Physics Letters B 713 (2012) 91–94

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Influence of shear viscosity on the correlation between the triangular flow and initial spatial triangularity

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ARTICLE INFO

Article history:
Received 4 April 2012
Received in revised form 14 May 2012
Accepted 17 May 2012
Available online 23 May 2012
Editor: J.-P. Blaizot

ABSTRACT

In a hydrodynamic model, with fluctuating initial conditions, the correlation between triangular flow and initial spatial triangularity is studied. The triangular flow, even in ideal fluid, is not strongly correlated with the initial triangularity. The correlation is largely reduced in viscous fluid. Elliptic flow on the other hand appears to be strongly correlated with initial eccentricity. Weak correlation between triangular flow and initial triangularity indicates that a part of triangular flow is unrelated to initial triangularity. Triangularity acquired during the fluid evolution also contributes to the triangular flow.

In ultra-relativistic nuclear collisions, a deconfined state of quarks and gluons, commonly called Quark–Gluon–Plasma (QGP) is expected to be produced. One of the experimental observables of QGP is the azimuthal distribution of the produced particles. In a non-zero impact parameter collision between two identical nuclei, the collision zone is asymmetric. Multiple collisions transform the initial asymmetry into momentum anisotropy. Momentum anisotropy is best studied by decomposing it in a Fourier series,

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_n v_n \cos(n\phi - n\psi_n)\right], \quad n = 1, 2, 3, \ldots, \qquad (1)$$

ϕ is the azimuthal angle of the detected particle and ψ_n is the plane of the symmetry of initial collision zone. For smooth initial matter distribution, plane of symmetry of the collision zone coincides with the reaction plane (the plane containing the impact parameter and the beam axis), $\psi_n \equiv \Psi_{RP}$, $\forall n$. The odd Fourier coefficients are zero by symmetry. However, fluctuations in the positions of the participating nucleons can lead to non-smooth density distribution, which will fluctuate on event-by-event basis. The participating nucleons then determine the symmetry plane (ψ_{PP}), which fluctuate around the reaction plane [1]. As a result odd harmonics, which were exactly zero for smoothed initial distribution, can be developed. It has been conjectured that third hadronic v_3, which is a response of the initial triangularity of the medium, is responsible for the observed structures in two particle correlation in Au + Au collisions [2–12]. The ridge structure in pp collisions also has a natural explanation if odd harmonic flow develops. Recently, ALICE Collaboration has observed odd harmonic flows in Pb + Pb collisions [13]. In most central collisions, the elliptic flow (v_2) and triangular flow (v_3) are of similar magnitude. In peripheral collisions however, elliptic flow dominates.

In a hydrodynamic model, collective flow is a response of the spatial asymmetry of the initial state. For example, elliptic flow is the response of ellipticity of the initial medium. If ellipticity in the initial medium is characterized by spatial eccentricity, $\epsilon_2 = \frac{\langle\langle y^2 - x^2\rangle\rangle}{\langle\langle y^2 + x^2\rangle\rangle}$, more eccentric is the initial medium, more flow will be generated, $v_2 \propto \epsilon_2$. Similar correlation is expected between the triangular flow and initial triangularity. Recently in [14], the correlation between triangular flow and initial triangularity is studied for fluctuating initial conditions. However, the study is limited to ideal hydrodynamics and dependence on viscosity has not been well studied. Since viscosity introduces additional length scales, qualitatively, one can argue that correlation between momentum anisotropy of produced particles and asymmetry of initial density distribution will reduce in presence of viscosity. In the present Letter, in a hydrodynamic model with fluctuating initial conditions, we have studied the effect of (shear) viscosity on the correlation between triangular flow and initial triangularity. For comparison, we have also studied the correlation between elliptic flow and initial eccentricity. In ideal fluid, elliptic flow shows strong correlation with spatial eccentricity. The correlation is weakened with viscosity. For triangular flow, even in ideal fluid, the correlation is not strong. In viscous fluid, it gets even weaker.

For the fluctuating initial conditions, we have used a model of hot spots in the initial states. Similar models are used to study elliptic flow in pp collisions at LHC [15–17]. In [18], a similar model was used to study anisotropy in heavy ion collisions due to fluctuating initial conditions. Recently, we have used the model to study viscous effects on elliptic and triangular flow [19]. In the model, it is assumed that in an impact parameter **b** collision, each

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0370-2693/$ – see front matter © 2012 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.physletb.2012.05.041

participating nucleon pair randomly deposit some energy in the reaction volume, and produce a hot spot. The hot spots are assumed to be Gaussian distributed. The initial energy density is then super position of $N = N_{participant}$ hot spots.

$$\varepsilon(x, y) = \varepsilon_0 \sum_{i=1}^{N_{participant}} e^{-\frac{(\mathbf{r}-\mathbf{r}_i)^2}{2\sigma^2}}. \tag{2}$$

The participant number $N_{participant}$ is calculated in a Glauber model. We also restrict the center of hotspots (r_i) within the transverse area defined by the Glauber model of participant distribution. The central density ε_0 and the width σ are parameters of the model. We fix $\sigma = 1$ fm. The central density ε_0 is fixed to reproduce approximately the experimental charged particles in a peripheral (30–40%) Pb + Pb collisions.

We characterize the initial density distribution in terms of eccentricity ϵ_2 and triangularity ϵ_3.

$$\epsilon_2 e^{i2\psi_2} = -\frac{\iint \varepsilon(x, y) r^2 e^{i2\phi}\, dx\, dy}{\iint \varepsilon(x, y) r^2\, dx\, dy}, \tag{3a}$$

$$\epsilon_3 e^{i3\psi_3} = -\frac{\iint \varepsilon(x, y) r^3 e^{i3\phi}\, dx\, dy}{\iint \varepsilon(x, y) r^3\, dx\, dy}. \tag{3b}$$

ψ_2 and ψ_3 in Eqs. (3a), (3b), are participant plane angle for elliptic and triangular flow respectively. Note that for the triangularity, we have used the definition due to Teaney and Yan [7]. An alternate definition was used by Alver and Rolland [5], where r^3 terms in Eq. (3b) are replaced by r^2. However, Teaney and Yan argued from theoretical consideration that in the definition of triangularity, r^3 terms are more appropriate than r^2.

Space–time evolution of the fluid was obtained by solving Israel–Stewart's 2nd order theory. We assume that in $\sqrt{s_{NN}} = 2.76$ TeV, Pb + Pb collisions at LHC, a baryon free fluid is formed. Only dissipative effect we consider is the shear viscosity. Heat conduction and bulk viscosity is neglected. Space–time evolution of the fluid was obtained by solving the following equations,

$$\partial_\mu T^{\mu\nu} = 0, \tag{4a}$$

$$D\pi^{\mu\nu} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle}\right) - \left[u^\mu\pi^{\nu\lambda} + u^\nu\pi^{\mu\lambda}\right]Du_\lambda. \tag{4b}$$

Eq. (4a) is the conservation equation for the energy-momentum tensor, $T^{\mu\nu} = (\varepsilon + p)u^\mu u^\nu - pg^{\mu\nu} + \pi^{\mu\nu}$, ε, p and u being the energy density, pressure and fluid velocity respectively. $\pi^{\mu\nu}$ is the shear stress tensor. Eq. (4b) is the relaxation equation for the shear stress tensor $\pi^{\mu\nu}$. In Eq. (4b), $D = u^\mu\partial_\mu$ is the convective time derivative, $\nabla^{\langle\mu}u^{\nu\rangle} = \frac{1}{2}(\nabla^\mu u^\nu + \nabla^\nu u^\mu) - \frac{1}{3}(\partial.u)(g^{\mu\nu} - u^\mu u^\nu)$ is a symmetric traceless tensor. η is the shear viscosity and τ_π is the relaxation time. It may be mentioned that in a conformally symmetric fluid the relaxation equation can contain additional terms [20]. Assuming boost-invariance, the equations are solved in ($\tau = \sqrt{t^2 - z^2}, x, y, \eta_s = \frac{1}{2}\ln\frac{t+z}{t-z}$) coordinates, with the code "'AZHYDRO-KOLKATA"', developed at the Cyclotron Centre, Kolkata. Details of the code can be found in [21].

Hydrodynamic equations are closed with an equation of state (EoS) $p = p(\varepsilon)$. Currently, there is consensus that the confinement–deconfinement transition is a cross over and the cross over or the pseudo critical temperature for the transition is $T_c \approx 170$ MeV [22–25]. In the present study, we use an equation of state where the Wuppertal–Budapest [22,24] lattice simulations for the deconfined phase is smoothly joined at $T = T_c = 174$ MeV, with hadronic resonance gas EoS comprising all the resonances below mass $m_{res} = 2.5$ GeV. Details of the EoS can be found in [26].

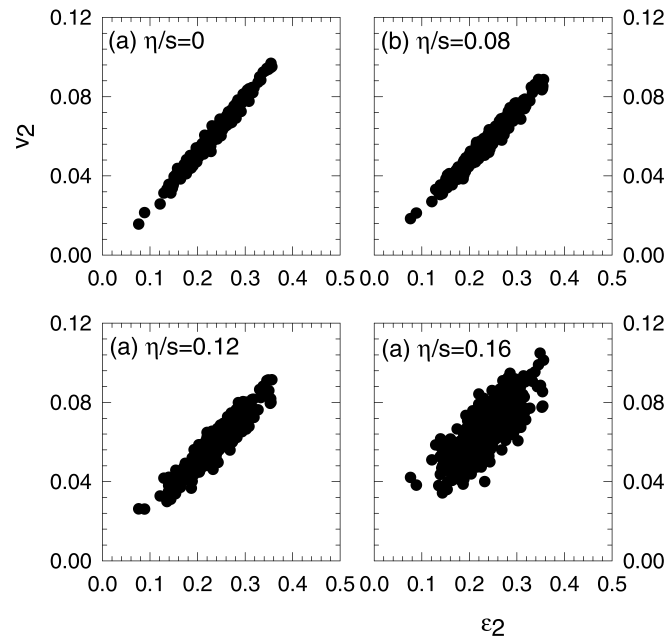

Fig. 1. In four panels (a)–(d), for fluid viscosity to entropy ratio $\eta/s = 0$, 0.08, 0.12 and 0.16, the correlation between elliptic flow (v_2) and initial eccentricity (ϵ_2) is shown. Event size is $N_{event} = 500$.

In addition to the initial energy density for which we use the model of hot spots, solution of partial differential equations (Eqs. (4a), (4b)) requires to specify the fluid velocity ($v_x(x, y)$, $v_y(x, y)$) and shear stress tensor ($\pi^{\mu\nu}(x, y)$) at the initial time τ_i. One also needs to specify the viscosity (η) and the relaxation time (τ_π). A freeze-out prescription is also needed to convert the information about fluid energy density and velocity to particle spectra. We assume that the fluid is thermalized at $\tau_i = 0.6$ fm and the initial fluid velocity is zero, $v_x(x, y) = v_y(x, y) = 0$. We initialize the shear stress tensor to boost-invariant values, $\pi^{xx} = \pi^{yy} = 2\eta/3\tau_i$, $\pi^{xy} = 0$ and for the relaxation time, we use the Boltzmann estimate $\tau_\pi = 3\eta/2p$. We also assume that the viscosity to entropy density (η/s) remains a constant throughout the evolution and simulate Pb + Pb collisions for a range of η/s. The freeze-out is fixed at $T_F = 130$ MeV.

For fluid viscosity to entropy ratio $\eta/s = 0$, 0.08, 0.12 and 0.16, we have simulated b = 8.9 fm Pb + Pb collisions. b = 8.9 fm collisions approximately corresponds to 30–40% collision. In viscous evolution, entropy is generated. To account for the entropy generation, the Gaussian density ε_0 was reduced with increasing viscosity, such that in ideal and viscous fluid, on the average, π^- multiplicity remains the same. In the present study, we have used $N_{event} = 500$ events. In each event, Israel–Stewart's hydrodynamic equations are solved and from the freeze-out surface, invariant distribution ($\frac{dN}{dy\, d^2p_T}$) for π^- was obtained. In analogy to Eqs. (3a), (3b), invariant distribution can be characterized by 'harmonic flow coefficients' [27].

$$v_n(y)e^{in\psi_n(y)} = \frac{\int p_T\, dp_T\, d\phi\, e^{in\phi}\frac{dN}{dy\, p_T\, dp_T\, d\phi}}{\frac{dN}{dy}}, \quad n = 2, 3. \tag{5}$$

In a boost-invariant version of hydrodynamics, flow coefficients are rapidity independent and in the following, we drop the rapidity dependence. Present simulations are applicable only in the central rapidity region, $y \approx 0$, where boost-invariance is most justified.

In Fig. 1, in four panels, for fluid viscosity $\eta/s = 0$, 0.08, 0.12 and 0.16, simulated elliptic flow (v_2) is plotted against initial