University doctoral (PhD) thesis booklet

Exploring Hot, Strongly Interacting Matter with the PHENIX Experiment at RHIC

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Summary of results

RHIC operations started in 2000 and during the past decade, our understanding about the medium behavior of strong interactions radically changed. In my thesis I summarize the context and the main milestones of RHIC achievements that culminated in the official announcement of the discovery of the perfect fluid in 2005 and the strongly interacting Quark Gluon Plasma in February 2010. I give an overview of the accelerator complex, with focus on the PHENIX experiment in which I participate. I present my work in the field of high energy heavy ion collisions. I cover several subfields including Bose-Einstein correlation measurements of the bulk matter in PHENIX and connected theoretical work, as well as PHENIX measurements of soft and hard photon and hadron properties. Although these results are interesting on their own, they also provide elements to the new picture that has emerged from the 1st decade of RHIC operation.

During my PhD studies I contributed to the Experiment at several levels from detector calibration, operation, software development and maintenance to the preparation of scientific publications. The thesis points listed below summarize my most important new scientific contributions.

1. Calibration of the PHENIX Electromagnetic Calorimeter

I have calibrated the time of flight measurements in the PHENIX Electromagnetic Calorimeter for the data colleced in 2005 Cu+Cu, 2006 p+p and 2007 Au+Au collisions. Prior to this calibration PHENIX used to determine the energy dependence of the timing signal with showers simulated in the detector units by laser impulses, which was not satisfactory in precision. I developed a new method that determines the time–energy dependence using solely real collision data, thus making the time of flight reconstruction more reliable. I maintained and developed the calorimeter reconstruction software, and prepared a package for online preliminary calibration of the PbSc timing that is operational from 2006 on [a]. The results of these calibrations are used in the energy dependent nuclear modification factor measurements of neutral pions with high transverse momenta [1], among others.

2. Selection of neutral pions with stochastic cuts

I developed a method for the identification of particles in the PHENIX Electromagnetic Calorimeter, using d+Au collision data taken in 2003. This fuzzy logic based, *stochastic* cut proved to be more efficient than any previous calorimeter-based particle identification method. My method is not only useful in selecting electromagnetic particles (therefore in the reconstruction of neutral pions and direct photons), but also for selecting hadrons such as antineutrons [b]. I verified the optimality of the results with an artificial neural network analysis. I participated in the PHENIX workgroup that applied this method e.g. for determining the *neutral pion* spectra in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions [2].

3. Simulation verification and direct photon production

I have systematically analyzed the PbSc and PbGl detector response from 2002 Au+Au and 2003 d+Au collision data and carried out the corresponding *simulation verification* studies [c]. These simulations contributed significantly for the determination of the neutral pion and *direct photon* spectra created in PHENIX $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions [d], published in [3].

4. PHENIX images and THERMINATOR simulations

I showed that THERMINATOR simulations, which focus on the correct handling of resonance decays, are able to reproduce the transverse momentum and centrality dependence of the one dimensional pion source observed in PHENIX $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions. I pointed out that THERMINATOR is not able to describe the direction-dependently measured PHENIX source functions. This suggests that the heavy tail observed in the PHENIX pion correlation measurements cannot be explained only by resonance decays [e, f].

The heavy, power-law-like tail seen in one-dimensional pion source functions can, however, be explained by considering the anomalous diffusion of hadrons. I pointed out that a possible comparison of the $\pi^{\pm}$, $K^{\pm}$ and $p^{\pm}$ source function shapes can differentiate between effects of resonance decays and anomalous diffusion [f]. With the PHENIX $K^{\pm}$–$K^{\pm}$ correlation measurements we have shown that the power-law tail is stronger in the kaon than the pion source image, even though there are less resonances resulting in kaons. Thus we demonstrated that the main reason of the power-law tails observed in PHENIX source images cannot be the resonance decays [4].

5. Observation of an η' mass reduction in a hot, dense medium

The axial, $U_A(1)$ part of the $U(3)_L \times U(3)_R$ chiral symmetry group of the strong interaction is broken in the physical vacuum. According to theoretical considerations, however, the $U_A(1)$ symmetry is partially restored in a hot and dense medium. As a consequence, the mass of the η' meson reduces from its vacuum value of 958 MeV and takes a value near to the mass of the other pseudo-scalar mesons. I modeled this effect with thermal simulations, and I found that the like-sign pion Bose–Einstein correlation data measured in RHIC 200 GeV Au+Au collisions can be explained only if one assumes that the mass of the η' drops with at least 200 MeV at the 99.9% confidence level [5]. The most probable value is $m^*_{\eta'} = 340^{+50}_{-60}{}^{+280}_{-140} \pm 42$ MeV, where the errors are statistical, model and systematic respectively [6, g]. I verified that the measured data was not reproducible in non-thermal models which do not assume a mass modification.

6. Spectra of the η' and η mesons in 200 GeV RHIC collisions

I determined the most probable spectra of the η' and η mesons created in the hot and dense medium. The other consequence of the symmetry restoration is that the η' and η spectra will differ from the naïve expectations. Besides the enhancement of the η' production the shape of its spectrum will also change: Low momentum η' mesons emerge in a high number, thus breaking the m_{T}-scaling. The spectrum of the η (one main decay product of the η') will also show a low-momentum enhancement, while its high-momentum part remains unchanged [6, g].

Connected publications

Selected peer-reviewed papers

[1] A. Adare, ... G. Dávid, R. Vértesi *et al.* [PHENIX Collaboration] *"Onset of π^0 Suppression Studied in Cu+Cu Collisions at $\sqrt{s_{NN}}$ =22.4, 62.4, and 200 GeV,"* Phys. Rev. Lett. **101**, 162301 (2008).

[2] A. Adare, ... G. Dávid, R. Vértesi *et al.* [PHENIX Collaboration] *"Suppression pattern of neutral pions at high transverse momentum in Au+Au collisions at* $\sqrt{s_{NN}} = 200$ GeV *and constraints on medium transport coefficients,"* Phys. Rev. Lett. **101**, 232301 (2008).

[3] K. Adcox, ... T. Csörgő, G. Dávid, R. Vértesi *et al.* [PHENIX Collaboration], *"Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration,"* Nucl. Phys. A **757**, 184 (2005).

[4] S. Afanasiev, ... T. Csörgő, R. Vértesi *et al.* [PHENIX Collaboration] *"Kaon interferometric probes of space-time evolution in Au+Au collisions at* $\sqrt{s_{NN}} = 200$ GeV,*"* Phys. Rev. Lett. **103**, 142301 (2009).

[5] R. Vértesi, T. Csörgő and J. Sziklai *"Significant in-medium reduction of the mass of η' mesons in* $\sqrt{s_{NN}} = 200$ GeV *Au+Au collisions,"* Nucl. Phys. A **830**, 631C (2009).

[6] T. Csörgő, R. Vértesi and J. Sziklai *"Indirect observation of an in-medium η' mass reduction in* $\sqrt{s_{NN}} = 200$ GeV *Au+Au collisions,"* Phys. Rev. Lett. **105**, 182301 (2010).

Selected notes, conference proceedings, talks

[a] R. Vértesi, G. Dávid, T. Csörgő
"EMCal ToF Calibration and Slewing Effects in Year 5 Cu+Cu, Year 6 p+p and Year 7 Au+Au collisions,"
PHENIX Technical Note 428, 2008/06/30,
`http://www.phenix.bnl.gov/phenix/WWW/publish/vertesi/tof_tn/tof_tn.pdf`

[b] R. Vértesi, G. Dávid
"Charge Veto and Antibaryon Cuts in the EMCal,"
PHENIX Hadron Physics Working Group talk, 2004/02/27.

[c] G. Dávid, T. Sakaguchi, R. Vértesi,
"Simulation Verification in the EMCal PbSc Shower Characteristics of Hadrons,"
PHENIX Analysis Note 330, 2004/10/11.

[d] T. Isobe, G. Dávid, T. Sakaguchi, B. Sahlmüller, H. Hamagaki, R. Vértesi, J. Imrek,
"Measurement of direct photon spectra with PbSc EMCal in $\sqrt{s_{NN}}$ = 200 GeV Au+Au Collisions at Run4,"
PHENIX Analysis Note 490, 2006/04/13.

[e] M. Csanád, T. Csörgő, M. I. Nagy, R. Vértesi
"Analyzing heavy tails in pion source function,"
PHENIX Analysis Note 527, 2006/11/02.

[f] R. Vértesi for the PHENIX Collaboration
"THERMINATOR simulations and PHENIX images of a heavy tail of particle emission in 200 GeV Au+Au collisions,"
Proceedings of 23rd Winter Workshop on Nuclear Dynamics, Big Sky, Montana, USA (EP Systema, Budapest, 2007).

[g] R. Vértesi, T. Csörgő and J. Sziklai
"Significant in-medium η' mass reduction in $\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions at RHIC,"
e-print: `[arXiv:0912.0258 [nucl-ex]]` (Submitted to PRC).