# Experimental and Theoretical Investigation of Relativistic Heavy Ion Collisions at RHIC – with Focus on Non-Central Collisions

PhD Theses


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2007

# 1 Subject

*"We simply do not yet know enough about the physics of elementary particles to be able to calculate the properties of such a melange with any confidence. ... Thus our ignorance of microscopic physics stands as a veil, obscuring our view of the very beginning."*

S. Weinberg, about the first hundredth of a second [1]

Ultra-relativistic collisions, so called "Little Bangs" of almost fully ionized Au atoms are observed at the experiments of the Relativistic Heavy Ion Collider of the Brookhaven National Laboratory, New York. The aim of these experiments is to create new forms of matter that existed in Nature a few microseconds after the Big Bang, the creation of our Universe.

Quantum Chromodynamics (QCD), the theory of quarks and gluons, their color degree of freedom and the strong force interacting between them was established soon after Weinberg's famous book [1] about the early Universe had been published. Confinement is an important (though mathematically never proven) property of QCD, its consequence is that quarks are bound into hadrons in a matter of normal temperature and pressure.

In the early Universe, energy density was many orders of magnitude higher than today, and at that high energy densities, deconfined phases of colored matter might have existed. Quark-gluon plasma (QGP) is such a phase, that might have existed during the first few microseconds after the Universe came into existence. This type of matter was searched for at the SPS, and experiments at RHIC are continuing this effort. Evidence for formation of a hot and dense medium in gold-gold collisions was found based on a phenomenon called jet quenching, and confirmed by its disappearance in deuteron-gold collisions [2].

A consistent picture emerged after the first three years of running the RHIC experiment: quarks indeed become deconfined, but also behave collectively, hence this hot matter acts like a liquid [3], not like an ideal gas theorists had anticipated when defining the term QGP. The situation is similar to as if prisoners (quarks and gluons confined in hadrons) have broken out of their cells at nearly the same time, but they find themselves on the crowded jail-yard coupled with all the other escapees. This strong coupling is exactly what happens in a liquid [4]. I was working at the PHENIX experiment of RHIC to gain insight on these questions.

# 2 Methods

I joined RHIC PHENIX as a member of ELTE in 2003, when three Hungarian institutions – besides ELTE the Debrecen University and the MTA KFKI RMKI – became members of PHENIX under leadership of Tamás Csörgő. This enabled students and researchers at these institutions to join the investigations done at PHENIX. I also performed theoretical calculations from 2003 in the team lead by Tamás Csörgő.

For all this work, I needed various kinds of practical knowledge. Among the methods of theoretical physics, I was engaged in solving hydrodynamical differential equations. I delved into calculating final states of hydrodynamical processes in high energy heavy ion collisions and calculating observable quantities from these final states. In particular I was working on the Buda-Lund hydrodynamical model. This model previously described hadronic observables such as spectra and correlations from central collisions. My task was to generalize this model to describe semi-central and peripheral collisions. On the experimental side I learned to measure observable quantities from the physical properties of the observed particles and their distributions.

For the above tasks, besides analytic ("paper based") calculations I availed myself of the help of mathematical program packages. I mostly used the Maple ® software of Waterloo Maple Inc., which is capable of analytic formula-manipulation and exact solution of equations, figure and 2- or 3-D animation production, as well as numeric solution of regular and differential equations.

My experimental and theoretical work was also based on reliable and widespread programming applications. I used different simulation packages (Pythia, PISA, Therminator and HRC), the software system of the PHENIX Offline Computing and Online Monitoring, the Concurrent Version System, as well as various RHIC Computing Facility applications (such as Condor and LSF batch job systems or tape storage solutions). For figure production I also used ROOT, Gnuplot and SigmaPlot ® of Systat Software Inc., as well as different Microsoft Office ® products.

For numeric calculations I used various softwares besides the above ones, for example the Gnu Scientific Library functions or the Minuit optimization package.

I also needed to acquire extensive knowledge on programming languages, especially C++, as it is standard within PHENIX. Softwares developed by me in PHENIX were written in C++, as well as program-packages I wrote for our theoretical calculations with the Buda-Lund model.

I had to become a little bit acquainted with the formerly standard Fortran language as well. I also used simpler languages (e.g. Perl) or different scripting languages (Bash or csh). Last, but not least, for visualization and communication of our works on the web and developing web interfaces, I immersed myself in the HTML, JavaScript and PHP languages.

# 3 Results

## 3.1 Online monitoring of the ZDC and the SMD

The Zero Degree Calorimeter (ZDC) is a neutron detector of three modules, which is placed in the line where the two beams of RHIC cross each other. It measures the energy of the neutrons that evaporated from the spectators of the collision, as these are not deflected by the magnets that keep the ions on their track. Thus the ZDC enables the experiment to determine the centrality of the observed collisions, as this clearly effects the number of evaporated collisions. The ZDC is furthermore capable of determining the longitudinal position of the collision. The Shower Max Detector (SMD), placed between first two ZDC modules, measures the transverse distribution of the evaporated neutrons, thus the geometry of the beam. I automated these measurements and solved the real-time plotting and the database-storage of the results of them within the PHENIX Online Monitoring. [c5-c14,d5]

## 3.2 Measurements and simulations with the ZDC

I determined the expected distribution of neutrons in the ZDC at RHIC and LHC energies with Pythia simulations. I measured in 200 GeV ultra-peripheral Au+Au collisions (characterized by impact parameters higher then the nucleus size) the production cross-section of $J/\Psi$ particles in incoherent processes and of $e^{\pm}$ pairs in coherent processes. Results are in agreement with theoretical predictions. [c1,d4]

## 3.3 Partial coherence in Au+Au collisions at PHENIX

I measured two- and three-particle correlation functions in 200 GeV Au+Au collisions. I fitted these with calculated correlation functions using Gaussian, Lévy and Edgeworth shapes, and from this I determined the allowed region for the fraction of the hydrodynamically evolving core ($f_c$) and the fraction of a partially coherent part ($p_c$) within the core. Nonzero partial coherence is allowed when having larger core size than the one allowed at total incoherence ($p_c = 0$). [c4,d1,d2]

### 3.4 Analysis of two-pion correlations

Is is known [5], that in case of chiral $U_A(1)$ symmetry restoration the mass of the $\eta'$ boson (the ninth, would-be Goldstone boson) is decreased while it's production cross section is heavily enhanced. Thus $\eta'$ bosons are copiously produced. They decay into five low-momentum pions, hence change the strength of two-pion correlation functions at low momenta [6].

Hence I measured the transverse momentum dependence of the strength of the two-pion correlation functions. These measurements are not incompatible with a large decrease of the $\eta'$ mass. Regarding $U_A(1)$ symmetry restoration, I concluded that at present, additional analysis and the agreement of the Collaboration is required to make a definitive statement. [c4,d1,d2]

### 3.5 Lévy-stability of the particle emitting source

In second order phase transitions the basic observables to characterize processes are critical exponents. One of these exponents characterizes the spatial distribution of the order parameter, traditionally denoted by $\eta$. It is known [7], that this exponent can be measured by looking at two-particle correlation functions. One can show, that $\eta$=$\alpha$, where $\alpha$ is the Lévy-stability index of two-particle correlation functions. It is known furthermore [8], that the universality class of QCD at the critical point is the same as the one of 3d Ising models. The exponent of the correlation function is very small in these models, $\eta = 0.03{\pm}0.01$. In high energy heavy-ion collisions however random fields can be present, which change the universality class and increase $\eta$. These are the random field Ising models, which have $\eta(=\alpha) = 0.50 \pm 0.05$.

I compared two-particle source functions measured in $\sqrt{s_{\rm NN}}$=200 GeV Au+Au collisions at PHENIX [9] to Lévy-stable distributions, and measured the Lévy-stability exponent of the source ($\alpha$), which corresponds to the critical exponent in a second order phase transition. I found, that the $\alpha$ parameter takes a value of around 1.4$\pm$0.1. In case of second order phase transitions this value was predicted to be maximally $\alpha$=0.5, which, based on this analysis, is not in agreement with the experimental data. [a2,c3,d3]

## 3.6 Generalization of the Buda-Lund model

I generalized the Buda-Lund model [10] for ellipsoidally symmetric fireballs arisen from high energy heavy ion collisions. I calculated the transverse momentum and rapidity dependence elliptic flow from the model, and found it to be in agreement with experimental data of peripheral Au+Au collisions at RHIC that could not could not have been described previously by many numerical and analytic models. With this comparison of the generalized, ellipsoidally symmetric model I confirmed the previously found indirect evidence for a deconfinement of quarks and gluons, based on the central temperature of the fireball compared to critical temperatures calculated from lattice QCD. I also found, that the volume, where the temperature is higher than the critical one is only a small part of the total volume, however, the surface of the fireball is rather cold. [a4-a7]

## 3.7 Correlations from the Buda-Lund model

I calculated the two-particle correlations from the generalized Buda-Lund model. I showed, that the transverse momentum and rapidity dependence of the HBT radii can be merged to a single scaling function. I also suggested a method for experimentally testing this scaling as a method of testing the validity of the perfect hydro picture at RHIC. [a3,b5]

## 3.8 Scaling of the elliptic flow at RHIC

I calculated the elliptic flow from the generalized Buda-Lund model. I showed, that the elliptic flow depends on any physical parameter (transverse or longitudinal momentum, mass, center of mass energy, collision centrality, type of the colliding nucleus etc.) only through a scaling variable. I showed that this scaling is present in RHIC Au+Au data, and this provides a quantitative evidence for the validity of the perfect fluid picture of soft particle production in Au+Au collisions at RHIC up to transverse momenta of $\sim$1.0-1.5 GeV and that this perfect fluid extends far away from mid-rapidity, up to a pseudorapidity of $\eta_{\mathrm{beam}} - 0.5$. Finally I showed that the kinetic energy scaling of the elliptic flow found experimentally at PHENIX is a consequence of this universal scaling. [a3,b3,b4,c2]

## 4 Conclusions

In summary, we can make the definitive statement, based on elliptic flow measurements and the broad range success of analytic hydro models, that in relativistic Au+Au collisions observed at RHIC we see a perfect fluid. Based on our estimates on the temperature and energy density we also conclude that the observed matter is in a deconfined state. We also see a possible signal of partial symmetry restoration in the mass reduction of $\eta$' bosons. Future plan is to explore all properties of the Quark Matter, by analyzing more data and using higher luminosity. We are after the full map of the QCD phase diagram, and in order to explore it, we also have to go to higher energies and compare them to lower energy data. If the Quark Matter is the New World, then Columbus just realized he is not in India, but on a new continent. [b1]

> *"In general we look for a new law by the following process. First we guess it. Then we compare the consequences of the guess to see what would be implied if this law that we guessed is right. Then we compare the result of the computation to nature, with experiment or experience, compare it directly with observation, to see if it works. If it disagrees with experiment it is wrong. In that simple statement is the key to science."*
>
> R. P. Feynman, about discovering new laws [11]

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# Coauthored papers that form the basis of the above theses

## a. Publications in refereed journals

[a1] **Accelerating solutions of perfect fluid hydrodynamics for initial energy density and life-time measurements in heavy ion collisions**
T. Csörgő, M. I. Nagy and M. Csanád, nucl-th/0702043, To appear in Braz.J.Phys.

[a2] **Anomalous diffusion of pions at RHIC**
M. Csanád, T. Csörgő and M. Nagy, hep-ph/0702032, To appear in Braz.J.Phys.

[a3] **Universal scaling of the rapidity dependent elliptic flow and the perfect fluid at RHIC**
M. Csanád, T. Csörgő, B. Lörstad and A. Ster, Nucl. Phys. A **774**, 535 (2006)

[a4] **Indication of quark deconfinement and evidence for a Hubble flow in 130 GeV and 200 GeV Au + Au collisions**
M. Csanád, T. Csörgő, B. Lörstad and A. Ster, J. Phys. G **30**, S1079 (2004)

[a5] **A hint at quark deconfinement in 200 GeV Au + Au data at RHIC**
M. Csanád, T. Csörgő, B. Lörstad and A. Ster, Nukleonika **49**, S49-S55 (2004)

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## b. Other papers

[b1] **From quark gluon plasma to a perfect fluid of quarks and beyond**
M. Csanád, T. Csörgő, B. Lörstad, M. Nagy and A. Ster, nucl-th/0702045
To be published in The Subnuclear Series - Vol. 44, Proceedings of the International School of Subnuclear Physics

[b2] **A New Family of Simple Solutions of Perfect Fluid Hydrodynamics**
T. Csörgő, M. I. Nagy and M. Csanád, nucl-th/0605070

[b3] **Universal scaling of the elliptic flow at RHIC**
M. Csanád, T. Csörgő, R. A. Lacey and B. Lörstad, nucl-th/0605044
Proceedings of the 22nd Winter Workshop on Nuclear Dynamics

[b4] **Universal scaling of the elliptic flow and the perfect hydro picture at RHIC**
M. Csanád *et al.*, nucl-th/0512078

[b5] **Understanding the rapidity dependence of the elliptic flow and the HBT radii at RHIC**
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## c. Papers of the PHENIX Collaboration

[c1] **Coherent photoproduction of J/psi and high-mass e+ e- pairs in ultra-peripheral Au + Au collisions at $\sqrt{s_{\rm NN}}$= 200 GeV**
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[c2] **Scaling properties of azimuthal anisotropy in Au+Au and Cu+Cu collisions at $\sqrt{s_{\rm NN}}$= 200 GeV**
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[c3] **Evidence for a long-range component in the pion emission source in Au + Au collisions at $\sqrt{s_{\rm NN}}$= 200 GeV**
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[c4] **Measurement and analysis of two- and three-particle correlations**
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[c5] **Systematics of identified hadron spectra at PHENIX**
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[c7] **Jet structure from dihadron correlations in d + Au collisions at $\sqrt{s_{\mathrm{NN}}}$= 200 GeV**
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[c12] **Jet structure of baryon excess in Au + Au collisions at $\sqrt{s_{\mathrm{NN}}}$= 200 GeV**
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## d. PHENIX internal analysis notes

[d1] **Two- and three-particle correlations analysis note**
PHENIX internal analysis note 404
`https://www.phenix.bnl.gov/WWW/p/forms/info/show_note.php?editkey=an404`

[d2] **Addendum to the two- and three-particle correlations analysis note (about the error of the Coulomb-correction)**
PHENIX internal analysis note 436
https://www.phenix.bnl.gov/WWW/p/forms/info/show_note.php?editkey=an436

[d3] **Analyzing heavy tails in pion source function**
PHENIX internal analysis note 527
https://www.phenix.bnl.gov/WWW/p/forms/info/show_note.php?editkey=an527

[d4] **Analysis of incoherent J/$\Psi$ production and coherent $e^{\pm}$ continuum production in ultra-peripheral collisions**
PHENIX internal analysis note 593
https://www.phenix.bnl.gov/WWW/p/forms/info/show_note.php?editkey=an593

[d5] **Online Monitoring System for the PHENIX ZDC and SMD**
PHENIX internal technical note 419
https://www.phenix.bnl.gov/phenix/WWW/publish/csanad/zdc/note/