample) are excluded from the analysis.

Clusters passing all the above cuts will be referred to as Good Clusters. They represent 91% of all clusters: the number of clusters and the number of Good Clusters per track are plotted in Fig. 2.
The specific cluster energy loss \(dE/dx\) (expressed in units: MeVg\(^{-1}\)cm\(^2\)) is derived from the cluster charge taking into account the average energy needed to create an electron-hole pair, \(W = 3.68 \pm 0.02\) eV/pair [6], the path in silicon \(x = d/\cos \alpha\) and the silicon density \(\rho\):

\[
\frac{dE}{dx} = \frac{Q W \cos \alpha}{e \rho d}
\] (1)

Figure 3a shows the effect of the cluster selection cuts on the distribution of the cluster \(dE/dx\) thus demonstrating that the tails at low charge are effectively reduced.

Figure 3b shows the \(dE/dx\) distribution for the Good Clusters for data and Monte Carlo. The agreement is good, the peak positions of data and Monte Carlo differ by only 0.2%.
Figure 3: The cluster dE/dx distribution before (full) and after (dashed) having applied the Good Cluster cuts is shown in Figure a. Figure b shows the cluster dE/dx for the Good Clusters in data and Monte Carlo.

3.2 Track dE/dx

The ionization loss per unit length (dE/dx) of a given track is measured calculating the truncated mean of the dE/dx of the clusters associated with the track. This technique is frequently used when many ionization samplings are available [7] and the truncated mean is typically calculated averaging over the 70% lowest energy deposit measurements. This is meant to exclude those measurements laying in the Landau tail and tends to reduce the truncated mean distribution to a Gaussian, therefore improving the dE/dx resolution. In the case of the ATLAS Pixel detector only a few measurements per track are available as shown in Fig. 2 and therefore the track dE/dx is calculated excluding the clusters with the highest dE/dx, according to the prescriptions indicated in Table 1. This leaves some "memory" of the Landau tail in the track dE/dx as shown in Fig. 4a. Further details of the dE/dx distributions can be seen plotting Figure 4a in log-linear scale (Fig. 4b) and extending the range of dE/dx considered. The good agreement between data and simulation is evident up to energy losses corresponding to 10 MIPs.
Table 1: Resolution of the truncated mean. The resolution is computed as the RMS of a Gaussian fit to the distribution of the $dE/dx$ for tracks with momentum larger than 3 GeV. Only the fit errors are quoted.

<table>
<thead>
<tr>
<th># of Good Clusters</th>
<th># of GC excluded</th>
<th>Mean (MeV g$^{-1}$ cm$^2$)</th>
<th>Resolution %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1.253 ± 0.004</td>
<td>16.2 ± 0.4</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1.169 ± 0.001</td>
<td>13.9 ± 0.1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1.202 ± 0.001</td>
<td>10.9 ± 0.1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1.230 ± 0.001</td>
<td>10.1 ± 0.1</td>
</tr>
<tr>
<td>≥ 5</td>
<td>2</td>
<td>1.256 ± 0.001</td>
<td>9.5 ± 0.1</td>
</tr>
</tbody>
</table>

Table 1 summarizes the resolution of the truncated mean with respect to the number of Good Clusters used to measure it. The resolution is significantly worse when only one Good Cluster is available (6% of all tracks), these cases are therefore excluded from the analysis.

3.2.1 The Behaviour of $dE/dx$ as a Function of Momentum

A first analysis of the ionization loss measurement with the Pixel detector was described in [8] using a sample of cosmic rays event recorded by the ATLAS experiment in 2009. Only the relativistic rise of the ionization loss was measured in that case as all the tracks were cosmic ray muons of momentum greater than 0.5 GeV.

In the 2010 data sample instead, tracks are reconstructed using a $p_T$ threshold of 100 MeV and the sample contains different particles emerging from the collisions. In order to obtain a pure sample of particles of the same type, pions are selected from the $K^0_S$ decay, reconstructed as defined in [9].

Pion-tracks are selected if they belong to $K^0_S$ candidates and if they pass the track selection criteria described in Section 2. Moreover they are required to have at least 3 Good Clusters. Applying the same selection criteria on $K^0_S$ candidates in data and Monte Carlo, the purity of the pion sample is evaluated to be ≈ 98%.

Figure 5 shows the dependence on momentum of the MPV of the $dE/dx$ distribution of the selected pion tracks obtained by fitting the data sample in each momentum bin with a convolution of a Gaussian and a Landau functions. The binning is optimized in order to have similar statistics in each momentum bin.

The relativistic rise between the minimum and the plateau for momentum larger than 20 GeV is ≈ 8%, in good agreement with what was measured in different experimental conditions using cosmic ray muons [8], the plateau is reached, as expected, at $\beta \gamma \approx 30$. The mismatch between data and Monte Carlo for $100 < p < 200$ MeV was traced back to momentum mismeasurement which happens more frequently in this momentum range where the conditions on track quality are weakened (see Sec. 2 for details).

4 Particle Identification

4.1 Energy Loss Fit

The first step in the particle identification process consists of parameterizing the probability density function (pdf) for the specific energy loss $dE/dx$ and the $\beta \gamma$ of a charged particle. This pdf can be factorized into: a) a function that describes how the most probable value of the specific energy loss distribution ($MPV_{dE/dx}$) of a charged particle depends on $\beta \gamma$, and b) a function that describes how, for a charged particle of given $\beta \gamma$, the measured $dE/dx$ fluctuates around $MPV_{dE/dx}(\beta \gamma)$.
By looking at a sample of MC simulated tracks, whose $\beta \gamma$ value is known at generation level and ranges between 0.3 and 10, we find that a suitable parametric expression for function $MPV_{\text{fs}}(\beta \gamma)$ is given by:

$$MPV_{\text{fs}}(\beta \gamma) = \frac{p_1}{\beta^{p_5}} \ln(1 + (|p_2|\beta \gamma)^{p_5}) - p_4$$

(2)

where $p_1, \ldots, p_5$ are 5 free parameters whose values are eventually obtained as a result of a fitting procedure that is described in the following paragraph and that doesn’t rely on any prior knowledge of the particle species. Figure 6 shows the agreement between the 5 parameters function (2) and the measured $MPV_{\text{fs}}$ for pion, kaon and proton tracks in Monte Carlo simulation.

The specific energy loss fluctuations around the MPV at fixed $\beta \gamma$ are described by a Crystal Ball function peaked at $MPV_{\text{fs}}(\beta \gamma)$ with 3 free parameters: the standard deviation $\sigma$ of the Gaussian core, the distance $\alpha$ from the peak (in units of $\sigma$) where the Gaussian gives place to a power law behavior in the higher-end tail, and the power coefficient $n$ describing this tail.
Figure 7: $dE/dx$ distribution in several momentum intervals, equally spaced in $\ln(p)$, compared with the fitted function accounting for pions, kaons and protons. The deuteron peak, visible for $p > 0.4$ GeV, is not used in the fit.

Given a sufficiently large sample of reconstructed tracks whose $dE/dx$ and momentum $p$ are measured, and having $p \in [0.3, 1]$ GeV, the values of the 8 free parameters $(p_1, \ldots, p_5, \sigma, \alpha, n)$ of the pdf are obtained by fitting to the observed distribution of $dE/dx$ and $p$, under the hypothesis that the sample contains three charged particles species: $\pi$, $K$ and protons. This is achieved by first subdividing the sample in a set of 10 momentum slices of equal width in $\ln(p)$ and then fitting the observed $\ln(dE/dx)$ distribution in each momentum interval. The fit is performed summing three Crystal Ball functions for $\pi$, $K$ and protons. For each particle and each momentum interval the Crystal Ball peak position in $dE/dx$ is obtained through Eq. 2.

In addition to the 5 parameters of $MPV_{dE/dx}^\pi(\beta \gamma)$ and to the 3 parameters of the Crystal Ball function, the relative fraction of $\pi$, $K$ and protons in each interval are left free in the fit. Data and MC samples are fitted separately, and, since the observed $dE/dx$ vs $p$ distribution appears to be slightly different for tracks of positive and of negative charge and to depend on the number of Good Clusters associated with the track, in both cases the fit is separately performed for six mutually exclusive track categories (positive or negative tracks, having two, three and four or more Good Clusters).

Figure 7 shows an example (positive tracks having three Good Clusters in data) of the $dE/dx$ distribution observed in each of the 10 momentum slices, as well as the result of the global fit. A similar fit agreement is found in all 6 categories, both for data and MC.

The relative difference of the fitted $MPV_{dE/dx}^\pi(\beta \gamma)$ for the various categories is always below 15%.

Figure 8 shows the bi-dimensional distribution of $dE/dx$ and momentum with the $MPV_{dE/dx}^\pi(\beta \gamma)$ functions superimposed. These are shown for both data (left) and Monte Carlo (right).

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1) This amounts to a total of $2 \times n_{\text{slices}}$ additional free parameters, where $n_{\text{slices}} = 10$. 

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8
4.2 Tagging Efficiency

The likelihood probabilities $p_p$, $p_K$, $p_L$ derived from the energy loss fit can be used to identify protons, kaons and light particles $^2$. As the ionization resolution is not good enough to separate pion, muon and electrons, "light particle" is used to identify any of the three, although pion population is by far predominant.

The normalized likelihoods defined as

$$p_{L}^{\text{norm}} = \frac{p_L}{p_L + p_K + p_P}, \quad p_{K}^{\text{norm}} = \frac{p_K}{p_L + p_K + p_P}, \quad p_{P}^{\text{norm}} = \frac{p_P}{p_L + p_K + p_P}$$

are introduced because they are independent of the number of Good Clusters, while the absolute likelihoods are not. The agreement between data and Monte Carlo of the likelihood probabilities has been tested on controlled samples of tracks from $K_0^0$ and $\Lambda$ decays and with similar momentum distributions.

$^2$Protons, kaons, pions will include both particles and antiparticles, if not differently stated.
A particle is tagged to be of a certain type if the normalized likelihood for that type exceeds a defined value. A first method to measure the tagging efficiency relies completely on Monte Carlo. Proton and kaon tagging efficiencies, $\varepsilon_p$ and $\varepsilon_K$, are defined as follows:

$$\varepsilon_p = \frac{N(\text{Truth} = p, \text{Tag} = p)}{N(\text{Truth} = p)}, \quad \varepsilon_K = \frac{N(\text{Truth} = K, \text{Tag} = K)}{N(\text{Truth} = K)}$$

where in general $N(\text{Truth} = x)$ is the number of selected tracks having at least 2 Good Clusters associated with a generated $x$ particle ($x = \pi, K$ or $p$); $N(\text{Truth} = x, \text{Tag} = y)$ is the subset of $N(\text{Truth} = x)$ that is tagged as a $y$ particle ($y = \pi, K$ or $p$).

The efficiency is rather symmetric for protons and antiprotons and it rapidly decreases for momentum larger than 1 GeV. Also for kaons the efficiency is rather symmetric for positive and negative particles. The range of identification is smaller than the one for protons; with the efficiency rapidly decreasing for momentum larger than 0.4 GeV.

When selecting protons through a cut on $p_p^{\text{norm}}$, it is also important to know the mistag rate for pions and kaons, i.e. the probability for a generated pion or a kaon to be erroneously tagged as a proton. In the following, mistag rates $r_{\pi}^p$ and $r_{K}^p$ are defined as:

$$r_{\pi}^p = \frac{N(\text{Truth} = \pi, \text{Tag} = p)}{N(\text{Truth} = \pi)}, \quad r_{K}^p = \frac{N(\text{Truth} = K, \text{Tag} = p)}{N(\text{Truth} = K)}$$

The efficiency to identify protons with respect to the mistag rate $r_{\pi}^p$ ($r_{K}^p$), for particles of 0.5, 0.7 and 1.0 GeV momentum is shown in Figure 9a (9b).

![Figure 9: Proton efficiency with respect to mistag rate for pion (left) and kaon (right) for particles of 0.4 GeV (triangles) and 0.7 GeV (circles) and 1.0 GeV (squares), as a function of the cut on $p_p^{\text{norm}}$ ($p_p^{\text{norm}} > 0.1$, black; $p_p^{\text{norm}} > 0.3$, red; $p_p^{\text{norm}} > 0.5$, green; $p_p^{\text{norm}} > 0.7$, blue; $p_p^{\text{norm}} > 0.9$, magenta).](image-url)

The mistag rates $r_{\pi}^K$ and $r_{K}^p$, i.e. the probability for a generated pion or a proton to be erroneously tagged as a kaon, are defined as:

$$r_{\pi}^K = \frac{N(\text{Truth} = \pi, \text{Tag} = K)}{N(\text{Truth} = \pi)}, \quad r_{K}^p = \frac{N(\text{Truth} = p, \text{Tag} = K)}{N(\text{Truth} = p)}$$

The efficiency to identify kaons with respect to mistag rate $r_{\pi}^K$ ($r_{K}^p$), for particles of 0.3, 0.5 and 0.7 GeV momentum is shown in Figure 10a (10b).

A second method that is used to measure the proton tagging efficiency relies on $\Lambda^0(\bar{\Lambda}^0)$ decays, reconstructed as defined in [9], to select protons (antiprotons) and is completely data-driven. Proton
Figure 10: Kaon efficiency with respect to mistag rate for pion (left) and proton (right) for particles of 0.3 GeV (triangles) and 0.5 GeV (circles) and 0.7 GeV (squares), as a function of the cut on $p^norm_K$ ($p^norm_K > 0.1$, black; $p^norm_K > 0.3$, red; $p^norm_K > 0.5$, green; $p^norm_K > 0.7$, blue; $p^norm_K > 0.9$, magenta).

(antiproton) tracks are selected if they belong to $\Lambda^0$($\bar{\Lambda}^0$) candidates and if they pass the track selection criteria described in Section 2. Moreover they are required to have at least 2 Good Clusters.

The proton ($\bar{p}$) tagging efficiency for a given cut on $p^norm_P$ is obtained by fitting the $\Lambda^0$ ($\bar{\Lambda}^0$) mass distribution using a Gaussian over a second order polynomial function before and after having applied the cut.

Figure 11: Distribution of the $\Lambda^0$ mass before (black) and after (full red) applying a tagging cut $p^norm_P$ larger than 0.5. Equally distributed slices for proton momentum in the range (0.3-1.2) GeV are shown.

The fits on the $\Lambda^0$ ($\bar{\Lambda}^0$) signals shown in Figure 11 are performed in equally spaced slices of the positive (negative) track momentum. This allows an efficiency measurement that might be compared with the results obtained with Monte Carlo method applied on protons (antiprotons) from $\Lambda^0$($\bar{\Lambda}^0$) decays.
Figure 12 shows the tagging efficiency obtained from the data-driven method using the cut $p^\text{norm}_p > 0.5$ and the comparison with the Monte Carlo efficiency, which uses protons (antiprotons) from $\Lambda^0$ ($\bar{\Lambda}^0$) identified at generation level. The agreement is good, with the exception of the highest momentum bin.

![Proton Tagging Efficiency](image1)

![AntiProton Tagging Efficiency](image2)

Figure 12: In the left figure, the proton identification efficiency for a cut $p^\text{norm}_p$ larger than 0.5 using protons from $\Lambda^0$ decays. Efficiency obtained using simulated protons identified via the Monte Carlo truth and coming from $\Lambda^0$ decays is superimposed. In the right figure the same information is shown for $\bar{p}$ from $\bar{\Lambda}^0$. Only the statistical errors of the fits are shown.

4.3 PID Validation: Light Hadron Mass Spectrum

For all tracks having a reconstructed momentum $p$ and a measured specific energy loss $dE/dx$, a mass estimate $M^{31}$ is obtained by inverting the fitted function $M \rho \gamma(p/M) = dE/dx$ for the unknown $M$. Given the observed dependence of the $dE/dx$ distribution on the sign of charge $q$ and on the number of Good Clusters associated with the reconstructed track (see Section 4.1), the mass estimate is tested separately on each of the 6 categories: $q = +e, -e$ and 2, 3, and 4+ Good Clusters. Figure 13 shows the distribution of the mass estimate $M$ obtained on $\sim 12 \times 10^6$ data events as well as the result of an asymmetric Gaussian fit of each of the $2 \times 6$ peaks. Only tracks with a reconstructed $p$ in the range considered for the calibration of the fit function described in Sec. 4.1 ($p \in [0.3, 1]$ GeV) are considered. The fitted peak masses agree with the nominal $K$ and proton masses respectively within $\sim 10$ MeV, both in the data sample and in simulation, while the relative width of the peaks ranges from 10% to 14%.

The stability over time of the fitted mass values for the $K$ and proton peaks has been investigated: the results are shown in Figure 14. The first 7 runs are the ones used for the calibration of the system (i.e. the 12 million events), while the following runs are taken in different run periods distributed throughout the 2010 p-p data taking. The mass values are stable within 1% over 9 months of p-p data taking with luminosities ranging from $10^{27}$ cm$^{-2}$ s$^{-1}$ to $10^{32}$ cm$^{-2}$ s$^{-1}$ and with the timing window ranging from 5 to 1 LHC clock cycles.

3) Whenever $dE/dx < 1.9$ MeV g$^{-1}$ cm$^2$ we assume that the measured $dE/dx$ is compatible with the value expected for a MIP and the mass estimate $M$ is arbitrarily assigned a value $M = M_k$. 

12
Figure 13: Distribution of the mass estimate $M$ obtained from $\sim 12 \times 10^6$ Minimum Bias data events for tracks satisfying the track quality cuts described in section 2 and having a measured specific energy loss $dE/dx > 1.9$ MeV g$^{-1}$ cm$^2$. Solid lines: $q = +e$; broken lines: $q = -e$. Number of Good Clusters = 2 (red), = 3 (green), $\geq 4$ (blue). The $K$ and proton mass peaks observed in each category are fitted with an asymmetric Gaussian function.

Figure 14: Fitted $K$ peak mass values (left) and proton peak mass values (right) as a function of date for a set of Minimum Bias data runs spanning more than 9 months of ATLAS data taking and 5 orders of magnitude in luminosity. The vertical line separates the calibration runs (on the left of the vertical line) from the validation runs (on the right).

4.4 Mass Spectrum for heavier particles

The method we have described above is able to fit the mass of the $K$ and proton and therefore to identify these particles in some momentum range. High mass exotic particles are foreseen in several extension of the Standard Model [10, 11]. These particles can be detected, and their mass measured, through their ionization in the Pixel Detector and the momentum measured in the Inner Detector. It is therefore important to establish the predicting power of the method described in this note, i.e. to show the ability to find peaks of particle masses higher than those used for the fit (namely $\pi$, $K$ and proton).
Figure 15: The mass peaks found in data (left Figure) and in simulation (right Figure) for positive tracks with impact parameters ranging from 10 mm to 100 mm, with $dE/dx > 1.9$ MeV g$^{-1}$ cm$^2$ and number of Good Clusters $> 1$.

4.4.1 The Deuteron Case

The detection of the deuteron mass peak is the obvious first step in the verification of the predictive power of the method. Deuterons are produced in secondary hadronic interactions. Only those few interactions which happen in the beam pipe may give deuteron tracks measurable by the Pixel detector. Fig. 15 shows the mass peak found in data (a) and in simulation (b) for the particles with unsigned impact parameter $|d_0|$ ranging between 10 and 100 mm (and therefore likely to come from secondary hadronic interactions).

We observe that:

- the triton peak is visible in the simulation and not in the data. This can be explained by an overestimate of the triton production in Monte Carlo.
- the mass value of the deuteron is larger than expected (1876 MeV), both in data ($1938 \pm 3$ MeV) and in simulation ($1912 \pm 6$ MeV), only the statistical errors of the fits are quoted.

The main contribution to the mass overestimation has been traced back to the momentum mis-measurement for low-momentum particles. In the track reconstruction the energy loss due to ionization in the apparatus material is evaluated assuming all particles are pions. When a particle is heavier than a pion and has low-momentum the correction for the energy loss in the detector material is underestimated during track reconstruction and consequently the momentum is underestimated. This effect becomes significant for $\beta \gamma < 1$ and can reach 25% at $\beta \gamma \approx 0.3$.

The fit to the $\pi$, $K$ and proton peaks automatically takes into account the systematic bias in the momentum measurements for the three different particle species. Under these conditions it is not surprising that the deuteron (that has a different momentum correction factor) has a measured mass which is slightly overestimated.

4.4.2 The $R$-hadron Case

The correction to the momentum measurement for the ionization energy loss is negligible for high momentum particles even if they have $0.3 < \beta \gamma < 1.0$. As illustrated above, the mass fit to the low mass particles is made on a distorted momentum measurement. This cannot be avoided as the particle species are not known while executing the track reconstruction algorithm. This data driven mass fit has the definite advantage of checking the performance and stability of the method throughout the data taking
periods. This implies that, for a high mass low-$\beta\gamma$ particle like the $R$-hadron [12], the calculated value of the mass will be overestimated. The detection of this hypothetical particle as a peak in the mass plot can be done because the method (even if based on distorted momentum distributions) does not appreciably deteriorate the mass peak width. This is shown in Fig. 16, where events containing 300 GeV $R$-hadrons have been reconstructed. The $R$-hadron mass peak is indeed displaced to 320 GeV, but the width of the distribution has a r.m.s. value of 35 GeV. This corresponds to the same relative width obtained for the low mass particles. A fit done with the ideal momentum distribution gives the same width. The average overestimation of the $R$-hadron mass is 8% over the range 100-1000 GeV.

The use of the Pixel detector in the search for $R$-hadrons offers two definite advantages:

- the $dE/dx$ relativistic rise is limited by the density effect (see Sec. 3.2.1) and is therefore small compared to the same effect measured in a gaseous detectors like the TRT. This minimizes overlap of the $dE/dx$ of standard model particles and $R$-hadrons both of high momentum.
- the measurement of $dE/dx$ within $\approx 15$ cm from the interaction vertex allows us to detect metastable $R$-hadrons provided they have a lifetime exceeding few hundreds of picoseconds.

5 Conclusions

The specific ionization $dE/dx$ of a track can be measured by the ATLAS Pixel detector with a typical resolution of 10%. Thanks to the stability of the detection process and of the Pixel environment, the average $dE/dx$ value and dispersion do not change appreciably with experimental conditions. This allows us to define a method for non relativistic particle identification, based on the well known $dE/dx$ dependence on $\beta\gamma$, which has been shown to be stable over a 9 month run with luminosity ranging from $10^{27}$ cm$^{-2}$s$^{-1}$ to $10^{32}$ cm$^{-2}$s$^{-1}$. Applications of this identification method are possible both in the framework of the Standard Model and in some of its Supersymmetric extensions.

The Standard Model applications are limited to the lowest momenta measured in ATLAS (typically below 1 GeV) and are related to soft QCD issues (e.g. $\phi$ or $\Lambda$ production) or to Quantum Mechanical tests (e.g. Bose-Einstein Correlations of identical particles).

Very heavy stable or metastable particles (e.g. R-hadrons) are foreseen in some Supersymmetric models. It is expected that a large fraction of these particles will be produced with $0.2 < \beta\gamma < 1.5$ and can therefore be identified with the same method defined and tested for low momentum standard model hadrons.
References


