# Recent Results from RHIC

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The Relativistic Heavy Ion Collider (RHIC) has opened a new era in experimental nuclear physics. Among the most important discoveries of this new era are the jet quenching phenomenon, the energy loss suffered by a hard scattered parton traversing the medium, and the collective flow, approaching the limit of ideal hydrodynamics. RHIC experiments have introduced a number of novel correlation methods for studies of jets and jet-medium interactions in the high multiplicity environment of ultra-relativistic heavy ion collisions. The di- and multi-hadron correlation techniques have since been quintessential to the understanding of the properties of the created medium in many complementary ways. In this work selected recent results are presented for the RHIC's top energy collisions at 200 GeV. Di-hadron correlation measurements from Au–Au collisions, illuminating the properties of the hot nuclear medium, are confronted with the recent findings from d–Au data at the same energy. Understanding of initial state properties and collision evolution is tested by unexpected similarities in the di-hadron correlation measurements between the two systems.

## 1. Introduction

Quantum Chromodynamics (QCD) predicts a transition from ordinary (hadronic) matter to a deconfined state of quarks and gluons, the Quark Gluon Plasma (QGP), at sufficiently high energy densities. The RHIC facility was originally conceived as a heavy ion collider dedicated to production and experimental studies of such deconfied state of matter. Within the first few years of RHIC experimental operations a number of discoveries, both expected and unexpected, has been made, advancing our understanding of QCD. For obvious reasons, the QGP phase could not be studied directly, but most of its properties have to be inferred from the final state observables. There is, perhaps, no single experimental measurement that could undoubtedly prove the creation of a deconfined matter in heavy ion collisions; nevertheless mounting amount of evidence supports the discovery of the partonic medium with "Perfect Liquid" properties [1]. In recent years, the RHIC physics program has evolved in a number of different directions. The polarized *pp* collisions at 200 and 500 GeV provided a new ground for studies of nucleon spin structure. Flexibility of the collider facility has allowed a change of the center-of-mass energies of the delivered ion beams by more than an order of magnitude, leading to the successful start of the Beam Energy Scan (BES) program. This ongoing program carries out systematic studies of the QCD phase diagram in search for the tri-critical point on the phase boundary [2] and the on-set of deconfinement. At the higher end of RHIC energies the systematic studies of the QGP medium are continuing with new beam species. The p, d, Cu, Au, and U beams, delivered by RHIC facility, have allowed studies of the system size and initial state geometry effects on medium properties.

The discovery of jet-quenching effect has brought new attention to the hard sector probes, that were traditionally not a focus for nuclear experiments. Physics interest in rare processes (high transverse momentum ($p_T$) particles, jets, heavy flavor hadrons) put new demands on both the collider facility, reaching for higher integrated luminosities, and the experiments, putting forward suitable detector upgrades to advance such measurements.

Of the original four, there are two experimental collaborations continuing operations at RHIC: PHENIX [3] and STAR [4]. Each of the two detectors consists of multiple sub-systems that allow to study a variety of physics observables simultaneously. The main parts of the PHENIX detector include Drift, Pad, and Time-Extension Chambers; RICH detector and Electro-Magnetic Calorimeters. These collectively called "Central Arms" detectors provide tracking and particle identification at mid-rapidity within two 90-degree-wide azimuthal slices. The total pseudorapidity ($\eta$) coverage of the Central Arms is 0.7 units. Another set of detectors provides the forward region coverage for PHENIX. The forward Muon Arm Detectors provide measurements in $1.2 < |\eta| < 2.2$ and $3 < |\eta| < 4$ ranges within the full azimuth. Additionally, PHENIX experiment has recently installed a new silicon detector for higher precision reconstruction of primary and secondary vertices and thus enhancement of PHENIX capabilities for heavy flavor studies.

The STAR detector set-up has a distinctly different layout and acceptance. The main workhorse of STAR is a large gas-filled Time Projection Chamber, that provides mid-rapidity tracking, momentum measurements and particle identification capabilities across full azimuth with a uniform acceptance in $|\eta| < 1$. The Electro-Magnetic Calorimeters (EMC) compliment charged particle measurements, provided by the TPC, and cover pseudorapidity range of $-1 < \eta < 4$. The EMC measurements and triggering capabilities greatly enhance the hard sector studies for STAR. Recently added Muon Telescope detector and the ongoing Heavy Flavor tracking upgrade will substantially advance the heavy flavor studies in the near future.

Both experiments have dedicated significant efforts to systematic studies of medium properties and jet-medium interactions via di-hadron correlations. In this report recent results from correlation measurements in Au–Au collisions at 200 GeV assessing the systematic trends of azimuthal anisotropies in heavy ion events are presented. These results are put in the context with a new and surprising observation of similar correlation structures from d–Au data at the same energy. Until recently the d–Au collisions were mostly sought after to provide a reference measurement for the cold nuclear mater effects. Unexpected similarities in di-hadron correlations from both systems challenge mainstream concepts of the heavy ion physics and may shed new light on the initial state properties of the collisions studied.

## 2. Precision studies of medium properties

In the first few years of RHIC operations it has been established experimentally that the matter created in the high energy Au–Au collisions is dense, strongly interacting, and exhibiting multiple unusual features. Among the main findings from this period, summarized in four experimental "Whitepapers" [5], are strong partonic collectivity of the explosive system with an unexpectedly short mean free path. The system created in these collisions was found to be highly opaque to the propagating partons, leading to the quenching phenomenon at high $p_T$ due to in-medium energy loss. The collective properties of the created medium were evident in the magnitude of the elliptic flow, the second order (elliptical) modulation of the azimuthal distributions with respect to reaction plane. Strong elliptic flow has been observed for multiple hadron species, including strange and multi-strange hadrons. The magnitude of $v_2$, the second coefficient of the Fourier expansion, was found in a good agreement with the ideal hydrodynamic calculations for the soft sector particles (below 2 GeV/$c$), yielding the concepts of medium thermalization (across $u$, $d$, $s$ flavors) and "Perfect fluid." At intermediate momenta, the mass-dependent ordering of the identified hadron $v_2$ was found taken over by the constituent quark scaling behavior – specific grouping of the observed $v_2$ trends for mesons and baryons separately – further supporting the partonic collectivity idea.

It has been since realized that the initial state density and/or geometry fluctuations can leave an imprint on the final state distributions resulting in significant magnitudes of higher order Fourier terms [6, 7]. This idea has been confirmed experimentally in the precision measurements of multiple $v_n$ harmonics. Compilation of recent RHIC results from [8] is presented in Fig. 1. Significant amplitudes of Fourier coefficients up to the 5th order were observed by both STAR [9] and PHENIX [10] experiments. The

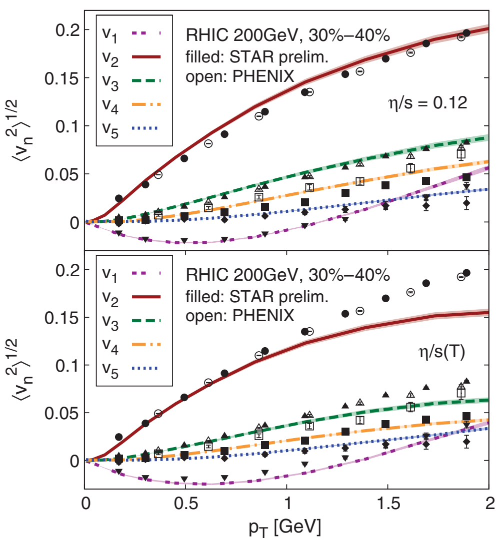


Fig. 1. Transverse momentum dependence of azimuthal anisotropies measured for charged hadrons by STAR [9] (open symbols) and PHENIX [10] (filled symbols). The compilation of data and theoretical calculations are from [8].

transverse momentum, energy and centrality dependence of the Fourier harmonics constrain the shear viscosity over entropy density ratio ($\eta/s$) for the evolving medium. The $v_2$ measurements along, while consistently described in hydrodynamic calculations with low viscosity values [11], are the least sensitive to the viscous effects. Different sensitivities of the higher order terms are illustrated in Fig. 1 by comparing the data with two viscous hydrodynamic calculations within IP-Glasma model [8]. Within this model the RHIC data are found to be best described by the $\eta/s$ value of 0.12.

## 3. Di-hadron correlations in the d–Au collisions

The extent of the azimuthal anisotropies observed in heavy ion collisions goes far beyond the soft sector, the commonly accepted applicability range of hydrodynamic description. At high-$p_T$ these anisotropies are attributed to the effects of jet quenching, where path-length dependence of the parton energy loss produces the correlation of the hard-scattering products with the reaction plane. At RHIC the di-hadron correlation measurements with high-$p_T$ particles (leading hadrons or "triggers") have become a well-recognized tool for studies not only of the collective effects but of jet properties and the jet-medium interactions. However, the interpretation of such di-hadron correlations in heavy ion collisions is complicated by the variety of correlated signals, from both soft and hard processes, that could be intertwined through mutual correlation with reaction plane.

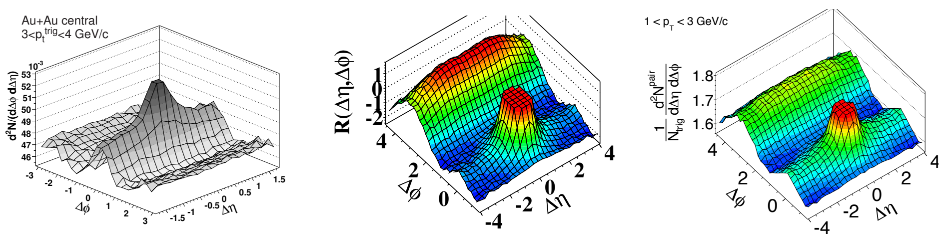


Fig. 2. Ridge in di-hadron correlations from high multiplicity events. Left: central 200 GeV Au–Au collisions from STAR/RHIC experiment. Middle: di-hadron correlations from high multiplicity $pp$ collisions at 2.76 TeV reported by the CMS experiment at LHC. Right: di-hadron correlations from high multiplicity p–Pb collisions at 5.02 TeV measured by CMS/LHC.

To quantify the effects of the medium on propagating partons, the jet-like correlations from heavy ion collisions are compared with the reference, created from either $pp$ or d–Au data, where no QGP medium was expected to be formed. To separate the collective effects, described in previous section, the initial analysis of di-hadron correlations in relative azimuth ($\Delta\phi$) was later expanded by adding the second dimension on relative pseudorapidity ($\Delta\eta$). The first 2D angular correlation data from [12] is shown in the left panel of Fig. 2. A novel feature, the *ridge*, discovered for the first time at RHIC in that study, could be seen in the figure on the near side of the trigger particle (small $\Delta\phi$), extending to large relative pseudorapidities. The correlation visually splits into a small-angles peak, resembling the jet structures from the elementary collisions, and a long-range $\eta$-independent part, that has not been seen before. The short-range correlations contain the majority of jet-related contributions, but also may include HBT effects and products of resonance decays. The later contributions are expected to be negligible for high-$p_T$ triggers. The ridge-like $\eta$-independent part of the correlated signal was commonly attributed in recent years to the higher order flow harmonics, specifically, the triangular flow $v_3$. New experimental results from the CMS experiment at LHC have uncovered a similar ridge structure first in the very-high multiplicity $pp$ collisions at 2.76 TeV [13], see middle panel of Fig. 2. Last year another ridge discovery has been reported by CMS Collaboration (Fig. 2, right), this time in high multiplicity p–Pb data at 5.02 TeV [14], which was also confirmed by ALICE and ATLAS experiments [15, 16]. The Fourier analysis of the long-range correlations from the p–Pb data yielded magnitudes for the second and third harmonics comparable to those measured in Pb–Pb events of similar multiplicity.

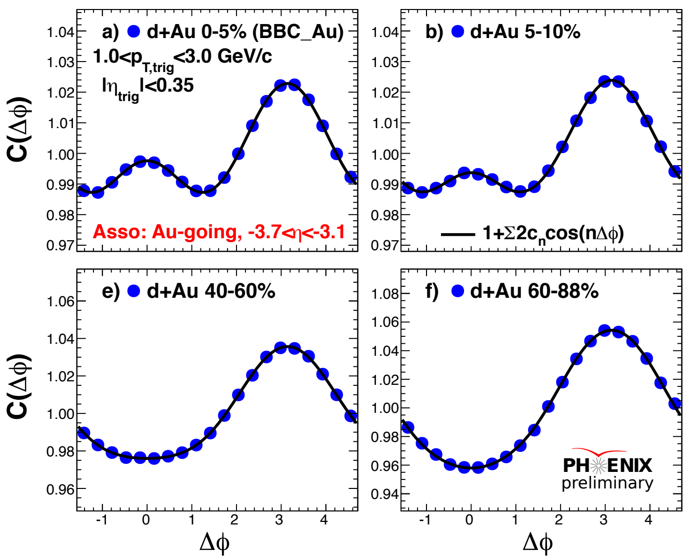


Fig. 3. Azimuthal projections of long-range di-hadron correlations for different multiplicity classes of 200 GeV d–Au collisions from PHENIX. Mid-rapidity hadrons with transverse momentum above 1 GeV/$c$ were selected as triggers. The correlations are then constructed with forward (Au-going) hadrons in the rapidity region of -3.7< $\eta$ <-3.1. Fourier fits to the data are shown as solid lines.

In light of these discoveries the long-range correlation measurements were revisited for 200 GeV d–Au collisions with a new larger data set recorded at RHIC in the year 2008. For the PHENIX experiment, this new data set has also allowed to take advantage of the newly commissioned Muon Piston detectors, providing charged track measurements at forward(backward) rapidities at $3.1 < |\eta| < 3.7$ (3.9). The hadrons reconstructed in the Central Arms and the Muon Piston detectors have an significant rapidity gap, suppressing the jet-like contributions to the di-hadron correlations constructed between them. The analysis has been performed for various event multiplicities, and separately for d- and Au-going directions [17]. In most central (high multiplicity) d–Au events a ridge-like structure at small $\Delta\phi$ angles has been reported as shown in Fig. 3, while no such feature was seen in lower multiplicity events or in the d-going direction. The STAR experiment is in the process of analyzing the long-range correlations from the new d–Au data as well. At the moment the preliminary STAR data do not show significant ridge-like yield on the near side of the trigger hadron [18]. A direct comparison of correlation structures for two

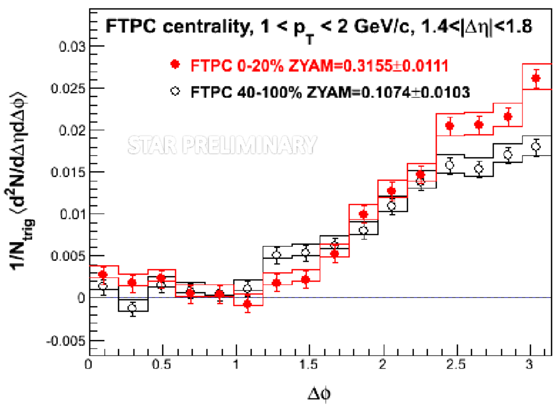


Fig. 4. Long-range di-hadron correlations from 20% most central (filled symbols) and 50-100% most peripheral (open symbols) 200 GeV d–Au collisions from STAR. The kinematic selection is indicated on the figure; the random combinatoric background is subtracted with a zero-yield-at-minimum method.

multiplicity bins (20% central and 50-100% peripheral) of d–Au collisions from STAR experiment is shown in Fig. 4: no appreciable difference can be seen on the near-side for the events selected.

The discovery of the ridge in high multiplicity *pp* and p–Pb collisions at LHC, and in d–Au collisions at RHIC (if confirmed) challenge the understanding of a phase structure of nuclear matter. The flow-attributed correlation features were unanticipated for the cold nuclear matter, where neither phase transition nor thermalization were predicted to happen. Despite this, theoretical calculation describing the RHIC and LHC observations of the flow-like behavior in the p–Pb and d–Au data within hydrodynamic approach have quickly followed [19, 20]. An alternative interpretation has also been put forward, in which the ridge-like correlations observed in the final state are linked to the initial state color field fluctuations in the incoming nucleons [21]. Detailed systematic investigation of the newly observed phenomenon is necessary to differentiate between these (and other possible) descriptions.

## 4. Summary

In this work recent di-hadron correlation measurements for RHIC has been discussed. Collective dynamics studies illuminated importance of the higher order azimuthal anisotropies in the final state hadron measurements. The precision measurements of corresponding higher order Fourier harmonics have been carried out, providing experimental constraints on the initial state properties of the system and the value of shear viscosity over entropy density ratio for the created medium. Unexpected long-range correlation structures have been reported by PHENIX experiment in the high multiplicity d–Au collisions at 200 GeV. Even more surprisingly, the systematic trends of the second and third Fourier harmonics extracted from the d–Au correlation analysis are found similar to those in heavy ion data. Additional studies are underway to help discriminate between the theoretical interpretations that are put forward to explain the new phenomenon.

## References


[1] H. Song, S. Bass, U. Heinz, T. Hirano, and C. Shen, Phys. Rev. Lett. **106**, 192301 (2011).

[2] M. Stephanov, PoS **LAT2006**, 024 (2006).

[3] PHENIX Collaboration, `http://www.phenix.bnl.gov`.

[4] STAR Collaboration, `http://www.star.bnl.gov`.

[5] J. Adams *et al.*, Nucl. Phys. A **757**, 102 (2005); K. Adcox *et al.*, Nucl. Phys. A **757**, 184 (2005); B.B. Back *et al.*, Nucl. Phys. A **757**, 28 (2005); I. Arsene *et al.*, Nucl. Phys. A **757**, 1 (2005).

[6] B. Alver and G. Roland, Phys. Rev. C **81**, 054905 (2010).

[7] J. Xu and C. M. Ko, Phys. Rev. C **84**, 014903 (2011).

[8] C. Gale, S. Jeon, B. Schenke, P. Tribedy, and R. Venugopalan, Phys. Rev. Lett. **110**, 012302 (2013).

[9] Y. Pandit *et al.*, Nucl. Phys. A **904-905**, 357 (2013).

[10] A. Adare *et al.*, Phys. Rev. Lett. **107**, 252301 (2011).

[11] S. A. Voloshin, A. M. Poskanzer and R. Snellings, Landolt-Brnstein Database "Relativistic Heavy Ion Physics," Vol. **23**, 5 (2010).

[12] B. Abelev *et al.*, Phys. Rev. C **80**, 064912 (2009).

[13] V. Khachatryan *et al.*, J. High Enegy Phys. **1009**, 091 (2010).

[14] S. Chatrchyan *et al.*, Phys. Lett. B **718**, 795 (2013).

[15] B. Abelev, *et al.*, Phys. Lett. B **719**, 29 (2013).

[16] G. Aad, *et al.*, Phys. Rev. Lett. **110**, 182302 (2013).

[17] A. Sickles, arXiv:1310.4388.

[18] F. Wang, *Jet Quenching at RHIC vs LHC*, RIKEN BNL Workshop (2013).

[19] G. Qin and B. Mller, arXiv:1306.3439.

[20] P. Bozek, Phys. Rev. C **85**, 014911 (2012).

[21] K. Dusling, R. Venugopalan, Phys. Rev. D **87**, 054014 (2013).