The centrality dependence of v_2/ε: the ideal hydro limit and η/s

H. Masui, J-Y. Ollitrault, R. Snellings, A. Tang

Abstract

The large elliptic flow observed at RHIC is considered to be evidence for almost perfect liquid behavior of the strongly coupled quark-gluon plasma produced in the collisions. In these proceedings we present a two parameter fit for the centrality dependence of the elliptic flow v_2 scaled by the spatial eccentricity ε. We show by comparing to viscous hydrodynamical calculations that these two parameters are in good approximation proportional to the shear viscosity over entropy ratio η/s and the ideal hydro limit of the ratio v_2/ε.

1. Introduction

The goal of the ultra-relativistic nuclear collision program is the creation and study of a new state of matter, the quark-gluon plasma. The azimuthal anisotropy of the transverse momentum distribution in non-central heavy-ion collisions is thought to be sensitive to the properties of this state of matter. The second Fourier coefficient of this anisotropy, v_2, is called elliptic flow. For a recent review see [1].

In ideal hydrodynamics v_2 is proportional to the spatial eccentricity with a magnitude which depends on the Equation of State EoS. This spatial eccentricity is defined by

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

where x and y are the spatial coordinates of the colliding nucleons in the plane perpendicular to the collision axis and where the brackets denote an average. In practice ε is not a measured quantity but obtained from model calculations, using Glauber or Color Glass Condensate (CGC) models, for instance.

The ratio v_2/ε versus particle density is a sensitive gauge to test if the system approaches ideal hydrodynamic behavior [2]. It was observed that this ratio reaches the expected ideal hydrodynamic values only for the more central collisions at the highest RHIC center of mass energy [3, 4] which indicates that certainly for non-central collisions, as well as at lower energies, and away from mid-rapidity the elliptic flow contains significant non-ideal hydro contributions.

Much of this discrepancy can be explained by incorporating the viscous contribution from the hadronic phase [5, 6, 7]. However, we expect that also the hot and dense phase must deviate from an ideal hydrodynamic description. Kovtun, Son and Starinets (KSS) [8], showed that conformal field theories with gravity duals have a ratio of shear viscosity η to entropy density s of, in natural units, $\eta/s = 1/4\pi$. They conjectured that this value is a lower bound for any relativistic thermal field theory. In addition, Teaney [9] pointed out that very small shear viscosities, of the magnitude of the bound, would already lead to a significant reduction in the predicted elliptic flow.

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Based on the centrality dependence of v_2/ε, the magnitude of η/s for the created system has been estimated recently from a transport theory motivated calculation [10, 11] and from viscous hydrodynamical calculations [12, 13]. Both approaches have their merits and drawbacks.

In these proceedings we explore how well a parameterization can be used to estimate η/s as well as the ideal hydrodynamical limit of v_2/ε which is closely related to the EoS.

2. Simple Parameterization

We use the parameterization from [2, 10] which is defined by

$$\frac{v_2}{\varepsilon} = \frac{h}{1 + B/(\frac{1}{S}\frac{dN}{dy})}, \tag{1}$$

where S is the transverse area of the collision region and h and B are the two free parameters in the fit. The parameter h corresponds to the ideal hydro limit of v_2/ε and B is proportional to η/s.

Figure 1 shows how the parameterization behaves for two different values of the ideal hydro limit (the dashed line represents the harder EoS) and two different values of η/s (the full line represents the smaller η/s). The effect of the EoS is clearly seen in the magnitude of v_2/ε in Fig. 1 and the value of η/s is reflected by the change in this magnitude versus $1/S\,dN/dy$ (for $\eta/s = 0$ the magnitude will be constant). The magnitude of η/s is easier to quantify if one plots $v_2/h\varepsilon$, as is done in Fig. 2. A larger deviation from unity at fixed value of $1/S\,dN/dy$ then indicates a larger η/s.

To test if this simple parameterization does describe a state of the art viscous hydrodynamical calculation we fit the calculations from Luzum and Romatschke [14]. Figure 3 shows that Eq. 1 well describes results from viscous hydrodynamical calculations, done with three different values of η/s and two different parameterizations of the spatial eccentricity (Glauber and CGC). As expected, v_2 is to good approximation proportional to the initial spatial eccentricity. In addition, it is seen that the deviation of v_2/ε from unity at a given $1/S\,dN/dy$ increases for larger values of η/s.

Figure 4 shows $v_2/h\varepsilon$ from viscous hydrodynamical calculations [12, 13, 14] done by different groups using the same set of values of η/s but different parameterization of the EoS and ε. The value of ε is that used in the hydrodynamical calculations while the value of h is obtained

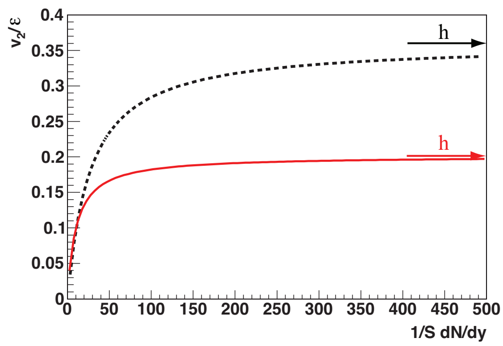

Figure 1: The dependence of v_2/ε versus transverse density of equation 1 for two values of h and two values of η/s.

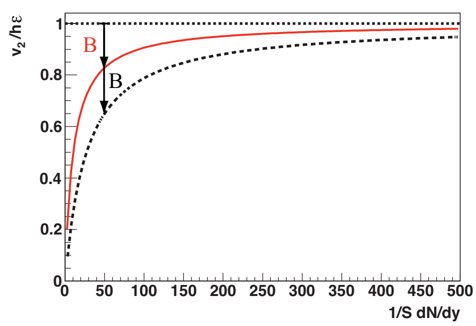

Figure 2: The dependence of $v_2/h\varepsilon$ versus transverse density of equation 1 for the same parameters as Fig. 1.

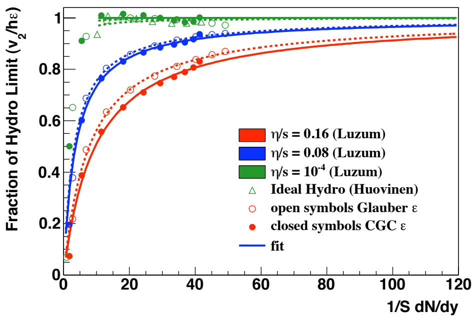

Figure 3: A fit of viscous hydrodynamical model results using CGC and Glauber initial eccentricities with Eq. 1.

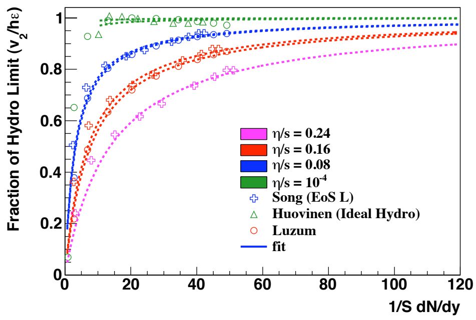

Figure 4: Comparing viscous hydrodynamical calculations of different groups with the fit

from the fit. We conclude that our parameterization yields curves that depend on the value of η/s but are roughly independent of the EoS and ε. However it turns out that if the EoS is very different (e.g. not incorporating a phase transition) this scaling does break down (not shown).

Using Eq. 1, we can now compare the various viscous hydrodynamical results with data and estimate the value of η/s. Since the value of ε is not known we take the eccentricity calculated assuming CGC [15] or Glauber (wounded nucleon) initial conditions as two extremes. It is seen from Fig. 5 that, assuming the CGC initial conditions, the STAR data is well described with twice the KSS bound, $\eta/s = 2/4\pi$. Using the Glauber initial conditions, however, the STAR data is not described within the range of η/s currently used by the viscous hydrodynamic calculations. From the deviation from unity one can estimate that the corresponding value of η/s would be approximately four times the KSS bound. Using the CGC or Glauber initial conditions we find for the ideal hydro limit of v_2/ε the value 0.20 ± 0.01 and 0.36 ± 0.07, respectively.

For the CGC initial conditions the value of h approximately matches the EoS used by Luzum and Romatschke [13]). This is illustrated in Fig. 6 where the centrality dependence of v_2 [14] is well described by CGC initial conditions, a value of $h \approx 0.2$ and $\eta/s = 2/4\pi$.

Using viscous hydrodynamics with these CGC initial conditions, EoS, and magnitude of

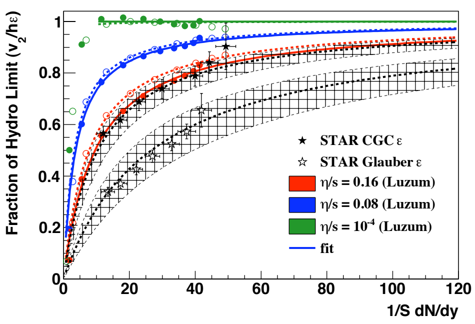

Figure 5: Comparing viscous hydrodynamical calculations with STAR data.

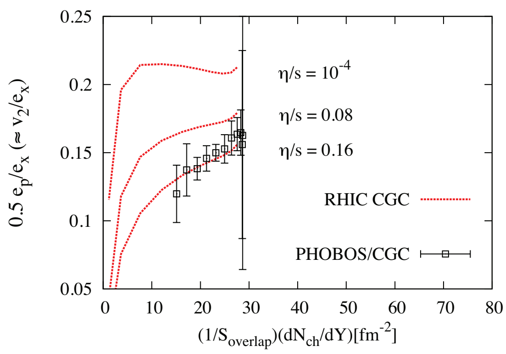

Figure 6: A direct comparison of viscous hydro calculations with PHOBOS data (from [14]).

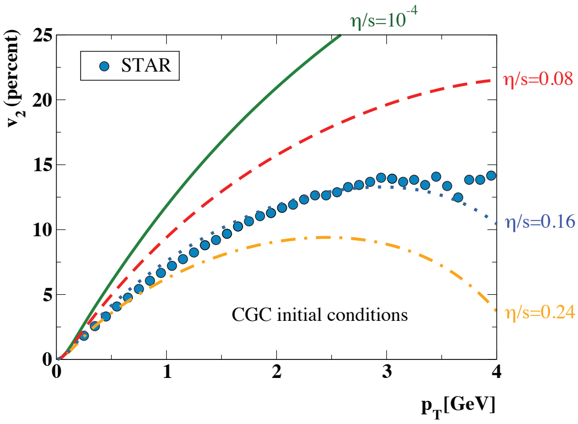

Figure 7: v_2 from STAR (approximately corrected for nonflow) compared to viscous hydrodynamical calculations (from [13]).

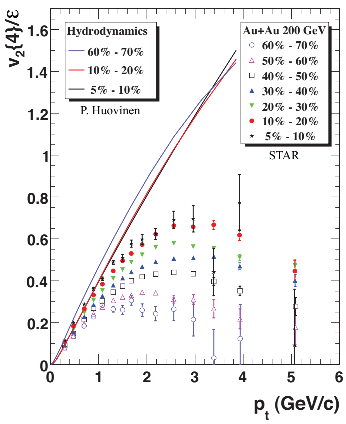

Figure 8: v_2 from STAR as function of transverse momentum and centrality.

η/s, the transverse momentum dependence of v_2 is also well described, as shown in Fig. 7. The figure illustrates that the p_t dependence is very sensitive to the viscous correction such that larger corrections decrease the magnitude of v_2 and shift its maximum to lower p_t. Figure 8 shows the centrality dependence of $v_2(p_t)$ where one clearly observes that the deviation with $\eta/s = 0$ increases from central to peripheral collisions and that the peak position shifts to lower p_t, consistent with larger viscous effects.

3. Conclusions

We have shown that a simple parameterization can describe the centrality dependence of v_2/ε. When compared to viscous hydrodynamical calculations such a parameterization yields an estimate of η/s. We find that the current RHIC data is described well by a spatial eccentricity based on CGC initial conditions, a soft EoS with $v_2/\varepsilon \approx 0.2$ and η/s twice the KSS bound.

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