Vorticity and Λ polarization in event-by-event (3+1)D viscous hydrodynamics

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Abstract. We visualized the vortical fluid in fluctuating QGP using (3+1)D viscous hydrodynamics, computed the spin distribution and correlation of hyperons and estimated the polarization splitting between Λ and $\bar{\Lambda}$.

1. Introduction

In high energy heavy ion collisions, the large fluctuations and fluid velocity shear present in the colliding system lead to non-vanishing local vorticity in the hot and dense sQGP. The local vorticity couples to the large orbital angular momentum and strong magnetic field in non-central collisions [1, 2, 3, 4, 5, 6, 7, 8, 9]. As a result of spin-vorticity and spin-magnetic coupling, quarks and anti-quarks become polarized along the normal direction of the reaction plane [1, 2, 5]. After hadronization the hyperons and vector mesons also become locally and globally polarized in the final state [6, 7, 8, 9, 10, 11, 12]. Recently STAR collaboration measured the Λ polarization in Au+Au collisions at various beam energies [13], and showed that (1) the Λ polarization is stronger at low beam energies than high beam energies. (2) the polarization for $\bar{\Lambda}$ is always stronger than that for Λ. In this paper, we visualize the rotational fluid velocity vectors in transverse and reaction plane, and propose to measure the azimuthal angle distribution and correlation of Λ spins (the bridge between collective flow and quantum properties of individual particles). We also estimate quantitatively the splitting of Λ and $\bar{\Lambda}$ polarization by spin-vorticity and spin-magnetic coupling.

2. Vortical fluid in event-by-event (3+1)D viscous hydrodynamics

The rotational fluid velocity vectors are obtained from Helmholtz-Hodge decomposition [14] of the fluid four-velocity vector u^μ, which is given in CLVisc [15, 11], through numerically solving second-order viscous hydrodynamic equations. We employ AMPT [16] to generate fluctuating initial conditions, where angular momentum is given by the asymmetric distribution of forward-backward going participants and their associated strings whose lengths fluctuate strongly [17].

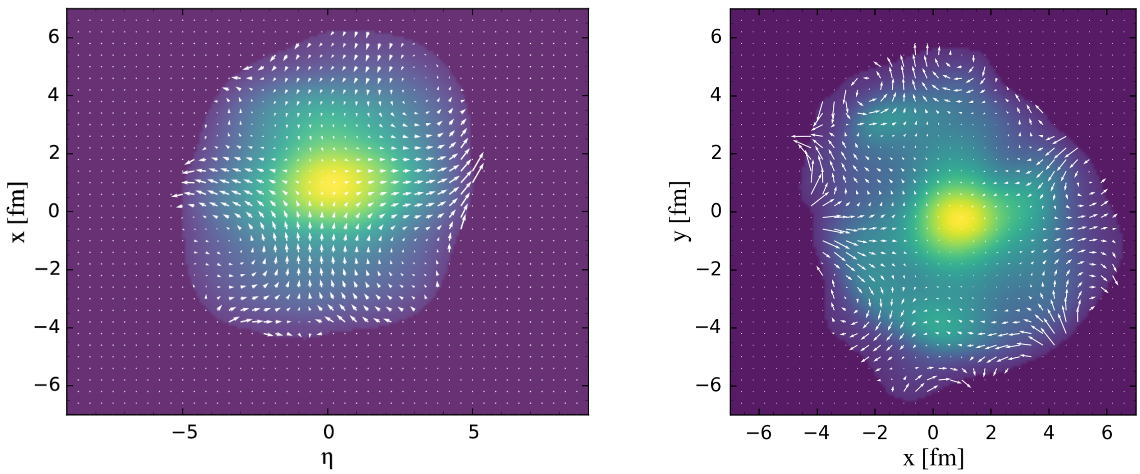

Figure 1: (color online) The rotational fluid velocity vectors in reaction plane (left) and transverse plane (right), at proper time $\tau = 3.4$ fm, for (3+1)D viscous hydrodynamic simulations with fluctuating initial condition given by AMPT.

As shown in Fig. 1, the transverse vorticity of the sQGP (left) has a circular structure around the beam direction due to the convective longitudinal flow in addition to the global alignment along the direction of the orbital angular momentum of non-central collisions. The longitudinal vorticity (right), however, has a vortex-pairing structure in a given transverse plane due to the convective radial flow of hot spots. Fermions are locally polarized on the freeze-out hypersurface given by [18, 10],

$$P^{\mu} \equiv \frac{d\Pi^{\mu}(p)/d^3p}{dN/d^3p} = \frac{\hbar}{4m}\frac{\int d\Sigma_{\alpha}p^{\alpha}\Omega^{\mu\nu}p_{\nu}f(1-f)}{\int d\Sigma_{\alpha}p^{\alpha}f}, \tag{1}$$

where f is the Fermion distribution function, $\Omega^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}\partial_{\rho}(\beta u_{\sigma})$ the thermal vorticity consisting of not only convective flow (spatial gradients of fluid velocity), but also acceleration (temporal gradients of fluid velocity) and conduction (space-time gradients of the temperature), with the temperature $T = 1/\beta$. Because of strong collectivity, four momentum of hadrons particalized on the freeze-out hypersurface have strong correlation with their space-time coordinates and their local polarization. This correlation brings azimuthal angle distribution of Λ spins. It is thus feasible to measure not only the global polarization, but also the spin correlation of two hyperons, to study these vortical structures of sQGP. The detailed studies on the hyperon spin correlations and their dependence on collision energy, rapidity, centrality and the shear viscosity are given in Ref. [11] .

3. Λ polarization from spin-vorticity and spin-magnetic coupling

Owing to spin-vorticity and spin-magnetic coupling, the energy levels of the fermions are shifted according to their spin states [19], as a result, there are more fermions or anti-fermions staying in lower energy states, which brings spin polarization that is defined as the number difference between different spin states,

$$\Pi = \frac{1}{2}\int\frac{d^3p}{(2\pi)^3}\left[f\left(E_p - \delta E_p\right) - f\left(E_p + \delta E_p\right)\right] \approx -\int\frac{d^3p}{(2\pi)^3}\delta E_p\frac{\partial f(E_p)}{\partial E_p}, \tag{2}$$

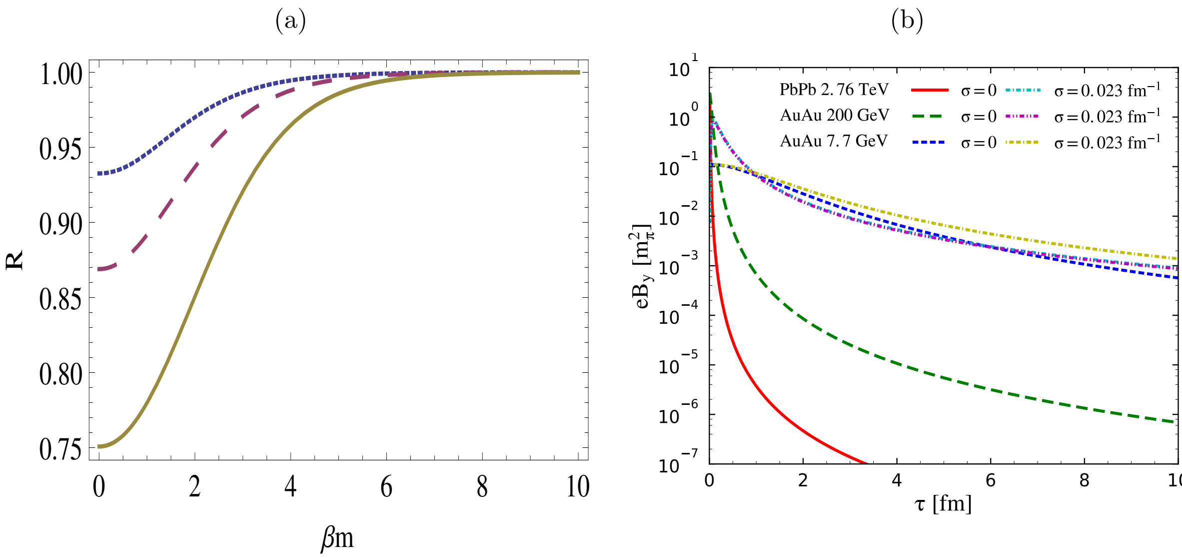

Figure 2: (color online) (a) The ratio R as functions of βm at three values $\beta\mu = 0.5, 1, 2$ corresponding to short-dashed, long-dashed and solid lines respectively. (b) The time evolution of magnetic field for Pb+Pb 2.76 TeV (solid line for $\sigma = 0$ and dash-dot line for $\sigma = 0.023$ fm^{-1}), Au+Au 200 GeV (long dashed line for $\sigma = 0$ and dash-dot-dot line for $\sigma = 0.023$ fm^{-1}), and Au+Au 7.7 GeV collisions (short dashed line for $\sigma = 0$ and dot-dash-dash line for $\sigma = 0.023$ fm^{-1}).

where $\delta E_p = \frac{\hbar}{2}\mathrm{n}\cdot\omega$ for spin-vorticity coupling and $\delta E_p = e_q\hbar\frac{\mathrm{n}\cdot\mathrm{B}}{E_p}$ for spin-magnetic coupling. The $\frac{\partial f(E_p)}{\partial E_p} = -\beta f(1-f)$ term is called susceptibility which describes how difficult it is for the fermions/anti-fermions to be polarized. The polarization per fermion for Λ and $\bar{\Lambda}$ are,

$$P_\Lambda = \beta \int \frac{d^3p}{(2\pi)^3}(\omega/2 + \mu_\Lambda B) f(1-f) \Big/ \int \frac{d^3p}{(2\pi)^3} f, \tag{3}$$

$$P_{\bar{\Lambda}} = \beta \int \frac{d^3p}{(2\pi)^3}(\omega/2 - \mu_\Lambda B) \bar{f}(1-\bar{f}) \Big/ \int \frac{d^3p}{(2\pi)^3} \bar{f}, \tag{4}$$

where f and $\bar{f}$ are distribution functions for Λ and $\bar{\Lambda}$ respectively.

The splitting between Λ and $\bar{\Lambda}$ polarization is caused by two reasons: one is the non-zero baryon chemical potential and the other is the magnetic field on the freeze-out hypersurface. If we only consider spin-vorticity coupling, the anti-fermions are much easier to be polarized than fermions due to Pauli blocking, considering that there are more fermions than anti-fermions with positive baryon chemical potential in the distribution function. The ratio of integrated polarization per particle $R = P_\Lambda/P_{\bar{\Lambda}}$ is computed as functions of βm and $\beta\mu$ where μ is the baryon chemical potential [10]. As shown in Fig. 2a, the ratio is very sensitive to baryon chemical potential and fermion mass. However, using the mass of Λ baryon brings a big βm and a very small splitting. On the other hand, spin-magnetic coupling also brings splitting between Λ and $\bar{\Lambda}$ polarization,

$$\Delta P = P_{\bar{\Lambda}} - P_\Lambda = -2\mu_\Lambda B\beta \int \frac{d^3p}{(2\pi)^3} f(1-f) \Big/ \int \frac{d^3p}{(2\pi)^3} f \approx -2\mu_\Lambda B\beta, \tag{5}$$

where $\mu_\Lambda = -0.613\mu_N$ is the Λ magnetic moment, B the strength of the magnetic field and f the distribution function for both Λ and $\bar{\Lambda}$ neglecting baryon chemical potential. The average splitting between Λ and $\bar{\Lambda}$ polarization from STAR experiment is about 0.03 at beam energy scan region ($\sqrt{s_{NN}} = 7.7$ GeV). From this the magnetic field along y direction estimated from $B = \frac{\Delta P}{-2\mu_\Lambda \beta}$ is about $1.05 m_\pi^2$ [20]. It worth noting that the current splitting measured by STAR bears an error bar of 0.02, which may increase or decrease the strength of estimated magnetic field by 60%. As a comparison, we computed the magnetic field in vacuum and a conducting medium with electric conductivity $\sigma = 0.023$ fm^{-1} following [21]. As shown in Fig. 2b, the magnetic field for Au+Au $\sqrt{s_{NN}} = 7.7$ GeV collisions is stronger than that for Au+Au 200 GeV and Pb+Pb 2.76 TeV collisions, after $\tau = 1$ fm, which qualitatively agrees with the experimental observation that the splitting at lower beam energies is bigger than top RHIC and LHC energies [20]. Quantitatively, the maximum magnetic field strength for Au+Au $\sqrt{s_{NN}} = 7.7$ GeV collisions is smaller than 0.1 m_π^2, from which the estimated splitting is 10 times smaller than what one gets from STAR experiment. Considering that hadronization usually happens at large radius and later time where magnetic field is very small, the splitting from spin-magnetic coupling would be even smaller. Notice that the electric conductivity at low beam energies does not affect the magnetic field so strongly, because the spectators fly away from each other much slower than top RHIC and LHC energies. For a fully consistent study, event-by-event (3+1)D relativistic magnetohydrodynamics is required to provide decent knowledge of the magnetic field.

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