Particle Production in $p+p$ and $d+Au$
Collisions at $\sqrt{s_{NN}} = 200$ GeV

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Preface

In ultra-relativistic heavy ion physics, heavy nuclei such as lead, gold and copper have been accelerated to ultra-relativistic velocity and brought to collide with each other in order to study the properties of the extreme hot and dense matter created in such violent interactions in the laboratory. Although the main aim is the study of the deconfined phase of the strongly interacting matter created in central Au+Au collisions, measurements of p+p and d+Au reactions are essential for the understanding of the properties of the new state of matter. The data from the small (binary) systems is not only needed as a reference for the nucleus-nucleus system, e.g. for the nuclear modification factor, and to disentangle initial state effects (already visible in d+Au) from final state effects due to the deconfined phase, but also allows to verify models like pQCD and provides a testbed for the study of new phenomena like the Colour Glass Condensate.

The Broad RAnge Hadron Magnetic Spectrometer (BRAHMS) experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) collected data from d+Au and p+p collisions in 2003 and 2005. The calibration of the raw detector data and the event reconstruction turned out to be complicated due to the incomplete installation in 2003 and to unstable performance of both the trigger and spectrometer detectors, e.g. the inelasticity and beam-beam counters and time-of-flight (TOF) detectors (H1 and H2) in the forward spectrometer. The reconstruction process had to be iterated several times, and the selection of good runs was time consuming.

Most of the work went into the quality analysis of runs in order to select valid runs/settings, into the development and improvement of (fault-tolerant) particle identification methods and into the development of correction and normalization schemes (Chapter 4). The result, spectra of identified charged hadrons ($\pi^\pm$, $K^\pm$ and $\bar{p}(p)$) at different rapidities, is shown in Chapter 5 for minimum bias p+p, d+Au and centrality selected d+Au collisions. Particle ratios are presented in Chapter 5. A systematic study was performed on the extrapolation of the spectra outside the transverse momentum acceptance (Chapter 4). The extrapolation procedure yields rapidity densities and mean transverse momenta (Chapter 5). A special emphasis is on the net-proton yields in Chapter 7. The nuclear modification factors $R_{dAu}$ are discussed in Chapter 6. Since the p+p and d+Au data are a reference for theoretical models and nucleus-nucleus collisions, they are compared to data from other experiments when available and checked for consistency in Chapter 8.
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Chapter 1

Nuclear Collisions at Ultra-relativistic Energies

We can learn from nuclear collisions at ultra-relativistic energies about the properties of strongly interacting matter at high energy density. In a central collision, a large fraction of the energy of the two beams, consisting of two bunches of nuclei which have been accelerated to relativistic energy, is deposited in a small region of space. This fact results in the formation of a very high energy density in the collision region. After the collisions, this high energy density is eventually converted into particle production (mostly pions), and probably also a blast of thermal waves accompanied with the particle production. The aim of nuclear collisions at ultra-relativistic energies is to study the matter at high energy density and the evolution of the collision system from two slats of Lorentz contracted nuclei at the initial stage till the final freeze-out of the produced particles.

The RHIC at Brookhaven National Laboratory makes nuclei collide with each other and produces this matter with high energy density in the laboratory. The collider is designed to accelerate nuclei to an energy of 100 GeV per nucleon in the center-of-mass (CM) system, which accounts for about a CM energy of 40 TeV in the collision when the nucleus is gold (Au).

1.1 Collision phenomenology

After being accelerated to relativistic energy, two colliding nuclei become two fast moving slats. There are two different collision scenarios, transparency and stopping by Bjorken [2] and Landau [3] respectively. If the two nuclei are transparent to each other, as shown in figure 1.1, the colliding nuclei lose only a small fraction of their energy and move forward with their original speed which would result in a net-baryon free central region. A fully stopping picture is shown in figure 1.2. In this picture, all the nucleons in the colliding nuclei are fully stopped. All the initial energy carried by nucleons are deposited in the vicinity of the center of mass of the collision.
1.1.1 Collision evolution

The evolution of the collision system is phenomenologically described as the following four stages: initial parton scattering, fireball formation, hadronization and freeze-out of hadrons. Figure 1.3 shows the evolution of the collision system in light-cone coordinate system. When two nuclei are approaching each other, partons from nucleons inside nuclei scatter at partonic level, which is regarded as the initial condition of the collisions, and a partonic fireball is created. When the energy density in the central rapidity region is high enough, the system gets thermalized, and a quark gluon plasma (QGP) may be created. As the system expands, it cools down and starts to hadronize. Finally, hadrons will freeze-out when the temperature of the system drops.

1.1.2 Experimental observables

In the experiment, what characterize the particle production are the particles’ momenta. From those information, one can study the degree of stopping in the collisions, construct invariant differential cross sections, from which particle yields and ratios
can be extracted for the study of the chemistry of the system. Furthermore, nuclear modification factors can be constructed to study medium effects. Angular correlations of particles are the result of di-jets, and the Hanbury-Brown Twiss (HBT) effect leads to momentum correlations of identical particles. Last but not least, flow is an important observable, from which one can study the collective effects and the degree of the thermalization in the system. In the following, the observables related to the discussion in this thesis will be introduced.

**Nuclear stopping power**

Nuclear stopping power was introduced in high energy nuclear collisions by Busza and Goldhaber [5] in 1983 to discuss the degree of stopping power which an incident nucleon suffers when it collides with nuclear matter. The kinetic energy loss of the incident nuclear matter which is correlated to the rapidity loss of the incident protons, is converted into the production of a large number of particles (mostly pions). The distribution of protons with momentum fraction \( x_F \) is approximately uniform over the whole range of \( x_F \) in p+p collisions at \( p_{lab} = 100 \) and 175 GeV/c [6], as shown in figure 1.4. A constant \( x_F \) distribution corresponds to an exponential distribution in rapidity with the maximum near beam rapidity (see figure 1.5). A quantitative analysis shows that only approximately 50% of the beam energy is available for particle production in minimum bias p+p collisions; 50% of the beam energy is carried away by the projectile and target fragments.

![Figure 1.4](image)

Figure 1.4: Cross section \( d\sigma/dx \) for the reaction \( p+p \rightarrow p+X \) after integration over the transverse momentum [6]. Here, \( x \) is the Feynman variable \( x_F \).

Figure 1.6 shows the total net-proton density as function of \( x_F \) (left panel) and projectile component of net-proton density (right panel) in p+p and p+Pb collisions

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1Feynman variable is defined as \( x_F = (E+p_L)/(E_0+p_0) \). The relation between \( x_F \) and \( \Delta y = y-y_0 \) is \( \ln x_F = \Delta y + \ln m_T/m \). It was labeled as \( x \) in figure 1.4.
with different centralities at SPS energy $\sqrt{s_{NN}} = 17.2$ GeV using the NA49 detector. p+Pb collisions show an approximately exponential decrease of the net-proton yield with increasing $x_F$. The decrease is stronger for central p+Pb collisions. For $x_F < 0.1$ (corresponding about 2.3 units of rapidity away from the beam), the yield in central p+Pb collisions is larger than the yield in semi-central collisions; for $x_F > 0.1$ the semi-central collisions dominate. Plotted vs rapidity, the distribution of the leading proton from p+A fixed-target collisions has been characterized by a flat distribution for approximately $2 \sim 3$ units of rapidity, without obvious energy dependence (figure 1.7 [8]).

In high energy central nucleus nucleus collisions, a large fraction of the longitudinal energy is converted into the energy of the matter which was produced in the vicinity of the center of mass of the colliding system [9]. The degree of stopping will reveal whether the energy density deposited in the vicinity of the center of mass is high enough to allow a phase transition, leading to the formation of QGP. From the measurements on the remaining baryon rapidity density from the beams, one can study the degree of stopping power.

The net-proton rapidity density can be obtained by subtracting the $\bar{p}$ yields from proton yields, which can be extracted by fitting their spectra with certain functions at different rapidities. The method will be discussed later in detail in Chapter 4. In Chapter 7, results from d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV will be
Figure 1.6: a) total net-proton density as function of $x_F$; b) projectile component of net-proton density. This figure is taken from [7].

Figure 1.7: Rapidity distribution of protons from $p+A$ collisions as a function of rapidity loss, $\Delta y \equiv y - y_{\text{beam}}$. The dashed curve is from Busza and Goldhaber [5] for $p+Pb$ collisions. This figure is taken from [8] presented.
Transverse momentum spectrum

The invariant differential cross section of produced particles, measured by counting the number of particles in a two dimensional $y$-$p_T$ phase space bin then scaled by a factor of $2\pi$ and $p_T$, is defined as

$$E \frac{d^3\sigma}{d^3p} = \frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy}. \quad (1.1)$$

It is the basic measurement which can be used to compare with theory calculations. From the spectra, we can construct the nuclear modification factor to study nuclear effects in nucleus nucleus collisions. The spectra of identified particles will be presented in Chapter 5.

Particle rapidity density and particle ratios

Based on the particle spectra and particle identification ability one can obtain the particle rapidity density $dN/dy$ as a function of rapidity. Besides the rapidity density, particle ratios are thought to be a tool to study the chemistry of the system. In Chapter 5, the rapidity density and particle ratios are presented.

Nuclear modification factors

The nuclear modification factor for A+B collisions is defined as the following

$$R_{AB} = \frac{1}{\langle N_{\text{coll}} \rangle} \cdot \frac{d^2N_{AB} / dp_T dy}{d^2N_{NN} / dp_T dy}. \quad (1.2)$$

It is used to quantitatively study the nuclear medium effects, which modify the expected scaling e.g. the suppression of the high $p_T$ hadron spectra in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. In equation 1.2, $\langle N_{\text{coll}} \rangle$ is the average number of binary collisions in A+B collisions, and $N_{AB}^A$($N_{NN}^N$) is the yield per event in A+B (N+N) collisions. If there are no initial or final state effects, $R_{AB} = 1$. The central to peripheral ratio, $R_{CP}$ is used as an alternative to $R_{AB}$, for the centrality study of the nuclear modification factor. $R_{CP}$ is defined as:

$$R_{CP} = \frac{\langle N_{\text{peripheral}} \rangle_{\text{coll}}}{\langle N_{\text{central}} \rangle_{\text{coll}}} \cdot \frac{d^2N_{\text{central}} / dp_T dy}{dN_{\text{peripheral}} / dp_T dy}, \quad (1.3)$$

where $N_{\text{central}}$($N_{\text{peripheral}}$) is the yield per event in the central (peripheral) collision, and $\langle N_{\text{central}} \rangle_{\text{coll}}$($\langle N_{\text{peripheral}} \rangle_{\text{coll}}$) is the average number of binary collisions in central (peripheral) collisions. If the yield of the process scales with the number of binary collisions, $R_{CP} = 1$. In Chapter 6, the centrality and rapidity dependence of $R_{dAu}$ of identified hadrons will be presented.

1.2 Recent results from RHIC

A very high energy density has been reached in the laboratory at RHIC [10]. The hot and dense matter is produced by colliding heavy nuclei (gold) at ultra-relativistic energies. To investigate the nuclear matter under extreme condition of high temperature
and pressure and advance the understanding of the QCD vacuum, quark confinement, chiral symmetry breaking, and new unexpected phenomena in this outer limit of the QCD phase diagram, the produced particles, for instance, mesons and baryons are detected and identified in various experiments.

Results from RHIC are presented in the following for stopping, elliptic flow at partonic level, hadron suppression at high $p_T$, and the disappearance of back-to-back jets in the central Au+Au collisions.

### 1.2.1 Stopping

![Figure 1.8: Net-proton rapidity distribution and rapidity loss in central Au+Au collisions measured by the BRAHMS experiment at RHIC. Left panel, the comparison of the net-proton rapidity density at RHIC with that at AGS and SPS energies; right panel, the rapidity loss at different energies. [11]](image)

The left panel in figure 1.8 shows the recent results on rapidity density of net protons measured at AGS (5 $A$ GeV), SPS (17 $A$ GeV) and BRAHMS/RHIC (200 $A$ GeV) for top 5% most central Au+Au (Pb+Pb) collisions [11]. The right panel shows the rapidity loss estimation by an extrapolation to the full net-baryon distribution as a function of projectile rapidity (in the CM system). The hatched area indicates the unphysical region, and the dashed line shows a phenomenological scaling $\langle \delta y \rangle \sim 0.58 y_p$.

As shown in figure 1.8, at RHIC a broad minimum has developed spanning several units of rapidity, indicating that at RHIC energies collisions are quite transparent. The rapidity loss at RHIC is clearly less than the phenomenological linear rapidity scaling would predict; about 73% of the initial energy is deposited in the collisions region [11].

### 1.2.2 Jet quenching

Particles with high momenta are informative for probing the conditions of the produced medium in relativistic energy nuclear collisions. They are thought to be associated with the jet production in the initial hard parton scattering, as illustrated by figure 1.9. After they are produced, they are expected to suffer energy loss when they traverse...
a medium with high density of color charges because of the induced gluon radiation on their way. This would result in a depletion of high $p_T$ particles. The energy loss effect for the high $p_T$ particles in the medium is called jet quenching. As a fact, high $p_T$ suppression in nuclear collisions at RHIC has been observed comparing to the particle production in p+p collisions at the same energy, and also the disappearance of back-to-back di-jets has been seen in central Au+Au collisions.

Disappearance of the back-to-back jets

Figure 1.10 is the measurement done by the STAR experiment at RHIC [12]. The back-to-back dihadron correlation is absent in central Au+Au collisions, but in peripheral Au+Au collisions the correlation appears quite similar to that seen in p+p and d+Au collisions. This suppression in Au+Au central collisions can be explained by the dense medium effect on the hard-scattered partons.

![Figure 1.10: Disappearance of back-to-back jets in central Au+Au collisions at RHIC [12].](image)
1.2 Recent results from RHIC

High $p_T$ suppression

Figure 1.11: Nuclear modification factor measured by the BRAHMS experiment in minimum bias collisions of d+Au and central Au+Au collisions. [13].

BRAHMS has measured the nuclear modification factor for charged hadrons in minimum bias d+Au collisions and in central Au+Au collisions (0-10%), shown in figure 1.11. $R_{dAu}$ shows no suppression at intermediate $p_T$, but an enhancement instead, while $R_{AuAu}$ in the most central collisions exhibits a significant suppression at high $p_T$. The completely different result at high $p_T$ in minimum bias d+Au collisions and the most central Au+Au collisions reveals the fact that the medium suppresses the jets before they finally fragment. Other experiments at RHIC have reported similar results [14, 15, 12].

1.2.3 Elliptic flow $v_2$ at partonic level

Elliptic flow $v_2$ is considered as an effect of the pressure in the interaction region, and is defined as the second Fourier expansion coefficient of the azimuthal momentum distribution,

$$ E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{d^2 N}{p_T dp_T dy} \left\{ 1 + \sum_{n=1}^{\infty} 2v_n \cos \left[ n(\phi - \Psi_r) \right] \right\}, \quad (1.4) $$

where $\phi$ is the azimuthal angle of the produced particle, and $\Psi_r$ stands for the real reaction plane angle which is defined as the angle between the $x$-axis and the reaction plane. Therefore, $v_2$ can be evaluated by

$$ v_2(p_T, y) = \left\langle \cos [2\phi(p_T, y)] \right\rangle \quad (1.5) $$

where $\langle ... \rangle$ represents an averaging over many particles and events in the $y$-$p_T$ space. Elliptic flow $v_2$ is sensitive to the equation of state of nuclear matter and also to the degree of thermalization reached in the system.
Flow for heavier particles is particularly interesting because it is less sensitive to the final stage of the evolution, e.g. the freeze-out temperature. For example, $\phi$-mesons are not created via kaon coalescence, and do not participate strongly in hadronic interactions. Figure 1.12 shows the elliptic flow $v_2$ for mesons and baryons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured by PHENIX [16] and STAR experiments [17]. These results show e.g. the heavier $s$ quarks flow as strongly as the lighter $u$ and $d$ quarks, which demonstrate the partonic collectivity in central Au+Au collisions at RHIC.

### 1.3 Objective of the thesis

This thesis will focus on the $p_T$ ($m_T$) spectra of $\pi^\pm$, $K^\pm$, and p(p) in both p+p and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV over a wide rapidity range ($-0.2 < y < 3.6$). Various data sets, minimum bias p+p and d+Au collisions, and three different centrality classes (i.e. 0-30%, 30-60% and 60-80%) in d+Au collisions are analyzed for this purpose. Nuclear stopping will be discussed, as well as the nuclear modification factor for the smaller system, $R_{dAu}$ ($R_{CP}$).

The following results will be presented:

- Identified particle $p_T$ spectra, for different centrality ranges, and at different rapidities;
- Centrality, rapidity dependence of particle ratios: negative/positive, $K/\pi$, $p/\pi$;
- Centrality, rapidity dependence of nuclear modification factors $R_{dAu}$ ($R_{CP}$);
- Centrality, rapidity dependence of charged hadron and net-proton rapidity density $dN/dy$. 

Figure 1.12: Elliptic flow $v_2$ for mesons and hadrons at partonic level in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured by PHENIX [16] (left) and STAR experiment [17] (right).
The aim of this thesis is twofolded:

- Systems like p+p and d+Au collisions are needed as a reference for Au+Au collisions to disentangle the modification of the parton distributions in nuclei (e.g. shadowing) and the change of $p_T$ spectra of produced particles caused by initial and final state multiple scattering in cold nuclear matter (e.g. Cronin effect [18]).

- On the other hand, p+p data is needed to check the validity of pQCD calculations, at mid-rapidity and at forward rapidities to shed light on the (soft) baryon transfer processes during stopping and to test new small-$x$ phenomena like gluon saturation at very forward rapidities in d+Au.
Nuclear Collisions at Ultra-relativistic Energies
Apart from the phenomenological descriptions in Chapter 1, various models have been developed to study nuclear collisions at high energies. The Quark Gluon Plasma (QGP) created in relativistic heavy ion collisions with high enough temperature and energy density, is an unavoidable consequence of the fundamental strong interactions, and is quantitatively calculable by the SU(3) theory, Quantum Chromo-Dynamics (QCD) [19]. QCD is a theory of strong interaction (strong force) and a representation of the interactions between partons (quarks and gluons), mediated by color charged gluons. There are 6 flavors of quarks in 3 generations, \((u, c, t)\) with positive charge \(+\frac{2}{3}\) and their corresponding counterparts \((d, s, b)\) with negative charge \(-\frac{1}{3}\) in the unit of the electron charge. They carry the colors, red, green and blue, which are thought to be the source of the strong force [20]. Interactions between partons of specific flavors are propagated via a number of possible color exchanges.

![Phase diagram](image)

(a) Critical temperature vs baryon density [9];  
(b) Lattice QCD prediction, a rapid increase in energy density around a certain temperature \(T_c\) [21]

Figure 2.1: Phase diagram (a) and LQCD prediction (b).

In reality, not a single free quark has been seen. Quarks are assumed to be confined inside hadrons. In relativistic heavy ion collisions quarks may be deconfined from nucleons when the energy density in the system is high enough. A new form of matter
which consists of deconfined quarks and gluons, the so-called QGP, was first proposed by Shuryak [22]. Figure 2.1 (a) shows a phase diagram of nuclear matter i.e. the critical temperature as a function of baryon density. The phase change from a hadronic phase to a partonic one is predicted by Lattice QCD (LQCD) [21]. Figure 2.1 (b) shows that the energy density strongly increases at the vicinity of the transition temperature $T_c$. The drastic change in the behaviour of the energy density which indicates that the QCD (phase) transition to the plasma phase indeed is deconfining [21].

The details about the SU(3) gauge theory of QCD and the calculation of LQCD are beyond the range of this thesis, but a brief introduction to the perturbative QCD (pQCD) will be given. A number of other models, such as a recent gluon saturation model of the Color Glass Condensate (CGC) [4] which is more concerned about the gluon saturation effect at the initial stage of the nuclear collisions, and the LUND string model of PYTHIA [23] which is based on a string breaking mechanism for particle production will also be briefly introduced.

2.1 Perturbative QCD (pQCD)

Without medium effects, nuclear collisions might be described as the superposition of many binary nucleon nucleon collisions. The standard pQCD calculation of hard scattering process in the basic nucleon nucleon collisions is based on the following factorization [24]

$$\frac{d\sigma_{pp}}{dy dp_T^2} = K \sum_{a,b,c,d} \int dx_a dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \frac{d\sigma}{dt}(ab \rightarrow cd) \frac{D_0^{h/c}}{\pi z_c}, \quad (2.1)$$

in which $f_a(x_a, Q^2)$ and $f_b(x_b, Q^2)$ are the parton distribution functions (PDF) for parton $a$ and $b$, $x_a$ and $x_b$ are the initial momentum fraction carried by the parton $a$ and $b$, $\frac{d\sigma}{dt}(ab \rightarrow cd)$ is the differential cross section for $ab \rightarrow cd$ scattering, and $\frac{D_0^{h/c}}{\pi z_c}$ is the fragmentation function for the parton of flavor $c$. The factor $K$ in the formula is phenomenologically introduced to describe the difference between the leading and higher order cross sections, which has no precise definition [25]. The differential cross section $\frac{d\sigma}{dt}(ab \rightarrow cd)$ can be calculated by pQCD at leading order (LO) or the next-to-leading order (NLO) of the coupling constant $\alpha_s$.

The comparison between NLO pQCD calculations with the measurement of $\pi^0$ by the PHENIX experiment in p+p collisions at $\sqrt{s} = 200$ GeV [28] and the BRAHMS experiment at 62.4 GeV [27] are shown in figure 2.2 and figure 2.3 respectively. The invariant differential cross section for inclusive $\pi^0$ production (points) and the results from NLO pQCD calculations using different fragmentation functions are shown in figure 2.2. A good agreement between experiment and the “Kniehl-Kramer-Pöttler” (KKP) pQCD calculation is observed. Figure 2.3 shows the differential cross sections for $\pi^-$ at rapidity $y = 2.7$ and $y = 3.3$ at $\sqrt{s_{NN}} = 62.4$ GeV, compared to the NLO pQCD calculation using the KPP fragmentation function evaluated at $\mu = p_T$ scale [27]. As concluded in [27], the NLO pQCD gives a satisfactory description of the charged pion data at high rapidity though at rapidity $y = 3.3$ there is a tendency for the pQCD calculation to underestimate the $\pi^-$ cross section at higher $p_T$. 
Figure 2.2: Comparison of PHENIX measurement of invariant differential cross section for inclusive $\pi^0$ production at mid-rapidity to NLO pQCD calculations for $p+p$ collisions at $\sqrt{s} = 200$ GeV. Panel a) shows the PHENIX data (points) and the results from NLO pQCD calculation with equal renormalization and factorization scales of $p_T$ using the KKP (solid line) and “Kretzer” (dashed line) sets of fragmentation functions. b) The relative statistical (points) and point-to-point systematic (band) errors. c,d) The relative difference between the data and the theory using KKP (c) and Kretzer (d) fragmentation functions with scales of $p_T/2$ (lower curve), $p_T$, and $2p_T$ (upper curve). This figure is taken from [26].

The nuclear structure functions in nuclei are different from the superposition of the constituent nucleons [29, 30]. The ratio $R_{F_2}^A(x, Q^2)$ is defined as the nuclear structure function per nucleon divided by the nucleon structure function

$$R_{F_2}^A(x, Q^2) = \frac{F_{2}^{A}(x, Q^2)}{F_{2}^{\text{nucleon}}(x, Q^2)}, \quad \text{(2.2)}$$

where $F_{2}^{A}$ is the nuclear structure function, and $F_{2}^{\text{nucleon}}$ the nucleon structure function. The nuclear effects observed in this ratio are usually discussed according to different regions of Bjorken-$x$ variables. The ratio $R_{F_2}^A < 1$ corresponds to small $x$ region $x \leq 0.1$ with shadowing effect; anti-shadowing, $R_{F_2}^A > 1$, at $0.1 \leq x \leq 0.3$; EMC effect, $R_{F_2}^A < 1$ at $0.3 \leq x \leq 0.7$; Fermi motion, $R_{F_2}^A > 1$ at $x \to 1$ and beyond.
Figure 2.3: Comparison of invariant cross sections for $\pi^-$ at $y = 2.7$ and $y = 3.3$ to NLO pQCD calculations with factorization and renormalization scales set equal to $p_T$ [27].

Figure 2.4: Scale evolution of the $R_g^A(x,Q^2)$ as a function of $x$ for nucleus Pb ($A=208$) at a fixed $Q^2$. This figure is taken from [31].

Similarly, the ratio $R_i^A(x,Q^2)$ for parton $i$ is defined as

$$ R_i^A(x,Q^2) = \frac{f_i^A(x,Q^2)}{f_i^p(x,Q^2)}, \quad (2.3) $$

where $f_i^p$ and $f_i^A$ are the distributions of parton $i$ in a free proton and a nucleus with
mass number A respectively. Figure 2.4 shows the gluon modification $R^A_g(x, Q^2)$ for heavy nucleus (Pb) obtained from a DGLAP analysis. The ratio $R^A_g$ turns below 1 at small $x$, indicating shadowing effects.

In d+Au collision this additional shadowing effects have to be considered. By replacing one projectile by a heavy nucleus, its PDF has to be modified by taking into account the depletion of small-$x$ partons in the nucleus (nuclear shadowing). Secondly, multiple scattering of a projectile parton on partons in the nucleus before a hard collision gives the scattering parton an additional $p_T$-kick which leads to the Cronin effect. Both effects are initial state effects and can be taken into account by adding appropriate factors to equation 2.1. Final state effects like the scattering of produced particles in cold nuclear matter might also contribute e.g. to the nuclear modification factor.

pQCD (LO) calculations for d+Au collisions are shown in figure 2.5 and figure 2.6 [32]. Figure 2.5 shows the pQCD calculations using two different parameterizations, FGS1 and EKS98 parameterizations of nuclear shadowing, compared to the nuclear modification factor $R_{dAu}$ at different pseudo-rapidities measured by BRAHMS experiment at RHIC [33]. Figure 2.6 shows the pQCD calculation for $R_{CP}$ using the FGS1 parameterization, compared to the BRAHMS results. The results for minimum bias d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in the aforementioned figures agree reasonably well with the BRAHMS data, while the calculated centrality dependence underestimates the data [32]. Other efforts made recently by Armesto, based on pQCD calculation and including multiple scattering approaches [34] suggest a large amount of shadowing and tend to indicate that shadowing for gluons is stronger than that for quarks, but DGLAP evolution disfavors such situation in view of the existing data on $Q^2$-evolution of nuclear modification factors.

On the other hand, at lower energies, $\sqrt{s_{NN}} = 19.4, 23.8, 27.4$ GeV, Cronin
et al have measured the effect of the propagation and scattering of projectile particles through the color field of a nucleus [35]. The enhancement of particle production in p+A collisions leading to $R_{pA} > 1$ was observed in [18] and is usually referred to as Cronin effect. Cronin effect is interpreted as the result of multiple scattering of partons inside the nucleus though it is not enough to explain the species dependence of this effect, namely the enhancement of baryons in p+A collisions being significantly larger than that of mesons. Phenomenologically, various models have been established in the last decade, which are to be discussed in the next sections.

### 2.2 Color Glass Condensate (CGC)

CGC is an effective gluon saturation theory of QCD at high energy, providing initial condition for the high energy nuclear collisions. The study of gluon saturation was initiated from the small $x$ problem in deep inelastic scattering (DIS) experiment at HERA, as shown in Figure 2.7. The gluon density $xG(x, Q^2)$ is rising rapidly as a function of decreasing $x$. At high energy (or small $x$), gluons are the most abundant partons in nucleons, see figure 2.8 [4].

Using pQCD one can calculate the evolution of the PDFs, but not the PDFs themselves. Various calculations were made for the purpose. The evolution of gluon distribution function has been formulized by Dokshitzer-Gribov-Lipatov-Altarelli-Parisi
2.2 Color Glass Condensate (CGC)

Figure 2.7: The HERA data for the gluon distribution function as a function of \( x \) for various values of \( Q^2 \) [4].

(DGLAP) evolution equation [36, 37, 38], which is known as the renormalization group equation for the parton number operator. According to the DGLAP formalism, the gluon distribution function \( xG(x, Q^2) \) grows fast with both \( x \) and \( Q^2 \) for a fixed coupling constant \( \alpha_s \),

\[
xG(x, Q^2) \sim e^{\sqrt{\alpha_s \log(1/x \log Q^2)}}.
\]  

(2.4)

While when \( Q^2 \) is limited, the approximation made by Balitsky-Fadin-Kuraev-Lipatov (BFKL) [39, 40] approach yields

\[
xG(x, Q^2) \sim e^{\lambda \log 1/x},
\]  

(2.5)

with \( \lambda \equiv 4 \log 2 \cdot N_c \alpha_s / \pi \) for a fixed coupling constant. This means that pQCD radiation leads to a fast growth of the gluon distribution function with increasing energy or decreasing \( x \), which makes a hadron a dense system of gluons at high energy.

According to the BFKL and DGLAP approaches, which only include radiation of gluons, the gluon density increases linearly with energy, i.e. a fast growth of gluon distribution with increasing energy or decreasing \( x \). But this growth can not go on forever since this would lead to the violation of unitarity for physical cross section. As being pointed out firstly by Gribov, Levin and Ryskin [41] and later by Muller and Qiu [42] (GLR-MQ), some recombination processes of gluons with smaller \( x \) into gluons with larger \( x \) may slow down the growth of the gluon distribution function.

2.2.1 Properties of a CGC

CGC is an effective theory of QCD at high energy (small \( x \)) which extends the applicability of pQCD to a dense system of gluons [4, 43, 44, 45, 46, 47, 48]. In this system,
the density of gluons is high but limited, and small $x$ gluons are closely packed together. Strong interactions between partons become weak, i.e. $\alpha_s \ll 1$. This weakly coupled system is called a CGC [46, 47, 48] because of the reasons below:

**Color:** the gluons carry color charge.

**Glass:** gluons at smaller $x$ are generated from gluons at larger $x$, whose time scales are Lorentz time dilated for their large velocity in the infinite momentum frame, which corresponds to a slow evolution.

**Condensate:** gluons are very dense in hadrons, the high density limit of which is expected to be a Bose condensate because gluons are massless.

### 2.2.2 Applications of CGC to RHIC

The CGC model [4, 43, 44, 45, 46, 47, 48] has provided a valuable tool to study the interaction of hadrons and nuclei at relativistic energies. The idea that the rapid growth of the gluon distribution at high energy is tamed by gluon recombination leads to a saturated gluon density described by a saturation scale $Q_s$. Due to the high occupation numbers of the gluons, the system can be treated approximately by a classical field. In high energy nuclear collisions the gluon density in each nucleus is enhanced by a factor $\sim A^{1/3}$ due to the Lorentz contraction of the longitudinal size of the nucleus and it has been argued that the CGC can provide the initial conditions for the formation of the QGP [49].

CGC predicts a strong suppression of pion production at large rapidities, where small-$x$ value of about $10^{-3}$ can be reached. A comparison between the CGC calculation to the hadron multiplicity production at RHIC was made. One can see good agreements with data in figure 2.9. Another success of the model is the agreement with nuclear modification factors for hadrons in d+Au collision from the BRAHMS experiment. Figure 2.10 shows the comparison to $R_{dAu}$ from BRAHMS experiment [33],

![Diagrams showing gluon density at low and high energy](image-url)
Figure 2.9: Comparison of a CGC prediction to hadron multiplicity measurements in Au+Au (left) and d+Au (right) collisions at RHIC [44].

and figure 2.11 shows the comparison to $R_{CP}$.

Figure 2.10: Nuclear modification factor $R_{dAu}$ of charged hadrons at different rapidities. CGC calculation (curves) [45] and BRAHMS experimental data (points) [33].

The top two plots in figure 2.10 correspond to $\eta = 0$ and $1$, in which the solid line represents the $(h^- + h^+)/2$ contribution calculated with $\kappa = 0$ in the isospin-
Theoretical Concepts for Describing Nuclear Collisions

Figure 2.11: CGC calculation of nuclear modification factor $R_{CP}$ of charged particles $(h^+ + h^-)/2$ at mid-rapidity and $R_{CP}$ of negatively charged particles $h^-$ at forward rapidity (curves) [45], compared to BRAHMS experimental data (symbols) [33]. The solid symbols and lines stand for the $R_{CP}$ from central-to-pheripheral ratios, and open symbols and dashed lines are for $R_{CP}$ from semi-central-to-pheripheral ratios.

independent approximation\(^1\), the dashed lines give the same $(h^- + h^+)/2$ contribution but with $\kappa = 1$ GeV. The bottom two plots correspond to $\eta = 2.2, 3.2$, in which the solid lines give the $h^-$ contribution calculated in the constituent quark model with $\kappa = 0$, the dashed line gives the same $h^-$ contribution for $\kappa = 1$ GeV, while the dotted lines at $\eta = 2.2$ and 3.2 give the $(h^+ + h^-)/2$ contribution with $\kappa = 0$.

The top two plots in figure 2.11 correspond to pseudo-rapidity $\eta = 0$ and 1, and the bottom two correspond to $\eta = 2.2$ and 3.2. The solid curves and solid symbols stands for $R_{CP}$ from central-to-pheripheral ratios (0-20%/60-80%), and the dashed curves and open symbols gives that from semi-central-to-pheripheral ratios (30-50%/60-80%). Good agreement with the data is seen.

2.3 pQCD vs CGC

The unitarity can be naturally preserved by implementing the Glauber-Eikonal (GE) [53, 54, 55] approach [52], in which sequential multiple partonic collisions are computed in the framework of pQCD. As a result, the low $p_T$ spectra in p+A collisions are

\(^1\kappa\) is the typical non-perturbative scale [45]
suppressed by unitarity, but enhanced at moderate $p_T$ by the accumulation of transverse momentum. And on the other hand, high $p_T$ spectra in $p+p$ collisions are to be recovered, which suggests that no high $p_T$ shadowing would occur in this approach. Figure 2.12 shows the Cronin effect on pion production at Fermilab (left panel) and PHENIX experiment (middle panel for $R_{dAu}$ and right one for $R_{CP}$), compared to the GE computation (solid curves). pQCD explains the nuclear effects without the violation of unitarity.

## 2.4 Other theoretical models

Three main type of theoretical models have been developed in the past decades. They are hydrodynamical models, statistical models and microscopic models.

Hydrodynamical models treat nuclear matter under extreme conditions as an expanding relativistic fluid. Statistical models assume that thermal dynamical laws govern the hadron gas. Some results from several microscopic models will be presented, such as the Heavy Ion Jet Interaction Generator (HIJING) and A Multi-Phase Transport model (AMPT).

### 2.4.1 HIJING

HIJING [56], proposed by Gyulassy and Wang, is a QCD inspired model for multiple jets production. It is a Monte Carlo program designed to study jet and the associated particle production in high energy $p+p$, $p+A$ and $A+A$ collisions. The physics behind the program includes multiple mini-jet production, soft excitation, nuclear shadowing of parton distribution functions and jet interactions in dense matter. In this model, multiple mini-jet production is combined together with a Lund type string model for soft interactions ($p_T < 2 \text{ GeV}/c$). The number of binary collisions at a given impact parameter can be determined from a Glauber calculation [57, 9]. Dashed curves in figure 2.13 shows HIJING estimation to the pseudo-rapidity distributions of charged
particles in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with centralities determined from $N_{\text{part}}$ (solid curves are from AMPT model calculation).

2.4.2 AMPT

![Figure 2.13: Pseudo-rapidity distributions of charged particles in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with centralities determined from $N_{\text{part}}$. Solid and dashed curves represent results from the AMPT model and the HIJING model (without quenching), respectively [58].](image_url)

AMPT, developed by Ko et al., includes both final state partonic and hadronic interactions [59, 60, 61]. It consist of four components: the initial conditions, the parton cascade, the conversion from partonic to hadronic matter and the hadron cascade. The AMPT model uses the number of initial mini-jet partons from HIJING calculation as input, and Zhang’s parton cascade model (ZPC) [62] to describe interactions among mini-jet partons. After the partons stop interacting, they are recombined with their parents strings, which are produced from initial soft nucleon nucleon interactions, and fragment into hadrons according to the Lund string fragmentation model [63, 23]. The dynamics of resulting hadronic matter is described by a hadronic cascade based on the relativistic transport model [64]. Final hadronic observables including contributions from the strong decay of resonances are determined when the hadronic matter freezes out.

This model has been very useful for understanding various observables in Au+Au collisions at RHIC, such as the rapidity distribution and transverse momentum dis-
2.4 Other theoretical models

The parton recombination model is a final-state effect model. Recombination mechanism assumes a fast hadron can be created by the recombination of a hard parton with a slow anti-quark, which may come from the sea quarks in a hadron, or be generated from the excitation of a gluon. In the quark deconfined QGP (if it is formed), coales-
Figure 2.15: (left) The invariant yield for $\pi^+$ in 0%-20% $d+Au$ collisions as a function of $p_T$. The open circles are data points. (right) The invariant yields for $\pi^+$ in minimum bias and centrality selected $d+Au$ collisions as a function of $p_T$. The symbols represent STAR data points. The curves on the top of the symbols are the corresponding calculation results from recombination model. The figure is taken from [67].

Emission of the abundant thermal partons in the QGP might provide another important hadron production mechanism. At RHIC energies, the parton recombination model assumes that coalescence proceeds via constituent quarks in hadrons [65, 66].

Figure 2.16: (left) The invariant yield for $p$ at 0%-20% $d+Au$ collisions as a function of $p_T$. (right) The invariant yields for $p$ in minimum-bias and centrality selected $d+Au$ collisions as a function of $p_T$. The symbols represent STAR data points. The curves on the top of the symbols are the corresponding calculation results from recombination model. The figure is taken from [67].

In [67], a comparison between results for $d+Au$ collisions measured by the STAR experiment and the parton recombination model [65, 66] was made. Figure 2.15 shows...
the invariant yield for $\pi^+$ in d+Au collisions from STAR (symbols), compared to a parton recombination model calculation. Different centrality cases are shown in the right panel. Figure 2.16 shows the similar comparison for proton production.

These two figures show that the parton recombination model reproduces the spectra of pion and proton in minimum bias and centrality selected d+Au collisions at mid-rapidity in STAR. This agreement suggests that the Cronin enhancement may be not only an initial state effect (multiple scattering or gluon saturation), but that the final state effect (parton recombination) plays an important role too [67].
Chapter 3

RHIC and the BRAHMS Experiment

The data analyzed for this thesis were collected by the BRAHMS, one of the four experiments at RHIC during the physics run of d+Au collisions at full energy (\(\sqrt{s_{NN}} = 200\) GeV) in 2003 and p+p collisions in 2005. A brief introduction to the accelerator and a more specific introduction to the BRAHMS experiment will be given in this chapter.

3.1 The Relatistic Heavy Ion Collider

Figure 3.1: Schematic overview of the RHIC accelerator complex [68].
RHIC at the Brookhaven National Laboratory has a top beam energy of $\sqrt{s} = 100$ GeV per nucleon for nuclei of mass $A \sim 200$. Figure 3.1 shows a schematic overview of the complete accelerator complex, consisting of the Tandem Van de Graaff, the Booster Accelerator, the Alternating Gradient Synchrotron (AGS) and RHIC. The Tandem accelerator is used as an ion source. Beams from the Tandem are injected into the Booster for extraction and get stripped fully by colliding with one more stripping target on their way to the synchrotron (AGS). For the protons runs, 200 MeV protons from a LINAC are transferred to the Booster. Each bunch of ions from the Booster is accelerated to top AGS energy (28 GeV for protons; 11 GeV/nucleon for gold) and then transferred to the collider by a magnet system installed in the existing transfer line tunnels. 57 separate bunches of ions are injected into two RHIC rings (3833 m in total circumference for each ring) with opposite directions, which are identified as the blue and yellow beams. Thus, the RHIC machine could provide C.M. collision energies for gold beams ranging from $1.5+1.5$ GeV/nucleon to $100+100$ GeV/nucleon. For more detailed information see [69, 70].

At four of the six beam crossing points (see figure 3.1), the blue and yellow beams are brought to collision, where the four RHIC detectors (STAR [71], PHENIX [72], PHOBOS [73] and BRAHMS [74]) study the relativistic heavy ion collisions. In table 3.1 a full list of RHIC runs from 2000 up to the summer of 2006 is shown.

<table>
<thead>
<tr>
<th>Run Period</th>
<th>System</th>
<th>$\sqrt{s}$ [A GeV]</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run I</td>
<td>Au+Au</td>
<td>130</td>
<td>Summer 00</td>
</tr>
<tr>
<td>Run IIa</td>
<td>Au+Au</td>
<td>200</td>
<td>Autumn 01</td>
</tr>
<tr>
<td>Run IIb</td>
<td>p+p</td>
<td>200</td>
<td>Autumn 01</td>
</tr>
<tr>
<td>Run IIIa</td>
<td>d+Au</td>
<td>200</td>
<td>Winter 02/03</td>
</tr>
<tr>
<td>Run IIIb</td>
<td>p+p</td>
<td>200</td>
<td>Spring 03</td>
</tr>
<tr>
<td>Run IVa</td>
<td>Au+Au</td>
<td>200</td>
<td>Winter 03/04</td>
</tr>
<tr>
<td>Run IVb</td>
<td>Au+Au</td>
<td>62.4</td>
<td>Spring 04</td>
</tr>
<tr>
<td>Run IVb</td>
<td>p+p</td>
<td>200</td>
<td>Spring 04</td>
</tr>
<tr>
<td>Run Va</td>
<td>Cu+Cu</td>
<td>200</td>
<td>Winter 04/05</td>
</tr>
<tr>
<td>Run Vb</td>
<td>Cu+Cu</td>
<td>62.4</td>
<td>Spring 05</td>
</tr>
<tr>
<td>Run Va</td>
<td>p+p</td>
<td>200</td>
<td>Spring 05</td>
</tr>
<tr>
<td>Run Vfa</td>
<td>p+p</td>
<td>200</td>
<td>Spring 06</td>
</tr>
<tr>
<td>Run Vfb</td>
<td>p+p</td>
<td>62.4</td>
<td>Spring/Summer 06</td>
</tr>
</tbody>
</table>

Table 3.1: The running periods at RHIC until now.

### 3.2 The BRAHMS experimental Setup

BRAHMS is designed to measure charged hadron ($\pi^\pm$, $K^\pm$, $p$ ($\bar{p}$)) production over a wide pseudo-rapidity range $0 \leq \eta \leq 4.0$ ($2^\circ \leq \theta_{lab} \leq 90^\circ$) in relativistic nuclear collisions and to provide a very good particle identification [74]. The experiment consists of two moveable spectrometers, namely the mid-rapidity spectrometer (MRS) and the forward spectrometer (FS), and a set of global detectors, like Zero Degree Calorimeters (ZDC), inelasticity counters (INEL), Beam-Beam counters (BB) and Multiplicity Arrays (MA). It is located at the 2 o’clock intersection of the RHIC ring.
3.2 The BRAHMS experimental Setup

Figure 3.2: Schematic view of the BRAHMS experiment (top view). The mid-rapidity spectrometer (MRS) and forward spectrometer (FS) are rotatable.

Figure 3.2 shows the schematic layout of the BRAHMS experimental detector system. In the following, the detectors in the BRAHMS experimental apparatus shown in the figure will be briefly described.

3.2.1 Mid-rapidity spectrometer (MRS)

The mid-rapidity arm is a single dipole magnetic spectrometer of 8 mrs solid angle designed to cover the angular region 30-90°. It is designed to measure and identify particles with momenta in the range of \( p \sim 0.2 - 5 \text{ GeV}/c \). TPM1 and TPM2 are two Time Projection Chambers (TPCs) sitting on each side of the dipole magnet D5. TPCs determine the trajectories of charged particles within the TPC active volume and together with the magnet, their momenta and the interaction vertex. The time-of-flight is measured by the Time-Of-Flight Wall (TOFW), an array of 225 plastic scintillators placed 4 m away from the Interaction Point (IP). Each element is 22 cm high with a cross section of \( 0.6 \times 0.6 \text{ cm}^2 \), and it is instrumented with two fast photomultiplier tubes resulting in a time resolution of \( \sigma \leq 75 \text{ ps} \). This gives a \( \pi/K \) separation up to 2 GeV/c and a K/p separation to about 3.5 GeV/c.

3.2.2 Forward Spectrometer (FS)

The forward spectrometer arm contains four magnets, D1-D4, for sweeping and analyzing primary particles created in the collisions. There are two TPCs, T1 and T2 in the front forward spectrometer (FFS), and three drift chambers (DCs), T3, T4 and T5 in the back forward spectrometer (BFS), to measure the positions and thus the momenta of tracks.
Particle identification of particles with lower momentum is based on two time-of-flight hodoscopes, H1 and H2, with a time resolution $\sigma \leq 75$ ps. The H1 array, located 9 m away from the IP, can provide a $4\sigma$ separation of $\pi$ and K up to 3.3 GeV/$c$ and up to 5.7 GeV/$c$ for K/p. The H2 array is 20 m away from the IP, behind magnet D4, and can separate $\pi$ and K up to 5.0 GeV/$c$ and K and p to 8.5 GeV/$c$. For higher momentum particles, Čerenkov detectors are used. C1, at the end of the FFS, behind H1, is a conventional segmented Čerenkov tank. A ring imaging Čerenkov detector (RICH) with $C_4F_{10}$ as radiator gas, sitting behind H2 at the end of the BFS, is used to separate K and $\pi$ up to 25 GeV/$c$, and K and protons at even higher momenta.

### 3.3 Detectors

In this section, global detectors and tracking and PID detectors will be described in more detail.

#### 3.3.1 Global detectors and trigger system

In the BRAHMS experiment Beam-Beam counters, inelasticity counters, zero degree calorimeters and multiplicity arrays are used to provide global characteristics of collisions from which trigger decisions are derived (see figure 3.3).

![Top view of the BRAHMS experiment.](image)

**Figure 3.3:** *Top view of the BRAHMS experiment.*

**Beam-Beam counters (BB)**

Beam-beam counters [76] are designed to measure the primary vertex location along the z-axis. They consist of two arrays of fast Čerenkov radiators coupled to photomultipliers. The arrays are placed at 2.19 m on each side of the IP. Each array (left and right) is composed of two types of tubes for a finely segmented detection. Half
of the right array is missing to allow particles to fly undisturbed into the FS. The pseudo-rapidity covered by BB counters is \(2.2 < |\eta| < 4.6\). When charged particles hit the Čerenkov radiators, they produce Čerenkov photons if their velocity \(\beta\) is above the threshold \(c/n\) \((n \approx 1.5, \beta \approx 0.67)\). The intrinsic time resolution is 50 ps; for further characteristics of the BB counters cf. [74]. This detector is installed in almost all BRAHMS measurements, but in d+Au and p+p collisions its efficiency drops due to the small event multiplicity. Therefore, in d+Au and p+p collisions the vertex position is determined mainly by the INEL counters and the CC counters.

**Inelasticity counters (INEL)**

The inelasticity (INEL) counter system from the pp2pp experiment [77] was designed to have a high efficiency for detecting minimum bias double diffractive p+p events (95% of the total inelastic cross section), and it has been implemented in the BRAHMS d+Au and p+p runs. It is used as a minimum bias trigger, when signals from BB counters and ZDCs can not detect low multiplicity events. The INEL counter system consists of 8 rings of plastic scintillators, 4 on each side of the IP, positioned at \(z = \pm 75, \pm 155, \pm 416\) and \(\pm 660\) cm. Each ring has 4 scintillation plates surrounding the beam pipe and connected to a photomultiplier. By the difference of timing signals from a pair of rings from each side of the IP, collision vertices are determined with a resolution of \(\sim 5\) cm.

**CC counters**

In p+p collisions at \(\sqrt{s} = 200\) GeV (RUN V), the vertex is measured by a set of Čerenkov radiators (CC counters), which are placed symmetrically with respect to the interaction point. The Monte Carlo study using GEANT with PYTHIA generator shows that the CC counters measure 70±5% of the total inelastic proton-proton cross
Figure 3.5: The inelasticity counter setup. The eight rings are placed such that they cover angles from $0.58^\circ$ to $9.75^\circ$ on each side of the nominal interaction point. The figure is taken from [68].

section of 42 mb at 200 GeV, but only 80% of the total number of tracks reach the CC counters, which requires a correction of 87.5% on spectra in total due to this inefficiency from CC counters.

**Zero degree calorimeters (ZDC)**

Figure 3.6: Schematic view of the interaction region and the locations of the left and right ZDCs [68].

Zero degree calorimeters are the common detector for all RHIC experiments. RHIC operators also use them for beam intensity measurements [70]. The ZDCs are lead-tungsten calorimeters sitting at 18 m on each side of the IP, behind the focusing
3.3 Detectors

DX magnets, which sweep away charged nuclear fragments coming along with the neutrons. The ZDCs are designed to measure the spectator neutrons which continue at very small angles after the collisions. The measurement of neutrons are used for centrality determination, the arrival time can be used to determine the vertex of the collisions [74].

**Multiplicity array (MA)**

The multiplicity arrays measure the energy deposited by charged particles when they traverse the detector elements, from which the particle multiplicity and collision centrality can be calculated. The MAs consist of two hexagonal detector barrels that surround the interaction region and cover a pseudo-rapidity range $|\eta| < 2.2$. The inner part of the MA is a silicon detector and the outer part consists of plastic scintillator tiles. Details about the MAs and how the MAs can be used to determine the centrality is given in [79].

Figure 3.7 shows an example of the centrality cut by a GEANT simulation, which allows the calculation of the number of collisions for the centrality bin 30-60%. There is a 5% uncertainty for the total multiplicity inside the MA acceptance.

**Spectrometer trigger detectors**

Spectrometer trigger detectors are used to enhance the fraction of events which have at least one track in the spectrometers. The T0 detector in the MRS (MRST0) was used during the d+Au and p+p runs in 2003. It consists of 6 scintillator slats placed in front of TPM1. They cover the complete azimuthal $\phi$ acceptance of the spectrometer and $\pm 15$ cm in the $x$ direction (in front of TPM1). The MRST0 has two purposes: the signals from the 6 slats are used as an MRS trigger (trigger 3) in the d+Au and

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Run IIIa (d+Au)</th>
<th>Run V (p+p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BB</td>
<td>BB</td>
</tr>
<tr>
<td>2</td>
<td>FS</td>
<td>FS</td>
</tr>
<tr>
<td>3</td>
<td>MRS</td>
<td>MRS</td>
</tr>
<tr>
<td>4</td>
<td>ZDC</td>
<td>ZDC</td>
</tr>
<tr>
<td>5</td>
<td>INEL (MB)</td>
<td>CC</td>
</tr>
<tr>
<td>6</td>
<td>FFS</td>
<td>FFS</td>
</tr>
<tr>
<td>7</td>
<td>Pulser</td>
<td>Pulser</td>
</tr>
<tr>
<td>8</td>
<td>Sync.</td>
<td>Sync.</td>
</tr>
</tbody>
</table>

Table 3.2: Trigger overview for Run IIIa and Run V. Detailed information on the setup can be found in ref. [80].
p+p runs; the time signals were used as a start time for the TOFW and TFW2 time-of-flight measurements. The trigger counters used for the data which are analyzed for this thesis are listed in table 3.2.

Signals from single subdetectors or combinations of them are used to trigger the DAQ system to record data from all the detectors. Triggers are scaled down by different factors during data taking, which means only a certain fraction of the data is recorded. For instance, if we want to collect as many as possible FS events, we set the scale down factor for trigger 2 to 1; on the other hand, we have to consider the limited bandwidth of the DAQ system and the limited storage capacity of the system. INEL counters and CC counters are used to derive a minimum bias (MB) trigger. They are also used to determine the collision vertex in d+Au collisions in Run III and p+p collisions in Run V respectively.

### 3.3.2 Tracking detectors

The purpose of tracking detectors is to measure the trajectories of the produced particles by recording the energy deposited in the medium they traverse. In the BRAHMS experiment, the hits and the interactions between produced particles with the medium, are recorded by time projection chambers (TPCs) and drift chambers (DCs).

**Time projection chambers (TPC)**

BRAHMS has four TPCs, two in the FS spectrometer, namely T1 and T2, located behind magnets D1 and D2, and two in the MRS spectrometer, TPM1 and TPM2, sitting at the front and the back of the magnet D5. The TPCs are designed to provide high position resolution measurements of charged particle trajectories in 3 dimensions. Figure 3.8 shows an example of tracks found in TPM2. Characteristics of the four TPCs are listed in table 3.3

<table>
<thead>
<tr>
<th>TPCs</th>
<th>Width [cm]</th>
<th>Height [cm]</th>
<th>Length [cm]</th>
<th>Gas-mixture</th>
<th>N\textsubscript{row}</th>
<th>N\textsubscript{pads/row}</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>33.60</td>
<td>19.80</td>
<td>56.00</td>
<td>Ar-CO\textsubscript{2}</td>
<td>14</td>
<td>96</td>
</tr>
<tr>
<td>T2</td>
<td>39.60</td>
<td>19.80</td>
<td>75.50</td>
<td>Ar-CO\textsubscript{2}</td>
<td>16</td>
<td>112</td>
</tr>
<tr>
<td>TPM1</td>
<td>38.40</td>
<td>20.00</td>
<td>36.60</td>
<td>Ar-CO\textsubscript{2}</td>
<td>12</td>
<td>96</td>
</tr>
<tr>
<td>TPM2</td>
<td>67.68</td>
<td>19.80</td>
<td>50.00</td>
<td>Ar-CO\textsubscript{2}</td>
<td>20</td>
<td>144</td>
</tr>
</tbody>
</table>

Table 3.3: Summary of the main characteristics of TPCs. The gas-mixture is 90% Ar and 10% CO\textsubscript{2}. For more information about the TPCs see [74, 80, 81, 82].

**Drift chambers (DC)**

Three DCs (T3, T4 and T5) are located in the back arm of the FS spectrometer. They are multi-wire proportional chambers, and each of them is composed of three modules with 8-10 planes. With the spatial information coming from 3 modules combined, tracks can be reconstructed by the intersection of wires which were hit (see [74, 83, 84] for more details about drift chambers in BRAHMS). The tracking detectors thus provide information on positions and directions of local tracks.
Dipole magnets

BRAHMS has five magnets. D1 to D4 are in the FS spectrometer, and D5 is in the MRS. All are conventional dipole magnets, sitting between tracking chambers. Inside the magnets the field is approximately constant and has only a vertical component, i.e. particles are deflected only in the x direction. The acceptance of the BRAHMS experiment is determined by the magnetic field strength and the magnet gap dimension. The field strength determines that only particles within a certain momenta range can be deflected into the subsequent magnets or detectors. In table 3.4 the average momentum ($p$) are determined under various magnetic fields. For D1-D4, numbers like 1/8 and 1/5 etc. stand for the magnetic field as the fraction of the full field for each magnet, but for D5, corresponding numbers represent the fields in Gauss unit. In the

<table>
<thead>
<tr>
<th>magnet</th>
<th>gap dimension [cm]</th>
<th>$I_{max}$ [A]</th>
<th>$B_{max}$ [T]</th>
<th>aver. mom. $\langle p \rangle$/setting [GeV/c]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Width</td>
<td>Height</td>
<td>Length</td>
<td>1/8</td>
</tr>
<tr>
<td>D1</td>
<td>8.0</td>
<td>20.0</td>
<td>200.0</td>
<td>3400</td>
</tr>
<tr>
<td>D2</td>
<td>30.0</td>
<td>13.5</td>
<td>160.0</td>
<td>4000</td>
</tr>
<tr>
<td>D3</td>
<td>40.0</td>
<td>25.4</td>
<td>200.0</td>
<td>3000</td>
</tr>
<tr>
<td>D4</td>
<td>44.6</td>
<td>32.1</td>
<td>183.0</td>
<td>2750</td>
</tr>
<tr>
<td>D5</td>
<td>35.0</td>
<td>10.0</td>
<td>76.2</td>
<td>2500</td>
</tr>
</tbody>
</table>

|        | 164    | 350    | 500    | 700   | 1000 |
| D5     | 0.30   | 0.35   | 0.40   | 0.45  | 0.55 |

Table 3.4: Summary of the main characteristics of magnets used in the BRAHMS experiment. For more information about the magnets see [74, 80, 85].
FS, the A polarity is for detecting negative particles, and the B polarity for positive ones. In the MRS, due to large acceptance behind D5, a single polarity setting can detect particles with both positive and negative charges. Table 3.4 gives a list of the characteristics of the five magnets.

### 3.3.3 Particle identification (PID) detectors

#### Time-of-flight detectors

![Figure 3.9: Basic TOF principle. The figure is taken from [86]](image)

Particle identification is accomplished by a combination of two main techniques, namely Time-Of-Flight hodoscopes and Čerenkov detectors. In the MRS spectrometer, we used a time-of-flight wall (TOFW) and a Čerenkov radiator (C1), and in the FS spectrometer we used two TOF hodoscopes (H1 and H2) and a Čerenkov ring imaging detector (RICH) for PID. In the following, a brief overview over these two techniques is given.

<table>
<thead>
<tr>
<th>TOF name</th>
<th>distance from IP</th>
<th>species separation</th>
<th>maximum p (GeV/c) within 3-sigma cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>8.7 m</td>
<td>π/K</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K/p</td>
<td>6.5</td>
</tr>
<tr>
<td>H2</td>
<td>18.6 m</td>
<td>π/K</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K/p</td>
<td>9.7</td>
</tr>
<tr>
<td>TOFW</td>
<td>4.3 m</td>
<td>π/K</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K/p</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Table 3.5: Performance of the TOF PID devices in BRAHMS (with a 3-σ cut); parameters are taken from [85].

Table 3.5 shows the basic characteristics of the TOF systems used in the BRAHMS experiment, H1 and H2 in the FS and TOFW in the MRS. Each TOF consists of a row of rectangular scintillator slats wrapped in aluminum foil for guiding the light, and dark tape for light insulation. When a charged particle traverses through a plastic scintillator, molecules along its path are excited. The de-excitation produces photons, which are collected by the PMTs at the ends of the slat. See figure 3.9 for the basic principle of TOF.
From the measurement of the time-of-flight and the path length of the track one can calculate the velocity by \( \beta = \frac{L_{\text{path}}}{c t_{\text{tof}}} \). The identification is done by evaluating the \( m^2 \) of the particle when the velocity and the momentum of the particle are known,

\[
m^2 = p^2 \left( \frac{1}{\beta^2} - 1 \right). \tag{3.1}
\]

Čerenkov detectors

All Čerenkov detector designs are based on the fact that a charged particle with a velocity \( \beta \) larger than the speed of light in the medium \( c/n \) emits electromagnetic radiation when traversing the medium whose refractive index is \( n > 1 \). BRAHMS has three Čerenkov detectors, C1 and C4 are threshold Čerenkov detectors in the FFS and MRS, and RICH is a ring imaging Čerenkov detector (BFS). They all use the same radiator gas \( \text{C}_4\text{H}_{10} \).

C1 and C4, are similarly designed as a single volume of radiator gas. At the back of the volume, two mirrors reflect the emitted Čerenkov light up or down to arrays of photomultiplier (PM) tubes. There are 32 PM tubes in C1, and 16 in C4. A side view of C1 is shown in figure 3.10. When a charged particle traversing the radiator gas volume has a velocity above the light speed in the gas \( \nu_{\text{threshold}} \) it will give a signal.

The RICH consists of a radiator gas volume, a spherical mirror which reflects and focuses the emitted Čerenkov photons and a segmented photons detection plane. From the radius of the ring on the image plane, the velocity of the particle can be calculated from the Čerenkov angle \( \theta_C \),

\[
\tan \theta_C = \frac{r}{L_f}, \cos \theta_C = \frac{1}{\beta n}, \tag{3.2}
\]
where $L_f = 150$ cm is the focal length of the mirror, $\beta$ is the velocity of the particle and $n$ is the refractive index of the gas in the volume. Then finally the mass square of the particle can be reconstructed according to equation 3.1, by which particles can be identified. Figure 3.11 shows a side view of the RICH, and figure 3.12 shows a typical ring image found by the ring finding algorithm [74].

---

**Figure 3.11:** *Side view of the RICH. The emitted Čerenkov photons are reflected on the mirror and form a ring image on the sensitive image plane. The line with arrows in the horizontal direction (red) represent a particle track through the detector and all the other lines indicate the photon reflection on the mirror.*

**Figure 3.12:** *An example of a ring image on RICH. For details see [68, 74].*
Acceptance

The spectrometers described above determine the rapidity and momentum coverage of the BRAHMS experiment. The following figure shows the acceptance in $y$-$p_T$ for identified hadrons after combining different angle and magnetic field settings. Analysis details will be discussed Chapter 4.

Figure 3.13: BRAHMS acceptance maps for pions (upper panel), kaons (middle panel) and protons (lower panel). The regions with different patterns represent the $y$-$p_T$ coverage for different spectrometer settings, and PID methods as indicated in the legend on the top right corner in the upper panel. The figure is taken from [85].
Chapter 4

Spectra Analysis

Raw data, mainly the analog to digital convertor (ADC) and the time to digital convertor (TDC) signals, have to be transformed into physics data, from which a physics analysis can be carried out. The process of transforming raw data to physics data is called event reconstruction. The basic procedure of the reconstruction consists of detector calibration, tracking, the reconstruction of the primary vertex (interaction point), the momentum determination of tracks and the particle identification (PID).

Detailed descriptions of the detector calibrations are given in [86, 87], and in [86, 68] one can find the basic ideas of the event reconstruction processes, which are therefore not repeated here. This chapter will focus on the physics analysis, namely the analysis method starting from the reconstructed data summary tree (DST) to obtain normalized identified particles spectra in d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV in run IIIa (2003) and run V (2005).

The spectrum is defined as the invariant cross section in a narrow rapidity $y$ interval as a function of transverse momentum

$$f(p_T) = \frac{1}{N_{evt}} \frac{d^2N}{2\pi p_T dy dp_T}, \quad (4.1)$$

where $N_{evt}$ is the total number of events. All necessary steps to obtain the identified particles spectra, such as event and track selections, corrections (including tracking efficiency, multiple scattering and decay correction, geometrical acceptance corrections and particle identification efficiency), as well as particle identification methods are discussed in this chapter.

4.1 Data selection

Table 4.1 gives a list of all the data sets collected by the BRAHMS experiment in d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV which are used in this analysis, for both MRS and FS. A (B) is the polarity of the magnets, as mentioned earlier in Chapter 3. In the MRS settings, 90°, 60°, 45°, 40° and 34° are the angles of the MRS arm relative to the beam pipe. Numbers after the polarity, 2255, 2000, 1050, 700, 500 and 350, are the fields strength in Gauss unit. In the FS settings we have data with the FS arm at angles 4° and 2.3°, and with field strengths of 3450, 2442, 1723, 1692, 861 (843)
Table 4.1: All data settings in d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV used in the analysis for this thesis.

and 430 Gauss. In the following, selections of data, more specifically, cuts on global variables and local tracks are explained in detail.

4.1.1 Event and track selection

For the event selection, a number of cuts are implemented in order to obtain clean data for physics analysis.

Global selection

Events are selected by different triggers. MRS events are defined by the MRS spectrometer trigger, i.e. trigger 3, while FS events are determined by trigger 2, which is an FS spectrometer trigger, in both d+Au and p+p data, as listed already in table 3.2. The spectrometer trigger conditions are given by an energy deposition above a threshold in the MA corresponding to 20% central events and a BB vertex restriction consisting of a narrow time difference between left and right arrays and a track in the spectrometer. As explained earlier in Chapter 3, spectrometer triggers are usually not scaled down during the data taking, which means that all events satisfying the trigger conditions have been recorded.

Minimum bias triggers are used to count the total number of events, which is essential for the normalization of the spectra. For d+Au collisions in Run III the INEL counters determine trigger 5. For p+p collisions in Run V, the reaction rate from the CC counters was used for the normalization purpose. Cuts are applied to the MRS/FS events in order to select good events. A cut on the vertex determined by global detectors (INEL counters or CC counters) selects events within the certain range around the interaction point. For MRS/FS events a cut on the vertex range [-30 cm, 30 cm] is used in d+Au collisions, and [-40 cm, 40 cm] in p+p collisions.

A centrality cut has been implemented in the d+Au analysis for the centrality dependence study. The centrality was determined from the MA charged particle multiplicity. The uncertainty on the centrality determination comes from the uncertainty in the minimum bias trigger efficiency and from the finite statistics and binning of the distribution from which the centrality is determined. Spectra of particles for three centrality bins 0-30%, 30-60%, 60-80% and in minimum bias events have been constructed; see table 4.2 for a summary of the cuts at event selection level.
4.1 Data selection

<table>
<thead>
<tr>
<th>Cuts</th>
<th>d+Au √s_{NN} = 200 GeV</th>
<th>p+p √s = 200 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex</td>
<td>−30 cm ≤ V_Z(INEL) ≤ 30 cm</td>
<td>−40 cm ≤ V_Z(CC) ≤ 40 cm</td>
</tr>
<tr>
<td>MB trigger</td>
<td>trigger 5 (INEL)</td>
<td>-</td>
</tr>
<tr>
<td>MRS trigger</td>
<td>trigger 3</td>
<td>trigger 3</td>
</tr>
<tr>
<td>FS trigger</td>
<td>trigger 2</td>
<td>trigger 2</td>
</tr>
<tr>
<td>FFS trigger</td>
<td>trigger 6</td>
<td>trigger 6</td>
</tr>
<tr>
<td>Centrality</td>
<td>MB, 0-30%, 30-60%, 60-80%</td>
<td>MB</td>
</tr>
</tbody>
</table>

Table 4.2: Event selection at global level, cuts on vertex position in beam direction, selection of spectrometer trigger, and centrality cuts.

Track selection

Figure 4.1: Selected tracks by cutting on the $\chi^2$ of tracks (the curve represents the $\chi^2$ function) at FS. A factor of 4 is used for the FS settings (this setting is 4A3450). The solid curve is the empirical function.

The electrostatic field and thus the drift velocity close to the walls of the TPC field cage are not perfectly uniform, which results in distorted local track segments. By implementing fiducial cuts on the magnet gaps one can remove those tracks. Usually a volume with a width of 1 cm is removed in both $x$ and $y$ direction. Alternatively, as done in this analysis, a cut on the $\chi^2$ removes those tracks. The $\chi^2$ has been calculated by matching local tracks from different tracking detectors. A track with a certain momentum $p$ which has a $\chi^2$ value larger than a value determined by an empirical function

$$f(p) = \text{factor} \times (28.5 + 180.0/p) ,$$

is removed from the track sample ($p$ is the momentum in units of GeV/c). Factors of 4 and 10 are chosen for the FS and MRS respectively. An example of the effects of such cuts on $\chi^2$ is shown in figure 4.1 for the FS. Only very few percent of the tracks are removed by the cut on $\chi^2$.

A fiducial cut was applied to the RICH. In p+p collisions, a narrow fiducial cut on TPM2 at MRS is implemented because the TOFW behind it was inefficient for
a range of certain slats. The dead slats range is excluded by defining the good slats both in the acceptance map generation and in the cuts on tracks.

![3-σ cut on TOF matching (MRS)](image)

**Figure 4.2:** *An example of a 3-σ cut on the matching between hits on TOFW and tracks.*

Tracks which do not have a matching hit in the TOF detector are removed by a 3-σ cut on the difference in $y$:

$$\frac{\Delta y - \Delta y_{off set}}{\sigma_{\Delta y}} \leq N_\sigma ,$$  \hspace{1cm} (4.3)

where $\Delta y = y_{track} - y_{hit}$ is the difference between the $y$-coordinates of the reconstructed track and that of the hits on TOFW, $\Delta y_{off set}$ is the offset of the $\Delta y$ distribution, and $\sigma_{\Delta y}$ is the width. Figure 4.2 is an example of a 3-σ cut on the matching between hits on TOFW and tracks.

The last criterion is the selection of primary tracks. Not all the particles detected by the spectrometers come from the primary collisions. One has to compare the track vertex, which is defined as the projection of the front part of the global track to the $z$-$y$ plane (the beam pipe defines the $z$ direction) with the primary vertex in order to reject most of the secondary particles. The intersection with the plane gives the track vertex in $y$-$z$ plane, i.e $V_y$ and $V_z$. In d+Au and p+p collisions the following condition is used for the primary track selection (for both MRS and FS)

$$\left( \frac{\Delta V_z - \Delta V_{z off set}}{\sigma_{\Delta V_z}} \right)^2 + \left( \frac{V_y - V_{y off set}}{\sigma_{V_y}} \right)^2 \leq N_\sigma^2 ,$$  \hspace{1cm} (4.4)

where $\Delta V_z = V_{z global} - V_{z track}$. In d+Au collisions $V_{z global} = V_{z INEL}$. In p+p collisions $V_{z global} = V_{z CC}$. Figure 4.3 shows an example of primary track selection for both MRS (left) and FS (right). Typically, few percent of the total tracks are removed. Table 4.3 gives a summary of all the parameters used in this analysis.
Figure 4.3: An example of primary track selection at both MRS (left) and FS (right). Scattered points are the data before track selection, and the contours (colored) represent the selected tracks.

<table>
<thead>
<tr>
<th>Cuts for track selection</th>
<th>d+Au $\sqrt{s_{NN}} = 200$ GeV</th>
<th>p+p $\sqrt{s} = 200$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial cuts at FS</td>
<td>D1 X: 0 cm, Y:0 cm</td>
<td>D1 X: 0 cm, Y:0 cm</td>
</tr>
<tr>
<td></td>
<td>RICH X: 20 cm, Y:15 cm</td>
<td>RICH X: 20 cm, Y:15 cm</td>
</tr>
<tr>
<td>Fiducial cuts at MRS</td>
<td>D5 X: 0 cm, Y:0 cm</td>
<td>D5 X: 0 cm, Y:0 cm</td>
</tr>
<tr>
<td></td>
<td>TPM2 X: (-20 cm,8 cm)</td>
<td>TPM2 X: (-20 cm,8 cm)</td>
</tr>
<tr>
<td>TOFW slats range</td>
<td>33-110</td>
<td>33-110</td>
</tr>
<tr>
<td>$\chi^2$ cut at FS</td>
<td>factor = 4</td>
<td>factor = 4</td>
</tr>
<tr>
<td>$\chi^2$ cut at MRS</td>
<td>factor = 10</td>
<td>factor = 10</td>
</tr>
<tr>
<td>Matching TOF hits and tracks</td>
<td>3-σ</td>
<td>3-σ</td>
</tr>
<tr>
<td>Primary track selection</td>
<td>3-σ</td>
<td>3-σ</td>
</tr>
</tbody>
</table>

Table 4.3: Track selections including fiducial cuts on magnets, and PID detectors, and cuts on tracks in beam direction, selection of spectrometer trigger.

### 4.2 Particle Idenfication

#### 4.2.1 Particle identification by Time-of-Flight

As described earlier in Chapter 3, particle identification can be done by calculating $m^2$ of the particles by the relation between $p$ and $\beta$

$$m^2 = p^2 \left( \frac{1}{\beta^2} - 1 \right), \quad (4.5)$$

from which the TOF $m^2$ resolution can be derived according to the error propagation [86]

$$\left( \frac{\sigma_{m^2}}{m^2} \right)^2 = 4 \frac{\sigma_p^2}{p^2} + 4 \frac{\sigma_\beta^2}{\beta^2 (1-\beta^2)^2}, \quad (4.6)$$

where $\sigma_p$ and $\sigma_\beta$ are the resolution of momentum $p$ and velocity $\beta$. $\sigma_p^2/p^2$ can be parametrized by $\sigma_p^2/p^2 = p^2 \sigma_{\text{angular}} + (1 + m^2/p^2) \sigma_{\text{ms}}^2$ [86], where $\sigma_{\text{angular}}$ is the track...
angular resolution and depends on the field setting, $\sigma_{ms}$ takes multiple scattering into account, and the velocity resolution $\beta$ can be parametrized by $\sigma_\beta^2 \equiv \sigma_t = c\sigma_{t,\mathrm{TOF}}/L$ \cite{86}. Thus, the $m^2$ resolution becomes

$$
\sigma_{m^2}^2 = 4\left[(m^2 + p^2)^2\sigma_t^2 + m^4p^2\sigma_{\text{angular}}^2 + m^4(1 + m^2/p^2)\sigma_{ms}^2\right]. \quad (4.7)
$$

Figure 4.4 shows an example of the measured $m^2$ distribution as a function of the momentum by TOFW (MRS), in which the curves indicate $\pm 2\sigma_{m^2}$ around the $m^2$ for pions, kaons and protons. Three parameters in this function, namely $\sigma_t$, $\sigma_{\text{angular}}$, and $\sigma_{ms}$, are obtained by fitting simultaneously the width of $m^2$ in narrow momentum intervals in a range of $m^2$ of $[-0.1, 0.1]$, $[0.15, 0.35]$ and $[0.6, 1.2]$ for pions, kaons and protons respectively. The parameters for different settings (MRS) in d+Au and p+p collisions which are used in this thesis are given in table 4.4 and table 4.5.

![Figure 4.4: Particle identification by TOFW by a simultaneous fit using equation 4.7, A 2-$\sigma$ cut on $m^2$ width was used.](image)

**Table 4.4: Particle identification by TOFW (MRS): resolution parameters for different settings in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.**

<table>
<thead>
<tr>
<th>settings</th>
<th>$\sigma_t$</th>
<th>$\sigma_{\text{angular}}$</th>
<th>$\sigma_{ms}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>90A1050</td>
<td>0.014</td>
<td>0.009</td>
<td>0.010</td>
</tr>
<tr>
<td>90B1050</td>
<td>0.018</td>
<td>0.025</td>
<td>0.008</td>
</tr>
<tr>
<td>90A350</td>
<td>0.013</td>
<td>0.014</td>
<td>0.027</td>
</tr>
<tr>
<td>90B350</td>
<td>0.018</td>
<td>0.0001</td>
<td>0.043</td>
</tr>
<tr>
<td>40A1050</td>
<td>0.014</td>
<td>0.0001</td>
<td>0.012</td>
</tr>
<tr>
<td>40B1050</td>
<td>0.015</td>
<td>0.0001</td>
<td>0.010</td>
</tr>
<tr>
<td>40A500</td>
<td>0.014</td>
<td>0.0001</td>
<td>0.027</td>
</tr>
<tr>
<td>40B500</td>
<td>0.012</td>
<td>0.0001</td>
<td>0.026</td>
</tr>
<tr>
<td>40B2000</td>
<td>0.010</td>
<td>0.0001</td>
<td>0.006</td>
</tr>
</tbody>
</table>

The performance of the two time-of-flight hodoscopes H1 and H2 in the FS is not as good as expected. Figure 4.5 shows the $m^2$ distribution measured by H1 and H2 at forward rapidity. Setting 4A3450 in the d+Au collisions is used as an example. No reliable particle identification can be done for most of the runs. Therefore, one has to rely on the RICH detector for PID in the FS.

### 4.2.2 Particle identification by Čerenkov detectors

As mentioned earlier in Chapter 3 two types of Čerenkov detectors were used. One is a threshold detector (C1 and C4) and the another one is a RICH. In the d+Au and p+p runs the threshold detectors were not efficient, thus in the analysis for the thesis RICH
Table 4.5: Particle identification by TOFW (MRS): resolution parameters for different settings in $p+p$ collisions at $\sqrt{s} = 200$ GeV.

<table>
<thead>
<tr>
<th>settings</th>
<th>$\sigma_t$</th>
<th>$\sigma_{\text{angular}}$</th>
<th>$\sigma_{ms}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>90A2255</td>
<td>0.008</td>
<td>0.0001</td>
<td>0.008</td>
</tr>
<tr>
<td>90B2255</td>
<td>0.009</td>
<td>0.008</td>
<td>0.007</td>
</tr>
<tr>
<td>90A1050</td>
<td>0.008</td>
<td>0.0001</td>
<td>0.013</td>
</tr>
<tr>
<td>90B1050</td>
<td>0.008</td>
<td>0.0001</td>
<td>0.013</td>
</tr>
<tr>
<td>60A700</td>
<td>0.008</td>
<td>0.0001</td>
<td>0.024</td>
</tr>
<tr>
<td>60B700</td>
<td>0.008</td>
<td>0.0001</td>
<td>0.025</td>
</tr>
<tr>
<td>45A1050</td>
<td>0.008</td>
<td>0.009</td>
<td>0.012</td>
</tr>
<tr>
<td>45B1050</td>
<td>0.009</td>
<td>0.009</td>
<td>0.013</td>
</tr>
<tr>
<td>45A700</td>
<td>0.007</td>
<td>0.0001</td>
<td>0.034</td>
</tr>
<tr>
<td>45B700</td>
<td>0.008</td>
<td>0.0001</td>
<td>0.021</td>
</tr>
<tr>
<td>40A700</td>
<td>0.007</td>
<td>0.0001</td>
<td>0.034</td>
</tr>
<tr>
<td>34B2255</td>
<td>0.008</td>
<td>0.006</td>
<td>0.005</td>
</tr>
<tr>
<td>34A700</td>
<td>0.009</td>
<td>0.0003</td>
<td>0.021</td>
</tr>
<tr>
<td>34B700</td>
<td>0.008</td>
<td>0.016</td>
<td>0.020</td>
</tr>
</tbody>
</table>

Figure 4.5: $m^2$ measurement by $H1$ and $H2$. Setting 4A3450 (FS) in $d+Au$ collisions is used as an example. There are no peaks.

was the only Čerenkov detector used for particle identification at FS. The ring finding algorithm reconstructs the radius of the ring image on the RICH surface and one can identify particles by calculating their mass from their ring radius by equation 3.2 and get

$$m^2 = p^2 \left( \frac{1}{(n \cos \theta_c)^2} - 1 \right) = p^2 \left( \frac{n^2 L_f^2}{L_f^2 + r^2} - 1 \right),$$

where $L_f = 150$ cm is the focal length and $n$ is the refractive index of the gas in the RICH. $n$ is constant for a certain range of runs. Table 4.6 shows the change of the index with run number.

The relation between ring radius $r$ and particle momentum $p$ is derived from equa-
Spectra Analysis

<table>
<thead>
<tr>
<th>run range</th>
<th>8173-8306</th>
<th>8307-8459</th>
<th>8524-8543</th>
<th>for all p+p data</th>
</tr>
</thead>
<tbody>
<tr>
<td>refractive index</td>
<td>1.00193</td>
<td>1.00188</td>
<td>1.00173</td>
<td>1.00172</td>
</tr>
</tbody>
</table>

Table 4.6: Refractive index vs run number.

![Graph showing refractive index vs run number](image)

Figure 4.6: An example of the direct PID method by the RICH: the ring radius as a function of momentum. The solid curves are defined by equations 4.10 and 4.11, the dashed line is determined by equation 4.9, where $\delta r = n_\sigma \cdot \sigma_r$, and a $n_\sigma = 3$ cut are used.

Equation 3.2

$$r = L_f \tan \left[ \cos^{-1} \frac{1}{n} \sqrt{1 + \frac{m^2}{p^2}} \right]. \tag{4.9}$$

The calculation of the particle selection envelope is defined by the following equations:

$$r_{\text{upper}} = L_f \tan \left[ \cos^{-1} \frac{1}{n} \sqrt{1 + \frac{m^2}{(p + \Delta p)^2}} \right] + \Delta r; \tag{4.10}$$

$$r_{\text{lower}} = L_f \tan \left[ \cos^{-1} \frac{1}{n} \sqrt{1 + \frac{m^2}{(p - \Delta p)^2}} \right] - \Delta r. \tag{4.11}$$

The ring radius is assumed to have an uncertainty of $\Delta r = 0.45$ cm, and the uncertainty of the momentum for each species is 0.4, 0.6 and 0.8 GeV/c for pions, kaons and protons respectively; $m$ is the rest mass. Figure 4.6 shows the particle identification by the envelopes as defined above.
4.2.3 Treatment of RICH inefficiency

In the data analysed for this thesis, the RICH detector has not always been 100% efficient to give ring images for all particles above their momentum threshold, or the ring finding algorithm did not reconstruct all the rings on the mirror. Particles which did not give rings in the RICH were recorded as having \( r = 0 \). We can try to identify those particles by the time-of-flight hodoscopes in the FS spectrometer (H1 and H2). The information from hodoscopes H1 and H2 can only be used for certain runs/settings.

Figure 4.7 gives an example of the reconstructed \( m^2 \) correlation from H1 and H2. From the projection onto each axis, a 2-\( \sigma \) cut was made on two Gaussian fits centered at the kaon and proton \( m^2 \) to separate kaons and protons (\( \bar{p} \)) in cases where the
particles did not give reconstructable ring images on the RICH.

When H1 and H2 are not available for PID and the ring radius is zero, an indirect method is used to identify protons. For particles without a ring image on RICH, if their momenta are above the kaon threshold and below that of the proton, namely $10 \text{ GeV}/c < p < 17 \text{ GeV}/c$, the particle is regarded as a proton with a certain contamination of pions and kaons. The contamination introduced by this indirect method will be estimated later in the PID efficiency correction discussion.

### 4.3 Corrections

BRAHMS can only measure the produced particles from hadronic collisions in a very small solid angle due to the small geometrical acceptance of the magnetic spectrometers. Spectra measured in a small solid angle have to be corrected by the geometrical acceptance to obtain the yield in $2\pi$. The geometrical correction is done by multiplying the number of detected particles by a factor of $2\pi/\Delta \phi$ where $\Delta \phi$ is the azimuthal coverage of the spectrometer. Additional factors $1/\Delta y (or \Delta \eta)$ and $1/\Delta p_T$ normalize the yield per unit rapidity and $p_T$. Furthermore, the spectra have to be corrected for the trigger counter inefficiency. This correction has to be considered in the analysis of the p+p data of Run V.

The efficiency of the detector has to be taken into account to restore the produced particles’ real spectra, i.e. trigger efficiencies (both minimum bias trigger and spectrometer trigger efficiencies), tracking efficiencies of the Drift Chambers (DCs) and the Time Projection Chambers (TPCs). In addition, other effects such as the decay and absorption of the produced particles in the materials, multiple scattering, secondary interactions in the beam pipe and detector materials have to be estimated.

#### 4.3.1 Geometrical acceptance correction

The geometrical acceptance is defined as the fraction of the particles we can detect by our spectrometers in a narrow $y$-$p_T$ bin

$$\text{Acceptance}(p_T, y) = \frac{\text{detected number of particles}}{\text{total number of produced particles}}. \quad (4.12)$$

A Monte Carlo simulation is used to estimate the acceptance. Exactly the same geometry and magnetic fields as those in the real data-taking are used in the BRAHMS GEANT (BRAG) simulation to generate the acceptance maps for different settings, namely different polar angle and magnetic field combinations. By tracing a very large number of charged particles with certain momentum from the same vertex through the spectrometer and counting the accepted particles which fall inside the fiducial volumes, the fraction of the accepted particles comparing to the total number of thrown particles can be calculated as

$$\epsilon_{\text{geom}}(p_T, y) = \frac{\text{accepted number of particles}}{\text{total number of thrown particles}} \times \frac{\Delta \phi}{2\pi}. \quad (4.13)$$

The fractions in each two dimensional $\Delta p_T$-$\Delta y$ bin for all vertex bins are the acceptance maps. The content of the acceptance map in each $\Delta p_T$-$\Delta y$ bin for a certain
vertex range shows the azimuthal ($\phi$) acceptance of that $\Delta p_T$-$\Delta y$ bin. Figure 4.8 shows a typical geometrical acceptance map.

### 4.3.2 Tracking efficiency correction

The tracking efficiency in the MRS is studied using a track embedding method [82]. Tracks are generated by a Monte Carlo simulation, within the acceptance of the MRS and merged with raw data. They are then reconstructed according to the same processing procedures as the raw data. Tracking efficiencies are determined by

$$
\epsilon_{\text{trk}}^{\text{embedding}} = \frac{\text{number of reconstructed tracks}}{\text{number of embedded tracks}}.
$$

(4.14)

The results from [82] are used in the MRS analysis for this thesis

$$
\varepsilon(H) = p_0 + p_1 \cdot H,
$$

(4.15)

where $p_0$ and $p_1$ are fit parameters, and $H$ is the total number of hits (occupancy) in the MRS. Typical values of $H$ are below 10 in both d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV. Table 4.7 gives the tracking efficiency functions at MRS, which are used in this analysis.

<table>
<thead>
<tr>
<th>particle species</th>
<th>pion</th>
<th>kaon</th>
<th>proton</th>
</tr>
</thead>
<tbody>
<tr>
<td>eff. function</td>
<td>$0.948 - 9.6 \cdot 10^{-9} \cdot H$</td>
<td>$0.955 - 9.0 \cdot 10^{-9} \cdot H$</td>
<td>$0.959 - 7.2 \cdot 10^{-9} \cdot H$</td>
</tr>
</tbody>
</table>

Table 4.7: Tracking efficiency function for pions, kaons and protons as a function of the total number of hits (MRS). Functions and parameters are the results from [82].
Figure 4.9: T1 efficiency as a function of centrality, horizontal hit position in the detector and track momentum in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

The tracking efficiency in the FS is calculated by a reference track method [88]. The tracking efficiency for each detector is estimated by comparing the number of tracks fully reconstructed by all detectors except the one under investigation and the number of tracks by matching track segments in itself:

$$\epsilon^{\text{reference}}_{\text{trk}} = \frac{\text{number of tracks having a matching track segment in the detector}}{\text{number of tracks fully reconstructed by all other detectors}}.$$  \hspace{1cm} (4.16)

Figure 4.9 shows the centrality (upper), the horizontal hit position in the detector (middle) and the track momentum (lower) dependence of the tracking efficiency of T1 in d+Au collisions.

In the final analysis, the tracking efficiency at the FS is calculated by

$$\epsilon^{\text{FS}}_{\text{trk}} = \epsilon_{T1} \cdot \left[ \epsilon_{T2} \cdot (1 - \epsilon_{T3}) \right] \cdot \epsilon_{T4} \cdot \epsilon_{T5}$$  \hspace{1cm} (4.17)
for tracks with only T1, T2, T4 and T5 segments, or

$$\epsilon_{trk}^{FS} = \epsilon_{T1} \cdot \epsilon_{T2} \cdot \epsilon_{T3} \cdot \epsilon_{T4} \cdot \epsilon_{T5}$$  \hspace{1cm} (4.18)$$

for regular FS tracks with T1, T2, T3, T4, and T5 segments.

Figure 4.10: An example of the tracking efficiency as a function of momentum for setting 4B3450 (FS).

Figure 4.10 shows a typical momentum dependence of the FS tracking efficiency in d+Au collisions. The efficiency is around 90% and shows little dependence on the track momentum.

4.3.3 PID efficiency correction

Time of flight efficiency

The efficiency of TOFW in the MRS is determined by its geometry. 4 panels of slats are in the TOFW in the MRS, and are stacked together in a single row. Therefore tracks can pass through the wrapping of the slats, and the energy deposition in the slat becomes too low to allow the hit to be reconstructed. The efficiency is studied by reference track method [88] and can be estimated by equation 4.19,

$$\epsilon = \frac{N_{identified}}{N_{reference}}.$$  \hspace{1cm} (4.19)$$

where $N_{identified}$ is the number of identified reference tracks and $N_{reference}$ is the total number of reference tracks. No slat dependence has been observed in the MRS and the efficiency of TOFW is found to be $\sim 93 \pm 2\%$ [87].
RICH efficiency

The PID efficiency by the RICH detector has been calculated as 97% for all settings and for particles above the pion threshold 3 GeV/c producing ring images in the RICH using a GEANT simulation. But for protons (anti-protons) identified by the indirect method in the range 10 GeV/c < p < 17 GeV/c the extent of contamination by pions and kaons needs to be determined. A study on contamination in Au+Au collisions has been done [89] in the BRAHMS collaboration, and a 3% inefficiency was discovered to correct the contaminated protons. Due to the stable performance of the RICH detector throughout all physics runs in the BRAHMS experiment, these 3% are used in this analysis.

4.3.4 Physics corrections by BRAG/GEANT

![Graphs showing physics corrections by BRAG simulations.](image)

Figure 4.11: Physics corrections by BRAG simulations, for multiple scattering, decay and absorption of particles when traversing the detectors.

Corrections of effects due to multiple scattering, decay and absorption of produced hadrons are treated separately by a BRAG simulation. For each particle species $\pi^+$, $\pi^-$, $K^+$, $K^-$, $p$ and $\bar{p}$, primary particles within the geometrical acceptance are simulated with a given momentum at different angles. The BRAG/GEANT simulations are carried out with the following conditions. (1) The BRAG setup is done for each angle for both MRS and FS; (2) Single particles are thrown at the nominal angle $\sim \pm 0.2^\circ$; (3) The magnetic fields are scaled according to the momentum so that the ideal tracks follow the same path for each field setting. Physics processes in the simulations, namely multiple scattering, decay and absorption, are switched on and off to calculate the corrections for each particle. The simulation output is treated as the real data, including digitization, track reconstruction and DST production. DSTs are analyzed as real data, from which the correction can be obtained by dividing the results with physics processes switched on by those with physics process switched off.
Figure 4.11 shows an example of the corrections as a function of momentum in both MRS and FS.

### 4.4 Normalization and spectra construction

#### 4.4.1 Corrections and normalization

The counts of identified hadrons in each $y$-$p_T$ bin have been corrected as explained above, and a normalization factor of $2\pi N_{\text{evt}}$ has been applied. Spectra for each particle species $i$ in a certain rapidity range are thus given by

$$
\frac{d^2N^i(p_T, y)}{2\pi N_{\text{evt}} p_T dp_T dy} = \frac{N^i_{\text{data}}(p_T, y)}{2\pi N_{\text{evt}} p_T \Delta p_T \Delta y} \times \text{Corr}_{\text{total}}(p_T, y),
$$

where $N_{\text{evt}}$ is the total number of events in the sample, $N^i_{\text{data}}(p_T, y)$ is the number of particles $i$ measured in a $\Delta y$-$\Delta p_T$ bin. In the analysis for this thesis, $\Delta p_T = 50$ MeV/c and $\Delta y = 0.2$ rapidity units ($[y - \Delta y/2, y + \Delta y/2]$) are normally used and when necessary and a coarser rapidity binning is used in addition. $\text{Corr}_{\text{total}}$ includes all the corrections and is defined as

$$
\text{Corr}_{\text{total}}(p_T, y) = \frac{\epsilon_{\text{trig}} \epsilon_{\text{phys}}}{\epsilon_{\text{acc}}(p_T, y) \epsilon_{\text{trk}} \epsilon_{\text{pid}}},
$$
where $\epsilon_{\text{trig}}$ is the trigger efficiency, $\epsilon_{\text{phys}}$ the BRAG correction for multiple scattering, decay and absorption, $\epsilon_{\text{acc}}(p_T, y)$ the geometrical acceptance correction, $\epsilon_{\text{trk}}$ and $\epsilon_{\text{pid}}$ the tracking and PID efficiency respectively. Figure 4.12 shows an example of the momentum space coverage for different FS settings.

**Trigger counter efficiency**

The minimum-bias trigger is estimated to select $91\pm3\%$ of the d+Au inelastic cross section and $71\pm5\%$ of the total inelastic proton-proton cross section of 41 mb [33]. To avoid the bias caused by the limited trigger counter acceptance, the p+p yields have been corrected. Our trigger selects non-single-diffractive events and we estimate using the PYTHIA generator that the correction is $13\pm5\%$. Please refer to the BRAHMS analysis note [90] for detailed information about how this correction factor was estimated. In this analysis an efficiency of $\epsilon_{\text{trig}}=87.5\%$ was assumed and the particle spectra in p+p collisions have been rescaled accordingly.

### 4.4.2 Settings combination and final spectra

![Figure 4.13: An example of the final $p_T$ spectra for $\pi^\pm$ in rapidity interval $2.90 < y < 3.10$, fully corrected by all corrections discussed above in p+p collisions. Subfigures (a) and (b) are the $dN/dp_T$ spectra for positive and negative pions, which demonstrate the coverage in transverse momentum.](image)

Different settings with the same MRS/FS angle but different magnetic fields are combined to produce the final spectra in order to cover a larger $p_T$ range at each rapidity. The weighted average of results from different settings is the final spectra. The weight for setting $s$ in a certain $\Delta y$-$\Delta p_T$ bin is defined as

$$\omega_s = \frac{1}{\text{Corr}_{\text{total}}(p_T, y)} ,$$  

(4.23)
which ensures that settings with larger corrections have lower weights. Therefore, the final spectra for identified species \( i \) can be constructed by

\[
\frac{d^2 N_i(p_T, y)}{2\pi N_{\text{evt}} p_T dp_T dy} = \frac{\sum_s d^2 N_i^{s+}(p_T, y) \times \omega_s}{\sum_s \omega_s}.
\]

Figure 4.13 shows the spectra of \( \pi^+ \) (left panel) and \( \pi^- \) (right panel) at forward rapidity \( y = 3 \) in p+p collisions. Subfigures (a) and (b) are the \( dN/dp_T \) spectra for positive and negative pions, which demonstrate the fraction of the covered cross section.

### 4.4.3 Errors from setting combinations

As discussed above, the spectrum at a certain rapidity is constructed by combining measurements from different settings. The variation in the result from different individual settings provides an estimation of the systematic error coming from the normalization and all the corrections discussed in the last section.

Figure 4.14: Ratio (left figure) between spectra from different settings and the average spectrum for positive pions at \( 2.90 < y < 3.10 \) in p+p collisions. Distribution of ratios (right figure) centers at 1, fit by a Gaussian function (curve).

The left panel in figure 4.14 shows the ratio between the individual settings to the average of all settings, the right one shows the projection of the ratios for different settings within the overlapping \( p_T \)-range. The bands around ratio = 1 illustrate the spread of the ratios. The systematical errors for all other identified particles in d+Au and p+p collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) are studied in the same way. The projection represents the systematic variation of the spectra; the distribution is centered at 1 but has non-Gaussian tails. A systematic error of approximately 20% (\( \pi^+ \) at forward rapidity) is deduced from the RMS.

### 4.5 GEANT simulation study

A GEANT simulation was made to understand the efficiency of the reconstruction process and to estimate the systematic error of the spectra associated with it. Pions
Figure 4.15: GEANT simulation study at $2.95 < y < 3.05$ in $p+p$ collisions at $\sqrt{s} = 200$ GeV. The left panel shows the combined acceptance from different settings, the right one shows the combined spectrum.

are generated by a Monte Carlo simulation with GEANT, with a fixed rapidity density $dN/dy$ at both mid-rapidity ($y = 0$) and forward rapidity ($y = 3$). All physics processes are switched on in the simulation. In the following, the simulation of the pion production at the forward rapidity $2.95 < y < 3.05$ will be used as an example.

Figure 4.16: GEANT simulation study at $2.95 < y < 3.05$ in $p+p$ collisions at $\sqrt{s} = 200$ GeV. The left plot shows the spectrum after corrections (points), and the input function (curve). The right one shows the ratio of the fully corrected spectrum to the input function.

Negative pions are generated with the FS placed at $4^\circ$ and with magnet settings for D1 (A polarity) at 6 different magnetic fields of 3450, 2442, 1723, 1219, 861 and 430 Gauss. Figure 4.15 shows good matching between settings. Figure 4.16 shows the comparison between the input function in the GEANT simulation and the analysis results from the simulated data. The consistency is within 5-10%, which is marked as a band at ratio = 1 in the right plot in figure 4.16. This consistency shows that the corrections implemented in the analysis are correct within 5-10%. A similar study was
done for the corrections at the mid-rapidity and demonstrates a similar reconstruction quality.

4.6 $p_T$ extrapolation

Since the spectrometer acceptance does not cover all $p_T$, various fit functions are used to extrapolate the spectra to low and high $p_T$ and to extract physics variables like particle yields $dN/dy$ and average transverse momenta $\langle p_T \rangle$. The extrapolation introduces systematic errors originating from the choice of a specific fit function and the $p_T$ range used in the fit.

Two equivalent forms of the invariant cross section as a function of $p_T$ and $m_T$

$$f(p_T) = \frac{1}{N_{ext}} \frac{d^2N}{2\pi p_T dp_T dy} ,$$

$$f(m_T) = \frac{1}{N_{ext}} \frac{d^2N}{2\pi m_T dm_T dy} ,$$

are used to extract the yields $dN/dy$ of identified particle production in nuclear collisions. The method is to use the fit function to extrapolate the spectra under consideration to the regions outside the acceptance and to extract the yields for the full $p_T$ ($m_T$) range.

The functions which have been used for this purpose are a power law function in $p_T$ (equation 4.24), an exponential function in $p_T$ ($m_T$) (equation 4.25-4.26) and a Boltzmann function in $m_T$ (equation 4.27):

$$f(p_T) = \frac{(n-1)(n-2)}{2\pi p_0^2} \frac{dN}{dy} \left(1+\frac{p_T}{p_0}\right)^{-n} , \quad (4.24)$$

$$f(m_T) = \frac{1}{2\pi T (T + m)} \frac{dN}{dy} e^{-(m_T - m)/T} , \quad (4.25)$$

$$f(p_T) = \frac{1}{2\pi T^2} \frac{dN}{dy} e^{-p_T/T} , \quad (4.26)$$

$$f(m_T) = \frac{m_T}{2\pi (2T^2 + 2mT + m^2)} \frac{dN}{dy} e^{-(m_T - m)/T} . \quad (4.27)$$

See Appendix D for details of the deduction of these equations.

4.6.1 Particle yields

Yields are extracted by extrapolation, using the functions listed above. Different functions are used to fit the final spectra. In figure 4.17, the upper panels in subfigure (a) and (b) show an example of the extrapolation using a power law function and an exponential function in $p_T$ for pion spectra at rapidity $-0.10 < y < 0.10$ in $p+p$ collisions at $\sqrt{s} = 200$ GeV. The ratio of the spectra to the corresponding fit function are shown in the lower panels.
Figure 4.17: Pion spectra extrapolations at $-0.10 < y < 0.10$. In subfigures (a) and (b), the upper panels show the spectra, and the lower panels show the spectra to the ratio of the spectra to the corresponding fit functions.

In figure 4.18 the upper panels in subfigures (a)-(d) show an example of the extrapolation using a power law function, an exponential function in $p_T$, an exponential function in $m_T$ and a Boltzmann function for charged kaon spectra. The corresponding fit parameters are shown. The spectra to the corresponding fit functions ratio are shown in the lower panels in each subfigure.
From the fit study at both mid-rapidity and forward rapidity in p+p collisions and d+Au collisions, a power law function in $p_T$ for pions, an exponential function in $m_T$ for kaons and a Boltzmann function in $p_T$ for protons are finally chosen to estimate the integrated yields. Results from the other functions are used to estimate the systematic errors.
Figure 4.19: Proton spectra extrapolations at $-0.10 < y < 0.10$. In subfigures (a) and (b), the upper panels show the spectra, and the lower panels show the spectra to the ratio of the spectra to the corresponding fit functions.

### 4.6.2 Mean transverse momentum $\langle p_T \rangle$

Calculations of the averaged tranverse momentum $\langle p_T \rangle$ are done by equation 4.28,

$$\langle p_T \rangle = \frac{\int_0^\infty p_T \frac{d^2N}{d^2p_Tdy} dp_T}{\int_0^\infty \frac{d^2N}{d^2p_Tdy} dp_T}, \quad (4.28)$$
where $f(p_T)$ is the fully corrected and normalized spectrum

$$f(p) = \frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy}.$$ (4.30)

In the calculation equation 4.29 is used for the $\langle p_T \rangle$ estimation. A power law function, an exponential function in $m_T$ and a Boltzmann function are used for pions, kaons and protons respectively. The results will be presented in Chapter 5.

### 4.6.3 Yields for net-proton

![Graphs showing pT spectra of net-protons in p+p collisions at mid-rapidity $-0.10 < y < 0.10$, fitted by an exponential function in pT in subfigure (a) and a Boltzmann function in subfigure (b).](image)

Figure 4.20: An example of the $p_T$ spectra of the net-protons in $p+p$ collisions at mid-rapidity $-0.10 < y < 0.10$, fitted by an exponential function in $p_T$ in subfigure (a) and a Boltzmann function in subfigure (b).

Yields of net-protons can be calculated by subtracting the anti-proton yield from that of the protons, which are obtain by the method discussed above. However, the subtraction of the yields of protons and anti-protons obtained from a fit may increase the systematic error of the estimation of net-proton yields by propagating the errors.
coming from each fitting procedure. In this analysis, the net-proton yields at a certain rapidity bin are estimated by fitting the net-proton spectra, which are defined as the spectra of the differences between the normalized and corrected proton and anti-proton counts in each $p_T$ bin. The yields are extracted by a combination of direct counts inside the acceptance and the extrapolation by the fit functions in the region outside the acceptance.

In figure 4.20, the left panels in subfigure (a) and (b) show the spectra of protons, anti-protons at $-0.10 < y < 0.10$ and the right panels show the net-proton spectrum, fitted by (a) an exponential function in $p_T$ and (b) a Boltzmann function within the acceptance $0.9 \text{ GeV}/c < p_T < 2.5 \text{ GeV}/c$. In figure 4.21, the left panels in subfigure (a) and (b) show the spectra of protons and anti-protons at $2.90 < y < 3.10$ and the right panels show the net-proton spectrum, fitted by (a) an exponential function in $p_T$ and (b) a Boltzmann function within the acceptance $0.9 \text{ GeV}/c < p_T < 2.5 \text{ GeV}/c$.

### 4.6.4 Systematic errors

There is a systematic dependence of the integrated yields $dN/dy$ on the choice of the fit range and fit function, which has to be included in the overall systematic error besides
the systematic errors coming from combining spectra which have been discussed in the previous section.

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
p_T \text{ range} & 0.7-1.5 & 0.7-2.0 & 0.7-2.5 & 0.7-3.0 & 0.7-3.5 \\
\hline
\text{exp in } p_T & 0.104\pm0.003 & 0.116\pm0.002 & 0.115\pm0.002 & 0.115 \pm0.002 & 0.114\pm0.002 \\
\text{exp in } m_T & 0.070\pm0.001 & 0.070\pm0.001 & 0.066\pm0.001 & 0.0065\pm0.001 & 0.065\pm0.001 \\
\text{Boltzmann} & 0.068\pm0.001 & 0.067\pm0.001 & 0.063\pm0.001 & 0.061\pm0.001 & 0.061\pm0.001 \\
\hline
\end{array}
\]

Table 4.8: Fit function and fit range dependence of proton yield $dN/dy$ at $2.90 < y < 3.10$ in $p+p$ collisions.

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
p_T \text{ range} & 0.7-1.5 & 0.7-2.0 & 0.7-2.5 & 0.7-3.0 & 0.7-3.5 \\
\hline
\text{exp in } p_T & 0.048\pm0.003 & 0.051\pm0.002 & 0.050\pm0.002 & 0.050 \pm0.002 & 0.050\pm0.002 \\
\text{exp in } m_T & 0.025\pm0.001 & 0.024\pm0.001 & 0.023\pm0.001 & 0.022\pm0.001 & 0.022\pm0.001 \\
\text{Boltzmann} & 0.024\pm0.001 & 0.023\pm0.001 & 0.021\pm0.001 & 0.021\pm0.001 & 0.021\pm0.001 \\
\hline
\end{array}
\]

Table 4.9: Fit function and fit range dependence of anti-proton yield $dN/dy$ at $2.90 < y < 3.10$ in $p+p$ collisions.

The dependence of the integrated yields on the choice of fit function and fit $p_T$ range has been studied. In tables 4.8-4.9, the integrated yield for proton and anti-proton in the full $p_T$ space are used as an example to show the dependence of the yield $dN/dy$ on the fit function and fit range.

For the proton and anti-proton spectra, a power law function can be excluded because its inability to fit the spectra. The exponential functions (in $p_T$ and $m_T$) give larger yields than the Boltzmann function (difference up to a factor of two) while the difference between different fit ranges for the same fit function is not so large, about 5%-15%.
Chapter 5

Spectra and yields

Particle spectra are built using the method which has been discussed in Chapter 4. Spectra of identified particles are investigated in d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV at both mid-rapidity and forward rapidity, namely the spectra of positive pions, kaons and protons and their corresponding negative counterparts. Particle ratios, such as negative to positive like-particle ratios, $K/\pi$ and $p/\pi$ unlike-particle ratios are studied, as well as the centrality dependence of those ratios in the d+Au system. Mean transverse momentum $\langle p_T \rangle$ and rapidity densities $dN/dy$ are extracted from the spectra.

5.1 $p_T$ spectra

The spectra of identified particles in both d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV are organized in the following way. For d+Au data, spectra at 3 different rapidities ($y = 0, 1$ and $3$) are displayed for 3 different centrality classes (0-30%, 30-60% and 60-80%), as well as for minimum bias data. For p+p collisions, the spectra at 5 different rapidities, from mid-rapidity $y = 0$ to the most forward rapidity $y = 3.5$ are presented.

Figures 5.1 and 5.2 show the spectra of the identified positive and negative particles at different rapidities in minimum bias d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Figures 5.3-5.6 show the spectra at different rapidities for different centralities in d+Au collisions. Figures 5.7 and 5.8 show the spectra of the identified positive and negative particles at different rapidities. Due to the limited number of good runs/settings at $y = 1$, only pion spectra could be extracted with sufficient statistics. In p+p collisions at $\sqrt{s} = 200$ GeV, figure 5.9 shows the identified particle spectra at mid-rapidity $y = 0$ and $y = 1$. Figure 5.10 presents the identified particle spectra at forward rapidities, $y = 3$, 3.3 and 3.5. Errors in figures are statistical only. The systematic errors are estimated to be 20% as mentioned in the previous chapter.

5.2 Particle ratios

As mentioned in Chapter 1, particle ratios are the most direct tool to study the chemistry of the collision systems. The results for like-particle ratios (negative/positive),
and unlike-particle ratios ($K/\pi$ and $p/\pi$) versus transverse momentum ($p_T$) in both d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV are presented in the following subsections.

### 5.2.1 Like-particle ratios

Figures 5.11-5.12 show the like-particle ratios at three rapidities in d+Au collisions. For pions, the ratio does not change much when going from mid-rapidity to forward rapidity, while for kaons and protons the ratios decrease. The ratios are independent of the centrality (figure 5.12).

Figure 5.13 shows the like-particle ratios at both mid-rapidities (upper panel) and forward rapidities (lower one) in p+p collisions at $\sqrt{s} = 200$ GeV. At mid-rapidity, the
5.2 Particle ratios

![Graphs showing spectra of $\pi^\pm$, $K^\pm$ and $p$ or $\bar{p}$ at rapidity $y = 0$, 1 and 3 in minimum bias $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV.]

Figure 5.3: Spectra of $\pi^\pm$, $K^\pm$ and $p$($\bar{p}$) at rapidity $y = 0$, 1 and 3 in minimum bias $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV.
Figure 5.4: Spectra of $\pi^\pm$, $K^\pm$ and $p(\bar{p})$ at rapidity $y = 0$ in $d+Au$ collisions for centralities 0-30%, 30-60%, 60-80%.
Figure 5.5: Spectra of $\pi^{\pm}$ at rapidity $y = 1$ in d+Au collisions for centralities 0-30%, 30-60%, 60-80%.
Figure 5.6: Spectra of $\pi^\pm$, $K^\pm$ and $p(\bar{p})$ at rapidity $y = 3$ in $d+Au$ collisions for centralities 0-30%, 30-60%, 60-80%.
5.2 Particle ratios

Figure 5.7: Spectra for positive hadrons in p+p collisions at $\sqrt{s} = 200$ GeV, scaled by factors which are given in the figure.

Figure 5.8: Spectra for negative hadrons in p+p collisions at $\sqrt{s} = 200$ GeV, scaled by factors which are given in the figure.

ratios are rather constant with $p_T$. Going to forward rapidities, the $K^-/K^+$ and $\bar{p}/p$ ratios decrease dramatically, and they also have a transverse momentum dependence.
The $\bar{p}/p$ ratios at forward rapidities are as low as 10%.

### 5.2.2 Unlike-particle ratios

Unlike-particle ratios $K/\pi$ and $p/\pi$ versus transverse momentum $p_T$ are presented in this subsection for both d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV.

**K/$\pi$ ratios**

Figure 5.14 shows $K/\pi$ ratios at rapidity $y = 0$ and $y = 3$ in minimum bias d+Au collisions compared to those in p+p collisions at the same rapidities. There is little difference between the results in p+p collisions and the d+Au collisions. Figure 5.15 shows $K/\pi$ ratios at rapidity $y = 0$ and $y = 3$ in d+Au collisions within different centralities, (0-30%, 30-60% and 60-80%). There is no centrality dependence of $K/\pi$ ratios in d+Au collisions.
Figure 5.10: Spectra of $\pi^\pm$, $K^\pm$ and p($\bar{p}$) at forward rapidity $y = 3$, 3.3 and 3.5 in $p+p$ collisions at $\sqrt{s} = 200$ GeV.
Figure 5.11: Like-particle ratios ($\pi^-/\pi^+$, $K^-/K^+$, and $\bar{p}/p$) at rapidities $y = 0, 1$ and $3$ in minimum bias $d+Au$ collisions.
Figure 5.12: Like-particle ratios ($\pi^-/\pi^+$, $K^-/K^+$, and $\bar{p}/p$) at rapidities $y = 0$, 1 and 3 in $d+Au$ collisions in centrality classes 0-30% and 30-60%.
Figure 5.13: Like-particle ratios at/near mid-rapidity (upper panel) and forward rapidities (lower panel) in p+p collisions.

Figure 5.16 shows K/π ratios at rapidity y = 0, 1, 3, 3.3, 3.5 in p+p collisions at √s = 200 GeV. All ratios at all rapidities increase slightly with p_T for both systems.

p/π ratios

Figure 5.17 shows p/π ratios at rapidity y = 0, 1.0, and 3 in minimum bias d+Au collisions, compared to those in p+p collisions at the same rapidities. There is no difference between the antiproton-to-pion ratios in p+p collisions and the d+Au collisions while the proton-to-pion ratios seem to be different for the two systems. Note that the protons start to dominate at high p_T at forward rapidities. Figure 5.18 shows p/π ratios at rapidity y = 0, 1.0, 3 in d+Au collisions for different centralities (0-30%, 30-60% and 60-80%). There is no centrality dependence of p/π ratios in d+Au collisions.
Figure 5.14: $K/\pi$ ratios at rapidity $y = 0$ and $y = 3$ in d+Au collisions compared to those in p+p collisions at the same rapidities.

Figure 5.19 shows $p/\pi$ ratios at/near mid-rapidity ($y = 0, 1$) and at forward rapidities ($y = 3, 3.3$ and $3.5$) in p+p collisions at $\sqrt{s} = 200$ GeV. At mid-rapidity, both the positive and negative $p/\pi$ ratio are similar (upper panel). At forward rapidities the positive and negative $p/\pi$ ratios behave very differently; the negative ratio is much smaller than that of the positive and constant with $p_T$.

## 5.3 Rapidity densities

Rapidity densities $dN/dy$ are obtained by integrating the particle spectra over the full $p_T$ range. Due to the lack of data at very low and high $p_T$, spectra are fitted by certain functions. The fit function is then used to extrapolate to regions outside the acceptance. For the fit, a power law function in $p_T$ (equation 4.24), an exponential
Figure 5.15: K/π ratios at rapidity \( y = 0 \) and \( y = 3 \) in d+Au collisions within different centralities (0-30%, 30-60% and 60-80%).

function in \( m_T \) (equation 4.26) and a Boltzmann function (equation 4.27) are used to extract the yield of pion, kaon and protons correspondingly (see details in Chapter 4).

The results are shown in figures 5.20 and 5.21, in which (a)-(c) show the results for pions, kaons and protons respectively from p+p collisions and from d+Au collisions. ¹

All particle yields, except the protons in p+p collisions at very forward rapidity, are highest at mid-rapidity and decrease when going to larger rapidities. All \( p_T \)-integrated like-particle ratios decrease with increasing rapidity in p+p reactions, while \( \pi^-/\pi^+ \) ratio stays at 1 in d+Au collisions.

¹Systematic errors due to different fit functions used in the extrapolation are shown in figures 5.20 and 5.21 as error bars for kaons and protons, but not for pions because only the power law function gives a reasonable interpretation of the spectra.
5.4 Mean transverse momentum $\langle p_T \rangle$

Figure 5.22 shows the rapidity dependence of the $\langle p_T \rangle$ in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Subfigure (a) shows the $\langle p_T \rangle$ for charged hadrons in minimum bias collisions, (b) and (c) show that for positive and negative hadrons within different centrality classes respectively. Asymmetric errors show the systematic errors coming from the different extrapolations using different fit functions. There is no significant centrality or rapidity dependence. Figure 5.23 shows the rapidity dependence of the $\langle p_T \rangle$ in p+p collisions at $\sqrt{s} = 200$ GeV. Asymmetric errors shows the systematic errors coming from the different extrapolations using different fit functions. There is no strong rapidity dependence. In general, the $\langle p_T \rangle$ is larger for heavier hadrons in both system, and $\langle p_T \rangle$ in d+Au collisions is slightly larger than in p+p collisions.
Figure 5.17: $p/\pi$ ratios at rapidity $y = 0$ and $y = 3$ in minimum bias $d+Au$ collisions compared to those in $p+p$ collisions at the same rapidities.
Figure 5.18: $p/\pi$ ratios at rapidity $y = 0$ and $y = 3$ in $d+Au$ collisions within different centralities.
Figure 5.19: \( p/\pi \) ratios at/near mid-rapidity (upper panel) and forward rapidities (bottom panel) in p+p collisions.
Figure 5.20: Rapidity densities and $p_T$ integrated particle ratios versus rapidity in $p+p$ collisions at $\sqrt{s} = 200$ GeV.

(a) Pion yields and $\pi^-/\pi^+$ ratio ($p_T$ integrated) versus rapidity in $p+p$ collisions

(b) Kaon yield and $K^-/K^+$ ratio ($p_T$ integrated) versus rapidity in $p+p$ collisions

(c) Proton yields and $\bar{p}/p$ ratio ($p_T$ integrated) versus rapidity in $p+p$ collisions
Figure 5.21: Rapidity densities and $p_T$ integrated particle ratios versus rapidity in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV.
Figure 5.22: $\langle p_T \rangle$ in $d+Au$ collisions vs rapidity. Systematic errors are shown as asymmetric error bars, which come from the different extrapolations using different fit functions.
Figure 5.23: $\langle p_T \rangle$ for charged hadrons in $p+p$ collisions at $\sqrt{s} = 200$ GeV.
Chapter 6

Nuclear Modification Factors

In this chapter, nuclear modification factors in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV are presented. As introduced in Chapter 1, nuclear modification factors for identified particles in d+Au collisions may reveal the properties of the cold nuclear matter and may shed light on initial state effects such as parton saturation, nuclear shadowing and the Cronin effect. By studying the effects in d+Au collisions one can distinguish between effects due to the initial conditions in central Au+Au collisions and final state effects like jet quenching in the deconfined matter created in these reactions.

In this thesis the centrality and rapidity dependence of the nuclear modification factors are presented, using the reference spectra from p+p collisions measured by BRAHMS in RUN V, which have been presented in Chapter 5. The nuclear modification factor is defined as

$$R_{dAu} = \frac{1}{\langle N_{\text{centrality}} \rangle} \cdot \frac{d^2N_{dAu}/dp_Tdy}{d^2N_{NN}/dp_Tdy}. \quad (6.1)$$

$R_{dAu}$ is calculated by equation 6.1, in which the average number of collisions for different centrality classes $\langle N_{\text{coll}}^{MB} \rangle = 7.2 \pm 0.3$, $\langle N_{\text{coll}}^{0\text{--}30\%} \rangle = 12.6 \pm 0.3$, $\langle N_{\text{coll}}^{30\text{--}60\%} \rangle = 7.2 \pm 0.5$ and $\langle N_{\text{coll}}^{60\text{--}80\%} \rangle = 3.3 \pm 0.4$ are used. Note that the numbers of collisions in minimum bias and in semi-peripheral collisions are identical. These numbers are calculated by a Monte Carlo simulation [78] based on theoretical models of nuclear collisions, from which the event centrality is determined. The Glauber Model [57] is used for all RHIC experiments. Systematic uncertainties are introduced by the simulation, which are the main contribution to the systematic error of the nuclear modification factors. Most of the systematic errors related to the construction of the spectra from different settings and to efficiency corrections cancel each other because both data sets are recorded by identical detectors and identical spectrometer settings. Figure 6.1 shows the rapidity dependence of $R_{dAu}$ for charged pions, kaons and protons in minimum bias d+Au collisions. Isospin effects due to the isospin-asymmetric p+p reference are reduced by adding particles and antiparticles. At mid-rapidity $R_{dAu}$ is above 1 for $p_T$ greater than approximately 1 GeV/c and the enhancement increases with $p_T$ at least for p (p) (subfigure (a)). At forward rapidity (subfigure (c)) the pion curve stays below 1 (pions) or approach 1 at higher $p_T$. Figure 6.2 shows the centrality dependence of $R_{dAu}$ for charged pions, kaons and protons in d+Au collisions at various rapidities. The dark bands around $R_{dAu}=1$ on the left plot of each figure indicate the systematic
Figure 6.1: Rapidity dependence of $R_{d\text{Au}}$ for charged pions, kaons and protons in minimum bias $d+\text{Au}$ collisions. Grey bands around $R_{d\text{Au}} = 1$ indicate the systematic uncertainties in $\langle N_{\text{coll}} \rangle$. Uncertainties in $\langle N_{\text{coll}} \rangle$ for each centrality class, namely the right band stands for 60-80% peripheral collisions, the middle one for 30-60% semi-central collisions and the left one for 0-30% central collisions. In peripheral collisions, $R_{d\text{Au}}$ approaches 1 or is
Figure 6.2: Centrality dependence of $R_{dAu}$ for charged pions, kaons and protons in $d+Au$ collisions at rapidity $y=0$, $y=1$ and $y=3$. Systematic uncertainties are shown as dark bands around 1.0 on the left plots in each panel.

above 1 at all rapidities. In central collisions a strong suppression is observed for pions and kaons at forward rapidity (c).

In figure 6.3 subfigure (a) shows that at mid-rapidity $y = 0$, the differences in
Figure 6.3: $R_{dAu}$ for positive and negative pions and kaons and for protons (antiprotons) in minimum bias $d+Au$ collisions at rapidity $y = 0$, 1 and 3. Systematic uncertainties are shown as bands around 1.0 in each panel.

$R_{dAu}$ between the positive and negative hadrons are negligible. But at the forward rapidity $y = 3$ (subfigure (c)), the negative hadrons show larger nuclear modification factors than those of the positive ones. These differences may be due to isospin effects.
Figure 6.4: $R_{dAu}$ for positive and negative pions and kaons and for protons (anti-protons) in the most central (0-30%) d+Au collisions at rapidity $y = 0$, 1 and 3. Systematic uncertainties are shown as bands around 1.0 in each panel.

Figure 6.4 shows the comparison for the most central (0-30%) d+Au collisions. Similar results are observed here. Instead of using $R_{dAu}$ one can construct a similar measure $R_{CP}$. Here the spectra
for central and semi-central collisions are normalized to the spectrum measured in peripheral reactions

\[ R_{CP}^{central} = \frac{\langle N_{\text{peripheral}} \rangle}{\langle N_{\text{central}} \rangle} \cdot \frac{d^2 N_{\text{central}}/dp_T dy}{d^2 N_{\text{peripheral}}/dp_T dy}. \] (6.2)

The evolution of \( R_{CP} \) with rapidities for charged hadrons of different species is shown in figure 6.5. Charged hadrons of the same species are added up to obtain better statistics. In figure 6.5 at mid-rapidity \( R_{CP} \) (subfigure (a)) shows no difference between different centrality selections. Hadrons with larger mass give a larger enhancement at this rapidity. It is worthwhile to mention that the systematic errors coming from the larger uncertainty of the \( \langle N_{\text{coll}} \rangle \) in the peripheral (60-80%) d+Au collisions result in larger errors in \( R_{CP} \). At forward rapidity \( y = 3 \) (subfigure (c)) all the ratios are suppressed. As can be seen from the figure the suppression is stronger for the central-to-peripheral ratio than for semi-central-to-peripheral ratios for all particle species.

Figure 6.6 summaries the centrality dependence of \( R_{dAu} \) for charged pions, kaons, and protons in d+Au collisions at mid-rapidity and forward rapidity. There is a difference of \( R_{dAu} \) in central and peripheral collisions. \( R_{dAu} \) for protons reach 2 at \( p_T \approx 2 \text{ GeV/c} \) at mid-rapidity in central and about 1.5 in peripheral collisions. At forward rapidity \( y = 3 \), \( R_{dAu} \) for identified charged particles is suppressed up to \( p_T < 2.5 \text{ GeV/c} \) for central collisions.
Figure 6.5: $R_{CP}$ as a function of $p_T$ for charged hadrons of different species at mid-rapidity $y = 0$, 1 and 3. The errors shown here are only statistical, and the bands around 1.0 are the systematic errors caused by the uncertainties of $\langle N_{coll} \rangle$. The band at the most right-hand side is for the uncertainty of $R_{CP}$ for 30-60%/60-80%, the one at the left-hand side is for 0-30%/60-80%.
Figure 6.6: Nuclear modification factor $R_{dAu}$ for identified charged hadrons at rapidity $y = 0$ and $y = 3$. The top panel shows 0-30% centrality bin, and the bottom one shows 60-80% centrality bin. Grey bands around $R_{dAu} = 1$ are the systematic uncertainties propagated from $\langle N_{\text{coll}} \rangle$. 

**Nuclear Modification Factors**
Chapter 7
Stopping

Net-proton rapidity distributions in both d+Au and p+p systems are studied in order to understand stopping. The rapidity dependence of the net-proton yield in d+Au and p+p collisions may shed light on the baryon number transport in nuclear collisions. The net-proton transverse momentum spectra are constructed by subtracting the anti-proton spectra from the proton spectra $p_T$-bin-by-$p_T$-bin, using the method which has been explained earlier in Chapter 4. In this chapter, the net-proton production in d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV are presented.

Figure 7.1: Net-proton rapidity density in p+p collisions at $\sqrt{s} = 200$ GeV. The squares are the net-proton yields obtained by using a Boltzmann function, and the dots are those obtained using an exponential function in $p_T$. The gray boxes between the two sets of extrapolations indicate the range of solutions which cannot be distinguished by our data.
Figure 7.2: Net-proton rapidity density in minimum bias d+Au collisions, compared to results by HIJING/B estimation.

Figure 7.3: Centrality dependence of net-proton rapidity density in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.
Figure 7.1 shows the net-proton rapidity distribution in p+p collisions at $\sqrt{s} = 200$ GeV and a comparison to PYTHIA [23] and the HIJING model with baryon junction [91], including single diffractive processes. The squares are the results of a Boltzmann extrapolation, while the dots represent those from an exponential function in $p_T$. The region around mid-rapidity (between 0 and 1) is almost baryon-free, while a large net-proton density is observed at forward rapidity (around 3). Even though we have an uncertainty of about 50% due to the extrapolation procedure HIJING/B’s estimate is closer to our data, while PYTHIA’s is systematically lower at mid-rapidity and higher at forward.

Figure 7.2 and 7.3 show the net-proton rapidity density in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV of different centrality selections. Statistical errors and systematic errors ($\approx 20\%$) from the the spectra construction and extrapolation are included in the error bars shown in the figure. Figure 7.2 shows a comparison with a HIJING/B estimation (histogram) in minimum bias d+Au collisions. Figure 7.3 shows the net-proton rapidity density for various centrality bins.

The experimental results at mid-rapidity are consistent with the model estimation within the errors, but HIJING/B overestimates the yield at the forward rapidity. At both rapidities, $y = 0$ and $y = 3$, the net-proton rapidity density increases with centrality.
Chapter 8

Comparisons and Discussion

In this chapter, comparisons are made between the results on spectra of identified particles in this thesis and the published data from other RHIC experiments.

The PHENIX and STAR Collaborations at RHIC have published the spectra for identified particles in the d+Au and p+p collisions at mid-rapidity. The consistency between these measurements and the one by BRAHMS is crucial for the understanding of our experiments. In the following the results presented in this work are compared to those from PHENIX and STAR, even though very different detectors were implemented, and very different techniques were used in the analysis.

8.1 Minimum bias d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

At mid-rapidity $y = 0$ our results for charged hadrons for the minimum bias d+Au data are compared with the identified particle spectra, published by both STAR [92] and PHENIX [51] Collaborations. In figure 8.1, the upper panel shows the comparison for pions, the middle one shows that for kaons, and the bottom one shows that for protons. Note that PHENIX has corrected the spectra for protons (anti-protons) for feed down from weak decays. There is agreement amongst the data sets.

8.2 p+p collisions at $\sqrt{s} = 200$ GeV

The results for p+p collisions at mid-rapidity $y = 0$ are also compared with the identified particle spectra, published by both the STAR [92] and PHENIX [51] experiments. In figure 8.2, the upper panel shows the comparison for pions, the middle one shows that for kaons, and the bottom one shows the one for protons. Errors are only statistical.

Note that the spectra for protons (anti-protons) from PHENIX have been corrected for feed down from weak decay, which explains the difference between the BRAHMS results (open diamond symbols) and those from PHENIX (round points). PHENIX $\pi$ and $K$ spectra agree with BRAHMS data within the errors, while STAR data is above the BRAHMS spectra, and for kaons the slope is also different.

At the forward rapidity $y = 3$ the published BRAHMS results [28] of particle spectra in p+p collisions are compared to the results presented in this thesis. The published
data represent the analysis status of 2006 and is based on this work and an analysis done at BNL. Figure 8.3 shows the comparison for charged pions (upper panels), kaons (middle ones) and protons (bottom ones); consistency of the two analyses within the errors is seen. The most recent comparison between NLO pQCD calculations with the measurement by BRAHMS experiment for p+p collisions at $\sqrt{s} = 200$ GeV [28] are
Figure 8.2: Spectra of charged hadrons at rapidity $y = 0$ in $p+p$ collisions, compared to the results from other RHIC experiments at mid-rapidity. Errors are statistical only.

shown in figure 8.4. In the top row of figure 8.4, the modified KKP ($m$KKP) set of fragmentation functions (solid line) produce the best agreement with the $\pi^-$ and $K^+$ data. The $p$ and $\bar{p}$ are compared with the calculation using the AKK set divided by 2 (dashed line). In the bottom row, relative differences between data and calculations is shown. A good agreement between experiment and pQCD calculation had been reached for $\pi$ and $K$ production, while the $p(\bar{p})$ spectra are not properly described.
Comparisons and Discussion

Figure 8.3: Spectra of charged hadrons at rapidity $y = 3$ in $p+p$ collisions compared to recently published BRAHMS results [28] at $y = 2.95$.

### 8.3 Nuclear modification factors at mid-rapidity

Figure 8.5 shows $R_{dAu}$ for charged pions, kaons and protons (including $\bar{p}$) at mid-rapidity measured by the BRAHMS experiment, compared to PHENIX and STAR results. Note that the average number of binary collisions $\langle N_{\text{coll}} \rangle$ used to rescale the spectra are $7.5\pm0.1$, $8.5\pm0.4$ and $7.5\pm0.4$ for BRAHMS, PHENIX and STAR respectively. Results from both PHENIX and STAR experiments show smaller $R_{dAu}$.
8.4 Pseudo-rapidity density

Figure 8.4: Comparison of invariant cross sections for $\pi^-$, $K^+$, $\bar{p}$ and $p$ at $y = 2.95$ in $p+p$ collisions at $\sqrt{s} = 200$ GeV and NLO pQCD calculations with factorization and renormalization scales set equal to $p_T$ [28].

It is worth noting that when using the same $\langle N_{\text{coll}} \rangle$ to rescale the spectra in $d+Au$ collisions, the PHENIX results agree with our nuclear modification factors results within 15%.

Figure 8.5: Comparison of $R_{dAu}$ for charged pions (left), kaons (middle) and protons (including $\bar{p}$) (right) BRAHMS experiment to PHENIX [51] and STAR [93] results at mid-rapidity in minimum bias collisions. Note that the average number of binary collisions $\langle N_{\text{coll}} \rangle$ used to rescale the spectra are $7.5\pm0.4$, $8.5\pm0.4$ and $7.5\pm0.4$ for BRAHMS, PHENIX and STAR respectively.
8.4 Pseudo-rapidity density

The integrated yields \( dN/dy \) of all charged hadrons obtained in this thesis are converted into \( dN/d\eta \) by multiplying a Jacobian factor in order to enable a comparison
with existing data or results from other experiments. Figure 8.6 shows a comparison between the $dN/d\eta$ of all identified charged hadrons obtained in this thesis, and the published BRAHMS charged hadron pseudo-rapidity distribution [1]. There is an excellent agreement for minimum bias and semi-central collisions, while the yields differ by 1-2\sigma for central and peripheral collisions. Figure 8.7 shows a comparison between $dN/d\eta$ of all identified charged hadrons and the preliminary results from PHOBOS [94] and the published UA5 [95] measurements in p+p and p+\bar{p} inelastic collisions at $\sqrt{s} = 200$ GeV. The agreement is within the errors.

8.5 Net-proton $dN/dy$

The net-proton rapidity density in d+Au and p+p at $\sqrt{s_{NN}} = 200$ GeV are compared with our published rapidity density in central Au+Au collisions (0-5%) [11] in figures 8.8 and 8.9. In figures 8.8 the net-proton rapidity density in central (0-30%) d+Au collisions is scaled by the ratio of the number of participants from the projectile side in Au+Au collisions to that in central d+Au collisions. After being rescaled the data points from d+Au and Au+Au overlap at the forward rapidity, while relative more net-protons are found at mid-rapidity in d+Au collisions.

![Graph showing net-proton dN/dy](image)

Figure 8.8: Net-proton rapidity density in central Au+Au collisions (0-5%) at $\sqrt{s_{NN}} = 200$ GeV is compared with that in central (0-30%) d+Au collisions scaled by the ratio of number of participants from the projectile in central Au+Au collisions to that number in d+Au.

In figure 8.9 the net-proton rapidity density in minimum bias p+p collisions are scaled by the average number of participant protons in central Au+Au collisions. The scaling seems to work at $y = 3$ but many more net-protons have been transported.
Comparisons and Discussion

Figure 8.9: The net-proton rapidity density central Au+Au collisions (0-5%) at $\sqrt{s_{NN}} = 200$ GeV is compared with the net-proton rapidity density in minimum bias $p+p$ collisions scaled by the average number of participant protons in central Au+Au collisions.

to mid-rapidity in central Au+Au collisions, indicating a higher degree of stopping in nucleus nucleus collisions.

For a comparison between our result for net-protons, net-protons at mid-rapidity [67] and net-Λ at both forward and backward rapidities measured by the STAR experiment [96] are shown in figure 8.10.

Figure 8.10: Net-proton rapidity density in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV, compared to measurements of net-protons [67] and net-Λ [96] (open symbols) measured by STAR experiment.
STAR’s centrality selection is slightly different from the one used here (more central). However, the agreement between the different net-proton data at mid-rapidity is good. At forward rapidity the BRAHMS net-proton yields might be consistent with the STAR net-Λ yields, taking into account that the net-protons include the net-Λ to a large extent via the decay products and assuming a p/Λ ratio larger than 1. However, all data sets show the same centrality dependence; central collisions have the highest yields at all rapidities.
Chapter 9
Summary and Conclusion

Data from d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV recorded during RUN03 and RUN05 by the BRAHMS experiment at RHIC have been analyzed. Minimum bias triggers and three different centrality classes (0-30%, 30-60% and 60-80%) for d+Au collisions have been employed.

Spectra for identified charged hadrons ($\pi^\pm, K^\pm$ and $\bar{p}(p)$) in both d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV are constructed by combining different spectrometer settings, thus covering a wide $y$-$p_T$ range from mid-rapidity $y = 0$ to forward $y = 3.5$. Because of the limited number of good runs/settings in d+Au collisions at rapidity $y = 1$ due to the inefficiency of the detectors for particle identification, only the spectra of charged pions have sufficient statistics. Spectra are compared with existing published data where available (mainly at mid-rapidity) and proved to be consistent within the errors. The invariant cross sections of pions and kaons produced in p+p collisions can be described by NLO pQCD calculations at all rapidities, whereas the model fails to reproduce the proton (antiproton) spectra especially at forward rapidity.

The particle ratios, such as negative/positive, K/$\pi$ and p/$\pi$ ratios have been studied as a function of the transverse momentum $p_T$ at different rapidities. In d+Au collision, like-particle-ratios show no centrality dependence. At forward rapidities the positive p/$\pi$ ratio is much larger than the negative one even at high $p_T$.

Integrated yields $dN/dy$ and average momentum $\langle p_T \rangle$ of each species have been extracted by extrapolating particle spectra to those regions of low $p_T$ and high $p_T$ which are outside the acceptance of the BRAHMS detectors. Systematic errors are carefully estimated by using various fit functions. $dN/dy$ of identified hadrons in d+Au collisions are converted into a pseudo-rapidity distribution in order to compare with our published pseudo-rapidity density $dN/d\eta$ for charged hadrons in various centrality bins. There is an excellent agreement for minimum bias and semi-central collisions. The deduced $dN/d\eta$ for charged hadrons in p+p collisions agree with measurements by PHOBOS and UA5 p+\bar{p} data.

Net-proton rapidity distributions in both systems are extracted by subtracting the anti-proton spectra from the proton spectra $p_T$-bin-by-$p_T$-bin, using the same extrapolation method. In p+p collisions, we found that the region around mid-rapidity ($y$ between 0 and 1) is almost baryon-free and a large net-proton density is observed at forward rapidity. The data disfavours the PHYTIA model and favors HIJING/B. In d+Au collisions, HIJING/B agrees with our data at mid-rapidity, while it overesti-
Summary and Conclusion

mates that yield at forward rapidity. A comparison of the net-proton rapidity density $p+p$ collisions, scaled by the number of participant protons, to central $Au+Au$ collisions indicates a higher degree of stopping in the nucleus-nucleus system. In conclusion, the baryon transport in nuclear collisions is not understood.

Nuclear modification factors $R_{dAu}$ are constructed for $d+Au$ collisions, using the reference from $p+p$ collisions presented in the thesis. The rapidity and centrality dependence of $R_{dAu}$ of pions is consistent with the measurements of charged hadrons by BRAHMS. The strong suppression of pions in central collisions at forward rapidity may indicate the role of the initial state effect e.g. gluon saturation at small-$x$. The difference between $R_{dAu}$ for positive and negative hadrons at forward rapidity may be due to isospin effects.

The results for $d+Au$ and $p+p$ collisions presented in this thesis are needed as a control system for $Au+Au$ collisions and the $p+p$ data is needed for the verification of model calculations e.g. pQCD. Due to the limitation of the acceptance of the BRAHMS detector and particle identification ability, the results presented in this thesis suffer from insufficient statistics and large systematical errors. More reference data with good statistics of $p+p$ and $p(d)+A$ collisions at ultra-relativistic energies at RHIC and at LHC are needed, especially at high rapidity which would allow to study gluon saturation effects at really small-$x$ and thereby improve the understanding of the initial conditions in nuclear collisions.
Appendix A

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(48 physicists from 11 institutions)
Appendix B

Kinematics

Momentum vector

The momentum vector of a particle $p$ is defined by a contravariant vector with four components $p^\mu$:

$$p^\mu = (p^0, p^1, p^2, p^3) = (E, \vec{p}) = (E, p_T^x, p_T^y, p_T^z) = (E, \vec{p}_T, \vec{p}_z) ,$$

where $\vec{p}_T$ is the transverse momentum, and its value is defined as

$$p_T = \sqrt{p_x^2 + p_y^2} = \sqrt{p^2 - p_z^2} .$$

$p_z$ is the longitudinal momentum. In the spherical coordinates system $(\vec{p}, \theta$ and $\phi)$,

$$p_T = p \cdot \sin \theta ,$$
$$p_z = p \cdot \cos \theta .$$

The transverse mass of a particle is defined as

$$m_T = \sqrt{p_T^2 + m^2} .$$

Rapidity and pseudo-rapidity variables

The rapidity variable $y$ for describing the kinematic condition of a particle, is defined in terms of its energy-momentum components,

$$y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) ,$$

which is an additive constant in the Lorentz frame of reference. From equation B.4, one can obtain the following relations:

$$E = \sqrt{p_T^2 + m^2 \cosh y} = m_T \cosh y ,$$
$$p_z = \sqrt{p_T^2 + m^2 \sinh y} = m_T \sinh y .$$
It is convenient to calculate the pseudo-rapidity $\eta$ when the energy and momentum of the particle are not available, while the longitudinal angle $\theta$ between particle momentum $\overrightarrow{p}$ and the beam axis is available. The pseudo-rapidity variable of a particle is defined as

$$\eta = -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right],$$  \hspace{1cm} (B.6)

which can be written as

$$\eta = \frac{1}{2} \ln \left( \frac{p + p_z}{p - p_z} \right).$$  \hspace{1cm} (B.7)

From equations B.6 and B.7 one can obtain similar relation between energy-momentum and $\eta$:

$$p = p_T \cosh \eta,$$
$$p_z = p_T \sinh \eta.$$  \hspace{1cm} (B.8)

From equations B.5 and equations B.8, one can find the relation between rapidity and pseudo-rapidity, with a Jacobian factor from the variable transformation,

$$\frac{dN}{d\eta dp_T} = \sqrt{1 - \frac{m^2}{m_T^2 \cosh^2 y}} \frac{dN}{dy dp_T},$$  \hspace{1cm} (B.9)

where $m_T$ is the transverse mass determined by equation B.3, and $\sqrt{1 - \frac{m^2}{m_T^2 \cosh^2 y}}$ is the Jacobian factor. The integral of $dN/dy dp_T$ ($dN/d\eta dp_T$) with respect to $p_T$ gives the integrated rapidity (pseudo-rapidity) density $dN/dy$ ($dN/d\eta$).
Appendix C

Some Characteristics of RHIC

At RHIC, the nuclei are fully accelerated to \( E/A = 100 \text{ GeV} \),

- velocity of a nucleon

\[
\beta_N = \frac{\sqrt{(E/A)^2 - m_N^2}}{E/A} = 0.999956 \; ; \quad (C.1)
\]

- rapidity of beam:

\[
y_{200 \text{ GeV}} = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) = \frac{1}{2} \ln \left( \frac{1 + \sqrt{1 - (A \cdot m_N/E)^2}}{1 - \sqrt{1 - (A \cdot m_N/E)^2}} \right) = 5.36 \; ; \quad (C.2)
\]

- design luminosity of the machine, for Au+Au collisions:

\[
\mathcal{L} = \frac{f \cdot n_1 \cdot n_2}{4\pi \cdot \sigma_x \cdot \sigma_y} = 2 \cdot 10^{26}/\text{cm}^2\text{s} \; , \quad (C.3)
\]

in which \( f \) is the frequency of the collider, \( n_1 \) and \( n_2 \) are the number of particles in each beam bunch, and \( \sigma_x \) and \( \sigma_y \) are the width of Gaussian characterizations of the bunches profiles in the horizontal and vertical directions in the plane of the RHIC ring.

- collision rate for A+B collisions:

\[
R_{\text{coll}} = \mathcal{L} \cdot \sigma_{AB} \; , \quad (C.4)
\]

which is \( \approx 1400 \text{ Hz} \) for Au+Au collisions, where \( \sigma_{\text{AuAu}} \sim 6.8b \).
Appendix D
Fit functions

In an experiment the normalized particle spectrum is measured as:

\[ f(p_T) = \frac{d^2N}{2\pi p_T dp_T dy} = f(m_T) = \frac{d^2N}{2\pi m_T dm_T dy}. \]  \tag{D.1}

from which one can estimate the rapidity density \(dN/dy\) by integrating the spectrum in terms of \(p_T\) or \(m_T\).

A series of fit functions, such as a power law function in \(p_T\), an exponential function in \(p_T\) or \(m_T\), and a Boltzmann function in \(m_T\) are used in this analysis, and are meant to describe the \(p_T\) or \(m_T\) spectra over the measured momenta range. They are

Power law in \(p_T\): \( A \cdot \left(1 + \frac{p_T}{p_0}\right)^{-n}, \)

Exponential in \(p_T\): \( B \cdot e^{-p_T/T}, \)

Exponential in \(m_T\): \( C \cdot e^{-m_T/T}, \)

Boltzmann in \(m_T\): \( D \cdot m_T \cdot e^{-[m_T-m]/T}, \)

in which the coefficients \(A, B, C\) and \(D\) are normalization factors to be determined. These functions are used to extrapolate particle spectra to low and high \(p_T\), which are outside the BRAHMS acceptance, to estimate the rapidity density \(dN/dy\), or so-called integrated particle yields.

\[ \frac{dN}{dy} = \int_{0}^{\infty} 2\pi p_T f(p_T) dp_T = \int_{0}^{\infty} 2\pi m_T f(m_T) dm_T. \]  \tag{D.2}

By inserting the fit functions listed above into equation D.2, one can determine the constants \(A, B, C\) and \(D\), and yield

Power law in \(p_T\): \( f(p_T) = \frac{(n-1)(n-2)}{2\pi p_0^2} \frac{dN}{dy} \left(1 + \frac{p_T}{p_0}\right)^{-n}; \)

Exponential in \(p_T\): \( f(p_T) = \frac{1}{2\pi T^2} \frac{dN}{dy} e^{-p_T/T}; \)

Exponential in \(m_T\): \( f(m_T) = \frac{1}{2\pi T(T+m)} \frac{dN}{dy} e^{-(m_T-m)/T}; \)

Boltzmann in \(m_T\): \( f(m_T) = \frac{m_T}{2\pi(2T^2+2mT+m^2)} \frac{dN}{dy} e^{-(m_T-m)/T}. \)
Appendix E
Spectra and fit study

![Image of spectra and fit study graphs]
Spectra and fit study

fit range 0.500-2.000 GeV/c

fit range 0.500-1.500 GeV/c

fit range 0.800-3.000 GeV/c

fit function: exp_m (GeV/c)

fit function: exp_p (GeV/c)

fit function: Boltzmann

0.012 ± dN/dy = 0.617 ± 0.102
T = 267.274 ± 4.25E

0.013 ± dN/dy = 0.587 ± 0.097
T = 261.224 ± 4.21E

0.011 ± dN/dy = 0.558 ± 0.097
T = 261.224 ± 4.21E

0.011 ± dN/dy = 0.536 ± 0.097
T = 261.224 ± 4.21E

0.005 ± dN/dy = 0.130 ± 0.005
T = 268.285 ± 4.30E

0.008 ± dN/dy = 0.121 ± 0.008
T = 236.615 ± 5.05E

0.004 ± dN/dy = 0.108 ± 0.004
T = 230.639 ± 5.03E

0.007 ± dN/dy = 0.101 ± 0.007
T = 205.268 ± 4.91E

0.003 ± dN/dy = 0.090 ± 0.003
T = 197.787 ± 4.81E

0.005 ± dN/dy = 0.092 ± 0.005
T = 190.812 ± 4.70E

0.004 ± dN/dy = 0.091 ± 0.004
T = 184.231 ± 4.60E
Spectra and fit study

fit function: exp \( p \)

fit function: exp \( m \)

fit range 0.800-3.000 GeV/c

dN/dy = 0.064

T = 260.368 ± 2.337

fit range 1.100-3.000 GeV/c

dN/dy = 0.050

T = 237.488 ± 2.337

fit function: \( \exp \)
The page contains several graphs and text related to particle physics experiments. The graphs show distributions of particle momenta and yields, with fit functions applied. The text includes fit ranges, yields, and errors for different particle species and kinematic regions. The data is presented for different experiments, including mini-bias and specific triggers like $0.794 \text{ GeV/c} < p_T < 0.800 \text{ GeV/c}$.

Some key points from the text:

- **Fit Range**: The fit range for different plots varies, with examples given as $0.500-2.000 \text{ GeV/c}$ and $0.800-3.500 \text{ GeV/c}$.
- **Yield**: The yield $dN/dy$ is given with errors, e.g., $dN/dy = 0.420 \pm 0.008$, $dN/dy = 0.398 \pm 0.005$, etc.
- **Temperature**: The temperature $T$ is also quoted, e.g., $T = 269.531 \pm 3.413$.
- **Fit Function**: The fit function used is either exp or Boltzmann, as indicated by the text.
Spectra and fit study

---

- **$dN/dy = 0.228 \pm 0.010$**
  - Fit range: 0.500-2.000 GeV/c
  - $T = 200.603 \pm 5.896$

- **$dN/dy = 0.225 \pm 0.012$**
  - Fit range: 0.500-2.000 GeV/c
  - $T = 200.603 \pm 5.896$

- **$dN/dy = 0.149 \pm 0.013$**
  - Fit range: 0.800-3.500 GeV/c
  - $T = 144.000 \pm 7.684$

- **$dN/dy = 0.166 \pm 0.013$**
  - Fit range: 0.800-3.500 GeV/c
  - $T = 144.000 \pm 7.684$

---

**Fit function:**

- **Exp**
  - $p_T > 0.722$ GeV/c

- **Boltzmann**
  - $p_T > 0.654$ GeV/c

---

**Fit range:**

- 0.500-2.000 GeV/c
- 0.800-3.500 GeV/c

---

**Spectra and fit function:**

- $dN/dy = 0.228 \pm 0.010$
  - Fit range: 0.500-2.000 GeV/c
  - $T = 200.603 \pm 5.896$

- $dN/dy = 0.225 \pm 0.012$
  - Fit range: 0.500-2.000 GeV/c
  - $T = 200.603 \pm 5.896$

- $dN/dy = 0.149 \pm 0.013$
  - Fit range: 0.800-3.500 GeV/c
  - $T = 144.000 \pm 7.684$

- $dN/dy = 0.166 \pm 0.013$
  - Fit range: 0.800-3.500 GeV/c
  - $T = 144.000 \pm 7.684$
The plots show the distribution of pions in different y bins with the following key points:

- **Fit Function**: Various fit functions are used, including exponential and Boltzmann.
- **Energy Range**: The energy range is set from 0.500 to 3.000 GeV/c.
- **Statistics**: The number of events (N) is indicated for each bin.
- **dN/dy**: The differential yield per unit y is given for each fit.
- **T**: The temperature parameter for the Boltzmann fit is shown.
- **p**: The momentum in GeV/c is indicated.

Specifically:
- **0.80 < y < 1.00**:
  - Fit range: 0.500-3.000 GeV/c
  - dN/dy = 0.066 ± 0.052
  - T = 224.323 ± 1.089
- **1.10 < y < 1.30**:
  - Fit range: 0.500-3.000 GeV/c
  - dN/dy = 0.060 ± 0.050
  - T = 259.251 ± 2.787

These plots compare the experimental data with the theoretical fits, providing insights into the particle production mechanisms at high-energy collisions.
Appendix F

Publications

As main contributor

- I. Arsene et al. [BRAHMS Collaboration], *Production of mesons and baryons at high rapidity and high $p_T$ in proton-proton collisions at $\sqrt{s} = 200$ GeV*, Phys. Rev. Lett. 98, 252001 (2007)

As collaborator


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