Estimation of shear viscosity based on transverse momentum correlations

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Abstract

Event anisotropy measurements at RHIC suggest the strongly interacting matter created in heavy ion collisions flows with very little shear viscosity. Precise determination of “shear viscosity-to-entropy” ratio is currently a subject of extensive study [1]. We present preliminary results of measurements of the evolution of transverse momentum correlation function with collision centrality of \( \text{Au} + \text{Au} \) interactions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). We compare two differential correlation functions, namely inclusive [2] and a differential version of the correlation measure \( \tilde{C} \) introduced by Gavin et al. [1,3]. These observables can be used for the experimental study of the shear viscosity per unit entropy.

Key words: azimuthal correlations, QGP, Heavy Ion Collisions 25.75.Gz, 25.75.Ld, 24.60.Ky, 24.60.k

1. Introduction

Measurements of elliptic flow at RHIC (Relativistic Heavy Ion Collider) indicate based on comparisons with ideal hydrodynamics calculations that the quark gluon plasma produced in heavy ion collisions is a nearly perfect liquid [4]. A measure of fluidity is provided by the ratio of shear viscosity to entropy density (\( \eta/s \)). Calculations based on Super-symmetric gauge theories [5] and uncertainty principle [6] suggest a lower bound, \( \eta/s \geq 1/4\pi \). Elliptic flow has been the basic experimental probe for the estimation of \( \eta/s \). Based on recent measurements of elliptic flow and comparison with hydro models, the estimated range is \( 1 < 4\pi\eta/s < 5 \). This suggests that the matter produced in \( \text{Au} + \text{Au} \) collisions is indeed a low viscosity medium [7].

In this paper, we present preliminary results of an alternative technique to determine the medium viscosity. The technique, proposed by Gavin et al. [1], relies on measurements of the collision centrality evolution of transverse momentum two-particle correlation functions. This \( \eta/s \) is estimated based on the longitudinal broadening of the correlations with increasing collision centrality. The broadening arises from longitudinal diffusion of momentum currents. It is quantitatively determined by the magnitude of the kinematic viscosity, \( v = \frac{\eta}{T} \) (where “\( T \)” stands for temperature), and the lifetime of the colliding system. We use differential extensions of the integral correlation observable \( \tilde{C} \) proposed by Gavin et al. [1].
We present measurements of $\tilde{C}$ and inclusive ($\tilde{\rho}_2^{\Delta\eta,\Delta\varphi}$) as a function of the relative pseudorapidity and azimuthal angles of the measured particles. The observable $\tilde{C}$ is defined as

$$
\tilde{C} = \frac{\left\langle n_i(\eta, \varphi) n_i(\eta, \varphi) \sum_{j=1}^{n_i} p_{a,i}(\eta, \varphi, 1) p_{a,j}(\eta, \varphi, 2) \right\rangle}{\left\langle n_i(\eta, \varphi) \right\rangle \left\langle n_i(\eta, \varphi) \right\rangle} - \left\langle \left( \sum_{j=1}^{n_i} p_{a,i}(\eta, \varphi, 1) \right) \left( \sum_{j=1}^{n_i} p_{a,j}(\eta, \varphi, 2) \right) \right\rangle
$$

and inclusive is defined as

$$
\tilde{\rho}_2^{\Delta\eta,\Delta\varphi} = \frac{\sum_{i=1}^{n_i} \sum_{j=1}^{n_j} (p_{a,i}(\eta_1, \varphi_1) - \langle p(\eta_1, \varphi_1) \rangle) (p_{a,j}(\eta_2, \varphi_2) - \langle p(\eta_2, \varphi_2) \rangle)}{\left\langle n_i(\eta, \varphi) \right\rangle \left\langle n_i(\eta, \varphi) \right\rangle}
$$

$n_i(\eta_i, \phi_i)$ represents the number of particles detected in an event $\alpha$ at pseudorapidity $\eta_i$ and azimuthal angle $\phi_i$. $p_{a,i}(\eta, \varphi)$ stands for the transverse momentum of the $i^{th}$ particle in an event $\alpha$. $\langle p(\eta, \varphi) \rangle$ is the average of the particle transverse momentum at $\eta$ and $\phi$ over the whole event ensemble.

2. Analysis

This analysis is based on data recorded using the solenoidal tracker at RHIC (STAR) detector during the 2004 data RHIC run at Brookhaven National Laboratory. $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV were acquired with minimum bias triggers [8]. This analysis is restricted to charged particle tracks from the STAR-Time Projection Chamber (TPC) in the momentum range $0.2 < p_T < 2.0$ GeV/c within the pseudorapidity acceptance of $|\eta| < 1.0$. A nominal cut of distance of closest approach (DCA $< 3.0$ cm) was applied in order to limit the selected tracks to primary charged particle tracks only. An event was accepted for analysis if its collision vertex lay within $|z| < 25$ cm, where $z$ stands for the maximum distance along the beam axis from the center of the TPC. The results reported here are based on 10 million minbias events. We define centrality based on primary tracks within $|\eta| < 1.0$. Centrality bins are calculated as a fraction of the total multiplicity distribution.

3. Results

Figures 1(a, c) and (b, d) show a comparison of inclusive and $\tilde{C}$ correlations functions for 70-80% & 0-5% centrality, respectively, in $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The correlation function is plotted as a function of the particles’ relative pseudorapidity, $\Delta\eta$, and azimuthal angles, $\Delta\varphi$, using 31 and 36 bins, respectively. The two observables exhibit a ridge-like structure in the most central collisions (0-5%) which is narrow in azimuth (near $\Delta\eta = 0$) and extended over particles’ relative pseudorapidity, $\Delta\eta$. In peripheral collisions both $\tilde{C}$ and inclusive feature a near-side peak centered at $\Delta\varphi = 0$, and a broad away-side ($\Delta\varphi \sim \pi$) ridge. The near side peak broadens progressively with centrality reaching a maximum in the most central collisions while the away-side amplitude progressively decreases from peripheral to central collisions. The inclusive exhibits a single near-side peak structure whereas $\tilde{C}$ features a dip near $\Delta\varphi \approx \Delta\eta \approx 0$. The cause of this dip is under investigation. We assume in this analysis that the broadening of the correlation function $\tilde{C}$ in $\Delta\eta$ is solely due to viscous diffusion effects and proceed to determine
the evolution of the $\Delta \eta$ width with collision centrality. This is accomplished by fitting the $\Delta \eta$ projections of $\tilde{C}$ in the range $|\Delta \phi| < 1.0$ radians. Figures 2(a, c) and (b, d) show $\Delta \eta$ projections for $|\Delta \phi| < 1.0$ radians for inclusive and $\tilde{C}$ correlations functions for peripheral (70-80%) and central (0-5%) collisions, respectively. We parameterize the projections with a 5-component model. A wide Gaussian approximates the overall shape of the correlation function.

$$\tilde{C}(b, a_w, \sigma_w, a_n, \sigma_n) = b + a_w \exp\left(-\Delta \eta^2 / 2\sigma_w^2\right) + a_n \exp\left(-\Delta \eta^2 / 2\sigma_n^2\right)$$

where $a_n$ and $a_w$ are the amplitude of the narrow and wide Gaussians, respectively. Similary $\sigma_n$ and $\sigma_w$ are the widths of the narrow and wide Gaussians. “b” stands for baseline in Eq. (3)

Widths obtained for peripheral ($\sigma_w, 70-80\%$) and central ($\sigma_w, 0-5\%$) collisions for $\tilde{C}$ are 0.53±0.01, 1.3±0.4, respectively. Assuming the shear viscosity dominates the broadening of the correlation function for increasing system life times, the following expression provides an estimate of the viscosity:

$$\sigma_c^2 - \sigma_p^2 = 4\nu \left( \tau^{-1}_{f,p} - \tau^{-1}_{f,c} \right)$$

where $\tau^{-1}_{f,p}$ and $\tau^{-1}_{f,c}$ stand for the freeze-out time estimates in peripheral and central collisions. $\sigma_c$ and $\sigma_p$ represent the width of the correlation functions in the central and peripheral collisions.

4. Summary

We presented measurements of differential transverse momentum correlation functions in order to estimate the value of $\eta/s$ based on the model by Gavin et.al. The determination
of $\eta/s$ will be sensitive to the freeze-out time estimate of the peripheral collisions posited by Gavin et al. [1]. However, STAR measurements [9] indicate a larger freeze-out time in peripheral collisions than that used in Ref. [1].

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