Measurement of the charged particle density with the ATLAS detector: First data at \( v_s = 0.9, 2.36 \) and 7 TeV

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Chapter 4

TRACK RESOLUTIONS IN COSMIC RAY DATA

After the complete installation of the inner detector in the ATLAS cavern in fall 2008 and in absence of collision data from the LHC, first measurements of the inner detector performance were performed with muons originating from cosmic ray events. The results presented here have been published in the paper The ATLAS Inner Detector commissioning and calibration [79] in the European Physical Journal C. Cosmic rays are high-energy particles that originate from outer space and reach the atmosphere of the Earth from all directions [121]. Energies beyond $10^{11}$ GeV have been measured for single cosmic ray particles. In collisions with atmospheric atoms, showers of particles are created of which mostly muons and neutrinos reach the surface of the Earth. Generally these muons are loosely called cosmic muons. Cosmic ray events provide an excellent test-bed for studying the initial performance of the detector for various reasons:

- **Low multiplicity**
  In a cosmic ray event, there is usually only one muon, which allows for less stringent requirements on the pattern recognition and the track reconstruction algorithms compared to the busy environment of proton proton collisions.

- **Non-pointing tracks**
  In collision events almost all particles are produced at the primary vertex. Certain systematic distortions of the detector cannot be resolved if the alignment algorithms rely on collision data only. Cosmic ray muons however do not originate from a common vertex and help solving these systematic distortions.

- **High energy muons**
  Cosmic ray events compose a sample of muons with high transverse momenta. These muons, which are rarely produced in proton collisions (about 1.6 per 1000 events [122]), are recorded in abundance from cosmic ray events. Hence large-scale
Track resolutions in cosmic ray data

studies on muon reconstruction combining information from the muon system and the inner detector can be performed.

However, certain properties of cosmic ray events had to be taken into account in preparation of analysing tracks from collision data. For these studies requirements were imposed to emulate collision events as good as possible as the cosmic ray muons do not originate from the nominal interaction region and arrive randomly in time. The first goal of the cosmic ray data taking was operating the various components of the inner detector under stable conditions and obtaining a first set of calibration constants for the completely installed detector. Having achieved this, the combined performance of the inner detector was studied. This includes investigating various trigger configurations to record the data, providing an initial set of alignment constants for the detector modules and studying track parameter resolutions. The measurement of the track parameter resolutions was performed with the split track method, which allows to determine the resolutions solely from data and is the main subject of this chapter.

4.1 Split track method

Before data from cosmic ray events were available the resolutions of track parameters were analysed using simulated events only. The resolution was obtained by computing the difference of the track parameters from a generated particle and the corresponding reconstructed track. This method will be referred to as the Monte Carlo method in the following and the results were published for example in [17]. A unique feature of cosmic ray muons is that they traverse the entire detector from top to bottom. Splitting such a track into parts traversing only the upper or lower hemisphere of the detector and performing the track fit again separately for the two arms, two distinct tracks that resemble tracks from collision events are obtained. The difference between the measured track parameters, which is illustrated for the transverse impact parameter \( d_0 \) in Figure 4.1, gives information about their resolution.

As explained in Chapter 3, the helical track parameter model in ATLAS has five free parameters \( \Lambda \) that are defined at the interaction point called perigee. The perigee is the point of closest approach to the beam axis. It is well defined also for cosmic ray muons as it corresponds to the point of closest approach to the origin \((0,0,0)\) of the global ATLAS coordinate system. The perigee parameters of a track are

\[
\Lambda^T = (d_0, z_0, \phi_0, \theta, q/p),
\]

which represent the transverse and longitudinal impact parameters, the azimuthal and polar angles as well as the charge-signed inverse momentum or curvature. The mean difference between the parameters of the arms of a muon track \( (\Delta \lambda = \lambda_{up} - \lambda_{down}) \) has an expectation value of zero. The variance is given by the quadratic sum of the resolutions \( \sigma(\lambda) \) of the upper and lower track:

\[
\sigma^2(\Delta \lambda) = \sigma^2(\lambda_{up} - \lambda_{down}) \approx \sigma^2(\lambda_{up}) + \sigma^2(\lambda_{down})
\]
4.1 Split track method

Figure 4.1: Illustration of a cosmic particle (dashed line) leaving hits in the inner detector. The solid lines represent the tracks reconstructed separately in the upper and lower hemisphere of the detector. The difference of the measured track parameters (here the difference of the transverse impact parameter \(\Delta d_0\)) provides information about the resolution.

This equation obviously only holds if correlations between the measurements of the upper and lower track segments are negligible. As both tracks originate from the same particle it is assumed that the upper and the lower track have on average the same resolution \(\sigma(\lambda)\). The resolution of a track parameter \(\lambda\) is thus given by

\[
\sigma(\lambda) = \frac{\sigma(\Delta \lambda)}{\sqrt{2}},
\]

where the resolution is calculated as the root mean square (RMS) of the \(\Delta \lambda\) distributions divided by \(\sqrt{2}\). The boundaries for the calculation of the resolutions are estimated as three times the RMS around the mean of the \(\Delta \lambda\) distribution. This definition is chosen to ensure compatibility with [17] and to be able to include most of the significant tails while being robust against single outliers. To guarantee statistically meaningful results resolutions are only quoted in bins of a track parameter if at least 50 tracks were
reconstructed in the particular bin.

The validity of the split track method was verified on a sample of simulated cosmic ray events. In Figure 4.2, a comparison between the split track method and the Monte Carlo method is shown for transverse impact parameter resolution and the relative curvature resolution as a function of the transverse momentum. Both methods yield consistent results over the whole range of momenta. This justifies the assumption that the correlation between upper and lower track is negligible.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure42}
\caption{Comparison of the Monte Carlo (solid marker) and the data-driven split track method (open markers) to extract resolutions of the transverse impact parameter (a) and the relative curvature (b) as a function of $p_T$.}
\end{figure}

In the following the split track method is used to extract resolutions from data and simulation. Differences between the track parameter resolutions in data and simulation provide valuable information about possible imperfections of the calibration constants and remaining misalignments in the detector.

## 4.2 Event and track selection

Several millions of events were recorded during the combined ATLAS cosmic ray data taking in September and October 2008. This study focuses on a data taking period with stable operating conditions of the trigger and the inner detector sub-systems.\footnote{The runs 91885, 91888, 91890, 91891 and 91900 recorded during October 17th - 19th were selected.}

The events were triggered using Resistive Plate Chambers and Thin Gap Chambers of the ATLAS muon system as well as the Liquid Argon Calorimeter. To reduce the high rate of cosmic ray muons only events with at least one track in the inner detector were selected.

In total the data set comprises 56073 events with at least one track containing a pixel hit. The solenoid was operated at its nominal strength providing a field of $B_z = 2$ T. Once
4.2 Event and track selection

the offline detector calibration had been complete and an initial set of alignment constants had become available, the data sample of cosmic ray events was re-reconstructed using this information and the track parameter resolutions were studied.

The simulated cosmic ray events were produced by generating single muons at the surface above the ATLAS cavern according to the cosmic ray flux in [123] and the momentum spectrum in [80]. The ATLAS detector simulation programme [124], which is based on Geant4 [125], propagates the muons through the rock, the cavern structure and the ATLAS detector itself. Only muons which point to a sphere inside the cavern representing the detector are selected. To make a collection that has some resemblance to tracks from collision events only events with at least one hit in the pixel detector were kept for analysis.

An example of a typical cosmic ray event is shown in Figure 4.3. The traversing muon leaves hits in the inner detector and is reconstructed as one track across the whole detector. The major modifications of the track fit were to remove the assumption of a collision vertex and to fit the traversing particle as one track across both hemispheres.

To obtain separate tracks in the upper and lower detector arm, the hits produced by a cosmic muon were separated according to their global y-coordinate in the ATLAS coordinate frame. Subsequently track fits were performed on the hits in the upper and lower half. Additionally, these tracks were also fit omitting the TRT information. The two resulting samples are referred to as Si only tracks and full ID tracks in the following.

Requirements were imposed to select only well reconstructed tracks and tracks that resemble collision events as much as possible while retaining a sufficient size of the data set. The selection criteria applied to the tracks are listed in Table 4.1.

Table 4.1: Selection cuts applied to events and to track pairs after the fit of the upper and lower track arms. SCT hits are counted one for each module side.

<table>
<thead>
<tr>
<th>Selection criterion</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRT event phase</td>
<td>$5 &lt; T_{TRT} &lt; 30,\text{ns}$</td>
</tr>
<tr>
<td>number of pixel barrel hits of each track</td>
<td>$n_{\text{pix}} \geq 2$</td>
</tr>
<tr>
<td>number of SCT barrel hits of each track</td>
<td>$n_{\text{SCT}} \geq 6$</td>
</tr>
<tr>
<td>number of TRT barrel hits of each track</td>
<td>$n_{\text{TRT}} \geq 25$</td>
</tr>
<tr>
<td>impact parameter $d_0$ of each track</td>
<td>$</td>
</tr>
<tr>
<td>transverse momentum $p_T$ of each track</td>
<td>$p_T &gt; 1,\text{GeV}$</td>
</tr>
</tbody>
</table>

The synchronisation of the readout of the individual detector component is crucial for their performance as shown in Figure 2.12(a) for the SCT. The TRT event phase $T_{TRT}$, which measures the time when a cosmic track passes through the TRT detector, is used here to select a good time window for the readout. In general the read-out of the ATLAS detector is timed in bins of 25 ns corresponding to the expected spacing between collisions at the LHC. As cosmic ray particles arrive randomly in time and need approximately 10 ns to traverse the inner detector, a spread in the time of arrival is unavoidable. Additionally, large differences in the timing of the Resistive Plate Chambers
Figure 4.3: Event display of a cosmic ray muon with a reconstructed track (solid line) from hits in the pixel, SCT and TRT detectors (squares). The $x - y$ (a) and $y - z$ (b) projections show how the muon curves in the magnetic field of the inner detector. The $R - z$ projection (c) illustrates that the cosmic muon traverses the central part of the detector.
were observed as different regions of these detectors were not yet fully synchronised with respect to one another. The most effective selection is to require values of $T_{\text{TRT}}$ between 5 and 30 ns. This guarantees high hit efficiencies for the TRT and, at the same time, also for the SCT and pixel detectors.

Due to the geometry of cosmic rays events the end-caps of the detectors are only poorly illuminated. Hence the hit requirement is imposed on hits in the barrel part of the detector. The value $|d_0| < 40\text{ mm}$ means that the track parameters are compared at a point inside the beam pipe, including uncertainties from the extrapolation through the beam pipe wall due to material effects. This requirement is relaxed when the resolutions are studied as a function of $d_0$. The TRT hit requirement is not used for tracks fitted only with information from the silicon detectors. However, the requirement on the event phase $T_{\text{TRT}}$ is retained to guarantee a good timing and the comparability of the two sets of track pairs.

Altogether these cuts represent a tight selection of cosmic muons: 2528 (5.3%) track pairs remain from an initial number of 47628 for full ID tracks.

### 4.3 Performance

The illumination of the inner detector with cosmic ray muons is strongly influenced by the properties of the ATLAS cavern. The cavern is situated approximately 100 m under ground and can be accessed by two supply shafts directly above the detector and two smaller elevator shafts next to the cavern as illustrated in Figure 4.4.

Most muons traverse the detector vertically. This can be seen in Figure 4.5 where the number of recorded hits in the pixel and SCT detectors are shown as a function of $\eta$ and $\phi$ of the module identifiers. The $\phi$ identifier starts in horizontal direction corresponding to $x = 0$ and increases counter clockwise. The $\eta$ identifier starts at $z = 0$ and increases (decreases) with increasing (decreasing) $z$. It can be clearly seen that most hits are recorded in the top and bottom parts of the detectors. Bins with no recorded hits correspond to disabled modules.

The distributions of the azimuthal angle $\phi_0$ and the polar angle $\theta$ are shown in Figure 4.6(a) and (b). The shapes of the distributions reflect the fact that particles can reach the ATLAS detector more easily when traversing the access shafts than the rock. The distribution of $\phi_0$ is always negative as both upper and lower tracks were reconstructed from top to bottom. The highest peak at $\phi_0 = -1.7$ originates from the two supply shafts ((1) and (2) in Figure 4.4) whereas the two satellite peaks represent the elevator shafts ((3) in Figure 4.4). The distribution of the polar angle $\theta$ shows that the tracks are restricted to the barrel region ($0.7 < \theta < 2.4$). The two peaks correspond to the two supply shafts directly above the detector. The peak at $\theta = 1.8$ is higher as the supply shafts differ in size which is also seen in Figure 4.5 where more hits are recorded in the negative $\eta$ region. Figure 4.6(c) shows a x-z projection of the selected tracks extrapolated to a surface directly above the detector. One can clearly recognise the two supply shafts with their different sizes as well as the two elevator shafts.

The signed momentum distribution is shown in Figure 4.6(d). The distribution has
Figure 4.4: Cut-away graphic of the ATLAS cavern with the two supply shafts (1,2) and one elevator shaft (3). The second elevator shaft (4) is not displayed. In general more particles are reconstructed that pass through the shafts than through the rock.

Figure 4.5: Number of recorded hits in the pixel (a) and SCT (b) barrel layer 2 as a function of $\eta$ and $\phi$ of the module identifiers.
4.3 Performance

Figure 4.6: Track parameter distributions of the azimuthal angle $\phi_0$ (a), polar angle $\theta$ (b) and the signed momentum (d). (c) An x-z projection of tracks extrapolated to a surface above the detector is also shown. The numbers correspond to the shafts as shown in Figure 4.4.

its maximum around 10 GeV and decreases rapidly towards higher momenta. Only few muons are reconstructed with a momentum above 150 GeV. The observed charge asymmetry of positive and negative muons is caused by the muon charge ratio $\mu^+ / \mu^-$ of approximately 1.3 [80] for cosmic ray muons and by the influence of the toroidal magnetic field in the muon system. The majority of muons reaching the inner detector traverses the bigger supply shaft (shaft (2) in Figure 4.4) and negatively charged muons originating from this direction are deflected away from the inner detector.

As expected, the transverse and longitudinal impact parameters have flat distributions between the boundaries imposed by the track requirements while they peak at zero for collision events when computed with respect to the primary vertex.

The track parameter resolutions strongly depend on the accuracy to which the position and orientation of the inner detector readout sensors and wires are known. The requirement on the alignment precision from the Technical Design Report [64] is that
the resolution of the track parameters should not be degraded by more than 20% with respect to the intrinsic resolution. This translates into an alignment precision of approximately 7 µm for the pixel modules and 12 µm for SCT modules in the R−φ direction as discussed in Section 2.1.1. The intrinsic hit resolutions in R−φ are 10 µm for pixel and around 17 µm for SCT modules. The initial accuracy to which the position of the detector structures were known was $\mathcal{O}(1 \text{ mm})$ within the volume of the inner detector for an entire barrel or end-cap, of $\mathcal{O}(100 \text{ µm})$ for a single layer or disk and of $\mathcal{O}(10 \text{ µm})$ for individual modules. Within this range track-based alignment algorithms are expected to be able to recover the remaining misalignments.

![Figures](a) and (b) show the comparison of hit residual distributions of the most sensitive coordinate for the pixel (a) and SCT (b) before and after the alignment procedure together with the ideal distribution from simulation. The resolutions are quoted as the width of a Gaussian fit to the core of the distribution.

In general the modules are aligned in six degrees of freedom - three translational and three rotational directions. The alignment procedure consists of a $\chi^2$ minimisation of the hit residuals, i.e. the distance from the predicted track position on a given detector module to the hit position recorded in the module. The $\chi^2$ minimisation is performed with respect to the alignment parameters by a global $\chi^2$ algorithm [126]. A comparison of the hit residuals obtained before and after the alignment procedure together with the expectation from a perfectly aligned geometry in simulation is shown in Figure 4.7. The alignment was performed on a data sample containing tracks reconstructed with and without magnetic field. The widths of the barrel residual distributions are consistent with a random misalignment of approximately 17 µm estimated from the quadratic difference of the resolutions after the alignment procedure and from simulation.

Other possible remaining misalignments are so-called weak modes, which preserve the helical trajectory of the tracks and leave the $\chi^2$ of the track fit unchanged while they systematically bias the track parameters (illustrated in Figure 4.8). Certain torsions introduce a systematic mis-measurement of the momentum and may lead to a wrongly observed charge asymmetry; while tracks with a particular charge are reconstructed with
higher momentum on average, the oppositely charged tracks are in general reconstructed with lower momentum. As tracks from cosmic ray events do not point to a common vertex they can help to resolve weak modes and are even used in the alignment procedure when data from collision events is available.

Figure 4.8: (a) Illustration of the R-Δφ weak mode. The measured curvature differs from the true one while the hit residuals stay unchanged. (b) Illustration of the R − ΔR weak mode. The difference between true and reconstructed secondary vertex introduces a bias in the decay length.

Another possible weak mode is a radial extension of the modules with increasing radius of a layer - called dR-R weak mode. This weak mode may introduce a bias in lifetime measurements as the position of secondary vertices is systematically mismeasured as illustrated in Figure 4.8(b). This weak mode can be constrained by looking at so-called overlap residuals on cosmic ray data. Overlap residuals are computed as the difference of two hit residuals of overlapping modules that were both traversed by the same track. A systematic deviation of the mean from zero can be an indication of a radial extension of a barrel layer. To illustrate this effect the mean of the overlap residuals as a function of the $\phi$ module identifier is shown in Figure 4.9(a) and (b) on simulated events. A perfectly aligned detector is compared to a detector geometry where the radius of the pixel and SCT layers was extended as a function of the radius itself to emulate the dR-R weak mode. The maximal radial shift was defined to be 200 $\mu$m in the outermost SCT layer leading to a shift of approximately 35 $\mu$m of the residual distribution on a single module in its sensitive direction due to the module tilt angle of approximately 10°. In both the pixel and the SCT detector these significant deviations of the mean from zero are observed. The regions in $\phi$ with large statistical errors correspond to the horizontal
area of the detector which is less illuminated by cosmic ray muons.

Figure 4.9: (a), (b) Mean of the overlap residuals in pixel and SCT barrel layer 2 as a function of the $\phi$ module identifier. A systematic radial extension of the detector is compared to a perfectly aligned detector in simulation. (c), (d) Comparison of the mean of the overlap residuals before and after the alignment procedure in data.

In Figure 4.9(c) and (d) the mean of the overlap residuals is compared before and after the alignment procedure on cosmic ray data. The mean of the overlap residuals improves significantly over the whole range in the pixel and the SCT detectors. The remaining small deviations from zero do not show a systematic structure and thus no hints of possible weak modes in the detector.

### 4.4 Resolutions

#### 4.4.1 Impact parameters

Figure 4.10 shows a comparison between data and simulation of the transverse and longitudinal impact parameter resolutions as a function of transverse momentum. At
low momenta the resolution is largely determined by multiple scattering in the beam pipe and in the pixel layers. For higher momenta above 10 GeV the impact parameter resolutions derived from data rapidly approach an asymptotic limit while the measured resolutions in simulation decrease over the whole range shown. The impact parameter resolution in data is limited by the intrinsic resolution of the modules and the remaining misalignments while the resolution in simulation is only limited by the design of the modules.

Most of the resolutions measured as a function of \( \eta \) are approximately constant and symmetric around \( \eta = 0 \) as shown in Figure 4.11. Both Figures 4.10 and 4.11 compare the resolutions of full inner detector tracks with Si only tracks. The \( d_0 \) resolution is considerably better for full tracks, as the TRT measurements improve the \( \phi_0 \) and \( p_T \) resolutions and thus to the precision of the track extrapolation to the perigee point.

The transverse impact parameter resolution is also studied as a function of \( d_0 \) itself on a sample without the requirement on \( |d_0| < 40 \text{ mm} \). The results are presented in Figure 4.12 and show an increase of the resolution towards larger \( |d_0| \) which corresponds to tracks crossing pixel layers at low incidence angles. Pixel clusters from such tracks are wider and possibly recorded as multiple hits as the traversed length of depleted silicon per pixel is reduced. These effects lead to a degradation of the resolution. As expected the resolutions also degrade if less pixel layers are traversed (entries beyond the first and second vertical lines from the centre in Figure 4.12). The latter aspect is further investigated in Section 4.5. A possible correlation between the charge of the reconstructed tracks and the resolution is investigated in Figure 4.12(b). Small differences appear in some bins but do not allow for a conclusive result.

The mean value of the \( \Delta d_0 \) distribution shows a significant deviation from zero of around 10 \( \mu \text{m} \) on average. It is most pronounced for high momentum tracks and shows

Figure 4.10: Transverse (a) and longitudinal (b) impact parameter resolutions as a function of transverse momentum. Resolutions of full ID (solid triangles) and Si only (open triangles) tracks in data are compared to those from full ID tracks in simulation (stars).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig410}
\caption{
Figure 4.10: Transverse (a) and longitudinal (b) impact parameter resolutions as a function of transverse momentum. Resolutions of full ID (solid triangles) and Si only (open triangles) tracks in data are compared to those from full ID tracks in simulation (stars).
}
\end{figure}
Track resolutions in cosmic ray data

Figure 4.11: Resolutions of the transverse (a) and longitudinal (b) impact parameters as a function of pseudorapidity $\eta$.

Figure 4.12: (a) Transverse impact parameter resolution as a function of transverse impact parameter for full ID, Si only and simulated full ID tracks. (b) Comparison of the $d_0$ resolution for full ID tracks with positive (open markers) and negative charge (solid markers). The vertical lines indicate the positions of the pixel barrel layers.

A dependence on the $d_0$ parameter itself, as can be seen in Figure 4.13. This effect has been understood to arise from an incorrect treatment of the Hall angle in the track reconstruction software. The Hall angle is the drift angle of the charge carriers in a silicon detector in the presence of a magnetic field and its measurement on cosmic-ray data was presented in Figures 2.7(a) and 2.12(b). In more recent versions of the software, which are used in the remainder of this thesis, a correct treatment of the Hall angle has been implemented. The mean of the $\Delta z_0$ distribution however is compatible with zero.
4.4 Resolutions

4.4.2 Angular parameters

An accurate reconstruction of the angular track parameters is vital for finding decay vertices and matching with signals from other detectors. The track directions $\phi_0$ and $\theta$ for high momentum tracks are measured with an accuracy of 0.2 mrad and 1 mrad respectively. The angular resolutions as a function of $p_T$ and $\eta$ are shown in Figures 4.14 and 4.15. The slight increase of the $\theta$ resolution at $p_T = 20$ GeV in data is not completely understood. The statistical uncertainty is however too large to identify a systematic mis-measurement. The observed feature is also not observed in simulation.

Figure 4.14: Resolutions of the azimuthal (a) and the polar angle (b) determined from data and simulation as a function of transverse momentum.

The angular resolutions have been found to be independent of other track parameters, except for a small rise at $|d_0| > 50$ mm that is due to the track missing the innermost pixel.
Figure 4.15: Resolutions of the azimuthal (a) and the polar angle (b) determined from data and simulation as a function of pseudorapidity.

layer. The means of the $\Delta \phi_0$ and $\Delta \theta$ distributions are compatible with zero. However, a dependency of $\Delta \theta$ as a function of $\phi_0$, which is not present in simulation, is observed as shown in Figure 4.16.

Figure 4.16: Comparison between data and simulation of the mean of $\Delta \theta$ as a function of the azimuthal angle $\phi_0$.

4.4.3 Momentum

In Figure 4.17 the relative resolution of the curvature ($p \times \sigma(q/p)$) is shown as a function of transverse momentum and pseudorapidity. The relative resolutions are flat in $\eta$ and degrade at higher transverse momenta. This is expected as the bending of particles in the magnetic field is proportional to $1/p_T$ while the uncertainty on the determination of the curvature remains approximately constant. At higher transverse momenta the contribution of the TRT to the momentum resolution becomes significant. The magnetic
field integral $\int |\vec{B} \times \vec{d}l|$ for tracks including the TRT measurements is higher, which allows a more precise determination of the curvature. The effect can be seen when comparing the tracks using only pixel and SCT information (Si only tracks) with the full ID tracks in Figure 4.17.

![Figure 4.17](image1)

**Figure 4.17:** The relative curvature resolutions as a function of $p_T$ (a) and $\eta$ (b).

The mean of the $(p \times \Delta(q/p))$ distribution shows a rising deviation from zero at higher transverse momenta for both distributions derived from cosmic ray data. This bias is not observed in simulation as shown in Figure 4.18. Probably the bias relates to the deviations seen in the mean of the $\Delta d_0$ distribution (see Figure 4.13) as the measurement of the transverse impact parameter and the curvature are highly correlated.

![Figure 4.18](image2)

**Figure 4.18:** Mean of $p \times \Delta(q/p)$ as a function of $p_T$. The mean values for full ID tracks determined in data and simulation are compared to Si only tracks.
4.5 Resolution studies with the pixel detector

In this thesis, special emphasis is put on reconstructing tracks from charged particles with the pixel detector. The pixel detector plays a crucial role for the measurement of the charged particle densities performed in Chapters 5 and 6 as the tracks used in this analysis are reconstructed from pixel hits only. In this section the impact of a missing hit in a particular pixel barrel layer on the track parameter resolutions is studied. For this three samples have been constructed by removing pixel hits from the original tracks and subsequently re-fitting these tracks:

- tracks with one hit on all three pixel layers respectively;
- tracks with two pixel hits of which one is on the middle and one on the outer pixel layer;
- tracks with two pixel hits of which one is on the innermost pixel layer and one on another pixel layer.

The number of compared tracks and their track parameter distributions is consistent and the observed differences can be attributed to the varying number of pixel hits per track and are only marginally influenced by effects from the pattern recognition. Figure 4.19(a) shows the resolutions of the transverse impact parameter $d_0$ as a function of transverse momentum. The resolution for tracks that miss a hit on the innermost layer is considerably worse over the whole range of transverse momenta shown. The same behaviour is observed for the longitudinal impact parameter $z_0$ as can be seen in Figure 4.19(b). To first order one would expect the ratio of the resolutions with and without a hit in the innermost layer as a function of transverse momentum to be constant. This is due to the fact that the extrapolation distance from the first pixel hit on a track to the perigee point dominates the impact parameter resolutions. When computing the ratio of the transverse impact parameter resolutions for example, one obtains a ratio of approximately 1.6 over the whole range of momenta shown. The expected value would be $\approx 1.8$ derived from the ratio of the distance of the first and second pixel barrel layer from the nominal interaction point (50.5 mm and 88.5 mm).

The effect of missing pixel hits was also investigated for the resolutions of the curvature and the azimuthal angle. As the magnetic field integral $\int |\vec{B} \times \vec{d}|$ virtually does not change, the resolutions of the curvature remain the same. Only a very small effect in $\phi_0$ due to the increased extrapolation distance to the perigee was observed for low momentum tracks missing the hit on the innermost layer.

4.6 Track segment matching

Another method to validate the quality of the alignment and the consistency of the track reconstruction is to look at track segments reconstructed with different detector parts. For this study, four track segments are reconstructed separately in the silicon detectors and the TRT, two in the upper and two in the lower hemisphere. All track segments
4.7 Track parameter uncertainties

Figure 4.19: Transverse (left) and longitudinal (right) impact parameter resolutions determined from data as a function of $p_T$. Resolutions of full Inner Detector tracks are compared for tracks with hits on all pixel layers (solid markers), for tracks with two pixel hits of which none is on innermost layer called layer 0 (open markers) and for tracks with two pixel hits of which one is on the innermost layer (stars).

were obtained from the same cosmic ray muon and comparisons between silicon and TRT segments are performed separately in the upper and lower part of the detector. The interesting quantity to investigate is the mean of the difference of a track parameters $\Delta \lambda$. A shift of the mean from zero would indicate misalignments of larger structures inside a sub-detector or of the sub-detectors relative to each other.

Tracks reconstructed solely with the TRT measure the transverse impact parameter $d_0$, the azimuthal angle $\phi_0$ and the curvature $q/p$. In Figure 4.20, the mean values of these three track parameter distributions are shown as a function of transverse momentum. As the values for the upper and lower distributions obtained from simulation show only marginal differences, it was decided to average the distributions to maintain clarity. The mean values of the data distributions are mostly consistent with zero for the comparison of upper and lower track segments. The observed deviations indicate the remaining uncertainties of the alignment precision.

4.7 Track parameter uncertainties

Track reconstruction involves the computation of the track parameters along with their uncertainties. The main sources of these uncertainties are the scattering in the material of the detector and the measurement uncertainties on the hits in the detector. For the hits in the pixel and SCT detectors a conservative strategy was chosen. Their measurement uncertainty was assigned as $\sigma_{x,y} = d_{x,y}/\sqrt{12}$, where $d_x, d_y$ are the widths of the cluster in the local coordinates of the module. Once the calibration and the alignment precision are sufficiently well known, the measurement uncertainty will be determined using charge
Figure 4.20: Means of the $\Delta \phi_0$ (a), $\Delta d_0$ (b) and $p \times \Delta(q/p)$ (c) distributions as a function of transverse momentum. Comparisons of track segments reconstructed separately with the silicon detectors and the TRT are shown for the upper (closed triangles) and lower (open triangles) half. The distribution obtained from simulation (stars) was averaged over upper and lower half.

Sharing in the pixel detector resulting in considerably smaller hit uncertainties than assigned here (see Figure 2.7). Estimating the uncertainties on the track parameters due to energy loss and multiple scattering relies on an accurate description of the material distribution in the detector [96]. Clearly the contribution of the multiple scattering is dependent on the transverse momentum of the track as can be seen in a degradation of the intrinsic resolution of a track parameter at low $p_T$ shown in Figures 4.10 and 4.14. The energy loss correction is applied according to the well known Bethe-Bloch formula. All of the uncertainties due to the description of the material distribution are taken into account during the extrapolation of the track parameters and their covariance matrix in the inner detector [95].

The pull distribution of a track parameter $\lambda$ is given by the resolution divided by its
uncertainty and is derived for the split track method according to:

$$\text{pull}(\lambda) = \frac{\lambda_{up} - \lambda_{low}}{\sqrt{\sigma_{\lambda_{up}}^2 + \sigma_{\lambda_{low}}^2}}$$

(4.4)

A Gaussian distribution was fit to all pull distributions. When the parameterisation is correct, the fit yields zero for the mean ($\mu$) and one for the width ($\sigma$) of the pull distribution. Mean values differing from zero indicate a bias in the measurement of a track parameter and a width different from one indicates an over- or underestimation of the assigned uncertainties.

The pull distributions for the transverse and longitudinal impact parameters are shown in Figure 4.21. The bias found in the mean of the $\Delta d_0$ distribution on data (see Figure 4.13) is also observed here in a shifted mean value of the fit. The estimation of the uncertainties for the data distributions is good whereas the uncertainties are overestimated in simulation. No bias is observed in the pull distribution of the $z_0$ distribution for data and simulation. Both uncertainties are slightly overestimated likely caused by the conservative measurement uncertainty assigned to the hits in the pixel detector.

![Figure 4.21:](image)

(a) Transverse impact parameter (b) Longitudinal impact parameter

The pull distributions for the azimuthal and polar angles are shown in Figure 4.22. A bias in the data distribution of $\phi_0$ is observed, while the estimate of size of the uncertainties is correct for the data and the simulation sample. A shifted mean value is also observed for the polar angle distribution in simulation. This effect was already observed in Figure 4.22. While the estimate of the uncertainties in data is correct, the uncertainties in the simulation are slightly overestimated.

The pull distribution of the curvature ($q/p$) is displayed in Figure 4.23. The estimate of the uncertainties is good for both samples. Given the momentum distribution of the cosmic muons, the hit resolution and alignment effects are here less important and hence the agreement between data and simulation is better. The shifted mean of the
Figure 4.22: Comparisons of the pull distribution of the $\phi_0$ (a) and $\theta$ (b) resolutions between data and simulation.

data distribution corresponds to the shifted mean observed in the relative curvature resolution (see Figure 4.18).

Figure 4.23: Comparison of the pull distribution of the curvature resolution between data and simulation.

4.8 Summary

The analysed data set containing 2528 track pairs from cosmic ray events recorded in October 2008 has allowed the determination of track parameter resolutions for tracks reconstructed with the ATLAS inner detector. An overview of the resolutions and their statistical uncertainties obtained from data and simulation is given in Table 4.2. The resolutions for the impact parameters and track angles are quoted for tracks with a $p_T > 30$ GeV to reduce the contribution from multiple scattering. The curvature resolution
\(\sigma(q/p)\) is quoted from fitting the \(q/p\) distribution to the function \(\sigma^2 = A^2 + (B/p)^2\) over the whole \(p_T\) range investigated. The constant term \(A\) represents the detector resolution and the term depending on \(1/p\) accounts for multiple scattering [127].

**Table 4.2:** Overview of the track parameter resolutions from 2008 cosmic ray data and from simulation. The resolutions for the impact parameters and track angles are quoted for tracks with a \(p_T > 30\) GeV to reduce the contribution from multiple scattering.

<table>
<thead>
<tr>
<th>Track parameter</th>
<th>Data</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma(d_0)) (mm)</td>
<td>0.022 ± 0.001</td>
<td>0.014 ± 0.0002</td>
</tr>
<tr>
<td>(\sigma(z_0)) (mm)</td>
<td>0.112 ± 0.004</td>
<td>0.101 ± 0.001</td>
</tr>
<tr>
<td>(\sigma(\phi_0)) (rad)</td>
<td>((1.47 ± 0.06) \times 10^{-4})</td>
<td>((1.15 ± 0.01) \times 10^{-4})</td>
</tr>
<tr>
<td>(\sigma(\theta)) (rad)</td>
<td>((8.80 ± 0.3) \times 10^{-4})</td>
<td>((7.79 ± 0.06) \times 10^{-4})</td>
</tr>
<tr>
<td>(\sigma(q/p)) (GeV(^{-1}))</td>
<td>((4.83 ± 0.16) \times 10^{-4})</td>
<td>((3.28 ± 0.03) \times 10^{-4})</td>
</tr>
</tbody>
</table>

A comparison of the resolutions between data and dedicated cosmic ray event simulation shows a fair agreement. The most notable differences are observed in the transverse impact parameter \(d_0\). Previously ATLAS has published studies with simulated single muon tracks originating from the nominal interaction region and reconstructed with the aimed final calibration and perfect alignment [128]. A design resolution \(\sigma(d_0)\) slightly below 10 \(\mu\)m was presented, which is in good agreement with the design value in the ATLAS Technical Design Report [129]. These values are however considerably lower than the ones presented here. In this cosmic ray study the track parameter resolutions were measured for the first time in data. The resolutions are expected to improve with further operation of the detector as the alignment precision will be better. The size of the measured difference to the design values however indicates that the design resolution can only be reached if significant changes are made to the detector itself.

In addition to the track parameter resolutions, several other vital aspects of the track reconstruction were investigated: the internal dependencies of resolutions on the track parameters, the size of residual biases on reconstructed parameters, the matching quality of sub-detector segments and the quality of the determination of the track parameter uncertainties. No major problems were revealed and a very good understanding of the detector and its performance have been demonstrated.