Measurement of the charged particle density with the ATLAS detector

First data at $\sqrt{s} = 0.9$, 2.36 and 7 TeV

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THE SIGNIFICANT PROBLEMS WE FACE CANNOT BE SOLVED AT THE SAME LEVEL OF THINKING WE WERE AT WHEN WE CREATED THEM.

Albert Einstein

EMANCIPATE YOURSELF FROM MENTAL SLAVERY
NONE BUT OURSELVES CAN FREE OUR MINDS.

Bob Marley - Redemption Song
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The start-up of the Large Hadron Collider (LHC) in November 2009 at the CERN research complex in Geneva, Switzerland, marks the beginning of a new era in the research field of particle physics. The LHC is the most powerful particle accelerator ever built and will provide an enormous amount of data over the coming decades that will inevitably lead to new insights about the structure and the origin of the universe. The most prominent goal is the discovery of the Higgs boson that was postulated by Peter Higgs already in 1964. The Higgs particle is responsible for giving mass to the elementary particles and with its discovery the last missing particle of the Standard Model of particle physics would be identified. The Standard Model however is not a complete theory and open questions remain; some of them may be answered by theories like Supersymmetry, a theory that is extensively searched for at the LHC.

To prepare for these spectacular discoveries, a lot of effort is devoted to re-evaluate already known phenomena of the Standard Model and investigate if these phenomena behave according to their theoretical predictions at LHC energies. Within this context, not only processes involving the production of high energy objects are studied, but also collisions with predominantly soft interactions, which are characterised by small energy transfers. In fact, more than 99.9% of the particles in proton proton collisions at the LHC are produced by these soft processes. A typical collision event at the LHC, where several charged particles are detected, is shown in Figure 1. The analysis of such events leads to the measurement of the charged particle density and is presented in this thesis. It is based on simple questions that arise when particles collide at high energies, e.g. "How many particles are produced when two bunches of protons collide? What is the momentum of these particles and in which direction in space are they travelling?".

The answers to these rather basic questions are however far from trivial and have been explored ever since particle colliders were built. The theory describing these interactions within the Standard Model is known as Quantum Chromo Dynamics (QCD). QCD unfortunately lacks accurate predictive power for processes with small energy transfers because the strength of the interaction is characterised by a coupling constant ($\alpha_s$) that increases when the energy transfer decreases. The theoretical predictions can therefore not be calculated in perturbation theory and empirical assumptions in general not valid at all energy scales have to be introduced to describe existing data well.
Figure 1: Event display of a proton proton collision at the LHC recorded with the ATLAS detector. The trajectories of the particles produced by the collision in the centre are identified in the detector. The figure shows the plane transverse to the initial direction of the protons.

The lack of an accurate prediction for the charged particle density makes it all the more important that the understanding of the detector performance is excellent. The most important detector of the ATLAS experiment to perform this measurement is the inner detector. Its purpose is to accurately reconstruct the trajectories of charged particles and to identify the vertex position of the collision. Studying the performance of the inner detector on data started already in the fall of 2008 long before the first proton proton collisions were delivered. The complete ATLAS detector was then switched on for the first time and the trajectories of muons originating from cosmic rays were recorded. From this data sample an initial set of calibration constants for the detector was derived that was continuously improved with further cosmic ray data taking. Once the first proton proton collisions were delivered by the LHC, the studies of the detector performance continued and produced impressive results, for example on the reconstruction of resonances from known hadrons.
Thesis layout

Chapter 1 of this thesis introduces the LHC and deals with the underlying physics of the measurement of the charged particle density. The implementation of these models by the Monte Carlo event generators Pythia and PHojet is discussed in detail.

In Chapter 2, the experimental setup of the measurement, the ATLAS experiment, is presented. The focus is put on the most important detector in this thesis - the inner detector.

The reconstruction of the trajectories of charged particles and the identification of vertices in the inner detector form the core of Chapter 3. The algorithms to find these tracks and vertices are discussed in detail and hadron searches in early data are presented to illustrate the performance.

In Chapter 4, the resolution of the trajectories of charged particles are investigated on data from cosmic rays. These track parameter resolutions are an important specification when building a detector that could already be studied and compared to their expectation values using muons from cosmic rays.

Chapter 5 deals with the method used to extract the charged particle density. This method is based on the reconstruction of tracks using only the innermost component of the inner detector - the pixel detector. This technique reduces the dependence on simulated samples when determining the efficiency of the track reconstruction.

The measurement of the charged particle density at the centre-of-mass energies $\sqrt{s} = 0.9$, 2.36 and 7 TeV is presented in Chapter 6. The focus lies on the measurement at $\sqrt{s} = 2.36$ TeV as the application of the method explained in the previous chapter is especially suitable here.
Chapter 1

SOFT INTERACTIONS AT THE LARGE HADRON COLLIDER

At the Large Hadron Collider (LHC), measurements of soft hadronic processes such as the extraction of the charged particle density are amongst the early analyses. Many of these measurements have been performed at various experiments over a wide range of centre-of-mass energies [1–14]. The momentum transfer in soft hadronic processes is in general too small to calculate the interactions in perturbative QCD. Hence most of the models describing these Minimum Bias events rely on phenomenology and introduce tuneable parameters. The theoretical models can be adjusted to describe certain data sets well, but their predictive power is somewhat restricted.

This chapter first introduces the LHC and Quantum Chromo Dynamics (QCD) followed by a description of the properties of proton proton collisions. The focus is then put on the models used by the PYTHIA and PHOJET Monte Carlo event generators to predict the charged particle density in hadron collisions.

1.1 The Large Hadron Collider

The LHC [15] has been built at the European Organisation for Nuclear Research (French: Organisation Européenne pour la Recherche Nucléaire), also known as CERN in Geneva, Switzerland. The LHC is a circular proton proton (pp) collider with a circumference of 26.7 km where two proton beams are accelerated in opposite direction and collide at four interaction points. The design centre-of-mass energy of the pp collisions is $\sqrt{s} = 14$ TeV. Figure 1.1 presents an overview of the LHC accelerator complex including the LHC itself and its chain of pre-accelerators. The most notable of these accelerators is the Super Proton Synchrotron (SPS), from which protons with an energy of 450 GeV are injected into the LHC. The first proton proton collisions on November 23rd, 2009 were delivered at this energy.

The LHC is housed in the same tunnel as the electron positron collider LEP [16], which was operational between 1989 and 2000. Two interaction points are dedicated to
Soft interactions at the Large Hadron Collider

Figure 1.1: Schematic overview of the CERN accelerator complex showing the LHC and its chain of pre-accelerators. The location of the ATLAS experiment is also marked.

Apart from the centre-of-mass energy, the luminosity - denoted as $\mathcal{L}$ - is the most important benchmark parameter of a particle collider. The number of observed events per time interval $dN/dt$ is given by their production cross section $\sigma$ and the luminosity via $dN/dt = \mathcal{L} \cdot \sigma$. The instantaneous luminosity in a particle collider is defined as

$$\mathcal{L} = \frac{N_b^n b_f \gamma_r}{4\pi \epsilon_n \beta^*} F,$$

(1.1)

where $N_b$ the number of protons per bunch, $n_b$ the number of bunches per beam, $f_{\text{rev}}$ is the revolution frequency of the machine, $\gamma_r$ the relativistic gamma factor, $\epsilon_n$ the normalised transverse beam emittance, $\beta^*$ the beta function at the collision point and $F$ the geometric luminosity reduction factor due to the crossing angle of the beams at the interaction point. The LHC is designed to deliver a peak luminosity of $\mathcal{L} = 10^{34} \text{cm}^{-2}\text{s}^{-1}$.

Operating the LHC has not been without any problems. After the first proton beams circulated in September 2008, a quench in one of the dipole magnets caused extensive damage leading to repair works that lasted more than one year. As a safety precaution, it was decided to start operating the LHC at a centre-of-mass energy of $\sqrt{s} = 7 \text{ TeV}$ and upgrade to $\sqrt{s} = 14 \text{ TeV}$ after another shutdown period. As mentioned above, the first collisions were finally delivered in November 2009 at a centre-of-mass energy of
1.2 Quantum Chromo Dynamics

\( \sqrt{s} = 900 \text{ GeV} \), which corresponds to the injection energies of the proton beams from the SPS. Soon after, the LHC set a new world record for hadron collisions with the highest centre-of-mass energy at \( \sqrt{s} = 2.36 \text{ TeV} \) on November 30th, 2009. In March 2010, the LHC resumed operation with pp collisions at \( \sqrt{s} = 7 \text{ TeV} \) and delivered an integrated luminosity of 50 pb\(^{-1}\) in 2010. Data recorded at all three energies is used in this thesis to measure the charged particle density. At the end of 2010, the heavy ion programme of the LHC commenced with collisions of lead ions.

1.2 Quantum Chromo Dynamics

The theoretical framework to describe the fundamental interactions between the constituents of a proton - quarks and gluons - is known as Quantum Chromo Dynamics (QCD) [21]. It is based on the special unitarity group SU(3)\( _C \), which is the theoretical manifestation of the fact that quarks occur in three colour charges. QCD is a non-abelian gauge theory, which implies that the gauge bosons themselves also carry the charge of the theory and hence interact with each other. The fundamental parameters describing QCD are the coupling constant \( g_S \) that is often used in \( \alpha_S = g_S^2/4\pi \), and the quark masses \( m_q \).

The two experimentally most striking features QCD is able to explain are:

- **Confinement**
  Single quarks are not observed as states which propagate over macroscopic distances, but they are confined inside hadrons. As the potential of the colour field increases at large distances (the potential behaves as \( V(r) \sim \lambda r \)), quarks and gluons are never observed as free particles. If two interacting partons are separated, the energy of the field increases to such an amount that new interacting particles are created and new colourless hadrons can be formed.

- **Asymptotic freedom**
  Quarks and gluons, which are probed at high momentum transfers, can be treated as freely moving partons inside a hadron. This is due to the fact that the coupling constant is small at short distances. Thus high-energy collisions of hadrons are described perturbatively in terms of interactions between the partons. This behaviour is denoted as asymptotic freedom.

Both phenomena are reflected in the running of the coupling constant \( \alpha_S \). The renormalisation scale \( \mu_R \) is an unphysical parameter corresponding to the chosen scale at which the removal of ultraviolet divergences is performed. These ultraviolet divergences occur in higher order corrections when calculating physical observables such as cross sections. When one chooses this scale close to the scale of the momentum transfer \( Q^2 \) in a given process, the coupling constant \( \alpha_S (\mu_R^2 \approx Q^2) \) indicates the effective strength of QCD in that process. The running coupling constant is determined by the renormalisation group equation, which is based on the fact that physical observables cannot depend
on the scale $\mu_R$ when the coupling is fixed, and given by:

$$Q^2 \frac{\partial \alpha_S}{\partial Q^2} = \beta(\alpha_S).$$

(1.2)

In QCD, the $\beta$ function has the perturbative expansion

$$\beta(\alpha_S) = -b\alpha_S^2 \left(1 + b'\alpha_S + b''\alpha_S^2 + \mathcal{O}(\alpha_S^3)\right),$$

(1.3)

where the $b$ parameter refers to the leading order contribution and is given by $(33 - 2n_f)/12\pi$ with $n_f$ the number of considered quark flavours. The expressions for the $b'$ and $b''$ parameters, which denote contributions from higher order processes, can be found in [21]. The value of $\beta(\alpha_S)$ is negative, which reflects the fact that the strong coupling decreases with increasing momentum transfer $Q^2 (\partial\alpha_S/\partial Q^2 < 0)$. The world average of $\alpha_S$, which is commonly evaluated at the mass of the $Z$ boson, is [22]:

$$\alpha_S(m_Z^2) = 0.1184 \pm 0.0007.$$  

(1.4)

The strong coupling constant is often parameterised as a function of $\Lambda_{\text{QCD}}$, which is referred to as the scale of QCD. When considering only processes at leading order, an exact solution to Equation 1.3 is given by

$$\alpha_S(Q^2) = \frac{1}{b \ln (Q^2/\Lambda_{\text{QCD}}^2)}.$$  

(1.5)

The value of $\Lambda_{\text{QCD}}$ is approximately 200 MeV and is in general considered to denote the scale where perturbation theory is not applicable any more. Below this scale phenomenological models are introduced to describe the interaction processes.

### 1.3 Proton proton collisions

According to their final state, pp interactions ($pp \rightarrow \text{anything}$) are classified as elastic or inelastic interactions, which are in turn decomposed into single, double and non-diffractive processes [23]. The total cross section for pp interactions $\sigma_{\text{tot}}(s)$ is given as the sum of the cross sections of the individual sub-processes:

$$\sigma_{\text{tot}}(s) = \sigma_{\text{el}}(s) + \sigma_{\text{sd}}(s) + \sigma_{\text{dd}}(s) + \sigma_{\text{nd}}(s).$$

(1.6)

Whereas both protons emerge intact in elastic scatterings ($p_1p_2 \rightarrow p'_1p'_2$), new particles are produced in inelastic scattering processes as illustrated in Figure 1.2. In single or double diffractive processes, no internal quantum numbers are exchanged between the colliding particles, but at least one of the incoming protons is excited and dissociates into a spray of particles ($p_1p_2 \rightarrow p'_1X$ or $p_1p_2 \rightarrow X_1X_2$). Diffractive processes produce particles dominantly in the forward direction with a gap at low rapidity. Non-diffractive events are characterised by an interaction between the constituents of the proton and typically produce particles in the central region. Due to the high centre-of-mass energies
at the LHC the final states of the individual production mechanisms overlap significantly. For Monte Carlo event generators the differentiation of these mechanisms is nevertheless vital to make meaningful predictions of the charged particle density.

A widely used method to calculate the total cross section in Equation 1.6 is based on the Pomeron exchange model, in which pp interactions are described by the exchange of a colourless and flavourless particle called the Pomeron (P) [24]. This model is applied in a simultaneous fit to experimental data from various colliders. The optical theorem [25], which is a general law of scattering theory based solely on the conservation of probability, is used to obtain the total cross section. It relates the imaginary part of the hadronic scattering amplitude $f_h$ to the total cross section in the limit of a vanishing momentum transfer $t \approx 0$:

$$\sigma_{\text{tot}} = \frac{4\pi}{s} \text{Im}(f_h(s, t = 0)).$$  \hspace{1cm} (1.7)

The differential scattering cross section is in general given as the scattering amplitude squared: $d\sigma_{\text{tot}}/d\Omega = |f_h|^2$, where the scattering amplitude can be described by a
diagram as shown in Figure 1.3(a). The interaction between the protons (elastic or inelastic) are characterised by their momentum transfer $t$. Following the optical theorem from Equation 1.7, the integral over this complex amplitude squared is then proportional to the imaginary part of the scattering amplitude for momentum transfers $t \approx 0$. This is represented by the exchange of a Pomeron with the proton Pomeron coupling $\beta_{PP}$ in the model used here (see Figure 1.3(b)). In principle the exchange of other particles than the Pomeron also contributes to the total cross section. These contributions are however negligible at LHC energies. The Pomeron exchange and hence the total cross section is parameterised by an exponential function given by $\sigma_{\text{tot}}(s) = X^{pp}s^\epsilon$. The free fit parameters were found to be $X = 21.7 \text{ mb}$ and $\epsilon = 0.0808$ resulting in a total hadronic cross section of 76.1 mb at $\sqrt{s} = 2.36 \text{ TeV}$ and 90.7 mb at $\sqrt{s} = 7 \text{ TeV}$ [24]. This parameterisation of the total cross section eventually leads to an infinite cross section as the Froissart-Martin bound [26] implies that the increase of the total cross section is at most proportional to $\ln^2 s$ based on the conservation of energy. But with the above smallness of $\epsilon$, the Froissart-Martin bound is respected up to energies of about $10^{23} \text{ GeV}$ [27].

Figure 1.3: (a) Diagram of an interaction between protons with the four-momenta $p_1$ and $p_2$. The interaction can be elastic or inelastic here. (b) For a vanishing momentum transfer, the squared interaction diagram is represented by the exchange of a Pomeron with the vertex $\beta_{PP}$.

To disentangle the contribution from the individual production processes, again the optical theorem provides an estimate of the elastic cross section $\sigma_{el}$. Neglecting the small real part of the scattering amplitude and assuming an exponential fall-off, the elastic cross section is approximated by [28]:

$$\frac{d\sigma_{el}}{dt} = \sigma_{el}^2 \exp(B_{el}t).$$

(1.8)

The exponential behaviour of the elastic cross section is expressed by the slope
parameter $B_{el}$, which is derived from experimental data. Integrating over $t$ the total elastic cross section is obtained as $\sigma_{el} = \sigma_{tot}/16\pi B_{el}$. This results in an elastic cross section of $\approx 16$ mb at $\sqrt{s} = 2.36$ TeV and $\approx 20$ mb at $\sqrt{s} = 7$ TeV [23]. The inelastic cross section is then derived as $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$.

Inelastic processes are described by interactions of the constituents of the proton. Only a fraction $x$ of the four-momentum of the incoming protons is carried by the partons, which can be either valence quarks, sea quarks or gluons. The momentum fractions $x_1$ and $x_2$ of the colliding partons are given by [29]:

$$x_1 = \frac{M}{\sqrt{s}} e^{+y} \quad \text{and} \quad x_2 = \frac{M}{\sqrt{s}} e^{-y}, \quad (1.9)$$

where $M$ is the total invariant mass produced in the hard scattering process, $s$ the centre-of-mass energy squared and $y$ the rapidity of $M$ in the centre-of-mass frame. The rapidity $y$ can be expressed as $y = 1/2 \ln ((E + p_z)/(E - p_z))$ with $E$ being the energy and $p_z$ the momentum component parallel to the beam axis of $M$.

![Figure 1.4](image_url)

**Figure 1.4:** MSTW leading order parton distribution functions for the two energy scales $Q^2 = 10$ GeV$^2$ (a) and $Q^2 = 10^4$ GeV$^2$ (b) as a function of the momentum fraction $x$ of the protons. The gluon densities are scaled by a factor of ten in both graphics. [30]

---

$^1$For massless particles, the rapidity is equal to the pseudorapidity, which is defined as $\eta = -\ln (\tan \frac{\theta}{2})$, where $\theta$ is the polar angle as explained in Section 2.1.
The probability \( f_P(x, \lambda) \) to find a parton \( i \) inside the incoming beam of protons \( P \) carrying a fraction \( x \) of the total four-momentum is described by the parton distribution functions (PDFs). These PDFs also depend on the energy scale \( \lambda \) of the observed process and have been measured amongst others in deep inelastic scattering experiments. Such experiments have been performed for example at the HERA collider, where the constituents of the proton were probed in electron (positron) proton collisions by the exchange of a high energy photon. Figure 1.4 shows the leading order proton PDFs of the Martin-Stirling-Thorne-Watt (MSTW) group [31] as a function of the momentum fraction \( x \) at the two energy scales \( \lambda = Q^2 = 10 \text{ GeV}^2 \) and \( \lambda = Q^2 = 10^4 \text{ GeV}^2 \). These PDFs were obtained by a simultaneous fit to deep inelastic and hadron hadron scattering processes considering only leading order contributions in the strong coupling constant \( \alpha_S \). Although the PDFs have been evaluated including higher order corrections as well, leading order PDFs in general yield the best predictions for Minimum Bias events when using leading order Monte Carlo generators such as PYTHIA. At both energy scales, the contributions of the \( u \) and \( d \) valence quarks to the PDFs are important at large values of \( x \) \( (x \approx 1/3) \) whereas the gluon density dominates for low momentum fractions. Due to the high centre-of-mass energy at the LHC, most collisions will involve low momentum fractions \( x \) and are thus dominated by gluon gluon interactions.

The cross section \( \sigma_{nd} \) for non-diffractive processes \( pp \rightarrow ab \) can be factorised into a sum over the partonic scattering cross sections over all sub-processes \( k \) between the interacting partons \( i \) and \( j \) \( (\hat{\sigma}_{ij}^k \rightarrow ab(\hat{s})) \) and the probability to find these partons, which is described by the PDFs. It is given by:

\[
\sigma_{nd} = \sum_{i,j,k} \int dx_1 \int dx_2 \int d\hat{t} \hat{\sigma}_{ij}^k \rightarrow ab(\hat{s}) f_P^i(x_1, \lambda = Q^2) f_P^j(x_2, \lambda = Q^2).
\] (1.10)

For massless partons, the effective centre-of-mass energy \( \hat{s} \) is derived from the centre-of-mass energy squared \( (s) \) and is defined by \( \hat{s} = x_1 x_2 s \). The factorisation scale \( \lambda \), at which the partons are probed, is in general chosen at the same value as the renormalisation scale \( \mu_R^2 \). Both scales are assumed to be best described by the squared momentum transfer \( Q^2 \), which reduces to the squared transverse momentum \( p_T^2 \) if \( Q^2 \ll \hat{s} \). In Figure 1.5, the calculated cross sections as a function of the centre-of-mass energy for various processes are presented. As explained above, the total cross section \( \sigma_{tot} \) only rises slowly as a function of the centre-of-mass energy. Contrary to that, the production cross section of the Higgs boson strongly increases with rising centre-of-mass energy. At an energy of \( \sqrt{s} = 7 \text{ TeV} \), it is already more than one order of magnitude higher than at the Tevatron, which is the former most energetic particle collider currently operating at \( \sqrt{s} = 1.96 \text{ TeV} \) at Fermilab close to Chicago.

1.4 Pythia

A widely used tool to simulate collisions in high energy physics is the PYTHIA [32] programme that has been developed by the Lund group. It comprises a coherent set
Figure 1.5: Predictions for cross sections of various physics processes as a function of the centre-of-mass energy $\sqrt{s}$. The dashed lines represent the centre-of-mass energies of the Tevatron and the LHC. The discontinuities arise from differences between proton proton and proton antiproton collisions. [30]

of physics models for the evolution from a few-body hard process to a complex multi-hadronic final state. This includes simulating hard processes (predominantly up to leading order), multiple parton parton interactions, initial and final-state parton showers, the behaviour of the beam remnants, string fragmentation and particle decays. For soft interactions the Pythia model makes frequent use of empirical assumptions, which allows to describe particular data sets well. Due to the non-universality of these assumptions however, the predictive power of the resulting tunes of the model is limited for other data sets at other centre-of-mass energies. The most important aspects to understand how Pythia predicts the charged particle density and how this model has been adapted to Minimum Bias measurements from previous experiments are discussed in the following.
1.4.1 Non-diffractive events

For non-diffractive events PYTHIA uses a phenomenological adaption of QCD to provide an accurate description of processes with low momentum transfer where perturbation theory is not applicable anymore. The starting point of this model is the perturbative QCD cross section \( \sigma_{\text{nd}} \) for parton parton interactions, which is given as a sum over all possible processes and energy transfers of the partonic cross sections as expressed in Equation 1.10.

The majority of interactions in hadron collisions is given by \( 2 \to 2 \) scattering processes, meaning that two incoming partons produce two outgoing partons such as \( qq' \to qq' \), \( qg \to qg \) or \( gg \to q\bar{q} \). The dominating \( 2 \to 2 \) parton scattering process, the \( \hat{t} \) channel gluon exchange \( gg \to gg \), is illustrated in Figure 1.6. The differential cross section of these processes as a function of \( p_T^2 \) is given by

\[
\frac{d\sigma_{\text{nd}}}{dp_T^2} = \sum_{i,j,k} \int dx_1 \int dx_2 \int dt f_{P_i}(x_1, Q^2) f'_{P_j}(x_2, Q^2) x_{P_i} \frac{d\hat{\sigma}_{ij}}{dt} \delta \left( p_T^2 - Q^2 \right). \quad (1.11)
\]

![Figure 1.6](image)

**Figure 1.6:** Schematic view of the dominating \( 2 \to 2 \) parton scattering process, the \( \hat{t} \) channel gluon exchange \( gg \to gg \).

In the \( |\hat{t}| \ll \hat{s} \) limit, where \( p_T^2 \approx |\hat{t}| \), the partonic cross sections \( \hat{\sigma}_{ij} \) for \( 2 \to 2 \) quark and gluon interactions show the same dependence on the \( p_T^2 \) scale and differ only by a set of constant factors - also known as the *colour factors* [21] - which can be absorbed into the PDFs. The summed-up partonic interaction cross section is then given by [33]:

\[
\frac{d\hat{\sigma}}{dp_T^2} = \frac{8\pi\alpha_s^2(p_T^2)}{9p_T^4}. \quad (1.12)
\]
Thus, for constant $\alpha_S$ and neglecting the $x$ integrals, the integrated cross section in Equation 1.10 above any chosen minimal transverse momentum $p_{T,min}$ is divergent in the limit $p_{T,min} \to 0$ [34]:

$$\sigma_{nd}(p_{T,min}) = \int_{p_{T,min}^2}^{s/4} \frac{d\sigma}{dp_T^2} \, dp_T^2 \propto \int_{p_{T,min}^2}^{s/4} \frac{\alpha_S^2(p_T^2)}{p_T^2} \, dp_T^2 \propto \frac{1}{p_{T,min}^2}. \quad (1.13)$$

As a consequence of this divergence, the interaction cross section $\sigma_{nd}$ as written in Equation 1.13 exceeds the total cross section $\sigma_{tot}$, which was derived in Section 1.3. This paradox occurs already at a minimal transverse momentum of approximately 2 GeV, which is well above $\Lambda_{QCD}$, so one cannot postulate a breakdown of perturbation theory. This contradiction is partly resolved by allowing various partons of the incoming protons to interact with each other - so-called multiple parton interactions (MPI).

### Multi-parton interactions

As illustrated in Figure 1.7, each of the incoming hadrons may be viewed as a beam of partons and hence there is a possibility of having several parton parton interactions when the hadrons collide [34]. If an event contains for example two partonic interactions, it also counts twice in $\sigma_{nd}$ as this is an inclusive number. The total cross section is however an exclusive number, meaning that any hadron hadron interaction is only counted once for its calculation. Events with $\langle n \rangle = \sigma_{nd}(p_{T,min})/\sigma_{tot} > 1$ are thus considered as events with $\langle n \rangle = 2 \rightarrow 2$ parton interactions above the minimal transverse momentum $p_{T,min}$ on average.

Assuming that all partonic interactions are equivalent and take place independently of each other, the actual number of interactions is then distributed according to a Poissonian distribution with mean $\langle n \rangle$:

$$P_n = \langle n \rangle^n \exp (-\langle n \rangle)/n! \quad (1.14)$$

To account for possible correlations between the individual scatterings, it is convenient to arrange them in falling sequence of $p_T$ values [33].

Up to this point it has been assumed that the initial state of all hadron collisions is the same. But as the incoming hadrons are extended objects, the probability for one or more partonic interaction also depends on both the matter distribution inside the hadron and on the overlap between the colliding hadrons. Nowadays, the most popular model uses an impact parameter dependent approach to describe the overlap and assumes a double Gaussian matter distribution $\rho(r)$ inside the hadrons, which is given by [35]:

$$\rho(r) \propto \frac{1-\beta}{a_1^2} \exp \left(-\frac{r^2}{a_1^2}\right) + \frac{\beta}{a_2^2} \exp \left(-\frac{r^2}{a_2^2}\right). \quad (1.15)$$

This corresponds to a distribution with a small core region of radius $a_2$, which contains the fraction $\beta$ of the total hadronic matter, embedded in a larger hadron of radius $a_1$. A small impact parameter $b$ corresponds to a large overlap between the colliding hadrons and thus to an enhanced probability for multiple interactions. On the other
Figure 1.7: Schematic view of two $2 \rightarrow 2$ parton scattering process. These multi-parton interactions explain why the interaction cross section can exceed the total cross section.

hand, larger impact parameters correspond to grazing collisions with a large probability that no parton interactions take place at all. Obviously the matter distribution inside the hadrons characterises the number of multiple interactions at a given impact parameter. In PYTHIA, $\text{PARP}(83)$ describes the fraction of matter $\beta$ in the inner Gaussian and $\text{PARP}(84)$ determines the size of the inner Gaussian $a_2$.

Evidence for multi parton interactions has been observed at the AFS [36] and UA2 [37] experiments and they were directly measured by the CDF collaboration [38].

Limitations of perturbative QCD

The introduction of multi-parton interaction only partly solves the problem of the diverging cross section in Equation 1.13. As the model of multiple interactions does not strictly obey energy and momentum conservation, the average energy $\hat{s}$ of a scatter decreases slower with $p_T^{\text{min}}$ than the number of interactions increases. This would imply that the total amount of partonic energy in the scattering processes becomes infinite as $p_T^{\text{min}} \to 0$. This is possibly prevented by the fact that the incoming hadrons are colourless objects. When the $p_T$ of the exchanged gluon is small and the corresponding transverse wavelength $\lambda_T$ ($p_T \sim 1/\lambda_T$) of the gluon is large, the gluon can no longer resolve the colour charge of the individual partons inside a proton. A crude estimate for the minimal transverse momentum of the gluon derived from Heisenberg’s uncertainty principle would be

$$p_T^{\text{min}} \sim \frac{\hbar}{r_P} \approx \frac{0.2 \text{ GeV} \text{ fm}}{0.7 \text{ fm}} \approx 0.3 \text{ GeV} \sim \Lambda_{\text{QCD}},$$

where $r_P$ denotes the radius of a proton. A minimal transverse momentum of 0.3 GeV was however found to be too small and the proton radius has been replaced by the colour
screening length $d$, which represents the average size of the region within which the net compensation of a given colour charge occurs as illustrated in Figure 1.8. Screening effects are already known from Quantum Electrodynamics (QED) [39]. Contrary to QED however, this effect becomes stronger at higher energies in QCD as the number of partons increases at low $x$ values. The partons then become more densely packed within a proton which in turn causes a decrease of the screening length.

![Diagram](https://via.placeholder.com/150)

**Figure 1.8**: Illustration of resolved and screened colour charges within a hadron depending on the transverse wavelength $\lambda_T$ of the gluon. The screening length $d$ is indicated as the distance between two coloured partons ($r$ and $\bar{r}$ symbolise the colour charge).

Rather than choosing a discrete value for $d$ and hence for the minimum $p_T$, the expression for the cross section formula as given in Equation 1.13 is multiplied by the factor [40]:

$$\frac{\alpha_s(p_T^2 + p_T^{2,\text{min}})}{\alpha_s(p_T^2)} \left(\frac{p_T^4}{(p_T^2 + p_T^{2,\text{min}})^2}\right)^2,$$

which compensates the divergence in the cross section for $p_T \to 0$. This approach is often referred to as the complex scenario compared to the simple scenario where a discrete value for $p_T^{\text{min}}$ is chosen. The complex scenario resolves not only the problem of the divergent cross section, but also provides a continuous $p_T$ spectrum and reduces the calculations to perturbative QCD for $p_T >> p_T^{\text{min}}$. The cut-off parameter $p_T^{\text{min}}$ is not known from first principles and is implemented in PYTHIA as

$$p_T^{\text{min}}(s) = p_{T,0} \left(\frac{\sqrt{s}}{1.8 \text{ TeV}}\right)^{\epsilon},$$

where $p_{T,0}$ is the bare value of $p_T^{\text{min}}$ and $\epsilon$ is used for the scaling to other centre-of-mass energies. Both parameters have been tuned to data from hadron colliders and the obtained values are approximately $\approx 2$ GeV for $p_{T,0}$ (PARP(82) in PYTHIA) and $\approx 0.25$ for $\epsilon$ (PARP(90) in PYTHIA). The cut-off parameter is evaluated at a fixed energy scale,
which is in general taken to be the centre-of-mass energy of Run I at the Tevatron ($\sqrt{s} = 1.8$ TeV).

**Parton showering**

The incoming and outgoing partons are coloured objects and hence radiate gluons which in turn undergo all kinds of strong interactions. This is called *parton showering*. The parton showers are ordered according to the $Q^2$ scale of the process and their evolution is described by the DGLAP splitting functions [41–44]. The process with the highest $Q^2$ is by definition treated as the hard scatter and all associated showering processes are then denoted as *initial state* or *final state* radiation depending on whether they occur before or after the hard scatter.

![Schematic figure illustrating an incoming parton in an event with a hard interaction occurring at $p_{T,1}$ and three further interactions, each at lower $p_T$ values. All interactions are subject to additional radiation (ISR) that is also described by the $p_T$ of the parton. There is also the possibility (case 2 and 3) of two interacting partons that have a common ancestor in the parton showers. [45]](image)

**Figure 1.9:** Schematic figure illustrating an incoming parton in an event with a hard interaction occurring at $p_{T,1}$ and three further interactions, each at lower $p_T$ values. All interactions are subject to additional radiation (ISR) that is also described by the $p_T$ of the parton. There is also the possibility (case 2 and 3) of two interacting partons that have a common ancestor in the parton showers. [45]

An important choice, which strongly influences the predictions of Minimum Bias distributions, is the association of the scale $Q^2$ with a property of the initial parton - denoted the ordering variable. The most common approach has been to use the virtuality or the mass $m$ of the parton ($Q^2 = m^2$). However, the current default has changed to the $p_T$ of the parton ($Q^2 = p_T^2$) [45].\(^2\) This choice allows a simpler combination

\(^2\)The switch was made in Pythia version 8.130. In previous versions, an option to enable the $p_T$
of parton showering with the multi-parton interaction model, which is illustrated in Figure 1.9. This is due to the fact that the squared transverse momentum transfer $p_T^2$ is a convenient measure for the hardness of an interaction (see Equation 1.11) and that the multi-parton interaction model relies on the $p_T$ as ordering variable. Additional gluon radiation can hence consistently be integrated within the individual interactions.

**Beam remnants and hadronisation**

As the strong interaction couples to the colour charge of the partons, the remaining protons - somewhat loosely denoted as the proton remnants - are also coloured objects. This leads to the formation of baryons and mesons from the proton remnants [33], which can have an influence on the products of the hard scatter. This phenomenon is known as *Colour Reconnection* and can also be tuned in *Pythia*. A stronger Colour Reconnection leads to a lower average momentum of the produced particles, which has been observed for example by the CDF experiment [46].

The last necessary step to predict the charged particle density is to describe how colourless hadrons, which are the objects eventually identified in the detectors, are formed from the coloured partons produced in scattering and parton shower processes. This non-perturbative process is denoted as *hadronisation* or *fragmentation*, which is described by the *string fragmentation* model in *Pythia* [47]. In this complex model, the colour field between partons is represented by strings, where the end of each string represents a quark or an antiquark. Gluons can be in between these quarks and cause kinks in the strings. As the partons move apart and a string piece is stretched out, it can break producing new quark antiquark pairs. The resulting quark pairs together with the already existing partons then form the colourless hadrons. Remarkably, the uncertainty on the hadronisation process is rather small for the prediction of the charged particle density. Assuming fragmentation universality, meaning that the hadronisation process in $e^+e^-$ collisions is also valid in pp interactions, most of the parameters in the string model are fixed to $e^+e^-$ data and little possibilities of modifying the predictions of the charged particle density remain.

Other issues such as the decay of unstable hadrons and a possible transverse momentum of the partons before the collisions (primordial $p_T$) possibly affect the predictions of soft hadronic processes as well and are discussed in [40].

### 1.4.2 Diffractive events

In the scope of this thesis, the contribution from diffractive events to the measured charged particle density is suppressed. At the edges of the considered phase space however, e.g. for events with low particle multiplicity and low $p_T$ particles, a significant contribution from diffractive events is expected.

The most common approach to describe these diffractive events is based on Regge theory, which is explained in Section 1.5, in terms of the exchange of a Pomeron ($\mathbb{P}$) [27]. In QCD, the Pomeron is regarded as a colourless and flavourless multiple gluon [48].
Diffraction occurs when the Pomeron interacts with the proton to produce a system of particles referred to as the diffractive system $X$. This is illustrated by a diagram for a single diffractive process in Figure 1.10(a). Using the optical theorem the size of the corresponding cross section is given by the squared diagram for small momentum transfers $t \approx 0$, which is explained in Section 1.3. As illustrated in Figure 1.10(b), the resulting diagram contains the triple Pomeron vertex $g_{3P}$ with each Pomeron coupling to a proton via the vertex $\beta_{PP}$ [49]. The proton-Pomeron coupling $\beta_{PP}$ is already known from the calculation of the total cross section (see Figure 1.3(b)). The diffractive system eventually dissociates into multi-particle final states with the same internal quantum numbers as the incoming protons.

The natural variables to describe these cross sections are the squared four momentum transfer $t = (p_1 - p_1')^2$ and the invariant mass $m_X$ of the diffractive system. In the Schüller-Sjöstrand model [27], which reverts to ideas from Good and Walker proposed already in the 1960s [50], the diffractive cross sections have an inverse dependence on $m_X^2$ and an exponential dependence on $t$. This model is in good agreement with existing data in the intermediate region, where $m_X$ is considerably larger than the proton mass and $m_X^2/s \lesssim 0.05$, which indicates a rather low momentum transfer $t$ [51]. The dominant contribution to the cross section then originates from the triple Pomeron diagram as shown in Figure 1.10(b).

As the triple Pomeron diagram is in principle only valid at small momentum transfers $t \approx 0$, the theory is not valid for arbitrary values of $t$ and $m_X^2$. Thus empirically derived correction factors are introduced as explained in [40]. In the low mass region, where $m_X \gg m_p$ does not hold any more, $\Delta$ resonances of the proton start playing an important role and the cross section is enhanced by the correction factors. In the region

---

**Figure 1.10:** (a) Feynman diagram of a single diffractive process. A diffractive system $X$ is formed by the exchange of a Pomeron $P$. (b) In Regge theory, the squared Feynman diagram is represented by the triple Pomeron vertex $g_{3P}$.
of \( m_X^2/s > 0.05 \) corresponding to a large momentum transfer, the correction factors cause a suppression of diffractive events. For double diffractive processes, the correction factors also account for a decrease of the cross section in regions where the two excited protons overlap in pseudorapidity space.

The formulae for the cross section of single diffractive (\( \sigma_{sd} \)) and double diffractive (\( \sigma_{dd} \)) processes in PYTHIA are

\[
\frac{d\sigma_{sd}(PP \to PX)(s)}{dt \, dm_X^2} = \frac{g_{3P}}{16\pi} \beta_{PP}^3 \frac{1}{m_X^2} \exp \left( B_{sd}(PX)t \right) F_{sd}
\]

\[
\frac{d\sigma_{dd}(PP \to XY)(s)}{dt \, dm_X^2 \, dm_Y^2} = \frac{g_{3P}^2}{16\pi} \beta_{PP}^2 \frac{1}{m_X^2} \frac{1}{m_Y^2} \exp \left( B_{dd}(XY)t \right) F_{dd}.
\]

\( F_{sd} \) and \( F_{dd} \) denote the correction factors explained above while the slope parameters \( B_{sd} \) and \( B_{dd} \) were introduced to account for a dependency between \( t \) and \( m_X \). The coupling \( \beta_{PP} \) is restricted by the expression \( \sigma_{tot}(s) = X^{pp,s}\epsilon \) for the total hadronic cross section as derived in Section 1.3. Picking a reference scale of \( \sqrt{s_{ref}} = 20 \) GeV, it is given as \( \beta_{PP}^2 = X^{pp,s}\epsilon_{ref} \).

The diffractive cross sections discussed here only incorporate so-called soft diffractive events. Experimental data however suggests more complex scenarios where the Pomeron has a partonic substructure, which e.g. can lead to high-\( p_T \) jet production [52]. In recent versions of PYTHIA\(^3\) these hard diffractive processes are implemented. According to the treatment of non-diffractive events in Section 1.4.1, proton-Pomeron hard scattering processes are introduced together with special Pomeron parton distribution functions (DPDFs). Once the partonic cross sections are defined, the standard PYTHIA machinery for multiple interactions, parton showers and hadronisation is applied. This procedure introduces tails with high-\( p_T \) particles and a high charged particle multiplicity in the spectrum of diffractive events [53].

### 1.4.3 Tuning to data

As many components of the soft interaction model are not known from first principles, they have to be obtained from tuning the model parameters to numerous distributions from Minimum Bias and Underlying Event measurements. These measurements have been performed at a wide range of centre-of-mass energies (50 GeV - 1.96 TeV) at pp and p\( \bar{p} \) colliders. Significant differences of the soft hadronic cross sections are only expected at centre-of-mass energies below approximately 100 GeV between pp and p\( \bar{p} \) colliders [24]. This section focuses on the impact on the following distributions that will also be measured in Chapter 6:

- **Multiplicity distribution:**
  the number of events as a function of the number of charged particles per event.

\(^3\)Starting with PYTHIA 8.130
Pseudorapidity distribution:

the total number of charged particles per unit of pseudorapidity as a function of $\eta$.

Previous experiments at pp colliders such as UA5 [54] and E735 [55] published their measurements of the multiplicity distribution as a function of the so-called KNO (Koba, Nielsen and Oelsen) variables, which are expressed in terms of the average particle multiplicity $\langle n \rangle$ and the probability $P_n$ of producing $n$ charged particles in an event [56]. Theses variables provide a clear display of the fluctuations observed for both very low and very high particle multiplicities. When the plots of $\langle n \rangle P_n$ as a function of $n/\langle n \rangle$ first appeared, it was suggested that these KNO distributions should be independent of the centre-of-mass energy of the collisions. This appeared to be true for centre-of-mass energies below 100 GeV at the pp ISR collider [57] until KNO scaling violation was observed by experiments such as UA5 at higher energies. The violation of KNO scaling was interpreted as a manifestation of the multi-parton interactions whose effects become measurable as the centre-of-mass energy increases.

![Figure 1.11](image_url)

**Figure 1.11:** Comparison of KNO distributions between data at $\sqrt{s} = 546$ GeV (a) and $\sqrt{s} = 1.8$ TeV and events simulated with PYTHIA where the value for the core size of the matter distribution $a_2$ (PARP(84) in PYTHIA) was varied. The shaded areas show the increase of events in the tail of the multiplicity distribution with a denser core. [23]

As explained above, PYTHIA incorporates multi-parton interactions and offers various ways to tune them. One possibility is to modify the double Gaussian matter distribution (see Equation 1.15) inside a hadron. Figure 1.11 shows a comparison between the KNO distributions at the centre-of-mass energies $\sqrt{s} = 546$ GeV and $\sqrt{s} = 1.8$ TeV
as measured by the UA5 and E735 experiments and predictions from PYTHIA \(^4\) with different values for \(a_2\) in Equation 1.15, which determines the core size of the matter distribution. Considerable changes of the predicted distributions, especially in the high multiplicity tail, are observed when varying the core radius. As the core is made harder and denser, which corresponds to a decrease of the radius \((a_2 = 0.2\, \text{fm})\), the overlap between two colliding cores causes more multiple interactions and results in an increase of the prediction for high multiplicity events.

Like the multiplicity distribution, the pseudorapidity distribution is strongly influenced by the rate of multi-parton interactions. Besides the matter distribution inside the hadron, the minimal transverse momentum \(p_{T,\text{min}}\) as defined in Equation 1.18 regulates the interaction rate. Figure 1.12 compares the pseudorapidity distribution in data at \(\sqrt{s} = 546\, \text{GeV}\) and \(\sqrt{s} = 1.8\, \text{TeV}\) with predictions from PYTHIA where the values for the bare minimal transverse momentum \(p_{T,0}\) was varied. All distributions show a central plateau at low pseudorapidity and a falling density in the forward regions. The effect of modifying the minimal transverse momentum is clearly visible. A significant increase of the particle multiplicity is observed for lower values of \(p_{T,0}\). In Chapter 6, the measured charged particle density is compared to various versions of PYTHIA that were tuned to different data sets at various centre-of-mass energies.

\(^4\)The figures in this section were produced with PYTHIA version 6.2.
1.5 Phojet

The PHOJET Monte Carlo event generator [58] provides an alternative approach to the modelling of charged particle production at hadron colliders. It combines the ideas of the Dual Parton Model [59] describing soft interactions and perturbative QCD describing hard interactions. The Dual Parton Model is a non-perturbative approach that relies on a large \( n \) expansion of QCD where \( n \) is the number of colours or flavours, which is described by the exchange of Pomerons and Reggeons for hard and soft interactions. Similar to the PYTHIA model however, PHOJET relies on empirical methods such as a minimal transverse momentum to calculate perturbative QCD processes for Minimum Bias data. The basic principles of the Dual Parton model are:

- **Unitarity**
  The concept of unitarity is based on the fact that the sum of probabilities of all possible outcomes of any event is always 1. The unitarity bound seems to be violated as the inelastic cross section becomes higher than the total cross section at centre-of-mass energies of \( \mathcal{O}(100 \text{ GeV}) \). Unitarity is preserved by allowing multiple interactions in hard and soft scatterings by introducing higher orders of Pomeron exchange [60].

- **Duality**
  The hypothesis of duality means that the same scattering process can be characterised by different diagrams such as a \( t \) channel and an \( s \) channel diagram. For example, the exchange of flavour such as charge in the process \( \pi^- p \rightarrow \pi^0 n \) is described either by a \( t \) channel exchange of a Reggeon or via an \( s \) channel \( \Delta \) resonance of the proton. These diagrams are considered to be duplicates, meaning that they give the same contribution to the scattering amplitude [48].

- **Regge theory**
  Regge theory provides a phenomenological framework to describe particle production processes, especially at low momentum transfers where the strong coupling constant is large. The basic idea of Regge theory is that scattering amplitudes are described by the exchange of particles, which can be parameterised by analytical functions \( \alpha(t) \) (so-called Regge trajectories). The behaviour of proton proton scattering is dominated by the exchange of a Pomeron. The corresponding Pomeron trajectory \( \alpha_P(t) \) is described by \( \alpha_P(t) = \alpha_P(0) + \alpha' t = (1 + \epsilon) + \alpha' t \). The Pomeron intercept \( \alpha_P(0) \) and the slope parameter \( \alpha' \) are then obtained from experimental data. The scattering amplitude \( f \) and hence the cross section is predicted to show a power law behaviour on the centre-of-mass energy \( s \): \( f \propto s^{\alpha_P(t)} \) [61]. This results in an exponential behaviour of the scattering cross section, which is also used in the PYTHIA model for diffractive events (see Equation 1.19).

The key concept of the Dual Parton Model at LHC energies is the exchange of Pomerons for both hard and soft interactions. In PHOJET, the Pomeron is regarded as a theoretical object providing an effective description of the important degrees of freedom of a sum of Feynman diagrams with low momentum transfer [62]. Contrary to
the \textsc{pythia} model, each exchanged Pomeron gives rise to two colour-neutral chains that
stretch between the valence quarks of one incoming hadron and the remaining di-quark
of the other incoming hadron. These chains can be regarded as the exchange of multiple
soft gluons compensating each others colour charge. An illustration of the dominant
two chain diagram responsible for diffractive interactions is given in Figure 1.13(a).
Additionally, higher order processes like loop, triple and double Pomeron exchanges
produce hard diffractive events [63]. Here the colourless chains couple to the sea quarks
of the incoming hadrons as well. Figure 1.13(b) shows how hard interactions like \( 2 \rightarrow 2 \)
gluon scattering are included in \textsc{phojet}. The hard scattering cross section is obtained
similar to Equation 1.10 and the outgoing gluons are split into quark-antiquark pairs by
Pomeron exchange [60]. Similar to the approach used by \textsc{pythia}, a cut-off parameter
\( p_{T \text{,min}} \) is introduced to veto hard interactions in the non-perturbative regime. This cut-off
parameter is taken as a constant with a value of \( \approx 2 \text{ GeV} \).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.13.png}
\caption{(a) Soft interaction diagram containing one Pomeron split in two chains.
(b) Exchange of one soft and one hard Pomeron. The hard \( 2 \rightarrow 2 \) gluon scattering
process is calculated in perturbative QCD.}
\end{figure}

In addition to the soft and hard interactions, \textsc{phojet} allows the possibility to include
initial and final state radiation generated in leading-log approximation [58]. To obtain
predictions of the charged particle density, the final state partons have to be hadronised
into colourless objects. For this, \textsc{phojet} is interfaced to \textsc{pythia}, which implies that any
\textsc{phojet} tune is linked with the particular version of \textsc{pythia} used for the hadronisation.

Due to the different underlying physics models used for the two generators, the
amount of free parameters that can be set by the user differs substantially. Whereas
\textsc{pythia} leaves the freedom to modify multiple parameters, the user is left with only a
few parameters to be adjusted in \textsc{phojet}. Several comparisons between the predictions
of \textsc{phojet} and published Minimum Bias measurements were made in order to validate
the use of \textsc{phojet} at LHC energy scales. Figure 1.14(a) shows a comparison of the
pseudorapidity distribution as measured by the UA5 experiment at \( \sqrt{s} = 900 \text{ GeV} \) with
the prediction from \textsc{phojet}. In Figure 1.14(b), a comparison of the charged particle
transverse momentum between data from CDF at $\sqrt{s} = 1.96$ TeV and the corresponding prediction from PHOJET is presented. The agreement is good for high as well as low transverse momenta. In the intermediate region of between approximately 1 - 2 GeV however, a slight discrepancy is observed, which is believed to originate from the fixed cut-off scale for hard interactions. This implies that the transverse momentum spectra of the partons at the end of the soft and hard chains does not match. A smooth transition as implemented in PYTHIA (see Equation 1.17) would probably result in a more accurate description of the experimental data in this region.

![Figure 1.14:](a) Comparison of the pseudorapidity distribution between data from the UA5 experiment at $\sqrt{s} = 900$ GeV and the corresponding prediction from PHOJET. (b) Comparison of the transverse momentum distribution between data from the CDF experiment at $\sqrt{s} = 1.96$ TeV and the corresponding prediction from PHOJET.]

**1.6 Summary**

This chapter explained the physics models which are implemented in the Monte Carlo simulation programmes (PYTHIA and PHOJET) used to describe charged particle production at hadron colliders. Both programmes have a firm theoretical basis in either QCD or Regge theory, but make substantial use of empirical assumptions to describe measurements from collider experiments. While PYTHIA starts the event generation
with hard partonic interactions and subsequently includes effects which lead to soft particle production, PHOJET initialises the event generation by describing the soft components. The hard component is subsequently introduced to complete the event generation. Despite their almost orthogonal approaches, both programmes have common features. Hard partonic interactions for example are described by an expression for the inelastic cross section, which is factorised in the partonic cross section and the PDFs (see Equation 1.10). The behaviour of the cross section at low transverse momenta is regulated by a cut-off parameter in both programmes. Moreover, the apparent violation of unitary, which appears when the inelastic cross section exceeds the total cross section, is resolved in a similar way. Both models introduce multiple partonic interactions to explain this paradox.

The measured charged particle densities in Chapter 6 will be compared to both Monte Carlo generators. PYTHIA also serves as the model to simulate acceptance effects of the detector as a lot of effort went into its development and the tuning to experimental data over the past decades. One can argue that PHOJET, which is more constrained and not used for the simulation of detector effects, will provide a more objective comparison between data and theory.
Chapter 2

The ATLAS experiment

The ATLAS (A Toroidal LHC ApparatuS) detector [17] has been built to fully exploit the physics potential of the LHC. The goals of the ATLAS physics programme are diverse: they reach from an improved measurement of the properties of well known particles like the mass of the $W$ boson or the top quark to the search for the Higgs boson and possible discoveries of physics beyond the Standard Model as predicted by supersymmetric theories for example. This chapter outlines the key components and design of the ATLAS detector, followed by a detailed description of the inner detector.

Figure 2.1: Cut-away view of the ATLAS detector.
The ATLAS experiment

A cut-away view of the ATLAS detector, which has a length of 44 m and a diameter of 25 m, is shown in Figure 2.1. The individual detectors are arranged in cylindrical layers around the beam pipe in the central part - the barrel - and as wheels perpendicular to the beam axis in the forward parts - the end-caps. The major detector components are the inner detector, the calorimeters and the muon spectrometer. Perhaps the most striking feature of the ATLAS detector is however its magnet system. Eight air-core toroids provide the magnetic field for the muon spectrometer while the magnetic field in the inner detector is produced by a solenoid. To reach its benchmark physics goals the following demands were imposed on the detector design:

- High reconstruction efficiency and precise momentum determination of charged particles in the inner detector as well as the ability to precisely determine secondary vertices for the identification of $\tau$ leptons and jets from $b$ quarks.

- Good electromagnetic calorimetry to identify electrons and photons as well as precise hadronic calorimetry for an accurate measurements of jet energy and the missing transverse energy.

- Efficient muon identification with a good momentum resolution over a wide range of momenta and the ability to unambiguously determine the charge of high $p_T$ muons.

- Highly efficient trigger system with sufficient rejection of background events.

Table 2.1: General performance design of the ATLAS detector. For high-$p_T$ muons, the muon-spectrometer performance is independent of the inner-detector system. [17]

<table>
<thead>
<tr>
<th>Component</th>
<th>Resolution</th>
<th>$\eta$ coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking</td>
<td>$\sigma_{p_T}/p_T = 0.05% \times p_T \oplus 1%$</td>
<td>$\pm 2.5$</td>
</tr>
<tr>
<td>EM calorimetry</td>
<td>$\sigma_E/E = 10% / \sqrt{E} \oplus 0.7%$</td>
<td>$\pm 3.2$</td>
</tr>
<tr>
<td>Hadronic calorimetry</td>
<td>$\sigma_E/E = 50% / \sqrt{E} \oplus 3%$</td>
<td>$\pm 3.2$</td>
</tr>
<tr>
<td>barrel and end-cap forward</td>
<td>$\sigma_E/E = 100% / \sqrt{E} \oplus 10%$</td>
<td>$3.1 &lt;</td>
</tr>
<tr>
<td>Muon spectrometer</td>
<td>$\sigma_{p_T}/p_T = 10%$ at $p_T = 1$ TeV</td>
<td>$\pm 2.7$</td>
</tr>
</tbody>
</table>

These requirements have also been quantified for each component of the detector and are summarised in Table 2.1. Besides these requirements, the detector has to cope with the harsh environment of high interaction rates, radiation doses and particle multiplicities at the LHC. Fast, radiation hard electronics and sensor elements that provide a high granularity for the reconstruction of physics objects and ensure a high data taking efficiency over several years are thus needed.

The measurement of the charged particle density as described in this thesis is one of the early physics measurements. The main detector components needed for this measurement are the Minimum Bias Trigger Scintillators (MBTS) and the inner detector.
2.1 General layout

The ATLAS coordinate system is a right-handed coordinate system with the nominal interaction point as origin. The positive $x$ axis is defined as pointing from the interaction point to the centre of the LHC ring and the positive $y$ axis is defined to point upwards marking the $x - y$ plane, which is transverse to the beam direction. The positive $z$ axis is then oriented parallel to the beam line in anti-clockwise direction.

Commonly a polar coordinate system is used in ATLAS. The radial component $R$ is defined in the $x - y$ plane and the azimuthal angle $\phi$ is defined as the angle in the $x - y$ plane with respect to the positive $x$ axis. The polar angle $\theta$ is the angle with respect to the positive $z$ axis. Often the pseudorapidity $\eta$ is used that is defined by

$$\eta = -\ln \left( \tan \frac{\theta}{2} \right).$$

(2.1)

Convenient properties of the pseudorapidity are that the difference in pseudorapidity of two particles is invariant under Lorentz boosts along the beam directions if the particles are massless and that the distribution of charged particles is approximately constant as a function of $\eta$.

2.1.1 Inner detector

The inner detector [64] as shown in Figure 2.2 provides an efficient detection of charged particles with high spatial and momentum resolutions and is capable of identifying primary and secondary vertices. It is located in a solenoidal magnetic field with a maximum field strength of $B_z = 2$ T parallel to the beam axis and provides full azimuthal coverage within the pseudorapidity range $|\eta| < 2.5$. The detector is able to detect charged particles with a transverse momentum as low as 100 MeV.

The inner detector is the component closest to the interaction point and is composed of three separate detectors: a silicon pixel detector, a silicon strip detector (SemiConductor Tracker, SCT) and a straw tube detector (Transition Radiation Tracker, TRT). The inner detector is contained within a cylindrical envelope of 7024 mm length and a diameter of 2300 mm. On average a reconstructed track has three pixel hits, eight SCT hits and approximately 35 hits in the TRT.

The hit resolutions of the three detector systems are summarised in Table 2.2 together with their required alignment precisions. The initial accuracy to which the position of the detector elements was known after they were installed in the cavern was according to plan. The relative precision within the volume of the inner detector was of $\mathcal{O}(1 \text{ mm})$ 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 [65] within a layer or disk. Track-based algorithms are used to resolve these residual misalignments. More information on the alignment procedure and the achieved hit resolutions are given in Section 4.3.
Figure 2.2: A schematic view of the inner detector. In the central part the detector elements are arranged in cylindrical layers. In the end-caps the modules are arranged in wheels perpendicular to the beam axes.
Table 2.2: Intrinsic measurement accuracies and mechanical alignment tolerances for the inner detector sub-systems. The quoted values refer to individual modules in the pixel and SCT detectors respectively individual straws in the TRT. [17]

<table>
<thead>
<tr>
<th>Detector component</th>
<th>Intrinsic accuracy (µm)</th>
<th>Alignment tolerances (µm)</th>
<th>Radial (R)</th>
<th>Axial (z)</th>
<th>Azimuth (R-φ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barrel layers</td>
<td>10 (R-φ) 115 (z)</td>
<td>10</td>
<td>20</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>End-cap disks</td>
<td>10 (R-φ) 115 (R)</td>
<td>20</td>
<td>100</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>SCT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barrel layers</td>
<td>17 (R-φ) 580 (z)</td>
<td>100</td>
<td>50</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>End-cap disks</td>
<td>17 (R-φ) 580 (R)</td>
<td>50</td>
<td>200</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>TRT</td>
<td>130 (R-φ)</td>
<td></td>
<td></td>
<td></td>
<td>30</td>
</tr>
</tbody>
</table>

2.1.2 Calorimeters

Electromagnetic calorimeter

The ATLAS calorimeter system [66] is located around the solenoid as shown in Figure 2.1. The electromagnetic calorimeter precisely measures the energy and direction of electrons and photons. It is a sampling calorimeter using lead as absorber material and LAr as active or sampling material. The $\Delta \eta \times \Delta \phi$ granularity is $0.025 \times 0.025$ in the barrel part which covers a pseudorapidity region of $|\eta| < 1.5$ while the end-caps provide a coverage of $1.375 < |\eta| < 3.2$. An accordion shaped geometry was chosen for the absorbers and the active material to ensure a full and homogeneous coverage in azimuth without any cracks. In total, the amount of material in the electromagnetic calorimeter corresponds to 25 to 35 radiation lengths ($X_0$) and to two to four nuclear interaction lengths ($\lambda$) over the whole range of pseudorapidity. The expected energy resolution is $\sigma_E/E = 10%/\sqrt{E} \oplus 0.7%$.

Hadronic calorimeter

The hadronic calorimeters surrounding the electromagnetic calorimeters have a coarser granularity which is still satisfactory to meet the specifications on jet reconstruction. They are divided in the tile calorimeter, the Hadronic End-cap Calorimeters (HEC) and the Forward Calorimeter (FCal). The tile calorimeter covers the central region ($|\eta| < 1.7$) and uses steel as absorber and scintillating tiles as active material. The HEC extends up to $|\eta| = 3.2$ and relies on LAr as active material and copper as absorber material. The expected energy resolution of the barrel and end-cap hadronic calorimeters is $\sigma_E/E = 50%/\sqrt{E} \oplus 3%$ for single pions.

In the very forward region up to $|\eta| = 4.9$, the LAr forward calorimeters have been installed to improve the measurement of the missing transverse energy which is produced.
by particles that escape the detector undetected such as neutrinos. Again LAr was chosen as active material while the absorbing material is composed of copper and tungsten. The expected energy resolution is \( \sigma_E/E = 100\% / \sqrt{E} \pm 10\% \) for single pions. The cumulative amount of material at the end of the active calorimetry region varies between 10 and 18 nuclear interaction lengths as a function of pseudorapidity.

2.1.3 Muon spectrometer

The muon spectrometer [67] is the outermost part of the ATLAS detector as shown in Figure 2.1. It provides a transverse momentum resolution of approximately 10\% for muons with a \( p_T \) of 1 TeV. The detection efficiency for muons up to 100 GeV is well above 90\%. In addition, it is used to trigger on events containing high-\( p_T \) muons. The muon spectrometer covers a radial distance from 5 m to approximately 11 m and a pseudorapidity region of \(|\eta| < 2.7\).

The momentum resolution is determined by the magnetic field integral \( \int |\vec{B} \times \vec{d}l| \) - often referred to as the bending power. The magnetic field to deflect the muons is provided by a toroidal magnet system. In contrast to a solenoidal field, the direction of flight is almost perpendicular to the direction of the magnetic field guaranteeing the highest possible bending power even for particles in the forward direction. The eight air-core coils in the barrel part provide a bending power between 1.5 Tm to 5.5 Tm over the pseudorapidity range \(|\eta| < 1.4\). In the forward region, the end-cap toroid magnets produce a bending power of approximately 1 Tm to 7.5 Tm. In the transition region between barrel and end-caps, the bending power is lower.

Four different detector types are used to reconstruct muon trajectories. Monitored Drift Tubes (MDTs) chambers provide a precision measurement of the coordinate in the bending direction of the particles in the central part of the detector. Due to the higher background rate in the forward region, Cathode Strip Chambers (CSCs), which have a higher granularity with respect to the MDTs, have been installed here. Furthermore, Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs) are used for triggering and the measurement of the coordinate orthogonal to the bending direction. The properties of the four muon chamber types are summarised in Table 2.3.

2.1.4 Trigger system

Proton-proton collision events are expected to take place every 25 ns once the LHC is operating at its design parameters. Bearing in mind that approximately 1.3 Mbyte of space are needed to store the detector response of a single event, a data flow of 50 Tbyte/s would be imposed on the data acquisition system if all events were saved for further processing. To reduce the amount of data and reach the desired event rate of about 200 Hz, ATLAS makes use of a three level trigger system composed of Level 1 (L1), Level 2 (L2) and the Event Filter (EF).

At Level 1, the information from on-detector readout electronics in the calorimeters and the muon system is processed to identify events containing high transverse momentum muons, electrons, photons or jets as well as events with large missing or large total
Table 2.3: Summary of the main parameters of the ATLAS muon spectrometer chambers. [17]

<table>
<thead>
<tr>
<th>Monitored Drift Tubes</th>
<th>MDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage</td>
<td>$</td>
</tr>
<tr>
<td>Readout channels</td>
<td>354,000</td>
</tr>
<tr>
<td>Function</td>
<td>Precision tracking</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cathode Strip Chambers</th>
<th>CSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage</td>
<td>$2.0 &lt;</td>
</tr>
<tr>
<td>Readout channels</td>
<td>31,000</td>
</tr>
<tr>
<td>Function</td>
<td>Precision tracking</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resistive Plate Chambers</th>
<th>RPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage</td>
<td>$</td>
</tr>
<tr>
<td>Readout channels</td>
<td>373,000</td>
</tr>
<tr>
<td>Function</td>
<td>Triggering, second coordinate</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thin Gap Chambers</th>
<th>TGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage</td>
<td>$1.05 &lt;</td>
</tr>
<tr>
<td>Readout channels</td>
<td>318,000</td>
</tr>
<tr>
<td>Function</td>
<td>Triggering, second coordinate</td>
</tr>
</tbody>
</table>

Transverse energy. The trigger decision is made in less than 2.5 µs and the event rate is reduced to about 75 kHz. At Level 2 and the Event Filter, software algorithms on large computer clusters are used to further select interesting events and to reduce the rate of stored events. The Level 2 trigger algorithms reduce the event rate to 3.5 kHz in approximately 40 ms. The analysis methods used in the Event Filter level further reduce the event rate to reach a maximum of 200 Hz within the allocated processing time of roughly four seconds.

Minimum Bias Trigger Scintillators

For an optimal measurement of the charged particle density, it is vital that the trigger selects as many events from pp collisions as possible while efficiently rejecting background events. Those background events arise from events where protons interact with the gas inside the beam pipe (beam gas events) or when outlier particles hit parts of the detector and cause a spray of particles (beam halo events).

Minimum Bias Trigger Scintillators (MBTS) [68] are used to select the desired minimum bias events. The MBTS consist of 32 scintillator counters of 2 cm thickness each that are arranged in two disks. At each side of ATLAS, one MBTS disk is mounted on the inside of the liquid argon end-cap calorimeters at $z = \pm 3560$ mm shown in Figure 2.3(a). The disks are divided in an inner and outer ring as illustrated in Figure 2.3(b) covering the pseudorapidity region of $2.09 < |\eta| < 2.82$ and $2.82 < |\eta| < 3.84$.
respectively. Light emitted by each scintillator counter is collected by optical fibres and transmitted to a photomultiplier tube (PMT). The PMT signals are read out, amplified and shaped by the electronics of the hadronic tile calorimeter. The signal is then transmitted to the Central Trigger Processor (CTP) where the trigger decision is made well within the allocated time for the L1 trigger of 2.5 μs.

Figure 2.3: (a) Photograph of a MBTS disk mounted on the inside of a LAr calorimeter end-cap. (b) Schematic view of a MBTS disk indicating the 16 scintillator counters per disk.

The requirements on the Minimum Bias trigger system differ substantially from the ones during long time detector operation explained in the previous paragraph. Due to the low instantaneous luminosities, which have been measured to be between $10^{26}$ cm$^{-2}$s$^{-1}$ and $10^{29}$ cm$^{-2}$s$^{-1}$ [69] for the data sets used in Chapters 5 and 6, the MBTS were operated without scaling their acceptance during this period. The trigger system thus recorded all potential collision events while the maximum event rate is not superseded.

The trigger criterion for the measurement of the charged particle density requires the presence of both proton beams confirmed by the beam pick up trigger system (BPTX, [70]) and at least one hit on one MBTS disk. Figure 2.4(a) shows a comparison between data and simulation of the measured charge deposit in a typical scintillator with at least one MBTS above threshold. Noise in the MBTS was emulated by adding a Gaussian contribution with a width of 0.02 pC around zero to the simulation of pp collisions. The two distributions are in good agreement although some residual differences remain. The detector simulation is however only used for studying possible correlations with other triggers. The MBTS signal and trigger efficiencies for the final analysis are purely obtained from data. The discriminator threshold for the MBTS was set to a charge deposit of 0.18 pC which is a compromise between suppressing noise hits and retaining a high trigger efficiency. Although some signal events are discarded per

\[ \text{This is denoted as } L1_{MBTS} \text{ trigger signal.} \]
individual counter, typically various scintillators are above threshold in pp collisions, which guarantees a high trigger efficiency as will be shown in Section 5.2.

![Figure 2.4](a) Comparison of the charge deposit in an individual scintillator between data and simulation with an additional term added for the noise in simulation. [71] (b) Time difference between the passthrough of a proton bunch and the recorded MBTS signal for LHC fills with one beam (beam1 and beam2) and two beams (beam1 & beam2). [68]

A simple method to reduce the contribution from background events is to study the time difference between the time of a bunch crossing in the detector and the arrival time of a signal in the MBTS detectors. The time at which a bunch of protons passes through the detector is measured by the LHC clock. For collision events, all scintillators measure roughly the same arrival time of the signal, whereas for background events this time is considerably smaller on one side than on the other. The measured time difference is shown in Figure 2.4(b) for periods where the LHC was filled with either one or two proton beams. At ± 30 ns, peaks originating from the passthrough of only one beam are clearly identified. Consequently only events with a time difference below 10 ns are considered to originate from pp collisions.

### 2.2 Pixel detector

The pixel detector [72] is the component closest to the beam pipe and it therefore has to cope with a higher particle flux than any other detector in ATLAS. This requires a high granularity to disentangle tracks from individual charged particles with a high efficiency and purity. The fine granularity also enables the identification of primary and secondary vertices.
Figure 2.5: View of a quarter-section of the inner detector showing each of the major detector elements with its active volumes.

Dimensions and envelopes. The lower graphic shows a zoomed-in view on the pixel detector.

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The pixel detector consists of 1744 modules that are grouped in three layers in the barrel and three disks in each end-cap. The barrel layers are arranged in 112 staves and the end-cap disks are comprised of a total of 48 end-cap sectors (eight sectors per disk) resulting in a total active area of silicon of approximately 1.7 m$^2$ with 80M readout channels. A schematic view of the inner detector showing the positions of the detector elements including a zoomed-in view on the pixel detector is presented in Figure 2.5.

Throughout the pixel detector the same module design has been used. The size of an individual pixel is 50 x 400 $\mu$m$^2$ in the local $x$ and $y$ direction. This size is dominated by the dimensions of the readout cells which are integrated in the front end ASICS [73]. The hit resolution of a single pixel is estimated to be \(\frac{\text{pixel pitch}}{\sqrt{12}} = 14 \mu m \times 173 \mu m\). The actual design hit resolution is better with 10 $\mu m \times 115 \mu m$ as quoted in Table 2.2. This is due to the fact that the recorded time over threshold allows to calculate the central position of a pixel cluster as explained below.

The hit efficiency and the corresponding noise occupancy are important characteristics of the pixel detector. In Figure 2.6(a), the efficiency of associating a hit to a track that crossed a detector layer or disk is shown. A high efficiency of approximately 99% is reached for all layers except for the two outermost end-cap disks where the efficiency is slightly lower. Figure 2.6(b) shows that an extremely low probability of recording random hits of $10^{-10}$ is achieved.

![Figure 2.6: (a) Hit to track association efficiency per barrel layer or end-cap disk. (b) Noise occupancy in the pixel detector as a function of various data taking periods for different levels of the event reconstruction. The bulk reconstruction composes the last step where noisy readout channels have already been excluded. [74]](image)

The pixel sensors are made of $n^+\text{-in-}n$ silicon and have a thickness of approximately 250 $\mu m$. The sensors are fully depleted at a bias voltage of approximately 20 V and will be operated at 150 V being affected by radiation damage. Irradiation of the modules due to the high flux of charged particles will lead to a type inversion of the n-bulk material into $n$- bulk.

\footnote{Approximately 10% of the pixels have the size 50 x 600 $\mu m^2$.}
an effective p-type material after several years of operation. This is expected to happen after an irradiation of a fluence [75] $F_{\text{neq}}$ of $\mathcal{O}(10^{13} \text{ neq cm}^{-2})$. After type inversion the effective concentration will grow continuously with time and the depletion voltage will rise up to 600 V after ten years of operation corresponding to an integrated luminosity of 700 fb$^{-1}$. To mitigate the effects from radiation damage the pixel detector is operated at low temperatures. The pixel detector has been designed to withstand a total fluence $F_{\text{neq}}$ of approximately $1 \cdot 10^{15} \text{ neq cm}^{-2}$ [76]. The hit efficiency in the innermost layer (Layer 0) is however expected to significantly decrease after approximately three years of operation and an additional pixel layer mounted on a new beam pipe will be inserted.

The expected radiation damage also influenced the development of the readout electronics. In the readout cells the signal is amplified and compared to a discriminator threshold. When the signal is above threshold, the pixel address, a hit time stamp and the recorded time over threshold are transferred to the module control chip for further processing. The communication with the off-detector data acquisition system is then performed via optical links. Laser diodes (VCSELs, [77, 78]) are used for the conversion from electronic to optical signals.

As mentioned above, the recorded time over threshold allows for a better hit resolution compared to a completely binary readout. In general not only a single pixel fires when a module is traversed by a charged particle, but clusters of neighbouring pixels over threshold are formed. This is illustrated in Figure 2.7(a) where the average cluster size is shown as a function of the track incidence angle from cosmic ray data with and without magnetic field. The time over threshold signal is related to the deposited charge in the pixels and the charge sharing ratio $\Omega$ for a cluster of two fired pixels is computed according to

$$\Omega_{x,y} = \frac{Q_{\text{last pixel}}}{Q_{\text{last pixel}} + Q_{\text{first pixel}}},$$

(2.2)

where $Q$ is the measured charge per pixel in the local $x$ or $y$ direction. A straight line is fit to the residual of the position of the extrapolated track on the module and the average position of the two pixels as a function of $\Omega_{x,y}$, which is shown in Figure 2.7(b). The position of the cluster centre is corrected by the slope of the straight line to obtain a better estimate of the actual cluster centre.

The average cluster size as a function of the track incidence angle as shown in Figure 2.7(a) is also used to measure the Hall angle. In the presence of a magnetic field the drift path of the created electron hole pairs in a silicon detector is deflected by the Lorentz force and the resulting drift angle is called the Hall angle [80]. A precise knowledge of the Hall angle is vital for the detector alignment and to fully exploit the spatial resolution of the detector. The Hall angle is given by the incidence angle at the minimal average cluster size. A clear shift of the minimal cluster size from zero is visible in presence of a magnetic field. The value is obtained by fitting a convolution of a geometrical function and a Gaussian distribution to the data points [79]. The resulting Hall angle for the pixel detector is $11.77^\circ \pm 0.03^\circ$ (stat) $^{+0.13^\circ}_{-0.23^\circ}$ (syst). The dominant source of the systematic uncertainty is the range to which the fit was applied. The measured value is consistent with the predicted value of $12.89^\circ \pm 1.55^\circ$ (syst). The rather high uncertainty
2.2 Pixel detector

Figure 2.7: (a) Average cluster size as a function of the track incidence angle. [79] (b) The residual between the track extrapolation and the cluster centre as a function of the charge sharing ratio $\Omega_y$ in different regions of pseudorapidity. [74]

on the prediction arises from the uncertainties on the mobility of the charge carriers and on the non-uniformity of the electric field in the readout sensors. Strictly speaking, the non-uniform electric field is a systematic uncertainty affecting the measurement rather than the prediction.

By the time of writing of this thesis, the pixel detector has been operated for more than two years in the ATLAS cavern taking both data from cosmic ray and pp collisions. By now the focus lies on stable detector operation during collision data taking. Approximately 97% of the modules have been operational since the first collisions were recorded at $\sqrt{s} = 900$ GeV in November 2009 [81]. The main reasons for disabled modules are failures in the data transfer system or in the high voltage supply. Furthermore, 0.16% of the remaining front end chips are disabled. As mentioned above, VCSELs are used for the generation of optical signals to and from the detector. The same design has been used for VCSELs located close to the modules (on-detector) and in the data acquisition racks (off-detector). Problems were encountered with the data transmission boards where the VCSELs are located on the off-detector site. As these boards are accessible and failing boards have been replaced, the data taking efficiency has only been marginally influenced so far. Failures of the on-detector VCSELs have not been observed yet, probably because the on-detector diodes are only in use if a L1 trigger signal was received whereas the off-detector VCSELs are operated at the 40 MHz design collision rate of the LHC.
2.3 Semiconductor Tracker

The SemiConductor Tracker (SCT) is a silicon strip detector which is located around the pixel detector. Its main purpose is to contribute to a precise and efficient identification of charged particles. In addition, it is possible to perform pattern recognition and track reconstruction exclusively from SCT hits (stand-alone), which will be used in Chapter 5 and for studies investigating the detector performance as presented below.

Figure 2.8: Photograph of the fully assembled SCT barrel prior to its insertion in the TRT barrel.

The SCT consists of one barrel and two end-caps. The barrel, which is shown prior to its insertion into the TRT in Figure 2.8, is composed of four cylindrical layers containing 2112 detector modules and each end-cap is made of nine disks containing 988 detector modules. Depending on the particular layer the barrel covers $|\eta| < 1.1$ to 1.4 and the end-caps cover the region up to $|\eta| = 2.5$. The exact position of the detector elements is shown in Figure 2.5. The SCT was designed to contribute with at least four precision measurements to each track within $|\eta| < 2.5$.

An SCT detector module [82, 83] consists of two sensors glued back-to-back under a small stereo angle of 40 mrad to provide a two-dimensional measurement. The same design is used for all barrel modules whereas three different module types varying in external dimensions and strip pitch are used in the end-caps. Photographs of a barrel and of a end-cap module are shown in Figure 2.9.

The sensors are manufactured using p-type readout strips on n-type bulk silicon. The strip pitch is 80 µm in the barrel and varies in the end-caps between 57 µm and 94 µm due to a fan geometry. A spatial resolution of approximately 17 µm in R-\phi as mentioned in Table 2.2 can be achieved. A smaller strip pitch would imply larger clusters and less deposited charge per strip. After irradiation of the modules, the deposited charge might not satisfy the readout threshold any more and a lowering of the threshold would in turn
imply an increase of noise hits. In total, there are 768 active readout strips per module side with a length of typically 126 mm.

As the number of readout channels is considerably smaller than in the pixel detector, a higher noise occupancy in the SCT is acceptable. It is required to be below $5 \cdot 10^{-4}$ at a hit efficiency of 99%. Figure 2.10 shows the noise occupancy as measured from cosmic-ray data averaged per readout chip (128 channels) in the barrel and end-cap regions. The few readout chips that did not satisfy the specification limit are not displayed. The slight variations of strip length and readout pitch cause the different behaviour of the various module types.

![Figure 2.9: Photographs of an SCT barrel (a) and end-cap (b) module.](image)

The hit association efficiencies are measured by computing the ratio of the actual and expected number of hits in the ideal case. This means that a stringent track selection has been applied and disabled modules and readout chips have been eliminated from

![Figure 2.10: Noise occupancy averaged over the number of readout chips as measured in cosmic-ray data. Due to their shorter strip length the noise occupancy of the inner end-cap modules is below the displayed range.](image)
the analysis. The efficiencies are either measured with tracks reconstructed stand-alone with the SCT or with the full inner detector information as shown in Figure 2.11 for the barrel and one end-cap (end-cap A). Independent of the method all barrel layers and end-cap disks meet the specification of 99% efficiency.

![Graph](image)

**Figure 2.11:** Hit efficiencies in the SCT barrel (a) and end-cap A (b) per module side of a layer or disk in $\sqrt{s} = 900$ GeV data. [84]

The SCT sensors have a thickness of approximately 300 $\mu$m and are fully depleted at a bias voltage of approximately 70 V. Similar to the pixel detector, irradiation is expected to influence the performance of the modules and the bias voltage will be adjusted accordingly. The maximal voltage will be reached at 500 V after an integrated luminosity of 700 fb$^{-1}$ has been collected. The SCT is using the same evaporative cooling system as the pixel detector to slow down effects from radiation damage and to dissipate the heat produced by the modules. The operating temperature of the modules is approximately 0° C. The detector has been designed to withstand a fluence $F_{\text{neq}}$ of approximately $2 \cdot 10^{14}$ neq cm$^{-2}$ [76].

The SCT sensors are read out by radiation hard ASICs named ABCD chips [85]. The readout is binary and the default threshold was chosen to be 1 fC. At this threshold the hit efficiency and the noise occupancy are within the specification limits as the most probable charge deposition of a minimum ionising particle is about 3.5 fC (22000 electrons) traversing 300 $\mu$m of silicon. Additionally, the noise was found to be significantly below 1 fC. Six ABCD chips per module are used to read out the strips. The readout is performed by amplifying the detector signals, discriminating the signals from background noise and then storing the binary signals in an on-chip pipeline memory. This memory is capable of holding the information from 128 bunch crossings. If a L1 trigger signal is received, the data of typically three bunch crossings is compressed and transferred to the off-detector readout electronics via optical links. For the conversion of electronic to optical signals VCSELs are used. VCSELs following the same design as in the pixel detector are used for transmitting control and clock signals to the modules. The VCSELs responsible for transferring the readout signal to the off-detector site were however constructed according to a different design [86].
Similar to the pixel detector, the measurement of the Hall angle is important. The same procedure as described in the previous section is used to fit the average cluster size per hit as a function of the track incidence angle, which is shown in Figure 2.12(b). In general the average cluster size in the SCT is smaller than in the pixel detector due to the wider strip pitch. The resulting Hall angle was determined to be \(-3.93^\circ \pm 0.03^\circ \) (stat) \( \pm 0.10^\circ \) (syst) in presence of the magnetic field which is in good agreement with the theoretical prediction of \(-3.69^\circ \pm 0.26^\circ \). The main systematic uncertainty on the measurement arises again from the range to which the fit function was applied. It is not surprising that different absolute values and signs were determined for the Hall angles in the SCT and pixel detectors as the mobility and the sign of the charge carriers differ; positively charged holes provide the dominant signal in the SCT and negatively charged electrons in the pixel detector.

By October 2010 the SCT has been operated for more than two years since its installation in the ATLAS cavern. The fraction of active readout channels is very high at 99.3\% with only few disabled readout channels (see Table 2.4). In end-cap C 13 modules suffer from a leaking cooling pipe and are excluded from data taking. A few other modules are disabled due to failures of either the high or low voltage supply. Problems have also been encountered with the evaporative cooling system. During its operation it became clear that the design temperature of \(-7^\circ \text{C}\) will not be reached and the modules will be operated at \(0^\circ - 5^\circ \) \text{C}\) instead [87]. This may affect the lifetime of the detector due to increased effects from radiation damage. Failures of the data transmission boards, which use the same design for the optical readout links on the off-detector site as in the pixel detector, were also observed in the SCT and disabled data transmission boards have been replaced. The on-detector VCSELs in the SCT follow a different design that seems to work more reliably.
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Table 2.4: Configuration of the SCT detector as of 2010. In total, more than 99% of the SCT readout channels are operational. [84]

<table>
<thead>
<tr>
<th>Disabled component</th>
<th>Barrel</th>
<th>End-cap A</th>
<th>End-cap C</th>
<th>Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modules</td>
<td>10</td>
<td>5</td>
<td>15</td>
<td>0.73</td>
</tr>
<tr>
<td>Chips</td>
<td>24</td>
<td>5</td>
<td>4</td>
<td>0.07</td>
</tr>
<tr>
<td>Strips</td>
<td>3,186</td>
<td>3,364</td>
<td>3,628</td>
<td>0.17</td>
</tr>
<tr>
<td>Total disabled components</td>
<td>0.97</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.4 Transition Radiation Tracker

The Transition Radiation Tracker (TRT) is the outermost sub-system of the inner detector covering a radial distance between 0.55 m and 1.1 m. It is a drift tube detector with the additional capability of generating and detecting transition radiation. The main goals of the TRT are to improve the transverse momentum resolution and to enhance the separation between electrons and pions. The design of a straw tube detector was chosen because straw tube detectors are more cost-efficient than silicon detectors, provide many hits per track and reduce the amount of material in front of the calorimeter compared to an all silicon tracker. However, only one coordinate is measured precisely compared to the two dimensional measurements of the pixel and SCT detectors. Figure 2.13 shows a drawing of the inner detector traversed by a track with a $p_T$ of 10 GeV where the lay-out of the individual straw layers in the TRT barrel is illustrated.

The barrel is divided into three layers of 32 sectors each and has a maximal number of 73 straw layers covering a pseudorapidity region of up to $|\eta| = 1$. In each end-cap 160 straw layers oriented perpendicular to the beam axis are arranged in 20 wheels which extend up to $|\eta| = 2$. The TRT consists of more than 170,000 straws in total.

The straw drift tubes are made of thin Kapton-based multilayer material filled with a Xenon gas mixture as active medium (70% Xe, 27% CO$_2$, 3% O$_2$). They have a diameter of 4 mm and contain a gold-plated tungsten anode wire in the centre with a diameter of 30 µm. When a high energy charged particle transits a straw, some atoms of the gas mixture are ionised and the created free electrons are multiplied after they drifted close to the anode wire. The positive ions on the other hand are attracted to the cathode and the resulting current is detected. The hit resolution in the TRT is 130 µm as quoted in Table 2.2. The maximal length of an individual straw is 144 cm in the barrel and 37 cm in the end-caps, which has been chosen such that the counting rate per wire does not exceed 20 MHz at the LHC design luminosity.

To achieve the best hit resolution it is crucial to determine the distance in a straw from the measured drift time of the ionised electrons towards the anode. Figure 2.14(a) shows the drift-time ($r-t$) relation as measured on cosmic ray data fitted by a third order polynomial. The actual measurement used in the track fit is a circle around the anode
wire with the radius of the calculated drift distance. In Figure 2.14(b), the distance from the predicted track position to the measured hit position in the module is shown for TRT barrel modules. The intrinsic hit resolution and uncertainties from the track extrapolation contribute to the width of this hit residual distribution. The consistency of the data with the predictions from simulation proves the excellent understanding of the hit resolutions.

An important figure of merit is the association efficiency of a hit to a track which is calculated as the ratio of the number of hits associated to a track and the number of straws crossed by a charged particle. Figure 2.15(a) shows that the efficiency is highest at approximately 95% if the track crosses the straw about 0.5 mm away from its centre while the efficiency decreases with increasing distance from the centre. The efficiencies measured in data closely follow the predicted values from simulation. In general the hit

---

3 This circle is also known as *drift circle.*
efficiency in the TRT is lower than in the silicon detectors. The impact on the track reconstruction is however marginal as there are approximately 35 TRT hits per track compared to only three respectively eight hits from the pixel and SCT detectors.

Figure 2.14: (a) Drift-time relation fitted with a third order polynomial on cosmic ray data. [79] (b) Comparison of hit residuals between data and simulation for all TRT barrel modules. The two sets of alignment constants on data were derived from cosmic-ray (Pre-Collisions Alignment) and collision data (Post-Collisions Alignment) respectively. [88]

Figure 2.15: (a) Hit efficiency as a function of the distance to the anode wire. [89] (b) The probability of a high threshold hit as a function of the $\gamma$. [89]

The capability of separating electrons from pions is based on the installation of material layers with different dielectric constants. When a high energetic charged particle crosses the boundaries between these layers, transition radiation photons with an energy between approximately 5 keV and 10 keV are produced in a cone around the particle.
The amount of transition radiation depends on the Lorentz $\gamma$ factor which is given by $\gamma = E/m$. As the pion mass is more than 250 times bigger than the electron mass, electrons in the energy range between 1 GeV and 200 GeV produce much more transition radiation photons that are in turn absorbed by the Xe gas mixture. In order to identify these transition radiation hits, the read out electronics are equipped with two thresholds: one high threshold of approximately 6 keV and one low threshold of a few hundred eV. The probability of a high threshold hit in the barrel is shown as a function of the Lorentz $\gamma$ factor in Figure 2.15(b). For $\gamma$ factors above $10^3$ the probability starts to rise and reaches a plateau at approximately 0.25 for $\gamma > 10^3$. This behaviour can be understood by looking at the yield of transition radiation as a function of the $\gamma$ factor. Whereas for $\gamma$ values between $10^3$ and $10^4$ the yield rises linearly with $\gamma$, the radiation spectrum of a periodic radiator does not become harder as the energy of the particle increases further and a saturation effect occurs for $\gamma$ factors above approximately $2 \cdot 10^4$ [90].

The TRT has been operated reliably since its first turn-on in the ATLAS cavern in fall 2008. 97.1% of the 350k readout channels are in operation [91]. Problems were encountered when ATLAS switched from its internal clock to the LHC clock at the beginning of a data taking period as parts of the detector loose synchronisation. Automatic recovery processes were installed to re-synchronise the detector and guarantee a good timing [92].
Chapter 3

TRACKS AND VERTICES

An efficient reconstruction of the trajectories from charged particles traversing the detector is a prerequisite for almost any physics analysis at particle colliders, in particular for the measurement of the charged particle density. The information from these identified tracks is also needed to find the primary interaction point of the collisions. Moreover, the identification of secondary vertices as produced by the decay of long lived particles relies on a precise reconstruction of the tracks from their decay products.

Charged particles in presence of a homogeneous magnetic field follow a helical trajectory. Commonly the track parameters are defined at the point of closest approach with respect to the beam axis - the so-called *perigee point*. As illustrated in Figure 3.1, the helix is defined by the following five track parameters [93]:

![Figure 3.1: Schematic view of the five track parameters in the helical track model projected onto the x – y plane (a) and the R – z plane (b). The transverse impact parameter \(d_0\) is > 0 in this figure.](image)

\[ \begin{align*}
\phi & \quad \text{dip angle} \\
\phi_0 & \quad \text{perigee angle} \\
T & \quad \text{momentum component along the beam} \\
p & \quad \text{momentum} \\
d & \quad \text{impact parameter} \\
d_0 & \quad \text{transverse impact parameter} \\
\theta & \quad \text{polar angle} \\
z_0 & \quad \text{z-coordinate of the perigee point} \\
R & \quad \text{radius} \\
\end{align*} \]
• $q/p$ is the charge-signed inverse momentum, which is related to the curvature $\kappa$ of the track by

$$\kappa \equiv \frac{1}{\rho [\text{m}]} = \frac{0.3 \cdot B [\text{T}]}{p [\text{GeV}]}$$

where $B$ is the magnetic field and $\rho$ the radius of the track in the $x-y$ plane.

• $\theta$ is the angle with respect to the $z$ axis in the $R-z$ plane at the point of closest approach and is referred to as the polar angle. For most analyses the pseudorapidity $\eta$ is used.

• $\phi_0$ represents the angle to the $x$ axis at the perigee point in the $x-y$ plane and is called the azimuthal angle.

• $z_0$ is the $z$ coordinate at the point of closest approach to the $z$ axis and is referred to as the longitudinal impact parameter.

• $d_0$ is the point of closest approach to the $z$ axis in the $x-y$ plane. The sign of the transverse impact parameter $d_0$ is determined via

$$\text{sign}(d_0) = \text{sign} \left( \left( \vec{p} \times \vec{l}_z \right) \cdot \vec{d} \right),$$

where $\vec{p}$ is the momentum vector, $\vec{l}_z$ is the unit vector in $z$ direction and $\vec{d}$ is composed of the $x$ and $y$ coordinates of the perigee point. This is consistent with the convention that the sign of $d_0$ is positive if $\phi - \phi_0 = \pi/2 + n \cdot 2\pi$ ($n \in \mathbb{Z}$), where $\phi$ is the angle of the perigee position with respect to the $x$ axis.

In pp collisions, a physical meaning is given to the track parameters by expressing them with respect to the primary vertex of the collision [94]. In general, the track parameters can be calculated with respect to any position within the detector if the magnetic field map as well as corrections due to multiple Coulomb scattering and energy loss effects are known [95].

### 3.1 Detector material

The performance of the track propagation is strongly influenced by the amount of material inside the inner detector. Two properties of the material are of great importance to understand the efficiency and the precision of the track finding procedure [80]:

• The **nuclear interaction length** $\lambda$ is the mean free path length between interactions of a hadron traversing the detector and nuclei of the detector material. It is given as $\lambda = 1/n \sigma_{\text{tot}}$, where $n$ is the number of nuclei per unit volume and $\sigma_{\text{tot}}$ the total cross section for a hadron-nucleus interaction. When a charged particle undergoes a nuclear interaction within the detector volume, many new particles are produced at the interaction vertex. These fragments may be reconstructed allowing to identify the vertex. As the trajectory of the incident particle ends at this vertex, there is in general no reconstructed track corresponding to this particle.
3.1 Detector material

- The **radiation length** $X_0$ is the characteristic amount of matter that high energy electrons traverse such that they lose all but $1/e$ of their energy by means of bremsstrahlung. Multiple Coulomb scattering and energy loss effects due to electromagnetic interactions are characterised by the traversed radiation length. These interactions lead to uncertainties in the track finding procedure and influence the precision of the reconstructed track parameters.

The material distribution in the inner detector expressed in radiation lengths and in nuclear interaction lengths is shown in Figure 3.2. The design goal was to keep the amount of material as low as possible, with the least material in the central part of the detector. In the transition region between barrel and end-caps, an onset in the amount of material is seen due to cables and support structures located between the TRT barrel and end-caps. A large fraction of the material is actually located outside of the active detector region and does not affect the track reconstruction itself. However, this material influences for example the measurement of photons in the calorimeters as their conversion rate is determined by the amount of traversed material. At the exit of the TRT, a charged particle has traversed approximately $0.5 \ X_0$ at $\eta = 0$ and $1.5 \ X_0$ at $|\eta| = 1.5$.

![Figure 3.2: Calculated material as a function of $\eta$ at the exit of the inner detector envelope indicating the contribution of the individual sub-detectors and external services: (a) expressed in nuclear interaction lengths $\lambda$; (b) expressed in radiation lengths $X_0$.](image)

To precisely model the consequences of the material distribution on the track finding procedure, a detailed description of the amount of material has been implemented into the reconstruction software [96]. The individual detector components are represented by *material layers* which hold a parametrisation of the material thickness in radiation lengths and allow the track fit to include multiple scattering and energy loss effects as explained in Section 3.2.2.

Several studies have estimated the uncertainty on the material description of the inner detector. Amongst others, the rate of photon conversions and nuclear interactions...
on data and simulation have been investigated [97,98]. Another approach studied differences in the reconstruction of the well known mass of the $K_S$ meson between data and simulation [99]. In Figure 3.3, the fitted $K_S$ mass ratio in data with respect to simulated samples, where the amount of material was increased by 5% and by 10%, is shown as a function of the $K_S$ decay radius. The data is measured to be consistent with the nominal material distribution for small decay radii and with all examined material descriptions over the whole range of decay radii shown. This indicates that the uncertainty on the amount of material is below 10%.

![Figure 3.3](image)

**Figure 3.3:** Fitted $K_S$ mass ratio as a function of the decay radius. The ratio of data and simulation samples with 5% and 10% increased material with respect to the nominal simulation sample is shown. The error band indicates the uncertainty from the magnetic field map. The errors on the data points are statistical only.

### 3.2 Track finding

The track finding procedure is performed in three steps: (1) the pattern recognition groups hits in the detector and forms track candidates. (2) The track fit obtains the best estimate of the track parameters for these candidates. (3) Ambiguities between tracks are resolved and hits in the TRT are added.

#### 3.2.1 Pattern recognition

The goal of the pattern recognition is to identify tracks from the hits of charged particles in the detector. A graphical representation of the involved steps is shown in Figure 3.4. Usually three hits in the pixel and SCT detectors are used to form a seed. Subsequently, a road width is defined in which hits are added to this seed throughout the silicon
3.2 Track finding

detectors. The resulting track candidates already provide a crude estimate of the track parameters [100]. Additionally, a track segment in the TRT can be associated to these track candidates.

Figure 3.4: Illustration of the pattern recognition in a simplified model. (1) Seeds are reconstructed from combinations of three hits. (2) The dashed line represents a seed where another seed corresponds to the trajectory of the same charged particle. (3) No additional hits could be added to this seed. (4) A track in the silicon detectors is found. (5) This track is rejected because it is inconsistent with the nominal interaction point. (6) An extension in the TRT was assigned to a track in the silicon detectors.

The seeds for the track reconstruction are created from three dimensional measurement points in the silicon detectors, so-called space points. As hit clusters in the pixel detector provide a two dimensional measurement on a fixed module surface, they are directly used as space points. In the SCT, the 40 mrad stereo angle between the two module sides is used to construct the space points. Hits in the pixel and SCT detectors
can hence be treated in the same way which ensures a high efficiency of the pattern recognition of almost 100%.

In the following step track seeds are created from three space points each. Neglecting effects from multiple scattering and energy loss, all five track parameters can be calculated. In the $x - y$ plane, the projected helix results in a circle that is described by the transverse momentum, the azimuthal angle and the transverse impact parameter. A crude estimate of the longitudinal parameters $z_0$ and $\eta$ is derived by assuming that the trajectory of the charged particle is a straight line in the $R - z$ plane.

A comparison of the transverse impact parameter, which was calculated with respect to the average position of the primary vertex (the beam spot), and of the pseudorapidity of the seeds between data and simulation is shown in Figure 3.5. Not surprisingly, the largest fraction of seeds has a small impact parameter with respect to the beam spot indicating that most particles originate from the primary vertex. The $\eta$ distribution reflects the fact that particles leave more hits and thus create more seeds in the forward regions as they traverse more layers of active material. The fair agreement between data and simulation proves the understanding of the track finding procedure already at this early stage.

**Figure 3.5:** Comparison between data and simulation of the transverse impact parameter (a) and the pseudorapidity (b) for track seeds. The transverse impact parameter $d_0$ was calculated with respect to the beam spot. Correction factors to both distributions were applied to account for the different $p_T$ spectra in the samples. [100]

Track candidates are formed from the seeds by propagating them through the detector and assigning further hits within a defined road window. A *Kalman fitter* algorithm [101] predicts the track position, which is used to decide whether a hit is compatible with the initial seed. During this procedure a seed is discarded if all hits of this seed were already used for other candidates or if the resulting candidate does not fulfil basic requirements. These requirements include a minimal transverse momentum of 150 MeV, a maximal transverse impact parameter of 10 mm and a minimum number of seven hits in the silicon detectors. Each seed can become at most one track candidate.
3.2 Track finding

3.2.2 Track fitting

The task of the track fitting procedure is to obtain the best estimate of the track parameters. Compared to the rough estimate of the parameters in Section 3.2.1, the track fit includes the uncertainties of the measurement points and treats the effects arising from the traversed material in the detector properly.

Throughout this thesis, a track fitter based on a global least squares approach [102] is used whereas other approaches like a Kalman fitter [101] technique have also been implemented in the reconstruction software. The global least squares fit is based on minimising a $\chi^2$ function, which is given by

$$\chi^2 = \sum_{\text{meas}} \frac{r_{\text{meas}}^2}{\sigma_{\text{meas}}^2} + \sum_{\text{scat}} \left( \frac{\theta_{\text{proj scat}}^2}{\sigma_{\text{scat}}^2} + \frac{\sin^2(\theta_{\text{loc}}) (\phi_{\text{proj scat}})^2}{\sigma_{\text{scat}}^2} \right). \quad (3.3)$$

The first part of the formula is a sum over the hit residuals $r_{\text{meas}}$ divided by their uncertainties. The residuals are obtained by propagating the track with a fourth order Runge-Kutta [103] extrapolator through the magnetic field to a measurement plane and then calculating the difference between the measured hit position and the track prediction. For hits in the pixel detector, these residual are calculated in two dimensions whereas only the precise measurement coordinate is used in the SCT [104]. The derivatives of the residuals with respect to the track parameters are calculated as well. These derivatives must be known for the $\chi^2$ minimisation and are essential ingredients of the alignment procedure.

The second term refers to multiple Coulomb scattering and is a sum over the scattering angles $\theta_{\text{proj scat}}$ and $\phi_{\text{proj scat}}$ at a material layer (see Section 3.1) divided by the corresponding uncertainties. As illustrated in Figure 3.6, a scattering angle is defined by the angular difference between the incoming and the outgoing track, which is then projected on the $R-z$ and $x-y$ plane to obtain $\theta_{\text{scat}}$ and $\phi_{\text{scat}}$. These projected scattering angles are supposed to be described by a Gaussian distribution. For a particle that traverses material with the thickness $t/X_0$ having the momentum $p$, the charge number $Z'$ and the velocity $\beta c$, the width of this Gaussian distribution is given by

$$\sigma_{\text{scat}} = \frac{13.6 \text{ MeV}}{\beta c p} Z' \sqrt{t/X_0(1 + 0.038 \ln (t/X_0))}. \quad (3.4)$$

Equation 3.4 is also known as the Highland formula [105], which is an empirical extension to Molière’s scattering theory [106, 107]. In Equation 3.3, the additional correction factor $\sin^2(\theta_{\text{loc}})$, where $\theta_{\text{loc}}$ is the incident angle of the incoming particle with respect to the scattering plane, accounts for the out-of-plane projection of the scattering angle $\phi_{\text{scat}}$. The uncertainty of $\phi_{\text{proj scat}}$ is hence given by $\sigma_{\phi,\text{scat}} = \sigma_{\text{scat}}/\sin^2(\theta_{\text{loc}})$ [95].

Energy loss effects also arise from the amount of traversed material and have to be corrected for. This energy loss is mostly due to ionisation and is described by the well known Bethe-Bloch formula [108]. This formula is valid for particles with a mass above 100 MeV in the relevant momentum range, which are more than 99.9% of the charged particles produced in pp collisions. In the track fitting procedure, the expected energy...
loss is taken into account by reducing the momentum of the charged particle according to the thickness of a traversed material layer.

The remaining fit parameters in the global least squares model are the five track parameters at the perigee point and two scattering angles per material layer. Given the fact that up to 15 material layers are traversed by a track, the total number of fit parameters can be up to 35 and the minimisation of Equation 3.3 involves the inversion of large matrices [109]. A fast matrix inversion algorithm based on the Bunch-Kaufman [110] method ensures a competitive execution time of the track fit.

3.2.3 Ambiguity solving and TRT extension

A considerable amount of the track candidates are incomplete, share hits or are fakes, which means that they are composed of random hits. To resolve ambiguities between these tracks, a weight is assigned to every track and the tracks with the highest weights are kept. This weight is based on the amount of hits and holes\(^1\) as well as on the goodness of the track fit. It is also possible to merge two tracks if the resulting track acquires a higher weight than the individual ones.

In order to add TRT measurements to a track, the propagation direction of a silicon track is followed through the TRT volume assigning hits within a window of $O(10 \text{ mm})$ around this direction. If the at least ten hits in the TRT are compatible with the initial track, a possible TRT track extension is fit from these hits. In a following step, a new track is created from the silicon track and its possible TRT extension, which is then compared to the original one by assigning weights similar to the procedure described above [104]. The track with the higher weight is kept for analysis.

\(^1\)A hole is produced when a particle traversed an active readout sensor without leaving a hit.
3.3 Performance

In the scope of this thesis, the performance of the track finding algorithms on minimum bias events, which are predominantly composed of pions, kaons and protons with a momentum of $O(1 \text{ GeV})$, is important. Some quantities like the efficiency and the purity of the track reconstruction cannot easily be derived from data and are in general obtained from Monte Carlo simulation. The efficiency to find tracks originating from primary charged particles of pp interactions was found to be approximately 80% with a high purity of more than 99% [111]. As a track is required to have at least seven hits in the pixel and SCT detectors, the main reason that a primary particle is not reconstructed as a track is because it undergoes an interaction or decay. While in the central part of the detector the reconstruction efficiency is close to 90%, it decreases towards higher values of $|\eta|$ to approximately 75% in correspondence with the increase of the material in this region as shown in Figure 3.2. When requiring that a primary charged particle does not interact within the volume of the silicon detectors, its reconstruction efficiency is close to 100%.

In order to validate the performance of the track finding algorithms in data, comparisons of various quantities between data and their predictions from simulated samples have been performed. In Figure 3.7 such a comparison is shown for the number of hits per sub-detector. The tracks were required to originate from the primary vertex and to have at least one pixel hit. Approximately 15% of the tracks have less than the expected three pixel hits and a slightly lower fraction of approximately 10% misses a hit in the innermost pixel layer as shown in Figures 3.7(a) and (b). This is mostly due to disabled pixel modules for which the simulation has been adjusted accordingly. The remaining tiny discrepancies between data and simulation probably originate from disabled front end chips that are not accounted for in simulation.

The number of SCT hits peaks at eight hits per track, which is expected as a charged particle typically crosses four layers or disks independent of its pseudorapidity. A track has at least ten hits in the TRT as this is a requirement for a track extension. Depending on the region of the detector that the charged particle traversed, a varying number of hits is expected with a maximum at around 35 TRT hits. As the hit efficiency in the TRT is difficult to model, slight discrepancies between data and simulation are observed, in particular at around 25 hits. For the other distributions, the agreement between data and simulation is excellent which indicates the good understanding of the track reconstruction procedure.

3.4 Vertex finding

Primary and secondary vertex finding is an essential ingredient for nearly any physics analysis. The identification of primary and secondary vertices relies on a well understood reconstruction of the charged particles from pp collisions, which was shown in the previous section. The reconstruction of the primary vertex is for example crucial for the measurement of the charged particle density. If the reconstruction of the primary vertex
Figure 3.7: The number of hits per track for each of the three detectors and for the innermost pixel layer (Layer 0) in data and simulation.

fails, the whole event and hence all the reconstructed tracks of this event are lost for this analysis.

The performance of the primary vertex identification is strongly influenced by the number of tracks associated to the vertex and their purity, where a high purity means that the majority of these associated tracks originate from the primary vertex. To reconstruct as many tracks as possible the transverse momentum is required to be above 150 MeV, which is close to the reconstruction threshold of the inner detector. The tracks are also required to be consistent with the transverse interaction region of the proton beams in ATLAS - the *beam spot* - to obtain a sample of tracks with the desired high purity.

The vertex finding algorithm [112] makes use of an iterative approach and is based on the following strategy:

- A vertex seed is determined by looking for the maximum in the distribution of the $z$ coordinate of the selected tracks, which is computed with respect to the beam
3.4 Vertex finding

The vertex position is determined using an adaptive vertex fitting algorithm [113], which takes as input the seed position and the tracks around it. The adaptive vertex fitter is a $\chi^2$-based fitting algorithm, which deals with outlying track measurements by down-weighting their contribution to the overall $\chi^2$.

Tracks incompatible with the vertex by more than approximately $7\sigma$ are used to seed a new vertex. This procedure is repeated until no unassociated tracks are left in the event or no additional vertex can be found.

Figure 3.8(a) shows a scatter plot of the $x$ and $y$ coordinate of the primary vertex in $\sqrt{s} = 7$ TeV collision data. The average collision point is displaced from the centre of ATLAS by approximately 0.5 mm in both directions. The RMS of the vertex position in the $x$ and $y$ directions were determined to be 0.024 mm and 0.040 mm. In Figure 3.8(b), the $z$ coordinate of the primary vertex candidates is compared between data at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 2.36$ TeV. The mean values of both distributions are displaced by approximately 10 mm from the origin indicating that the fine-tuning of the beam positions was not yet perfect. The spread of the longitudinal vertex position was observed to depend on the centre-of-mass energy and is smaller at higher centre-of-mass energies. All quantities measured as a function of $\eta$ are sensitive to the mean and the spread of the longitudinal vertex position since particles with the same pseudorapidity emerging from varying $z$ positions traverse different regions of the detector. In the remainder of this thesis weights will be applied to ensure consistent longitudinal vertex distributions if necessary.

![Figure 3.8(a)](image1.png)

![Figure 3.8(b)](image2.png)

**Figure 3.8:** (a) Scatter plot of the $x$ and $y$ positions of the primary vertex in pp collisions at $\sqrt{s} = 7$ TeV. (b) $z$ position of the vertex candidates as measured in data at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 2.36$ TeV.
3.5 Finding hadron resonances

3.5.1 \( K_S \) meson and \( \Lambda \) baryon

With the first data from pp collisions, well known hadron resonances like the \( K_S \) meson decaying to \( \pi^+\pi^- \) and the \( \Lambda \) baryon decaying to \( p\pi^- \) [114] were studied. The central values of the extracted masses measure the momentum scale in the inner detector and the obtained widths provide valuable information about the momentum and angular resolutions. Due to their high production cross section and their relatively low masses, these hadrons were studied on data sets with a small integrated luminosity of approximately 190 \( \mu b^{-1} \).

Figure 3.9 shows a comparison between data and simulation of the \( \pi^+\pi^- \) and the \( p\pi^- \) invariant mass distributions. As the \( K_S \) and \( \Lambda \) have a \( c\tau \) of several centimetres, pairs of oppositely charged tracks were required to intersect at a common vertex, which is displaced by at least four millimetres in the transverse plane from the primary vertex. Furthermore, the angle between the momentum vector and the flight direction of the reconstructed object, which is also referred to as the pointing angle, was required to have a cosine greater than 0.999. Clear signals of the \( K_S \) and \( \Lambda \) resonances are seen. A double Gaussian distribution convoluted with a polynomial to describe the background was fitted to the invariant mass spectrum in both cases. The distributions of signal and background candidates in the simulated sample have been normalised separately as the production processes of the \( K_S \) and \( \Lambda \) are quantitatively not well understood.

![Figure 3.9: Observation of the \( K_S \) meson resonance in the \( \pi^+\pi^- \) invariant mass spectrum (a) and of the \( \Lambda \) baryon in the \( p\pi^- \) invariant mass spectrum (b) in the central part of the detector (|\( \eta \)| < 1.2). The background and the signal have been normalised separately in simulation.](attachment:image.png)

A comparison of the measured central values and widths of the \( K_S \) and \( \Lambda \) mass on data and simulation with the mass values from the PDG is given in Table 3.1. The good
agreement of the mass values shows that the momentum scale is well measured and that the remaining systematic effects are only of $O(100 \text{ keV})$.

**Table 3.1:** Comparison of the measured mean and width of the $K_S$ and $\Lambda$ invariant mass spectrum with the values from the PDG [80] in the region $|\eta| < 1.2$. The width is obtained as the full width at half maximum divided by 2.35 of the signal peak. The errors on the fitted values are statistical only.

<table>
<thead>
<tr>
<th></th>
<th>mean (MeV)</th>
<th>width (MeV)</th>
<th>PDG mass (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_S$ Data</td>
<td>497.427 ± 0.006</td>
<td>5.60</td>
<td>497.614 ± 0.024</td>
</tr>
<tr>
<td>$K_S$ MC</td>
<td>497.329 ± 0.006</td>
<td>5.42</td>
<td>497.614 ± 0.024</td>
</tr>
<tr>
<td>$\Lambda$ Data</td>
<td>1115.73 ± 0.01</td>
<td>2.28</td>
<td>1115.683 ± 0.006</td>
</tr>
<tr>
<td>$\Lambda$ MC</td>
<td>1115.68 ± 0.01</td>
<td>2.18</td>
<td>1115.683 ± 0.006</td>
</tr>
</tbody>
</table>

The excellent understanding of the momentum scale is mainly due to an accurate measurement of the magnetic field map within the inner detector with a precision well below 1 mT [115]. This is illustrated in Figure 3.10, where the fractional sagitta residual, $\partial S/S$, which is evaluated along a straight trajectory from the nominal interaction point to the boundary of the inner detector, is shown as a function of $\eta$. While the error on the overall magnetic field scale is constant and contributes with 0.2% to the fractional sagitta residual, the uncertainty from a geometrical fit to the magnetic field measurement increases at higher pseudorapidity.

**Figure 3.10:** Fractional sagitta residual, $\partial S/S$, as a function of pseudorapidity. The contribution of the uncertainty on the magnetic field scale is pronounced. [17]

The good agreement of the measured widths and the corresponding predictions originates from the knowledge of the material distribution in the inner detector (see Figure 3.2). As shown in Figure 3.3, where the measured $K_S$ mass is shown as a function of the decay radius, the remaining uncertainty on the material distribution is at most 10%.

The observed experimental width of the $K_S$ is approximately twice as large as the width of the $\Lambda$. The reason for this is not entirely understood. The width depends on the momentum resolution and on the resolution of the opening angle between the decay
products. A possible explanation could be the kinematics of the decay products. Due to its high mass the momentum of the proton in the Λ decay is in general higher than the momentum of the pions in the K_S decay. As the contribution from multiple scattering to the momentum resolution depends approximately on 1/p, the proton momentum is possibly determined more precisely, which would then lead to a smaller width of the invariant mass peak. Another reason might be the decay length of the Λ, which is in general larger than the one of the K_S. This would imply that the decay products of the K_S have to traverse more material in the inner detector and exhibit a larger contribution from multiple scattering.

3.5.2 Φ meson

The specific energy loss dE/dx of charged particles traversing the detector can be calculated from the deposited charge in the pixel detector. As this energy loss depends on the squared velocity of the incident particle, protons and kaons with a momentum below approximately 1 GeV can be separated from pions. This particle identification capability is an essential ingredient to identify the Φ meson which decays in 48.9% of the cases into a positively and a negatively charged kaon [116]. Figure 3.11(a) shows the dE/dx distribution as a function of the momentum of the incident particle as measured on data. Three bands, which are caused by pions, kaons and protons respectively, are clearly identified. A likelihood estimate based on the energy loss as obtained from simulation was used to select the kaon candidates.

![Energy loss dE/dx distribution](a)

![Observation of the Φ meson resonance in the K^+K^- invariant mass spectrum](b)

**Figure 3.11:** (a) Energy loss dE/dx as a function of the momentum as derived from \( \sqrt{s} = 900 \) GeV data. The three bands correspond to pions (π), kaons (K) and protons (p) respectively. (b) Observation of the Φ meson resonance in the K^+K^- invariant mass spectrum. The background and the signal have been normalised separately in simulation.

The invariant mass of pairs of oppositely charged kaon candidates is shown in Figure 3.11(b). A clear peak is observed at the PDG mass value of the Φ meson of
1019.455 ± 0.020 MeV. The invariant mass spectrum was fitted by a superposition of a background shape and a Breit-Wigner convoluted with a Gaussian distribution. The extracted central value from data is 1019.5 ± 0.3 MeV (stat), which is in excellent agreement with both the prediction from simulation and the PDG value. This demonstrates again that the momentum scale in the inner detector is well understood. The experimental resolution was found to be 2.5 ± 0.5 MeV. The good agreement of the extracted width between data and simulation proves again the good understanding of the angular resolutions in the inner detector.

### 3.5.3 Ξ⁻ and Ω baryons

Particles with a measurable decay length like $B_0$, $K_S$ or $\Omega$ travel macroscopic distances in the detector and decay at a vertex displaced from the primary interaction point. The reconstruction of these secondary vertices allows the identification of these particles. The performance of the secondary vertex finding algorithms to identify $b$ jets is for example discussed in [117]. Figure 3.12 illustrates the decays of $\Xi^- \rightarrow \pi \Lambda(\rightarrow \pi p)$ and $\Omega \rightarrow K \Lambda(\rightarrow \pi p)$. The world averages of their masses are 1321.71 ± 0.07 MeV for the $\Xi^-$ and 1672.45 ± 0.29 MeV for the $\Omega$. In the following, the procedure to identify these cascade decays is summarised and the main results are presented. A detailed discussion including a complete overview of the imposed requirements can be found in [118,119].

![Figure 3.12: Schematic representation of the decay of the $\Xi^-$ and $\Omega$ baryons via a $\Lambda$ baryon as intermediate particle.](image)

The hadron resonances are identified with a dedicated cascade fitting algorithm such as described in [120]. This algorithm is able to fit a set of linked vertices including constraints on the mass and the decay point of the intermediate particle. Furthermore, the cascade fitting algorithm takes into account the magnetic field and the material distribution inside the detector.
For the identification of the $\Xi^-$ and $\Omega$ particles, the invariant mass of the intermediate $\Lambda$ baryon is constrained by $|m_{p\pi} - m_{\Lambda,PDG}| < 8$ MeV and the distance of the secondary vertex with respect to the primary vertex is required to be above 4 mm. An additional requirement has been made to ensure that the correct charge combination $p\pi^-$ respectively $p\pi^-K^-$ of the decay products was selected. The resulting invariant mass distributions $m_{\Lambda\pi}$ and $m_{\Lambda K}$ are shown in Figure 3.13. Clear peaks, which were fitted by Gaussian distributions, are observed on top of the background that was estimated by selecting the wrong charge combination. The measured central value of the $\Xi^-$ mass is $1322.22 \pm 0.07$ MeV (stat) and the detector resolution is determined to be $3.83 \pm 0.08$ MeV (stat). For the $\Omega$ baryon, the extracted values are $1672.8 \pm 0.3$ MeV (stat) for the mass and $4.0 \pm 0.3$ MeV (stat) for the width. Given that the uncertainties are only statistical, the systematic effects of this measurements are estimated to be approximately 0.5 MeV.

The good agreement between the extracted particle masses and their PDG values underline the good understanding of the track and vertex finding algorithms. The momentum scale in the detector is estimated to be known to less than 1% from a quantitative comparison of the numbers presented here.

### 3.6 Conclusions

Track and vertex finding are integral parts of analysing pp interactions. The track finding procedure is divided in grouping hits together that originate from the same particle
(pattern recognition) and obtaining the best estimate of the track parameters from these hits (track fitting). In ATLAS, a track fitter based on a global least squares approach is commonly used. The vertex identification procedure distinguishes between primary and secondary vertex finding. Whereas the primary vertex is used to identify the pp collisions themselves, the reconstruction of secondary vertices allows to identify decays of particles with a measurable decay length within these collisions.

The track and vertex finding algorithms have been extensively tested and calibrated. An overview of their performance based on an analysis of hadron resonances is given in Figure 3.14. Here the relative difference between the extracted central values and the world average of their masses, $\Delta m/m_{PDG}$, is shown. The uncertainties are statistical only for data and taken from the PDG for the world averages. The figure shows that the momentum scale in the inner detector is understood to the sub-percent level independent of the individual resonance. This achievement can be mainly attributed to the accurate measurement of the magnetic field map inside the volume of the inner detector.

![Figure 3.14](image_url)

**Figure 3.14:** Relative mass difference $\Delta m/m_{PDG}$ of the extracted mass values as a function of the hadron mass in data.
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:

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\sigma^2(\Delta \lambda) = \sigma^2(\lambda_{up} - \lambda_{down}) \approx \sigma^2(\lambda_{up}) + \sigma^2(\lambda_{down})
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\]
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

$$\sigma(\lambda) = \frac{\sigma(\Delta \lambda)}{\sqrt{2}}, \quad (4.3)$$

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.

![Figure 4.2: 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 $p_T$.](image)

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.\(^1\)

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

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\(^1\)The runs 91885, 91888, 91890, 91891 and 91900 recorded during October 17th - 19th were selected.
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 $|d_0| < 40$ 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.
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 \( \mu \)m for the pixel modules and 12 \( \mu \)m for SCT modules in the \( R - \phi \) direction as discussed in Section 2.1.1. The intrinsic hit resolutions in \( R - \phi \) are 10 \( \mu \)m for pixel and around 17 \( \mu \)m for SCT modules. The initial accuracy to which the position of the detector structures were known was \( O(1 \text{ mm}) \) within the volume of the inner detector for an entire barrel or end-cap, of \( O(100 \mu \text{ m}) \) for a single layer or disk and of \( O(10 \mu \text{ m}) \) for individual modules. Within this range track-based alignment algorithms are expected to be able to recover the remaining misalignments.

**Figure 4.7:** 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 \( \mu \)m 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-$\Delta\phi$ weak mode. The measured curvature differs from the true one while the hit residuals stay unchanged. (b) Illustration of the R$-\Delta R$ 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.

![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).](image)

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 $|d_0| < 40$ 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 $\mu$m on average. It is most pronounced for high momentum tracks and shows
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 $0.2 \text{ mrad}$ and $1 \text{ mrad}$ 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 $p_T = 20 \text{ GeV}$ 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 4.13: Mean of the $\Delta d_0$ distribution as a function of $p_T$ (a) and $d_0$ (b).

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 $|d_0| > 50 \text{ mm}$ that is due to the track missing the innermost pixel.
Track resolutions in cosmic ray data

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.

\[ \int |\vec{B} \times \vec{d}l| \]

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: 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 $\int |\vec{B} \times \vec{d}\ell|$ 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 $\sigma_{x,y} = \frac{d_{x,y}}{\sqrt{12}}$, 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:

$$\text{pull}(\lambda) = \frac{\lambda_{up} - \lambda_{low}}{\sqrt{\sigma_{\lambda_{up}}^2 + \sigma_{\lambda_{low}}^2}}$$  \hspace{1cm} (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: Comparisons between data and simulation of the Pull distributions for the resolutions of the transverse (a) and longitudinal (b) impact parameters.](image)

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 ( (\text{mm}) )</th>
<th>Data ( \pm )</th>
<th>Simulation ( \pm )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma(d_0) )</td>
<td>0.022 \pm 0.001</td>
<td>0.014 \pm 0.0002</td>
</tr>
<tr>
<td>( \sigma(z_0) )</td>
<td>0.112 \pm 0.004</td>
<td>0.101 \pm 0.001</td>
</tr>
<tr>
<td>( \sigma(\phi_0) ) (rad)</td>
<td>( (1.47 \pm 0.06) \times 10^{-4} )</td>
<td>( (1.15 \pm 0.01) \times 10^{-4} )</td>
</tr>
<tr>
<td>( \sigma(\theta) ) (rad)</td>
<td>( (8.80 \pm 0.3) \times 10^{-4} )</td>
<td>( (7.79 \pm 0.06) \times 10^{-4} )</td>
</tr>
<tr>
<td>( \sigma(q/p) ) (GeV(^{-1}))</td>
<td>( (4.83 \pm 0.16) \times 10^{-4} )</td>
<td>( (3.28 \pm 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.
Chapter 5

CHARGED PARTICLE RECONSTRUCTION
WITH PIXEL TRACKS

This thesis describes the measurement of the charged particle density\(^1\) at \(\sqrt{s} = 900\) GeV, 2.36 TeV and 7 TeV in pp collisions with the ATLAS detector. The focus will be on the analysis at \(\sqrt{s} = 2.36\) TeV using a technique that reconstructs the trajectories of charged particles with the pixel detector only. The silicon strip and straw tube detectors are used to derive the reconstruction efficiency of those pixel tracks from data. In this chapter the pixel track method is explained and the efficiency to detect charged particles with the pixel detector is determined from data. The extraction of the charged particle densities is presented in Chapter 6.

5.1 Pixel track method

The pixel track method uses tracks that are reconstructed from hits in the pixel detector only. In Figure 5.1 an event display from a pp collision with tracks reconstructed in the pixel detector is shown. It can be seen that most particles produce a hit in all pixel layers they traverse. As explained in Chapter 3, a reconstructed trajectory of a charged particle is described by five parameters \(\mathbf{\Lambda}^T = (d_0, z_0, \phi_0, \theta, q/p)\). The high hit efficiency and the low noise in the pixel detector allows in most cases to fully constrain these five parameters from the three measurement points recorded in the pixel detector as each of these hits provides a measurement in the local \(x\) and \(y\) coordinate.

The biggest uncertainty on the efficiency to reconstruct charged particles originates from the knowledge of the amount of material inside the detector. An advantage of the pixel track method is that it is only sensitive to material inside the volume of the pixel detector. To further constrain the reconstruction uncertainty the relative efficiency (\(\epsilon_{\text{rel}}\)) to find a track in the pixel detector if it was reconstructed in the silicon strip (SCT) and straw tube (TRT) detectors is used in the analysis. This relative track reconstruction

\(^1\)Primary, charged particles are defined as charged particles with a mean lifetime \(\tau > 3 \times 10^{-11}\) s directly produced in pp collisions or from the subsequent decays of particles with a shorter lifetime.
Figure 5.1: Event display of tracks recorded with the pixel barrel detector. The hits that are used in the track reconstruction are shown as bold squares. The small squares represent hits that were not assigned to a track and originate either from particles with low momentum or noise in the detector.

Efficiency is derived from data and is sensitive not only to uncertainties in the amount of material but also to disabled readout channels in the detector. The transverse momentum resolution of the pixel tracks is however limited, which makes measurements as a function of $p_T$ difficult. This is due to the smaller magnetic field integral $\int |\vec{B} \times d\vec{l}|$ for pixel tracks compared to full inner detector tracks.

An ideal case for the pixel track method was created when collisions at the centre-of-mass energy $\sqrt{s} = 2.36$ TeV were recorded with the ATLAS detector in December 2009. As it was the first time that the LHC was operated at this energy, the stable beam flag was never declared and safety measures were taken to protect the detectors. While the pixel detector was nevertheless switched on for a short period, the SCT remained in standby mode during the whole run period with a reduced bias voltage of 20 V compared to 150 V in nominal mode. As a bias voltage of approximately 70 V is needed to fully deplete the SCT [64], the efficiency to record hits was substantially lower.

The effect of the SCT in standby mode on the default track reconstruction is illustrated in Figure 5.2(a). The number of tracks using the full inner detector information with the SCT in nominal and standby mode are shown. The number of tracks is sig-
significantly reduced in the regions around $|\eta| = 0$ and 1.8, where tracks cross the barrel and end-cap modules under small incident angles. The path length ($L$) traversed by a particle in the depleted silicon with the thickness $d$ and thus the probability to record a hit depends on $\cos \alpha$, where $\alpha$ is the incidence angle of the track. The path length $L$ is smallest if a module is crossed perpendicularly ($\alpha = 0$) as can be seen in Figure 5.2(b). A precise modelling of the effects arising from the SCT in standby mode for the track reconstruction is difficult and makes the analysis of the data recorded at $\sqrt{s} = 2.36$ TeV challenging. As the pixel track method is mostly independent from the operation conditions of the SCT, these effects only have a minute influence on the analysis with the pixel track method.

![Figure 5.2](image)

**Figure 5.2:** (a) The number of tracks as a function of $\eta$ comparing nominal to standby mode of the SCT. The distributions are normalised to the number of events after trigger and data quality selection. (b) Illustration of the dependence of SCT hit efficiency on the track incidence angle when the sensor is partially depleted.

The track parameter distributions and selection efficiencies presented in this chapter will be used to perform the measurement of the charged particle densities with the ATLAS detector at $\sqrt{s} = 2.36$ TeV.
Charged particle reconstruction with pixel tracks

5.2 Data samples and track selection

5.2.1 Data samples

The data sample used for the analysis at $\sqrt{s} = 2.36$ TeV was collected with the pixel detector in nominal, but the SCT in standby mode.\(^2\) In addition, data at $\sqrt{s} = 900$ GeV with the whole inner detector at nominal settings is used and will be referred to as the reference dataset.

Table 5.1 summarises the information about the data sets. In total, only 8150 events at $\sqrt{s} = 2.36$ TeV remain for analysis after trigger and data quality criteria have been applied. This corresponds to an integrated luminosity of approximately $0.13 \pm 0.03 \mu$b\(^{-1}\).\(^3\) The data quality criteria require a reconstructed primary vertex and a high data taking efficiency of the pixel and TRT detectors. The events were triggered by Minimum Bias Trigger Scintillators (MBTS [71]) as described in Section 2.1.4.

Table 5.1: The number of events and the corresponding centre-of-mass energy after applying trigger and data quality criteria for the three runs used.

<table>
<thead>
<tr>
<th>Run</th>
<th>Energy (TeV)</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>142308</td>
<td>2.36</td>
<td>4224</td>
</tr>
<tr>
<td>142383</td>
<td>0.9</td>
<td>59498</td>
</tr>
<tr>
<td>142402</td>
<td>2.36</td>
<td>3926</td>
</tr>
</tbody>
</table>

The efficiency of the trigger was determined from data on a control sample for the analyses at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV. The control sample was selected by requiring beam presence and at least seven reconstructed space points in the pixel and SCT detectors respectively.\(^4\) The trigger efficiency was found to be $(99.75 \pm 0.03)\%$ at $\sqrt{s} = 900$ GeV [68] and at $\sqrt{s} = 7$ TeV [71]. As the data sample collected at $\sqrt{s} = 2.36$ TeV is too small to measure the trigger efficiency and the values obtained at the other two centre-of-mass energies show an almost fully efficiency trigger, the trigger efficiency is assumed to be identical to the one from the analysis at $\sqrt{s} = 900$ GeV.

5.2.2 Simulation samples

As explained in Chapter 1 and shown in Table 5.2, the fraction of diffractive events in hadron collisions is approximately 30%. In recorded events however, this fraction is strongly reduced by the event and track selection criteria, which will be explained in Section 5.2.3. A significant fraction of events at the edges of the considered phase

\(^2\)Runs 142308 and 142402 recorded on December 13th and 15th 2009.

\(^3\)The luminosity was determined using the end-caps of the LAr calorimeter. The acceptance was calculated for events where the timing difference of signals recorded in both end-caps was small [69].

\(^4\)A space point is a 3-dimensional hit representation formed from either one pixel cluster or two SCT clusters from both sides of the same module, see Section 3.2.1
space, e.g. for events with low multiplicity and low \( p_T \) tracks, is nevertheless produced by diffractive processes and may not be disregarded.

Table 5.2: The cross sections for non-diffractive (ND), double-diffractive (DD), single diffractive (SD) and all minimum bias (MB) events at \( \sqrt{s} = 900 \) GeV and \( \sqrt{s} = 2.36 \) TeV as used by the PYTHIA generator.

<table>
<thead>
<tr>
<th>Processes</th>
<th>( \sqrt{s} = 900 ) GeV</th>
<th>( \sqrt{s} = 2.36 ) TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma(ND) )</td>
<td>34.4 mb</td>
<td>40.2 mb</td>
</tr>
<tr>
<td>( \sigma(DD) )</td>
<td>11.7 mb</td>
<td>12.7 mb</td>
</tr>
<tr>
<td>( \sigma(SD) )</td>
<td>6.4 mb</td>
<td>7.7 mb</td>
</tr>
<tr>
<td>( \sigma(MB) )</td>
<td>52.5 mb</td>
<td>60.6 mb</td>
</tr>
</tbody>
</table>

One million non-diffractive, double diffractive and single diffractive events each were produced by the PYTHIA 6 [40] generator using the ATLAS MC09 [130] tune for the analysis. The events were processed with the Geant4 based ATLAS detector simulation programme [124,125] and analysed by the same algorithms as used for data. The simulation samples are used to determine detector acceptances and reconstruction efficiencies. A so-called mixed Monte Carlo sample was produced by weighting the non-diffractive, single diffractive and double diffractive components of the generated samples according to their production cross sections listed in Table 5.2. The mixed Monte Carlo sample will be referred to as Minimum Bias MC while the non-diffractive Monte Carlo samples will be labelled as MC ND for the figures shown in the following. Model dependencies on the reconstructed quantities will be discussed where applicable and systematic uncertainties will be derived from it.

5.2.3 Track reconstruction and selection

The inner detector track finding algorithms, which were explained in Chapter 3, were used to produce track segments from hits in the pixel detector - the so-called pixel tracks. Subsequently these pixel tracks are re-fit with the primary vertex as an additional measurement. This track fit is performed on a set of measurements composed of the hits in the pixel detector and the primary vertex together with their associated errors.

The pixel tracks were selected according to the following requirements, where the impact parameters were calculated with respect to the primary vertex (\( d_0^{PV} \) and \( z_0^{PV} \)):

- \( p_T > 500 \) MeV, \( |\eta| < 2.5 \),
- \( |d_0^{PV}| < 1.5 \) mm, \( |z_0^{PV} \sin \theta| < 1.5 \) mm,
- \( \geq 3 \) hits with at least one hit in the innermost pixel layer.

5983 events remain from the initial number of 8150 triggered events after the track selection criteria have been applied. Due to the re-fit with the primary vertex the impact
parameter distributions with respect to the primary vertex show narrow peaks at zero with few remaining outliers in the tails of the distributions. This makes the impact parameter requirements less powerful in rejecting tracks from non-primary interactions as only the far outliers ending up in the tails are rejected. Hence the requirement of a hit in the innermost pixel layer was introduced reducing the amount of tracks from non-primary interactions especially in the end-caps where pixel tracks typically have more than four hits on average. Here, particles produced in secondary interactions outside the innermost pixel layer could still leave three hits in the pixel detector and be reconstructed as a track (see Section 5.4.2).

To determine the relative efficiency a set of reference tracks from hits in the SCT and TRT detectors but ignoring the pixel hits entirely is needed. These SCT+TRT tracks are reconstructed with the same algorithms as the pixel tracks. The SCT+TRT tracks were required to have a transverse momentum above 500 MeV and $|\eta| < 2.5$. Furthermore a transverse impact parameter $|d_{0}^{PV}|$ below 5 mm and a longitudinal impact parameter $|z_{0}^{PV}\sin\theta|$ of less than 10 mm were required. The less stringent requirements compared to the pixel tracks originate from the somewhat limited impact parameter resolutions of the SCT+TRT tracks.

### 5.3 Tracking performance

The performance of the pixel track reconstruction is illustrated in Figure 5.3 where the track parameter distributions and the average number of hits per pixel track is shown. Data at $\sqrt{s} = 2.36$ TeV is compared to distributions from simulation. Only pixel tracks used in the analysis, i.e. pixel tracks that successfully pass the re-fit with the primary vertex, are shown. For the impact parameter distributions these pixel tracks are shown before the re-fit.

The transverse and longitudinal impact parameter distributions are reasonably well described by the simulation. However, fitting a constant line to the ratio between data and simulation yields a deviation of approximately 25% in the tails of the transverse impact parameter distribution ($|d_{0}| > 2$ mm, see Figure 5.3(a)). As these tails are sensitive to the rate of tracks from non-primary interactions, a systematic uncertainty will be estimated from this deviation. The transverse momentum distribution is measured for tracks above 500 MeV. The majority of particles has low momentum and the distribution decreases steeply towards higher values of $p_T$, which is well modelled by the simulation. The distribution of the average number of pixel hits can be understood by looking at the geometry of the pixel detector shown in Figure 2.5. In the central part, the average number of hits is slightly above three due to overlap in $\phi$ between the modules within the three layers. In the forward regions, additional hits are recorded in the pixel detector end-caps and the average number of hits rises above four. The agreement with the simulation indicates an excellent understanding of the detector geometry.

Figure 5.4 shows the $\eta$ and $p_T$ resolutions in simulation as a function of $\eta$. Pixel tracks reconstructed with and without re-fitting the primary vertex are compared to
5.3 Tracking performance

Figure 5.3: The impact parameter distributions $d_0$ (a) and $z_0 \sin \theta$ (b) with respect to the primary vertex, reconstructed $p_T$ (c) and average number of pixel hits (d) versus $\eta$ of pixel tracks in data and simulation.

The resolution is calculated from the difference between the generated and reconstructed track parameters. The pseudorapidity resolution for pixel tracks without the re-fit and full inner detector tracks are comparable because the $\eta$ resolution for both track types is dominated by the longitudinal resolution of the pixel modules. The $\eta$ resolution improves up to a factor three in the high $\eta$ region for pixel tracks using the primary vertex information. The transverse momentum resolution improves by up to factor of two. However, the $p_T$ resolution of 6% using the vertex information is still significantly worse than the 1.5% obtained for full inner detector tracks as it is dominated by the traversed magnetic field integral $\int |\vec{B} \times d\vec{l}|$.

The resolution is defined as the RMS within a 3$\sigma$ equivalent, as defined in Section 4.1 and [17].
Charged particle reconstruction with pixel tracks

Figure 5.4: (a) Comparison of $\sigma(\eta)$ as a function of $\eta$ of pixel tracks with and without primary vertex information as well as full inner detector tracks in simulation. (b) Same comparison for $p_T \times \sigma(q/p_T)$.

5.4 Selection efficiencies

5.4.1 Track reconstruction efficiency

The determination of the track reconstruction efficiency is split into two parts. First the absolute track reconstruction efficiency is derived from generated particles and their probability to be reconstructed. Subsequently the ratio of the relative efficiency of pixel tracks with respect to SCT+TRT tracks between data and simulation is used to correct the absolute efficiency.

The absolute track reconstruction efficiency $\epsilon_{\text{abs}}$ is derived from simulation and is defined as

$$\epsilon_{\text{abs}}(\eta) = \frac{N_{\text{rec,matched}}(\eta)}{N_{\text{ch}}(\eta)},$$

where $N_{\text{rec,matched}}$ denotes the number of reconstructed charged particles that pass the track selection criteria and were matched to a generated particle. $N_{\text{ch}}$ is the total number of generated particles with a mean lifetime $\tau > 3 \times 10^{-11}$ s directly produced in proton collisions with transverse momentum above 500 MeV. A pixel track is matched to a generated particle if at least 60% of its hits were produced by the corresponding generated particle. This means that for a typical pixel track at least two out of the three hits originate from the same particle. A systematic uncertainty is derived from comparing the hit matching method to a matching approach using a cone based on $\eta$ and $\phi$ around the generated particle in the following paragraph.

The dependence of the track reconstruction efficiency on the simulation is reduced by extracting a component of the track reconstruction efficiency from data. The relative track reconstruction efficiency of pixel tracks with respect to SCT+TRT tracks ($\epsilon_{\text{rel}}$) is
determined from

\[ \epsilon_{\text{rel}}(\eta) = \frac{N_{\text{matched SCT+TRT}}(\eta)}{N_{\text{SCT+TRT}}(\eta)}, \quad (5.2) \]

where \( N_{\text{matched SCT+TRT}} \) is defined by an SCT+TRT track that matches a pixel track. This matching is performed using a \( \chi^2 \) evaluated on a surface in between the pixel and SCT detectors. That way the uncertainty on the track parameters is reduced as the SCT+TRT tracks do not have to be extrapolated through a sizeable amount of material to the primary vertex. An SCT+TRT track is considered to match with a pixel track if the matching \( \chi^2 \) is smaller than 10. The \( \chi^2 \) is defined as

\[ \chi^2 = \frac{(\eta_{\text{SCT+TRT}} - \eta_{\text{pixel}})^2}{\sigma_{\eta_{\text{SCT+TRT}}}^2 + \sigma_{\eta_{\text{pixel}}}^2} + \frac{(\phi_{\text{SCT+TRT}} - \phi_{\text{pixel}})^2}{\sigma_{\phi_{\text{SCT+TRT}}}^2 + \sigma_{\phi_{\text{pixel}}}^2}, \quad (5.3) \]

where \( \eta_{\text{SCT+TRT}} - \eta_{\text{pixel}} \) and \( \phi_{\text{SCT+TRT}} - \phi_{\text{pixel}} \) are the differences in the angular parameters of the two tracks extrapolated to the surface in between the detectors. Figure 5.5 shows the two lowest matching \( \chi^2 \) values for each SCT+TRT track with a pixel track. A negligible fraction of \( \approx 0.05\% \) of the SCT+TRT tracks was matched to more than one pixel track. This fraction is illustrated by the hatched area for \( \chi^2 < 10 \), which represents the extrapolation of the background from wrong matches into the signal region.

![Figure 5.5: Comparison between data and simulation of the lowest two \( \chi^2 \) values for SCT+TRT and pixel track pairs.](image)

A comparison between the relative and absolute track reconstruction efficiency in simulation is shown in Figure 5.6. An overall inefficiency of approximately 25% is observed for the absolute efficiency in the central \( \eta \) region. The largest inefficiencies were found to originate from disabled pixel modules. This is significantly more than the 20% inefficiency of full inner detector tracks mentioned in Section 3.3 as the selection requirements on the pixel tracks are more stringent here. Around 15% of full inner detector
tracks have less than three pixel hits (see Figure 3.7) and hence cannot be reconstructed as stand-alone pixel tracks. The probability of a nuclear interaction within the pixel volume is estimated to be approximately 5% following the material description shown in Figure 3.2. Another 5% are estimated to originate from the limited momentum resolution of the pixel tracks (see Figure 5.4(b)) as particles with a generated transverse momentum above 500 MeV can be reconstructed as pixel tracks with $p_T$ below 500 MeV and are rejected. Further loss of tracks occurs due to multiple scattering and the refit of the pixel tracks with the primary vertex.

As expected, differences are observed between the relative and absolute track reconstruction efficiency. They originate from multiple scattering, nuclear interactions, particle decays and the production of tracks from secondary interactions. These processes can either increase or decrease the efficiency, depending on where they occur. The different components of the relative pixel track reconstruction efficiency are illustrated in Figure 5.7.

In general the relative efficiency is blind for decays of long lived charged particles like Σ or Ξ that can be hardly reconstructed in the detector since their $c\tau$ of several cm is too small to leave enough hits to be reconstructed as a track (see case (6) in Figure 5.7). This explains the slight difference between $\epsilon_{\text{rel}}$ and $\epsilon_{\text{abs}}$ in the central part of the detector.

The difference between $\epsilon_{\text{rel}}$ and $\epsilon_{\text{abs}}$ increases with $\eta$ reflecting the fact that more material is present in the forward region. In this region the probability rises that a

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**Figure 5.6:** Comparison of the relative and absolute pixel track reconstruction efficiency as a function of $\eta$. 

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Figure 5.7: The different cases affecting to the relative pixel track reconstruction efficiency. (1) The successful match; (2) the particle undergoes a nuclear interaction behind the pixel volume; (3) no pixel track due to disabled pixel modules or decays of long lived (charged or neutral) hadrons; (4) combination of inactive modules and nuclear interaction (the relative efficiency is blind for this category, while they appear as an inefficiency in the absolute one); (5) tracks are not matched due to multiple scattering or nuclear interactions; (6) long lived charged hadrons decay and do not leave enough hits.

track that was not reconstructed in the pixel detector (e.g. due to a disabled module) is also not reconstructed in the SCT and TRT detectors because the particle was lost due to a nuclear interaction (see case (4) in Figure 5.7). To illustrate this effect the absolute efficiency when a particle has passed through the detector without being lost due to nuclear interactions or particle decay is compared to the relative efficiency in Figure 5.8(a). It shows a slight excess of the absolute efficiency which originates from tracks from secondary interactions that are produced behind the innermost pixel layer and are hence only reconstructed as SCT+TRT tracks\(^6\) (see case (3) in Figure 5.7). Finally Figure 5.8(b) compares \(\epsilon_{\text{rel}}\) and \(\epsilon_{\text{abs}}\) with an additional veto on these tracks from secondary interactions in the SCT+TRT sample, where the agreement is good.

\(^6\)This includes the decay products of long lived neutral particles
The small residual differences in the outermost bins are believed to be due to problems in the reconstruction of the SCT+TRT tracks at very high $\eta$ which lead to an excess of SCT+TRT tracks. This has not been fully understood and will therefore be assigned as a systematic uncertainty on the track reconstruction efficiency.

As it has been shown that the relative efficiency does not fully describe the absolute track reconstruction efficiency, a combination of the relative and absolute efficiency is used. Effects caused by module inefficiencies such as disabled front end chips which are not incorporated in the simulation, alignment uncertainties and material interactions are best extracted from data using the relative efficiency. The following definition of the primary track reconstruction efficiency $\epsilon_{\text{tracking}}$ is used in the analysis:

$$\epsilon_{\text{tracking}}(\eta) = \epsilon_{\text{abs}}(\eta) \cdot \frac{\epsilon_{\text{rel}, \text{data}}(\eta)}{\epsilon_{\text{rel}, \text{MC}}(\eta)}. \quad (5.4)$$

A study on the sensitivity of the relative efficiency to the material description of the inner detector was performed on a sample where the amount of material was increased by approximately 10% in the SCT and pixel detectors. In general less tracks were reconstructed for both pixel and SCT+TRT tracks. More importantly, the fraction of SCT+TRT tracks matched to pixel tracks and hence the relative track reconstruction efficiency decreased by up to $\approx 1.5\%$ in the forward region where the amount of material is largest. As will be shown in the following paragraph the absolute track reconstruction efficiency $\epsilon_{\text{abs}}$ decreases $\approx 2\%$ in this region on the same sample. The absolute track reconstruction efficiency is thus scaled by the ratio of the relative efficiency between data
and simulation to account for possible uncertainties on how well the absolute efficiency is described by the simulation.

Figure 5.9(a) compares the relative efficiency as a function of $\eta$ in data and simulation at $\sqrt{s} = 900$ GeV. Excellent agreement between data and simulation is obtained. The shape of the distributions reflects the location of the disabled pixel modules. Both data and simulation were reconstructed with the same 3.3% of disabled pixel modules. Figure 5.9(b) compares the relative efficiency as derived from $\sqrt{s} = 900$ GeV data and $\sqrt{s} = 2.36$ TeV simulation samples. Small differences are observed between the data distributions in Figures 5.9(a) and (b) as the interaction regions of the proton beams in ATLAS were different at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 2.36$ TeV (see Figure 3.8(b)). Weights have been assigned such that the beam spot distribution of the $\sqrt{s} = 2.36$ TeV data is reproduced. The relative efficiency is well-modelled by the simulation over the full range in $\eta$.

In order to investigate possible migration effects, the resolution of the pixel tracks is studied. For this the same procedure of matching pixel tracks to SCT+TRT tracks (see Equation 5.3) as for the determination of the track reconstruction efficiency is used. By comparing the residual of the track parameters between pixel and matched SCT+TRT tracks, possible differences in the resolution between data and simulation are examined. As the $p_T$ resolution for SCT+TRT tracks is significantly better than for pixel tracks due to the larger magnetic field integral in the SCT and TRT detectors, the relative $p_T$ resolution mainly probes the resolutions of the pixel tracks. The relative $\eta$ resolution however reflects the resolution of the SCT+TRT tracks due to the better longitudinal...
hit resolution of the pixel tracks.

Figure 5.10(a) and (b) compare the relative $\eta$ and $p_T$ resolutions as a function of $\eta$ between data and simulation for pixel tracks with respect to SCT+TRT tracks. The agreement of the relative $p_T$ resolution between data and simulation is good and the measured values also agree with the absolute resolutions of the pixel tracks as shown in Figure 5.4(a). A good knowledge of the $p_T$ resolution is vital when computing the migration of low $p_T$ particles as explained in Section 5.4.3.

![Figure 5.10](image)

**Figure 5.10:** (a) Comparison between $\sigma(\eta)$ between data and simulation as a function of $\eta$. (b) Resolution of $p_T \times \sigma(q/p_T)$ as a function of $\eta$. The resolutions are derived for pixel tracks with respect to matched SCT+TRT tracks.

The relative $\eta$ resolution measured in data agrees well with the observed values in simulation. As the bin width of 0.1, which will be used for the final charged particle distributions, is significantly larger than the relative and absolute $\eta$ resolutions, effects due to bin migrations are safely neglected.

### Systematic uncertainties on the track reconstruction efficiency

Several studies have estimated the uncertainty on the amount of material in the inner detector to be less than 10% [98, 99]. The most notable study investigated differences between data and the well known mass of the $K_s$ on simulated samples with various material descriptions as shown in Figure 3.3. Another study was performed on the rate of nuclear interactions inside the detector volume which were identified by reconstructing the vertex of the nuclear interaction. The impact of the amount of material on the track reconstruction efficiency was estimated from a special sample with 10% extra material. As the efficiency changes by at most 2%, which is shown in Figure 5.11(a), this was taken as estimate for the systematic uncertainty. This can be considered as a conservative estimate as the correction of the track reconstruction efficiency with the ratio of the relative efficiencies on data and simulation is expected to account for effects due to the material distribution.
The uncertainty from the matching between generated particles and pixel tracks was investigated by studying the relative angular separation $dR = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$. A pixel track is considered as matched to its generated particle if at least 60% of the hits were generated by its associated truth particle. Figure 5.11(b) shows that all of these hit-matched tracks have a $dR < 0.035$. As an unambiguous matching result can neither be obtained with the hit-match nor with the $dR$ method, it was chosen to modify the $dR$ requirement to 0.05 and take the change in efficiency as systematic uncertainty. That way a conservative systematic uncertainty of 1% was obtained. The systematic uncertainties from the alignment are estimated to be below 1% following [111,131].

Long lived charged particles are hardly reconstructed in the detector with the given track selection requirements. The track reconstruction efficiency is sensitive to their production rate as they mainly contribute to the denominator of the absolute track reconstruction efficiency defined in Equation 5.1. Varying the amount of long lived charged particles by 40%, which is consistent with the disagreement between data and simulation in previous studies reconstructing hadron resonances [116], introduces a systematic uncertainty of 0.5%.

Figure 5.11: (a) Change in the track reconstruction efficiency as function of $\eta$ when the support structures of the pixel detector and the SCT are scaled by 10%. (b) Distance $dR$ of generated particles to hit-matched and all pixel tracks.

The remaining differences of the relative track reconstruction efficiency between data and simulation of up to 4% in the last $\eta$ bins in Figure 5.8 are assigned as systematic uncertainty in these bins. Varying the matching $\chi^2$ requirement (see Figure 5.5) resulted in a negligible change of the relative efficiency and thus no systematic uncertainty was assigned. Summing up the components in quadrature the systematic uncertainty on yields 2.5% and will compose the biggest uncertainty in the analysis of charged particle densities.
5.4.2 Tracks from non-primary particles

Tracks reconstructed from non-primary particles originate from the following sources: nuclear interactions with the beam pipe or the detector material, $\delta$ rays, photon conversions and charged particles from the decay of long lived hadrons. The sample of non-primary tracks also includes tracks that are either composed of hits from noise in the detector or tracks that share hits with various generated particles and can thus not be unambiguously matched to a single particle - denoted as fake tracks.

The fraction of fake tracks can only be investigated in simulation and is shown in Figure 5.12(a) as a function of $\eta$. Tracks are considered as fake tracks if less than 60% of the hits of the pixel track are produced by the associated generated particle. Due to the low noise occupancy in the pixel detector as shown in Figure 2.6(a), the ratio of these fake tracks is small (below $3 \cdot 10^{-3}$). Therefore their uncertainty will be combined with the uncertainty on tracks from secondary interactions.

![Fake Pixel Tracks](a)

![Secondary Tracks](b)

Figure 5.12: Fraction of pixel tracks considered as fakes (a) and of pixel tracks from secondary interactions (b).

Figure 5.12(b) compares the fraction of pixel tracks from secondary interactions with and without requiring a hit in the innermost pixel layer. Requiring a hit in the innermost pixel layer reduces the fraction of tracks from secondary interactions in the forward regions. Here more material is present and pixel tracks from an interaction outside the innermost pixel layer can also be reconstructed as the average number of pixel hits is above four (see Figure 5.3(d)). The distribution of tracks from secondary interactions including the requirement of a hit in the innermost layer follows an inverse cosine distribution of the track incidence angle. This is expected if tracks from secondary interactions are mainly produced by a homogeneous layer of material like the beam pipe. The uncertainty on the material of the beam pipe is assumed to be negligible compared to the uncertainty on the amount of material in the inner detector.

The systematic uncertainty on non-primary pixel tracks is derived from the discrepancy observed in the tails of the $d_0$ distribution ($|d_0| > 2$ mm) between data and
5.4 Selection efficiencies

Simulation (see Figure 5.3(a)) and is estimated to be 25%. The effect on the total number of tracks will be small.

5.4.3 Migration of low \( p_T \) particles

As the transverse momentum resolution of the pixel tracks is limited (see e.g. Figure 5.4(b)) and most generated particles have low \( p_T \), a significant fraction of particles with generated \( p_T < 500 \) MeV are reconstructed with a \( p_T > 500 \) MeV. This migration of low \( p_T \) particles can only be measured in simulation, hence a good understanding of the pixel track resolution in data and simulation as shown in Figure 5.10 is crucial.

Figure 5.13 compares the fraction of tracks from low \( p_T \) particles as a function of \( \eta \) for the diffractive, non-diffractive and mixed simulation samples. The fraction of tracks from low \( p_T \) particles is approximately 5% in the mixed simulation sample. For the diffractive components the ratio is twice as large since the average \( p_T \) of the produced particles is lower. The fraction of tracks from low \( p_T \) particles in the mixed simulation sample is however almost equal to the estimate from the non-diffractive sample as the diffractive components are suppressed by the event and track selection criteria.

![Figure 5.13](image)

**Figure 5.13:** (a) The fraction of tracks from low \( p_T \) particles with reconstructed \( p_T \) above and generated \( p_T \) below 500 MeV for the diffractive (SD/DD), non-diffractive (ND) and mixed simulation samples (Minimum Bias MC). (b) Comparison between data and simulation of the fraction of pixel tracks with \( p_T < 500 \) MeV matched to SCT+TRT tracks with \( p_T > 500 \) MeV.

The systematic uncertainty is derived by comparing SCT+TRT tracks, which have a good momentum resolution, with reconstructed \( p_T \) below and matched pixel tracks with \( p_T \) above 500 MeV. The minimum \( p_T \) of the SCT+TRT tracks was required to be 200 MeV. A comparison of the pseudorapidity distribution between data and simulation yields an absolute difference of approximately 1% as shown in Figure 5.13(b).
5.4.4 Primary vertex finding efficiency

The measurement of the primary vertex finding efficiency is an important aspect of the charged particle density measurement. A high efficiency is desired as events from proton collisions without a reconstructed primary vertex are not selected for analysis and have to be accounted for. The primary vertex finding strategy was discussed in detail in Section 3.4. The efficiency is calculated from data using the same sample as described in Section 5.2.1 but without requiring a reconstructed primary vertex.

The vertex reconstruction efficiency is parameterised as a function of the number of tracks passing all track selection requirements except for impact parameter requirements. As the calculation of the efficiency includes events which do not contain a primary vertex the transverse impact parameter is calculated with respect to the beam spot and required to be within $|d_{0}^{BS}| < 1.5$ mm. The multiplicity of these preselected tracks is termed $n_{BS}^{sel}$. The vertex reconstruction efficiency is also measured as a function of $\eta$ of the preselected pixel tracks. In case no primary vertex was found, the pixel tracks are fit with the mean of the beam spot as additional measurement to establish a consistent calculation of the vertex reconstruction efficiency.

Figure 5.14(a) shows a comparison of the vertex reconstruction efficiency as a function of $n_{BS}^{sel}$ between data at $\sqrt{s} = 2.36$ TeV and $\sqrt{s} = 900$ GeV. No changes to the standard track reconstruction requirements were made to account for the SCT in standby mode at $\sqrt{s} = 2.36$ TeV. Hence the efficiency for events with one selected track is lower at $\sqrt{s} = 2.36$ TeV. This has however no impact on the final analysis as the vertex reconstruction efficiency is measured on the same data set as used for the analysis.

In Figure 5.14(b) the vertex reconstruction efficiency as a function of $\eta$ of the preselected pixel tracks is shown for different track multiplicities. The efficiency for events with one selected track shows a dependence on $\eta$ although there is a non-negligible statistical error of approximately 5% per bin. For events with two selected tracks the efficiency is approximately flat at 98.6%. For higher multiplicities it is close to 100%.

![Figure 5.14](image-url)

**Figure 5.14:** The vertex reconstruction efficiency as a function of $n_{BS}^{sel}$ in data at $\sqrt{s} = 2.36$ TeV and $\sqrt{s} = 900$ GeV (a) and as a function of $\eta$ at $\sqrt{s} = 2.36$ TeV (b).
Possible contaminations from beam background events like beam gas or beam halo events were estimated by looking at the number of reconstructed vertices in events with non-colliding bunches. The contribution was found to be 1.4% for events with one reconstructed track and negligible for all other events which changes the efficiency by 0.4%. The overall vertex reconstruction efficiency is measured to be $95.8 \pm 0.03 \text{ (stat)} \pm 0.4 \text{ (syst)}\%$.

5.5 Summary

The determination of the track reconstruction efficiency is the most important aspect of the charged particle density measurement. In this chapter the extraction of this efficiency with the pixel track method was presented at a centre-of-mass of $\sqrt{s} = 2.36 \text{ TeV}$. I developed the pixel track method in order to reduce the sensitivity on the amount of material, which is the biggest systematic uncertainty of the measurement. The pixel track method makes use of tracks that are reconstructed from hits in the pixel detector only. The relative efficiency to reconstruct a pixel track if a track segment was already found in the strip and straw tube detectors is then computed on data and is used to derive the overall track reconstruction efficiency. The total systematic uncertainty on the track reconstruction efficiency was found to be 2.5%.

As the pixel tracks have a somewhat limited momentum resolution, particular attention was paid to estimate the fraction of tracks that have a true momentum below the analysis criterion of 500 MeV but are reconstructed as pixel tracks with $p_T > 500 \text{ MeV}$. The other quantities that are vital to measure the charged particle density are the trigger and vertex finding efficiencies as well as the fraction of tracks from non-primary particles, which have also been derived in this chapter.
Chapter 6

CHARGED PARTICLE DENSITY IN PP COLLISIONS

In this chapter the extraction of the inclusive charged particle density at a centre-of-mass energy of \( \sqrt{s} = 2.36 \) TeV is presented. The key ingredients to this measurement are the efficiencies to detect charged particles that were derived in Chapter 5. The measurements at \( \sqrt{s} = 900 \) GeV and \( \sqrt{s} = 7 \) TeV are presented as well. All measured charged particle densities are compared to predictions from several versions of the PYTHIA and PHOJET Monte Carlo event generators, which are based on various underlying physics models and were tuned to different data sets.

The measurement of the multiplicity and the pseudorapidity distributions at \( \sqrt{s} = 2.36 \) TeV was performed with the pixel track method as introduced in Section 5.1. However, due to the limited \( p_T \) resolution of the pixel tracks, the measurement was not performed as a function of transverse momentum. The measurement of the transverse momentum distribution at \( \sqrt{s} = 2.36 \) TeV was performed by a method complementary to the pixel track method, which uses modified versions of the reconstruction algorithms to account for the reduced hit efficiency in the SCT. This method uses information from the pixel, SCT and TRT detectors and is denoted as the standby track method [132]. The measurements at \( \sqrt{s} = 900 \) GeV and \( \sqrt{s} = 7 \) TeV were obtained with the standard track [111, 131] method that uses the default reconstruction settings and information from the pixel, SCT and TRT detectors. The results presented in this chapter have been published in the paper Charged-particle multiplicities in pp interactions measured with the ATLAS detector at the LHC [133], which has been accepted by the New Journal of Physics.

A thorough distinction has to be made between several variables that are relevant for the extraction of the charged particle densities. These most frequently used parameters are:
**Charged particle density in pp collisions**

\[
N_{ev} = \text{Total number of events with at least one primary, charged particle}
\]

\[
N_{ch} = \text{Total number of primary, charged particles}
\]

\[
n_{ch} = \text{Number of primary, charged particles per event}
\]

\[
n_{sel} = \text{Number of selected tracks per event before efficiency correction}
\]

The following distributions are measured for events containing at least one charged primary particle with \( p_T > 500 \) MeV and \( |\eta| < 2.5 \):

- **Multiplicity distribution** \( 1/N_{ev} \cdot dN_{ev}/dn_{ch} \):
  the number of events distributed over the number of charged particles per event. It is normalised to the total number of events. The total number of events \( N_{ev} \) is obtained by integrating over the non-normalised multiplicity distribution \( dN_{ev}/dn_{ch} \).

- **Pseudorapidity distribution** \( 1/N_{ev} \cdot dN_{ch}/d\eta \):
  the total number of charged particles distributed over units of pseudorapidity. This distribution is normalised to the total number of events.

- **Transverse momentum distribution** \( 1/N_{ev} \cdot 1/2\pi p_T \cdot d^2 N_{ch}/d\eta dp_T \):
  the total number of charged particles per \( \eta \) and \( p_T \) unit. This distribution is normalised to the total number of events \( N_{ev} \) and by \( 1/2\pi p_T \) to ensure Lorentz invariance.

### 6.1 Analysis method

The uncorrected distributions obtained from the reconstruction algorithms are the starting point of the analysis. These include the number of selected tracks as a function of pseudorapidity and the number of selected events as a function of the track multiplicity. The efficiencies to detect charged particles are used to extract the corrected charged particle density. These efficiencies were discussed in detail in Section 5.4 for the pixel track method and are derived similarly for the other methods.

In the following, the procedure to obtain the multiplicity and the pseudorapidity distributions is explained. The correction procedure is similar for all methods, only the values and the parametrisations of the efficiencies are different. As all distributions are normalised to the total number of events, \( N_{ev} \) is derived first by integrating over the corrected multiplicity distribution. Subsequently the normalised multiplicity and pseudorapidity distributions are derived. An important step in verifying the correction procedure and probing its precision is a consistency check on simulated samples. Such a check is performed by executing the full chain of the correction procedure and comparing the results with the generated multiplicities. These consistency checks are performed for the multiplicity and pseudorapidity distributions.

### 6.1.1 Multiplicity distribution

The corrected multiplicity distribution is derived from the number of selected events \( N_{ev,sel} \), which is the distribution of the number of events as a function of the number
of selected tracks per event \( n_{\text{sel}} \). This distribution has to be transformed to the \( N_{\text{ev, ch}} \) distribution, which describes the corrected number of events \( N_{\text{ev}} \) as a function of the number of charged particles per event \( n_{\text{ch}} \).

First, events lost due to trigger and vertex reconstruction inefficiencies are accounted for by applying a weight to every event. This weight is assigned according to the ratio of total and selected events as a function of the number of selected tracks:

\[
w_{\text{ev}}(n_{\text{BS sel}}) = \frac{N_{\text{ev}}(n_{\text{BS sel}})}{N_{\text{sel}}(n_{\text{BS sel}})} = \frac{1}{\epsilon_{\text{trig}}(n_{\text{BS sel}})} \cdot \frac{1}{\epsilon_{\text{vtx}}(n_{\text{BS sel}})},
\]

(6.1)

where \( \epsilon_{\text{trig}}(n_{\text{BS sel}}) \) and \( \epsilon_{\text{vtx}}(n_{\text{BS sel}}) \) are the trigger and vertex reconstruction efficiencies as a function of the number of selected tracks \( n_{\text{BS sel}} \) for which the track parameter requirements were applied with respect to the beam spot (see Section 5.4.4).

The resulting distribution now corresponds to the total number of events \( N_{\text{ev}} \), but is still computed as a function of the number of selected tracks per event \( n_{\text{sel}} \). This number differs from the number of primary, charged particles per event \( n_{\text{ch}} \) as charged particles can be lost due to track reconstruction inefficiencies or additional tracks can be reconstructed from secondary interactions or decays of long-lived hadrons. These effects are corrected for with a Bayesian unfolding technique [134] using a correction matrix \( M_{\text{ch, sel}} \), which expresses the probability that a particular multiplicity of selected tracks \( n_{\text{sel}} \) is due to a true multiplicity of \( n_{\text{ch}} \) particles. Hence the track reconstruction efficiency as well as effects from secondary interactions with the detector material or decays of long lived hadrons are included in the correction matrix. An illustration of \( M_{\text{ch, sel}} \) is shown in Figure 6.1(a). \( M_{\text{ch, sel}} \) is obtained from simulated samples and is applied to the vector with the number of events for a given \( n_{\text{sel}} \left(N_{\text{ev, sel}}\right)\) to obtain the vector with the number of events as a function of \( n_{\text{ch}} \left(N_{\text{ev, ch}}\right)\):

\[
N_{\text{ev, ch}} = M_{\text{ch, sel}} N_{\text{ev, sel}}.
\]

(6.2)

To minimise the model dependence from the simulated samples, \( M_{\text{ch, sel}} \) was subsequently re-populated with the resulting distributions and the matrix correction was re-applied. This procedure was repeated and converged after three iterations when the change with respect to the previous iteration was found to be smaller than 1%. Figure 6.1(b) shows the ratio of the result with respect to the previous iteration as a function of \( n_{\text{ch}} \).

The matrix procedure cannot correct for entire events that are triggered and have a reconstructed vertex, but do not contain a track that matches the selection criteria. In these events one or more charged particles are produced but not reconstructed due to track reconstruction inefficiencies. Hence the entire event is not selected. A simplified Monte Carlo study was performed to estimate the influence on the multiplicity distribution. In Figure 6.2 the generated multiplicity distribution is compared to the same distribution where 25% of the hadrons are randomly discarded. This leads to a decrease of the total number of events of about 5% in the Monte Carlo sample: 25% of the events with one generated hadron, \( (25\%)^2 \) of events with two generated hadrons and so forth.
Figure 6.1: (a) Correction matrix $M_{\text{ch,sel}}$ containing the probability that a number of selected tracks $n_{\text{sel}}$ is due to $n_{\text{ch}}$ generated charged particles. (b) Change in the ratio of the obtained $n_{\text{ch}}$ distribution with respect to the previous iteration.

Figure 6.2: Generated charged particle spectrum (solid line) and generated charged particle spectrum with simulated loss of events due to track reconstruction inefficiency (dashed line).

A correction factor is applied to the number of events as a function of $n_{\text{ch}}$ to account for the events that were not selected due to track reconstruction inefficiencies:

$$w_{\text{ev,lost}}(n_{\text{ch}}) = \frac{1}{1 - (1 - \langle \epsilon \rangle)^{n_{\text{ch}}}}.$$  \hspace{1cm} (6.3)

As the track reconstruction efficiency for events without selected tracks is unknown, the average track reconstruction efficiency $\langle \epsilon \rangle$ is used for the correction. $\langle \epsilon \rangle$ was found to be $(75.4 \pm 0.0 \text{ (stat)} \pm 2.5 \text{ (syst)})\%$ for the pixel track method (see Section 5.4.1).
After applying the corrections described above the integral of the multiplicity distribution is computed to obtain the total number of events \(N_{\text{ev}}\). In a following step the multiplicity distribution \(dN_{\text{ev}}/dn_{\text{ch}}\) is normalised by \(N_{\text{ev}}\) to obtain the normalised multiplicity distribution \(1/N_{\text{ev}} \cdot dN_{\text{ev}}/dn_{\text{ch}}\).

Figure 6.3 shows the consistency check of the multiplicity distribution on a logarithmic and a linear scale. The uncorrected multiplicity distribution, which is computed as a function of the number of selected tracks per event \(n_{\text{sel}}\), is compared to the corrected and the generated distributions, which are both computed as a function of the number of charged particles per event \(n_{\text{ch}}\). The maximum is observed for events with one charged particle. The distributions are rapidly decreasing towards higher values of \(n_{\text{ch}}\). The agreement of the generated with the corrected distribution is good for high as well as low multiplicities. Small differences are only observed in the bin with one charged particle. This is due to the fact that the average track reconstruction efficiency for events without selected tracks (see Equation 6.3) cannot be determined exactly. The discrepancy is however compatible within the systematic error that will be assigned to account for the uncertainty on the track reconstruction efficiency.

The successful consistency check verifies that the correction procedure explained above yields the correct multiplicity distribution over the full range.

### 6.1.2 Pseudorapidity distribution

To compute the pseudorapidity distribution the total number of produced charged particles \(N_{\text{ch}}\) has to be extracted from the total number of selected tracks \(N_{\text{sel}}\). This includes
charged particles that are produced in events that are not selected due to trigger and
vertex reconstruction inefficiencies. Hence the trigger and vertex reconstruction efficien-
cies are computed as a function of $\eta$ of the selected tracks (see Figure 5.14(b)) and
applied as weights to these selected tracks:

$$w_{ev, trk}(\eta) = \frac{1}{\epsilon_{\text{trig}}(\eta)} \cdot \frac{1}{\epsilon_{\text{vtx}}(\eta)}.$$ (6.4)

The weight assigned to the selected tracks that accounts for the track reconstruc-
tion efficiency $\epsilon_{\text{tracking}}$ (see Equation 5.4), the fraction of tracks from non-primary par-
ticles $f_{\text{non-prim}}$ (see Section 5.4.2) and the migration of low $p_T$ particles $f_{\text{lowpT}}$ (see
Section 5.4.3) is

$$w_{trk}(\eta) = \frac{1}{\epsilon_{\text{tracking}}(\eta)} \cdot (1 - f_{\text{non-prim}}(\eta) - f_{\text{lowpT}}(\eta)).$$ (6.5)

While the correction due to the track reconstruction efficiency leads to a higher num-
ber of charged particles compared to selected tracks, the corrections for the migration
from low $p_T$ particles and tracks of non-primary particles decrease this number. After
applying these corrections the multiplicity distribution is normalised by the total number
of events $N_{ev}$ as derived in Section 6.1.1.

Figure 6.4: Consistency check for the pseudorapidity distribution with the pixel track
method. The uncorrected distribution is compared to the corrected and generated dis-
tributions in simulation.

Figure 6.4 shows the consistency check for the charged particle pseudorapidity dis-
tribution in simulation. The corrected and the generated distributions are nearly flat in
the central region and decrease in the forward regions. The predicted average value of
6.2 Charged particle densities at $\sqrt{s} = 2.36$ TeV

The measurement of the charged particle densities was performed on a dataset composed of 8150 events collected in December 2009 as explained in Section 5.2.1.

The pixel track method is used to compute the charged particle multiplicity and the pseudorapidity distribution while the standby track method is used to derive the multiplicity as a function of transverse momentum. In addition to the consistency checks performed in the previous section, results with the pixel track method on the reference data sample taken at $\sqrt{s} = 900$ GeV are presented. The results obtained on this sample are compared to the published measurement with the standard track method, which is based on full inner detector tracks.

Table 6.1: Summary of Minimum Bias tunes. Besides the PDFs and the parton showering mechanism, the main data sets and physics processes to produce the tunes are displayed.

<table>
<thead>
<tr>
<th>Tune</th>
<th>PDFs</th>
<th>Parton showering</th>
<th>Data sets</th>
<th>Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS MBT1</td>
<td>MRST LO*</td>
<td>$p_T$</td>
<td>ATLAS ($\sqrt{s} = 0.9, 7$ TeV)</td>
<td>Minimum Bias</td>
</tr>
<tr>
<td>ATLAS MC09</td>
<td>MRST LO*</td>
<td>$p_T$</td>
<td>CDF run I ($\sqrt{s} = 1.8$ TeV)</td>
<td>Underlying event, Minimum Bias</td>
</tr>
<tr>
<td>DW</td>
<td>CTEQ5L</td>
<td>virtuality (mass)</td>
<td>CDF run II ($\sqrt{s} = 1.96$ TeV)</td>
<td>Drell-Yan, Underlying event</td>
</tr>
<tr>
<td>PYTHIA 8</td>
<td>CTEQ5L</td>
<td>$p_T$</td>
<td>E735 ($\sqrt{s} \leq 1.8$ TeV)</td>
<td>Minimum Bias, Underlying event</td>
</tr>
</tbody>
</table>

The extracted charged particle density in this section is compared to predictions from Monte Carlo simulation that were produced by the PYTHIA and PHOJET event generators. Table 6.1 gives an overview of the main properties of the PYTHIA tunes. These PYTHIA tunes include PYTHIA 8 [135], the DW [136] tune, the ATLAS MC09 [130] tune and the ATLAS MBT1 tune [137], which is an update of the ATLAS MC09 tune based on the measurements of the charged particle densities at $\sqrt{s} = 900$ GeV and...
\(\sqrt{s} = 7 \text{ TeV}\). More information about the Monte Carlo models and event generators are given in Sections 1.4 and 1.5.

The exact values of the tunable parameters obviously depend on the choice of the PDFs. In general, one picks a set of PDFs and then tunes the individual parameters to these PDFs. The MRST LO* [138] leading order parton distributions were chosen for the most recent ATLAS tunes as they provide a better description of physics processes when using a modified leading order Monte Carlo generator such as Pythia. For the Pythia 8 tune, the default PDFs from version 8.130 were used (CTEQ5L) as this version has not been extensively tuned to data yet. The other Pythia tunes use version 6. The predictions of the charged particle density are expected to vary as the tunes were derived from different data sets and the focus was put on different physics processes.

### 6.2.1 Multiplicity distribution

The corrected multiplicity distribution for events with at least one charged particle in the kinematic range \(p_T > 500 \text{ MeV} \) and \(|\eta| < 2.5\) at \(\sqrt{s} = 2.36 \text{ TeV}\) is shown in Figure 6.5. Additionally, predictions of Monte Carlo models tuned to a wide range of measurements are displayed. The vertical bars around the data points represent the statistical uncertainties, while the shaded areas show the combined statistical and systematic uncertainties. The curves represent the predictions from the various Monte Carlo models.

The multiplicity distribution has its maximum for events with one reconstructed charged particle and decreases steeply towards higher multiplicities. Not surprisingly, the best agreement with the Monte Carlo predictions is obtained by the Pythia ATLAS MBT1 tune as this tune was produced from the measurements at \(\sqrt{s} = 900 \text{ GeV}\) and \(\sqrt{s} = 7 \text{ TeV}\) where the contribution from diffractive events was suppressed. The predictions from the ATLAS MC09 tune also agree within the systematic uncertainties. All other tunes except PHOJET predict higher values at low \(n_{ch}\) and lower values at high \(n_{ch}\).

#### Systematic uncertainties

The systematic uncertainties on the multiplicity distribution and the total number of events are strongly correlated as the total number of events \(N_{ev}\) is obtained by integrating the corrected multiplicity distribution \(dN_{ev}/dn_{ch}\). The systematic uncertainties were derived by varying the various selection efficiencies in the range of their combined statistical and systematic uncertainties. The resulting relative differences on the results are taken as the overall systematic uncertainties and are quoted in the following. The uncertainties on the selection efficiencies were derived in Section 5.4 and the main ingredients are briefly summarised here.

Several tests were made to assess the model dependence of the correction matrix \(M_{ch,sel}\). Varying the cross sections of the diffractive and non-diffractive components ac-

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1 The following Pythia versions were used: 6.2 (DW tune), 6.4 (MC09, AMBT1) and 8.1 (Pythia 8).
6.2 Charged particle densities at $\sqrt{s} = 2.36$ TeV

Figure 6.5: Charged particle multiplicity distribution measured at $\sqrt{s} = 2.36$ TeV for charged particles with $p_T > 500$ MeV and $|\eta| < 2.5$. The dots represent the data and the curves the predictions from different Monte Carlo models. The vertical bars represent the statistical uncertainties, while the shaded areas show statistical and systematic uncertainties added in quadrature.

According to the predictions from the Phojet generator in the simulation modifies the correction matrix and yields a sizeable systematic uncertainty on the lower bins of the multiplicity distribution. The total number of events, however, varies by only 0.1%.

As the track reconstruction efficiency was not parameterised as a function of selected tracks per event and is unknown for events without selected tracks, a slightly higher uncertainty of 3% was assumed than derived in Section 5.4.1. This introduces a systematic uncertainty over the whole range of the multiplicity distribution and the total number of events changes by 0.5%. The statistical uncertainty on the total number
of events was found to be 1.3%, which was derived from the 5983 events with at least one reconstructed pixel track.

The various sources of uncertainties on the total number of events are summarised in Table 6.2. All sources are assumed to be uncorrelated and added in quadrature. The combined statistical and systematic uncertainty on \( N_{\text{ev}} \) is found to be 1.4%.

Table 6.2: Uncertainties on the number of events \( N_{\text{ev}} \). All sources are assumed to be uncorrelated.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex reconstruction efficiency</td>
<td>0.4%</td>
</tr>
<tr>
<td>Track reconstruction efficiency</td>
<td>0.5%</td>
</tr>
<tr>
<td>Different Monte Carlo Tunes</td>
<td>0.1%</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>1.3%</td>
</tr>
<tr>
<td><strong>Total uncertainty on ( N_{\text{ev}} )</strong></td>
<td><strong>1.4%</strong></td>
</tr>
</tbody>
</table>

### 6.2.2 Pseudorapidity and momentum distribution

The pseudorapidity distribution obtained at \( \sqrt{s} = 2.36 \) TeV is shown in Figure 6.6. It is measured to be approximately flat in the range \( |\eta| < 1.5 \) and decreases towards higher values. The best agreement is again achieved by the ATLAS MBT1 tune, although it predicts slightly lower values than observed. The difference is however compatible within the systematic uncertainties of the data points as the uncertainties are fully correlated. Good agreement is also reached with the ATLAS MC09 tune while the other predictions differ by at least 10% from the measured values. The plateau in the central region and the slight drop off in the forward regions of the pseudorapidity distribution are well predicted by all Monte Carlo models except the \textsc{Pythia} DW tune.

The transverse momentum distribution measured with the standby track method is shown in Figure 6.7. As predicted by the Monte Carlo models most reconstructed particles have low \( p_T \) and the distribution decreases rapidly towards higher transverse momenta. The predictions of the Monte Carlo models and the measured values agree mostly within the uncertainties, especially for lower transverse momenta.

### Systematic uncertainties

Varying the various selection efficiencies by their combined statistical and systematic uncertainties yields the systematic uncertainties on the pseudorapidity and the momentum distributions. The systematic uncertainties on the pseudorapidity distribution were taken from Section 5.4 and are briefly summarised below. The momentum distribution is subject to additional systematic uncertainties due to corrections for the reduced hit efficiency of the SCT which are discussed in [132]. The various contributions to the
systematic uncertainty on the charged-particle density at central pseudorapidity are summarised in Table 6.3.

The largest systematic uncertainty on the pseudorapidity measurement arises from the track reconstruction efficiency. The uncertainty on the amount of material in the inner detector, the matching of reconstructed tracks to generated particles and other uncertainties like the alignment precision and the amount of long-lived charged hadrons result in an absolute uncertainty on the track reconstruction efficiency of 2.5%, which changes the pseudorapidity distribution by 3.4% on average.

The uncertainty on the number of tracks due to migration of low $p_T$ particles was derived by a comparison between data and simulation. The distributions of tracks which are reconstructed in the SCT+TRT detectors with $p_T$ below 500 MeV but as pixel tracks

\[ n_{ch} \geq 1, p_T > 500 \text{ MeV}, |\eta| < 2.5 \]
Figure 6.7: Charged particle transverse momentum distribution measured at $\sqrt{s} = 2.36$ TeV for particles with $p_T > 500$ MeV and $|\eta| < 2.5$.

with $p_T$ above 500 MeV were investigated. The observed absolute difference of 1% was assigned as uncertainty and translates into a relative uncertainty on the pseudorapidity distribution of 1.1%.

The uncertainty on the fraction of tracks from non-primary particles was estimated from the tails of the transverse impact parameter distribution ($|d_0| > 2$ mm) as this region is sensitive to particles that do not originate from the primary vertex. Fitting a constant line to the ratio between data and simulation of the transverse impact parameter distribution yields a discrepancy of 25%, which varies the pseudorapidity distribution by 0.6%.

All sources of systematic uncertainties are assumed to be uncorrelated and added in quadrature except for the uncertainty on the track reconstruction efficiency. This is
6.2 Charged particle densities at $\sqrt{s} = 2.36$ TeV

Table 6.3: Summary of systematic uncertainties on the pseudorapidity distribution for $|\eta| < 0.5$. The uncertainty on $N_{ev}$ due to the track reconstruction efficiency is anti-correlated to the uncertainty on the pseudorapidity distributions. All other sources are assumed to be uncorrelated.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger and Vertex reconstruction efficiency</td>
<td>0.1%</td>
</tr>
<tr>
<td>Track reconstruction efficiency</td>
<td>3.4%</td>
</tr>
<tr>
<td>Low $p_T$ tracks</td>
<td>1.1%</td>
</tr>
<tr>
<td>Non-primary particles</td>
<td>0.6%</td>
</tr>
<tr>
<td>Correlated Uncertainty on $N_{ev}$</td>
<td>-0.5%</td>
</tr>
<tr>
<td>Uncorrelated Uncertainties from $N_{ev}$</td>
<td>1.3%</td>
</tr>
<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td><strong>3.5%</strong></td>
</tr>
</tbody>
</table>

because the pseudorapidity distribution is divided by the total number of events and both the total number of events and the measured particle multiplicity increase if the track reconstruction efficiency decreases. Hence these uncertainties on the number of events and on the pseudorapidity distributions are treated as anti-correlated.

Taking into account the statistical and systematic uncertainties, the measured charged particle density for particles with $p_T > 500$ MeV at central pseudorapidity ($|\eta| < 0.5$) is:

$$(1/N_{ev} \cdot dN_{ch}/d\eta) \big|_{|\eta|<0.5} = 1.739 \pm 0.019 \text{ (stat) } \pm 0.058 \text{ (syst)}$$

The estimated errors on this result at central pseudorapidity are dominated by the systematic uncertainty as it was obtained by averaging over one unit of pseudorapidity. The precision of the distributions with the binning as shown in Figure 6.6 is however limited by the statistical uncertainty arising from the limited size of the data set. A more precise determination of the systematic uncertainties would not considerably improve the precision of the data points shown.

6.2.3 Pixel track method at $\sqrt{s} = 900$ GeV

In addition to the consistency checks on simulated samples, the pixel track method was compared to the previously published measurement of the charged particle density at $\sqrt{s} = 900$ GeV [111]. In this data set, information from the full inner detector was available and the standard track method was used. At this point, these results are used as cross-check, but will be discussed in detail in Section 6.3.

Figure 6.8(a) compares the charged particle multiplicity distribution obtained on the reference data sample at $\sqrt{s} = 900$ GeV (see Section 5.2.1) to the previously published measurement. The previously published measurement is shown with systematic uncertainties while the errors of the distribution with the pixel track method only shows
statistical uncertainties. Good agreement is obtained over the full range. The small discrepancy for events with one charged particle arises from the difficult determination of the track reconstruction efficiency here.

In Figure 6.8(b) the comparison of the pseudorapidity distribution between the pixel track method and the measurement with the standard track method is shown. Good agreement is obtained between the two distributions and the remaining discrepancies can be attributed to the statistical uncertainties due to the limited size of the reference data sample.

**Figure 6.8:** Comparison between the multiplicity (a) and the pseudorapidity (b) distributions measured by the pixel track method at $\sqrt{s} = 900$ GeV and the published results at $\sqrt{s} = 900$ GeV. The ratios of the measured values to the published result is shown below the distributions. The blue bands correspond to the systematic uncertainties on the published result.

### 6.3 Charged particle multiplicities at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV

Measurements of the charged particle density were also performed at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV for particles with transverse momenta above 500 MeV and are presented in the following. As the results are compared to the same Monte Carlo models as before, the observed behaviour of data and simulation at $\sqrt{s} = 2.36$ TeV is either supported or contradicted by the measurements at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV. This allows for a more conclusive interpretation of the results spanned over a wide range of centre-of-mass energies.
Understanding the track reconstruction for particles with a $p_T$ smaller than 500 MeV is challenging since the amount of tracks is significantly higher and the particles undergo for example more multiple scattering. The measured selection efficiencies are thus more sensitive to the description of the amount of material inside the inner detector. Measurements with the $p_T$ threshold lowered to 100 MeV have been performed at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV \cite{139} and are discussed in Appendix A.

As mentioned above, the results presented here were produced with the standard track method. The main difference with respect to the pixel track method is the definition of the track reconstruction efficiency. While the pixel track method derives a part of the efficiency from the data itself (see Section 5.4.1), the standard track method relies completely on simulated samples. The $p_T$ resolution is however considerably better for standard tracks making a measurement of the charged particle multiplicities as a function of transverse momentum possible. The correction procedure to obtain the final distribution is similar to the procedure described in Section 6.1 for the pixel track method.

Figure 6.9: Charged particle multiplicity $1/N_{\text{ev}} \cdot dN_{\text{ev}}/dn_{\text{ch}}$ distribution measured at $\sqrt{s} = 900$ GeV (a) and $\sqrt{s} = 7$ TeV (b) for charged particles with $p_T > 500$ MeV and $|\eta| < 2.5$ on a logarithmic scale.

Figure 6.9 shows the corrected multiplicity distribution as a function of the number of
charged particles per event. The integrated luminosities of the data samples are \( \approx 7 \, \mu\text{b}^{-1} \) at \( \sqrt{s} = 900 \, \text{GeV} \) and \( \approx 9 \, \mu\text{b}^{-1} \) at \( \sqrt{s} = 7 \, \text{TeV} \). Only events with at least one charged particle with a \( p_T \) above 500 MeV were selected.

At both energies the highest fraction of events is measured for events containing one charged particle. The distributions decrease rapidly towards higher values of \( n_{\text{ch}} \). The \textsc{Pythia} models show an excess of events with \( n_{\text{ch}} = 1 \) with respect to the data as can be seen from the ratio of the Monte Carlo prediction to the measured values. For events with higher multiplicity (\( n_{\text{ch}} \gtrsim 10 \)) however, the predicted fraction of events is consistently lower than the data. The net effect is that the integral number of charged particles estimated by the Monte Carlo models are below that of the data. The \textsc{Phojet} generator models the number of events with \( n_{\text{ch}} = 1 \) better. However, the estimate for multiplicities up to \( n_{\text{ch}} \approx 10 \) are substantially higher and the predictions for multiplicities of \( n_{\text{ch}} > 20 \) are substantially lower than the measured values.

The corrected pseudorapidity distributions are shown in Figure 6.10 together with the predictions from various Monte Carlo models. Similar to the charged particles multiplicities at \( \sqrt{s} = 2.36 \, \text{TeV} \) the dominant systematic uncertainty is the uncertainty on the track reconstruction efficiency. The average values of charged particles per event

**Figure 6.10:** Charged particle pseudorapidity distribution \( 1/N_{\text{ev}} \cdot dN_{\text{ch}}/d\eta \) measured at \( \sqrt{s} = 900 \, \text{GeV} \) (a) and \( \sqrt{s} = 7 \, \text{TeV} \) (b) for charged particles with \( p_T > 500 \, \text{MeV} \).
6.3 Charged particle multiplicities at \( \sqrt{s} = 900 \text{ GeV} \) and \( \sqrt{s} = 7 \text{ TeV} \)

and unit of pseudorapidity in the range \( |\eta| < 0.2 \) are \( 1.333 \pm 0.003 \text{ (stat)} \pm 0.040 \text{ (syst)} \) \( (\sqrt{s} = 900 \text{ GeV}) \) and \( 2.418 \pm 0.004 \text{ (stat)} \pm 0.076 \text{ (syst)} \) \( (\sqrt{s} = 7 \text{ TeV}) \). All predictions from the Monte Carlo models shown are lower than the data by 5% to 15% at \( \sqrt{s} = 900 \text{ GeV} \) and up to 25% at \( \sqrt{s} = 7 \text{ TeV} \). The predicted shapes of the pseudorapidity distribution are approximately consistent with the data except for the curves from the PYTHIA DW tune.

The transverse momentum distributions are shown in Figure 6.11. The distributions decrease steeply towards higher values of \( p_T \) at both energies. The transverse momentum distributions are reasonably described by the predictions from the Monte Carlo models up to approximately 1 GeV. For transverse momenta between 1 GeV and 10 GeV the measured distributions are significantly below all the Monte Carlo predictions with the ATLAS MBT1 tune giving the smallest discrepancies. For \( p_T \) values above approximately 10 GeV the ratio between the Monte Carlo predictions and the measured values decreases again. In this region, the measured transverse momentum distribution is well predicted by PHOJET.

![Figure 6.11: Charged particle transverse momentum multiplicity distribution 1/\( N_{ev} \) \cdot 1/(2\pi p_T) \cdot d^2 N_{ch}/d\eta dp_T \) measured at \( \sqrt{s} = 900 \text{ GeV} \) (a) and \( \sqrt{s} = 7 \text{ TeV} \) (b) for charged particles with \( p_T > 500 \text{ MeV} \) and \( |\eta| < 2.5 \) on a double-logarithmic scale.](image)
6.4 Discussion

Comparisons between the measured charged particle density and the predictions from various Monte Carlo models yield common observations at the three centre-of-mass energies $\sqrt{s} = 900$ GeV, $\sqrt{s} = 2.36$ TeV and $\sqrt{s} = 7$ TeV.

The measurement of the pseudorapidity distribution as shown in Figures 6.6 and 6.10 does not only provide the angular distribution of the charged particles, but also the absolute multiplicity is extracted by taking the average value of the distribution. It turns out that, at all centre-of-mass energies, the Monte Carlo models predict a lower multiplicity than measured with differences of up to 25%. The estimates from the ATLAS MC09 and MBT1 tunes however were found to be compatible within the uncertainties of the measurements. This is not surprising as the ATLAS MBT1 tune was produced from a data set recorded with ATLAS at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV. The events were however required to contain at least six charged particles particles with a $p_T$ above 500 MeV tuning only the non-diffractive component effectively. The remaining discrepancies are believed to originate from the prediction of diffractive events. The modelling of the shape of the distributions with a plateau in the region of $|\eta| < 1.5$ showing a small dip around $\eta \approx 0$ and a steeper decrease towards higher values of $\eta$ is nearly identical for all tunes. The only exception is the PYTHIA DW tune, which predicts a shallower drop off at high $|\eta|$.

When looking at the curves from the predictions of the multiplicity distribution in Figures 6.5 and 6.9, it is notable that the PHOJET generator predicts a lower multiplicity for $n_{ch} = 1$ than for $n_{ch} = 2$, which is in contrast to the other Monte Carlo models. I think that this is connected to the different underlying physics model, which is a combination of the Dual Parton Model [59] and perturbative QCD and describes especially very soft processes differently from PYTHIA. Due to the large uncertainty on the measurement in the low $n_{ch}$ bins and the different analysis methods used to extract the results, this feature can however not be confirmed in the data. While the results obtained with the standard track method at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV seem to confirm the behaviour of PHOJET at low $n_{ch}$, the ATLAS MBT1 and MC09 tunes describe the measurement best at $\sqrt{s} = 2.36$ TeV obtained with the pixel track method. For higher values of $n_{ch}$, the predictions of PHOJET and PYTHIA DW on the one hand and of the other PYTHIA tunes on the other hand show the same trend. The reason for this is probably the ordering variable used for the parton showering, which describes the radiation of quarks and gluons from the final state partons. PHOJET and PYTHIA DW use the virtual mass of the parton as ordering variable while the other PYTHIA tunes use the $p_T$ of the parton. Differences are also observed between the particular analysis methods when comparing the measured multiplicities to the predictions at the three centre-of-mass energies. While no Monte Carlo model describes the multiplicity distributions obtained with the standard track method at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV correctly over the whole range, the distribution measured at $\sqrt{s} = 2.36$ TeV with the pixel track method closely follows the predictions of the ATLAS MBT1 and MC09 tunes.

Similar differences as for the multiplicity distribution are seen for the transverse momentum distributions in Figures 6.7 and 6.11. The estimates of the Monte Carlo
models can again be separated in virtuality and $p_T$ ordered tunes. While the measured values at the three centre-of-mass energies are higher than the predictions of the PHOJET and PYTHIA DW tunes over the full range, the predictions of the $p_T$ ordered PYTHIA tunes are mostly below the measured values for low $p_T$ and exceed the data points at high $p_T$. However, the transition point is at different $p_T$ values for the $p_T$ ordered PYTHIA tunes.

In summary, none of the Monte Carlo models provided a very good prediction for all the distributions measured. Different data sets and measured quantities have been used to produce the Monte Carlo tunes and hence diverse predictions of the charged particle density are expected. Furthermore, diffractive processes, which constitute a significant fraction of the events in the edges of the phase space (e.g. at low $p_T$ or low $n_{ch}$), are hard to model and little data exists to tune the models. In general the best agreement was obtained with the ATLAS MBT1 tune as it was produced by tuning the ATLAS MC09 tune to a data set recorded at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV. However, the contribution of diffractive events was suppressed in this data set and hence small differences between the predictions from the ATLAS MBT1 tune and the measured multiplicities are observed.

Similar trends were observed for Monte Carlo models that use the same ordering variable for parton showering. In general the predictions from the $p_T$ ordered tunes were closer to the measurements than the ones from the virtuality ordered tunes. The ordering variable is connected to the model of multiple interactions implemented in PYTHIA, as they generally depend on the $p_T$ of the produced partons. Multi-parton interactions can thus be implemented more consistently if the $p_T$ is used as ordering variable for the parton showering [40].

The optimisation of the Monte Carlo models also has implications on other physics analyses performed at the LHC, in particular on the investigation of high-$p_T$ scattering processes where the production of charged particles can be a direct background for the measurement. Moreover, an improved understanding of the Monte Carlo models might cause different predictions of the behaviour of signal and background distributions in an analysis. For example the measurement of the inclusive jet production cross section [140] is directly affected by the amount of produced particles that are identified as a jet. Other influences can arise on variables like the missing transverse energy of an event [141]. The missing transverse energy is an important variable in analyses of top quark production or searches for physics beyond the Standard Model like supersymmetric models. If the amount of produced particles and their energy exceed the predictions from Monte Carlo models, differences might be observed between the measured missing transverse energy and the predictions from Monte Carlo models that have to be accounted for.

6.5 Conclusion

The measurement of the charged particle density for events containing at least one charged particle with a transverse momentum above 500 MeV has been presented at centre-of-mass energies of $\sqrt{s} = 900$ GeV, 2.36 TeV and 7 TeV. The key prerequisite
for this measurement is the understanding of the track and vertex reconstruction with the inner detector. The charged particle density has also been studied with a lowered transverse momentum threshold of 100 MeV at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV. All results are summarised in Figure 6.12.

![Graph showing charged particle density](image)

**Figure 6.12:** Comparison between the measured charged particle density at central pseudorapidity and the predictions from different Monte Carlo tunes as a function of the centre of mass energy.

Most of the charged particles at hadron colliders are produced by soft QCD processes. As the strong coupling constant $\alpha_s(Q^2)$ becomes too large to calculate these processes in perturbation theory, Monte Carlo models rely on phenomenological approaches. As these models are tuned to different data sets at various centre-of-mass energies, the observed differences between the measured multiplicities and their predictions are not surprising. Primarily the measurements presented in this thesis are used to understand and further develop Monte Carlo models. The goal is to describe the observed distributions in an energy regime that became accessible for the first time at the LHC while and yet remain valid in the energy ranges of other hadron colliders.
Precise models of inclusive charged particle production are also important for analyses investigating high-\(p_T\) scattering processes. Measurements can be either directly sensitive to the produced amount of charged particles like the inclusive jet cross section or the analyses can rely on variables that are in turn influenced by the charged particle multiplicities like the missing transverse energy of an event.

The charged particle density measurement presented in this thesis is considered to be a final result from the ATLAS collaboration. However, further operation of the detector and hence more experience on the performance of the detector might still be able to reduce the systematic uncertainties. The main systematic uncertainty of the analysis is the accuracy to which the amount of material in the inner detector is known. With an increased data sample, techniques for estimating the amount of material like mapping the material distribution of the detector with photon conversions or hadronic interactions are expected to provide precise results and further improve the analysis. Finally, the size of the data sample determines the ranges up to which the measurements can be performed. More data may open the door to measure the charged particle densities precisely up to transverse momenta of several tens of GeV and to observe proton collisions of several hundreds of charged particles per event.
Appendix A

CHARGED PARTICLE DENSITY WITH LOWERED $p_T$ THRESHOLD

Reconstructing tracks with a transverse momentum below 500 MeV is challenging. The amount of charged particles is significantly higher and the particles undergo for example more multiple scattering. The measured selection efficiencies are thus considerably lower and more sensitive to the description of the amount of material inside the inner detector. Measurements of the charged particles densities with the $p_T$ threshold lowered to 100 MeV have been performed at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV [139] and are summarised here.

The integrated luminosity of the data sample at $\sqrt{s} = 7$ TeV is more than 20 times higher ($\mathcal{L} \approx 190 \mu$b$^{-1}$) compared to $\mathcal{L} < 10 \mu$b$^{-1}$ in Chapter 6. Hence the analysis of these data does not only include a measurement down to lower transverse momenta, but also extends the phase space up to higher transverse momenta of 50 GeV and 100 charged particles per event.

While the track reconstruction efficiency was found to be well described also for particles with a $p_T$ down to 100 MeV, tracks from non-Gaussian tails of the momentum resolution compose a significant fraction of the reconstructed tracks at high transverse momentum. Although the number of these mis-measured tracks is small relative to the number of events in the bulk of the distribution, they lead to a contamination of the high momentum tracks above 10 GeV of up to 50%. This is because the $p_T$ spectrum is steeply decreasing and only few tracks with high $p_T$ are expected. Additional requirements on the quality of the track fit were necessary to remove the majority of these tracks.

A.1 Results

In Figure A.1 the multiplicity distributions are shown for particles with $p_T > 100$ MeV. The results are again compared to different Monte Carlo. Contrary to the distributions obtained with the requirement of 500 MeV, the distributions rise at low multiplicity and reach a maximum at approximately 10 charged particles per event for both energies.
At higher multiplicities both distributions decrease steeply with a more pronounced decrease at $\sqrt{s} = 900$ GeV. The predictions of the Monte Carlo models are diverse especially at low multiplicity. At both energies higher and lower predictions than the measured values exist for low multiplicities, while the region of 10 to 20 particles is well described by the the PYTHIA ATLAS MC09 and ATLAS MBT1 tunes. At high multiplicities the measured values tend to exceed the predictions of the models except for PHOJET at $\sqrt{s} = 900$ GeV.

Figure A.1: Charged particle multiplicity $1/N_{ev} \cdot dN_{ev}/dn_{ch}$ distribution measured at $\sqrt{s} = 900$ GeV (a) and $\sqrt{s} = 7$ TeV (b) for charged particles with $p_T > 100$ MeV and $|\eta| < 2.5$.

Figure A.2 shows the charged particle pseudorapidity distribution at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV. The pseudorapidity distributions were found to be approximately flat over the whole $\eta$ range with central values measured to be $3.49 \pm 0.008$ (stat) $\pm 0.077$ (syst) ($\sqrt{s} = 900$ GeV) and $5.64 \pm 0.002$ (stat) $\pm 0.149$ (syst) ($\sqrt{s} = 7$ TeV). Almost all the predictions of the Monte Carlo models are at least 10% lower than the measured values while the shapes of the predictions describe the data well. However, the prediction from PHOJET agrees well with the result at $\sqrt{s} = 900$ GeV while the discrepancy at $\sqrt{s} = 7$ TeV is approximately 20%. This feature is not completely understood and still under investigation.
A.1 Results

\[ \eta \frac{dN_{ch}}{d\eta} N_{ev} \cdot \frac{d}{d\eta} \]

Data 2009
PYTHIA ATLAS AMBT1
PYTHIA ATLAS MC09
PYTHIA DW
PYTHIA 8
PHOJET

\[ |\eta| < 2.5, p_T > 100 \text{ MeV}, |\eta| < 2.5 \]

ATLAS \( \sqrt{s} = 900 \text{ GeV} \) (a) and \( \sqrt{s} = 7 \text{ TeV} \) (b) for charged particles with \( p_T > 100 \text{ MeV} \).

Figure A.2: Charged particle pseudorapidity distribution \( 1/N_{ev} \cdot dN_{ch}/d\eta \) measured at \( \sqrt{s} = 900 \text{ GeV} \) (a) and \( \sqrt{s} = 7 \text{ TeV} \) (b) for charged particles with \( p_T > 100 \text{ MeV} \).

The charged particle transverse momentum distributions are shown in Figure A.3. They stretch across eleven orders of magnitude. While at low transverse momenta below 300 MeV the measured values are up to 50% higher than the predictions the agreement of data and simulation is considerably better in the intermediate \( p_T \) region up to approximately 3 GeV. At high \( p_T \), higher and lower predictions exist compared to the measured distributions at both energies.

The results with the low \( p_T \) threshold of 100 MeV presented here are suited for an extrapolation down to \( p_T = 0 \). Although the needed scale factors are model-dependent, they are well understood as the extrapolation range is relatively small. These scale factors are obtained by fitting the \( p_T \) spectrum with a two component Tsallis [142] function resulting in \( 1.063 \pm 0.014 (\sqrt{s} = 7 \text{ TeV}) \) and \( 1.065 \pm 0.011 (\sqrt{s} = 900 \text{ GeV}) \). The uncertainties were derived by using two further ways of obtaining the scale factor: one method calculates this factor by using the ATLAS MBT1 tune of PYTHIA, the other assumes a flat \( p_T \) spectrum below 100 MeV.

The extrapolated charged particle density can be compared to the measurements of other LHC experiments such as ALICE [2, 4]. A comparison to the results of CMS is not attempted here as these results have not been corrected for detector effects yet.
Figure A.3: Charged particle transverse momentum multiplicity distribution $1/N_{ev} \cdot 1/2\pi p_T \cdot d^2 N_{ch}/d\eta dp_T$ measured at $\sqrt{s} = 900$ GeV (a) and $\sqrt{s} = 7$ TeV (b) for charged particles with $p_T > 100$ MeV and $|\eta| < 2.5$.

Figure A.4 shows the average charged particle density per unit of $\eta$ as a function of the centre-of-mass energy for the results from ALICE and ATLAS. Although slightly different requirements on the number of charged particles and on the $|\eta|$ regions were made, the results from ATLAS and ALICE ($n_{ch} \geq 1$ and $|\eta| < 1.0$) agree within uncertainties. The expected differences due to the different selection criteria can be estimated by comparing the corresponding predictions from the PYTHIA AMBT1 tune, which are also shown.

A.2 Discussion

In general the contribution of diffractive events is enhanced when lowering the $p_T$ threshold to 100 MeV. While many data sets are available to study charged particle productions in non-diffractive events from the Tevatron and the LHC, very little data is available for tuning the diffractive components. Hence the uncertainties on the diffraction models are large, which is also observed by the widespread predictions at low $n_{ch}$. The agreement between data and simulation tends to be better in the intermediate regions of $n_{ch}$ and
Figure A.4: The average charged particle multiplicity per unit of $\eta$ as a function of the centre-of-mass energy in different regions of phase space. The ALICE data points have been slightly shifted horizontally for clarity. The data points are compared to the predictions of the Pythia AMBT1 tune for the individual phase space regions.

$\rho_T$, where most of the particles are produced by non-diffractive processes. Here good predictions are in particular obtained by the ATLAS MBT1 tune, which was tuned to data at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV with a suppression of diffractive events.

Currently the measurement of charged particle densities is performed on a data set with an enhanced fraction of diffractive events and preliminary results have been released [143]. The events for this study have been selected by requiring a signal on only one side of the Minimum Bias Trigger Scintillator detector. The data has however not yet been corrected for experimental effects due to detector or reconstruction inefficiencies or mis-measurements. A measurement of the charged particle densities similar to the one performed in this thesis on this data set would lead to a better understanding and the possibility to tune the diffractive processes of Monte Carlo generators. This in turn improves the predictions for the non-diffractive models as the uncertainty on the diffractive component decreases. Furthermore, the results can also be used to improve the measurement of the luminosity based on counting the number of inelastic collisions.
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Almost 20 years have elapsed between the ATLAS collaboration signed a 'Letter of Intent' to build a particle detector and the publication of the first physics results. The Large Hadron Collider (LHC), which is the world’s highest energetic particle collider, is meant to provide ATLAS with collisions of protons for another 20 years to study elementary particles in great detail. This thesis documents an exciting period in the timeline of the ATLAS experiment where several milestones have been achieved. An important part of this thesis is the study of the first cosmic ray events recorded with the completely installed detector. Yet the emphasis is on the analysis of the first proton proton collisions.

Figure 1: The result of one proton proton collision recorded with the ATLAS detector. Trajectories of charged particles are displayed as orange lines.
At the LHC, particle collisions involving the production of high energy objects may lead to spectacular discoveries such as evidence for the existence of the Higgs boson. A Higgs boson will however only be created once every $10^{13}$ collisions according to the predictions. The vast majority of the collisions is reigned by soft processes characterised by their small energy transfers. An example of such a proton proton collision is shown in Figure 1, where the trajectories of several charged particles are seen in the ATLAS tracking detector.

The results presented in this thesis probe our understanding of the strong force - known as QCD - in an energy regime that has become accessible at the LHC. QCD describes interactions between the constituents of the proton - the quarks and gluons. The increase of the coupling constant $\alpha_S$ with decreasing energy transfer does however not allow exact calculations of the observed processes in perturbation theory and implies the need of empirical assumptions. These assumptions are only valid in a limited energy range and measurements at various energy scales are used to improve the theoretical models.

The measurement of the charged particle density requires minute calibration and performance studies of the detector. In the fall of 2008, a large amount of muons from cosmic ray events was acquired with the fully operational detector. Although these cosmic muons have a different topology compared to proton proton collisions, they are very suitable to obtain for example a preliminary alignment of the individual detector modules. The performance of reconstructing charged particles was studied in detail and is presented in Chapter 4. This study focuses on the inner detector of the ATLAS experiment, which consists of a silicon pixel detector, a silicon strip detector (SCT) and a drift tube detector (TRT). To measure the resolutions of the charged particle trajectories I used a method that extracts this information only from data. A comparison of the results with predictions from Monte Carlo simulation provided deep insight on the expected performance on collision data. Once the LHC delivered the first collisions, the performance studies continued with the identification of hadron resonances. Many hadrons like the $K_S$, $\Lambda$, $\Phi$, $\Xi$ and $\Omega$ have been identified and are documented in Chapter 3. Again, comparisons with the predictions from Monte Carlo simulation demonstrate the excellent understanding of the detector performance.

Chapters 5 and 6 present the measurement of the charged particle density: the number of charged particles produced in proton proton collisions distributed over a wide range of momenta and pseudorapidities. The analysis has been performed at the centre-of-mass energies 0.9, 2.36 and 7 TeV. For the measurement at 2.36 TeV, I developed a novel method that reduces the dependency on samples from Monte Carlo simulation by deriving a part of the efficiency to identify charged particles from data. For this, charged particles are reconstructed solely with the pixel detector and the efficiency of the resulting pixel tracks is derived with respect to trajectories found in the SCT and TRT. Another peculiarity of the analysis at 2.36 TeV is the fact that only the pixel detector was fully operational during data taking. The beams of protons in the LHC were not considered stable and this activated safety measures to protect the other detectors. The pixel track method was nevertheless applied to this data set and the charged particle density per unit of pseudorapidity $\eta$ is measured to be:
\[ (1/N_{\text{ev}} \cdot dN_{\text{ch}}/d\eta) |_{|\eta|<0.5} = 1.739 \pm 0.019 \text{ (stat)} \pm 0.058 \text{ (syst)}, \]

where \( N_{\text{ev}} \) represents the number of investigated events and \( N_{\text{ch}} \) is the number of produced charged particles with transverse momentum above 500 MeV.

Both the results of the cosmic ray study and the measurement of the charged particle density are considered to be final results of the ATLAS collaboration and have been published in scientific journals. This is especially remarkable because the data sample at \( \sqrt{s} = 2.36 \) TeV was extremely small with only 8150 collision events and because the detector was only partly operational. The measured charged particle densities have been used to adapt theoretical models leading to an improved description of soft processes at LHC energies. These improved models are used as an important constraint for the searches of new physics phenomena.
Samenvatting

Dichtheid van geladen deeltjes gemeten met de ATLAS detector

Bijna 20 jaar liggen tussen de intentieverklaring voor de bouw van het ATLAS experiment en de publicatie van de eerste fysica resultaten in 2010. Volgens de planning zal de Large Hadron Collider (LHC), de krachtigste deeltjesversneller van de wereld, de komende 20 jaar protonen op elkaar botsen in ATLAS. Hierdoor is het mogelijk de elementaire deeltjes gedetailleerd te bestuderen. In dit proefschrift beschrijf ik een spannende periode waarin met het ATLAS experiment verschillende mijlpalen zijn behaald. Het uitgangspunt is de analyse van de gegevens van kosmische straling, voor het eerst gemeten met een volledig geassembleerde detector. Het belangrijkste onderwerp van dit proefschrift is de analyse van de eerste proton proton botsingen waarmee wij ons begrip van de fundamentele deeltjes en hun eigenschappen kunnen testen.

Bij de LHC kunnen botsingen met grote energieoverdracht mogelijk leiden tot spectaculaire ontdekkingen zoals een bewijs voor het bestaan van het Higgs boson. Deze botsingen zijn echter uiterst zeldzaam. Volgens de voorspellingen wordt het Higgs boson slechts eens per $10^{13}$ botsingen gemaakt. De overgrote meerderheid van de interacties zijn “zacht”, ze worden gekenmerkt door hun relatief kleine energieoverdracht. Hierdoor is al na een korte periode de hoeveelheid data groot genoeg om de zachte processen nauwkeurig te bestuderen.

De gepresenteerde resultaten testen ons theoretisch begrip van de krachten van de natuur in een energie bereik dat toegankelijk is geworden bij de LHC, vooral de theorie van de sterke kracht. Deze theorie staat bekend als Quantum Chromo Dynamica (QCD) en beschrijft de interacties tussen de bestanddelen van het proton - quarks en gluonen. De toename van de koppeling constante $\alpha_S$ met afnemende energie overdracht maakt exacte berekeningen van de waargenomen processen onmogelijk in storingstheorie en vraagt om empirische randvoorwaarden. Deze randvoorwaarden zijn echter alleen in een beperkte energiebereik geldig en metingen bij verschillende energiën zijn gebruikt om de theoretische modellen te verbeteren.

De meting van de dichtheid van geladen deeltjes zou niet mogelijk zijn geweest zonder het harde werk aan het ijken van het kalibreren en de performance metingen. In het najaar van 2008 is een grote dataset van muonen uit kosmische straling met de volledig operationele detector gemeten. Hoewel deze muonen andere eigenschappen dan proton
proton botsingen hebben, zijn ze gebruikt om onder andere de individuele detector modules uit te lijnen. Ook de efficiëntie van de identificatie van geladen deeltjes werd bestudeerd en wordt gepresenteerd in hoofdstuk 4. Voor deze studies is voornamelijk gebruik gemaakt van de Inner Detector van het ATLAS experiment. Deze bestaat uit een silicium pixel detector, een silicium strip detector (SCT) en een dradenkamer (TRT). Ik heb een methode gebruikt waarmee men de resolutie van de reconstructie van de sporen van geladen deeltjes met behulp van de data kan meten. Een vergelijking van deze resultaten met de voorspellingen van Monte Carlo simulatie leverde een dieper inzicht over de te verwachten performance in proton proton botsingen. Zodra de eerste protonen hadden geboost in de LHC, gingen de performance studies verder met de identificatie van hadron resonanties. Verschillende hadronen zoals de \( K_S \), \( \Lambda \), \( \Phi \), \( \Xi \) en \( \Omega \) zijn geïdentificeerd en worden gepresenteerd in hoofdstuk 3. De goede overeenkomst met de voorspellingen van Monte Carlo simulatie toont opnieuw de uitstekende kennis van de werking van de detector aan.

De hoofdstukken 5 en 6 presenteren de meting van de dichtheid van geladen deeltjes: het aantal geladen deeltjes geproduceerd in proton proton botsingen verdeeld over een groot bereik van impuls en pseudorapidity. De analyse is uitgevoerd bij botsingsenergieën van 0.9, 2.36 en 7 TeV. Voor de meting bij 2.36 TeV heb ik een methode ontwikkeld die de efficiëntie om geladen deeltjes te vinden met de data zelf bepaalt. Daardoor is deze methode minder afhankelijk van Monte Carlo simulaties. De sporen van geladen deeltjes worden alleen met de pixel detector gereconstrueerd. De efficiëntie voor het vinden van het spoor wordt gevonden met behulp van de sporen in de SCT en TRT. Een andere bijzonderheid van de analyse bij 2.36 TeV is het feit dat alleen de pixel detector volledig operationeel was tijdens de data acquisitie. Dit komt doordat de protonenbundels in de LHC niet stabiel waren, zodat veiligheidsmaatregelen de andere detectoren beschermden. De pixel track methode werd toch op deze dataset toegepast en de dichtheid van geladen deeltjes per eenheid van pseudorapidity \( \eta \) is gemeten als:

\[
(1/N_{ev} \cdot dN_{ch}/d\eta) \big|_{|\eta|<0.5} = 1.739 \pm 0.019 \text{ (stat)} \pm 0.058 \text{ (syst)},
\]

waarin \( N_{ev} \) het aantal onderzochte botsingen en \( N_{ch} \) het aantal geproduceerde geladen deeltjes met een transversale impuls boven de 500 MeV vertegenwoordigt.

De resultaten van zowel de studie met muonen uit de kosmische straling als de meting van de dichtheid van geladen deeltjes zijn uiteindelijke resultaten van het ATLAS experiment en zijn gepubliceerd in wetenschappelijke tijdschriften. Dit is vooral bijzonder omdat de data sample bij 2.36 TeV beperkt was met alleen 8150 botsingen en omdat de detector gedeeltelijk uitgezet was. De gemeten dichtheiden van de geladen deeltjes zijn verder gebruikt om de theoretische modellen die tot een betere beschrijving van de onderzochte processen leiden aan te passen. Deze verbeterde modellen zullen worden gebruikt als fundering bij het zoeken naar nieuwe natuurkundige fenomenen bij de LHC.
ZUSAMMENFASSUNG

Messung der Dichte geladener Teilchen mit dem ATLAS Detektor


Abbildung 1: Schematische Darstellung des LHC Tunnels und des ATLAS Experiments.
Zusammenfassung


Nach dem erfolgreichen Start des LHC im November 2009 haben sich die wissenschaftlichen Aktivitäten deshalb auf die ”Wiederentdeckung” bereits bekannter Prozesse innerhalb des Standardmodells konzentriert. Ein Beispiel dafür ist die Messung der Dichte geladener Teilchen, die in dieser Arbeit behandelt wird. Diese Messung geht von den folgenden relativ naheliegenden Fragen aus:

- Wie viele geladene Teilchen werden durchschnittlich pro Kollision erzeugt?
- Welche Energie haben diese Teilchen?
- In welche Richtung fliegen diese neu produzierten Teilchen?

Die Antworten auf diese eher einfachen Fragen sind jedoch bei Weitem nicht trivial. Die Theorie, die die zugrunde liegenden Wechselwirkungen innerhalb des Standardmodells beschreibt, ist unter dem Namen Quanten Chromo Dynamik (QCD) bekannt und...
Abbildung 2: Vereinfachte Darstellungen einer Teilchenkollision. (a) Nach der Kollision der Protonen entsteht eine Vielzahl neuer Teilchen (rot und blau), die in der Regel weiteren Wechselwirkungen unterliegen und stabile Objekte (grün und gelb) formen. (b) Darstellung der Teilchen derselben Kollision, die mit dem Detektor identifiziert werden können.

Die Teilchendichte wird in dieser Arbeit bei drei verschiedenen Schwerpunktsenergien gemessen (0.9, 2.36 und 7 TeV), d.h. dass die kollidierenden Protonenstrahlen auf jeweils unterschiedliche Energien beschleunigt wurden. Das Hauptaugenmerk richtet sich auf die Analyse bei 2.36 TeV, da hier eine neuartige von mir entwickelte Messmethode angewendet wurde. Die wichtigste Größe dieser Messung ist die Effizienz mit welcher ein bei der Kollision produziertes Teilchen im Detektor nachgewiesen werden kann. Normalerweise kann man diese Effizienz ausschließlich mit Hilfe von Simulationen bestimmen. Die neuartige Methode bestimmt jedoch jene Effizienz teilweise mit Hilfe von Daten, die...
Zusammenfassung

mit dem Detektor genommen wurden, und verkleinert so den Messfehler gegenüber der herkömmlichen Methode. Darüber hinaus war ein Teil des Detektors, der für die Rekonstruktion der Spuren von geladenen Teilchen verantwortlich ist, nicht voll funktionsfähig, da die Protonenstrahlen noch nicht als stabil angesehen wurden und deshalb Sicherheitsvorkehrungen getroffen wurden. Die neue Messmethode konnte jedoch trotzdem verwendet werden und die gemessene Anzahl der produzierten Teilchen pro Kollision und Einheit der Pseudorapidität $\eta$ ist:

\[
\frac{1}{N_{\text{ev}}} \cdot \frac{dN_{\text{ch}}}{d\eta} \bigg|_{|\eta|<0.5} = 1.739 \pm 0.019 \text{ (stat)} \pm 0.058 \text{ (syst)},
\]

wobei $N_{\text{ev}}$ die Anzahl der Kollisionen und $N_{\text{ch}}$ die Anzahl der geladenen Teilchen mit einem transversalen Impuls von mehr als 500 MeV bezeichnet.


This is it - the book - my book. I want to take this opportunity to thank all the people that contributed directly and indirectly to the successful completion of this thesis. If I compare the four years of my PhD project with my great passion of playing American Football, a lot of analogies pop up that I will try to explain in the following.

First I want to thank my ‘coaches’, Auke and Els. From the first moment I met coach Auke (and Paul de Jong) at a workshop on the legendary Ringberg Castle he gave me the feeling that Nikhef is the team I want to play for during the upcoming seasons (and made me never regret my choice). The supervision of my head coach, Els, turned out to be extremely efficient and converged in the instructive and painless process of writing this thesis. Not to forget my coach of the technical skills, Wolfgang. Thanks to his effort I learned how to sharpen the mandatory surviving skills of C++ and python and use them successfully in the competitive environment of more than 3000 physicists. I also want to thank the ‘president’ of the club, Stan, to always support me and to honour me with considering me as a potential successor in his position in the (far) future.

And of course, what would a team be without the teammates? Once I joined Nikhef I felt immediately integrated thanks to Alex, Dox, Erik, Gossie, Tristan and Manouk, which lead to friendships also ‘off the field’. With the years more players like Ido, Menelaos, Egge and Jörg joined and made events like the ‘training camps’ in Spa and Texel unforgettable... My one and a half years ‘on loan’ at CERN turned out to be very successful, both privately and professionally; in particular due to my multi-national teammates including the whole Minimum Bias Analysis team (Copenhagen ATLAS week was the best ...) and also Carolina, Giuseppe, Anne, Barbara, Präsi and especially Andi. Thanks to all of you!

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And finally, my 'cheerleader', Bettina. Thank you for giving me your support when I needed it most, but especially thank you for keeping my feet on the ground in times I get overconfident. I often tried, but it is very difficult to express in words what you mean to me. Maybe the best expression is that we have the thing.