Why is $v_4/(v_2)^2$ larger than predicted by hydrodynamics?[1]

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Abstract

The second and fourth Fourier harmonics of the azimuthal distribution of particles, v_2 and v_4, have been mesured in Au-Au collisions at the Relativistic Heavy Ion Collider (RHIC). The ratio $v_4/(v_2)^2$ is significantly larger than predicted by hydrodynamics. Effects of partial thermalization are estimated on the basis of a transport calculation, and are shown to increase the ratio by a small amount. We argue that the large value of $v_4/(v_2)^2$ seen experimentally is mostly due to elliptic flow fluctuations. However, the standard model of eccentricity fluctuations is unable to explain the large magnitude of $v_4/(v_2)^2$ in central collisions.

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1. Introduction

The azimuthal distribution of particles emitted in non central nucleus-nucleus collisions at RHIC is a good tool for understanding the bulk properties of the matter created during the collisions. Near the center of mass rapidity, it can be expanded in the following Fourier series:

$$\frac{dN}{d\phi} \propto 1 + 2v_2\cos(2\phi) + 2v_4\cos(4\phi) + \cdots \tag{1}$$

where ϕ is the azimuthal angle with respect to the direction of the impact parameter. The large magnitude of elliptic flow, v_2, suggests that the matter created in Au-Au collisions at RHIC behaves like an almost perfect fluid. However, ideal hydrodynamics predicts $v_4 = \frac{1}{2}(v_2)^2$ [2]. while recent experiments [3, 4] find $v_4 \simeq (v_2)^2$. In this talk, I investigate this discrepancy.

2. Fluctuations in initial conditions

2.1. Initial eccentricity fluctuations

Figure1 (left) presents a schematic picture of a non central heavy-ion collision (HIC). The overlap area between the colliding nuclei has an almond shape, which generates elliptic flow. This shape is not smooth: positions of nucleons within the nucleus fluctuate from one event to another, even for a fixed impact parameter. Therefore, the participant eccentricity, ϵ_{PP}, which is the eccentricity of the ellipse defined by the positions of participating nucleons, also fluctuates. Since elliptic flow appears to be driven by the participant eccentricity [5], eccentricity fluctuations translate into fluctuations of the flow coefficients v_2 and v_4.

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[1] These proceedings are a condensed version of [1]

Preprint submitted to Nuclear Physics A *October 2, 2009*

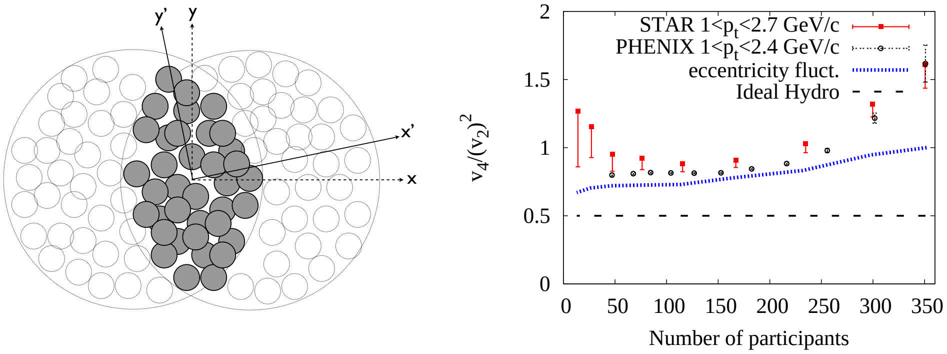

Figure 1: (Color online) Left: Picture of the two frames used for defining the initial eccentricity (from [5]). The x axis defines the reaction plane while the x' axis is the minor axis of the ellipse defined by the participants (grey dots). Right: Centrality dependence of $v_4/(v_2)^2$: data from STAR [6] and PHENIX [7]; error bars on STAR data points are our estimates of nonflow errors [1]. Lines are predictions from ideal hydro with or without fluctuations.

2.2. *Impact of flow fluctuations on* $v_4/(v_2)^2$

There is no direct way of measuring v_2 and v_4. Analysis methods rely on multiparticle correlations. Experimentally, v_2 can be extracted from the 2-particle correlation and v_4 from the 3-particle correlation using $\langle\cos(2\phi_1 - 2\phi_2)\rangle = \langle(v_2)^2\rangle$ and $\langle\cos(4\phi_1 - 2\phi_2 - 2\phi_3)\rangle = \langle v_4(v_2)^2\rangle$, where angular brackets denote an average value within a centrality class. Thus any experimental measure of $v_4/(v_2)^2$, obtained using these methods, is rather a measure of $\langle v_4(v_2)^2\rangle/\langle(v_2)^2\rangle^2$. Inserting the prediction from hydrodynamics $v_4 = \frac{1}{2}(v_2)^2$, we obtain

$$\left(\frac{v_4}{(v_2)^2}\right)_{\text{measured}} = \frac{1}{2}\frac{\langle(v_2)^4\rangle}{\langle(v_2)^2\rangle^2} > \frac{1}{2}. \tag{2}$$

We assume that v_2 scales like ϵ_{PP}, whose fluctuations can be estimated using a Monte-Carlo Glauber model [5]. The resulting prediction for $v_4/(v_2)^2$ is displayed in figure 1 (right). Fluctuations clearly explain most of the difference between hydro and data. However, experimental data are still slightly higher than our prediction from fluctuations. We argue that for peripheral to midcentral collisions, the small residual difference may be understood in terms of deviations from local equilibrium.

3. Partial thermalization effects

So far, we have assumed that ideal hydrodynamics correctly describes the expansion of matter created in a HIC. But ideal hydro assumes that the system remains in local thermal equilibrium (regime where the average number of collisions per particle n_{coll} is large) throughout the evolution. In a previous work [8] we have shown that, in order to reproduce the centrality dependence of elliptic flow, the deviation from local thermal equilibrium must be taken into account ($n_{coll} \propto 3-5$ would be a typical value for Au-Au collisions at top RHIC energy).

In the limit of small n_{coll}, one expects both v_2 and v_4 to scale like n_{coll}, so that $v_4/(v_2)^2$ scales like $1/n_{coll}$: we thus expect that the farther the system from equilibrium, the larger $v_4/(v_2)^2$ [9]. In order to have a more quantitative estimate of this effect, we use a 2+1 dimensional solution

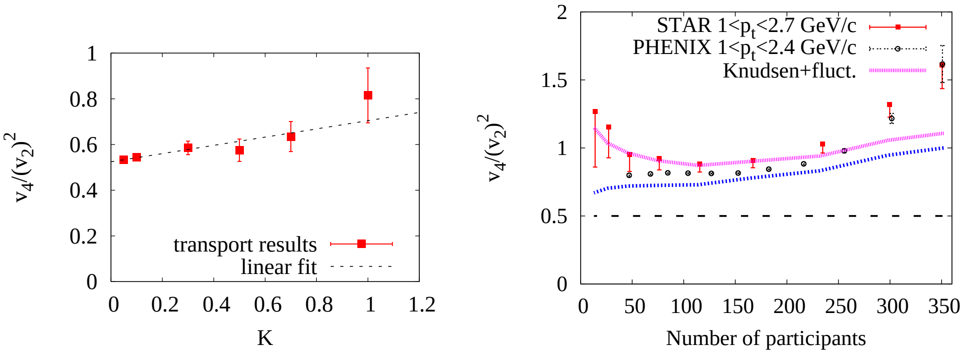

Figure 2: (Color online) Left: Variation of $v_4/(v_2)^2$ with the Knudsen number. The point at $K = 0$ are obtained using an independant ideal hydro calculation. Right: Same plot as figure 1 (right), with one additional curve showing the effect of the deviation from local equilibrium.

of the relativistic Boltzmann equation to study systems with arbitrary n_{coll}. We use the Knudsen number [9], $K \propto 1/n_{coll}$, as a measure of the degree of thermalization of the system. Figure 2 (left) displays the variation of $v_4/(v_2)^2$ with K (see [1] for details). Extrapolation to the hydrodynamic limit $K = 0$ yields the value 0.52, quite close to the expected $\frac{1}{2}$. For nonzero values of K, $v_4/(v_2)^2$ slightly increases. The effect of this increase on the centrality dependence is shown in figure 2 (right). The values of K are borrowed from a previous study [8]. When both fluctuations and partial thermalization are taken into account, our calculation slightly overshoots data for midcentral and peripheral collisions, but the overall agreement is good. We do not yet understand the large value of $v_4/(v_2)^2$ for central collisions.

4. Conclusion

We conclude that: 1) v_4 is mainly induced by v_2; 2) the deviation from local equilibrium has a small effect on $v_4/(v_2)^2$; 3) eccentricity fluctuations explain the observed values of $v_4/(v_2)^2$, except for the most central collisions which require further investigation.

Acknowledgments

This work is funded by 'Agence Nationale de la Recherche' under grant ANR-08-BLAN-0093-01.

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