PHENIX Measurements of Correlations at RHIC

To cite this article: Arkadiy Taranenko and for the PHENIX Collaboration 2016 J. Phys.: Conf. Ser. 668 012029

View the article online for updates and enhancements.

You may also like
- The spin structure of the nucleon
  Alexandre Deur, Stanley J Brodsky and Guy F de Téramond
- Heavy-flavor measurements by the PHENIX experiment at RHIC
  Marisilvia Donadelli and (for the PHENIX Collaboration)
- A CROSS-CORRELATION ANALYSIS OF Mg ii ABSORPTION LINE SYSTEMS AND LUMINOUS RED GALAXIES FROM THE SDSS DR5
  Britt F. Lundgren, Robert J. Brunner, Donald G. York et al.
PHENIX Measurements of Correlations at RHIC

Arkadiy Taranenko (for the PHENIX Collaboration)
National Research Nuclear University “MEPhI” (Moscow Engineering Physics Institute), Kashirskoe Shosse 31, 115409 Moscow, Russia
E-mail: AVTaranenko@mephi.ru

Abstract. Relativistic heavy-ion collisions provide a unique opportunity to study the expansion dynamics and the transport properties of the produced strongly interacting quark gluon plasma (QGP). This article reviews the recent soft physics results obtained via correlation measurements from the PHENIX experiment at RHIC: space-time extent of the pion emission source and azimuthal anisotropy of the particle production.

1. Introduction
Since the discovery of the strongly interacting matter, quark gluon plasma (QGP) produced in relativistic Au+Au collisions at RHIC in 2005 [1, 2], the central goal of the experimental heavy-ion programs at both the RHIC and the LHC is the full characterization of the transport properties of the novel state of matter. The experimental observation of the large flow anisotropies at both RHIC and LHC indicates that the QGP has very low specific shear viscosity \( \eta/s \) close to its quantum limit of \( \eta/s = 1/4\pi \) [3, 4]. A crucial open question is whether a fundamental change occurs in the reaction dynamics and the particle production mechanism, when the collision system-size is reduced from the values produced in central and mid-central heavy-ion collisions, to those obtained in p+p, p+A, d+A, and peripheral heavy-ion collisions [4].

At top energies of the RHIC and the LHC, the produced QGP is essentially baryon free and the quark-hadron transition is thus a smooth crossover according to the results from the Lattice QCD calculations. For larger values of baryon chemical potential \( \mu_B \) or lower \( \sqrt{s_{NN}} \), several model calculations have indicated a first order transition [5, 6] and hence, the possible existence of a critical end point (CEP). The next crucial open question is how to locate the possible CEP point. Thus, a current strategy for experimental mapping of the phase diagram is centered on the RHIC beam energy scans, which sample reaction trajectories with the broadest possible range of \( \mu_B \) and temperatures.

This article reviews the recent soft physics results obtained via correlation measurements from the PHENIX experiment at RHIC: anisotropic flow of produced charged particles and space-time extent of the pion emission source.

Track and momentum reconstruction for charged particles were performed by combining hits from the drift chambers (DC) and pad chambers in the PHENIX central spectrometers (\(|\eta|<0.35\)). Charged particles were identified by combining time-of-flight from the two time-of-flight detectors, as well as the electromagnetic calorimeters [7, 8], with momentum reconstructed from the DC and pad-chamber hits in the magnetic field.

The magnitude of anisotropic flow of produced charged particles was quantified by the Fourier
coefficients: $v_n\{\Psi_n\} = \left< \cos n(\phi_p - \Psi_n) \right>/\text{Res}\{n, \Psi_n\}$, where $n$ is the order of the harmonics, $\phi_p$ is the azimuthal angle of the charged track reconstructed in the PHENIX central arms ($|\eta| \leq 0.35$), $\Psi_n$ is the azimuth of the estimated $n$-th order event planes and Res$\{n, \Psi_n\}$ is the event plane resolution. The azimuth of the estimated $n$-th order event planes $\Psi_n$, determined via hits in the two BBCs, and the two inner (i), outer (o) and combined (io) rings of the Reaction-Plane Detectors (RXN). The respective $\eta$ coverage for these event-plane detector pairs are $3.1 < |\eta|_{\text{HBC}} < 3.9$, $1.5 < |\eta|_{\text{RXN}} < 2.8$ and $1.0 < |\eta|_{\text{RXN}}| < 1.5$. This references to us the Event Plane (EP) method of $v_n$ measurements [7, 8, 9]. In addition we used the the long-range two-particle correlation (2PC) method, which pairs the hadrons with deposited charges in the RXN segments [9]. The relative azimuthal angle of particle hits in separate $\eta_p$ ranges $A$ and $B$, $\Delta \phi \equiv \phi_A - \phi_B$, reflects the products of the $v_n$ via $dN/d\Delta\phi \propto 1 + \sum_{n=1}2v_n^{A\phi}v_n^{B\phi}\cos(n\Delta\phi)$ [9]. We analyze the $\Delta \phi$ correlations using event mixing technique for two pair combinations; $(A, B)$=$\{\text{HAD, RXN}\}$ and $(A, B)$=$\{\text{RXN-N, RXN-S}\}$. These correlations then fix the event-averaged products $\left< v_n^{\text{HAD, RXN}}v_n^{\text{RXN}} \right>$ and $\left< v_n^{\text{RXN}}v_n^{\text{RXN}} \right>$, and allow us to obtain the $v_n$ for hadrons as $v_n^{\text{HAD}} = \left< v_n^{\text{HAD, RXN}} \right>/\sqrt{\left< v_n^{\text{RXN, RXN}} \right>$. Results in a wide centrality range are obtained by integrating centrality differential measurements with their multiplicity weight [9].

The interferometry technique of Hanbury Brown and Twiss (HBT) [10] was used to perform detailed differential measurements of two-pion correlation functions. The two-pion correlation function is defined as the ratio $C_2(q) = A(q)/B(q)$, where $A(q)$ is the measured distribution of the relative momentum difference $q = p_2 - p_1$ between particle pairs with momenta $p_1$ and $p_2$; $B(q)$ is the uncorrelated distribution, obtained from particle pairs in which each particle is selected from a different event but with similar event centralities, vertex positions, and charge sign. The relative momentum $q$ is calculated in the longitudinally co-moving system, where the longitudinal pair momentum (along the beam direction) is zero. It is also decomposed into its three components, $q_{\text{out}}$, $q_{\text{side}}$, and $q_{\text{long}}$, following the Bertsch–Pratt convention [10, 11, 13], i.e. the “out” axis points along the pair transverse momentum, the “side” axis is perpendicular to the out axis, and the “long” axis points along the beam. Correlation functions were studied as a function of collision centrality, as well as for different pion-pair transverse momenta $k_T = |p_{T,1} + p_{T,2}|/2$ or transverse mass $m_T = \sqrt{(k_T^2 + m_\pi^2)}$, where $m_\pi$ is the pion mass. The correlation functions were fitted with the following expression (in which cross-terms are assumed to be negligible) which accounts for the Bose–Einstein enhancement and the Coulomb interaction between pion pairs [11, 13]:

$$
C_2(q) = \frac{N[(\lambda(1+G(q)))]F_c + (1-\lambda)]}{G(q) \equiv \exp(-R_{\text{side}}^2q_{\text{side}}^2 - R_{\text{out}}^2q_{\text{out}}^2 - R_{\text{long}}^2q_{\text{long}}^2)},
$$

(1)

where $N$ is a normalization factor, $\lambda$ is the correlation strength, $F_c$ is the Coulomb correction factor [11, 13] evaluated with the Coulomb wave function, and $R_{\text{out}}$, $R_{\text{side}}$ and $R_{\text{long}}$ are the Gaussian HBT radii which characterize the emission source. $R_{\text{long}}$ is related to medium lifetime and $(R_{\text{out}}^2 - R_{\text{side}}^2)$ is sensitive to emission duration $\Delta \tau$ [10]. Similarly, $(R_{\text{side}} - \sqrt{2}R)$ gives an estimate for the expansion radius for small values of $m_T$. Collision centrality was determined from the charge distribution measured in the beam-beam counters. In a Monte Carlo Glauber (MC-Glauber) calculation [13] a subset of the nucleons become participants ($N_{\text{part}}$) in each collision by undergoing an initial inelastic N+N interaction. The transverse distribution of these participants in the X-Y plane has RMS widths $\sigma_s$ and $\sigma_y$ along its principal axes. We define $\bar{R}$, the characteristic initial transverse size, as $1/\bar{R} = \sqrt{(1/\sigma_s^2 + 1/\sigma_y^2)}$ [12, 13]. The $\bar{R}$, $N_{\text{part}}$ and participant eccentricity $\varepsilon$ were computed as a function of collision centrality. This simulation includes modeling of the BBC response.
2. System size and beam energy dependence of $v_2$ and HBT radii

The $N_{\text{part}}$ dependence of the elliptic flow signal $v_2$ for charged hadrons from Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}=62.4 - 200$ GeV is presented in the left part of Fig. 1 for three bins in transverse momentum $p_T$ [8]. As seen in Fig. 1, the measured $v_2$ in Cu+Cu collisions is smaller than that of Au+Au at a comparable $N_{\text{part}}$. The lower part of the panel of Fig. 1 shows the same $v_2$ data normalized by participant eccentricity $\varepsilon$. $v_2/\varepsilon$ plots show strong centrality dependence. For ideal fluids one should observe the eccentricity scaling of $v_2$: that at a given energy $v_2/\varepsilon$ should be independent on the transverse size of the system $R$. If equilibration is incomplete, then eccentricity scaling is broken and $v_2/\varepsilon$ also depends on the Knudsen number $K = \lambda/R$, where $\lambda$ is the mean free path [14]. Several works based on the assumption of the acoustic nature of the anisotropic flow suggest that viscous corrections to $v_n/\varepsilon_n$ grow exponentially as $n^2$ and $1/R$ [15, 16];

$$\ln \left( \frac{v_n(\text{cent})}{\varepsilon_n(\text{cent})} \right) \propto -\frac{\beta''}{R} \Rightarrow \beta'' = \frac{4 n^2 \eta}{3 T_s},$$

or a given $n$, Eq. 2 indicates a characteristic linear dependence of $\ln(v_n/\varepsilon_n)$ on $1/R$, with slope $\beta'' \propto \eta/s$. The validation of the linear dependence of $\ln(v_n/\varepsilon_n)$ on $1/R$ for the viscous hydrodynamical calculations for $v_n$ of charged hadrons from Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV was performed in [16]. The right part of Fig. 1 shows $\ln(v_n/\varepsilon_n)$ vs. $1/R$ for the measured $v_2$ values of charged hadrons with $p_T=1-2$ GeV. The dashed and dot-dashed curves are linear fits.

![Figure 1](image_url)

**Figure 1.** (Color online) (left) $N_{\text{part}}$ dependence of $v_2$ and $v_2/\varepsilon_2$ for charged hadrons with $p_T = 1-2$ GeV/c emerged from Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}=62.4$ GeV and 200 GeV. (right) $\ln(v_2/\varepsilon_2)$ vs $1/R$ for the same set of data points. The solid lines are linear fits. The data points are from [8].

The data confirm the linear dependence of $\ln(v_n/\varepsilon_n)$ on $1/R$. The slopes $\beta''$ are found to be the same within errors for Au+Au collisions at $\sqrt{s_{NN}}=62.4$ and 200 GeV. However, they are different for Au+Au and Cu+Cu at $\sqrt{s_{NN}}=200$ GeV, which may indicate the larger viscous damping for smaller colliding systems. The slope $\beta''$ is larger for Cu+Cu at 62.4 GeV than for 200 GeV. The later observation may suggest the beam energy scan performed for several colliding systems will provide more information which will help to constrain the temperature dependence of $\eta/s$. 

3
PHENIX Collaboration has also measured HBT radii ($R_{out}$, $R_{side}$, and $R_{long}$) for charged pion pairs in Au+Au collisions at $\sqrt{s_{NN}} = 200$, 62.4 and 39 GeV. Figure 2 shows the resulting $m_T$ dependence of the HBT radii and comparison with published results from the STAR collaboration. The results for two centrality or $N_{part}$ selections indicate the characteristic $1/\sqrt{m_T}$ dependence of $R_{out}$, $R_{side}$, and $R_{long}$ for each beam energy presented. It is consistent with hydrodynamic expansion and also indicates good agreement between the PHENIX and STAR data sets [13, 17].

Figure 3 shows the detailed centrality and $m_T$ dependence of the extracted radii for Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Figures 3(a), (b) and (c) show that the $R_{side}$, $R_{out}$ and $R_{long}$ scale linearly in transverse size of the system $\bar{R}$ and that the magnitudes of the radii for each system, are comparable at similar values of $\bar{R}$ and $m_T$. The space-time extent of the emission source at freeze-out, as measured by the HBT radii, reflects the initial size of the system, the expansion time, as well as transverse expansion rate, visible via the $1/\sqrt{m_T}$ dependence of the HBT radii. Since the expansion time is expected to scale with $\bar{R}$ [16, 15], the HBT radii are also expected to scale with $\bar{R}$ in a given $m_T$ range.

**Figure 2.** (Color online) Comparison of PHENIX and STAR HBT radii for Au+Au collisions at $\sqrt{s_{NN}} = 39.0$, 62.4 and 200 GeV as indicated. The STAR data are taken from Ref. [17]. The dashed curves are linear fits to the combined data sets.
Figure 3. (Color online) HBT radii vs. $\bar{R}$ for several $m_T$ cuts (as indicated) for (a) $R_{side}$, (b) $R_{out}$ and (c) $R_{long}$ for 0%–10%, 10%–20%, 20%–30% and 30%–40% Cu+Cu collisions, and 0%–5%, 5-10%, 10%–15%, 15-20%, 20%–30%, 30%–40%, 40%–50%, 50%–60% and 60%–70% Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV.

The quantities $(R^2_{out} - R^2_{side})$ and $[(R_{side} - \sqrt{2}\bar{R})/R_{long}]$ are related to the emission duration and expansion velocity respectively, were investigated as a function of $\sqrt{s_{NN}}$. Figures 4(a) and (b) show these dependencies obtained at $m_T = 0.26$ GeV/$c^2$ for the 5% most central Au+Au collisions of the combined PHENIX and STAR data sets [13, 17]. The observed non-monotonic pattern near $\sqrt{s_{NN}}=40$ GeV could be an indication of the softening of the equation of state near the deconfinement transition. Further detailed studies are required to make a more precise mapping, as well as to confirm that the observed patterns are linked to the critical end point in the QCD phase diagram [13].

3. Scaling properties of $v_n$ for identified hadrons

After 15 years of experiments at RHIC, the most extensive set of elliptic flow $v_2$ measurements for various hadrons with different masses, charges, quark content and hadronic cross-sections became available for the first time in the history of heavy-ion collisions. They show that, for a given centrality, elliptic flow for all observed hadrons at the top RHIC energy scale to a single curve when plotted as $v_2/n_q$ versus $K E_T/n_q$, where $n_q$ is the number of constituent quarks in a given hadron species ($n_q=2$ for mesons, $3$ for baryons) and $K E_T$ is the transverse kinetic energy for these hadrons [18, 19]. The observed $v_2$ scaling suggests that the bulk of the elliptic flow at the top RHIC energy is partonic, rather than hadronic [18, 19]. PHENIX recently measured the anisotropic flow coefficients $v_n$ for identified charged pions, kaons and protons, relative to the n-th order event planes, in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV [9].

Figures 5(a) - (c) show a comparison of $v_2(p_T)$, $v_3(p_T)$, and $v_4(p_T)$ for $\pi^+$, $K^+$, and $p + \bar{p}$ for the EP (solid points) and 2PC (open points) methods in 0%–50% central Au+Au collisions; they indicate good agreement between the two methods of analysis. $v_3(p_T)$ and $v_4(p_T)$ results show exactly the same patterns, which have been observed previously in $v_2$ measurements for identified
Figure 4. (Color online) The $\sqrt{s_{NN}}$ dependence of (a) $(R_{out}^2 - R_{side}^2)$, (b) $[\langle R_{side} - \sqrt{2} \bar{R} \rangle / R_{long}]$. The HBT radii are taken from the present work and Refs. [13, 17]. The PHENIX and STAR data points represent the results from fits to the $m_T$ dependence of the combined data sets.

4. Conclusions
In summary, the recent soft physics results obtained via correlation measurements from the PHENIX experiment at RHIC were presented and discussed. At top RHIC energy $\sqrt{s_{NN}} = 200$ GeV the higher-order harmonics $v_n$ of azimuthal anisotropy show mass ordering at low $p_T$ and and baryon-meson difference at intermediate $p_T$ very similar to what has been seen already for $v_2$. The anisotropies obey a generalization of quark number scaling where $v_n / (n_q)^{n/2}$ falls on a common trend against $K E_T / n_q$ for each $n$, which can be taken as an indication of hydrodynamic expansion, a quark coalescence process, and/or an acoustic nature of the azimuthal anisotropy. The observation of the linear dependence of $\ln(v_n/\varepsilon_n)$ on $1/R$ for charged hadrons emerged from Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 62.4$ GeV and 200 GeV provides another confirmation of an acoustic nature of the azimuthal anisotropy at RHIC. The extracted HBT radii for charged pions, which are compared to recent STAR and ALICE data allow an investigation of the
dependence of the quantities $R_{\text{out}}^2 - R_{\text{side}}^2$ and $R_{\text{side}} - \sqrt{2R/R_{\text{long}}}$ which are sensitive to the emission duration and expansion velocity, respectively. Non-monotonic dependencies observed in these variables close to $\sqrt{s_{NN}} = 40$ GeV may be linked to trajectories that spend a significant fraction of time near the softest point in the equation of state. Further detailed studies are required from both experimental and theory side before any quantitative conclusions can be drawn from these results.

![Figure 5](image-url)

**Figure 5.** (Color online) Fourier coefficients for charge combined $\pi^\pm$, $K^\pm$, and $p + \bar{p}$ at midrapidity for 0%-50% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The green bands indicate the $p_T$ correlated systematic uncertainties of the $\pi^\pm$ results from the EP method. The shaded boxes around the data points are $p_T$-uncorrelated systematic uncertainties.

References

[1] K. Adcox et al. [PHENIX Collaboration], Nucl. Phys. A 757, 184 (2005).
[2] J. Adams et al. [STAR Collaboration], Nucl. Phys. A 757, 102 (2005)
[3] U. Heinz and R. Snellings, Ann. Rev. Nucl. Part. Sci. 63, 123 (2013)
[4] Y. Akiha et al., arXiv:1502.02730 [nucl-ex].
[5] M. A. Stephanov, Prog. Theor. Phys. Suppl. 153 (2004) 139 [Int. J. Mod. Phys. A 20 (2005) 4387]
[6] S. Ejiri, Phys. Rev. D 78, 074507(2008)
[7] A. Adare et al. [PHENIX Collaboration], Phys. Rev. Lett. 107 (2011) 252301
[8] A. Adare et al. [PHENIX Collaboration], Phys. Rev. C 92 034913 (2015)
[9] A. Adare et al. [PHENIX Collaboration], arXiv:1412.1038 [nucl-ex].
[10] M. A. Lisa, S. Pratt, R. Soltz and U. Wiedemann, Ann. Rev. Nucl. Part. Sci. 55 (2005) 357
[11] S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. Lett. 93 (2004) 152302
[12] M. L. Miller, K. Reygers, S. J. Sanders and P. Steinberg, Ann. Rev. Nucl. Part. Sci. 57 (2007) 205
[13] A. Adare et al. [PHENIX Collaboration], arXiv:1410.2559 [nucl-ex].
[14] R. S. Bhalerao, J. P. Blaizot, N. Borghini and J. Y. Ollitrault, Phys. Lett. B 627 (2005) 49
[15] P. Staig and E. Shuryak, Phys. Rev. C 84 (2011) 034908
[16] R. A. Lacey, A. Taranenko, J. Jia, D. Reynolds, N. N. Ajitanand, J. M. Alexander, Y. Gu and A. Mwai, Phys. Lett. 112 (2014) 8, 082302
[17] L. Adamczyk et al. [STAR Collaboration], Phys. Rev. C 92 (2015) 1, 014904
[18] A. Adare et al. [PHENIX Collaboration], Phys. Rev. Lett. 98 (2007) 162301
[19] R. A. Lacey and A. Taranenko, PoS C FRNC2006 (2006) 021
Figure 6. (Color online) Quark-number ($n_q$) scaling for 0%–50% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, where $n_q$ is the constituent valence quark number of each hadron. Systematic uncertainties are shown as in Fig. 5.