Transverse Characteristics of Hadron Production in Elementary and Nuclear Collisions at the CERN SPS Energies

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Ph.D. Dissertation

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Warsaw 2004
Abstract

A comprehensive study of transverse phenomena at CERN-SPS energies has been performed using data collected by the NA49 experiment. Results on $p$, $\bar{p}$, $\pi^+$ and $\pi^-$ production in elementary hadronic interactions ($p+p$, $\pi^++p$ and $\pi^-+p$) as well as in nuclear collisions (centrality-defined $p+$Pb, C+C, Si+Si and Pb+Pb) are presented. The dependence of transverse momentum spectra, and in particular the $<p_T>-x_F$ correlations, on particle species, collision energy, size and structure of the colliding objects has been investigated. Particle composition, in terms of the nuclear modification factors - $R_{pA}(p_T)$ for different $x_F$ regions - and particle ratios, has been also studied. The whole set of experimental data puts strong constraints on theoretical models aiming at the description of hadron production in the studied reactions.
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Chapter 1

Introduction

Our current understanding of the Universe is contained in the theory called the Standard Model [Spie00]. All experimental observations are in agreement with this model. The model describes the basic constituents of matter and their interactions. The fundamental blocks of matter come in two main species: quarks and leptons. Four different forces act upon the matter: electromagnetic, weak, strong and gravitational.

The electromagnetic and weak forces are unified in the Standard Model. Quantum Electro-Dynamics (QED), describing electromagnetic interactions, was combined with Fermi’s theory of weak interactions into the Glashow-Weinberg-Salam electroweak theory [Sala59, Glas61, Wein67]. The strong and gravitational\(^1\) interactions are described by Quantum Chromo-Dynamics (QCD) and General Relativity, respectively. Leptons interact via the electroweak interactions. Quarks carry an additional internal degree of freedom which allows them to bind into hadrons via the strong interactions. The strength of the interaction of a given type is characterized by a coupling constant. The coupling constant of the electroweak force is small (\(\alpha \approx \frac{1}{137}\)). Quarks in hadrons, on the contrary, are strongly bound. As the subject of the present thesis concerns hadronic physics, in the following sections more information on the theory of strong interactions (QCD) as well as a short discussion of the theoretical and experimental situation in the field of hadronic physics can be found.

1.1 QCD and Hadronic Physics

A rich hadronic spectrum has been observed experimentally. The explanation of the spectrum, in terms of the quark model, was proposed independently by Gell-Mann and Zweig already in the early 1960s [Gell64, Zwei64]. The quark model describes hadrons as consisting of quarks. Baryons, of which the nucleons (proton and neutron) are two examples, consist of three quarks\(^2\) whereas mesons, such as pions, are made up of a

\(^1\)The gravity sector is attached \textit{ad hoc} to the other sectors of the Standard Model; it is not properly formulated yet as a quantum phenomenon. At the scale of the subatomic world, however, the effects of gravity can be neglected with respect to the other three fundamental forces.

\(^2\)Recently, experimental evidence for the existence of baryonic states identified as candidates for \textit{pentaquarks} has been found [Alt03, Naka03].
quark and an antiquark. The first experimental evidence for such objects (quarks) came from deep inelastic lepton–nucleon scattering [Brei69, Frie72], which revealed the inner structure of the nucleon (each nucleon was found to be built of three pointlike elementary particles).

The full hadronic spectrum can be accounted for by six different types (flavours) of quarks, which are listed in Table 1.1 together with their quantum numbers. All quarks have spin $\frac{1}{2}\hbar$, baryon number $B=\frac{1}{3}$ and a colour charge$^3$ (either red, green or blue). Each of the quarks has a corresponding antiquark which are denoted by $\bar{d}$, $\bar{u}$, $\bar{s}$, $\bar{c}$, $\bar{b}$ and $\bar{t}$, respectively. Antiquarks have the opposite charge and quantum numbers to their quark counterparts.

Quarks have never been observed outside of the confines of “colourless” hadronic particles. The energy put into pushing a single quark ($q$) out of a hadron will eventually create a new quark-antiquark ($q\bar{q}$) pair rather than freeing the bound quark. This property is called quark confinement and its explanation is provided by Quantum Chromo-Dynamics. QCD is a relativistic, non-Abelian gauge field theory that describes the interactions of partons: quarks and gluons (the gauge bosons mediating the strong force). Unlike photons, which mediate the electromagnetic force in QED, gluons carry the quanta of the strong force. That is, gluons have a colour charge whereas photons are electrically neutral. The fact that gluons are not colour neutral means that they can interact amongst themselves and it also finds its manifestation in the behaviour of the strong force potential. The potential, $V_{QCD}$, between two quarks at a distance $r$ apart is of the following form

$$V_{QCD}(r) \sim -\frac{\alpha_s(r)}{r} + k r,$$

where $k$ is a constant and $\alpha_s(r)$ is the strong coupling constant. For $r \gtrsim 1\text{fm}$, corresponding to small momentum transfers ($Q^2$), the second term in Eq. 1.1 dominates and $V_{QCD}(r) \to \infty$, thus confinement of quarks in hadrons can be explained.

In case of small distances (or equivalently large momentum transfers), however, the strong interaction is in fact rather weak, $V_{QCD}(r) \to 0$. This property is called asymptotic

$^3$The introduction of colour is necessary in order not to violate the Pauli exclusion principle for such hadronic states as $\Delta^{++}(uuu)$ or $\Omega^-(sss)$. The colour degree of freedom distinguishes quarks of the same flavour and spin and allows the three quarks to coexist in one particle.
1.1. QCD and Hadronic Physics

freedom, and results from the dependence of the strong coupling constant \( \alpha_s \) on \( r \) (\( r \) is inversely related to the momentum transfer):

\[
\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f) \ln(Q^2/\Lambda_{QCD}^2)},
\]

where \( n_f \) is the number of quark flavours and \( \Lambda_{QCD} \) can be thought of as the energy scale at which the strong force becomes strong\(^4\). At short distances, \( \alpha_s(r) \to 0 \) faster than \( r \to 0 \), which leads in consequence to \( V_{QCD}(r) \to 0 \). Quarks are then said to be free within the hadron volume.

Since on the one hand quarks are confined to hadrons but on the other they can be quasi-free, it is to be expected that there must be a transition between these two distinct regimes. Outside of the domain of large momentum transfers (hard hadronic physics), where the strong coupling constant is small and perturbative calculations may be employed, understanding and using of Quantum Chromo-Dynamics as a predictive theory is not possible. Therefore, in the non-perturbative regime (soft hadronic physics) calculations are restricted to numerical simulations on a discrete space-time lattice (lattice QCD) or to the use of phenomenological models. Lattice QCD is a computational technique that places quarks at lattice sites, which are linked by gluons, and simulates their interactions. The calculations allow a description of strongly interacting matter in terms of thermodynamic quantities such as temperature - \( T \) (related to energy density) or chemical potential - \( \mu \) (related to matter density). From lattice calculations, the existence of the hadron - parton phase transition has been predicted. At a sufficiently high temperature or/and density of matter, hadronic matter undergoes a phase transition and melts into a deconfined partonic state which is called the Quark-Gluon Plasma (QGP) [Meye96].

Values of the parameters for the phase transition (and the order of the transition as well) depend on the number of quark flavours (\( n_f \)) assumed in the calculation (the order depends also on the assumptions about the quark masses). For example, results of the lattice QCD calculations with \( n_f = 2 + 1 \) (2 light + 1 massive flavours) dynamical quarks with “semi-realistic” masses\(^5\), taken from [Fodo02], are presented in Fig. 1.1, showing the QCD phase diagram in the baryochemical potential (\( \mu_B \)) - temperature (\( T \)) plane. According to these calculations, at high \( \mu_B \) and finite \( T \) the transition is of the

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{fig1.1.png}
\caption{QCD phase diagram in the \( \mu_B \cdot T \) plane. The dashed line illustrates the crossover, and the solid line the first order phase transition. The plot is taken from [Fodo02].}
\end{figure}

\(^4\)At distances of about 1 fm, corresponding roughly to the size of a hadron, \( \Lambda_{QCD} \approx 200 \text{ MeV} \).

\(^5\)The mass of the strange quark, \( m_s \), was set to about its physical value, whereas masses of the light quarks, \( m_{u,d} \), were four times larger than their physical values.
first order (solid line). For smaller baryochemical potentials and larger temperatures a crossover takes place (dashed line). Since the order of the transition changes there must exist a critical point separating the two regions. Indeed, as shown in Fig. 1.1, the 'endpoint'-a critical point with a second order phase transition-has been predicted at $T \approx 160$ MeV and $\mu_B \approx 725$ MeV.

The Quark-Gluon Plasma state may exist in the Universe. First, it is thought that up to a few microseconds after the Big Bang, the Universe itself existed in a similar state and then it expanded and cooled down sufficiently for the formation of hadronic matter that exists today [Reev91]. It has also been proposed [Glen97, Grig99] that large volumes of deconfined quark matter might exist at the center of neutron stars. In the laboratory, can such conditions be brought about which allow the creation of a QGP? It is believed that the best way to produce the state of deconfined quarks and gluons in the laboratory is by colliding relativistic heavy nuclei. For such colliding systems, high enough energy density extended over a rather large volume can be obtained.

Although high energy heavy-ion collisions seem attractive in this respect, there are still many problems with the interpretation of the results in order to prove (or falsify) the creation of a QGP in these collisions. There have been many suggestions from theory concerning possible QGP signatures [Bass99]. Among them are, for example:

- **Strangeness enhancement** [Rafe82, Rafe82a]
  In the case of QGP formation, it becomes energetically favourable to thermally produce strange ($s$) quarks instead of the lighter flavours ($u, d$). This leads to the increased production of strange hadrons in the QGP phase, as compared to the hadronic phase.

- **$J/\psi$ suppression** [Mats86]
  If a deconfined partonic state with a sufficient lifetime is created, the separation of a $c\bar{c}$ pair may be too large to bind into $J/\psi$, resulting in the decreased production of $J/\psi$ and simultaneously in the increased yield of open charm mesons.

- **Suppression of high $p_T$ particles - "jet quenching"** [Gyul90, Gyul94, Wang95]
  It has been predicted that interactions of highly energetic partons with a hot and dense coloured matter, created in the collision, would induce gluon radiation which carries off a significant fraction of the parton’s energy, thus leading to the depletion of high $p_T$ particle yields (more information on this topic can be found in Chapter 6).

In order to interpret and fully understand the heavy-ion results a sequence of steps should be carried out:

1. study the production process of interest in elementary hadron+hadron ($h+h$) interactions to determine its behaviour in the absence of any bulk medium;
2. study its behaviour in normal nuclear matter as cold, confined medium given by hadron+nucleus ($h+A$) collisions;
3. check if in nucleus+nucleus ($A+A$) reactions there are deviations from the “normal” behaviour defined by the results from the mentioned above, less complex collisions.
Thus, the basic task, for experiment as well as for theory, is to first define and understand the conventional behaviour and then identify the eventual unconventional signs.

The other, complementary approach towards interpreting the heavy-ion data is by comparing the experimental results to the predictions of theoretical models in which nuclear collisions are described as a superposition of elementary hadronic interactions. Assuming that a given theoretical model is constructed correctly, any departure of the data from its predictions can indicate the presence of “new” phenomena in nuclear collisions. The correctness of the model should, therefore, be first tested on the level of elementary interactions. This also means that high quality experimental data on elementary hadronic collisions are of great importance here as well.

Since the bulk of the total hadronic cross-section belongs to the “soft” (non-perturbative) sector, where using of QCD as a predictive theory is not possible, models employed for the comparison purposes are, in fact, phenomenological ones. In the present thesis, predictions from two phenomenological models are shown and compared to the experimental results. The models are detailed and briefly described below.

1.2 Phenomenological Models

There is a variety of theoretical models aiming at the description of available data on high energy elementary hadronic and nuclear collisions. Among them, there are so-called statistical-thermal models. It was R. Hagedorn who introduced statistical methods into the strong interaction physics in order to calculate the momentum spectra of particles produced in high energy hadron+hadron collisions. He noticed that in these collisions the transverse mass distributions of final state particles show a common slope; this may be interpreted as a hint that it is phase space which governs the reaction. In the model of Hagedorn et al. [Hage65, Hage72], the transverse momentum distributions, and in particular the average transverse momenta of particles, are connected with the temperature of the “fireball” or “fireballs”, which are produced by merging of the two incident hadrons. One may think of the fireball as a “liquid drop at the boiling point” from which “evaporate” the particles. Increasing the energy inside the drop does not lead to the increase of its temperature, nor of the average transverse momentum of the produced particles, but results in the increased production of particles.

Later on, various models built upon a statistical framework have been developed to describe elementary hadronic interactions as well as heavy ion collisions, see e.g. [Beca02, Brau03]. These models attempt to describe particle production by using only a few parameters, such as: temperature, chemical potentials, strange-quark suppression parameter $\gamma_s$, etc. In general, the results they deliver can reproduce main features of the experimental data fairly well, but in the soft physics domain only.

A completely different approach is implemented in so-called string models such as FRITIOF and VENUS models (available as Monte Carlo event generators), the results from which can be found in the present thesis. Models of this kind use strings as basic
objects. There are two mechanisms of the interaction considered: *longitudinal momentum transfer* and *colour exchange*, see Fig. 1.2. Longitudinal excitation (Fig. 1.2a) requires all partons in a string to originate from one hadron, whereas colour exchange (Fig. 1.2b) provides strings with partons from different hadrons.

There is a gluon field acting between the two ends of the string, whose energy is proportional to the separation distance. The colour field induces the production of $q\bar{q}$ pairs, which screen the field and thus produce two substrings; the substrings may continue to break up. These new string pieces are finally hadrons and resonances.

Thus, there are two main building blocks of the string models: *string formation* and *string fragmentation*. First, before the interaction occurs, the colliding hadrons are resolved into their parton substructure and the initial parton momentum distributions are generated according to the experimentally measured structure functions. Then, as a result of the collision, the strings are formed and subsequently their fragmentation proceeds in the same way as for strings from $e^+e^-$ annihilation or lepton+nucleon scattering; this is sometimes referred to as *universality of string fragmentation*.

The generalization to hadron+nucleus and nucleus+nucleus collisions is rather straightforward in these models. It is done by taking into account the nuclear geometry of the collision, as given by the Glauber Model approach [Glau70]. It is assumed that the nucleons from the projectile pass through the target nucleus on a straight line geometry. Nucleons inside the nucleus are distributed according to the Wood-Saxon type distribution. Having defined the nucleon density distribution, the impact parameters of the incident nucleon to each of the target nucleons can be calculated. The probability of whether there will be an interaction between two nucleons is related to the calculated impact parameter. A set of target nucleons that would interact with the incident nucleon can thus be determined. A nucleon from the projectile interacts independently with the encountered target nucleons and each of these sub-collisions is treated as usual hadron+hadron collision, as described above.
1.2. Phenomenological Models

1.2.1 FRITIOF

FRITIOF is a Monte Carlo implementation [Nils87, Pi92] of the LUND string model [Ande87] for inelastic hadron+hadron, hadron+nucleus and nucleus+nucleus collisions. In the present work, FRITIOF version 7.02 is used. The basic hadron+hadron interaction mechanism is longitudinal excitation (see Fig. 1.2a); it is assumed that no net colour is exchanged between the hadrons. The collision between two hadrons is modeled by many momentum transfers. After the exchange of momenta, the hadrons are assumed to become two excited string states. Each string contains exactly the quarks of one of the incident hadrons, so that the colour singlet structure of the hadrons is not changed.

The break-up of a string into two substrings in the Lund model is allowed only when one of the substrings is an on-shell hadron. Thus, this model has a “salami structure”: a hadron is chopped off at the end of the string, then another one from the remaining string, and so on. The procedure terminates, whenever the string masses are below some cut off value. Those strings are identified with stable hadrons or known resonances. The string fragmentation scheme as in the Lund Monte Carlo JETSET [Sjö95] is used.

The occurrence of semi-hard and hard processes with increasing energy of the collision dictates the inclusion of these processes in the model. In FRITIOF 7.02, hard interaction effects are taken into consideration through PYTHIA [Beng87, Sjö95]. In this approach, the effects are related to the gluon bremsstrahlung radiation and produce “kinks” on the strings.

In the FRITIOF model, collisions with nuclei involve only independent interactions between constituent nucleons. The nucleons remain excited over the time scale of the collision but preserve their nucleonic state and do not fragment while traversing the nuclear matter. Thus, intranuclear rescattering is not included in FRITIOF.

1.2.2 VENUS

The VENUS (Very Energetic NUclear Scattering) model [Wern93], designed to treat high energy nucleon+nucleon, nucleon+nucleus and nucleus+nucleus collisions, is based on Gribov-Regge theory [Reg59, Osta03]. This is an effective field theory with the phenomenological object called Pomeron. The Pomeron exchange is considered in this theory as the basic process in high energy hadron+hadron scattering. Using the general rules of field theory, one may express cross sections in terms of a couple of parameters characterizing the Pomeron. Thus, the VENUS model is not a classical string model, as strings are not truly basic objects in it. The dynamics and fragmentation of strings are nevertheless crucial ingredients of this model.

The interaction between two nucleons is realized by colour exchange between a quark of the projectile and a quark of the target (see Fig. 1.2b). It is assumed that the colour exchange occurs without any momentum transfer. The production of strings is due to the fact that colour exchange causes the formation of colour singlets - stretched between partons from different nucleons.

VENUS uses the string fragmentation model AMOR. This model has a “tree structure”:
a string decays into two substrings, each substring may then decay into two substrings, and so on. Substrings may have arbitrary masses, i.e. each of the substrings may be a stable hadron, a resonance, or a high mass string. Similarly as for FRITIOF, there is some cut off value for string masses. If the string mass is below this value the string break-up stops.

This thesis contains results from VENUS version 4.12. In this version, not only soft but also hard processes can be taken into account. In case of including the hard effects, a Pomeron has a “hard” component, in addition to the “soft” one. Both soft and hard colour exchanges provide strings in an identical procedure. However, for the hard colour exchange, the string endpoints may acquire larger transverse momenta than for the soft colour exchange.

For nuclear collisions, the basic assumption of the model is that the projectile nucleon - whatever its nature is after the first collision - moves through the nucleus on a straight line, interacting with nucleons coming into its way. Each interaction means colour exchange and string formation. It is also argued that relativistic heavy nuclei collisions cannot be treated as a sequence of independent binary nucleon+nucleon interactions, due to the produced high hadron densities. Therefore, in the VENUS generator, intranuclear rescattering is introduced. When two or more objects are coming close to each other the clusters are formed. Light clusters are identified with known resonances, while heavy ones decay according to the available phase space.

From what has been said above, it follows that the basic processes in FRITIOF and VENUS are too some extent similar, but there are also differences between the models. Some features of the two models are summarized in Table 1.2.

Both models have a large number of parameters. These parameters concern, for example, processes of string formation and string fragmentation. One may, thus, attempt to tune the models to the experimental data or to restrict himself to a comparison in terms of the default parameters. In this work, results for standard settings of the models’ parameters as well as for modified ones are presented.

<table>
<thead>
<tr>
<th>Model</th>
<th>N+N Interaction</th>
<th>Fragmentation</th>
<th>Considered Processes</th>
<th>Nuclear Collisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRITIOF</td>
<td>longitudinal excitation</td>
<td>JETSET model ( \text{string} \rightarrow \text{string} + \text{hadron} )</td>
<td>soft(+hard)</td>
<td>no rescattering</td>
</tr>
<tr>
<td>VENUS</td>
<td>colour exchange</td>
<td>AMOR model ( \text{string} \rightarrow \text{string} + \text{string} )</td>
<td>soft(+hard)</td>
<td>rescattering included</td>
</tr>
</tbody>
</table>

Table 1.2: Comparison of FRITIOF and VENUS features.
1.3 Experimental Status and Requirements

Hadronic physics has been extensively studied in the past. A lack of good theoretical understanding of the “soft” QCD domain led, however, to the retreat of high-energy experimental physicists from the studies of soft elementary hadronic interactions. Their interest has turned towards the investigation of “hard” processes, for which the perturbation theory can be applicable. The sector of soft hadronic physics has been, on the other hand, still very intensively studied in heavy-ion reactions, where one searches for QGP formation.

Analyses of soft elementary hadronic interactions were mostly carried out in the 1970’s, in bubble chamber and single-arm spectrometer experiments [Albr73, Albr74, Blob74, Capi74, Whit74, Alpe75, Ross75, Guet76, Guet76a]. In general, the data collected by these experiments suffered from some shortcomings, such as:

- limited statistics
- limited phase space coverage
- poor or non-existing particle identification
- limited energy range.

Nowadays, the available experimental techniques (accelerators, detectors, analysis software etc.) give the opportunity to obtain complete, high quality data sets, constituting an experimental basis indispensable for a deeper understanding of hadronic physics. Such an experimental basis should fulfill several requirements:

- **wide phase space coverage**
  With a wide acceptance coverage, a detailed information on particle production mechanisms and their importance in different phase space regions can be obtained.

- **particle identification**
  Particle production mechanisms can be different for different particle species, and therefore particle type dependence studies are very important in order to gain in understanding of these mechanisms.

- **various colliding systems**
  Reactions of different complexity, starting from elementary h+h interactions via h+A and ending at the most complex A+A collisions, should be studied experimentally (using various projectiles and targets). In this way, a better understanding of elementary interaction processes (e.g. the influence of the projectile’s valence quark structure on the measured characteristics) as well as of the evolution with the size/complexity of the colliding system can be achieved.

- **different collision energies**
  A process of interest can depend on the energy at which the interaction takes place. The collision energy is, thus, the next parameter helping in finding the right explanation of the phenomena observed experimentally.
• different collision centralities
For reactions involving nuclei (h+A, A+A), more complete information on the interaction process can be obtained when the study includes the collision centrality control, as characteristics of final state particles can depend on this parameter as well.

• large statistics
Large data samples are indispensable for precise analyses and studies of the internal correlations.

The present thesis contains results of the analysis of data collected by the one of the CERN experiments, the NA49 experiment. In the following chapters, features and possibilities of this experiment are described and discussed in detail, in order to illustrate how well it fulfills the requirements that are listed above.

1.4 Thesis Objectives and Outline

Hadron production in high energy collisions can be studied by analysing particle momentum spectra. Longitudinal and transverse momentum distributions of final state particles are the simplest characteristics carrying information about production mechanisms.

For the longitudinal spectra, studied in high energy collisions for many years, anisotropy is observed. It reflects the "privilege" of the direction of motion of the initial colliding objects. By investigating the shape of longitudinal momentum distributions, in both elementary and nuclear reactions, the "stopping" mechanism can be studied [Appe99, Coop99, Coop00, Rybi02, Vere02, Fisc03].

The present work is not dedicated to the study of longitudinal spectra but to the analysis of transverse momentum characteristics. The reason is that, transverse effects are a cleaner signature of the reaction dynamics than longitudinal ones, as a large fraction of longitudinal momenta of the produced hadrons is due to the initial motion of the colliding objects, whereas all transverse momenta are generated by the collision itself.

In this thesis, inclusive transverse spectra of charged hadrons \( p, \bar{p}, \pi^+, \pi^- \) from hadron+hadron, hadron+nucleus and nucleus+nucleus collisions at CERN-SPS energies are presented. The spectra are used to study particle production mechanisms. In particular, the following items are considered:

1) transverse momentum behaviour dependence on
   ▶ phase space region
   ▶ produced particle species
   ▶ size and structure of the colliding system
   ▶ collision energy

2) particle composition in different phase space regions.

The aim of this work is, first, to provide detailed and comprehensive experimental results, and then, to try to understand the observed phenomena. Good quality exper-
1.4. Thesis Objectives and Outline

imenal data put constraints on the existing theoretical/phenomenological models, and thus can help in eliminating wrong descriptions of the studied interactions. Additionally, as a wide range of colliding systems is investigated here, the $h+\rightarrow h+A \rightarrow A+A$ evolution of the transverse momentum behaviour can be traced. This particular study is not directly motivated by the search for a QGP, but its purpose is rather to find similarities and differences between the considered reactions.

The remainder of this thesis is organized as follows.
- **Chapter 2** provides a brief description of the NA49 experiment.
- Methods of particle identification employed in the present work are described in **Chapter 3**.
- Kinematic variables and physical quantities appearing in the thesis are defined in **Chapter 4**. This chapter contains also the description of the analysis procedures for obtaining particle spectra and information on analysed data sets.
- **Chapter 5** and **Chapter 6** contain results on transverse momentum spectra and particle composition, respectively. First, a detailed motivation for these studies is given. Then, the experimental results are shown and compared to the model predictions. A possible explanation of the presented results is also provided.
- The work is summarized in **Chapter 7**.
- Three appendices are included. In **Appendix A**, abbreviations used in the thesis are explained. **Appendix B** contains details concerning the selection of proton+proton interactions from deuteron+proton collisions. **Appendix C** records the transverse momentum distributions from which the results on particle composition, presented in Chapter 6, were obtained.

**Author’s Contribution:**
The experiment which collected the data analysed in this thesis is large and complex. The recording and analysis of data is therefore a collaborative effort. As a member of the NA49 Collaboration, the author participated in the acquisition of data in the years 1998-2000. Some of these data are used in the study presented in this thesis.

All results, based on the already calibrated NA49 data, shown and discussed in this work have been obtained by the author, except results from the most complex reactions - Pb+Pb collisions.

The analysis programs have been written by the author (with one exception concerning the program for extracting invariant particle yields). In the programs, corrections necessary for obtaining physical results have been implemented. The corrections have been worked out by other members of the Collaboration; the author participated in the testing of the acceptance corrections.

In the present study, the experimental results are confronted with the predictions of phenomenological models. The Monte Carlo event samples have been generated and analysed by the author.

Some ideas explaining the observed phenomena can be found in the thesis. These ideas are also the author’s contribution to this work.
Chapter 2

The NA49 Experiment

2.1 The SPS Accelerator

The NA49 experiment is a fixed target experiment. It is located on the H2 extraction beam line of the North experimental area of the CERN-SPS accelerator. This line transports the injected heavy ion beam or a variety of secondary beams produced from primary protons to the experiment. Fig. 2.1 shows the present and future CERN accelerators and the location of the NA49 experiment.

The beam particles are accelerated in a few steps. The first acceleration stage is the LINear ACcelerator (LINAC), which is used as an injector to the Proton Synchrotron Booster (PSB). After this stage of the acceleration, the beam particles emerge with an energy of 94 A•MeV, then they are injected into the Proton Synchrotron (PS) where their energy reaches 4.25 A•GeV. The final acceleration is performed in the Super-Proton Synchrotron (SPS). The maximum possible energy is 158 A•GeV for Pb-ions and 450 GeV for protons. The particles are delivered to the experiment in short and separate spills.

2.2 The NA49 Detector

The NA49 experiment has been collecting data since 1994. The apparatus of the experiment is used to investigate the hadronic final states produced in collisions of beam particles delivered by the SPS accelerator with a variety of fixed targets. The design of the experiment was motivated primarily by the desire of studying central Pb+Pb collisions, in a search for the transition from ordinary hadronic matter to quark-gluon plasma. Nowadays not only Pb+Pb collisions but diverse colliding systems are studied.

The NA49 experimental apparatus is shown schematically in Fig. 2.2. The detector is a large acceptance magnetic spectrometer with momentum measurement and identification of charged particles. It provides a possibility of studying hadron+proton (h+p), hadron+nucleus (h+A) and nucleus+nucleus (A+A) collisions in the projectile hemisphere.
2.2. The NA49 Detector

Figure 2.1: Schematic drawing of the CERN accelerator complex.

LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso
Figure 2.2: Set-up of the NA49 detector with different beam definitions and target arrangements for a) A+A, b) h+p and c) h+A collisions. The target position is at the front face of the first Vertex Magnet (VTX-1). Also shown are the definitions of the NA49 coordinate system and the azimuthal angle $\phi$.

The main components of the detector are four large volume Time Projection Chambers (TPCs). Two of them, so-called vertex TPCs (VTPC-1, VTPC-2), are located in separate large aperture superconducting dipole magnets (VTX-1, VTX-2), placed directly adjacent to one another. Two larger chambers, called Main TPCs (MTPC-L, MTPC-R), are located just downstream of the second vertex magnet (VTX-2), in a field free region. The TPCs provide charged particle tracking and momentum reconstruction as well as Particle IDentification (PID) via specific energy loss measurements ($dE/dx$). Energy loss measurements have to be supplemented by independent methods in the region of minimum ionization, $\beta\gamma \approx 3$. Four walls of Time-Of-Flight (TOF) scintillator detectors are therefore installed behind the MTPCs. In order to extend identification of charged hadrons into the target hemisphere two arrays of PesTOF counters are positioned between the two magnets. There are two calorimeters: the Ring CALorimeter (RCAL) and the Veto CALorimeter (VCAL). The RCAL is used to measure transverse energy. In addition, in low multiplicity reactions, the information from the RCAL together with the information from the Veto Proportional Chamber (VPC) is used to distinguish between charged and neutral particles passing through the TPCs and reaching the RCAL. The VCAL is a zero-degree calorimeter which is used to measure centrality in A+A collisions, and thus provides a convenient trigger on impact parameter in heavy ion running. In case of h+A collisions, the triggering on centrality of the collision is possible using a special target detector, the Centrality Detector (CD), which measures the number of target recoil ("grey") protons from nuclear targets.

A comprehensive description of the NA49 apparatus is given in [Afan99]; next paragraphs give more detailed information only on these parts of the NA49 detector which are important for the analysis presented in this thesis.
2.2. The NA49 Detector

2.2.1 The NA49 Coordinate System

The NA49 coordinate system is schematically shown in Fig. 2.2. The beam defines the $z$ axis, the $y$ axis is vertically upwards leaving the $x$ axis horizontal and positive to the left, looking downstream of the beam. The origin of these coordinates is chosen to be the center of VTPC-2. Thus in this coordinate system the location of the target T is (0,0,-580), in cm.

2.2.2 Beam Detectors, Projectiles, Targets, Trigger Conditions

A series of beam detectors operate both upstream and downstream of the target. The beam position detectors (BPD) - two-dimensional multi-wire proportional counters giving $x$ and $y$ coordinates for the beam - are located in the beam line upstream of the target and interaction counters (S4-scintillation or S3-Čerenkov counters) downstream of the target. They provide precise timing reference, charge and position measurement of the incoming beam particles. The set-up depends on the collision system ($h+p$, $h+A$ and $A+A$) being studied (see Fig. 2.2a, b, c).

Beam particles can be extracted either directly from the SPS accelerator (protons, Pb-ions), or secondary beams can be produced from interactions of the primary beam particles with the “production” or “fragmentation” target. Pions, deuterons and also heavier nuclei were used by the NA49 as secondary beams so far. An example of Pb-beam fragmentation spectrum is shown in Fig. 2.3. In this case, a secondary fragmentation beam was produced by the “fragmentation” target (10mm Carbon) from the extracted Pb-beam. Fragments with $Z/A=1/2$ were then transported to the experiment. The on-line selection based on a pulse height measurement in a scintillator beam counter was used to select particles with $Z=6$ (Carbon) and $Z=13, 14, 15$ (Aluminium, Silicon, Phosphorus).

![Figure 2.3: Pb-beam fragmentation spectrum from a 10mm Carbon target with the beam line set to select $Z/A=1/2$. A clear $Z$-separation is achieved all the way from Boron to Phosphorus [Bäch99a].](image-url)
Chapter 2. The NA49 Experiment

A versatile set of target stations, including a liquid hydrogen target, are used for different running conditions. For example, as nuclear targets Pb (224 mg/cm²), Si (1170 mg/cm²) and C (561 mg/cm²) foils were used. In case of proton, pion and deuteron beams interacting with proton target, a cigar shaped, 20 cm long (3 cm in diameter) and 60 μm thick mylar container was filled with a liquid hydrogen and installed on the way of the beam.

For hadron+proton reactions, interactions with the target are selected by an anti-coincidence of the incoming beam particle with the S4 scintillation counter (Fig. 2.2b; see also Sec. 4.4.1 for a trigger cross section determination for inclusive “minimum bias” p+p collisions at 158 GeV/c beam momentum). For centrality controlled h+A collisions, additional information from the Centrality Detector (see Sec. 2.2.6) surrounding the nuclear target is used on a trigger level (Fig. 2.2c). A requirement of a given number of hits in the CD detector is applied. Minimum bias nucleus+nucleus interactions are selected by an anti-coincidence with the S3 Čerenkov counter (Fig. 2.2a). The centrality can be also controlled in A+A collisions; it is done using the VCAL calorimeter (Sec. 2.2.5).

2.2.3 The Vertex Magnets

The kinematics of the fixed target experiment results in produced particles being emitted in a narrow cone surrounding the beam. In order to enable the reconstruction of charged particle tracks in this cone, a magnetic field with a large total bending power is needed. The use of the magnetic field leads to the separation of the tracks and also allows for the determination of the spatial components of the particle's momentum by measuring the curvature of the particle's trajectory. To achieve these goals NA49 uses two identical superconducting dipole magnets (VTX-1, VTX-2). They are placed in series and centered on the beam line downstream of the target. The standard current settings correspond to full field - nominally 1.5 T - in the first and reduced field 1.1 T in the second magnet. Inside the magnets the two TPCs (VTPC-1, VTPC-2) are placed.

2.2.4 The NA49 Time Projection Chambers

It has already been said that NA49 uses four TPCs. The VTPCs operate in a magnetic field and two larger chambers - the MTPCs - are placed in a field free region. Since heavy ion beams cause a very high ionization density, the NA49 TPC system has to be split, leaving the beam area not covered (Fig. 2.2). In this paragraph arguments advocating the choice of a TPC design as a main subdetector for the NA49 experiment are given, as well as basic parameters of the NA49 TPCs.

In order to deduce information on the production of specific particle species (i.e. pions, protons, kaons etc.) it is necessary to have PID capabilities. For this purpose, the complete determination of a particle's four-momentum is necessary. The spatial components
of the particle momentum can be determined by measuring the curvature of a particle’s trajectory in a magnetic field. This requires some sort of tracking detector. To complete the PID, a measurement of the particle’s mass, energy or velocity is needed. This could be carried out by a measure of a particle’s specific energy loss ($\frac{dE}{dx}$) using tracking chambers, since this quantity depends of the velocity of the particle.

In fixed target experiments, most of the produced particles are highly relativistic (i.e. $\beta \gamma \gg 1$). The specific energy loss of such a particle is a weak function of its velocity (see Fig. 3.1). In order to ensure high precision of a measurement, many samplings over a long track length must be made. Furthermore, since the track density in Pb+Pb collisions is very high\(^1\), the granularity of the detector must be sufficient, implying a large number of electronics channels. All these requirements can be well fulfilled by the Time Projection Chamber. Detectors of this type are able to track very efficiently and enable PID through the measurement of $\frac{dE}{dx}$ in a wide range of experimental conditions and over large volumes of phase space.

A TPC is based on the same principles as a Multi-Wire Proportional Chamber (MWPC)[Char68]. In the case of a TPC, however, the drift length is extended to the order of meters, instead of centimeters, and as such it is ideally suited for covering large volumes. As shown in Fig. 2.4, a TPC can be segmented into three separate components: a containing vessel (gas envelope), field cage, and readout chambers. A charged particle traversing the TPCs active volume, defined by the field cage, produces electrons and ions through ionization processes. Under the influence of a drift field, produced by the field cage, this ionization is swept towards a readout plane. The readout chambers are

---

\(^{1}\)In central Pb+Pb collisions more than $10^3$ charged hadrons are produced.

Figure 2.4: Schematic drawing of the assembly of one of the VTPCs showing the support plate housing the readout chambers, the two field cages on both sides of the beam, and the gas envelope (a double layer of Mylar window).
constructed much like a conventional MWPC. A system of anodes and field shaping wires are strung above a segmented cathode plane (Fig. 2.5). This cathode plane is made up of electrically isolated “pads” which are capacitively coupled to the sense wires. Electrons produced by ionizing particles in the active volume of the TPC drift towards the anodes and are multiplied in the avalanche process. The movement of the positive ions (produced in this avalanche) away from the anode wires, induces a signal on the cathode pads. The position of this signal on the pad plane provides two of the three spatial coordinates of a charge cluster (a point on a track). The third coordinate is deduced from the time it takes the electrons produced by the charged particle traversing the TPC to reach the sense wires.

In the case of TPCs usually preferred are argon-methane gas mixtures because they are cheap and the drift velocity has a plateau at a relatively low drift field. These mixtures, however, are not adequate for chambers subjected to a high track density because they have a rather large electron diffusion coefficient which limits the Two Track Resolution (TTR). Furthermore, because of its high atomic number, Z, argon based mixtures produce large amounts of ionization and large multiple scattering effects. A large ionization increases the space charge inside the chamber and a multiple scattering degrades the position (and hence momentum) resolution, neither of which are desirable. By adding He or CO₂ one can significantly reduce the drift velocity and the diffusion coefficients [Albe94], and further reduction of these quantities can be achieved by the replacement of Ar with Ne. Although Ne has the favorable property of lower Z, it is more expensive than Ar. Therefore a two component gas - NeCO₂ (90/10) - was chosen for the VTPCs because they have to cope with the highest track density, owing to their proximity to the target. Since the MTPCs have a much larger volume than the VTPCs, and the region they cover is subjected to a somewhat reduced track density throughout most of the chamber, they are filled with a less expensive three component gas - ArCO₂CH₄ (91/4.5/4.5).

\(^2\)Typically of the order of 30 e⁻ cm⁻¹ [Saul77].
2.2. The NA49 Detector

Table 2.1 gives a short summary on the NA49 TPCs parameters.

<table>
<thead>
<tr>
<th></th>
<th>VTPC</th>
<th>MTPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width [cm]</td>
<td>200</td>
<td>390</td>
</tr>
<tr>
<td>Length [cm]</td>
<td>250</td>
<td>390</td>
</tr>
<tr>
<td>Height [cm]</td>
<td>98</td>
<td>180</td>
</tr>
<tr>
<td>No. of pads</td>
<td>27648</td>
<td>63360</td>
</tr>
<tr>
<td>Pad size [mm]</td>
<td>$3.5 \times 16$</td>
<td>$3.6 \times 40$</td>
</tr>
<tr>
<td></td>
<td>$3.5 \times 28$</td>
<td>$5.5 \times 40$</td>
</tr>
<tr>
<td>Drift length [cm]</td>
<td>66.6</td>
<td>111.7</td>
</tr>
<tr>
<td>Drift velocity [cm/μs]</td>
<td>1.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Drift field [V/cm]</td>
<td>200</td>
<td>175</td>
</tr>
<tr>
<td>Gas mixture</td>
<td>NeCO\textsubscript{2} (90/10)</td>
<td>ArCO\textsubscript{2}CH\textsubscript{4} (91/4.5/4.5)</td>
</tr>
</tbody>
</table>

Table 2.1: Parameters of the NA49 TPC system.

The energy loss of charged particles due to ionization processes and methods of particle identification, based on the $dE/dx$ information, used in this thesis are described in detail in Chapter 3.

2.2.5 The Calorimeters

Ring Calorimeter

The ring calorimeter (RCAL) has been used in previous CERN experiments (NA5, NA22, NA35) and is described in detail in [DeMa83, Bäch91]. It consists of electromagnetic and hadronic sections. The electromagnetic part of the calorimeter is formed by lead and scintillator layers and corresponds to 16 radiation lengths ($16 \ X_0$), and is 1 interaction length (1 $\lambda_{int}$) thick. The electromagnetic section is followed by iron and scintillator layers, which constitute the hadronic section - 6 $\lambda_{int}$ thick. The RCAL is tube shaped with an inner (outer) radius of 0.28 (1.5) m, segmented into 240 separate cells, 24 azimuthally and 10 radially. It is stationed behind the MTPCs, 18 m from the target. Its energy resolution can be parametrized in the form $\sigma(E) \over E = \frac{1.2}{\sqrt{E[Gev]}}$.

For heavy ion reactions, the RCAL is used to measure transverse energy (the magnetic field is then switched off). In addition, in case of hadron induced reactions, the combined information from the RCAL and the VPC can be used to measure neutral particle production in the projectile hemisphere.
Veto Calorimeter

The veto calorimeter (VCAL) [DeMa83], constructed originally for the NA5 experiment, comprises a lead/scintillator section of 16 \( X_0 \), followed by an iron/scintillator section of 7.5 \( \lambda_{\text{int}} \). It is a total absorption Pb-Fe sampling calorimeter divided into 4 separate cells. Its energy resolution can be parametrized by \( \frac{\sigma(E)}{E} = \frac{1.0}{\sqrt{E \text{[GeV]}}} \).

The VCAL is a zero-degree calorimeter, and is used as a trigger detector to select central A+A interactions. It is placed about 20 m downstream of the target behind a collimator. The opening of the collimator is adjusted in such a way that non-interacting beam particles, projectile fragments and spectator neutrons/protons can reach the calorimeter. Central collisions of heavy nuclei from the beam with a heavy nuclear target remove a large fraction of the beam energy and these events are clearly identifiable by a small energy deposit in the VCAL. Triggering is accomplished by placing an upper threshold on the summed signals from VCAL photomultipliers in coincidence with valid signals from the beam detectors.

The centrality in nucleus+nucleus collisions can be defined by specifying, for example, the impact parameter \( (b) \), the number of elementary subcollisions \( (\nu) \) suffered by the projectile and target nucleons or the number of nucleons participating in the collision, so-called wounded nucleons \( (N_w) \) [Bial76]. In order to obtain these quantities, the veto energy distributions, measured in the experiment, are compared to simulations including the Glauber Model [Glau70] calculations and the response of the detector.

2.2.6 The Centrality Detector for Hadron+Nucleus Collisions

While passing through a nucleus, a projectile hits nucleons on its way, as shown in Fig. 2.6. Some of the hit nucleons can knock out other nucleons from the nucleus. The knocked out nucleons have various momenta. It is known from the earlier studies [Ferr96, Sikl03], that the impact parameter (thus centrality) in hadron+nucleus collisions is correlated to the number of “grey” target protons, having the laboratory momentum in the range 0.15 to 1.0GeV/c.

For a detailed study of hadron+nucleus phenomena, the information on the centrality of the collision is very useful. Therefore a centrality detector (CD) surrounding the nuclear target has been developed (Fig. 2.2c). The detector has the shape of a vertical

[Figure 2.6: Sketch showing nucleons knocked out from the nucleus after the passage of a projectile.]
cylinder with 20 cm height and 16 cm diameter. It is a gas detector consisting of drift tubes (Fig. 2.7). A thin foil target (about 0.3% interaction length) is placed in its center. The counter subtends lab polar angles from 45° to 315°, leaving free the tracking acceptance wedge of the NA49 spectrometer. Particles with momenta smaller than 0.15 GeV/c are cut off by range in a Cu absorber located between target and drift tubes, thus the copper foil eliminates evaporation ("black") protons and also nuclear fragments. A detection of fast particles (e.g. pions produced in the collision) is suppressed by proper placing of the electronics detection threshold. In addition, "grey" protons entering the tracking acceptance wedge of the NA49 TPCs are identified using the \( \frac{dE}{dx} \) method (Sec. 3.3). The detector simulation gave the estimation of the CD acceptance to be about 40% of all produced "grey" protons.

Similarly as in nucleus+nucleus collisions, the centrality in hadron+nucleus collisions can be defined by specifying the impact parameter \( b \), the number of elementary subcollisions \( \nu \) suffered by the projectile or the number of wounded nucleons \( N_w \). Also here, by using the Glauber Model calculations and a simulation of the CD detector response, the number of observed "grey" protons can be translated into the corresponding \( b \), \( \nu \) or \( N_w \).

### 2.2.7 The Veto Proportional Chamber

The Veto Proportional Chamber (VPC) is the newest subdetector of the NA49 detector system; it was built in 1999. The VPC consists, in fact, of two proportional chambers. They have a cathode strip readout, in this way a relatively large sensitive area (80 cm × 160 cm) could be covered without using a large number of electronics channels. Each chamber has a wire plane in the middle of a gap between the two readout planes. On the inner side of the readout planes, facing the wire plane, silver strips were sprayed. The strips on the first plane are tilted in the opposite direction than the strips on the second plane on the other side of the gap.

The whole detector is placed between the MTPCs and the RCAL (Fig 2.2), which is then shifted orthogonally to the beam by about 23 cm. Thus, the VPC sensitive volume covers the gap between the TPCs, the region so far "blind" to the detection. The detector is used for studying \( \text{proton+proton} \), \( \text{proton+nucleus} \) and \( \text{deuteron+proton} \) collisions. It

![Figure 2.7: Centrality Detector used in hadron+nucleus collisions.](image)
cannot be used in case of heavy ion beams since the electronics cannot handle the necessary
dynamic range.

The VPC offers a reliable detection of charged particles crossing its planes. It makes
also possible the distinction of neutrons and protons reaching the RCAL, when used as
an off-line “veto” for charged particles. Some of physics applications of the VPC are listed
below:

- a measurement of the momentum spectra of fast, forward going protons
- a measurement of the momentum spectra of neutrons (relies on the veto function of
the VPC + the energy measurement from the RCAL)
- for deuteron+proton collisions, a separation of the data sample into proton+proton
and neutron+proton interactions by the selection of spectators (non-interacting
nucleons from deuteron). For example, for the neutron spectator selection - p+p
collisions at 40 GeV/c - see Appendix B.

2.3 Tracking Method and Performance

The NA49 track reconstruction software is structured into several consecutive steps:

1. charge cluster finding in the TPC system
2. construction of “local” tracks in each TPC
3. matching of “local” tracks from different TPCs into “global” tracks
4. track fitting through the magnetic field and a momentum determination.

In the first step, by using the information from pads of the TPC readout chambers, two-
dimensional charge clusters are formed in the $x$-$y$ plane. The $z$ coordinate of the cluster
is given by the position of a pad row. The center-of-gravity method is then applied to
the charge distribution of the clusters and thus the $x$ and $y$ coordinates of each cluster (a
point on a track) are found. Knowing the position of the clusters subsequent steps of the
track reconstruction can be performed.

The achieved space resolution varies from 120 $\mu$m to 270 $\mu$m, depending on the drift
length. The momentum resolution depends on the track length and the number of
measured points along the track\(^3\). Therefore, a general parametrization of the momentum
resolution cannot be given. Typical values of the total momentum resolution are $\frac{d\sigma}{dp^2} = 7 \cdot 10^{-4}$ (GeV/c)$^{-1}$ for “local” tracks detected only in the VTPC-1 ($0.5$ GeV/c < $p$ < $8$ GeV/c)
and $\frac{d\sigma}{dp^2} = 0.3 \cdot 10^{-4}$ (GeV/c)$^{-1}$ for “global” tracks from the VTPC-2 and one of the MTPCs
($4$ GeV/c < $p$ < $100$ GeV/c).

A good measurement of the position of the primary interaction vertex is of importance
for the separation of secondary decay vertices (e.g. neutral strange particles) and
for the elimination of background tracks and events originating in the target walls. For

\(^3\)For “global” tracks, the number of points on a track varies between 10 and 234.
heavy ion collisions (high multiplicity events), the primary vertex is reconstructed using the trajectories of the produced particles. In low multiplicity topologies (hadron+proton, hadron+nucleus collisions), the measured coordinates of the beam particle, from the BPDs, are used in addition. The position of the primary vertex is constrained in the transverse plane with a precision of a few hundred microns. The resolution along the beam axis is about 2 mm in case of central Pb+Pb interactions, and about 6.5 mm in hadron induced reactions. For h+p and h+A collisions, the efficiency and resolution of the reconstruction of the primary vertex depend on the number of tracks. Thus, multiplicity-dependent corrections due to the vertex resolution have to be applied when analysing the data (see Sec. 4.4.2).

A tracking efficiency close to 100% has been found in hadron+proton and hadron+nucleus interactions. In high multiplicity reactions (e.g. Pb+Pb collisions), this efficiency is determined by embedding Monte-Carlo generated tracks into real events and then measuring the reconstruction efficiency of these additional tracks. In general, it was found to be higher than 95%, but in the regions of high track density it drops to about 30%. Analyses of high multiplicity reactions have therefore to include corrections on tracking efficiency.

The separation of neighbouring tracks (two track resolution - TTR) is a major concern in the high track density regions of Pb+Pb collisions. TTR is a spatial distance of track pairs defined as a mean distance over the tracks length, measured in several points. The separation efficiency is 100% for mean distances larger than 2 cm, and drops to 50% at 1 cm.
Chapter 3

Particle Identification Using dE/dx

3.1 Energy Loss of a Charged Particle

Using the quantum theory of collisions between a charged particle and an atom, Bethe has shown that the energy loss, \( dE \), per unit length, \( dx \), is a function of the velocity of the particle and physical properties of the medium [Beth53]. With the inclusion of relativistic effects, the average energy loss is given by the Bethe-Bloch formula:

\[
\langle -\frac{dE}{dx} \rangle = 4\pi N_A r_e^2 m_e c^2 Z \frac{1}{A} \beta^2 \gamma^2 \left[ \ln \left( \frac{2m_e c^2}{I} \beta^2 \gamma^2 \right) - \beta^2 - \delta(\beta) \right],
\]

where:

- \( N_A \) - Avogadro number, \( N_A = 6.022 \cdot 10^{23} \text{ mol}^{-1} \)
- \( m_e, e \) - electron mass and charge
- \( r_e \) - classical electron radius, \( r_e = \frac{e^2}{4\pi\varepsilon_0 m_ec^2} = 2.82 \cdot 10^{-15} \text{ m} \)
- \( \rho, Z, A \) - medium’s density, atomic, and mass number respectively
- \( z \) - projectile charge
- \( I \) - ionization potential of the medium
- \( \delta(\beta) \) - parameter describing a “density effect” - the saturation of the energy loss at highly relativistic velocities

and \( \beta = \frac{v}{c}, \gamma = \frac{1}{\sqrt{1-\beta^2}} \).

Eq. 3.1 defines the average energy loss of heavy charged particles due to ionization processes. Non-relativistic particles (i.e. for \( \beta \gamma < \sim 1 \)) lose energy proportionally to \( \frac{1}{\beta^2} \). With \( \beta \gamma \) increasing, the energy loss goes through a wide minimum (\( \beta \gamma \sim 3 \)) and then starts to increase (relativistic rise\(^1\)). The ionization potential \( I \) determines the strength of the rise. The increasing energy loss occurs because the transverse electric field increases in strength at relativistic energies. In vacuum, this increase is strictly proportional to \( \gamma \). However, in a medium the electric field will induce a polarization in the material which effectively screens atomic electrons at large distances from the ionizing particle. As a result, the

\(^1\text{This domain is most important for the NA49 particle identification.}\)
Bethe-Bloch function approaches a plateau for very large $\beta \gamma$ (i.e. $\beta \gamma \gg 1000$). This effect has been investigated in detail and a simple parametrization is used for $\delta(\beta)$. Values of the parameters describing $\delta(\beta)$ are usually obtained from a fit to the experimental data.

The behaviour of the energy loss due to ionization is schematically shown in Fig. 3.1. In solids, liquids, and high density gases, the plateau is only a few percent above the minimum. In noble gases (and some molecular gases) at atmospheric pressure, it reaches values of 40-60%. This variation allows the measurement of a particle’s velocity, and knowing in addition a particle’s momentum from a curvature of the track in a magnetic field, PID is possible. Fig. 3.1 shows the dependence of the Bethe-Bloch function on $\beta \gamma = (\frac{p}{m c})$ variable. When $\frac{dE}{dx}$ is plotted versus a particle’s momentum, a clear mass dependence can be seen, as shown in Fig. 3.2. If the resolution of the ionization measurement is sufficient, the separation of different particle species is possible, excluding of course regions where the Bethe-Bloch curves cross each other.

### Figure 3.1: Energy loss of charged particles due to ionization. On vertical axis $\frac{dE}{dx}$ normalized to the minimum ionization is plotted.

### Figure 3.2: Bethe-Bloch curves for different particle species plotted versus momentum.

#### 3.2 Specific Ionization Measurements

To be precise, a detector does not measure the energy loss of a particle but rather the energy deposited by ionization processes in its active volume. When carrying out PID by specific ionization measurements, one assumes that these quantities are directly proportional. The amount of the produced ionization is determined by a measurement of the total number of electrons collected per unit length of a track, after a linear amplification. There are two different components contributing to the total yield of the ionization production: **primary** and **secondary ionization**. The ionization produced directly by the incident track is referred to as primary ionization. If any primary electrons have
an energy $E$, above the value required to produce an ion pair, further ionization (secondary ionization), can be produced. In fact, most of the ionization produced is due to secondary processes. Since there is non-negligible probability of producing high energy electrons - delta electrons, such particles could carry the energy away from the point of the interaction, and thus this energy is lost (will not appear as the energy deposit along the particle trajectory). In practice, the energy a particle deposits in a detector is limited to some cut-off value. The above mentioned considerations modify the Bethe-Bloch equation and the measured $\frac{dE}{dx}$ is better parametrized by [Fano63]:

$$
\langle -\frac{dE}{dx} \rangle_{\text{meas.}} = 4\pi N_A \epsilon^2 m_e c^2 Z A \frac{1}{\beta^2} \gamma^2 \left[ \ln \left( \frac{\sqrt{2 m_e c^2 \beta^2 \gamma^2 E_{\text{max}}}}{I} \right) - \beta^2 - \delta(\beta) \right], \quad (3.2)
$$

where $E_{\text{max}}$ is a parameter defining a cut-off energy (typically of the order of some 10s of keVs).

It has already been said that the total amount of ionization is a sum of the primary and secondary ionization. The first fluctuates according to Poissonian statistics, and the second superimposes a $\frac{1}{E^2}$ energy distribution on the spectra. Such a convolution results in large fluctuations of the ionization process that are non-Gaussian in character. The energy loss distribution for particles which have lost energy through ionization processes is described by the Landau distribution (not available in closed analytical form). A very good approximation to the Landau distribution is the Moyal's function - $M(\lambda)$, given by the following analytic expression:

$$
M(\lambda) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(\lambda+e^{-\lambda})} \quad (3.3)
$$

with

$$
\lambda(\epsilon) = \frac{\epsilon - \epsilon_p}{R}, \quad (3.4)
$$

where $\epsilon_p$ is the most probable energy loss, $\epsilon$ is the actual energy loss, and $R$ depends on the properties of the absorbing medium. The Moyal's function is shown in Fig. 3.3.

From Fig. 3.3 it follows that a single $\frac{dE}{dx}$ measurement carries little information regarding the mean or the most probable energy loss, and therefore many individual measurements need to be made\(^2\). The mean is an unstable characterization of such a distribution

\(^2\)This is the reason for the size of the NA49 TPCs. For a track that crosses the entire NA49 TPC system, a maximum of 234 individual ionization measurements (charge clusters) are possible.
because it is sensitive to the large energy fluctuations in the ionization process. Because of the reduced sensitivity to high energy transfer processes in a real detector, the most probable energy loss is easier to characterize in a stable and reproducible manner. Therefore, the truncated mean technique is used in quantifying $\frac{dE}{dx}$. In this method, the highest and lowest measurements are rejected for each track, their ratio is fixed, and a Gaussian distribution is fitted to the remaining distribution.

For all data used in the analyses presented in this thesis, the (0:50) truncation was applied, which means that only the 50% smallest clusters were kept for the determination of the $\frac{dE}{dx}$. Before the truncation, electronics and gas gain calibrations were performed, as well as temperature, pressure and drift length dependencies were taken into account and corrected for. By truncating the larger values in the distribution of charge clusters, the sensitivity to large fluctuations is reduced, and the truncated mean is able to characterize the most probable value of the distribution in a stable and reproducible way.

As a large number of tracks have points measured in the different gas mixtures of VTPC’s (NeCO₂) and MTPC’s (ArCO₂CH₃), it is necessary to take into account differences between respective Bethe-Bloch functions. To obtain “global” $\frac{dE}{dx}$ values, which were used for the analysed data, first, the truncated mean values for the two TPC systems were calculated separately, and then, they were summed up with the proper weights.

Methods used to obtain truncated mean $\frac{dE}{dx}$ values for the data analysed in the framework of this thesis are described in great detail in [Vere02].

### 3.3 Methods of Particle Identification

A scatter plot of the energy loss, the truncated mean $\frac{dE}{dx}$ value of the track (in MIP units³), for positive particles produced in p+p interactions versus the particle’s laboratory momentum together with the Bethe-Bloch curves for electrons, pions, kaons, and protons are shown in Fig. 3.4a. As can be seen, the total momentum of the reconstructed tracks varies between a few hundred MeV/c and about 100GeV/c. When the truncated mean $\frac{dE}{dx}$ spectrum is plotted in momentum bins (an exemplary spectrum is shown in Fig. 3.4b), different particle species should separate into distinct peaks, if the resolving power is sufficient.

Due to relatively small differences between values of the Bethe-Bloch function for different particle types in the region of the relativistic rise, the separation of various particle species is a challenging task. A reliable PID requires the $\frac{dE}{dx}$ resolution ($\sigma_{dE/dx}$) of the order of a few percent. The resolution depends on the number of clusters on a track ($N$), and $\sigma_{dE/dx} \sim \frac{1}{\sqrt{N}}$, so a better resolution is obtained for longer tracks. Thus, a “global” tracking (i.e. track matching between detectors) allows better precision. A reliable identification is typically possible for $N \geq 30$, and this constraint was applied in the presented analyses. The mean $\sigma_{dE/dx}$ is about 4% and it is sufficient to separate particles of different types, thus the abundance of various particle species can be measured.

³MIP unit - the amount of ionization caused by a Minimum Ionizing Particle.
Figure 3.4: a) Truncated mean $\frac{dE}{dx}$ as a function of laboratory momentum for positive particles produced in p+p collisions at 158 GeV/c beam momentum. b) Example of the truncated mean $\frac{dE}{dx}$ spectrum in a selected momentum bin from the region of relativistic rise.

Different procedures employing the $\frac{dE}{dx}$ information are used to identify particles. A choice of the method depends on the physics issue being studied, required precision, time scale of the analysis etc. Identification methods used in the analyses described in this thesis are discussed below.

### 3.3.1 $\frac{dE}{dx}$ Cut Method

The $\frac{dE}{dx}$ cut method is a simple method of particle identification. In this method, a band around the Bethe-Bloch function, corresponding to a given particle type, is defined. Thus, only particles with the measured truncated mean $\frac{dE}{dx}$ value inside this band are accepted.

The method is schematically illustrated in Fig. 3.5, in case of positive pion identification. By applying an appropriate cut on the positive particle truncated mean $\frac{dE}{dx}$
3.3. Methods of Particle Identification

Figure 3.5: a) Simplified illustration of the $\frac{dE}{dx}$ cut method, showing an exemplary identification of $\pi^+$'s. The contributions of different particle species to the total spectrum, and positions of the respective four Bethe-Bloch functions, are also marked. b) Magnification of the $\pi^+$ contribution, from panel (a), and an explanation of the correction factor $F_{\text{corr}}$ calculation.

spectrum, a sample of $\pi^+$'s is obtained. The number of selected “pion candidates” is then multiplied by a correction factor $-F_{\text{corr}}$. This factor takes into account the pions remaining outside the cut region. To calculate $F_{\text{corr}}$, a Gaussian shape of the truncated mean distribution is assumed, with a mean equal to the value of the Bethe-Bloch function ($BB$) for a given particle type, and a standard deviation $\sigma$ equal to the absolute value of the experimental resolution $-\sigma_{\text{exp}}$. This assumption is well fulfilled for particles with more than 30 points on a track, that is why only such particles are used in the analysis. The correction factor can be easily computed, as explained in Fig. 3.5b. In general, particles are selected by applying the $(-a\cdot\sigma_1+b\cdot\sigma)$ cut around the value of the $BB$, where $a, b \geq 0$, and the cut does not have to be symmetric (could be $a \neq b$).

There are two main sources of a systematic error in this method:
- contamination coming from a misidentification of a given particle type “candidates”
If a width of the band is not correctly set, particles of a different type than required can also be selected.

- limited precision of an adjustment of the Bethe-Bloch functions
  This precision is typically better than 1%. However, even a small shift of the nominal position of the Bethe-Bloch function can have a sizeable effect on measured yields.

The sensitivity of results to both sources depends on physics item, phase space region and reaction type being studied. Usually, it is investigated by comparing the results obtained with a wide variety of \( \frac{dE}{dx} \) cuts, and the optimal cut is chosen. The \( \frac{dE}{dx} \) cut method introduces higher systematic uncertainties than the \( \frac{dE}{dx} \) fit method, discussed in Sec. 3.3.2, but it is not limited by statistics (highly enriched samples of particles of a given type can be obtained). This identification procedure is technically much simpler, and therefore less time-consuming, than the \( \frac{dE}{dx} \) fit method. In many cases, for which the systematic errors are not limiting the relevance of the physics argument, the above simple selection of particles is used.

### 3.3.2 \( \frac{dE}{dx} \) Fit Method

The \( \frac{dE}{dx} \) fit method is based on fitting the experimental truncated mean \( \frac{dE}{dx} \) distribution with a Monte-Carlo generated \( \frac{dE}{dx} \) distribution, in a defined bin of phase space (see Fig. 3.6). Depending on a particular physics goal of a given analysis, fits could be done in bins of the total momentum \( p, [p, p_T], [x_F, p_T] \), or other kinematic variables. The experimental distribution is fitted with a sum of four distributions, corresponding to the particular particle species \( (e, \pi, K, p) \). Free parameters of the fit are the contributions of electrons, pions, kaons and protons to the spectrum. The input parameters of the Monte-Carlo are positions of the four Bethe-Bloch functions (expected peak positions)

![Figure 3.6](image-url)

**Figure 3.6:** Example of the truncated mean \( \frac{dE}{dx} \) distribution together with adjusted Monte-Carlo curves and positions of Bethe-Bloch functions for \( e^+, \pi^+, K^+ \) and \( p \).
3.3. Methods of Particle Identification

and a common resolution (width) parameter. Following steps are performed:

- **Selection of a specific region (bin) of phase space**
  In the relativistic rise region, the Bethe-Bloch functions increase with momentum (as shown in Fig. 3.2), therefore the width of the bin should be small enough to avoid smearing of the spectrum.

- **Filling of the experimental spectrum - \( \left( \frac{dE}{dx} \right)^{\text{EXP}} \)**
  For each track, information on its momentum, measured \( \frac{dE}{dx} \) and \( \sigma_{dE/dx} \) is available. Particles of a given charge (positive or negative), belonging to the selected region, are used to fill the \( \left( \frac{dE}{dx} \right)^{\text{EXP}} \) spectrum.

- **Filling of the Monte-Carlo spectrum - \( \left( \frac{dE}{dx} \right)^{\text{MC}} \)**
  For every selected track, knowing its total momentum \( p \), four values of the Monte-Carlo \( \frac{dE}{dx} \) are calculated, assuming in turn that the track was left by an electron, pion, kaon and proton. The Monte-Carlo \( \left( \frac{dE}{dx} \right)^{\text{MC}}_j \) value, corresponding to a given particle type \( j \), is generated according to a Gaussian distribution, with a mean equal \( BB_j \left( \frac{1}{m_j} \right) \), where \( j \in \{1(e), 2(\pi), 3(K), 4(p)\} \), and rescaled (comparing to the experimental one) width - different for different particle species. \( BB \) denotes here the Bethe-Bloch function, and \( m_j \) is a mass of a given particle type. The \( \left( \frac{dE}{dx} \right)^{\text{MC}} \) spectrum is filled with these generated numbers.

- **Fitting of the \( \left( \frac{dE}{dx} \right)^{\text{MC}} \) spectrum to the \( \left( \frac{dE}{dx} \right)^{\text{EXP}} \) spectrum**
  A quality of the fit is given by finding a minimum of the variable \( \chi^2 \), defined as\(^4\):

  \[
  \chi^2 = \frac{1}{N_{\text{tracks}}} \sum_{i=1}^{K} \left[ \left( \frac{dE}{dx} \right)^{\text{EXP}}_i - \sum_{j=1}^{4} f_j \cdot \left( \frac{dE}{dx} \right)^{\text{MC}}_j \right]^2,
  \]

  where \( f_j \) are fit coefficients (\( 0 \leq f_j \leq 1 \) and \( \sum_{j=1}^{4} f_j = 1 \)), \( j \) runs over particle types, \( i \) runs over histogram bins (thus \( K \) is a number of histogram bins), and \( N_{\text{tracks}} \) is a total number of tracks in a selected bin of phase space.

  This way, the abundance of particle species, in the specified phase space bin, can be determined. The number of particles of a given type \( j \) is equal \( N_j = N_{\text{tracks}} \cdot f_j \), which gives for example for protons \( N_4 = N_{\text{tracks}} \cdot f_4 = N_{\text{tracks}} \cdot f_{\text{prot}} = N_{\text{prot}} \), and so on.

  In this method, positions of the four Bethe-Bloch functions with respect to the actual positions of the peaks in the experimental distribution, as well as the overall resolution, are optimized in an iterative process. This can be easily done as they are the input parameters of the fit. Thus, possible imperfections of the \( \frac{dE}{dx} \) calibration procedure, like slightly wrong Bethe-Bloch functions adjustments, are corrected at the analysis stage.

\(^4\)Using this formula instead of a standard \( \chi^2 \) definition does not allow the distribution tails (bins with a small number of entries) to give too much importance to the fit.
Chapter 4

Kinematic Variables and Particle Distributions

4.1 Introduction

In high energy hadronic and nuclear collisions many particles are produced in final state\(^1\). The final state is fully characterized by an exclusive measurement in which all produced particles are observed. However, to perform such a measurement is difficult or sometimes even impossible in practice. Also, especially for nuclear collisions, it is very hard to analyse such a state because of a large number of produced particles, implying a large number of independent variables describing it. Therefore, very often inclusive processes are considered. In such a process a single particle, or small set of produced particles, are of interest to the measurement. In this thesis, only single-particle inclusive processes will be considered:

\[ A + B \rightarrow C + X. \]  

Here, \( A \) and \( B \) are the projectile and target, \( C \) is the produced particle of interest, \( X \) is everything else what is produced together with \( C \).

In this chapter, the definition of the kinematic variables and quantities appearing in the thesis is given. Explanations of the extraction methods of these physical quantities from the experimental data (including corrections being used) are given as well. Finally, the information on analysed data sets can be also found.

4.2 Physical Quantities and Variables

From a measurement of the curvature of the particle’s trajectory in a magnetic field, spatial components of the particle’s momentum in a laboratory frame (LAB) can be determined\(^2\) - \((p_{x}^{LAB}, p_{y}^{LAB}, p_{z}^{LAB}) = p^{LAB}\). Transverse and longitudinal components of

\(^1\)For example, at 158 A·GeV/c beam momentum about 7, 20 and more than 10\(^3\) charged particles are detected in the NA49 detector in p+p, central p+Pb and central Pb+Pb collisions, respectively.

\(^2\)For a definition of the NA49 coordinate system see Fig. 2.2.
the particle’s **momentum** in LAB are then given by the following relations:

\[
p_T^{LAB} = \sqrt{(p_x^{LAB})^2 + (p_y^{LAB})^2}
\]  

(4.2) and

\[
p_L^{LAB} = p_z^{LAB}.
\]  

(4.3)

Further, by identifying a particle using PID capabilities of a given experiment one finds its **mass**, \(m\), and this way can also determine its **energy**\(^3\) in the LAB frame:

\[
E^{LAB} = \sqrt{m^2 + (p^{LAB})^2}.
\]  

(4.4)

A Lorentz transformation defines relations between quantities in LAB and center of mass (CM) frames:

\[
\begin{pmatrix}
E^{CM} \\
p_L^{CM}
\end{pmatrix} = \gamma \begin{pmatrix}
1 & -\beta \\
-\beta & 1
\end{pmatrix} \begin{pmatrix}
E^{LAB} \\
p_L^{LAB}
\end{pmatrix}
\]  

(4.5)

and

\[
p_T^{CM} = p_T^{LAB} = p_T.
\]  

(4.6)

\(\beta\) and \(\gamma\) are defined as:

\[
\beta = \frac{p_{\text{in}}}{E_{\text{in}}},
\]  

(4.7)

and

\[
\gamma = \frac{1}{\sqrt{1 - \beta^2}},
\]  

(4.8)

where \(p_{\text{in}}\) and \(E_{\text{in}}\) are the total momentum and total energy in initial state. For a collision of a beam particle \(A\) (with mass \(m_A\) and momentum \(p_A\)) and a target particle \(B\) (with mass \(m_B\)), in a fixed target geometry \((p_B = 0)\), one gets \(\beta = \frac{p_A}{m_B + E_A}\). This gives, for example, for \(p+p\) collisions at 158 GeV beam momentum \(\beta \approx 0.994\), which leads to \(\gamma \approx 9.2\). The **center of mass energy**:

\[
\sqrt{s} = (E_A + E_B)^2 - (\vec{p}_A + \vec{p}_B)^2 = m_A^2 + m_B^2 + 2E_AE_B - 2\vec{p}_A\vec{p}_B
\]  

(4.9)

is then equal \(\sqrt{s} = \sqrt{m_A^2 + m_B^2 + 2m_BE_A} \approx 17.27\) GeV. For nucleus+nucleus and nucleon+nucleus collisions, the same Lorentz transformation is used. This means that to calculate a boost to the CM system one does not use a mass of a target or projectile nucleus but a mass of a nucleon. For example, for a nucleon+nucleon collision, this means that a projectile nucleon does not interact with a target nucleus as a whole but with its components - nucleons.

To parametrize a longitudinal direction in momentum space one can use the **Feynman variable** \((x_F)\) or **rapidity** \((y)\). In the CM frame, \(x_F\) is defined as:

\[
x_F = \frac{p_L^{CM}}{p_L^{CM,\text{max}}},
\]  

(4.10)

\(^3\)Units are used in which \(c=1\).
Chapter 4. Kinematic Variables and Particle Distributions

where \( p_{L, \text{max}}^C \) is a maximal momentum that the produced particle can have, \( p_{L, \text{max}}^C \approx \frac{\sqrt{s}}{2} \). Rapidity is defined by

\[
y_{CM} = \frac{1}{2} \ln \left( \frac{E_{CM} + p_{L}^C}{E_{CM} - p_{L}^C} \right) = \tanh^{-1} \left( \frac{p_{L}^C}{E_{CM}} \right) .
\]

(4.11)

The advantage of this variable is an additivity; under a Lorentz-boost by velocity \( \beta \) along the longitudinal axis

\[
y_{CM} = y_{LAB} - \frac{1}{2} \ln \left( \frac{1 + \beta}{1 - \beta} \right) .
\]

(4.12)

The choice between these two variables depends on phenomena one wants to study. In rapidity, it is more difficult to study regions of high momenta, but it is suitable for studies in the central region \( (y_{CM} \approx 0) \). In order to study correlations between longitudinal and transverse directions the use of \( x_F \) is more adequate, since rapidity contains both \( p_L \) and \( p_T \) (is included in \( E \)) in its definition. This is illustrated in Fig. 4.1, for protons produced in p+p collisions at 158 GeV. By fixing the rapidity value, one does not fix the longitudinal momentum, which is true in case of fixing the \( x_F \) value.

Figure 4.1: Illustration of the difference between rapidity and Feynman variable. Calculations (for CM system) of the \( p_T \) dependence on \( p_{L}^C \) are done for protons produced in p+p collisions at 158 GeV/c beam momentum, for: a) constant values of \( y_{CM} \) (lines), b) constant values of \( x_F \) (lines).
4.3 Invariant Inclusive Cross Sections and Yields

The momentum space in the transverse direction is parametrized by \( p_T \), sometimes a \textit{transverse mass} defined as
\[
m_T = \sqrt{m^2 + p_T^2}
\] (4.13)
is also used.

4.3 Invariant Inclusive Cross Sections and Yields

Independently on a reference frame, the single-particle inclusive process - defined by Eq. 4.1 - is characterized by the invariant cross section \( \sigma^\text{inv}_C = E_C \frac{d^3 \sigma}{d \phi d \rho_T dp_L} \), where \( \frac{d^3 \sigma}{d \phi d \rho_T dp_L} \) is the differential cross section (\( \frac{d^3 \sigma}{d \phi d \rho_T dp_L} \) is the rate for producing particle \( C \) in the momentum cell \( dp_C^3 \) per unit incident flux). \( E_C \) is the energy of the particle \( C \), measured in the same frame as the momentum \( p_C \), and it is included to ensure the Lorentz invariance of the quantity. The process can be also characterized by the invariant yield \( E C \frac{d^3 N_C}{d \phi d \rho_T dp_L} \), where \( d^3 N_C \) is the number of particles \( C \) in the momentum cell \( dp_C^3 \) per event. The invariant cross section and yield are related by
\[
E C \frac{d^3 N_C}{d \phi d \rho_T dp_L} = \frac{1}{\sigma_{A+B}} E C \frac{d^3 \sigma}{d \phi d \rho_T dp_L},
\] (4.14)
where \( \sigma_{A+B} \) is the cross section for \( A + B \) collisions which meet the conditions defining the inclusive event sample.

The Lorentz invariant cross section and yield may be rewritten in terms of the kinematic variables\(^4\):
\[
\sigma^\text{inv} = E \frac{d^3 \sigma}{d \phi d \rho_T dp_L} = \frac{E}{p_T} \frac{d^3 \sigma}{d \phi d \rho_T dp_L} (4.15)
\]
\[
= \frac{E}{p_T p_{L,\text{max}}} \frac{d^3 \sigma}{d \phi d \rho_T dx_F} (4.16)
\]
\[
= \frac{1}{p_T} \frac{d^3 \sigma}{d \phi d \rho_T dy} (4.17)
\]
\[
= \frac{d^3 \sigma}{m_T d \phi d m_T dy} (4.18)
\]

and
\[
E \frac{d^3 N}{d \phi d \rho_T dp_L} = \frac{E}{p_T} \frac{d^3 N}{d \phi d \rho_T dp_L} (4.19)
\]
\[
= \frac{E}{p_T p_{L,\text{max}}} \frac{d^3 N}{d \phi d \rho_T dx_F} (4.20)
\]
\[
= \frac{1}{p_T} \frac{d^3 N}{d \phi d \rho_T dy} (4.21)
\]
\[
= \frac{1}{m_T} \frac{d^3 N}{d \phi d m_T dy} (4.22)
\]

\(^4\)Subscript \( C \), indicating the particle of interest, is omitted for clearness of the notation.
where $\phi$ is the azimuthal angle (see Fig. 2.2 for its definition). The distributions are often integrated over $\phi$ and plotted as a function of $p_T$ ($m_T$) at fixed $p_L$, $x_F$ or $y$, or plotted versus longitudinal variables at constant values of $p_T$. They can also be integrated over both $\phi$ and $p_T$ ($x_F$ or $y$) and drawn as a function of $p_T$, or integrated over $\phi$ and $p_T$ and plotted versus $p_L$, $x_F$ or $y$.

### 4.4 Extraction of Experimental Distributions

Let us consider, for example, the extraction (from data) of invariant cross sections in $[\phi, p_T, x_F]$ bins, as defined by Eq. 4.16. Because of the $\phi$-symmetry of the collision (the beam is unpolarized) we can integrate over $\phi$, and get bins of $[p_T, x_F]$ only. In order to determine the invariant cross section, let us say, for proton in a given $[p_T, x_F]$ bin - the bin width is $\Delta p_T$ and $\Delta x_F$ - all particles falling into this bin are selected (assuming for each particle a proton mass). In order to identify particles we can use one of the methods described in Sec. 3.3, for example the $dE/dx$ fit method. After performing the $dE/dx$ fit, the invariant cross section is calculated according to

$$
\sigma_{prot}^{inv} = \frac{f_{prot} \sum_{i=1}^{N_{tracks}} \frac{E_i^t}{p_T} \sigma_{trig}}{2\pi p_{L,\max} \Delta x_F \Delta p_T N_{ev}},
$$

(4.23)

where $f_{prot}$ is a fraction of particles in the $[p_T, x_F]$ bin identified as protons (see Sec 3.3.2), $N_{tracks}$ is the number of all particles in the bin, $N_{ev}$ is the number of events, $E_i^t$ and $p_T^i$ are the energy and transverse momentum of the $i$-th particle, $\sigma_{trig}$ is a trigger cross section and $2\pi$ comes from the integration over the azimuthal angle $\phi$. If one is interested in the invariant cross sections expressed in bins of different kinematic variables (e.g. $p_T$ and $y$) then by applying an appropriate Jacobian determinant and after transforming the given $[p_T, x_F]$ bin location to the location of the bin in new variables, $\sigma_{prot}^{inv}$ in bins of required kinematic variables can be calculated.

Very often distributions of particle number densities, like $dN/dx_F$ or $dN/dp_T$ per event\(^5\), are presented. In case of hadron+proton collisions, however, there are events where there was an interaction but the momentum transfer was too small, and the scattered beam hadron hit the S4 detector in the trigger system (see Fig. 2.2b and Sec. 2.2.2), indicating no interaction\(^6\). Also, because of the gap between the TPCs, it can happen that particles miss the volume of the TPC system, and the event cannot be reconstructed. Thus, the detector sees only a part (large) of the inelastic cross section, a part (small) of the diffractive cross section, and misses almost all elastic scatterings. Therefore, for h+p collisions, to obtain any physical result concerning particle spectra, a trigger cross section $\sigma_{trig}$ has to be calculated and corrected for. For example, $dN/dx_F$ and $dN/dp_T$ per (inelastic) event

\(^5\)In this thesis, when quoting any quantity per event, event means an inelastic collision.

\(^6\)For example, for central h+A and central A+A collisions, the response of the trigger system fulfills all necessary conditions, and none of the events is lost for the analysis.
for protons are equal:
\[
\frac{dN_{\text{prot}}}{dx_F} = \frac{1}{N_{ev}} \frac{f_{\text{prot}}N_{\text{tracks}} \sigma_{\text{trig}}}{\Delta x_F \sigma_{\text{inel}}} \tag{4.24}
\]
and
\[
\frac{dN_{\text{prot}}}{dp_T} = \frac{1}{N_{ev}} \frac{f_{\text{prot}}N_{\text{tracks}} \sigma_{\text{trig}}}{\Delta p_T \sigma_{\text{inel}}} \tag{4.25}
\]
where \( \sigma_{\text{inel}} \) is the inelastic cross section for a given reaction (known from other measurements, tables). Here, \( f_{\text{prot}} \) and \( N_{\text{tracks}} \) are, respectively, the fraction of all particles identified as protons and the number of all particles, in the considered bin of \( x_F \) (for \( \frac{dN}{dx_F} \) - after \( p_T \) integration) or \( p_T \) (for \( \frac{dN}{dp_T} \) - after \( x_F \) integration).

### 4.4.1 Trigger Cross Section Determination

The interaction cross section, \( \sigma_{\text{inter}} \), is defined by the following expression:
\[
dN_{\text{inter}} = \sigma_{\text{inter}} n_1 n_2 |\vec{v}_1 - \vec{v}_2| dV dt ,
\tag{4.26}
\]
describing the relation between \( dN_{\text{inter}} \), a number of interactions in the intersection region of two beams, and \( \sigma_{\text{inter}} \). \( n_1 \) and \( n_2 \) are beam densities, \( \vec{v}_1 \) and \( \vec{v}_2 \) are velocities of the beam particles, \( dV \) and \( dt \) are, respectively, a volume element and a time interval in which interactions take place.

For a fixed target experiment, one gets
\[
dN_{\text{inter}} = \sigma_{\text{inter}} n_2 n_1 v S l dt ,
\tag{4.27}
\]
where \( n_2 \), \( S \), \( l \) are the density, surface and length of the fixed target, \( v \) and \( n_1 \) are the velocity and density of the beam. Thus, \( n_1 v \) is the beam flux and \( n_2 v S \) is the number of beam particles traversing the target in a unit time interval. After integrating over the time of a measurement
\[
N_{\text{inter}} = \sigma_{\text{inter}} n_2 N_{\text{beam}} \rightarrow \sigma_{\text{inter}} = \frac{1}{n_2} \frac{N_{\text{inter}}}{N_{\text{beam}}} ,
\tag{4.28}
\]
where \( N_{\text{beam}} \) is the number of beam particles. Since \( n_2 = \frac{\rho N_A}{A} \) (where \( N_A \) - Avogadro number, \( \rho \) - density and \( A \) - atomic molar weight of the target), \( \sigma_{\text{inter}} \) can be rewritten as
\[
\sigma_{\text{inter}} = \frac{A}{l \rho N_A} \frac{N_{\text{inter}}}{N_{\text{beam}}} ,
\tag{4.29}
\]

The trigger cross section, \( \sigma_{\text{trig}} \), measures the probability of a given interaction specified by trigger conditions, and Eq. 4.29 can be used for its determination
\[
\sigma_{\text{trig}} = \frac{A}{l \rho N_A} \frac{N_{\text{trig}}}{N_{\text{beam}}} ,
\tag{4.30}
\]
where \( N_{\text{trig}} \) is the number of triggers. For example, in order to calculate the \( \sigma_{\text{trig}} \) for \( p+p \) collisions, one has to take into account interactions which triggered the Data AcQuisition
system (DAQ) of the experiment but were not caused by interactions with the target. Therefore, the actual trigger cross section is defined by

\[
\sigma_{\text{trig}} = \frac{A}{l \rho N_A} \left[ \left( \frac{N_{\text{trig}}}{N_{\text{beam}}} \right)^{\text{FT}} - \left( \frac{N_{\text{trig}}}{N_{\text{beam}}} \right)^{\text{ET}} \right],
\]

where superscripts FT and ET denote full target (the target container is filled with a liquid hydrogen) and empty target, respectively. For inclusive (“minimum bias”) p+p interactions at 158 GeV/c beam momentum (target density \( \rho = 0.0708 \text{g/cm}^3 \), target length \( l = 20 \text{cm} \), atomic weight of the target material \( A=1 \text{g/mol} \), \( N_A=6.022 \times 10^{23} \text{mol}^{-1} \)), after taking into consideration non target interactions, the \( \sigma_{\text{trig}} \) of about \( 2.85 \times 10^{-26} \text{cm}^2 = 28.5 \text{mb} \) was obtained. At this beam momentum, the total cross section \( \sigma_{\text{tot}}^{\text{pp}} = 38.7 \text{mb} \), diffractive cross section \( \sigma_{\text{dif}}^{\text{pp}} = 6.5 \text{mb} \) and elastic cross section \( \sigma_{\text{el}}^{\text{pp}} = 7 \text{mb} \). A simple Monte-Carlo study, performed to estimate the fraction of the elastic and diffractive cross sections rejected by the trigger, showed that about 85% of the elastic (6 mb) and about 65% of the diffractive cross section (4.2 mb) are rejected. This gives for the \( \sigma_{\text{trig}} = 38.7 - 6.2 - 28.5 \text{mb} \), in agreement with the result obtained using Eq. 4.31.

### 4.4.2 Corrections

In this paragraph corrections which should be applied in order to obtain final physical results are discussed.

#### Acceptance Correction

The acceptance coverage of the NA49 TPC tracking system amounts to about 80% of all charged particles produced in hadronic interactions at 158 GeV/c beam momentum. The average acceptance of the TPC system in the \( y^{CM} - p_T \) and \( x_F - p_T \) planes, for protons coming from collisions at 158 GeV/c beam momentum, is presented in Fig. 4.2. The acceptance is determined using a Monte-Carlo based on the parametrization of the sensitive volume of the chambers obtained from the experimental data. A given \((y^{CM}, p_T, \phi)\) or \((x_F, p_T, \phi)\) point is accepted if a charged particle with such characteristics crosses at least 30 pad rows in the whole TPC system (thus potentially leaves 30 clusters). The obtained acceptance \( \text{Acc}(y^{CM}, p_T, \phi) \) or \( \text{Acc}(x_F, p_T, \phi) \) is then averaged over the azimuthal angle \( \phi \) in a given range, as indicated in Fig. 4.2. Since the TPCs are horizontally separated, the acceptance losses occur if no \( \phi \) restriction is applied (see panels (a1) and (b1) of Fig. 4.2). By limiting the \( \phi \) wedge, a 100% acceptance can be obtained in a wider range of kinematic variables on the \((y^{CM}, p_T)\) and \((x_F, p_T)\) planes; see panels (a2) and (b2) of Fig. 4.2 for

---

7A part of all triggers comes from interactions of beam particles with walls of the mylar vessel containing a liquid hydrogen or with other materials in the beam line.

8Both processes being anyway outside the acceptance for particle tracking.

9Kinematical constraints were applied and white, not coloured, regions in Fig. 4.2 correspond to kinematically not allowed regions.
4.4. Extraction of Experimental Distributions

![Diagram](image)

Figure 4.2: Geometrical acceptance of the NA49 TPC system for protons produced in hadronic interactions at 158 GeV/c beam momentum. a1), a2), a3) Acceptance in the $y^{CM}$ - $p_T$ plane averaged over the full azimuthal angle, $|\phi|<90^\circ$ and $|\phi|<50^\circ$, respectively. b1), b2), b3) Acceptance in the $x_F$ - $p_T$ plane averaged over the full azimuthal angle, $|\phi|<90^\circ$ and $|\phi|<50^\circ$.

For protons, within the $|\phi|<90^\circ$ wedge, and panels (a3) and (b3) for the $|\phi|<50^\circ$ wedge. For protons, within the $\phi$ wedge of $\pm50^\circ$, the TPCs provide a full acceptance in the regions $-1<y^{CM}<2.5$, $p_T<2.5\text{GeV/c}$ and $-0.2<x_F<0.6$, $p_T<2.5\text{GeV/c}$. However, for protons at $y^{CM}\approx-0.5$, or $x_F\approx-0.1$, the identification via $\frac{dE}{dx}$ is not possible because the Bethe-Blot functions for protons and pions cross each other, thus analyses in the backward hemisphere have to be limited to these values. For pions (not shown in Fig. 4.2), for the $|\phi|<50^\circ$ wedge, the regions $0<x_F<0.55$, $p_T<2.5\text{GeV/c}$ and $0<y^{CM}<2.5$, $p_T<2.5\text{GeV/c}$ have a full acceptance\textsuperscript{10}. For negative particles, the situation is very similar to that which has been

\textsuperscript{10} $y^{CM}$ of pions produced in collisions at 158 GeV/c beam momentum can reach values even larger than 3, but within the $\phi$ wedge of $\pm50^\circ$, for large $p_T$ values, acceptance losses appear already at $y^{CM}\approx2.5$. The situation can be improved by restricting further the $\phi$ wedge.
presented for positive particles. The only difference comes from the fact that antiparticles
are bent by the magnetic field in the opposite direction than their positive counterparts,
therefore the $\phi$ wedge is centered at $\phi = 180^\circ$, and not $0^\circ$.

In analyses, the problem of acceptance losses can be solved by:

- using the acceptance table obtained from the Monte-Carlo, as explained above, and
  applying appropriate acceptance corrections. This solution, however, can lead to
  large systematic errors, especially in the regions of phase space where the corrections
  are large.

- constraining the studies to the regions where the acceptance is 100\% (by restricting,
  for example, the $\phi$ wedge), if it is acceptable from a physics goal of the analysis point
  of view. In this case no real acceptance correction is needed, besides (if necessary)
  the correction which takes into account the cut off regions.

In the analyses described in this thesis the second solution is used.

**Tracking Efficiency Correction**

The information on a tracking efficiency has been given in Sec. 2.3. The tracking efficiency
is very different in low and high track density environments. In high multiplicity reactions
(e.g. $\mathrm{Pb+Pb}$ collisions) it could be much below 100\%, therefore analyses have to include
corrections on losses of tracks in the reconstruction procedure. In low multiplicity reac-
tions, like $\mathrm{h+p}$ and $\mathrm{h+A}$, there are almost no track losses due to the reconstruction. It
has been confirmed by the *eye-scan* study; inside the geometrical acceptance, a 100\% effi-
ciency was found, with a percent accuracy. That is why, the tracking efficiency correction
is not used for these reactions.

**Interaction Vertex Correction**

The resolution of the interaction vertex reconstruction depends on the multiplicity of
charged particles in the event, $n_{\text{ch}}$, as seen by the NA49 detector. The problem is schemati-
cally explained in Fig. 4.3a, in case of interactions on a liquid hydrogen target. In order
to exclude from analyses the collisions of beam particles with a mylar\textsuperscript{11} container, filled
with a $\mathrm{H}_2$ target, a geometrical cut (*target cut*) on the $z$ position of the reconstructed
interaction vertex is applied. Only events with the vertex inside the 18 cm wide window
are accepted. In this way, the contamination by these background interactions is reduced
to a percent level. The observed vertex $z$ resolution gets worse with decreasing event
multiplicity, and more events are lost due to the target cut, as shown in Fig. 4.3a. Addi-
tionally, sometimes for very low multiplicity events the reconstruction software fails to
find the interaction vertex. There can be also events for which the reconstruction chain
does not reconstruct any tracks (*zero prongs*). In all these cases events are triggered,
resulting in the trigger cross section increase. However, these events do not enter into
analyses, therefore all the effects mentioned above need to be corrected for. Methods

\textsuperscript{11}Mylar is composed of 63\% C, 33\% O and 4\% H.
used to obtain the corrections are described in detail in [Chv01]. Briefly, calculations of the final correction factors are divided into calculations of the correction resulting from the interaction vertex position smearing and the correction caused by the reconstruction losses, as explained below.

- **vertex smearing correction** - $\text{Corr}_{\text{smear}}(\text{mult})$ First, in each multiplicity bin, a proper normalization of the full target ($FT$) and empty target ($ET$) trigger rates is established. Then, in order to obtain the vertex $z$ position distribution for “clean” hadron+proton interactions, from the $FT$ vertex $z$ distribution the $ET$ distribution is subtracted. The vertex smearing correction is determined by comparing the number of events outside the target cut to the number of all events in the subtracted $FT-ET$ vertex $z$ distribution.

- **vertex reconstruction losses correction** - $\text{Corr}_{\text{rec}}(\text{mult})$ This correction, also as a function of multiplicity, is derived by comparing the multiplicity distribution of events which are used in analyses (corrected by the vertex smearing corrections) with the $FT-ET$ multiplicity distribution. From this comparison the **zero prong correction** - $F_{ZP_{\ell}}$, taking into account events with 0 tracks, is obtained as well.

The final multiplicity dependent correction, is a product of these two corrections, $w(\text{mult}) = \text{Corr}_{\text{smear}}(\text{mult}) \cdot \text{Corr}_{\text{rec}}(\text{mult})$. The correction factors are typically of the order of several percent, but they increase very strongly with decreasing of the event multiplicity. For $h+\Lambda$ collisions, the Centrality Detector is included in the trigger system, and for each trigger setting empty target runs have to be carried out, and similarly as in $h+p$ case, the correction factors are then calculated. Here, for different collision centralities, different multiplicity dependent correction tables are obtained.

Since the interaction vertex correction depends on $n_{ch}$ of the event it has to be applied event-by-event; each particle in the event has to be weighted by an appropriate correction.
Chapter 4. Kinematic Variables and Particle Distributions

factor. For example, after taking into consideration the vertex correction factors, the proton invariant cross section (given by Eq. 4.23) can be rewritten as

\[
\sigma_{\text{prot}}^{\text{inv}} = \frac{f_{\text{prot}} \sum_{i=1}^{N_{\text{trac}}} E_i w_i(m_j)}{2\pi p_{L,\text{max}} \Delta x_F \Delta p_T N_{\text{ev}}} \sigma_{\text{trig}},
\]

(4.32)

where

\[
N_{\text{ev}} = F_{ZP} \sum_{j=1}^{N_{\text{mult}} \geq 0} w(m_j).
\]

(4.33)

\[N_{\text{mult}} \geq 0\] is the number of events with at least 1 track, \(w(m_j)\) is the weight factor for the \(j\)-th event having multiplicity \(m_j\), and \(w^i(m_j)\) is the weight factor for the \(i\)-th particle, from the analysed \([p_T, x_F]\) bin, belonging to this \(j\)-th event, so \(w^i(m_j) = w(m_j)\).

\[\frac{dE}{dx}\] Cut Correction

In case of particle identification exploiting the \(\frac{dE}{dx}\) cut method, the correction factor, \(F_{\text{corr}}\), has to be applied. It takes into account particles of a given type remaining outside the \(\frac{dE}{dx}\) cut region, see Sec. 3.3.1 for more details.

Feed-Down Correction

Usually, final physical results are presented for primarily produced particles, therefore the contamination by daughters of weakly decaying particles has to be properly taken into consideration and corrected for. If one is interested in primarily produced \(p, \bar{p}, \pi^+\) or \(\pi^-\), then one should consider contributions from the following hyperon decays:

- \(\Lambda^0 \rightarrow p + \pi^-\) (63.9%)
- \(\bar{\Lambda}^0 \rightarrow \bar{p} + \pi^+\) (63.9%)
- \(\Sigma^+ \rightarrow p + \pi^0\) (51.6%)
- \(\Sigma^- \rightarrow \bar{p} + \pi^0\) (51.6%)
- \(\Sigma^+ \rightarrow n + \pi^+\) (48.3%)
- \(\Sigma^- \rightarrow n + \pi^-\) (48.3%)
- \(\bar{\Sigma}^- \rightarrow \bar{n} + \pi^-\) (48.3%)
- \(\bar{\Sigma}^+ \rightarrow \bar{n} + \pi^+\) (48.3%)

as well as from the \(K_S^0\) decay: \(K_S^0 \rightarrow \pi^+ + \pi^-\) (BR=68.6%). The contribution of all other weakly decaying particles is negligible.

The problem is illustrated in Fig. 4.3b, for the \(\Lambda^0\) hyperon decay case. The \(\Lambda\) decays away from the interaction vertex, but there is a certain probability that the daughter particles (proton and pion) can be fitted, by the reconstruction software, back to the vertex. These particles are then assigned as originating from the interaction point and contaminate the experimental spectra. The probability of finding the daughter particles as vertex particles depends on rather complicated details of the geometrical acceptance, particles’ momenta, the reconstruction software, and details of the analysis (conditions of the track assignment to the interaction vertex, various applied cuts, etc.). A preliminary analysis on the feed-down from weak decays has been done for \(p+p\) interactions at 100 GeV/c and
158 GeV/c beam momentum, as well as for π± + p and p + Pb collisions at 158 GeV/c. The results are reported in [Krep01]. The study was based on a Monte-Carlo simulating the emission and decay of the parent particles (Λ, Σ, K*). These particles were generated according to the results obtained by the NA49 experiment (where exist) or compiled results published by earlier experiments\textsuperscript{12}. The probability of the daughter particle to be assigned to the interaction vertex was obtained from a detailed GEANT-based Monte Carlo simulation of the detector with the inclusion of the NA49 reconstruction software. The study has shown that the contamination from the feed-down is not azimuthally symmetric due to the detector acceptance and reconstruction. Results presented in [Krep01] were obtained for the |φ|<50° wedge only, and can be solely applied in the data analysis using the same restriction on the φ angle. The outcome of the simulation study is the relative correction to the experimentally observed yield of p, p̅, π⁺ and π⁻, as a function of x_F. For all examined reactions, the relative correction to pion yields is below 4% (for each x_F value); it is smaller in h + p interactions than in p + Pb collisions. For the elementary hadronic reactions, the contamination to the p yield from the feed-down is everywhere below 10%, and to the p̅ yield below 18%. However, for the investigated nuclear reactions the found contamination is larger, especially in the p case where at maximum it is close to 40%.

The analyses done within this thesis do not include correction on the feed-down from weakly decaying particles, since it would require a dedicated, very detailed study, including not only the dependence on longitudinal momentum (x_F) but also on p_T. In order to obtain reliable results from this study, one needs more precise input data on the parent particles production than presently available. As it has been said, the feed-down correction depends on different cuts used in the study (e.g. on the φ cut), therefore a given analysis should include the corrections obtained using the same cuts as the ones used in it.

### 4.5 Analyzed Data Sets

Table 4.1 gives a summary information on the data sets used in the analyses described in this thesis. The studied reactions are specified in the first column, then applied trigger conditions are written out - there are minimum bias data samples, as well as centrality selected interactions on nuclear targets (for p + Pb case, the value of N_{CD} defines the collision centrality). Next three columns state, in turn, the beam particle energy, year of the measurement and the name of a given data production. In the last column, for each reaction, the number of events is given. This number refers to the “clean” sample of events, after all selection cuts applied. The bolded ones are the numbers of events available for analyses (if there is more than one data sample of a given reaction type this number is the sum of all events for this reaction). The analysed data sets were processed using the same “production chain”, and in each case the same calibration method of the

\textsuperscript{12} Certain assumptions (sometimes quite strong) had to be made if no measured results were available.
ionization measurement was applied\textsuperscript{13}.

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<th>year of meas.</th>
<th>product.</th>
<th>No. of events</th>
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<td>158 GeV</td>
<td>1999</td>
<td>00E</td>
<td>33 243</td>
</tr>
<tr>
<td>p+Pb</td>
<td>(N_{CD} \geq 1)</td>
<td>158 GeV</td>
<td>1999</td>
<td>00E</td>
<td>224 884</td>
</tr>
<tr>
<td>p+Pb</td>
<td>(N_{CD} \geq 2)</td>
<td>158 GeV</td>
<td>1999</td>
<td>00E</td>
<td>246 619</td>
</tr>
<tr>
<td>p+Pb</td>
<td>(N_{CD} \geq 3)</td>
<td>158 GeV</td>
<td>1999</td>
<td>00E</td>
<td>35 214</td>
</tr>
<tr>
<td>p+Pb</td>
<td>(N_{CD} \geq 4)</td>
<td>158 GeV</td>
<td>1999</td>
<td>00E</td>
<td>18 134</td>
</tr>
<tr>
<td>p+Pb</td>
<td>(N_{CD} \geq 7)</td>
<td>158 GeV</td>
<td>1999</td>
<td>00E</td>
<td>287 421</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>\textbf{845 515}</td>
</tr>
<tr>
<td>C+C</td>
<td>semi-central</td>
<td>158A-GeV</td>
<td>1998</td>
<td>00V</td>
<td>31 494**</td>
</tr>
<tr>
<td>Si+Si</td>
<td>semi-central</td>
<td>158A-GeV</td>
<td>1998</td>
<td>00X</td>
<td>16 953**</td>
</tr>
</tbody>
</table>

* after a proton projectile selection from the deuteron beam, see Appendix B  
** after a charge selection of the “fragmentation” beam, see Fig. 2.3

Table 4.1: Analysed data sets.

\textsuperscript{13}In this thesis, in comparative studies, results on more complex Pb+Pb collisions are also used. For Pb+Pb collisions, however, a different production chain and \(\frac{dE}{dx}\) calibration method were used.
Chapter 5

Transverse Momentum Spectra

5.1 Motivation

In high-energy hadronic physics, the $p_T$ distribution ($E_T^{p_T}$ dependence on $p_T$) is a strongly decreasing function: for $p_T$ up to about 1-2 GeV/c it decreases nearly exponentially\(^1\) and then like a power of $\frac{1}{p_T}$ (see e.g. [Wang01]). As the energy increases, higher and higher $p_T$ values show up in the spectrum. Simultaneously, a contribution of the large $p_T$ “tail” to the spectrum grows up, which manifests in a decrease of the power exponent in the $\frac{1}{p_T}$ dependence. The $p_T$ spectra at the SPS energies show mainly the low $p_T$ regime characteristics - soft hadronic physics connected with non-perturbative QCD. Assuming that with increasing energy a gradual transition from the low $p_T$ to high $p_T$ regime - hard hadronic physics described by perturbative QCD - takes place, it is interesting to investigate whether already in the analysed collision energy range one can observe and recognize any signs of the eventual hard processes appearing.

A comparative study of hadron+hadron and hadron+nucleus collisions offers a possibility of investigating the nuclear medium influence on the measured particle characteristics. Nowhere except inside a nucleus are the strongly interacting particles so densely packed in space and are the target nucleons within the range of their mutual strong forces. As a projectile hadron passes through a target nucleus, it interacts with the target nucleons met along its way. This study is expected to reveal differences in transverse characteristics of hadrons produced off strongly bound and free nucleons. In particular, it is interesting to address the question whether an interaction with a nucleus is a simple incoherent superposition of collisions with individual free-like nucleons or to point out observations which contradict this picture.

Not only the energy dependence and the influence of the nuclear medium on the observed particle spectra can be studied. Another intriguing question is a size of the interaction volume dependence. The study can be already done on the level of h+A collisions, either by changing the size of the nucleus or by controlling the collision centrality. The latter method reduces the smearing of the collision impact parameter ($b$); in the sample of h+A collisions without centrality control, peripheral and central

\(^1\)A better description is given by a Bessel function ($exp$ is an approximation).
interactions are mixed. In the peripheral collisions, the impact parameter is large, and the “active volume” is small. The situation is different for the most central collisions (with $b=0$), where the projectile traverses the target nucleus along its diameter. In the NA49 experiment, the centrality control in hadron+nucleus collisions is performed employing the CD detector. Additionally, the system size dependence analysis can be also done for even more complex reactions, namely for A+A collisions. There are two possibilities (the NA49 exploits both): a study of different centrality A+A collisions, of a given nucleus A (e.g. Pb), or a comparison of results obtained for collisions of different size nuclei (e.g. C+C, Si+Si, Pb+Pb). Having these studies done, one may investigate the $h+h \rightarrow h+A \rightarrow A+A$ evolution as well.

Published results on high-energy hadron $p_T$ distributions are often limited to a specific region of phase space, usually to midrapidity, due to a geometrical acceptance of experiments. As it has been shown in Sec. 4.4.2, the NA49 spectrometer offers a good coverage of phase space, and thus allows for studies not only at midrapidity. This gives a chance of investigating the internal dynamics of the collision by studying correlations between transverse and longitudinal momenta.

The $p_T$ distributions are different for different types of produced particles, they get broader as the mass of the particle increases; the observation confirmed also by NA49 data [App99, Bäc99]. Owing to the NA49 ability of identifying particles, the produced particle type dependence study of the $p_T$ - $p_L$ correlations (for various colliding systems) can be also performed.

Particles in initial state, the colliding hadrons (nucleons, mesons), as well as hadrons observed in final state have their own parton composition. The structure of initial particles, e.g. flavours of their valence quarks, could have an impact on the transverse characteristics of particles in final state. The influence of the initially colliding particles’ structure on the final state characteristics is another considered item.

## 5.2 Data Analysis

The present analysis concerns the forward (projectile) hemisphere. Following elementary interactions are studied: $p+p$, $\pi^+ + p$, $\pi^- + p$ at 158 GeV ($\sqrt{s} \approx 17.3$ GeV), $p+p$ at 100 GeV ($\sqrt{s} \approx 13.8$ GeV) and, in addition, $p+p$ at 40 GeV ($\sqrt{s} \approx 8.8$ GeV)\(^2\). Independently on the collision energy the same magnetic field was set in the spectrometer, therefore with decreasing energy the geometrical acceptance of the NA49 TPC system extends more forward. In this chapter, more complex nuclear collisions are analysed as well. First, different centrality $p+Pb$ collisions, and then also $C+C$, $Si+Si$ and $Pb+Pb$ collisions, at 158 A-GeV beam energy, are examined.

The $p+Pb$ data sample was divided into four subsamples, of approximately equal statistics, by selecting events with a given number of “grey” protons. According to the Glauber Model [Gla70], the proton projectile undergoes multiple collisions as it traverses

\(^2\)Selected from among $d+p$ collisions (see Appendix B).
the target nucleus. The number of these collisions ($\nu$), or in other words the centrality, is correlated to the number of “grey” protons detected in the Centrality Detector (described in Sec. 2.2.6). The most peripheral $p+Pb$ collisions were obtained by requesting $0 \leq N_{CD} \leq 3$, this corresponds to the mean number of elementary subcollisions suffered by the projectile $\bar{\nu} \approx 3.1$. By limiting $N_{CD}$ to $4 \leq N_{CD} \leq 6$, a subsample with $\bar{\nu} \approx 4.6$ was obtained. The next subsample, with the $7 \leq N_{CD} \leq 9$ restriction, corresponds to $\bar{\nu} \approx 5.5$. Fourth, the most central subsample of $p+Pb$ collisions, was obtained by requesting $N_{CD} \geq 10$; this gives $\bar{\nu} \approx 6.2$.

In the centrality determination of the semi-central C+C and Si+Si collisions, information on the energy deposited in the VCAL calorimeter as well as information on the event multiplicity were used. From the Glauber Model calculations the following mean values of elementary subcollisions suffered by the projectile and target nucleons were obtained: for C+C collisions $\bar{\nu} \approx 1.7$, and for Si+Si $\bar{\nu} \approx 2.2$ [Höhn03].

In the system size dependence studies, results on Pb+Pb collisions are quoted. These collisions, however, were not analysed in the framework of this thesis. The presented results are the outcome of other analysis [Sikl01], and serve for the discussion purposes. Two centrality-defined $p+Pb$ samples are used, the first with $\bar{\nu} \approx 3.2$ and the second with $\bar{\nu} \approx 4.6$ (the highest centrality which is practically accessible in $p+Pb$ collisions). Here, the centrality selection is based on the VCAL calorimeter information [Coop00].

The present study contains a comparison of the experimental results with the predictions of VENUS 4.12 and FRITIOF 7.02 models. In case of elementary collisions ($p+p$ and $\pi^++p$), for each set of the studied models’ parameters, samples of $500k$ events were generated and analysed. For the most central $p+Pb$ collisions ($\bar{\nu} \approx 6.2$, which corresponds to the impact parameter $b<2$ fm), samples of about $600k$ events, for both VENUS 4.12 and FRITIOF 7.02, were generated and examined.

In Table 5.1 the information on cuts, corrections and the particle identification method used in the analysis is given.

<table>
<thead>
<tr>
<th>Analysed $\phi$ wedge</th>
<th>$\pm 50^\circ$ centered at:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\phi=0^\circ$</td>
</tr>
<tr>
<td></td>
<td>$\phi=180^\circ$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of clusters on a track</th>
<th>$N \geq 30$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Identification</td>
<td>$\frac{dE}{dx}$ cut method (Sec. 3.3.1)</td>
</tr>
<tr>
<td>$p$, $\bar{p}$</td>
<td>$(-3\sigma, 0\sigma)$</td>
</tr>
<tr>
<td>$\pi^\pm$</td>
<td>$(-1\sigma, +1\sigma)$</td>
</tr>
</tbody>
</table>

| Corrections                  | as discussed in Sec. 4.4.2 |

Table 5.1: Summary information on applied cuts and used analysis procedures.

Principal sources of systematic errors of the obtained results are: a misidentification of particles, an acceptance and a precision of the determination of the used corrections. Their influence on the results has been studied, by applying, for example, various $\frac{dE}{dx}$ or

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3The value close to the $\bar{\nu}$ value corresponding to minimum bias $p+Pb$ collisions, that is $\bar{\nu} \approx 3.7$. 

\( \phi \) cuts. Total systematic errors were calculated as a square root of the sum of squared estimated systematic errors coming from the sources mentioned above. If not stated directly, errors on the plots are statistical only (for most of the data points they are smaller than the symbols).

## 5.3 Transverse Momentum Distributions

As already mentioned in Sec. 5.1, transverse momentum distributions depend on the type of the produced particle. This fact is illustrated in Fig. 5.1 for protons and pions coming from p+p collisions at 158 GeV beam energy. The \( p_T \) spectrum for the heavier particle is broader, and the maximum of the distribution is shifted towards higher \( p_T \) values, compared to the pion case.

Effects of the projectile passage through the nuclear medium, and in particular the influence of multiple collisions suffered by the projectile, on the particle transverse momentum distributions are visible in Fig. 5.2, presenting results from p+p and very central p+Pb (\( \bar{\nu} \approx 6.2 \)) collisions. Panels (a) and (b) of Fig. 5.2 show the transverse momentum density distributions for protons and positive pions, respectively. Differences between the distributions from the nuclear and elementary interactions are better seen (especially for large \( p_T \)) in the inserts of Fig. 5.2, where the ratios of the \( dn/ dp_T \) distributions from p+Pb collisions to the ones from p+p interactions are presented. Also here, the \( p_T \) behaviour of the lighter particle is different than that of the heavier one:

**Proton** The transverse momentum density distribution of protons in central p+Pb collisions is wider with reference to p+p interactions; a considerable excess in the medium-large \( p_T \) region is seen for the studied nuclear collisions.

![Graph showing \( p_T \) distributions of positive pions and protons](image)

**Figure 5.1:** \( p_T \) distributions of positive pions and protons, from the 0.0<\( x_F < 0.5 \) region, produced in p+p interactions at 158 GeV/c beam momentum. Note: the left vertical axis refers to protons and the right one to pions; lines are drawn to guide the eye.
Figure 5.2: Transverse momentum density distributions of protons (panel (a)) and positive pions (panel (b)), from the $0.0 < x_F < 0.5$ region, for p+p and very central p+Pb interactions at 158 GeV beam energy. Note: distributions are surface-normalized to unity; lines are drawn to guide the eye. The inserts show the ratio of the $dN/dp_T$ distribution from p+Pb collisions to the one from p+p interactions.

**Pion** The $p_T$ distribution of pions from the analysed p+Pb collisions changes slightly compared to the distribution in the elementary interactions. Some, but less pronounced than in the proton case, excess of medium-large transverse momenta is observed for the nuclear collisions; also visible is a slight excess of low $p_T$ pions.

### 5.3.1 Mean Transverse Momentum

First-order characteristics of the $p_T$ behaviour can be analysed by studying a first moment of the $p_T$ distribution - $\langle p_T \rangle$ - mean (average) transverse momentum. It can be calculated according to

$$\langle p_T \rangle = \frac{\int p_T \frac{dN}{dp_T} dp_T}{\int \frac{dN}{dp_T} dp_T}.$$  \hspace{1cm} (5.1)

In Tables 5.2 and 5.3 the information on $\langle p_T \rangle$ of particles produced in p+p and central p+Pb collisions is given. For p+p interactions, the average transverse momenta were calculated for minimum bias collisions as well as for collisions with the defined event multiplicity.
<table>
<thead>
<tr>
<th></th>
<th>( \langle p_T \rangle ) ± stat. ± syst. [MeV/c]</th>
<th>( n_{ch} )</th>
<th>( \langle p_T \rangle ) ± stat. ± syst. [MeV/c]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p )</td>
<td>512</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>5.8 ( p )</td>
<td>506</td>
<td>1</td>
</tr>
<tr>
<td>( \bar{p} )</td>
<td>508</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>5.8 ( \bar{p} )</td>
<td>510</td>
<td>4</td>
</tr>
<tr>
<td>( \pi^+ )</td>
<td>338</td>
<td>&lt;1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5.8 ( \pi^+ )</td>
<td>341</td>
<td>&lt;1</td>
</tr>
<tr>
<td>( \pi^- )</td>
<td>334</td>
<td>&lt;1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5.8 ( \pi^- )</td>
<td>341</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

Table 5.2: \( \langle p_T \rangle \) of protons, antiprotons and pions, from the \( 0.0 < x_F < 0.5 \) region, for \( p+p \) collisions at 158 GeV. Average \( p_T \) values of the particles coming from events with different \( n_{ch} \) are also given.

**Multiplicity Dependence of \( \langle p_T \rangle \)**

\( p+p \) data sample was divided into three subsamples according to the event multiplicity, \( n_{ch} \). Selecting higher \( n_{ch} \) one presumably selects more violent \( p+p \) collisions. At this collision energy (\( \sqrt{s} \approx 17.3 \) GeV), all possible scenarios of the \( \langle p_T \rangle \) behaviour happen. The increase of \( n_{ch} \) does not influence antiprotons. It increases the proton \( \langle p_T \rangle \) and decreases the pion \( \langle p_T \rangle \); the latter effect is due to kinematics. At ISR energies, a different \( \langle p_T \rangle \) behaviour was found [Brea83]. The study was done for charged particles (most of them being pions) in the central region of rapidity. With increasing number of produced charged particles, no change of the \( \langle p_T \rangle \) for \( \sqrt{s} \approx 31 \) GeV and an increase of the mean \( p_T \) for \( \sqrt{s} \approx 63 \) GeV were observed. The phenomenon of the pion \( \langle p_T \rangle \) dependence on \( n_{ch} \) changing with a collision energy could be explained, for example, by the strengthened occurrence of hard processes at higher energies, resulting in the \( \langle p_T \rangle \) and \( n_{ch} \) rise.

**\( p+p \) Collisions versus Central \( p+Pb \) Collisions**

Conclusions on the proton and positive pion \( \langle p_T \rangle \) changes, while going from \( p+p \) to \( p+Pb \) collisions, can be already drawn out from Fig. 5.2. Direct information concerning the mean transverse momenta of particles is given in Tables 5.2 and 5.3. Proton and antiproton \( \langle p_T \rangle \) values, for the studied \( x_F \) range, in the central \( p+Pb \) collisions increase by about 100 MeV/c compared to \( p+p \) collisions. \( \langle p_T \rangle \) of the light particles - pions - does not change, taking into consideration the experimental errors.

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\( n_{ch} \) - the charged particle multiplicity in an event, as seen by the NA49 detector. On the average, about 7 charged particles are detected for minimum bias \( p+p \) collisions.
5.3. Transverse Momentum Distributions

<table>
<thead>
<tr>
<th></th>
<th>$\langle p_T \rangle$ ± stat.</th>
<th>± syst.</th>
<th>[MeV/c]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>616</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>$\bar{p}$</td>
<td>583</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>347</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>342</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 5.3: $\langle p_T \rangle$ of protons, antiprotons and pions, from the 0.0 $< x_F < 0.5$ region, for central ($\bar{\nu} \approx 6.2$) p+Pb collisions at 158 GeV/c beam momentum.

In both p+p and p+Pb collisions, the heavier particles ($p, \bar{p}$) have larger mean $p_T$ than the lighter ones ($\pi^+, \pi^-$). A possible explanation of this observation can be provided by the recombination (or coalescence) model. The formation of hadrons is, of course, an extremely complex process, which requires a detailed dynamical approach, but naively one can assume that the mean $p_T$ of a given hadron scales with the number of quarks forming it. The $\langle p_T \rangle$ for protons should then be $\frac{3}{2}$ times larger than that for pions, which is in rough agreement with the experimental observation. Since many pions, after coalescence, come from subsequent resonance decays, the ratio of proton to pion mean $p_T$ is also influenced by this effect - the resonance decays lead to the ratio increase.

**Evolution of $\langle p_T \rangle$ with Centrality of p+Pb Collisions**

So far, only the most central p+Pb collisions were used in the comparative study with p+p interactions. In order to analyse the evolution of the $\langle p_T \rangle$ with a collision centrality, other centralities of p+Pb collisions have to be considered as well. In Fig. 5.3 the dependence of the average $p_T$ on the mean number of collisions, $\bar{\nu}$, is shown. The study was done

![Figure 5.3: $\langle p_T \rangle$ dependence on the mean number of collisions - $\bar{\nu}$, for the region close to midrapidity. Note: filled symbols represent the positive and open ones the negative particles; error bars include statistical and estimated systematic errors (stat. $\oplus$ syst.).](image.png)
for p+p interactions ($\nu=1$) and p+Pb collisions with $\bar{\nu} \approx 3.1, 4.6, 5.5, 6.2$, and concerns $p$, $\bar{p}$, $\pi^+$ and $\pi^-$ particles coming from the region close to midrapidity ($0.0 < x_F < 0.05$).

While for pions the $\langle p_T \rangle$ at $x_F \approx 0$ is fairly constant as a function of the number of collisions undergone by the projectile proton, a continuous increase for protons is evident. The $\langle p_T \rangle$ of antiprotons increases considerably while going from p+p to peripheral p+Pb collisions and then, independently on $\bar{\nu}$, stays unchanged (within the experimental errors).

The next step of the $\langle p_T \rangle$ analysis is the opening of the longitudinal momentum scale, as reported in the following section of this chapter.

5.4 $P_T - P_L$ Correlations

It was suggested some time ago, that the differential cross section $f(p_T, p_L) \equiv E \frac{d^2\sigma}{dp_T dp_L}$ could in the first approximation be factorized into two terms, one depending on $p_T$ and the other on $p_L$, i.e. $f(p_T, p_L) = g(p_T)h(p_L)$. This was called a factorization. In this section the correlations between transverse and longitudinal momenta are studied in order to check whether the single-particle distribution function, $f(p_T, p_L)$, can be separated into a product of $p_T$ and $p_L$. The analysis consists in investigating the first moment of the $p_T$ distribution dependence on $x_F$, which was chosen as a longitudinal variable. This way the internal dynamics (transverse activity) of the collision can be studied.

5.4.1 p+p Collisions

Experimental Results

In Fig. 5.4, the mean $p_T$ values for various regions of $x_F$ are shown for different particle types produced in p+p collisions. Information on the estimated systematic $\langle p_T \rangle$
5.4. \( P_T-P_L \) Correlations

<table>
<thead>
<tr>
<th>syst. error(^*) on ( \langle p_T \rangle ) and ( \langle p_T \rangle_E ) [MeV/c]</th>
<th>syst. error on ( \langle p_T \rangle ) [MeV/c]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x_F \approx 0.0 )</td>
<td>( x_F \approx 0.15 )</td>
</tr>
<tr>
<td>( p )</td>
<td>10</td>
</tr>
<tr>
<td>( \bar{p} )</td>
<td>17</td>
</tr>
<tr>
<td>( \pi^+ )</td>
<td>4</td>
</tr>
<tr>
<td>( \pi^- )</td>
<td>4</td>
</tr>
</tbody>
</table>

\(^*\) obtained values were very similar, therefore a maximal error from the two is given

Table 5.4: Estimated systematic errors on \( \langle p_T \rangle \) and \( \langle p_T \rangle_E \) of particles produced in p+p collisions at 158 GeV/c beam momentum, for different \( x_F \) and \( y^{CM} \) values.

errors\(^5\), for some selected \( x_F \) values, is given in Table 5.4. By opening the \( x_F \) scale, one can observe the rise of the pion \( \langle p_T \rangle \) with increasing \( x_F \) - called the “sea-gull effect”. Also the average \( p_T \) of antiprotons increases with \( x_F \). Protons, on the other hand, show practically no dependence on \( x_F \).

One should comment on the observed difference between protons and antiprotons and a similar difference, although less pronounced, for \( \pi^+ \)-s and \( \pi^- \)-s. Here, the valence quark structure of the initial system (p+p) and the structure of the produced particles come into play, resulting in a larger contribution of the fragmentation mechanism to the production of protons and positive pions than to antiprotons and negative pions.

A part of the observed correlations may be due to a trivial phase space effect. The \( \langle p_T \rangle \) calculated from the \( \frac{dN}{dp_T} \) distribution contains the phase space term \( \frac{1}{E} \), which may cause a trivial non-dynamical correlation between \( \langle p_T \rangle \) and \( x_F \). The energy weighted mean transverse momentum - \( \langle p_T \rangle_E \) - calculated from the \( E \frac{dN}{dp_T} \) distribution gets rid of the \( \frac{1}{E} \) factor\(^6\):

\[
\langle p_T \rangle_E = \frac{\int p_T E \frac{dN}{dp_T} dp_T}{\int E \frac{dN}{dp_T} dp_T} .
\] (5.2)

The effect of the \( \frac{1}{E} \) factor on the \( \langle p_T \rangle \) - \( x_F \) correlations, for protons and positive pions, is shown in Fig. 5.5, where for different \( x_F \) the \( \langle p_T \rangle \) values are compared with the \( \langle p_T \rangle_E \) ones. Information on the systematic \( \langle p_T \rangle \) and \( \langle p_T \rangle_E \) errors can be found in Table 5.4. For pions, the comparison of the weighted and unweighted distributions makes evident that indeed a part of the observed “sea-gull effect” is due to the \( \frac{1}{E} \) term. In spite of that, a significant part of the effect still remains when the influence of this term is taken into consideration. For protons, the flatwise-looking \( \langle p_T \rangle \) vs. \( x_F \) distribution after the energy weighting becomes a more pronounced correlation of the \( \langle p_T \rangle_E \) and \( x_F \), as small

\(^5\)As already mentioned, corrections on the feed-down from weakly decaying particles were not applied. The estimated total systematic errors do not include the errors connected with this fact. A small study based on the FRITIOF 7.02 and VENUS4.12 models has been carried out, for p+p collisions at 158 GeV, in order to give a rough estimation of the effect. For a given \( x_F \), from the 0.0<\( x_F <0.5 \) region, the weak decays should not lower the \( \langle p_T \rangle \) value more than by about 8, 25, 4 and 10 MeV/c for \( p \), \( \bar{p} \), \( \pi^+ \) and \( \pi^- \), respectively.

\(^6\)Note that weighting by \( E \) does not fully correct for phase space effects (there are other terms where the strong interaction matrix element is convoluted with phase space, but in a more complicated way), but it is a good first approximation [Brae99].
Figure 5.5: Difference between the $\langle p_T \rangle$ and $\langle p_T \rangle_E$ dependences on the Feynman variable $x_F$ for a) protons and b) positive pions coming from p+p interactions at 158 GeV/c beam momentum.

$x_F$ protons show a tendency to have larger $\langle p_T \rangle_E$ than more forward ones.

The results on the $\langle p_T \rangle$ and $\langle p_T \rangle_E$ and $x_F$ correlations presented above clearly show that there is no factorization of a single-particle distribution function $f(p_T, p_L)$ into $p_T$ and $p_L$ terms, in p+p collisions at 158 GeV for protons, antiprotons, $\pi^+$’s and $\pi^-$’s. Therefore, it could be interesting to check whether the factorization in $p_T$ and $y$ variables exists, i.e. $F(p_T, y) \equiv \frac{\delta^2 \sigma}{\delta p_T \delta y} \geq G(p_T)H(y)$.

The mean transverse momentum dependence on the rapidity $y^{CM}$ (calculated in the p-p center of mass system), for protons and $\pi^+$’s, is shown in Fig. 5.6. Table 5.4 gives the information on the estimated systematic $\langle p_T \rangle$ errors. It appears that in the central region of rapidity, the factorization in $p_T$ and $y$ is observed but then, as the $y^{CM}$ increases towards the projectile rapidity, the $\langle p_T \rangle$ decreases. The decrease is an effect of the energy-

Figure 5.6: Average transverse momentum dependence on $y^{CM}$, for protons and positive pions from p+p collisions at 158 GeV.
5.4. $P_T$-$P_L$ Correlations

momentum conservation and it is more distinct for protons than for pions. The kinematic effect, limiting $\langle p_T \rangle$ at large rapidities, is smaller for $\pi$'s than for protons since at fixed large rapidity and moderate $p_T$ (in comparison to their $\langle p_T \rangle$) protons have a larger total momentum than pions, and the particle total momentum should be below the beam nucleon momentum.

The question of the factorization in two terms, one depending on the transverse and other on the longitudinal momentum, can be written as

$$\text{experimental result} = (\text{kinematics}) \times (\text{dynamics}),$$

where: kinematics = phase space, and dynamics = "physics". In view of the mentioned severe kinematic constraints on $\langle p_T \rangle$ at large rapidity values, phase space cannot be factorized in $p_T$ and $y$. Therefore it would be remarkable if the "physics" were such as to compensate for phase space deviations from the factorizability. Since we do not observe the factorization of the differential cross section in $p_T$ and $y$, such a compensation does not take place.

The dependence of the transverse momentum on the longitudinal one in hadron+hadron collisions at different energies has been studied earlier, see for example [Pern60, Morr72, Ston72, Ajin80, Ajin87, Bail87, Agui91]. The analyses consisted in studying the changes of a first (or second) moment, energy weighted or unweighted, of the $p_T$ distribution as a function of $p_T^{CM}$, $x_F$ or $y$. Most of the reported results, however, are based on low statistics data and often concern unidentified particles. The $p_T$-$p_L$ correlation has also been observed in $e^+e^-$ and lepton+hadron collisions [Derr78, Alle81, Alth84, Arne84, Alla85].

**Multiplicity Dependence of $\langle p_T \rangle$-$x_F$ Correlation**

In Sec. 5.3.1 the multiplicity dependence of the particle $\langle p_T \rangle$, for the whole $0.0<x_F<0.5$ region, has been studied. Fig. 5.7 shows the mean $p_T$ dependence on the event multiplicity, $n_{ch}$, but for various $x_F$ values. Systematic errors concerning the results presented in Fig. 5.7 are given in Table 5.5. For protons, the $\langle p_T \rangle$ increase with rising $n_{ch}$ is visible for $x_F>0.2$, and for this $x_F$ region the effect is rather independent on $x_F$. Also, positive pions with $x_F>0.15$ show a rise of the $\langle p_T \rangle$ as the multiplicity increases, but here the effect is stronger and non-uniform in $x_F$. It is the most distinct for $x_F \approx 0.25$ and then, for more forward $\pi$'s, weakens\(^7\). At $x_F \approx 0$, no multiplicity dependence for protons and a slight decrease, with rising $n_{ch}$, for pions are observed. The behaviour of negative pions (not shown) is much the same as their positive counterparts. For antiprotons (also not

\(^7\)At the time of finishing the writing of the thesis, the problem concerning the determination of the interaction vertex correction for low multiplicity events was discovered. It affects the $x_F \approx 0.1$ region most strongly, resulting there in too high $\langle p_T \rangle$ values, as seen in Fig. 5.7 for $n_{ch} = 1 \ldots 4$. Nevertheless, the $\langle p_T \rangle$ dependence on $n_{ch}$ at larger $x_F$ persists.
shown), within the experimental errors, no dependence on $n_{ch}$ is visible. Keeping in mind the shape of the $x_F$ distributions of the particles, the emerging picture of the multiplicity dependence of the $\langle p_T \rangle - x_F$ correlations is consistent with the observations on the “total” $\langle p_T \rangle$ dependence on $n_{ch}$ (see Sec. 5.3.1).

Assuming that, in hadronic collisions an onset of hard-like processes takes place already at the studied energy ($\sqrt{s} \approx 17.3$ GeV), or even below, the large mean transverse momenta of particles from the $0.15 < x_F < 0.5$ region, measured for high multiplicity events, could be explained. Therefore, an energy dependence study of the mean $p_T$ of particles produced in the presumably “sensitive” to the onset $x_F$ region would be very desirable; specially interesting would be pions as for them the effect of the multiplicity dependence of the $\langle p_T \rangle$ is more pronounced.

Some results on the multiplicity dependence of the correlation between the energy weighted first (and second) moment of the $p_T$ distribution and $x_F$, for meson-proton interactions at low and high energies, can be found in [Ajin80, Ajin87].

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$^{8}$ $x_F$ distributions of pions and antiprotons are strongly decreasing (for $\pi$’s see Fig. 5.12a), and the proton $x_F$ distribution, in the studied $x_F$ range, is flat (to zero-order).
5.4. $P_T-P_L$ Correlations

**Attempt to Understand the Results - Comparison to the Models**

Within the framework of parton-based models, one may consider three main sources of the hadron transverse momentum in elementary hadronic interactions, which may be symbolically written as

$$p_T = p_{T_{\text{frag}}} + k_T + p_{T_{\text{QCD}}}.$$  \hspace{1cm} (5.3)

The non-perturbative QCD part - $p_{T_{\text{QCD}}}$ - includes the fragmentation of quarks or gluons into hadrons, called $p_{T_{\text{frag}}}$, and the effect due to the primordial transverse momentum of quarks inside the nucleon, $k_T$. The perturbative part is given by $p_{T_{\text{QCD}}}$. All these factors, contributing to the hadron $p_T$, are naturally included in FRITIOF 7.02 and VENUS 4.12 models. The VENUS model, in addition, allows of arbitrary settings of the model parameters by the user, therefore, it can be helpful in understanding physics underlying the observed $\langle p_T \rangle - x_F$ correlations. In the analysis presented below, standard (std.) settings of the VENUS 4.12 model were used, except for parameters which influence on the $\langle p_T \rangle - x_F$ correlation was studied - for them different values were tested.

**Transverse Momentum from Fragmentation - $p_{T_{\text{frag}}}$**

Information on $p_{T_{\text{frag}}}$ comes mainly from data on $e^+e^- \rightarrow \text{hadrons}$ (see e.g. [Bieb01] and references therein), in which hadronization mechanisms manifest themselves most cleanly. The average transverse momentum arising from the hadronization was found to be $\langle p_T \rangle_f \approx 400$ MeV/c.

Fig. 5.8 shows a comparison of the experimental results and the VENUS model predictions, for various mean transverse momenta resulting from the fragmentation - $\langle p_T \rangle_f$, on the proton and positive pion $\langle p_T \rangle - x_F$ correlations. The rise of $\langle p_T \rangle_f$ increases the $\langle p_T \rangle$ more or less equally in the whole studied $x_F$ range, for both $p$ and $\pi^+$ (actually,
for pions the increase at $x_F \approx 0$ is somewhat smaller than for larger $x_F$ values). For the standard version of the model, with $\langle p_T \rangle_f \approx 400$ MeV/c, a rough description of the proton experimental results can be achieved. For pions on the contrary, the $\langle p_T \rangle_f$ even as high as 600 MeV/c is not able to account for the large $\langle p_T \rangle$ values in the intermediate $x_F$ region.

**Primordial Transverse Momentum of Quarks - $k_T$**

The analysis of a deep inelastic scattering of leptons off nucleons has demonstrated that, at high momentum transfer, a nucleon behaves like a collection of independent point-like partons [Brei69, Frie72]. These partons move approximately along the direction of the nucleon and each of them carries a fraction of the nucleon momentum. In addition to its longitudinal momentum component, a parton may also have some primordial transverse momentum $k_T$ [Köni83]. In fact, the uncertainty relation implies that the mean initial transverse momentum of a parton, $\langle k_T \rangle$, and the dimension $R$ of a volume in which partons are contained should satisfy the inequality $\langle k_T \rangle R > \hbar$, which gives $\langle k_T \rangle > 200$ MeV/c. This so-called primordial contribution to the transverse momentum is a consequence of the finite size of the parent hadron. In reality, the transverse momentum of a parton may include also some dynamical part and may therefore be significantly larger than about 200 MeV/c [Chek01]. In case of scattered partons with $k_T = 0$, the spectator partons follow exactly the direction of the incoming hadrons. The situation is different for $k_T \neq 0$; the spectator partons have to have a transverse momentum which compensates the $k_T$ of the scattered partons.

In Fig. 5.9 predictions of the VENUS 4.12 model concerning the $\langle p_T \rangle - x_F$ correlation are presented. The increase of the primordial transverse momentum of quarks causes the

![Figure 5.9: VENUS 4.12 model predictions on $\langle p_T \rangle - x_F$ correlations, for different mean primordial transverse momenta of quarks - $\langle k_T \rangle$, for a) protons and b) positive pions.](image)

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9Taking for $R$ the radius of a nucleon ($\approx 1$ fm), and $\hbar = 197.3$ MeVfm/c.

10In the framework of QCD, a natural explanation of large values of $\langle k_T \rangle$ is based on gluon bremsstrahlung.
5.4. $P_T$-$P_L$ Correlations

Figure 5.10: VENUS 4.12 model predictions on $\langle p_T \rangle$-$x_F$ correlations, for different probabilities of the occurrence of semi-hard processes - $P_{\text{hard}}$, for a) protons and b) positive pions.

Largest changes of the $\langle p_T \rangle$ for large $x_F$ values, for pions as well as for protons. The best conformity with the data, for protons, could be reached for $\langle k_T \rangle$ equal to the standard value (260 MeV/c). This is, however, far not enough to give a good description of the pion correlation. For pions, the increase of the $\langle k_T \rangle$ raises the large $x_F$ tip of the "sea-gull" distribution above the data, before a satisfactory improvement is reached in the intermediate $x_F$ region.

Transverse Momentum from Hard-Like Processes - $p_T \rho_{QCD}$

The last contribution to the hadron transverse momentum - $p_T \rho_{QCD}$ - results from hard-like processes, which might occur in different phases of the interaction. The initial partons may acquire a semi-hard transverse momentum before the hadronization either via gluon bremsstrahlung (gluons can be radiated by the interacting quark or by the spectator quark) or via semi-hard scattering.

Fig. 5.10 presents results on the $\langle p_T \rangle$-$x_F$ correlation from the VENUS model for different values of the $P_{\text{hard}}$ parameter, which determines the probability for the occurrence of semi-hard processes. The proton $\langle p_T \rangle$ vs. $x_F$ distribution can be roughly reproduced by the standard version of the model, for which semi-hard processes are switched off. Switching on the hard-like effects results in the proton $\langle p_T \rangle$ rise, above the experimental data, in the whole studied $x_F$ range; the effect of the mean $p_T$ rise with increasing $P_{\text{hard}}$ is slightly more visible at large $x_F$ values. For pions, an increase of the $P_{\text{hard}}$ affects mostly the 0.1<$x_F$<0.5 region, leading here to the $\langle p_T \rangle$ growth. Since a multiplicity dependence of the $\langle p_T \rangle$-$x_F$ correlation has been observed for the experimental data, one should mention that, from among the three discussed contributions to the hadron $p_T$, within the framework of the phenomenological models considered here, only the appearance of hard-like processes led to higher multiplicities.
From the above study it clearly follows that, within the VENUS 4.12 model, a simultaneous description of both proton and pion \( \langle p_T \rangle \) vs. \( x_F \) experimental distributions cannot be achieved. Protons are fairly well described by the standard version of the model, i.e. \( \langle p_T \rangle = 400 \text{ MeV}/c \), \( \langle k_T \rangle = 260 \text{ MeV}/c \) and \( P_{\text{hard}} = 0 \) (no hard-like processes). Pions, on the contrary, require a much larger \( \langle k_T \rangle \)\(^{11} \) and the inclusion of hard-like effects. This leads to higher multiplicities and to larger transverse momenta for intermediate and large \( x_F \) values.

A comparison of the predictions of the VENUS 4.12 and FRITIOF 7.02 models, concerning the \( \langle p_T \rangle - x_F \) correlation, is shown in Fig. 5.11. A role of hard-like effects could be checked also for FRITIOF 7.02, as it allows for switching these processes on or off. A modified version of the FRITIOF model (FRITIOF 7.02 modif.) includes hard processes, while in the standard version (FRITIOF 7.02 std.) they are switched off. For a modified version of the VENUS model (VENUS 4.12 modif.) the following settings were used: \( \langle p_T \rangle = 450 \text{ MeV}/c \), \( \langle k_T \rangle = 450 \text{ MeV}/c \) and \( P_{\text{hard}} = 0.25 \). A fair agreement between the proton experimental \( \langle p_T \rangle \) vs. \( x_F \) distribution and the prediction of the VENUS 4.12 model, in its standard version, is obtained. The FRITIOF 7.02 model on the other hand gives only a qualitative description of the data. Even the modified version, with hard processes included, underestimates the observed \( \langle p_T \rangle \) values. For pions, none of the standard version of the models predicts quantitatively the \( \langle p_T \rangle - x_F \) correlation visible in the experimental data. In the FRITIOF 7.02 model, by switching on the hard-like effects a better compatibility with the data can be reached. In order to achieve comparable agreement for VENUS 4.12, one has to increase the \( \langle k_T \rangle \) considerably and, of course, to add semi-hard processes. For both modified versions of the models, however, some discrepancy remains in the intermediate \( x_F \) region, which suggests that semi-hard processes are not yet sufficiently taken into consideration. Nevertheless, both models give, in general, a good description of the \( \pi^+ \) production in p+p collisions at 158 GeV, as it is illustrated in Fig. 5.12 for the FRITIOF model case. Panels (a) and (b) of Fig. 5.12 show the \( x_F \) and \( p_T \) distributions of \( \pi^+ \)'s, respectively.

\(^{11}\)At the studied energy, \( \sqrt{s} \approx 17.3 \text{ GeV} \), \( \langle k_T \rangle \) of about 400 - 500 MeV/c was measured [Chek01].
5.4. $P_T$-$P_L$ Correlations

Figure 5.12: Comparison of the experimental results and FRITIOF 7.02 (with hard processes) predictions on the $\pi^+$ production in $p+p$ interactions at 158 GeV: a) $x_F$ distribution and b) $p_T$ distribution for the $0.0 < x_F < 0.5$ region.

Resonance Contribution to $\langle p_T \rangle$-$x_F$ Correlation

In hadron+hadron reactions, a bulk of produced particles originates from resonance decays (see e.g. [Fial83] and references therein). The presence of resonance decays should lead to internal correlations observed for final state particles. It is therefore interesting to consider whether the observed $\langle p_T \rangle$-$x_F$ correlation may be partially caused by resonance decays. It is well-known that, for $p_T$ spectra, steep slopes in the small $p_T$ region are due to the resonance production [Bail87]. Thus, the observed pion correlation - a dip near $x_F = 0$ - could be easily explained by resonance decays if pions from the decays are confined to this specific $x_F$ region.

A study of the resonance influence on the positive pion $\langle p_T \rangle$-$x_F$ correlation was done employing the FRITIOF 7.02 model (hard processes included). As shown in Fig. 5.11b and Fig. 5.12, the model predictions on the $\pi^+$ production fit quite well to the experimental data, which justifies the use of the model. The decays of $\rho$'s (770), $\omega$ (782) and $\Delta$'s (1232) were considered in the analysis. In Fig. 5.13, the Feynman $x_F$, $p_T$ and $\langle p_T \rangle$ vs. $x_F$ distributions for all $\pi^+$'s produced in $p+p$ collisions at 158 GeV, as well as, the same distributions for positive pions originating from the considered resonances are presented. From panels (a) and (b) of Fig. 5.13 it follows that the resonance contribution to the spectra of finally observed $\pi^+$'s is large (for the considered resonances it is close to 45%), and is not confined to any specific $x_F$ or $p_T$ region. Fig. 5.13c displays the positive pion $\langle p_T \rangle$ dependence on $x_F$ - the “sea-gull” plot\textsuperscript{12}. The correlation visible for $\pi^+$'s coming from the decays of $\rho$'s, $\omega$ and $\Delta$'s is less pronounced than the one observed for all produced positive pions. This means that, within the FRITIOF 7.02 model, a removal of $\pi^+$'s from the decays would lead to a stronger correlation for directly produced pions.

\textsuperscript{12}This plot nicely explains the origin of the distribution name. The name comes from the shape of the plot, resembling a sea-gull with its head lowered at $x_F = 0$ and its wings raised around $|x_F| \approx 0.5$. 
Energy Dependence
A distribution particularly sensitive to the onset of hard effects in $e^+e^-$ and lepton+hadron collisions has turned out to be the energy dependence of the mean $p_T$ of particles produced in the intermediate $x_F$ region [Derr78, Alle81, Alth84, Alla85]. A rise of the mean transverse momentum in this $x_F$ region could have been explained by theoretical models after the inclusion of hard processes. In $e^+e^-$ annihilation, for example, these processes become significant already at the energy $\sqrt{s} \approx 10$ GeV. A rise of the “seagull” wings with a collision energy, for negatively charged hadrons, has also been observed in hadron+hadron collisions, namely in $K^+p$ interactions studied in the beam momentum range 12.7 to 250 GeV/c [Ajin87]. Now, the energy dependence of the $\langle p_T \rangle$ vs. $x_F$ distribution, for identified particles, can be also analysed in $p+p$ collisions.

Results on the energy dependence of the $\langle p_T \rangle - x_F$ correlations, for $\pi^+$’s, $p$’s and $\bar{p}$’s, in $p+p$ interactions are shown in Fig. 5.14. In the analysis data at the SPS energies were examined; for positive pions results for low energies, taken from [Morr72], are also presented. Estimated systematic errors on the $\langle p_T \rangle$ values can be found in Table 5.4 (for $\sqrt{s} \approx 17.3$ GeV) and Table 5.6 (for $\sqrt{s} \approx 13.8$ and 8.8 GeV).\(^{13}\)

\(^{13}\)The statistics of the two lower energy data sets was much lower than the data at $\sqrt{s} \approx 17.3$ GeV. Also, for the 13.8 GeV data, the applied interaction vertex corrections were of a worse quality, and for the 8.8 GeV data, these corrections did not exist at all. In addition, for the lowest SPS energy data, $p+p$ interactions were selected from $d+p$ collisions (as described in Appendix B). All these factors had to be taken into consideration, and resulted in larger total estimated systematic errors.
Figure 5.14: Energy dependence of the $\langle p_T \rangle$ vs. $x_F$ distribution for a) positive pions, b) negative pions, c) protons and d) antiprotons produced in p+p interactions.

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Table 5.6: Estimated systematic errors on $\langle p_T \rangle$ of particles produced in p+p interactions at center of mass energies $\sqrt{s} \approx 13.8$ and 8.8 GeV.
Panels (a) and (b) of Fig. 5.14 show that as the energy increases the pion average $p_T$ increases, at all $x_F$ values. The rise is small in the central region, $x_F \approx 0$, but it is significant in the projectile fragmentation region. The observed behaviour is in agreement with a scenario assuming the occurrence of hard-like processes already at the studied energies. Such a scenario was suggested by the multiplicity dependence analysis of the $\langle p_T \rangle - x_F$ correlation and the study based on the phenomenological models. For protons, shown in Fig. 5.14c, no definite statement on the energy dependence can be made, as the experimental errors for the two lower energy data sets are large. As for the $0.2 < x_F < 0.5$ region, a potentially interesting region with regard to the sensitivity to hard-like effects, it seems that some indications of the proton $\langle p_T \rangle$ rise with the energy are visible when the results for both data samples at lower energies are compared to the results at $\sqrt{s} \approx 17.3$ GeV. Owing to the extended coverage of phase space at lower energies, a behaviour of the proton $\langle p_T \rangle$ at $x_F > 0.5$ can be also observed; the $\langle p_T \rangle$ of protons decreases there with increasing $x_F$. The antiproton results are rather poor (Fig. 5.14d) and do not give any information on the change with a collision energy.

### 5.4.2 p+A Collisions

By studying p+A collisions the nuclear medium influence on the measured particle characteristics can be investigated. In these collisions, according to the Glauber picture, a projectile proton traversing a nucleus interacts with target nucleons met on its way; a number of interactions $\nu$ (or met target nucleons) depends on the impact parameter of the collision. In this paragraph, different centrality p+Pb collisions at 158 GeV/c beam momentum are analysed and compared to p+p collisions. A comparison with p+p interactions can answer the question whether p+A is a simple superposition of nucleon+nucleon collisions, or whether there are additional effects connected with the confinement of nucleons inside the target nucleus or resulting from multiple collisions of the projectile. By varying the collision impact parameter $b$, the dependence of the studied $\langle p_T \rangle - x_F$ correlation on the size of the interaction “volume” can be analysed. During the interaction hard-like processes might turn up, as discussed in Sec. 5.4.1. With decreasing $b$, the number of collisions $\nu$, which the projectile suffers, increases. Thus also the probability of hard-like processes to occur rises, which should leave a trace on the $\langle p_T \rangle$ vs. $x_F$ distribution.

### Experimental Results

The $\langle p_T \rangle - x_F$ correlations for various particle species produced in different centrality p+Pb collisions are shown in Fig. 5.15. In addition, as a reference, the results from p+p collisions are displayed. Information on the estimated systematic $\langle p_T \rangle$ errors is given in Table 5.7 (for p+Pb) and Table 5.4 (for p+p). While going from p+p to peripheral ($\bar{b} \approx 3.1$) p+Pb collisions, the $\langle p_T \rangle$ of protons and antiprotons rises at all $x_F$ values. With increasing centrality of p+Pb collisions, antiprotons do not show a further increase of the $\langle p_T \rangle$ (taking into consideration the experimental errors) and a shape of the $\langle p_T \rangle$ vs. $x_F$ distributions
5.4. $P_T$-$P_L$ Correlations

![Graphs showing $\langle p_T \rangle$ dependence on the Feynman variable $x_F$ for different particles and centrality classes.]

Figure 5.15: $\langle p_T \rangle$ dependence on the Feynman variable $x_F$ for a) protons, b) antiprotons, c) positive and d) negative pions from different centrality p+Pb collisions at 158 GeV; results for p+p interactions are also presented.

<table>
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<td>6.2</td>
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Table 5.7: Estimated systematic errors on $\langle p_T \rangle$ of particles coming from different centrality p+Pb collisions at 158 GeV.
imitates that in p+p collisions. The behaviour of protons is different; their \( \langle p_T \rangle \) does change with centrality. For higher \( \bar{\nu} \), larger proton \( \langle p_T \rangle \) values are measured and the increase with \( \bar{\nu} \) is more pronounced at large \( x_F \). At low \( x_F \) values, the target contribution plays a role, as pointed out in [Fisc03], leading to lowering of the proton mean \( p_T \). The pion \( \langle p_T \rangle \) at \( x_F \approx 0 \) practically does not change with the number of projectile collisions; some slight rise is visible, see Fig. 5.3. As \( x_F \) grows, the \( \langle p_T \rangle \) dependence on \( \nu \) becomes apparent. It might be worth to stress two observations:

- both the proton and pion \( \langle p_T \rangle \) manifest more pronounced dependence on the change of \( \nu \) for intermediate and large \( x_F \), the region presumably sensitive to hard-like processes;
- at large \( x_F \), the pion and proton mean transverse momenta reach similar values for a given reaction (or collision centrality) studied.

Trying to explain the observed dependences let us assume, similarly as it has been done for p+p interactions, that particle \( p_T \) distributions in p+A collisions have two components: “soft” and “hard”. Theoretical analyses of particle production in nuclear collisions suggest that the soft particle production scales with the number of wounded (participating) nucleons \( N_w \) [Bial76], whereas the hard contribution depends on the number of nucleon+nucleon collisions (hence on \( \nu \)), and dominates particle production at high transverse momenta (see e.g. [Khar01]). Results from Sec. 5.3 exhibit differences between the transverse momentum distributions of light (pions) and heavy (protons and antiprotons) particles. The differences are visible in elementary (p+p) as well as in nuclear (p+Pb) collisions. Therefore, one can assume that soft and hard processes act differently on the lighter particles than on the heavier ones\(^{14}\). Thus, for example, the comparison of the \( p_T \) distributions in the elementary and nuclear collisions (see Fig. 5.2) shows that at low \( p_T \), the region connected with soft processes, the pion transverse momenta practically do not change. On the contrary protons from the same \( p_T \) region obtain, on average, larger transverse momenta in p+Pb than in p+p collisions. As \( p_T \) increases, for both light and heavy particles, the contribution from hard processes becomes more and more important, and finally, at high \( p_T \) it dominates. Reactions involving heavy nuclei offer ideal conditions to test our understanding of this picture. A collision centrality is then a parameter by which the relative contributions of hard and soft processes to particle production can be varied. Additionally, by checking the behaviour of \( p_T \) for different \( x_F \) values the change of relative contributions of the two components can be analysed in the longitudinal momentum space.

Already in the 70’s it was discovered by Cronin et al. [Cron75, Antr79] that high \( p_T \) particle production in proton+nucleus collisions is enhanced beyond a simple scaling with the number of nucleon+nucleon collisions (see also Sec. 6.3.1). A survey of theoretical models trying to describe the Cronin effect can be found in [Acca02]; it is commonly accepted that the effect originates from initial state multiple scattering. In order to describe large \( p_T \) particle production in p+A collisions it is necessary to include both

\(^{14}\)Intuitively, one can expect, for example, that for a heavier particle hard processes could start to play a dominant role at larger \( p_T \) values than for a lighter particle.
5.4. $P_T-P_L$ Correlations

the intrinsic $k_T$ of partons from the projectile proton and its broadening due to multiple scattering. The $k_T$ broadening depends on the number of scatterings; thus as $\nu$ increases the parton can have larger $k_T$. It has been shown, for $p+p$ interactions (Fig. 5.9), that the increase of $k_T$ causes the biggest $\langle p_T \rangle$ rise at large $x_F$. This could explain large values of the proton and pion $\langle p_T \rangle$ observed in p+A collisions for $x_F \approx 0.5$ (Fig. 5.15). Particle production in this $x_F$ region depends on the characteristics of the projectile proton’s valence quarks [Fial83], hence one can expect that the particle mean $p_T$ is influenced there by the quark’s $k_T$. For $p+p$ collisions, the region of intermediate and large $x_F$ values has been shown to be sensitive to hard-like effects (Figs. 5.10 and 5.14). In p+A collisions, with increasing $\nu$ the probability of the occurrence of hard-like processes should increase, leading to the rise of $\langle p_T \rangle$. And indeed, for pions as well as for protons the increase of the mean transverse momenta for these $x_F$ values is observed.

A further discussion on the two component picture (“soft” and “hard”) of $p_T$ generation is carried on in Sec. 5.4.4, devoted to the study of the $p+p \rightarrow p+A \rightarrow A+A$ evolution.

The $\langle p_T \rangle-x_F$ correlation in meson-nucleus ($\pi^+, K^+; Al, Au$) collisions, without centrality control, has been investigated in [Agab91]. The study has been performed for negatively charged hadrons produced in both, forward and backward, hemispheres. By analysing the change of the $\langle p_T \rangle$ in the backward hemisphere, the influence of the nuclear cascading on $p_T$ spectra has been checked.

**Comparison with the Models**

A comparison of the experimental results for the most central ($\bar{\nu} \approx 6.2$) $p+Pb$ collisions and predictions of FRITIOF 7.02 and VENUS 4.12 models is presented in Fig. 5.16. For generated events, a restriction on the collision impact parameter $b<2\, fm$ was applied, which corresponds to $\bar{\nu} \approx 6.2$. The standard VENUS 4.12 and modified FRITIOF 7.02 versions are used in this comparison, as the first model has given a quite good description of protons and the second one of pions in $p+p$ interactions (see Fig. 5.11). Neither model, however, fits the $p+Pb$ data. Although the VENUS model has described the proton $\langle p_T \rangle-x_F$ correlation in the elementary collisions, for $p+Pb$ collisions it fails, giving too high $\langle p_T \rangle$ and not even reproducing the shape of the experimental distribution.

<table>
<thead>
<tr>
<th>$p+Pb$ at 158 GeV, $b&lt;2.0$ fm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
</tr>
<tr>
<td>protons</td>
</tr>
<tr>
<td>exp. data, $p=6.2$,</td>
</tr>
<tr>
<td>FRITIOF 7.02 modif.</td>
</tr>
<tr>
<td>VENUS 4.12 std.</td>
</tr>
</tbody>
</table>

| 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 |
|---|
| 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
| positive pions |

Figure 5.16: Comparison of the experimental results with FRITIOF 7.02 and VENUS 4.12 predictions on $\langle p_T \rangle-x_F$ correlations for a) $p$’s and b) $\pi^+$’s from central $p+Pb$ collisions ($\bar{\nu} \approx 6.2$, $b<2\, fm$) at 158 GeV.
The FRITIOF model, on the contrary, reproduces the trend visible for the experimental data, but underestimates the proton \( \langle p_T \rangle \) values. For pions, both models predict too low \( \langle p_T \rangle \) at intermediate and large \( x_F \). Since the FRITIOF 7.02 modif. includes hard processes, it is able to reproduce the \( \langle p_T \rangle \) increase at large \( x_F \) but the magnitude of the rise is not sufficient. This indicates that p+\( A \) collisions are not just a simple superposition of nucleon–nucleon collisions, but there must be some additional effects (e.g. parton \( k_T \) broadening in multiple collisions, increased resonance production, etc.) which are not properly included in the models.

### 5.4.3 A+\( A \) Collisions

#### Experimental Results

A+\( A \) collisions represent the highest collision complexity. The present paragraph contains results for collisions of small size nuclei (Carbon–C\( ^{12}_6 \), Silicon–Si\( ^{28}_6 \)) as well as large ones (Lead–P\( t^{208}_6 \)). The centrality selection in these collisions allows to study changes in \( \langle p_T \rangle - x_F \) distributions with increasing \( \bar{\nu} \), mean number of collisions undergone by the projectile and target nucleons. The distributions, for different particle types, are shown in Fig. 5.17; the results for Pb+Pb collisions are taken from [Sikl01]. As a reference, the distributions from p+p collisions are also presented. Estimated systematic errors on the \( \langle p_T \rangle \) values can be found in Table 5.4 (for p+p) and Table 5.8 (for C+C and Si+Si). Black curves visible on the plots correspond to the most central (\( \bar{\nu} \approx 6.2 \)) p+Pb collisions and will not be referred to here but in Sec. 5.4.4, while discussing the p+p→p+A→A+A evolution.

Fig. 5.17a shows the \( \langle p_T \rangle - x_F \) correlations for protons. More or less uniform (similar for all \( x_F \) values) rise of the proton \( \langle p_T \rangle \) is visible as \( \bar{\nu} \) increases. In particular, there is no special rise seen at intermediate and large \( x_F \). For antiprotons, as for protons, with increasing \( \bar{\nu} \) the growing of the \( \langle p_T \rangle \) (the errors are large) at all \( x_F \) is observed (Fig. 5.17b). The shape of the \( \langle p_T \rangle \) vs. \( x_F \) distributions in A+\( A \) collisions is similar to that in the elementary interactions. The dependence of the pion \( \langle p_T \rangle - x_F \) correlations on \( \bar{\nu} \) is more complicated, as it is shown in Fig. 5.17c and Fig. 5.17d for positive and negative pions, respectively. While going from p+p (\( \nu=1.0 \)) to C+C (\( \bar{\nu} \approx 1.7 \)) collisions, the \( \langle p_T \rangle \)

<table>
<thead>
<tr>
<th>data</th>
<th>systematic error on ( \langle p_T \rangle ) [MeV/c]</th>
<th>( \bar{\nu} )</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>( x_F \approx 0.0 ) ( x_F \approx 0.15 ) ( x_F \approx 0.3 ) ( x_F \approx 0.45 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( x_F \approx 0.0 ) ( x_F \approx 0.15 ) ( x_F \approx 0.3 ) ( x_F \approx 0.45 )</td>
<td></td>
</tr>
<tr>
<td>C+C</td>
<td>10  15  15  25</td>
<td>35  45  100  -</td>
</tr>
<tr>
<td>Si+Si</td>
<td>10  15  10  20</td>
<td>35  45  120  -</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>data</th>
<th>( p^+ )</th>
<th>( p^- )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C+C</td>
<td>5  10  15  35</td>
<td>5  10  15  25</td>
</tr>
<tr>
<td>Si+Si</td>
<td>5  10  15  20</td>
<td>5  10  20  30</td>
</tr>
</tbody>
</table>

Table 5.8: Estimated systematic \( p_T \) errors of particles produced in C+C and Si+Si collisions at 158 A-GeV.
of pions does not increase. In fact, for π−'s the ⟨p_T⟩ at all x_F is below the p+p results. Such a behaviour may be due to the fact that in a C-nucleus there are not only protons but also neutrons, and the isospin composition may influence the measured characteristics. The comparison of C+C and Si+Si collisions seems to support this hypothesis. Both nuclei (C and Si) have the same fraction of nucleons of a given type (50% of neutrons each), and for the larger system (Si+Si) the ⟨p_T⟩ of pions increases compared to C+C collisions, especially at large x_F. For Pb+Pb collisions with ∼3.2, the negative pion mean transverse momenta at intermediate x_F are even smaller than these for C+C and Si+Si, as shown in the insert of Fig. 5.17d (open squares). The reason is that a Pb-nucleus has more neutrons; about 60% of all nucleons are neutrons. In the most central (∼4.6) Pb+Pb collisions (stars), a further increase of the pion ⟨p_T⟩ at all x_F is seen, compared to Pb+Pb with ∼3.2. From the above observations it follows that the right reference for A+A collisions is a mixture of p+p and n+p interactions (in proper proportions), and not p+p collisions. More results on the dependence of the ⟨p_T⟩ - x_F correlations on the structure of colliding objects is presented in Sec. 5.4.5, where the projectile dependence, for elementary interactions, is discussed.

Figure 5.17: ⟨p_T⟩ dependence on x_F for a) p’s, b) p’s, c) π+’s and d) π−’s from p+p interactions and different centrality A+A collisions; results for the most central (∼6.2) p+Pb collisions are also shown (black curves).
5.4.4 $p+p \rightarrow p+A \rightarrow A+A$ Evolution

Let us now discuss the $p+p \rightarrow p+A \rightarrow A+A$ evolution. An understanding of complex A+A collisions requires first a good understanding of physics of the simpler systems, as characteristics measured for A+A reactions should contain an “elementary” ingredient, present already in $p+p$ and p+A interactions, and possibly “non-elementary” component. In order to disentangle the elementary component and possible “new”, non-elementary phenomena a comparative study of all these reactions is indispensable.

If there are strong interactions among partons in the early stage, and hadrons in the late stage of A+A reactions, the system will be driven to local thermal equilibrium. The information of initial multiple parton scattering contained in the initial parton spectra could be partially or completely erased by the thermalization. In hydrodynamic picture [Schn93, Kolb03], produced particles moving with high longitudinal or transverse velocity can collide with particles of lower velocity. This drives slow, more massive particles such as protons towards higher $p_T$ and fast moving, light particles such as pions towards lower $p_T$. In the limit of a large number of rescatterings, collective flow, which is characterized by a common flow velocity shared by all particles, will be developed and final hadron $p_T$ spectra will become broader than in $p+p$ and p+A collisions. The question is: how can one distinguish between these two apparently different dynamics, initial multiple scattering and hydrodynamic flow, which can produce very similar final hadron spectra? The mass dependence of the hadron $p_T$ spectra has been proposed as a unique measure of the collective flow effect in heavy-ion collisions. Since collective flow provides a common velocity boost for all particles, heavy particles will then acquire larger transverse momenta. One then should see the particle mass dependence of $\langle p_T \rangle$ in A+A collisions - a larger $\langle p_T \rangle$ for heavier particles. And indeed, such a dependence is observed, see for example [Bäch94, Appe99, Coop00].

Disentangling the effects of initial multiple scattering and collective flow requires a careful study of p+A collisions, especially the dependence on the final hadron mass. As shown in [Burw01], p+A interactions follow the trend visible for larger (A+A) systems. This is a remarkable observation as one does not expect a significant flow in p+A; secondary hadronic scattering and resulting collective flow should be small in these collisions. This leads, thus, to the conclusion that the mass dependence of the hadron $p_T$ spectra is not at all the unique measure and does not have to be the consequence of collective flow.

In order to explain dependences seen for the elementary as well as the nuclear collisions let us go back to the already mentioned two component picture of $p_T$ generation. In this picture:

i) two components can be separated, the first depends on $N_w$ (so-called “soft” part) and the second on $\nu$ (“hard” part);

ii) the two components are present in any region of longitudinal momentum space, but their relative contributions do not have to be the same everywhere, i.e. they could be different for different $x_F$;

iii) various particle species might be influenced differently by the processes belonging to these two parts;
5.4. \( P_T - P_L \) Correlations

In particular, as pointed out in Sec. 5.4.2 while discussing the transition from p+p to p+\( \Lambda \), at low \( p_T \) - where particle production scales with \( N_w \) - the pion \( p_T \) spectra practically do not change, differently than the proton spectra which show significant shift towards higher \( p_T \) values. At larger \( p_T \), the “hard” part (dependence on \( \nu \)) dominates, leading to the further \( \langle p_T \rangle \) increase of both light and heavy particles.

iv) both \( \nu \) and \( N_w \) are important in understanding of the measured characteristics.

Outcomes of the analyses of p+p and different centrality p+Pb collisions at 158 GeV suggest that at small \( x_F \) the “soft” part dominates, but as \( x_F \) increases a larger and larger contribution could come from the “hard” part, if \( \nu \) is large enough.

For purposes of a further discussion, the information given below can be useful. In the analysed A+A reactions, the following \( \nu \) and \( N_w \) were obtained from the Glauber Model calculations: C+C (\( \bar{\nu} \approx 1.7, \bar{N}_w \approx 14 \)), Si+Si (\( \bar{\nu} \approx 2.2, \bar{N}_w \approx 37 \)) [Höhn03]; 1-st Pb+Pb sample (\( \bar{\nu} \approx 3.2, \bar{N}_w \approx 88 \)) and 2-nd (central) Pb+Pb sample (\( \bar{\nu} \approx 4.6, \bar{N}_w \approx 352 \)) [Coop00]. For p+Pb interactions, with the projectile undergoing \( \nu \) collisions, \( N_w = \nu + 1 \).

A test of validity of the two component picture of \( p_T \) generation can be the investigation of the p+p \( \rightarrow \) p+Pb \( \rightarrow \) Pb+Pb evolution. The results concerning the evolution are shown in Fig. 5.17, where black points correspond to p+p interactions, and black curves and stars to the most central p+Pb and most central Pb+Pb collisions, respectively. When comparing these reactions at a given \( x_F \), a clear hierarchy is visible: for protons and antiprotons, the average transverse momentum increases from p+p via central p+Pb to the largest values observed in central Pb+Pb. For pions, on the contrary, central p+Pb collisions provide the highest \( \langle p_T \rangle \), except for \( x_F \approx 0 \), where the mean \( p_T \) of pions from central Pb+Pb collisions is the largest. The observed dependences are in agreement with the discussed two component picture:

- **small \( x_F \) \((\approx 0)\) region**, where the contribution from \( N_w \) mainly matters
  It has been already mentioned that the \( N_w \) dependence of the \( \langle p_T \rangle \) is weak for pions and stronger for the heavy particles (protons, antiprotons). Therefore, for the p+p \( \rightarrow \) p+Pb, the measured pion mean transverse momenta are very similar as the two systems have not very different \( N_w \). However, for the p+p \( \rightarrow \) Pb+Pb, the rise of pion \( \langle p_T \rangle \) is already significant (\( \sim 30 \) MeV/c) because \( N_w \) in central Pb+Pb is very large compared to p+p. For protons and antiprotons, the \( \langle p_T \rangle \) increases rapidly while going to larger systems as for these particles the dependence on \( N_w \) is stronger.

- **medium and large \( x_F \) region**, where not only \( N_w \) but also \( \nu \) counts
  For \( \pi \)'s, as \( x_F \) increases the contribution from \( \nu \) becomes more important. For that reason, the pion \( \langle p_T \rangle \) values in central p+Pb collisions, with \( \bar{\nu} \approx 6.2 \), are larger than in central Pb+Pb collisions, where \( \bar{\nu} \approx 4.6 \). At these \( x_F \), for protons the \( N_w \) part still dominates over the \( \nu \) contribution, that is why the \( \langle p_T \rangle \) values measured for central Pb+Pb collisions are higher than these for central p+Pb. However, in both reactions \( \nu \) is large, which should lead to the higher mean transverse momenta than
these at $x_F \approx 0$. And indeed, such an increase seems to take place; the effect is more pronounced for p+Pb interactions as for them $\nu$ is larger$^{15}$.

These qualitative considerations on the two component picture seem to indicate that the $p_T$ behaviour in A+A reactions can be explained by phenomena already present in the simpler (p+p and p+A) systems, without introducing additional effects such as, for example, collective radial flow. In this picture, both the number of wounded nucleons $N_w$, determining the size of the interaction “volume”, and the number of collisions $\nu$ are important.

### 5.4.5 Projectile Dependence

A structure of colliding objects, hadrons or nuclei, influences characteristics of particles produced in final state. Their spectra have been shown to be sensitive, both, to the valence quark structure of initial hadrons - for elementary interactions (Sec. 5.4.1, Fig. 5.4), and to the nucleon composition - for nuclear collisions (Sec. 5.4.3, Fig. 5.17). This paragraph deals with a study of the projectile type dependence of the $\langle p_T \rangle - x_F$ correlations, for elementary collisions.

#### Experimental Results

The correlations for $p$, $\bar{p}$, $\pi^+$ and $\pi^-$ particles produced in final state of p+p, $\pi^+$+p and $\pi^-+p$ collisions at 158 GeV are presented in Fig. 5.18. Information on the estimated systematic $\langle p_T \rangle$ errors is given in Table 5.4 (for p+p) and Table 5.9 (for $\pi^+$+p and $\pi^-+p$). The influence of the parton structure on the measured characteristics has been already noticed for p+p interactions (Fig. 5.4). Now, it can be further investigated thanks to the accessibility of interactions with pionic beams.

The proton $\langle p_T \rangle$ vs. $x_F$ distributions are similar in all three studied reactions (Fig. 5.18a); although it seems that the average transverse momenta of large $x_F$ protons in $\pi^+$+p are slightly larger than these in p+p and $\pi^-+p$ collisions. Antiprotons do not manifest any dependence on the projectile type, taking into account the $\langle p_T \rangle$ errors, as shown in Fig. 5.18b. For pions, on the contrary, such a dependence is visible (panels (c) and (d) of Fig. 5.18), particularly at larger $x_F$. The highest mean transverse momenta are measured for final state pions of the same kind as beam ones. This result may be a little surprising as one would rather expect for them the lowest $\langle p_T \rangle$ values. These pions are in some part the leading particles, i.e. they can be produced in the fragmentation process of the pion beam valence quarks, and therefore should have large $x_F$ and rather small $p_T$.

For that reason, for example, in p+p interactions large $x_F$ protons have smaller mean $p_T$ than antiprotons. A different behaviour observed for p+p and $\pi^+\pi^-$ interactions results probably from the fact that a proton projectile may consist of a quark-diquark system or of three independent quarks, and a pion projectile is simply a quark-antiquark pair.

$^{15}$A comparison of central p+Pb and C+C collisions, having not very different $N_w$ but significantly different $\nu$, also supports the considered scenario.
5.4. $P_T - P_L$ Correlations

![Graphs showing $P_T$ dependence on $x_F$ for protons, antiprotons, positive and negative pions.]

Figure 5.18: Comparison of the mean $p_T$ dependence on $x_F$ for a) $p$'s, b) $\bar{p}$'s, c) $\pi^+$'s and d) $\pi^-$'s from $p+p$, $\pi^+p$ and $\pi^-+p$ collisions at 158 GeV/c beam momentum.

<table>
<thead>
<tr>
<th>Data</th>
<th>Systematic Error on $\langle p_T \rangle$ [MeV/c]</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$x_F \approx 0.0$</td>
</tr>
<tr>
<td>$\pi^+ + p$</td>
<td>7</td>
</tr>
<tr>
<td>$\pi^- + p$</td>
<td>10</td>
</tr>
<tr>
<td>$\pi^+ + p$</td>
<td>4</td>
</tr>
<tr>
<td>$\pi^- + p$</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 5.9: Estimated systematic $\langle p_T \rangle$ errors of particles produced in $\pi^+ + p$ and $\pi^- + p$ interactions at 158 GeV.

Since initial partons may acquire some transverse momentum, for example a recoil $p_T$ due to the gluon emission, the leading particle which is supposed to contain such a parton (or partons) will have then an increased $p_T$. A quark is “lighter” than a diquark, therefore the effect of the recoil $p_T$ should be larger for it, and thus higher than expected $\langle p_T \rangle$ values of positive (negative) pions in $\pi^+ + p$ ($\pi^- + p$) collisions could be explained. The same arguments can be used to explain higher proton mean transverse momenta, at large $x_F$, observed in $\pi^+ + p$ collisions.
Figure 5.19: Comparison of the experimental results with FRITIOF 7.02 (hard processes included) predictions on $\langle p_T \rangle - x_F$ correlations for a) positive and b) negative pions from $\pi^+ + p$ collisions at 158 GeV.

**Comparison with the Models**

Predictions of the FRITIOF 7.02 model on the pion $\langle p_T \rangle - x_F$ correlations, together with the experimental results, for $\pi^+ + p$ collisions are shown in Fig. 5.19 for $\pi^+$'s and $\pi^-$'s. While for negative pions almost a perfect agreement between the model predictions and experimental data is obtained, for positive pions, at medium and large $x_F$, FRITIOF 7.02 gives too low $\langle p_T \rangle$ values. This indicates that the model does not include some effects present in the data or does it incorrectly. In fact, the results it delivers follow the naive expectations, as discussed above, which could suggest, for example, that FRITIOF 7.02 does not take into account the recoil $p_T$ effect correctly.

**5.5 Summary**

In this chapter, results on transverse momentum spectra obtained for elementary hadronic interactions ($p+p$, $\pi^+ + p$, $\pi^- + p$) as well as for nuclear collisions (centrality-defined $p+$Pb, C+C, Si+Si and Pb+Pb) at center of mass energy $\sqrt{s} \approx 17.3$ GeV were discussed. In addition, for $p+p$ collisions, the energy dependence of the transverse momentum behaviour was studied in the SPS energy range. Main conclusions from the performed analyses are specified below.

- Particles of various types, produced in final state, show different transverse momentum behaviour, both in elementary and nuclear collisions. In particular, heavier particles obtain, on average, a larger $p_T$ than lighter ones. Changes of their $p_T$ distributions for different regions of longitudinal momentum space, as described by $\langle p_T \rangle - x_F$ correlations, are also different.
5.5. Summary

- In order to explain the \( \langle p_T \rangle - x_F \) correlations observed in elementary hadronic interactions, within the framework of parton-based models, the inclusion of the transverse momentum from the fragmentation process \( p_{T \text{frag}} \) and the primordial transverse momentum of partons in colliding hadrons \( k_T \) is necessary. Additionally, at the studied SPS energies, the transverse momentum from hard-like processes \( p_{T \text{pQCD}} \) has to be taken into account as well.

- Similarly as in \( e^+e^- \) and lepton+hadron collisions, the \( \langle p_T \rangle - x_F \) correlation for final state particles from hadronic interactions has been shown to depend on energy, indicating presumably its sensitivity to the onset of hard-like effects.

- Nuclear collisions are not just a superposition of nucleon+nucleon collisions. There are extra effects resulting from the passage of a nucleon through the nuclear medium, such as for example a parton \( k_T \) broadening in multiple collisions.

- The correlations between transverse and longitudinal momenta observed for particles in final state have been found to depend on the valence quark structure of hadrons in initial state - for elementary collisions, and on the nucleon composition of colliding nuclei - for nuclear collisions.

- It seems that, the transverse momentum characteristics in the most complex collisions, namely in A+A reactions, can be already explained after taking into account phenomena present in collisions of simpler systems, in h+h and h+A. Thus, for example, the \( \langle p_T \rangle - x_F \) correlations in nucleus+nucleus collisions can be described using the two component picture, suggested by the results from \( p+p \) and \( p+A \) interactions. In this picture, two contributions can be separated: the first depends on the size of the collision “active volume” (dependence on the number of wounded nucleons - \( N_w \)), and the second one is connected with the “excitation” of the interacting nucleons (dependence on the number of collisions suffered by the nucleon - \( n \)).

- Based on the presented results one can conclude that, at SPS energies, A+A collisions do not occupy any special place in the \( p+p \rightarrow p+A \rightarrow A+A \) evolution. The transverse activity is already well developed on the level of p+A interactions, as shown by the analysis of different centrality p+Pb collisions.

First results from the NA49 experiment concerning some of the discussed items were published in [Bäch99]. Short progress reports on the presented study of \( \langle p_T \rangle - x_F \) correlations can be found in the internal documentation of the NA49 Collaboration [Boim98, Boim00, Boim01].
Chapter 6

Particle Composition

6.1 Motivation

Hadron transverse spectra, analysed in the previous chapter, carry information about the collision dynamics and the entire space-time evolution of the system from the initial to the final stage of collisions. In this chapter, results concerning particle composition, extracted from transverse spectra, are presented. The study of identified hadron yields, and in particular particle ratios, can shed more light on the importance of different mechanisms in particle production.

Modifications of particle production in nuclear collisions \((A+B)\)\(^1\) due to nuclear effects, in comparison to nucleon+nucleon interactions at the same energy, can be studied using the quantity \(R_{AB}\) - the nuclear modification factor. \(R_{AB}\) describes the change in the transverse momentum spectra in \(A+B\) reactions relative to the spectra in nucleon+nucleon (N+N) collisions. Since \(R_{AB}\) was designed to analyse the behaviour at large \(p_T\), where hard processes (scaling with the number of binary nucleon+nucleon collisions \(- N_{binary}\)) dominate, it is given as a ratio of the A+B and N+N spectra additionally normalized to account for the scaling with \(N_{binary}\). For example, for minimum bias A+B collisions the nuclear modification factor can be written as the ratio of the invariant cross sections scaled by a product of the atomic numbers of colliding nuclei:

\[
R_{AB} = \frac{E \frac{d\sigma^{AB}}{dp^3}}{AB \frac{d\sigma^{NN}}{dp^3}}. \tag{6.1}
\]

However, if only a given centrality class of A+B collisions is analysed then \(R_{AB}\) is defined as

\[
R_{AB} = \frac{E \frac{d\sigma^{NAB}}{dp^3}}{T_{AB} \frac{d\sigma^{NN}}{dp^3}} = \frac{E \frac{d\sigma^{AB}}{dp^3}}{\langle N_{binary} \rangle / \sigma_{incl}^{NN} E \frac{d\sigma^{NN}}{dp^3}}, \tag{6.2}
\]

where:

\(^1\)A notation: A+B refers here to hadron+nucleus as well as nucleus+nucleus collisions (symmetric A=B or asymmetric A≠B).
6.1. Motivation

\[ E \frac{d^2\sigma_{NN}}{dp_T^2} - \text{invariant inclusive cross section for N+N collisions} \]

\[ E \frac{d^2\sigma_{NAB}}{dp_T^2} - \text{invariant inclusive yield for a given centrality A+B collisions} \]

\[ T_{AB}\] - nuclear overlap function accounting for the collision geometry;

\[ T_{AB} = \langle N_{\text{binary}} \rangle / \sigma_{\text{inel}}^{NN} \]

\( \langle N_{\text{binary}} \rangle \) - average number of binary N+N collisions corresponding to a given centrality class of A+B collisions

\[ \sigma_{\text{inel}}^{NN} \] - N+N inelastic cross section at a given collision energy.

Thus, \( R_{AB} \) measures the deviation of A+B collisions from an incoherent superposition of N+N collisions in terms of suppression \((R_{AB}<1)\) or enhancement \((R_{AB}>1)\).

Recently, a lot of interest of high energy nuclear physicists has been devoted to very intriguing observations coming from the experiments (BRAHMS, PHENIX, PHOBOS and STAR) at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) concerning large suppression of high \( p_T \) hadron yields in central Au+Au collisions. One of the first published results showing the effect is presented in Fig. 6.1. The nuclear modification factor, noted here as \( R_{AA} \) (symmetric collisions were studied, B=A), was calculated for unidentified charged hadrons at midrapidity and studied as a function of \( p_T \). If scaling with the number of binary collisions \( N_{\text{binary}} \) holds true, \( R_{AA} \) should be unity, as indicated by the dashed line. At low \( p_T \), below 1-2 GeV/c, the nuclear modification factor must be smaller than one because the cross section in this \( p_T \) region is expected to scale with the number of participating (wounded) nucleons \( N_w \), which is smaller than the number of binary collisions. Thus scaling with \( \langle N_{\text{binary}} \rangle \) is expected only at large \( p_T \). As shown in Fig. 6.1, \( R_{AA} \) increases up to a \( p_T \) of about 2 GeV/c, where it saturates. In the region from 2 to 4 GeV/c, the nuclear modification factor might be consistent with unity, as the systematic uncertainties are large. However, at high \( p_T \) it is not converging towards one, as ex-

![Figure 6.1: Nuclear modification factor for central Au+Au collisions at \( \sqrt{s}=130 \text{GeV} \), calculated for midrapidity charged hadrons. The thin line indicates the estimated systematic uncertainty. Also given is the expectation for scaling with \( \langle N_{\text{binary}} \rangle \) (dashed line) and the nuclear modification factor deduced from CERN data (dash-dotted line). The plot is taken from [Dree02].](image-url)
pected from a simple binary scaling. Later, more precise measurements performed at RHIC \cite{Adio02, Adie02, Adam03, Adic03, Adie03, Adie03b, Arse03}, including also studies of Au+Au collisions at $\sqrt{s} = 200$ GeV, have confirmed the findings. In addition, they have shown the collision centrality dependence (the suppression increasing with centrality, with no effect for peripheral collisions) and particle type dependence (a strong effect for $\pi$’s and a lack of suppression for $p$’s and $\bar{p}$’s). In contrast to the RHIC results, $R_{AA}$ at the CERN-SPS energies shows an enhancement, as indicated by the dash-dotted line in Fig. 6.1. A better understanding of the energy dependence of the nuclear modifications of $p_T$ distributions requires therefore more detailed analyses not only at RHIC but also at SPS energies.

A new feature, never found before for elementary or nuclear interactions and observed for the first time at RHIC (see Fig. 6.2), is that in Au+Au collisions at $p_T \approx 2$ GeV/c the $\bar{p}$ yields are comparable to the $\pi^-$ yields. A similar behaviour is found for the $p$ and $\pi^+$ yields. This intriguing behaviour was studied further in \cite{Adie03, Adie03a} by analysing the midrapidity particle ratios as a function of $p_T$ for different centralities of Au+Au collisions. For all centralities, the baryon/meson ratios rise steeply at low $p_T$ and then, at a value of $p_T$ which increases from peripheral to central collisions, level off. At $p_T > 2$ GeV/c, the ratios from peripheral Au+Au collisions coincide with the ratios obtained for elementary collisions; thus they are in agreement with “standard” perturbative production mechanisms, which favour there the production of the lightest particle. The central Au+Au ratios, in the $2 < p_T < 4$ GeV/c region, are much larger and for their description additional mechanisms have to be considered.

The discussed

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6_2.png}
\caption{Inclusive transverse momentum distributions, at midrapidity, for negative (left) and positive (right) identified hadrons from minimum bias Au+Au collisions at $\sqrt{s}=130$ GeV. Plots are taken from \cite{Velk02}.}
\end{figure}
enhancement of the baryon production relative to the pion one is in agreement with the particle species dependent suppression of high \( p_T \) hadron yields described earlier.

The suppression pattern observed at RHIC can be understood as a product of two terms. One is due to initial state interactions, such as the Cronin effect [Cron75, Antr79], and the second factor arises from final state interactions with the produced medium. The most interesting explanation of the high \( p_T \) suppression relies not on an initial state nuclear effect but on a final state medium one, namely on a so-called jet quenching. It has been since long predicted [Gyul90, Gyul94, Wang95] that interactions of highly energetic partons with a hot and dense matter created in the collision would induce gluon radiation which carries off a significant fraction of the parton’s energy, thus leading to the depletion of the high \( p_T \) yields. This mechanism alone, however, cannot account for the observed particle type dependence, i.e. the absence of suppression for baryons along with the enhancement of the baryon/meson ratio in central Au+Au collisions. It has been recently proposed that such observations can be attributed to the recombination (or coalescence) of quarks, rather than fragmentation [Frie03, Grec03, Hwa03]. Yet another possible explanation is the baryon junction model [Khar96, Vite02]. On the other hand, it is also possible that initial state nuclear effects may result in the suppression and/or in the species dependence seen. To test this hypothesis, d+Au collisions at \( \sqrt{s}=200\text{GeV} \) have been studied [Adam03a, Adam03b, Ade03c, Arse03, Back03]. The results obtained for these interactions do not show the suppression of particle yields at large \( p_T \), in terms of the \( R_{AB} \) factor. They do, however, seem to reveal a difference in the behaviour of baryons and mesons. This would indicate that final state interactions are responsible for the suppression, and initial state effects, at least partially, can account for the particle type dependence visible in the Au+Au data.

As it has been shown discussing the RHIC results, a study of the relative abundances of different particle species and nuclear modifications of the spectra may result in very exciting findings. The complete understanding of such phenomena requires systematic and comprehensive analyses at different collision energies. For the SPS energy range, the results of such analyses practically do not exist; some results can be found in [Wang00, Wang01, Agga02, Reyg02], see also Sec. 6.3 for a review. It is therefore very important to perform the study in this energy region.

Fig. 6.1 shows the enhancement of high \( p_T \) yields at SPS (\( R_{AA}>1 \)), a behaviour very distinct from the one found at RHIC (\( R_{AA}<1 \)). This observation may rise many questions. Does it mean that matter created in Pb+Pb collisions at \( \sqrt{s} \approx 20 \text{GeV} \) is different than that in Au+Au at \( \sqrt{s} = 130 \) or 200 GeV? If the parton energy loss mechanism is responsible for the suppression at RHIC, does it imply that there is no “jet quenching” at SPS? In order to answer these and other emerging questions, one has first to establish a baseline behaviour for A+A collisions at SPS energies. This can be done by studying \( h+h \) and \( h+A \) reactions, for which only initial state effects are present, and differentiating, in addition, on particle species in final state. The NA49 detector offers a wide phase space coverage, therefore for the first time ever, such a study can be performed not only at midrapidity but also in a quite large region of the projectile hemisphere, which may reveal interesting features of the data.
Different theoretical (or phenomenological) models aiming at the description of production mechanisms at SPS energies can be tested against the results on nuclear modification factors as well as the results on particle ratios in nucleon+nucleon and nucleon+nucleus reactions, covering a large phase space region, as presented in this chapter.

6.2 Data Analysis

The present study is done for p+p and central p+Pb collisions at 158 GeV ($\sqrt{s} \approx 17.3$ GeV). The central p+Pb data sample (400 k events) corresponds to the sum of two most central subsamples analysed in Chapter 5, i.e. the selection $N_{CD} \geq 7$ is applied. This gives $\bar{v} \approx 5.8$, for the mean number of collisions suffered by the projectile. In case of p+p collisions the whole available statistics is used (2.5 M events).

The experimental results, concerning p+p interactions, are confronted with the predictions of FRITIOF 7.02 and VENUS 4.12 models. For a purpose of this comparison, for both models, samples of 500 k events were generated and analysed.

The production of identified charged hadrons as a function of $p_T$ is studied in the projectile hemisphere. The following $x_F$ regions are examined$^2$: (0.0-0.05), (0.0-0.1), (0.05-0.1), (0.1-0.15), (0.15-0.2), (0.1-0.3), (0.2-0.3), (0.3-0.45). Particles are identified employing the $\frac{d\phi}{dx}$ fit method. This method is more sophisticated than the $\frac{dE}{dx}$ cut method, used in the study reported in the previous chapter, and also more accurate if the analysis is done properly. It requires, however, some minimal number of tracks in the bin to perform the fitting$^3$. On the other hand, if a size of the bin is too large the $\frac{dE}{dx}$ resolution worsens. Thus, for each bin, one has to try to find an optimum. More information on details of the current analysis is given in Table 6.1.

<table>
<thead>
<tr>
<th>Analysed $\phi$ wedge (size adjusted)</th>
<th>centered at:</th>
</tr>
</thead>
<tbody>
<tr>
<td>positives</td>
<td>$\phi=0^\circ$</td>
</tr>
<tr>
<td>negatives</td>
<td>$\phi=180^\circ$</td>
</tr>
<tr>
<td>Number of clusters on a track</td>
<td>$N&gt;30$</td>
</tr>
<tr>
<td>Particle Identification</td>
<td>$\frac{d\phi}{dx}$ fit method (Sec. 3.3.2)</td>
</tr>
<tr>
<td>Corrections</td>
<td>as discussed in Sec. 4.4.2</td>
</tr>
</tbody>
</table>

Table 6.1: Summary information on used cuts, corrections and particle identification.

The results on particle composition presented here, in the form of ratios, were obtained from invariant $p_T$ distributions-invariant cross sections ($E \frac{d^\alpha}{d^\beta}$) for p+p interactions and invariant yields ($E \frac{d\alpha N}{d^\beta}$) for central p+Pb collisions. The distributions can be found in

$^2$In order to do the analysis for larger $p_T$ some of the $x_F$ bins had to be merged due to not sufficient (to perform the fitting) statistics.

$^3$To make full use of available statistics, the azimuthal wedges were adjusted separately for each analysed bin.
Appendix C together with the information on the estimated systematic errors. Main sources of the errors are the uncertainties in the fitting procedure used to extract particle yields from the $\frac{dN}{dx}$ distributions and uncertainties in the calculation of the corrections. For the ratios, a proper determination of the systematic errors is not always straightforward as errors from some of the sources may cancel.

### 6.3 Nuclear Modifications of $p_T$ Distributions at SPS Energies

Nuclear modifications of transverse momentum spectra for the SPS energy have been studied in [Wang00, Wang01, Agga02]. Data taken by the CERN heavy-ion experiments have been compiled in [Wang00, Wang01] and analysed in terms of the nuclear modification factor $R_{AB}$. Fig. 6.3 shows $R_{AB}$ for pions and negatively charged hadrons in proton+nucleus and nucleus+nucleus collisions with different centralities at 200 A-GeV beam energy. The nuclear modification factor was also calculated for central heavy-ion collisions at the energy equal exactly to the one studied in this thesis, namely at 158 A-GeV, and is presented in Fig. 6.4. For all studied reactions, $R_{AB}$ is smaller than one at low $p_T$. As the transverse momentum increases, the nuclear modification factor increases and becomes larger than one at $p_T$ of about 1-2 GeV/c. Then, in principle, $R_{AB}$ should peak at some value of $p_T$ and afterwards decrease again to approach unity at very large $p_T$ (not shown here). As pointed out in [Wang01], the full structure of $R_{AB}$ dependence on $p_T$ cannot be revealed at the discussed energies because of the finite phase space constrained by the kinematic limit of $\frac{\sqrt{s}}{2}$. At $p_T=4$ GeV/c one is already quite close to this limit, and the spectra may become there sensitive to other nuclear effects such as, for example, the Fermi motion that

![Figure 6.3: Nuclear modification factor $R_{AB}$ for midrapidity hadrons produced in p+A (bottom panel) and A+B (two upper panels) collisions at 200 A-GeV beam energy. The plot is taken from [Wang01].](image-url)
will increase the parton distribution function, leading to further increase of $R_{AB}$.

From Fig. 6.4 it is apparent that the behaviour of the nuclear modification factor, for $\pi$ and $h^{-}$, at $p_{T}>1.5 \text{ GeV/c}$ in central Pb+Pb collisions at $\sqrt{s} \approx 17.3 \text{ GeV}$ is well described by the pQCD parton model discussed in [Wang01]. This model includes the $p_{T}$ broadening due to multiple parton scattering (the Cronin effect) but no additional final state effects, such as the parton energy loss or “jet quenching” mentioned in Sec. 6.1. Thus, at the SPS energy, there seems to be no evidence of the suppression of large $p_{T}$ hadron spectra caused by dense partonic matter\footnote{New experimental results on $\pi^{0}$ production in heavy ion reactions at 158 A·GeV, from WA98 [Agga02], seem to indicate, however, some suppression of high $p_{T}$ $\pi^{0}$'s in central Pb+Pb. At large $p_{T}$, $R_{AB}>1$ for all collision centralities but for very central collisions the enhancement appears to be weaker than expected; the pQCD calculation overpredicts the experimental data by about 30\%.}, differently than at RHIC. The absence of the suppression implies that either there is no such dense partonic matter created in central Pb+Pb collisions or that the life time of such a medium is smaller than the mean free path for the parton interaction inside the medium. The energy density - estimated using the measured transverse energy production and Bjorken scaling picture - is found to be 2-3 GeV/fm$^{3}$ for central Pb+Pb collisions at SPS [Albe95], and for central Au+Au collisions at RHIC it is larger and is close to 5 GeV/fm$^{3}$ [Nagl01]\footnote{There are also calculations which show that the energy density at RHIC can be even as large as 20 GeV/fm$^{3}$.}, Thus indeed, the life time of the dense partonic system, before the density drops below a critical value of $\epsilon_{c} \approx 1$ GeV/fm$^{3}$, must be shorter for SPS energies than for RHIC ones, which could explain the difference in the $R_{AB}$ behaviour at SPS and RHIC. The results presented in Figs. 6.3 and 6.4 suffer from some shortcomings. First of all, they are not very accurate as they are burdened with large errors. Secondly, the study of particle species dependence has not been done\footnote{As shown in Fig. 6.3, for S+S collisions $R_{AB}$ at $p_{T} \approx 2$ GeV/c for $h^{-}$'s (containing $\pi^{-}$, $K^{-}$ and $\bar{p}$ particles) seems to be larger than for $\pi$'s, thus suggesting that particles heavier than pions show a stronger enhancement.}, and finally only midrapidity spectra were considered.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig6_4.png}
\caption{Nuclear modification factor $R_{AB}$ for midrapidity hadrons produced in central Pb+Pb and Pb+Au collisions at 158 A·GeV beam energy. The line is the pQCD parton model calculation. The plot is taken from [Wang01].}
\end{figure}
6.3. Nuclear Modifications of $p_T$ Distributions at SPS Energies

6.3.1 Initial State Effects

As already mentioned in Sec. 5.4.4, for nucleus+nucleus collisions collective radial flow, in hydrodynamic picture, leads to the $p_T$ broadening of hadron spectra. The flow should also lead to the increase of $R_{AB}$ as a function of $p_T$, showing the stronger effect for heavier particles. The analyses performed for different hadron species in $p+p$ and $p+A$ collisions are very important to find out whether nuclear modification factors have a mass dependence resulting from initial state effects. In this way, one can check whether the appearance of collective radial flow is really necessary in explaining the mass dependence observed in nucleus+nucleus collisions.

Cronin Effect

In the pioneering experiment studying the Cronin effect [Cron75, Antr79], the midrapidity production of hadrons in proton collisions with $A$-nuclei was parametrized as

$$E \frac{d^3 \sigma^{pA}}{dp^3} = A^{\alpha(p_T)} E \frac{d^3 \sigma^{pp}}{dp^3}. \quad (6.3)$$

At high $p_T$, particle production off a nucleus comes from the interactions of fast partons from the projectile. Fast partons “see” the whole target and the cross section for a hard interaction is proportional to the volume of the nucleus, thus $\alpha = 1$. Multiple scattering effects will modify the $A$-dependence, giving $\alpha \neq 1$, as it is shown in Fig. 6.5. At low

![Figure 6.5: Power $\alpha$ of the $A$ dependence of the invariant cross section versus $p_T$ for the production of midrapidity a) $\pi^+$'s, b) $\pi^-$'s, c) $p$'s and d) $\bar{p}$'s by 400-GeV protons ($\sqrt{s} \approx 27.4$ GeV). The values of $\alpha$ are taken from [Antr79] and replotted.](image)
$p_T$, for all particle species, $\alpha(p_T)$ is smaller than one. With increasing $p_T$, the exponent also increases and at some transverse momentum it overshoots unity. The value of $p_T$ at which it happens depends on particle type; it is equal about 1 GeV/c for $p$, and 1.5 GeV/c for $\pi^\pm$ and $\bar{p}$. For still higher $p_T$, $\alpha(p_T)$ increases further and its rise is stronger for the heavier particles. The exponent $\alpha$ is at most equal to 1.15 for pions, while one obtains values of $\alpha$ around 1.35 for $p$ and $\bar{p}$. Thus, at large $p_T$ the production of the baryons is particularly strongly enhanced. From results published in [Str92] it follows that for $p_T > 8$ GeV/c (the region not shown in Fig. 6.5), for both the baryons and mesons, $\alpha(p_T)$ is again smaller and it levels off at unity. The observation that the power $\alpha$ at large $p_T$ is significantly larger than unity was interpreted in [Cron75] as a cooperative behaviour of nucleons in the nucleus.

The intriguing particle species dependence of the Cronin effect has been studied in [Krzy79, Lev83], in the framework of the QCD inspired parton model. These studies concerned $\pi^\pm$, $K^\pm$ (also measured in [Cron75, Antr79]) and $\bar{p}$. According to the studies, the hierarchy of the exponents $\alpha$ can be understood as a result of a particularly intense multiple scattering of gluons, compared to that of quarks. This would lead to a stronger enhancement of the production of particles ($K^-$, $\bar{p}$) with flavour content very different from that of the projectile ($p$). Thus, in this picture, a heavy nucleus acts like a gluon “filter”. These theoretical calculations, however, do not reproduce the measured particle type dependence of the exponent $\alpha$ quantitatively.

**Hypothetical Picture of p+A Collisions - Attempt to Understand the Results**

Before presenting a possible explanation of the results discussed above, let us first summarize main observations concerning $\alpha(p_T)$. First of all, there is a particle species dependence of the exponent $\alpha(p_T)$ visible:

- $\bullet$ for all $p_T$ $\alpha_{\pi^\pm} \approx \alpha_{\pi^-}$
- $\bullet$ for $p_T < 2$ GeV/c $\alpha_{\pi^\pm} \approx \alpha_{\bar{p}} < \alpha_p$
- $\bullet$ for $2 < p_T \leq 8$ GeV/c $\alpha_p \approx \alpha_p > \alpha_{\pi^\pm}$
- $\bullet$ for $p_T > 8$ GeV/c $\alpha_{\bar{p}} \approx \alpha_p \approx \alpha_{\pi^\pm} \approx 1$.

Thus, the baryon production at large $p_T$ is more enhanced than the meson one, and in case of baryons the value of $p_T$ at which $\alpha(p_T)$ reaches the maximum is shifted towards higher $p_T$.

Now, one can try to explain these observations. Let us assume that three mechanisms contribute to the production of hadrons.

1. First mechanism is a multi-parton formation mechanism such as coalescence or recombination. The transverse momentum distribution of partons, from which final state particles are formed, would depend on the number of nucleons participating in the collision-$N_n$. With increasing number of wounded nucleons, the initial momentum distribution of partons would broaden. This, in turn, would lead to the
6.3. Nuclear Modifications of $p_T$ Distributions at SPS Energies

widenig of the $p_T$ region for which the soft production (controlled by $N_w$) matters. The effect should be stronger for baryons than mesons as they consist of more valence quarks.

2. The data show that proton yields are more strongly enhanced by nuclear targets (for proton beam) than those of mesons and antiprotons. This indicates the existence of an additional mechanism which is connected with the valence quark structure of particles. One may speculate that for protons the diquark is at the origin of the observed difference. Since pions also have a quark common with the projectile proton the mechanism should be important for them as well. In p+A collisions, the projectile undergoes $\nu$ collisions, this must leave a trace on the characteristics of its partons. Therefore, characteristics of final state particles containing these partons should also be influenced by this fact.

3. The last, third, contribution to particle production comes from true hard interactions, which scale with the number of binary nucleon+nucleon collisions. They dominate high $p_T$ region, giving there $\alpha=1$ for all particle species.

According to this hypothetical picture of p+A collisions, the Cronin effect - the anomalous nuclear enhancement - is a sum of the first two mechanisms\textsuperscript{7}. The picture implies much more strong enhancement for nucleus+nucleus reactions, as for them $N_w$ is much larger than for p+A. The effect should also extend to higher $p_T$ and be more pronounced for baryons than mesons. This also means that true hard processes dominate particle production starting from different $p_T$ values depending on the studied system. It happens earlier, at smaller $p_T$, for p+p interactions than for p+A, and at the largest $p_T$ values for nucleus+nucleus reactions. One thus sees that the broadening of the $p_T$ distribution in nucleus+nucleus collisions and its species dependence do not necessarily require collective radial flow, as these effects are already present in more elementary interactions.

**$R_{pA}(p_T)$ Dependence on $x_F$**

For the first time the $x_F$ dependence of the nuclear modification factor - $R_{pA}(p_T)$, for p+A collisions, is studied. Transverse spectra of identified particles from central p+Pb collisions are compared to those from p+p collisions by studying the behaviour of the nuclear modification factor in different intervals of $x_F$. $R_{pA}(p_T)$ is calculated according to Eq. 6.2; for the p+Pb data sample $\langle N_{\text{binary}} \rangle = \bar{\nu} \approx 5.8$, and at the studied energy $\sigma_{\text{inel}}^{pp}=31.7$ mb. The results for pions, protons and antiprotons are displayed in Fig. 6.6; the errors shown are statistical only. There are also the point-to-point uncertainties involved in the measurements. The estimates of the systematic errors are below 5% for $\pi^\pm$, $p$ and below 15% for $\bar{p}$. At high $p_T$, however, they can be as large as 15% and 35% for

\textsuperscript{7}Such an interpretation of the Cronin effect is beyond the framework of existing theoretical/phenomenological models aiming at the description of the effect.
Figure 6.6: Nuclear modification factor $R_{pA}$, in different $x_F$ intervals, for a) $\pi^+$'s, b) $\pi^-$'s, c) $p$'s and d) $\bar{p}$'s produced in central p+Pb collisions at 158 GeV. Note: lines are drawn to guide the eye; errors are statistical only.

$\pi^\pm$, $p$ and $\bar{p}$ respectively. Additionally, there is an overall systematic scale error of about 6%, which is the quadrature sum of the uncertainty of the $\langle N_{\text{bin,ary}} \rangle$ determination ($\sim$4%) and the error on the trigger cross section determination for p+p collisions (4-5%). It may shift the curves up or down but does not affect their shapes.

Some observations from the presented results are given below.

- The spectra of $\pi^\pm$, $p$ and $\bar{p}$ are harder in p+Pb than those in p+p collisions.

- For all particle species, with increasing $x_F$ the reduction of $R_{pA}(p_T)$ at all $p_T$ ($<1.8 \text{ GeV/c}$) is visible.

- For the $(x_F, p_T)$ region analysed here $R_{pA}^{\pi^+} \approx R_{pA}^{\pi^-} \approx R_{pA}^{\bar{p}}$, the behaviour similar to the one of the Cronin-$\alpha$ exponents for midrapidity particle production in this $p_T$ range\footnote{It would be very interesting to perform the current analysis for larger $p_T$ (not possible with present statistics), where at midrapidity $\alpha_p > \alpha_m$ in order to check also the behaviour of large $p_T$ particles in the forward region.}.
6.3. Nuclear Modifications of $p_T$ Distributions at SPS Energies

- $R_{pA}^e(p_T) > R_{pA}^\pi(p_T)$ and $R_{pA}^\pi(p_T)$ for all $x_F$, except for $x_F=0.3-0.45$ where $R_{pA}^e(p_T) \leq R_{pA}^\pi(p_T)$.

At much higher energy at RHIC, first results for $d+Au$ data also seem to indicate the reduction of the nuclear modification factor, while going more forward in rapidity. Data published in [Adam03a, Ade03c, Arse03] show the Cronin enhancement extending up to $p_T \approx 6$ GeV/c around $y \approx 0$, whereas at slightly forward rapidity around $y \approx 1$ no significant enhancement is seen [Back03]. One can observe the species dependence of the nuclear modification factor in $d+Au$ collisions as well [Adam03b, Ade03c].

There are many theoretical calculations concerning the Cronin effect at RHIC and LHC (Large Hadron Collider at CERN) energies, see for example [Wang00, Acca01, Kope02, Alba03, Vite03] and references therein. For SPS energies, some results can be found in [Wang00]. With increasing energy a reduced Cronin enhancement, compared to the one at SPS, is predicted [Wang00, Kope02, Vite03]. None of these calculations, however, studies the dependence on particle species. A comparison of the experimental results on the nuclear modification factors for $x_F \approx 0$ at the SPS energy, shown in Fig. 6.6, with the ones for $d+Au$ collisions at RHIC [Adam03b], would point towards a rather weak energy dependence of the Cronin effect in the $p_T$ region studied.

The rapidity dependence of the nuclear modification factor has been already addressed in [Acca01, Alba03, Khar03, Vite03]. According to [Acca01], the projectile crosses a denser and denser target and undergoes an average number of rescatterings that increases with rapidity. As an effect of rescatterings, the spectrum is lowered at small $p_T$ and is enhanced at large transverse momenta, the deformation being more pronounced at increasing rapidity. On the contrary, the authors of [Alba03] predict a uniform suppression of the nuclear modification factor for all transverse momenta with increasing energy or rapidity. The effect is rooted in the suppression of the nuclear gluon distribution due to quantum evolution. Also [Khar03] predicts that at high energies/rapidities quantum evolution becomes important. The effect of the inclusion of quantum evolution in the gluon production cross section is to introduce extra gluon suppression at high $p_T$, while indicating the onset of the Cronin effect by contributing towards gluon enhancement at lower $p_T$. The results presented in this section show a decrease of the nuclear modification factor $R_{pA}(p_T)$ with increasing $x_F$, for all transverse momenta studied ($p_T<1.8$ GeV/c). A discrimination between competing theoretical descriptions is not, however, fully possible as the behaviour in the high $p_T$ region has not been measured.

As pointed out in [Khar03], at moderate energy (like the SPS one) saturation effects in the gluon production in $p+A$ collisions result in the Cronin enhancement for which the magnitude is an increasing function of centrality. At higher energies or rapidities, when quantum evolution becomes important, it introduces suppression of gluons produced in $p+A$ collisions, as compared to the number of gluons produced in $p+p$ collisions scaled by the number of collisions $N_{binary}$. The resulting $R_{pA}$ at high energy/rapidity should be a decreasing function of centrality. It would be very interesting to check these predictions by studying less central $p+Pb$ collisions, in different regions of $x_F$, as well.
6.4 Particle Ratios from p+p and p+A Collisions

By studying ratios of particle yields information concerning mechanisms of particle production can be gained. The $p_T$ and $x_F$ dependences of the ratios are indicators of the dynamics of high energy collisions. In p+p and p+A collisions, one does not expect any final state interactions to occur, therefore, the ratios obtained for these systems set a baseline from which one can further investigate nucleus+nucleus collisions. They also provide constraints on current and future phenomenological models dealing with particle production in nucleon and nuclear collisions.

6.4.1 Antiparticle-Particle Ratio

$p/p$ Ratios

**Experimental Results**

The ratios of $\bar{p}/p$ from p+p and central p+Pb collisions at 158 GeV/c beam momentum are studied as a function of transverse momentum in different intervals of $x_F$, as shown in Fig. 6.7. The systematic uncertainties on these ratios are estimated to be of the order of 10%, however, at high $p_T$ or large $x_F$ they can be as large as 27%. In case of p+p collisions, the ratios are free of the normalization error present for the cross sections.

Below a short summary concerning the presented results is given.

* For both systems studied, the $\bar{p}/p$ ratios are always smaller than one.

* For p+p interactions, with increasing $p_T$ or $x_F$ the ratios decrease.

* For p+Pb collisions, the $\bar{p}/p$ ratios also decrease with increasing $x_F$, but the drop with $p_T$ is only visible at low $x_F$, as for higher $x_F$ the errors are large.

* The p+p ratios are larger than the p+Pb ones at small $x_F$. With growing $x_F$, however, the difference between them vanishes gradually, and finally, for $x_F=0.2$-0.3, within the statistical and systematic errors, the ratios are the same.

![Figure 6.7: Transverse momentum dependence of $\bar{p}/p$ ratios, in different $x_F$ intervals, from minimum bias p+p (black filled symbols) and central (v ÷5.8) p+Pb collisions (red open symbols) at 158 GeV. Note: lines are drawn to guide the eye; errors are statistical only.](image-url)
The magnitude of antiproton-to-proton yields ratios results from various mechanisms of particle production, such as for example baryon-antibaryon pair production, baryon number transport (baryon stopping) in nuclear collisions. Depending on the phase space region, these mechanisms contribute to particle production differently.

By charge and other quantum numbers conservation, fragmentation functions of a gluon into particle and anti-particle are identical, therefore equal numbers of protons and antiprotons are produced in the gluon fragmentation. On the other hand, more quarks (u-up and d-down) than antiquarks are produced in nucleon or nuclear collisions. Therefore, due to baryon number conservation, the $\bar{p}/p$ ratios are always smaller than one. With increasing $p_T$ (or $x_F$), the ratios should decrease since valence quarks are distributed at relatively large $x$ (partons’ fractional momenta of the nucleon) while gluons at small $x$. Due to the larger number of baryons in initial state in p+Pb, compared to p+p collisions, the $\bar{p}/p$ ratio at low $x_F$ is smaller in p+Pb than in p+p. As $x_F$ increases, the contribution from the target dies out and the projectile contribution only matters; since both systems have a proton projectile the ratios become similar at large $x_F$.

The $\bar{p}/p$ ratios in nuclear collisions should also depend on the collision centrality; the effect is not studied in the present analysis. The more central a collision is, the more collisions ($\nu$) a participating nucleon suffers and the greater baryon number transport to midrapidity. This, in turn, should lead to the reduction of the midrapidity $\bar{p}/p$ ratio.

**Comparison with the Models**

In Fig. 6.8 the experimental results, indicated by the lines, are compared with the FRITIOF and VENUS model predictions. For both models, the modified versions are used; details concerning settings of the models’ parameters are given in Sec. 5.4.1. The comparison is done for two selected $x_F$ regions: (0.0-0.05) and (0.15-0.2). None of the models describes the measured $\bar{p}/p$ ratios well. FRITIOF 7.02 fails completely, not even reproducing the trends visible in the experimental data. The results from VENUS 4.12, however, coincide with the measured $\bar{p}/p$ ratios for large $p_T$ values.

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As shown in Fig. 5.11, the modified version of FRITIOF 7.02 gives a better description of $\langle p_T \rangle$: $x_F$ correlations than the standard one. The modified VENUS4.12 model, however, does not describe the proton correlations well. They are better described by the standard version. Therefore, ratios of different particle species have been checked also for the standard VENUS settings. The particle ratios in p+p collisions from both versions of VENUS4.12 were much the same, and that is why results for the modified version only are shown.
\( \pi^- / \pi^+ \) Ratios

Experimental Results

The ratios of \( \pi^- \) to \( \pi^+ \) yields versus \( p_T \), in different regions of \( x_F \), for \( p+p \) and central \( p+\text{Pb} \) collisions are displayed in Fig. 6.9. The systematic errors on the ratios are estimated to be typically below 5\%. However, for large \( p_T \) or \( x_F \) they might be larger, but should be smaller than 15\%. In order to show the behaviour at high \( p_T \), data taken from [Antr79] and concerning the midrapidity \( \pi^- / \pi^+ \) ratios from \( p+p \) and minimum bias

![Graph showing \( \pi^- / \pi^+ \) ratios vs. \( p_T \) for different \( x_F \) intervals.](image)

**Figure 6.9:** Transverse momentum dependence of \( \pi^- / \pi^+ \) ratios, in different \( x_F \) intervals, for minimum bias \( p+p \) (black filled symbols) and central (\( \bar{b} = 5.8 \)) \( p+\text{Pb} \) collisions (red open symbols) at 158 GeV. The midrapidity ratios for \( p+p \) and minimum bias \( p+W \) collisions at 200 GeV (blue filled and open squares, respectively) taken from [Antr79] are also plotted. Note: lines are drawn to guide the eye; errors are statistical only.
p+W collisions\textsuperscript{10} at 200 GeV ($\sqrt{s} \approx 19.4$ GeV) are presented on the upper panel of Fig. 6.9.

The results shown in Fig. 6.9 are summarized underneath.

\begin{itemize}
  \item For p+p interactions, the $\pi^-/\pi^+$ ratios are smaller than one everywhere.
  \item There is an increase of $\pi^-/\pi^+$ for p+Pb collisions compared to the p+p ratios. With growing $p_T$ and $x_F$, the ratios from both systems approach each other.
  \item The $\pi^-/\pi^+$ ratios go down as $p_T$ and $x_F$ increase.
\end{itemize}

Because in p+p collisions there are more $u$-quarks than $d$-quarks, one should expect the $\pi^-/\pi^+$ ratio to be smaller than one. Since in Pb-nuclei there are more neutrons than protons, thus there are more valence $d$-quarks than $u$-quarks in initial state and the resulting $\pi^-/\pi^+$ ratio from p+Pb collisions increases compared to the p+p case. As shown on the upper panel of Fig. 6.9, for p+p interactions, the ratio of $\pi^-$ and $\pi^+$ yields decreases rapidly with $p_T$ (for $p_T \gtrsim 3$ GeV/c). A similar behaviour is visible for increasing $x_F$. It originates from the fact that with higher $p_T$ or $x_F$ the contribution from gluons to the cross section disappears and scattered quarks dominate. Since a pion with high transverse momentum, or large $x_F$, is a leading fragment of the fragmenting parton it carries in the mean its quantum numbers. The decrease of the $\pi^-/\pi^+$ ratios reflects the fact that there are more fast valence $u$-quarks in a proton than there are fast valence $d$-quarks.

\textbf{Comparison with the Models}

The experimental data on $\pi^-/\pi^+$ ratios are confronted with predictions of the models in Fig. 6.10. The comparison has been done for the following $x_F$ intervals: (0.0-0.05), (0.15-0.2) and (0.3-0.45). FRITIOF 7.02 and VENUS 4.12 provide a very similar description of the data. In general, they reproduce trends visible for the experimental ratios. For the last two $x_F$ bins, they give however slightly larger values of the $\pi^-/\pi^+$ ratios than the experimentally measured ones.

\textsuperscript{10}A projectile in minimum bias p+W interactions undergoes, on average, about 3.5 collisions.
6.4.2 Baryon- Meson Ratio

$\bar{p}/\pi^-$ Ratios

**Experimental Results**

Fig. 6.11 presents the $\bar{p}/\pi^-$ ratios as a function of $p_T$, in different regions of $x_F$, for 158 GeV protons incident on the H$_2$ and Pb targets. The systematic errors on the ratios are usually smaller than 10%. For larger $p_T$ or $x_F$ they might be higher, but should be below 27%. On the upper panel of Fig. 6.11, the ratios from p+p and minimum bias p+W collisions at 200 GeV ($\sqrt{s} \approx$ 19.4 GeV) are shown as well, in order to visualize the behaviour at high transverse momenta.

Below main observations concerning the $\bar{p}/\pi^-$ ratios are specified.

* First of all, for the $p_T$ range covered in this analysis ($p_T<1.8$ GeV/c), the $\bar{p}/\pi^-$ ratios change with $p_T$ differently than the antiparticle-particle ratios, for which a weaker $p_T$ dependence was observed.
* In the ($x_F$, $p_T$) range studied, within the experimental errors, the ratios are the same

![Graph](image-url)

**Figure 6.11**: Transverse momentum dependence of $\bar{p}/\pi^-$ ratios, in different $x_F$ intervals, for minimum bias p+p (black filled symbols) and central (Â $\bar{p} = 5.8$) p+Pb collisions (red open symbols) at 158 GeV. The midrapidity ratios for p+p and minimum bias p+W collisions at 200 GeV (blue filled and open squares, respectively) taken from [Antr79] are also shown. Note: lines are drawn to guide the eye; errors are statistical only.
for both p+p and central p+Pb collisions.

* For all $x_F$, the $\bar{p}/\pi^-$ ratios rise at low $p_T$ up to a $p_T$ value of about 1.5 GeV/c and then, for high $p_T$, fall off as shown on the top panel for midrapidity ratios.

* With increasing $x_F$, the production of $\bar{p}$ relative to $\pi^-$ becomes more intense at small $p_T$ while it is reduced for larger transverse momenta.

From Fig. 6.6 it follows that, the $p_T$ spectra of $\bar{p}$ and $\pi^-$ are harder in p+Pb than in p+p collisions. However, as discussed in Sec. 6.3.1, in the studied $(x_F, p_T)$ region nuclear modifications of the transverse momentum distributions in p+A collisions are very similar for $\bar{p}$ and $\pi^-$. This implies a lack of any effect on the ratios in central p+Pb collisions, as compared to p+p interactions.

The rise of $\bar{p}/\pi^-$ with increasing $p_T$ is in accordance with observations concerning the width of $p_T$ distributions, mentioned in Chapter 5 for the transverse momentum spectra analysis. Namely, in the elementary and nuclear collisions, the antiproton $p_T$ distributions are broader than the pion ones, resulting in higher mean transverse momenta of $\bar{p}$ compared to $\pi^-$ and also in the $\bar{p}/\pi^-$ ratio increase noted here. The drop visible for still higher $p_T$ is connected with the quark structure of the particles.

Results from Fig. 6.5 indicate that at higher $p_T (>2$ GeV/c) there should be a difference between nuclear modifications of the midrapidity $\bar{p}$ and $\pi^-$ spectra visible. This, in turn, should lead to the difference between the $\bar{p}/\pi^-$ ratios from p+p and p+A collisions. Some increase of the ratio in minimum bias p+W collisions, with regard to the p+p ratio, is observed but it is rather weak (see Fig. 6.11). Results on the Cronin-$\alpha$ exponents have been obtained for the proton beam energy of 400 GeV, and the results presented in Fig. 6.11 come from interactions at 200 GeV. Indeed, as published in [Antr79], at higher energy the difference between $\bar{p}/\pi^-$ ratios from p+p and p+A becomes more pronounced.

Additionally, in [Antr79] they have also studied the A-dependence of the ratio and found that at high $p_T$ the $\bar{p}/\pi^-$ ratio depends on the size of target nuclei (thus on $\nu$). Transverse momenta covered in the present analysis are, however, too low to observe this dependence; the midrapidity $\bar{p}/\pi^-$ ratios for central p+Pb collisions (having $\bar{p} \approx 5.8$) and minimum bias p+W (with the number of projectile collisions close to 3.5) at $p_T \approx 1.5$ GeV/c are equal within the experimental errors.

**Comparison with the Models**

Fig. 6.12 compares the $p_T$ dependence of the antiproton-to-pion yields ratios measured experimentally with the ones found using FRITIOF 7.02 and VENUS 4.12 models. Two $x_F$ regions: (0.0-0.05) and (0.15-0.2),

![Figure 6.12: Comparison of the experimental results with FRITIOF 7.02 and VENUS 4.12 predictions on the $p_T$ dependence of $\bar{p}/\pi^-$ ratios, in two selected $x_F$ regions, for p+p collisions.](image-url)
are used in this comparison. FRITIOF and VENUS predict the increase of the $\bar{p}/\pi^-$ ratio with $p_T$ - the trend visible also for the experimental data. The relative production of antiprotons with respect to $\pi^-$’s is, however, overestimated by both models.

$p/\pi^+$ Ratios

Experimental Results

The ratios of $p/\pi^+$ from p+p and central p+Pb collisions at 158GeV, for different regions of $x_F$, are plotted against the transverse momentum in Fig. 6.13. The systematic

Figure 6.13: Transverse momentum dependence of $p/\pi^+$ ratios, in different $x_F$ intervals, for minimum bias p+p (black filled symbols) and central ($\bar{p} = 5.8$) p+Pb collisions (red open symbols) at 158 GeV. The midrapidity ratios for p+p and minimum bias p+W collisions at 200 GeV (blue filled and open squares, respectively) taken from [Antr79] are also shown. Note: lines are drawn to guide the eye; errors are statistical only.
6.4. Particle Ratios from $p+p$ and $p+A$ Collisions

Uncertainties on the ratios are estimated to be typically below 5%, however, at large $p_T$ they can be even 15%. For midrapidity ratios, displayed on the top panel, results from $p+p$ and minimum bias $p+W$ collisions at 200 GeV [Antr79] are also presented, showing the behaviour in the $p_T$ region extending above that covered in the present analysis.

Some observations on the $p/\pi^+$ ratios are as follows.

- The ratios are an order of magnitude higher than the $\bar{p}/\pi^-$ ratios discussed above and, at all $p_T$ studied, they increase with growing $x_F$.
- In the $0.0<x_F<0.3$ region, for both $p+p$ and $p+Pb$ collisions, the $p/\pi^+$ ratios show a rise with increasing $p_T$ up to transverse momenta of about 1.5 GeV/c. For midrapidity ratios, results from [Antr79] indicate a further rise and afterwards a drop, which is however much slower than the one found for the $\bar{p}/\pi^-$ ratios.
- For $x_F=(0.3-0.45)$, the $p_T$ dependence of $p/\pi^+$ becomes weaker and the ratios for the two systems are getting more similar to each other.

Large values of the $p/\pi^+$ ratios, compared to the $\bar{p}/\pi^-$ ones, are due to baryon number conservation. As $x_F$ increases, for both $p+p$ and $p+Pb$ collisions, one observes the rise of $p/\pi^+$ at all $p_T$ studied. This increase comes from the fact that with increasing $x_F$ the contribution from the proton projectile dominates, resulting in a more copious production of $p$ relative to $\pi^+$.

In the study of nuclear modification factors different values of $R_{pA}^p$ and $R_{pA}^{\pi^+}$ have been found (see Fig. 6.6). For the $0.0<x_F<0.3$ region $R_{pA}^p>R_{pA}^{\pi^+}$, which leads to the higher $p/\pi^+$ ratios in central $p+Pb$ than in $p+p$ collisions, as presented in Fig. 6.13. The proton nuclear modification factor for $x_F=(0.3-0.45)$ is, however, smaller or equal to the $R_{pA}^{\pi^+}$. This should result in the ratios from the nuclear collisions which are smaller or equal to the ones from $p+p$ interactions. Both systems have a proton projectile, therefore with increasing $x_F$ one obtains more and more similar values of $p/\pi^+$.

For midrapidity particles, the $p/\pi^+$ ratios at high transverse momenta decrease much slower than the $\bar{p}/\pi^-$ ratios, see top panels of Figs. 6.13 and 6.11. The $p$ to $\pi^+$ yields ratios in $p+W$ collisions are, at high $p_T$, considerably larger than the $p+p$ ratios. In addition, as found in [Antr79], for the nuclear collisions the $p/\pi^+$ ratios show an opposite energy dependence than the $\bar{p}/\pi^-$ ratios. With increasing beam energy from 200 GeV to 400 GeV, the $p/\pi^+$ ratio from minimum bias $p+W$ collisions drops. Differences in the behaviour of $p/\pi^+$ and $\bar{p}/\pi^-$ ratios are due to the fact that reactions with a proton projectile are analysed.

In [Antr79] results on the $A$-dependence of $p/\pi^+$ can be found as well. They indicate a strong dependence on the nuclear number of the target nucleus. This is in accordance with the results obtained in the present analysis. At $x_F \approx 0$, central $p+Pb$ collisions with $\bar{p} \approx 5.8$ provide the larger ratios than minimum bias $p+W$ collisions with a projectile suffering about 3.5 collisions, as shown on the upper panel of Fig. 6.13.
Comparison with the Models

A comparison done for three selected regions of \( x_F: \) (0.0-0.05), (0.15-0.2) and (0.3-0.45), shows that the predictions of FRITIOF 7.02 agree with the experimental \( p/\pi^+ \) ratios fairly well, see Fig. 6.14. This statement is especially justified if one refers to the predictions of VENUS 4.12, which fails completely in describing the measured ratios.

![Figure 6.14: Comparison of the experimental results with FRITIOF 7.02 and VENUS 4.12 predictions on the \( p_T \) dependence of \( p/\pi^+ \) ratios, in selected \( x_F \) regions, for p+p collisions.](image)

6.5 Summary

This chapter contains results concerning particle composition. In particular, outcomes of the analysis of p+p and central (\( \bar{p} \approx 5.8 \)) p+Pb collisions at center of mass energy \( \sqrt{s} \approx 17.3 \) GeV were presented and discussed. A summary of the results shown here is given underneath.

- The analysed p+p and p+Pb collisions set a baseline from which Pb+Pb collisions at the SPS energy can be further investigated in a search for the effects of final state interactions. The present study concerned the nuclear modification factors and particle ratios.

- The particle species dependence of \( R_{pA} \) has been observed, and a comparison of the midrapidity nuclear modification factors at SPS with the ones at RHIC (\( R_{dA} \)) points towards a rather weak energy dependence (for \( p_T < 1.8 \) GeV/c).

- For the first time, the study of nuclear modification factors in p+\( A \) collisions has been carried out in a phase space region covering not only midrapidity but extending also into the forward (projectile) hemisphere. With increasing \( x_F \), the reduction of \( R_{pA} \) (for \( \pi^\pm \), p and \( \bar{p} \)) is visible at all transverse momenta studied.
The results on the Cronin-α exponents together with the ones on the nuclear modifications factors in proton+nucleus and nucleus+nucleus collisions indicated the particle species dependence. Based on these observations, the hypothetical picture of nuclear collisions has been formulated. In this picture, three contributions were separated: the first contribution depends on $N_w$, the second is connected with the quark structure of the colliding particles and depends on $\nu$, and the last one comes from true hard interactions. For SPS energies, the last contribution is negligible and the transverse characteristics of hadrons at these energies can be described by taking into account only the $N_w$- and $\nu$-dependent contributions, in agreement with the observations found in Chapter 5.

Particle ratios ($\bar{p}/p$, $\pi^-/\pi^+$, $\bar{p}/\pi^-$ and $p/\pi^+$) in p+p and central p+Pb collisions have been studied in a wide region of the projectile hemisphere, allowing to test the predictions of different models, such as for example FRITIOF 7.02 and VENUS 4.12. A comparison of the experimental ratios with the ones from the models has shown a good agreement for pions and disagreement for the ratios including yields of the baryons. Changes of the ratios in the nuclear collisions, with regard to the p+p ones, are connected with the particle type dependent behaviour of $R_{pA}$.

To be able to better discriminate between competing theoretical descriptions of nucleon and nuclear collisions a further analysis, extending the present one to higher $p_T$ and different centralities of p+Pb collisions, would be very desirable. Moreover, still left to do is a detailed, precise study of different centrality nucleus+nucleus collisions at SPS energies, covering large regions of $p_T$ and $x_F$, and concerning various particle species in final state.
Chapter 7

Summary and Outlook

In this thesis the results on transverse characteristics of charged hadrons produced in elementary hadronic and nuclear collisions at SPS energies have been presented and discussed. These characteristics yield information on the reaction dynamics. The study has been focused on transverse momentum spectra and particle composition.

The analysed data have been collected by the NA49 experiment, using a large acceptance magnetic spectrometer providing particle tracking and momentum determination as well as particle identification. The outcomes of the analysis carried out within the framework of the thesis constitute a unique, comprehensive experimental basis on transverse phenomena at CERN-SPS energies. The study has been done in the forward (projectile) hemisphere and concerned final state protons, antiprotons, positive and negative pions produced in collisions of various systems - ranging from the most elementary p+p, π⁺+p and π⁻+p interactions, via different centrality p+Pb collisions, up to semi-central C+C and Si+Si collisions; results from the analysis of Pb+Pb reactions have been also included. Since all these collision types have been studied using the same experimental apparatus, in the comparative studies, the possible experimental uncertainties are largely eliminated.

First, the transverse momentum spectra, and in particular the correlations between transverse and longitudinal momenta, were considered. In the study, the behaviour of the first moment of the $p_T$ distribution in different $x_F$ regions ($\langle p_T \rangle - x_F$ correlation) has been investigated. The dependence of the correlation on the particle species, collision energy, type and size of the colliding system has been studied. The results were presented and discussed in Chapter 5.

Next, in Chapter 6, the particle composition in terms of the nuclear modification factors and particle ratios has been studied for $p+p$ and central $p+$Pb interactions. This analysis has been to a large extent motivated by the results on “jet quenching” from the experiments at much higher energies at RHIC. For the first time, the $x_F$ dependence of the nuclear modification factors has been investigated - with increasing $x_F$, the reduction of $R_{p,A}$ has been observed for all particle species considered in the study. The results from $p+p$ and $p+$Pb collisions, together with the results from different centrality Pb+Pb reactions at SPS energies (possibly available in the near future) and the ones from $p+p$, d+Au and Au+Au collisions at RHIC energies should help in understanding of the energy dependence of the observed phenomena.
The transverse momentum distributions, $\langle p_T \rangle - x_F$ correlations and the nuclear modification factors have been found to depend on particle species. The transverse characteristics show also the dependence on size/complexity and structure of the colliding objects as well as on energy of the collision.

The experimentally measured characteristics can be used for testing the validity of various theoretical models in describing the studied reactions. In the present work, the predictions from two string models: FRITIOF 7.02 and VENUS 4.12, have been compared to the experimental data. In general, when the standard settings have been used the experimentally measured dependences were not reproduced well by the models. With some tuning of the models' parameters, a better description of the data could have been achieved, but usually for a given considered particle type only. Nevertheless, these models have been very helpful in studying the role of different mechanisms - by investigating the influence of a given parameter connected with the considered mechanism - and their importance in different phase space regions.

Assessing the relative strength of different effects in hadron production, and thus also processes responsible for transverse momentum generation, requires more detailed theoretical understanding. This understanding will benefit from the data presented in this thesis, together with the already available and future measurements at RHIC energies and, in the mid-term, the results from the collisions at still higher energies at LHC.
Acknowledgments

I am very grateful to Prof. Helena Białkowska for supervising this work. I am indebted to her for her patience, encouragement and support.

I would like to thank Prof. Ewa Skrzypczak for her interest in my work and friendly attitude.

The work documented in this dissertation has been done within the framework of the NA49 experiment, therefore I would like to thank all the members of the Collaboration for their contribution. In particular, I wish to express my gratitude to Dr. Hans Gerhard Fischer for his help in solving many of the problems concerning the presented analysis, for discussions, and for making possible some of my stays at CERN. I am very appreciative of the work done by Gábor Veres and Dezső Varga in calibrating the data and producing the $\mu$DSTs used in the study. I am also very grateful to Dezső for his comments and improvements to the manuscript. I wish to thank Ferenc Siklér for his work on the acceptance. Tatjana Šuša, Ondřej Chvála as well as Claudia Höhne and Kreso Kadija provided an indispensable contribution to the present thesis concerning the interaction vertex corrections and event centrality determination. I am also very thankful to Andrzej Rybicki for his help at the beginning of my Ph.D. studies.

I would like to thank warmly my colleagues with whom I have shared an office: Gosia Gladysz, Kasia and Jarek Grebieszkow, Waldek Retyk, Olga Stawarz and Victor Trubnikov, for a friendly atmosphere.

Finally, my warmest thanks go to my family and friends for their patience, support and friendship.
Appendix A

Abbreviations

BB       Bethe-Bloch function
BNL      Brookhaven National Laboratory, USA
BPD      Beam Position Detector
BR       Branching Ratio
BRAHMS   Broad RAnge Hadron Magnetic Spectrometer at RHIC
CD       Centrality Detector
CERES/NA45 Cherenkov Ring Electron Spectrometer at SPS
CERN     European Organization for Nuclear Research, Geneva, Switzerland
CM       Center of Mass frame
DAQ      Data AcQuisition
DST      Data Storage Tape
FRITIOF  Monte Carlo event generator for elementary hadronic and nuclear collisions
LAB      LAboratory frame
LHC      Large Hadron Collider at CERN
LINAC    LINear ACcelerator
MIP      Minimum Ionizing Particle
MTPC     Main TPC
NA35     North Area 35; Heavy Ion Experiment at SPS - precursor of NA49
NA49     North Area 49; Large Acceptance Hadron Spectrometer at the CERN SPS
PHENIX   Heavy Ion Experiment at RHIC
PHOBOS   Heavy Ion Experiment at RHIC
PID      Particle IDentification
PS       Proton Synchrotron
PSB      Proton Synchrotron Booster
QCD      Quantum Chromo-Dynamics
QED      Quantum Electro-Dynamics
QGP      Quark-Gluon Plasma
RCAL     Ring CALorimeter
RHIC     Relativistic Heavy Ion Collider at BNL
SPS      Super Proton Synchrotron
STAR     Solenoidal Tracker At RHIC

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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>TOF</td>
<td>Time-Of-Flight</td>
</tr>
<tr>
<td>TPC</td>
<td>Time Projection Chamber</td>
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<tr>
<td>TTR</td>
<td>Two Track Resolution</td>
</tr>
<tr>
<td>VCAL</td>
<td>Veto CALorimeter</td>
</tr>
<tr>
<td>VENUS</td>
<td>Very Energetic NUclear Scattering model</td>
</tr>
<tr>
<td>VPC</td>
<td>Veto Proportional Chamber</td>
</tr>
<tr>
<td>VTPC</td>
<td>Vertex TPC</td>
</tr>
<tr>
<td>WA80</td>
<td>West Area 80; Heavy Ion Experiment at SPS</td>
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<tr>
<td>WA98</td>
<td>West Area 98; Large Acceptance Photon and Hadron Spectrometer at SPS</td>
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Appendix B

Selection of p+p Interactions from d+p Collisions at 40 A·GeV

By observing a spectator nucleon - non-interacting nucleon from the deuteron - neutron+proton, proton+proton and real deuteron+proton interactions can be set apart. The p+p interactions at 40 GeV, analysed in Chapter 5, were chosen from d+p collisions by selecting events with neutron spectators.

Neutrons are detected using the information from the RCAL calorimeter and the VPC chamber. A particle is identified as a neutron if it is neutral (no signal from the VPC) and it is of a hadronic type, i.e. a photonic energy fraction of the total energy deposited in the RCAL is smaller than 73%. On such identified neutrons, different neutron spectator cuts were examined in order to find the optimal selection criteria, guaranteeing reasonable statistics and a “purity” of the sample of p+p interactions. Preliminary results on the neutron spectator selection are reported in [Vere00, Boim01].

Fig. B.1 explains the way of selecting neutron spectators; constraints are applied on the neutron momentum components resulting from the fact that values of the total momenta of the spectators are concentrated around the beam momentum and their transverse momenta are small. A $p_T-p_{\text{LAB}}$ scatter plot for all neutrons - neutral hadronic particles - is shown in Fig. B.1a. Three different neutron spectator selections are displayed in Fig. B.1b, c and d. These panels are showing the longitudinal momentum ($p_z^{\text{LAB}}$) distribution of all neutrons from the upper panel - dots - and $p_z^{\text{LAB}}$ distributions of rejected neutrons - hatched areas. Regions limited by the hatched areas and dots correspond to the selected neutron spectators. For further physics analysis the second selection criterion (as written in Fig. B.1c) was used. Such selected spectator neutrons are confined to the region marked by the red contour on the upper panel of Fig. B.1. This selection assures a good separation of neutron spectators and quite large statistics. The influence of the neutron spectator selection on the result of a given studied physics item can be check by applying different neutron spectator cuts, and thus an estimate of the systematic error connected with the selection of p+p interactions can be obtained.
Figure B.1: Selection of neutron spectators in d+p collisions at 40 A·GeV/c beam momentum: a) $p_T - p_{LAB}$ scatter plot for neutrons, b), c) and d) $p_{LAB}$ distributions of neutrons for different neutron spectator selections; dots - all neutrons form the upper panel, hatched areas - neutrons rejected by the neutron spectator cuts.
Appendix C

Invariant Inclusive $p_T$ Distributions at 158 GeV

This appendix records the $\vec{p}$, $p$, $\pi^-$ and $\pi^+$ transverse spectra obtained for $p+p$ and central ($\vec{p} \approx 5.8$) $p+Pb$ collisions at 158 GeV beam energy ($\sqrt{s} \approx 17.3$ GeV). The invariant $p_T$ distributions are presented in the form of a graphical display\(^1\), and also the $E \frac{dN}{d\phi}$ (for p+p) and $E \frac{dN}{d\phi}$ (for p+Pb) are tabulated in Tables C.1-C.8. On each data page the results for one particle species are shown.

There is a rather rich literature containing results for $p+p$ interactions at different collision energies, see for example [Albr73, Albr74, Capi74, Alpe75, Ross75, Guet76, Guet76a, Antr79, Drij82]. These data, however, were collected at different energies than the studied one. In addition, particle yields reported there were usually measured in a limited phase space region; thus the present analysis is quite exceptional in this regard as it covers the region: $0.0 < x_F < 0.45$ and $p_T < 1.8$ GeV/c. Interactions of hadrons with nuclear targets were not so often studied (see e.g. [Antr79], and for a review [Fred87]), and in particular there are no results of similar analyses for central $p+Pb$ at 158 GeV.

The particle yields presented here are not feed-down corrected. The quoted errors, in the figures and tables, include statistical errors only. As for the systematic errors, they come mainly from uncertainties resulting from the $\frac{dE}{dx}$ fit method (a procedure used to extract the yields) and a precision of the determination of the corrections applied in the analysis. Since the fitting procedure was not fully automatized, the extraction of yields was a rather lengthy process, therefore the estimation of the systematic errors was performed only in some $[p_T, x_F]$ bins for $p+p$ collisions. The systematic errors were found to be typically smaller than 3% for $\pi^+$ and $p$, and 10% for $\vec{p}$. For low statistics bins (e.g. at high $p_T$), however, they can be as large as 10% for $\pi^+$ and $p$, and 25% for $\vec{p}$. Additionally, the finite precision of the trigger cross section measurement results in a normalization uncertainty, estimated to be 4-5%. The yields for $p+p$ collisions were checked against the results of other analyses using the NA49 data [Chva00, Fisc02]. The average level of agreement is approximately 7% for $\pi^+$ and $p$, and 12% for $\vec{p}$. For central $p+Pb$ data, the systematic errors should be close to the ones found for $p+p$, apart from the normalization error (the problem of event losses does not apply to centrality-selected $p+Pb$ events).

\(^1\)Note: In order to guide the eye, lines connecting the measured points were drawn. Since for $x_F=(0.15-0.2)$ and (0.1-0.3) the calculated mean $x_F$ values were similar the same curve was used for both bins.
C.1 p+p Collisions

![Graph showing antiproton invariant inclusive cross sections for inelastic p+p collisions.](image)

**Figure C.1:** Antiproton invariant inclusive cross sections for inelastic p+p collisions.

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>antiproton $E d^3\sigma/dp^3 ; [\mu b/(GeV^2/c^3)]$</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>$p_T$ [GeV/c]</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
</tr>
<tr>
<td>0.0-0.05</td>
<td></td>
</tr>
<tr>
<td>$\pm 23$</td>
<td>543</td>
</tr>
<tr>
<td>$\pm 23$</td>
<td></td>
</tr>
<tr>
<td>0.0-0.1</td>
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<td>$\pm 21$</td>
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<td>0.05-0.1</td>
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<td>$\pm 20$</td>
<td>279</td>
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<td>0.1-0.15</td>
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</tr>
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<td>$\pm 13$</td>
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**Table C.1:** Antiproton invariant inclusive cross sections for inelastic p+p collisions.
Figure C.2: Proton invariant inclusive cross sections for inelastic p+p collisions.

<table>
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<tr>
<th>$x_F$</th>
<th>$p_T$ [GeV/c]</th>
<th>proton $E d^3\sigma/d^3$ [mb/(GeV$^2$/c$^3$)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.125</td>
<td>0.300</td>
</tr>
<tr>
<td>0.0-0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.088</td>
<td>1.656</td>
</tr>
<tr>
<td></td>
<td>±0.044</td>
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</tr>
<tr>
<td>0.0-0.1</td>
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<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td>0.05-0.1</td>
<td>2.218</td>
<td>1.798</td>
</tr>
<tr>
<td></td>
<td>±0.050</td>
<td>±0.030</td>
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<tr>
<td>0.1-0.15</td>
<td>2.869</td>
<td>2.193</td>
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<tr>
<td></td>
<td>±0.063</td>
<td>±0.056</td>
</tr>
<tr>
<td>0.15-0.2</td>
<td>3.702</td>
<td>2.730</td>
</tr>
<tr>
<td></td>
<td>±0.080</td>
<td>±0.045</td>
</tr>
<tr>
<td>0.1-0.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2-0.3</td>
<td>4.912</td>
<td>3.829</td>
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<tr>
<td></td>
<td>±0.075</td>
<td>±0.043</td>
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<tr>
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<td>6.507</td>
<td>4.961</td>
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<tr>
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<td>±0.084</td>
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Table C.2: Proton invariant inclusive cross sections for inelastic p+p collisions.
Figure C.3: $\pi^-$ invariant inclusive cross sections for inelastic p+p collisions.

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</thead>
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<td></td>
<td>0.125</td>
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<tr>
<td>0.0-0.05</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>±0.11</td>
</tr>
<tr>
<td>0.0-0.1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>±0.12</td>
</tr>
<tr>
<td>0.05-0.1</td>
<td>22.27</td>
</tr>
<tr>
<td></td>
<td>±0.12</td>
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<tr>
<td>0.1-0.15</td>
<td>12.64</td>
</tr>
<tr>
<td></td>
<td>±0.11</td>
</tr>
<tr>
<td>0.15-0.2</td>
<td>8.27</td>
</tr>
<tr>
<td></td>
<td>±0.11</td>
</tr>
<tr>
<td>0.1-0.3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>±0.11</td>
</tr>
<tr>
<td>0.2-0.3</td>
<td>4.52</td>
</tr>
<tr>
<td></td>
<td>±0.07</td>
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<tr>
<td>0.3-0.45</td>
<td>1.90</td>
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<tr>
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<td>±0.04</td>
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</tbody>
</table>

Table C.3: $\pi^-$ invariant inclusive cross sections for inelastic p+p collisions.
### C.1. $p+p$ Collisions

**Figure C.4:** $\pi^+$ invariant inclusive cross sections for inelastic $p+p$ collisions.

<table>
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<th>$x_F$</th>
<th>$p_T$ [GeV/c]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-0.05</td>
<td>0.125, 0.300, 0.490, 0.690, 0.890, 1.085, 1.255, 1.350, 1.425, 1.790</td>
</tr>
<tr>
<td>-</td>
<td>26.45, 7.89, 2.34, 0.739, 0.242, - 0.035</td>
</tr>
<tr>
<td>±0.12</td>
<td>±0.06, ±0.01, ±0.007, ±0.004</td>
</tr>
<tr>
<td>0.0-0.1</td>
<td>29.20, 18.16, 6.52, 2.09, 0.691, 0.229, - 0.030</td>
</tr>
<tr>
<td>±0.13</td>
<td>±0.07, ±0.04, ±0.01, ±0.007, ±0.004</td>
</tr>
<tr>
<td>0.05-0.1</td>
<td>19.10, 12.65, 5.25, 1.76, 0.594, 0.200, - 0.029</td>
</tr>
<tr>
<td>±0.14</td>
<td>±0.08, ±0.04, ±0.02, ±0.009, ±0.005</td>
</tr>
<tr>
<td>0.1-0.15</td>
<td>14.69, 9.39, 4.44, 1.45, 0.474, - -</td>
</tr>
<tr>
<td>±0.15</td>
<td>±0.08, ±0.04, ±0.02, ±0.009</td>
</tr>
<tr>
<td>0.15-0.2</td>
<td>- - - - - -</td>
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<tr>
<td>0.1-0.3</td>
<td>0.158, - 0.039, - 0.0044</td>
</tr>
<tr>
<td>±0.16</td>
<td>±0.02, ±0.001, ±0.002</td>
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<tr>
<td>0.2-0.3</td>
<td>10.64, 6.10, 2.96, 1.18, 0.369, - 0.040</td>
</tr>
<tr>
<td>±0.11</td>
<td>±0.05, ±0.03, ±0.01, ±0.007</td>
</tr>
<tr>
<td>0.3-0.45</td>
<td>4.24, 2.52, 1.29, 0.64, 0.240, 0.076, 0.0245, 0.0186, - 0.0019</td>
</tr>
<tr>
<td>±0.07</td>
<td>±0.03, ±0.02, ±0.01, ±0.005, ±0.002, ±0.0005, ±0.0007</td>
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</tbody>
</table>

**Table C.4:** $\pi^+$ invariant inclusive cross sections for inelastic $p+p$ collisions.
C.2 Central p+Pb Collisions

![Graph showing antiproton invariant inclusive $p_T$ distributions for central p+Pb collisions.]

Figure C.5: Antiproton invariant inclusive $p_T$ distributions for central p+Pb collisions.

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$p_T$ [GeV/c]</th>
<th>$E d^3N/dp^3 \times 10^3$ [c^3/GeV^2]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.125</td>
<td>0.300</td>
</tr>
<tr>
<td>0.0-0.05</td>
<td>27.6</td>
<td>23.1</td>
</tr>
<tr>
<td></td>
<td>±2.8</td>
<td>±1.7</td>
</tr>
<tr>
<td>0.0-0.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>±2.6</td>
<td>±1.5</td>
</tr>
<tr>
<td>0.05-0.15</td>
<td>10.8</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>±2.0</td>
<td>±1.2</td>
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<tr>
<td>0.15-0.2</td>
<td>5.50</td>
<td>3.80</td>
</tr>
<tr>
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<td>±1.52</td>
<td>±0.89</td>
</tr>
<tr>
<td>0.1-0.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>±2.0</td>
<td>±0.89</td>
</tr>
<tr>
<td>0.2-0.3</td>
<td>1.63</td>
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</tr>
<tr>
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<td>±0.29</td>
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</table>

Table C.5: Antiproton invariant inclusive yields ($\times 10^3$) for central p+Pb collisions.
Figure C.6: Proton invariant inclusive $p_T$ distributions for central p+Pb collisions.

<table>
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<th>$0.690$</th>
<th>$0.890$</th>
<th>$1.085$</th>
<th>$1.255$</th>
<th>$1.350$</th>
<th>$1.425$</th>
<th>$1.790$</th>
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<tbody>
<tr>
<td></td>
<td>$E d^3N/dp^3 \times 10^3$ [c$^3$/GeV$^2$]</td>
<td>$p_T$ [GeV/c]</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0-0.05</td>
<td>203</td>
<td>174</td>
<td>117</td>
<td>67.5</td>
<td>35.6</td>
<td>18.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.77</td>
</tr>
<tr>
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<td>±8</td>
<td>±5</td>
<td>±3</td>
<td>±1.4</td>
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<td>-</td>
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<td>±0.18</td>
<td>±0.18</td>
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<td>±0.18</td>
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<td>±8</td>
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<td>±1.6</td>
<td>±0.7</td>
<td>±0.5</td>
<td>±0.5</td>
<td>±0.10</td>
<td>±0.10</td>
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<td>±0.10</td>
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Table C.6: Proton invariant inclusive yields ($\times 10^3$) for central p+Pb collisions.
Figure C.7: $\pi^-$ invariant inclusive $p_T$ distributions for central p+Pb collisions.

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<th>$p_T$ [GeV/c]</th>
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<td>±3.0</td>
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<tr>
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<td>±1.3</td>
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</tbody>
</table>

Table C.7: $\pi^-$ invariant inclusive yields ($\times10^3$) for central p+Pb collisions.
**Figure C.8:** $\pi^+$ invariant inclusive $p_T$ distributions for central p+Pb collisions.

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$p_T$ [GeV/c]</th>
<th>$E d^3N dp^3 \times 10^3$ [c$^3$/GeV$^2$]</th>
</tr>
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<tbody>
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<td>970</td>
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<td>±13</td>
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<tr>
<td>0.1-0.15</td>
<td>±12</td>
<td>402</td>
</tr>
<tr>
<td>0.15-0.2</td>
<td>±9</td>
<td>200</td>
</tr>
<tr>
<td>0.1-0.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.2-0.3</td>
<td>±3.6</td>
<td>200</td>
</tr>
<tr>
<td>0.3-0.45</td>
<td>±1.9</td>
<td>86.4</td>
</tr>
</tbody>
</table>

**Table C.8:** $\pi^+$ invariant inclusive yields ($\times 10^3$) for central p+Pb collisions.
Bibliography


[Adle03a] S.S. Adler et al., Identified Charged Particle Spectra and Yields in Au+Au Collisions at $\sqrt{s_{NN}}=200$ GeV, e-print: nucl-ex/0307022.


[Alpe75] B. Alper et al., *Production Spectra of $\pi^\pm$, $K^\pm$, $p^\pm$ at Large Angles in Proton-Proton Collisions in the CERN Intersecting Storage Rings*, Nucl. Phys. B100 (1975) 237.


Bibliography


[Reyg02] K. Reygars et al., *High-pT Neutral Pion Production in Heavy Ion Collisions at SPS and RHIC*, e-print: nucl-ex/0202018.


