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Evolution of the differential transverse momentum correlation function with centrality in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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Measurements carried out at the Relativistic Heavy Ion Collider (RHIC) during the last decade indicate that a strongly interacting quark gluon plasma (sQGP) is produced in heavy nuclei collisions at very high beam energies [1]. It has emerged that this matter behaves as a "nearly perfect liquid", i.e., a liquid which has a very small shear viscosity per unit of entropy [1,2]. It is a fascinating observation that the medium produced in relativistic heavy ion collisions reaches exceedingly large temperatures, of the order of $2 \times 10^{12}$ K [3], in stark contrast to the very low temperature, $T < 3$ K, required to achieve superfluid $^4$He [4].

Conclusions concerning the shear viscosity per unit of entropy of the medium produced in Au+Au collisions at RHIC are based largely on comparisons of non-dissipative hydrodynamical calculations of the time evolution of collision systems with measurements of the particle production azimuthal anisotropy characterized by the elliptic flow coefficient $v_2$ [2,5]. These calculations describe the $v_2$ and momentum spectra measured in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV well at midrapidity ($|\eta| < 1.0$), low transverse momentum ($p_T < 1$ GeV/$c$), and for mid-central collisions (impact parameter $b < 5$ fm) [1,5,6]. A measure of fluidity is provided by the ratio of shear viscosity, $\eta$, to entropy density, $s$, henceforth referred to as $\eta/s$. It has been conjectured that the limit for all relativistic quantum field theories at finite temperature and zero chemical potential is close to the Kovtun–Son–Starinets (KSS) bound, $\eta/s_{KSS} = (4\pi)^{-1} \approx 0.08$ [27]. Estimates of $\eta/s$ based on $v_2$, measured in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, range significantly below the viscosity per unit of entropy ratio of superfluid $^4$He and very close to the quantum limit [25,8,9].

Given the importance of viscosity in furthering our understanding of QCD matter, it is of interest to consider alternative measurement techniques to estimate the magnitude of $\eta/s$. Measurements of di-hadron correlations in heavy ion collisions, carried out as a function of the relative azimuthal particle emission angle, $\Delta\phi$, have greatly advanced the studies of hot and strongly interacting matter at RHIC [10]. Indeed, studies of correlations between low and high $p_T$ particles have revealed the modification of away-side ($\Delta\phi \sim \pi/2$) jets and the formation of a longitudinally elongated near-side ($\Delta\phi \sim 0$) structure, known as the ridge, in central Au+Au collisions [11]. Meanwhile, low-$p_T$ di-hadron correlation studies reveal rich correlation structures, particularly on the away-side [11]. However, the interpretation of these different measurements is not trivial, and a number of competing models invoking different reaction mechanisms have been suggested to explain the data, each with relative success [12,13]. Thus, additional observables and measurements are required to discriminate fully among these competing models.

In this work, we present measurements of the differential extension of an integral observable $C$ [8] in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The correlation function $C$ is defined as follows:

$$C(\Delta\eta, \Delta\phi) = \frac{\left(\sum_{i=1}^{n_1} \sum_{j=1}^{n_2} p_T^i p_T^j \right)}{n_1 n_2} - \langle p_T^1 \rangle \langle p_T^2 \rangle$$

where $(p_T^k)_k = (\sum_{i=1}^{n_k} p_T^i)_k/\langle n_k \rangle$ is the average momentum, the label $k$ stands for particles from each event and the brackets represent event ensemble averages, $\langle n_i \rangle$ is the average number of particles emitted at $(\eta_i, \phi_i)$. The indices $i$ and $j$ span all particles in a $(\eta_i, \phi_i)$ bin. $\Delta\eta = \eta_1 - \eta_2$ and $\Delta\phi = \phi_1 - \phi_2$ are the relative pseudorapidity and azimuthal angle of measured particle pairs, respectively.

The correlation observable $C(\Delta\eta, \Delta\phi)$, defined above, is an extension of the number correlation function $R_2$ used in various studies [14]. By construction, it measures the degree of correlation between particles emitted at fixed relative pseudorapidity, $\Delta\eta$, and azimuthal angle difference, $\Delta\phi$, and is as such sensitive to various aspects of the collision dynamics. However, the explicit transverse-momentum weighing provides for additional sensitivity to discriminate and study soft (low $p_T$) vs. hard (high $p_T$) processes. Note that $C$ differs structurally and quantitatively from the observables $\langle p_T^1 p_T^2 \rangle$ [15] and $\Delta\eta^2$ [16] previously reported by STAR. Differences stem from the fact that $C$ is sensitive not only to number density fluctuations, but also to $p_T$ fluctuations, and as such reflects the magnitude of in-medium momentum current correlations [8].

This study is based on an analysis of $8 \times 10^6$ minimum bias (MB) trigger events recorded by the STAR experiment in the year 2004 (RHIC Run IV). The MB trigger was defined by requiring a coincident signal of two zero-degree calorimeters (ZDCs) located at $\pm 18$ m from the center of the STAR Time Projection Chamber (TPC). Data were acquired with forward (+$z$-axis) and reverse (−$z$-axis) solenoidal magnetic field polarity with nominal field strength of 0.5 T. Collision centrality was estimated based on the uncorrected primary track multiplicity within $|\eta| < 1.0$. Nine centrality classes corresponding to 0–5% (most central), 5–10% up to 70–80% (most peripheral) of the total cross-section were used. A mean number of participants, $N_{\text{part}}$, is attributed to each fraction of the total cross-section using a Glauber Monte Carlo simulation [17].

The analysis is restricted to charged-particle tracks measured in the TPC with $|\eta| < 1.0$. Particles of interest for our measurement are those emerging from the bulk of the matter. Comparisons of RHIC data to hydrodynamic models show that the (near) equilibrium description only holds for particles with $p_T < 2$ GeV/$c$. For larger momenta, particle production is dominated by hard processes. Thus, we restrict this measurement to low $p_T$, i.e., with both particles in the range $0.2 < p_T < 2.0$ GeV/$c$. Tracks were selected on the basis of standard STAR quality cuts [18]. To minimize acceptance effects, events were analyzed provided their collision...
the correlation function include the collision centrality definition. Sources of systematic errors on the amplitude and shape of relative statistical errors range from 0.8% in peripheral collisions to 1% in central collisions. In 70–80% peripheral collisions, the correlation function exhibits a sizable broadening of the near-side peak and anisotropic flow effects, initial state fluctuations, and modified jet fragmentation. In mid-central collisions (30–40%), the correlation function exhibits a sizable broadening of the near-side peak and the formation of a near-side ridge-like structure, as well as a strong elliptic flow, \( \cos(2\Delta \phi) \), modulation \[20\]. In the most central collisions (0–5%), we observe further longitudinal broadening of the near-side peak while the \( \cos(2\Delta \phi) \) modulation and away-side structures have a much reduced amplitude.

We next focus on the longitudinal broadening of \( C \) with increasing \( N_{\text{part}} \) based on \( \Delta \eta \) projections in the range \( |\Delta \phi| < 1.0 \) radians. Figs. 2(a)–2(c) show the projections for 70–80%, 30–40%, and 0–5% centrality in \( \text{Au} + \text{Au} \) collisions at \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \). \( C \) is plotted in units of \( (\text{GeV}/c)^2 \), and the relative azimuthal angle \( \Delta \phi \) in radians.
responds to the baseline, in determining Fig. 3. RMS as function of the number of participating nucleons for the correlation axis for 70–80% centrality, (b) 30–40% centrality, and (c) 0–5% centrality in Au \( \times \) Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV. The correlation function \( C_{b} \) for nine centrality classes in Au \( \times \) Au at \( \sqrt{s_{NN}} = 200 \) GeV. The correlation function \( C \) is plotted in units of \( \text{GeV}/c^2 \). The solid line shows the fit obtained with Eq. (2). The dotted line corresponds to the baseline, \( b \), obtained in the fit and shaded band shows uncertainty in determining \( b \).

\[
g(b, a_w, \sigma_w, a_n, \sigma_n) = b + a_w \exp(-\Delta \eta^2/2\sigma_w^2) + a_n \exp(-\Delta \eta^2/2\sigma_n^2) \quad (2)
\]

where \( a_w \) and \( a_n \) stand for the amplitude of wide and narrow Gaussians with widths \( \sigma_w \) and \( \sigma_n \), respectively. The offset, narrow Gaussian, wide Gaussian, and full fit are shown in Fig. 2(a) for peripheral collisions. The fits have \( \chi^2 \) per degree of freedom values of order unity. The fits are used uniquely for the determination of the offset \( b \). The amplitudes and widths of the Gaussians are not used in the remainder of this analysis. Uncertainties in the determination of the offset, \( b \), are shown as dark gray shaded areas in Fig. 2.

Fig. 3 shows the RMS of the correlation function as a function of \( N_{part} \). Vertical lines indicate statistical errors whereas systematic uncertainties on the RMS are indicated by the gray shaded band. Systematic uncertainties arise from several sources. The correlation width exhibits small instrumental dependencies on the magnetic field direction, and the collision vertex position of the order of 3% and 4% respectively in most central collision and much smaller in peripheral collisions. Track merging corrections, discussed above, account for particles losses at \( |\Delta \eta| < 0 \), \( |\Delta \phi| < 1.0 \) and lead to negligible, \( \ll 1 \% \), systematic errors on the RMS of the distributions. The correction technique used does not account for losses at \( |\Delta \eta| < 0.032 \) and \( |\Delta \phi| < 0.087 \) radian (bin at the origin) which are most severe in 0–5% central collisions. This bin is also subject to contamination from e\(^+\)e\(^-\) pairs resulting from photon conversions within the apparatus. We estimated the latter two effects introduce small systematic uncertainties, \( \ll 2 \% \), on the RMS of the correlation functions. The largest source of systematic uncertainties stems from the baseline determination and the lack of knowledge of the correlation’s long \( \Delta \eta \) range behavior, particularly in central collisions. In order to study these effects, we first estimated a lower bound of RMS values, shown as a dotted line in Fig. 3, by setting the offset equal to the value of the correlation signal at \( \Delta \eta = 2.0 \). This simplistic calculation shows that the RMS exhibits a monotonic growth from peripheral to central collisions. In peripheral collisions, the correlation peak stands atop an approximately flat background but in most central collisions the peak is manifestly broader than the acceptance and this simple estimate is therefore incorrect. We thus used Eq. (2) and systematically studied fits for various number of parameters and fit ranges. Estimated systematic uncertainties on the offset are shown as gray bands in Fig. 2. Uncertainties on the offset and shape of the distribution, particularly in central collisions, lead to systematic uncertainties on the RMS ranging from 10% in peripheral collisions to 15% in most central collisions. The above systematic uncertainties are summed in quadrature and shown as a gray shaded band in Fig. 3. The RMS exhibits a modest increase in the range \( N_{part} < 100 \) which may in part result from long range multiplicity fluctuations and from incomplete system thermalization achieved in small collision systems. The RMS rises rapidly in the range \( 100 < N_{part} < 250 \) after which it levels off.

According to [8], shear viscosity should dominate the broadening of the correlation function for sufficiently large and nearly thermalized collision systems. It should thus be possible to utilize the observed broadening to estimate the viscosity of the matter produced in these collisions. However, jets and jet quenching could also in principle contribute to changes in the shape and broadening of the width of the correlation function with varying collision centralities. To examine this possibility, we repeated our analysis in the \( 0.2 < p_T < 1.0 \) GeV/c and \( 0.2 < p_T < 20.0 \) GeV/c ranges. Our study shows that particles accepted between \( 0.2 < p_T < 20.0 \) GeV/c produce essentially identical widths in peripheral collisions. In central collisions, RMS reduces by \( \sim 7 \% \) from the RMS widths obtained for the \( p_T \) selection \( 0.2 < p_T < 2.0 \) GeV/c.

![Fig. 2](image1.png)  
Fig. 2. (a) Projection of the correlation function \( C \), for \( |\Delta \phi| < 1.0 \) radians on the \( \Delta \eta \) axis for 70–80% centrality, (b) 30–40% centrality, and (c) 0–5% centrality in Au \( \times \) Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV. The correlation function \( C \) is plotted in units of \( \text{GeV}/c^2 \). The solid line shows the fit obtained with Eq. (2). The dotted line corresponds to the baseline, \( b \), obtained in the fit and shaded band shows uncertainty in determining \( b \).

![Fig. 3](image2.png)  
Fig. 3. RMS as function of the number of participating nucleons for the correlation function \( C \), for nine centrality classes in Au \( \times \) Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV. The dotted line represents a lower limit estimate of the RMS explained in the text and the shaded band represents systematic uncertainties on the RMS.
However, lowering the upper $p_T$ cut to 1.0 GeV/c (0.2 $< p_T < 1.0$ GeV/c) does not change the widths within statistical errors for 0.2 $< p_T < 2.0$ GeV/c range for the most central collisions, and decreases the widths by ~10% in peripheral collisions. We conclude that broadening effects associated with jets or jet quenching are thus likely limited to less than a 10% effect on the RMS from peripheral to central collisions. We thus proceed to estimate the shear viscosity per entropy of the matter produced in central collisions based on the following formula from Ref. [8]:

$$\sigma_c^2 - \sigma_0^2 = 4\frac{\eta}{\tau_{c,s}^0 (\tau_{c,f}^0 - 1)}$$

(3)

where $\sigma_c$ and $\sigma_0$ stand for the longitudinal widths of the correlation function in central collisions and at formation time, respectively. $\tau_0$ refers to the formation time and $\tau_c$ is the kinematic freeze-out time at which particles have no further interactions [21]. $T_c$ stands for a characteristic temperature of the system through its evolution, and is here taken to be the critical temperature. We proceed by assuming that viscous broadening dominates the increase in $C$ with increasing centrality observed in this analysis and utilize Eq. (3) to estimate $\eta/s$. We estimate $\eta_0 = 0.54 \pm 0.02 (stat) \pm 0.06(sys.)$ by extrapolating the RMS width of $C$ to $N_{part} \to 2$. The RMS value for most central collisions is $\sigma_c = 0.94 \pm 0.06 (stat) \pm 0.17(sys.)$. Using commonly accepted estimates of 1 fm/c, 20 fm/c, and 170 MeV [8] for the formation time, central collision freeze-out, and effective temperature, we obtain a value of $\eta/s = 0.13 \pm 0.03$. Inclusion of systematic uncertainties on the widths leads to a range of $\eta/s = 0.06-0.21$.

Fig. 4 shows $\eta/s$ as a function of $\tau_{c,f}^0 - 1$ and provides an estimate of theoretical uncertainties based on a literature survey of theoretical estimates for $\tau_0$ and $T_c$. $\tau_0$ is typically assumed to be in the range 0.6–1.0 fm/c (e.g., [8,21,22]). Here, we have assumed that the broadening of $C$ is entirely due to viscous effects. Given that other (unknown) dynamical effects could perhaps also lead to the correlation function broadening, we conclude that our measurement provides an upper limit. Based on the statistical and systematic uncertainties of our measurement (using one standard deviation) and caveats of the used theoretical model, and using the ranges $150 < T_c < 190$ MeV and $0.6 < \tau_{c,f}^0 - 1 < 1.6$ (fm/c)$^{-1}$, we derive an upper limit of order $\eta/s \sim 0.3$.

In summary, we present first measurements of the differential transverse momentum correlation function $C$ from Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. In peripheral collisions, $C$ has a shape qualitatively similar to that observed in measurements of number density correlations, with a relatively narrow near-side peak near $\Delta \eta \approx \Delta \phi \approx 0$ and a longitudinally broad away-side [10,16]. We find that the near-side peak progressively broadens with increasing number of collision participants while the overall strength of the correlation function decreases monotonically. These results may be used to further constrain particle production and correlation models. We used the observed longitudinal broadening to estimate $\eta/s$ of the matter formed in central Au + Au collisions. Considering systematic uncertainties in the determination of correlation widths, particularly in central collisions, and assuming somewhat conservative estimates of the temperature, formation and freeze-out times, we obtain a range of $\eta/s = 0.06-0.21$. This result is remarkably close to the KSS bound, $(4\pi)^{-1}$, and is consistent with results obtained from hydrodynamical model comparisons to elliptic flow data [5].

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