Nuclear Modification at 17.3 GeV Nucleon-Nucleon Collision Energy, Measured by the Experiment CERN-NA49

Excerpts of Ph.D. dissertation

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1 Introduction

Quantum Chromodynamics (QCD) is part of the Standard Model of elementary interactions, which describes the interactions of elementary particles up to a very high accuracy, to our present knowledge. QCD is responsible for the realization of 'strong interactions' between Standard Model particles. The interactions between hadronic particles is a consequence of this. An important property of QCD is the asymptotic freedom, which means decreasing effective coupling factor with increasing elementary momentum transfer. At large momentum transfers, a series expansion in the small coupling factor becomes possible, thus the QCD predictions become calculable in a perturbative way. However, at small momentum transfers this approach fails due to the large coupling factor, therefore other strategy has to be considered. A possible strategy is the application of phenomenological models, which try to grab the most important aspects of momentum and charge transfers in an effective way. Unfortunately, most phenomenological models cannot be directly derived form the basic principles of QCD. Also other approaches exist for non-perturbative calculations: the lattice QCD. Such calculations are performed on a space-time mesh, and are based on the numerical evaluation of the Feynman integral of QCD. These calculations predict a phase transition: at sufficiently high temperatures, the formation of the quark-gluon phase is predicted by the model. Most high energy heavy ion experiments are designed for the verification of this prediction. The formation of the quark-gluon plasma is expected to be indicated by the sudden change of certain important observables, showing a deviation from the ordinary hadronic behavior.

The analysis of the 200 GeV per nucleon pair ($\sqrt{s_{NN}} = 200\,\mathrm{GeV}$) data, recorded at the RHIC experiments (Brookhaven), revealed an interesting phenomenon: the amount of produced particles at high transverse momentum in central nucleus-nucleus collisions is observed to be relatively smaller than that of in elementary reactions (peripheral nucleus, deuteron-nucleus or proton-proton).[1] This is called the high transverse momentum particle suppression. After the discovery of this phenomenon, it was believed to be a signature of the quark-gluon plasma formation, as a possible interpretation is parton energy loss in the strongly interacting plasma, before their fragmentation into hadrons.

The question naturally arises: if the collision energy is significantly decreased, do we observe a sudden vanish of this suppression phenomenon? If this question is to be answered, such an experiment is needed, which has recorded the necessarily high statistics of the mentioned reactions, and has particle identification. The latter is necessary, because a finer survey at RHIC shows that the amount of suppression is strongly particle type dependent; furthermore the composition of particle production at lower energies is largely different from what is observed at 200 GeV.

A very good candidate for such an experiment is the NA49 at CERN, which is basically a large acceptance hadron spectrometer. The experiment NA49 has recorded a sufficiently large low energy ($\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$) data sample for proton-proton, proton-nucleus and nucleus-nucleus collisions. Furthermore, it has good particle identification on the spectrum level, and has large acceptance and tracking efficiency.

[1] Provided that binary collision scaling of particle production holds. This is suggested by a partonic production scenario: it assumes that the particles are produced in the binary parton-parton interactions.

The scientific interest in this question is well illustrated by the fact, that the youngest CERN experiment, the NA61, a continuation of the experiment NA49, has begun data taking this year, and shall continue over the next years. One of the main motivations for the experiment NA61 is the precise measurement of the energy dependence of the high transverse momentum particle suppression [6, 7, 8, 12], the interest for which is partly due to the research work of the author in the experiment NA49.

The motivation of the dissertation is twofold.

- To provide precision data on single hadron production spectra at low energy ($\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$) and at high transverse momentum (up to about $4.5\,\mathrm{GeV/c}$), in proton-proton, proton-nucleus and nucleus-nucleus collisions, by using the NA49 data. This task is important because the existing experimental data do not fully cover this kinematic region.

- To measure the nuclear modification at $\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$, for different particle types, and at high transverse momentum (approximately at $2 - 4.5\,\mathrm{GeV/c}$), using the NA49 data. A comparison to the 200 GeV RHIC data would reveal, whether the nature of nuclear modification admits a sudden change with collision energy, i.e. whether the high transverse momentum particle suppression vanishes with decreasing collision energy.

2 Objectives

An important aim of the present experimental study was to extend our knowledge about the particle production mechanisms over the kinematic range in question.

One of the most important aims was the measurement of single hadron production spectra up to a high accuracy in this poorly covered kinematic region, and especially at high transverse momentum (above $2\,\mathrm{GeV/c}$). The studied reactions are inclusive particle production (with identified final state particle) in inelastic proton-proton, proton-nucleus and nucleus-nucleus reactions. The desired high accuracy ($\approx 5\%$) demanded significant effort invested in the fine-tuning of data handling, calibration, cut and correction procedures.

A further aim was the measurement of inclusive neutral pion production momentum spectrum, which demanded the solution of a problem in functional analysis / probability theory. Although the statistics of the experiment proved not to be enough for high transverse momentum π^0 spectrum measurement, the developed signal processing method has numerous potential application fields.

According to the motivations, I discuss the properties of the measured particle production spectra in detail, with a special emphasis on the nuclear modification and the energy dependence of the high transverse momentum particle suppression.

3 Applied Methods

The methods, developed by the author specially for the measurement of high transverse momentum identified charged hadron spectra, are discussed in detail in the dissertation.

NA49 is a fix-target experiment at a beam outlet of the SPS accelerator. The charged particles are detected by the four large volume Time Projection (TPC) chambers, which record a 3 dimensional image of the particle trajectories, bent in the field of the dipole magnets of the experiment. Momentum and charge reconstruction is possible from the curvature by off-line processing of the data, furthermore the pulse heights, left in the TPC chambers, provide information on the specific ionization of the particles. As the latter only depends on the particle velocity, the particle mass and thus the particle type can be determined, by knowing the charge and momentum.

Due to the fixed-target setup, the uncollided (spectator) part of the projectile nucleus in nucleus-nucleus collisions remains available for measurements, as it traverses the experiment undistorted. The beam energy fraction, carried away by the projectile spectator matter, is measured by the Veto Calorimeter, which makes the measurement of event centrality possible (the smaller the spectator energy is, the more central is the collision, as the spectator energy fraction equals to the spectator volume fraction). Due to the large exposition, the Veto Calorimeter suffers remarkable degradation in time, caused by the radiation damage. As the experimental results are rather sensitive to this effect, I developed a calibration method to correct for this. The method is based on the time-independence of the correlation between the Veto energy and the measured number of charged particles. Furthermore, I developed an accurate absolute calibration method, after which the Veto responses are directly comparable to Glauber calculations, thus the geometric properties of the collisions become well calculable.

As a side-effect of the fixed-target setup, the produced particles are strongly focused in the forward direction. This causes large track density, and thus low reconstruction efficiency and high fake track yield in the TPC volumes. This latter is even more serious issue for the high transverse momentum region, as there the amount of produced particles is very low, thus the signal completely disappears in the high fake track background. This was an unresolved issue in the experiment, which prevented the analysis at the high transverse momentum region ($> 2\,\mathrm{GeV/c}$). The key step of my work was to investigate this problem, and find a track selection criterion, which solves this issue. The solution was the rejection of discontinuous tracks, and a strict, optimized 3 dimensional momentum space cut. The application of the developed method resulted in a fake track yield of the order of permil in the available momentum space region, and the reconstruction efficiency was still well above 90%, even in the ultra high track density environment of central lead-lead collisions. An important advantage of the method is, that the acceptance is explicitly controlled, thus the acceptance correction can be performed without Monte Carlo methods.

Besides the charged hadrons, the momentum spectra of neutral hadrons, e.g. of neutral pions, are also interesting. The experiment NA49 can only detect π^0 particles via gamma conversion in the target material, which reduces the statistics of the detectable π^0-s to the amount of produced π^0-s times the square of the conversion probability. Therefore, I developed a method, which reconstructs the π^0 momentum distribution from the observed single gamma distribution, thus reducing the statistics only by the first power of the conversion probability. For this method, the solution of a mathematical problem becomes necessary, namely the inversion of a probability mixing (folding) operator. I developed an iterative method for solving this functional analysis / probability theory problem, for which I could prove convergence in an analytical way, in certain cases.

4 Excerpts

I group the results, presented in my dissertation, according to the following description.

1. **The calibration of the Veto Calorimeter.** I developed a time-dependence calibration procedure to correct for the degradation of the Veto Calorimeter, which is based on the absoluteness of the correlation of the spectator energy and the number of detected charged particles [11]. Furthermore, I developed an accurate absolute calibration method, after which, the agreement to the spectator energy predicted by the Glauber model based VENUS simulation was very good. Due to this fact, the quantities used in physical argumentation in connection to the centrality, bear sufficiently small systematic errors [10]. These results are used by many NA49 publications, such as [1, 5, 6, 7, 8, 12].

2. **The reconstruction of high transverse momentum particles.** The reconstruction of charged particles above 2 GeV/c transverse momentum in NA49 was not perfect: the reconstruction inefficiencies and the high fake track background posed a challenge. I found a solution for this problem, which is based on the rejection of discontinuous tracks and a strict, optimized 3 dimensional momentum space cut [9]. This is the key step of the dissertation, which is used practically by all the publications related to the excerpts [1, 3, 4, 5, 6, 7, 8, 12, 13, 15, 16], after which the particle production became measurable up to the statistical limit of the experiment (4.5 GeV/c transverse momentum, in the case of central Pb+Pb events).

3. **Extraction of identified charged hadron spectra.** I developed fine-tuned correction methods to correct the raw $\pi^{\pm}$, $p, \bar{p}$, $K^{\pm}$ spectra for various effects, after which the transverse momentum spectra of the above particles become available at zero rapidity in p+p, p+Pb and Pb+Pb reactions, at $\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$ center of mass energy [9]. The fully corrected results, which are accurate approximately up to 5%, are pulished in the experimental article [1].

4. **Extraction of neutral pion spectrum.** I developed an indirect method for the measurement of inclusive π^0 production, which is based on the inversion of probability mixing (folding) operators. I developed a robust iterative solution method for this general probability theory / functional analysis problem, for which I could prove convergence in analytic way in certain cases. The results concerning this method are published in the mathematical article [2]. Furthermore, in the talk [14] I drew the attention to the problems of high energy calorimetric measurements: although the energy resolution gets ideal in this limit, steep spectra are nevertheless distorted by the calorimeter, however this can be corrected by the method, proposed in [2]. I also investigated the possible effects of non-ideal momentum resolution in the case of my high transverse momentum charged particle analysis, which is a potentially dangerous source of systematic error for steep spectra, however I found the estimated distortion to be less than other systematic errors.

5. **Collective behavior at low transverse momentum.** I observed, that the particle production at low transverse momentum ($< 1.5\,\mathrm{GeV/c}$) is well reproduced

by the blast-wave picture [3, 13, 15], which assumes a thermal-like particle production, originating from a cylindrically expanding source. However, at high transverse momentum, this picture predicts too high baryon/meson ratio, which indicates the decreased role of collective motion at the higher transverse momentum region.

6. **Test for the applicability of perturbative QCD approximation at high transverse momentum.** After the extraction of produced-baryon/meson spectrum ratios, I compared the results to perturbative QCD predictions [3, 13, 15]. The comparison indicates, that the particle production at $\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$ energy is not purely perturbative event at around $4\,\mathrm{GeV/c}$ transverse momentum, as the perturbative QCD calculation leads to rather different baryon/meson ratios. The comparison of the experimental results to the $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ RHIC measurements suggests, that the net-baryon/meson ratios admit a centrality independent energy and transverse momentum factorization.

7. **The energy dependence of particle suppression at high transverse momentum.** Perturbative QCD predictions reproduce the observed qualitative properties of the nuclear modification factors. I compared my analysis results to the $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ RHIC results, and the comparison shows that the central / peripheral suppression does not vanish toward $\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$. On contrary: the measured modification curves are rather similar at this two very different energies [1], although the amount of charged pion suppression is reduced at lower energy.

Publications Related to the Excerpts

[1] A. László *et al.* (the NA49 Collaboration):
"High Transverse Momentum Hadron Spectra at $\sqrt{s_{NN}} = 17.3\,\text{GeV}$*, in Pb+Pb and p+p Collisions, Measured by CERN-NA49"*;
Physical Review **C77** (2008) 034906.

[2] A. László:
"A Robust Iterative Unfolding Method for Signal Processing";
Journal of Physics **A39** (2006) 13621.

[3] A. László *et al.* (the NA49 Collaboration):
"High p(T) Spectra of Identified Particles Produced in Pb Plus Pb Collisions at 158 GeV/nucleon Beam Energy";
Nuclear Physics **A774** (2006) 473.

[4] T. Schuster, A. László *et al.* (the NA49 Collaboration):
"High p(T) Spectra of Identified Particles Produced in Pb+Pb Collisions at 158 A GeV Beam Energy";
Journal of Physics **G32** (2006) S479.

[5] A. László *et al* (the NA49 Collaboration):
"New Results and Perspectives on R_{AA} *Measurements Below* 20 GeV *CM-energy at Fixed Target Machines"*;
International Journal of Modern Physics **E16** (2007) 2516.

Articles and Talks Related to the Excerpts

[6] A. László *et al.* (the NA61 Collaboration):
"Study of Hadron Production in Collisions of Protons and Nuclei at the CERN SPS";
NA49-future Letter of Intent (2006), Sections 2.2 and 4.2 [`CERN-SPSC-2006-001, SPSC-I-235`].

[7] A. László *et al.* (the NA61 collaboration):
"Study of Hadron Production in Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS";
NA49-future Proposal (2006), Sections 2.2, 3.5.3 and 4.2 [`CERN-SPSC-2006-034, SPSC-P-330`].

[8] A. László *et al.* (the NA61 Collaboration):
"Additional Information Requested in the Proposal Review Process";
Addendum to the NA49-future Proposal (2007), Section 8 [`CERN-SPSC-2007-004, SPSC-P-330`].

[9] A. László:
"High Transverse Momentum Identified Charged Particle Yields in 158 GeV/*nucleon*

Pb+Pb Collisions";
NA49 Technical Note (2007).

[10] A. László:
"*Calculating Mean Values of Collision Parameters as a Function of Centrality*";
NA49 Technical Note (2007).

[11] A. László:
"*Time-dependence Calibration of the Veto Calorimeter*";
NA49 Technical Note (2006).

[12] A. László (for the NA61 Collaboration):
"*NA61/SHINE at the CERN SPS*";
Invited talk at Critical Point and Onset of Deconfinement (Darmstadt, 2007);
Proceedings of Science **CPOD07** (2007) 054.

[13] A. László:
"*High p_T Spectra of Identified Particles Produced in Pb+Pb Collisions at $\sqrt{s}$ = 17.3 GeV/nucleon*";
Invited talk at Heavy Ion Forum (CERN, 2006).

[14] A. László:
"*Deconvolution of Noisy Data*";
Talk at Zimányi Winter School (Budapest, 2006).

[15] A. László:
"*High p_T Spectra of Identified Particles Produced in Pb+Pb Collisions at 158 GeV/nucleon Beam Energy*";
Talk at RHIC Winter School (Budapest, 2005).

[16] A. László:
"*High Transverse Momentum Identified Charged Particles at* 17.3GeV/nucleon *Center of Mass Energy*" in Hungarian;
Talk at Hungarian Nuclear Physics Meeting (Jávorkút, 2006).