Elliptic flow of thermal dileptons in event-by-event hydrodynamic simulation

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The elliptic flows of thermal di-electrons are investigated within a (2+1)-dimension event-by-event hydrodynamic model for Au+Au collisions at √sNN = 200 GeV. The fluctuating initial conditions are given by the Monte Carlo Glauber model. We find in our event-by-event calculation rather weak correlation between the dilepton emission angles and the event plane angles of charged hadrons. We observe strong fluctuation effects in dilepton elliptic flows when using the event plane angles of dileptons at specific invariant mass M. The correlation between the dilepton event plane angle and charged hadron one becomes stronger with decreasing M. This provides a possible measure of the interplay between the effect of geometric deformation and that of fluctuating "hot spots" in relativistic heavy ion collisions.

I. INTRODUCTION

One of the most exciting phenomena found in high-energy heavy ion collisions (HIC) at Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) is the strong collective flow of final charged hadrons [11]. This is developed by fast expansion of Quark Gluon Plasma (QGP) and the Hadron Resonance Gas (HRG) in the early/late stage of the HIC. The collective flow not only contributes to the transverse momentum spectra of hadrons but also leads to the anisotropic distribution in the transverse plane. This anisotropy is the consequence of the pressure gradient in non-central collisions which drives the initial geometric asymmetry of the overlapping region of the colliding nuclei to the momentum anisotropy of final hadrons. The second Fourier coefficient of the azimuthal distribution is called the elliptic flow. The big elliptic flow measured at RHIC and LHC suggests fast local thermalization and the formation of strongly coupled QGP close to ideal fluid [2–4]. So the space-time evolution of the hot and dense matter can be described by hydrodynamic equations [5].

One critical input in hydrodynamic simulation is the initial condition. Recently many models such as Monte Carlo Glauber, Monte Carlo Color Glass Condensate, UrQMD, AMPT and EPOS are used to produce fluctuating initial conditions for event-by-event (EBE) hydrodynamic simulations [6–9]. These EBE calculations can explain odd harmonic flows like the triangle flow and the ridge structure in two-dimensional di-hadron correlation [10], they can also provide much better fit to the transverse momentum spectra and elliptic flows of charged hadrons at RHIC and LHC energy in both central and semi-central collisions [11–16] than smooth one-shot (SM) hydrodynamic simulation with smooth initial conditions.

Different from the strongly interacting hadrons which escape from the fireball only on the equal-temperature hyper-surface at freeze-out, the electromagnetic probes like photons and dileptons, due to their instant emission once produced, are expected to provide undistorted information about the space-time information of the QGP and HRG matter [17–29]. The invariant mass spectra of dileptons are usually divided into the low, intermediate and high mass regions (LMR, IMR and HMR) based on the notion that each region is dominated by different sources of dileptons, thus provide a method to identify the different evolution stages of the expanding fireball.

The elliptic flows of dileptons have been studied in SM hydrodynamic simulations with smooth initial conditions [30–32]. However, the production rates of dileptons are sensitive to high temperature "hot spots" (fluctuations) in hot and dense medium. So the fluctuations are expected to play an important role in elliptic flows of dileptons in heavy ion collisions, which, to our knowledge, have never been investigated before. The aim of this paper is to calculate the elliptic flows of dileptons in an EBE hydrodynamic simulation with fluctuating initial conditions.

This paper is organized as follows. In Sec. II, we describe our EBE hydrodynamic model and use it to reproduce the transverse momentum spectra and elliptic flows of charged hadrons and compare to RHIC data. In Sec. III we calculate the invariant mass spectra and elliptic flows of dileptons from the EBE hydrodynamic simulation. We show the effect of fluctuations on dilepton elliptic flows with respect to the event plane defined by invariant mass dependent dilepton spectra and that defined by charged hadron spectra. We give a summary of our results in the final section.

II. EVENT-BY-EVENT HYDRODYNAMIC MODEL

We use a (2+1)-dimension ideal hydrodynamic model for the EBE simulation. Our model is similar to the AZHYDRO model [5, 6] which implements FCT-SHASTA algorithm [33, 34], but our codes are written in C++. The equation of state (EOS) with first order phase transition in the original AZHYDRO is replaced by Lattice QCD EOS which is pa-
rameterized as S95P-PCE-v0 with the chemical freeze-out temperature $T_{\text{chem}} = 165$ MeV. When the temperature of the medium is smaller than the kinetic freeze-out temperature $T_f$ (which is set to 120 MeV in this study), the spectra of the directly produced hadrons are calculated by the Cooper-Frye formula [36] that mesons/baryons are emitted from the freeze-out hyper-surface defined by $T_f$. In our model, the spatial rapidity $\eta$ is set to 0.4 fm/c. Since we use (2+1)-dimension hydrodynamic model with Bjorken boost-invariance [38] and focus on the central rapidity region, it is convenient to set the spatial rapidity $\eta$ zero.

Normally the freeze-out hyper-surfaces are calculated in cuboidal way [5, 39, 40] for each fluid cell. In the AZHYDRO model, in order to save the computing time, several fluid cells are used to generate a big piece of freeze-out hyper-surface. The flow velocity at the hyper-surface obtained in this way is an average of these cells. This will introduce accuracy with appropriately chosen bin size of the fluid velocity.

The Monte Carlo Glauber model [4] is employed to generate the profile of the fluctuating initial entropy density in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. In the Glauber model, the initial entropy density is assumed to be proportional to a linear combination of the number of participants $dN_{\text{part}}/d^2x_\perp$ and that of binary collisions $dN_{\text{coll}}/d^2x_\perp$ [41],

$$\frac{ds}{d\eta dxdy} = C \left( \frac{1 - \delta}{d^2x_\perp} + \frac{\delta}{d^2x_\perp} \right),$$

where $C = 16$ and $\delta = 0.14$ are two constants, and the initial time is chosen to be $t_0 = 0.4$ fm/c. Since we use (2+1)-dimension hydrodynamic model with Bjorken boost-invariance [38] and focus on the central rapidity region, it is convenient to set the spatial rapidity $\eta$ zero.

In Table I, the results are compared to the PHENIX data [41, 42] in the SM case, the event-averaged initial entropy density distributions are used in the hydrodynamic calculation. We use the reaction plane as reference to take event average in the SM simulation. Another method is to use the participant plane. The two methods are different in elliptic flow for most central collisions [3, 14, 16],

$$\frac{ds}{d\eta dxdy} \big|_{\eta = 0} = C \left( \frac{1 - \delta}{d^2x_\perp} + \frac{\delta}{d^2x_\perp} \right),$$

where $C = 16$ and $\delta = 0.14$ are two constants, and the initial time is chosen to be $t_0 = 0.4$ fm/c. Since we use (2+1)-dimension hydrodynamic model with Bjorken boost-invariance [38] and focus on the central rapidity region, it is convenient to set the spatial rapidity $\eta$ zero.

Table I: Centralities and numbers of participants for Au+Au@ $\sqrt{s} = 200$ GeV calculated in one million events. The centrality bins are determined by number of participants $N_{\text{part}}$. Here $N_{\text{minpart}}$ corresponds to the upper bound of the centrality bin.

| Centrality (%) | $N_{\text{minpart}}$ |
|----------------|---------------------|
| 0-10%          | 277                 |
| 10-20%         | 199                 |
| 20-30%         | 140                 |
| 30-40%         | 95                  |
| 40-50%         | 61                  |
| 50-60%         | 37                  |

Here the average is taken over final charged hadrons in one event. The second and third harmonic coefficient are often called elliptic and triangle flow.

In Fig. 1(a), we see that the $p_T$, spectra and elliptic flow of charged hadrons for both EBE (400 events for each centrality bins) and SM hydrodynamic simulation in a variety of centralities. The centrality bins are determined by the number of participants $N_{\text{minpart}}$ in TabI. The results are compared to the PHENIX data [41, 42]. In the SM case, the event-averaged initial entropy density distributions are used in the hydrodynamic calculation. We use the reaction plane as reference to take event average in the SM simulation. Another method is to use the participant plane. The two methods are different in elliptic flow for most central collisions [3, 14, 16].

We see in Fig. 1(a) that the $p_T$ spectra of charged hadrons in the EBE simulation is harder than the SM simulation in each centrality bin. The better agreement of the EBE result with data is due to the bigger pressure gradient produced from the “hot spots” which drives bigger collective flows in the early stage of hydrodynamic evolution [3, 14]. Charged hadron spectra are only sensitive to those “hot spots” which are close to the freeze-out hyper-surface, while thermal photon and dilepton spectra are influenced by all “hot spots” in whole space-time volume.

In Fig. 1(b), we see that the elliptic flows in the EBE case are lower than the SM results in semi-central and peripheral collisions, while they are higher than the SM results in central collisions. This clearly shows the fluctuation effect on the elliptic flow. We know that the elliptic flow is the result of geometric eccentricity and initial fluctuation. The geometric eccentricity gives a non-zero elliptic flow, while hot spot fluctuation gives almost an isotropic flow. In semi-central and peripheral collisions, the geometric eccentricity in the SM case is slightly smaller than that in the EBE case. The fluctuation effect greatly reduces the elliptic flow in the EBE case. In central collisions, the deviation of the participant plane from the reaction plane is larger for central collisions than peripheral collisions, so the eccentricity in the SM case is much smaller than that in the EBE case [16], which gives much smaller elliptic flow in the SM case even with the reduction effect from fluctuation in the EBE calculation.

To identify whether the harmonic flow is generated by geometric eccentricity or fluctuating “hot spots”, it is worth to study the azimuthal angle distribution of the event plane. In our hydrodynamic simulation, the reaction plane’s azimuthal angle is set to 0. In Fig. 2, we show the distribution associated with the second and third harmonic flows at centrality 20 – 30% by using 1000 hydrodynamic events with fluctuating initial energy density distributions. We see that $\Psi_3$
are completely uncorrelated with the reaction plane. The de-
correlation indicates that the triangle flows are mostly gen-
erated by fluctuating “hot spots”. However $\Psi_2$ are strongly
correlated with the reaction plane as expected since $\Psi_2$ is ac-
tually a collective flow response to the geometric deformation
[14] in semi-central and peripheral collisions.

Figure 1: (Color online) (a) Transverse momentum spectra and (b) elliptic flows $v_2$ for charged hadrons as functions of $p_T$ in different centrality bins for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The hydro-
dynamic simulations are done with fluctuating (black-solid lines) and smooth(blue-dash lines) initial conditions. In the top-down or-
der, the curves correspond to centrality bins (a) $0 - 10\%$, (10 - 20\%) $\times$ $10^3$, (20 - 30\%) $\times$ $10^2$, (30 - 40\%) $\times$ $10$, (40 - 50\%), (50 - 60\%) $\times$ $0.1$ and (b) (50 - 60\%) $\times$ 3, (40 - 50\%) $\times$ 2.5, (30 - 40\%) $\times$ 2, (20 - 30\%) $\times$ 1.5, (10 - 20\%), (0 - 10\%), where the number outside the parenthesis denotes the normalization factor of each curve. The data (symbols) are taken from the PHENIX collaboration\[41, 42\].

Figure 2: (Color online) The 2nd and 3rd event plane azimuthal angle distribution from EBE hydrodynamic simulation with 1000 fluctuat-
ing events.

Figure 3: (Color online) (a) Invariant mass spectra and (b) el-
lippetic flows of di-electrons in semi-central Au+Au collisions at $\sqrt{s_{NN}} =200$ GeV.

III. ELLIPTIC FLOW OF THERMAL DILEPTONS

The differential production rate of dileptons per unit vol-
ume can be written in the following form (see, e.g. [21, 25]),

$$
\frac{dN}{d^3x \, dp} = - \frac{\alpha}{4\pi^2} \frac{1}{M^2} n_b(p \cdot u) \left( 1 + \frac{2m_l^2}{M^2} \right) \times \sqrt{1 - \frac{4m_l^2}{M^2}} \text{Im} \Pi^R(p,T).
$$

(4)

Here $m_l$ is the lepton mass, $\alpha$ is fine structure constant, $p$
is the dilepton’s four momentum and $M = \sqrt{p^2}$ is the dile-
pton invariant mass, $n_b(p \cdot u) \equiv 1/(\exp(p \cdot u/T) - 1)$ ($T$ and
$u$ are the local temperature and fluid velocity, respectively) is
the Bose-Einstein distribution function, and $\Pi^R$ is the retarded
polarization tensor from the quark loop in the QGP phase or
the hadronic loop in the HRG phase. In the HRG phase, the
thermal dilepton production rate is dominated by in-medium $\rho$
meson decays. The details of the calculation of dilepton in-
variant mass spectra in Au+Au collisions at the RHIC energy
are given in Ref. [24, 31] by some of us. To simplify our cal-
culation, we will focus on $20 - 30\%$ centrality bin and neglect
the contribution from in-medium $\omega$ and $\phi$ meson decays.

In Fig. 3(a) we show the invariant mass spectra of di-
electrons in semi-central ($20 - 30\%$ centrality bin) Au+Au
collisions at the RHIC energy. The LMR thermal dilepton production rate is dominated by in-medium $\rho$ decays. The broadened dilepton invariant mass spectra around the mass of the free $\rho$ indicate a strong medium modification by scatterings between $\rho$ and other mesons and baryons in thermal medium. This modification is described by using hadronic many body theory \cite{33} and empirical scattering amplitude method \cite{44}. In the IMR the dileptons from QGP are dominant, and more dileptons are produced in the QGP phase in the EBE calculation (dash-dot-dot-dotted line, overlapping with the solid line) than the SM calculation (dashed). Such an enhancement is due to the “hot spots” in fluctuating initial conditions where larger-than-average temperature give a large contribution to the HMR dilepton. Similar results were found in the EBE calculation for thermal photons \cite{17}. The fluctuation effect on the invariant mass spectra in the HRG phase is negligible, since most of hadronic dileptons are produced later than the partonic ones \cite{31} and the HRG phase only appears below the transition temperature.

The differential elliptic flow coefficient $v_2(M)$ as a function of the invariant mass is given by

$$v_2(M) = \frac{\int d\phi (dN/dM d\phi dy) \cos(2(\phi - \Psi_2))}{\int d\phi (dN/dM d\phi dy)}, \quad (5)$$

where $\Psi_n$ with $n=2$ is the azimuthal angle of the event plane for final state charged hadrons in momentum space as defined in Eq. (3). The $v_2(M)$ results are shown in Fig. 3b). We see in the figure that the elliptic flows of dileptons in the HRG phase in the EBE and SM case increase with $M$. The small peak in the hadronic component around the $\rho$ mass is due to the temperature-dependent in-medium $\rho$ meson spectral functions. The elliptic flow in the QGP phase is much smaller than that in the HRG phase, since the QGP phase is in the early stage of the fireball evolution before the transverse flow is fully developed. The sharp decrease of the elliptic flow from the HGR dominated region to the QGP dominated region can be a possible signal for QGP formation in heavy ion collisions \cite{31}.

As shown in Fig. 3b), the elliptic flow with the fluctuating initial condition in the LMR/HMR is slightly larger/smaller than that without fluctuation. Such a small fluctuation effect is beyond our expectation since most IMR and HMR dileptons are produced at early time of the fireball expansion and their harmonic flow should be sensitive to the initial fluctuating “hot-spots”. The reason is that the dilepton elliptic flow is calculated with respect to the event plane azimuthal angle $\Psi_2$ for final charged hadrons according to Eq. (5), however $\Psi_2$ is strongly correlated to the initial geometric deformation but not to dilepton azimuthal angle with the fluctuating initial condition.

To support the above reasoning, we introduce the following event plane azimuthal angle $\phi_{n}(M)$ for dileptons,

$$\phi_n(M) = \frac{1}{n} \arctan \frac{\langle p_T \sin(n\phi) \rangle}{\langle p_T \cos(n\phi) \rangle}, \quad (6)$$

Here the average is taken over thermal dileptons at specific mass in one event. In Fig. 4 we show the distribution of $\phi_2(M) - \Psi_2$ for thermal dileptons at $M = 0.77$ GeV/c$^2$ (hadronic dominated region) and $M = 2.0$ GeV/c$^2$ (partonic dominated region) with the same events as in Fig. 3. \cite{58} $\phi_2/\Psi_2$ is the event plane azimuthal angle defined by dileptons/hadrons.

![Figure 4](image-url) (Color online) The distribution of $\phi_2 - \Psi_2$ at dilepton invariant mass $M = 0.77$ GeV/c$^2$ and $M = 2$ GeV/c$^2$ in EBE hydrodynamic simulation with the same 1000 events as in Fig. 4. $\phi_2/\Psi_2$ is the event plane azimuthal angle defined by dileptons/hadrons.

Notice that the contribution from hadronic phase to Eq. (7) is below that to Eq. (5) at $M > 1.2$ GeV/c$^2$. This is because the dilepton production rate at high mass region is dominated by the partonic contribution, the dilepton event plane defined by Eq. (6) in that mass region is almost that of dileptons from partonic phase instead of hadronic phase. Therefore when looking at $v_2$ of dileptons from hadronic phase in high mass region, it is more correlated to the orientation of charged hadrons than that of dileptons from partonic phase.
tons mainly from partonic phase. Mathematically the mean value of $|\phi_h(M) - \phi_2(M)|$ in Eq. 4 is bigger than that of $|\phi_h(M) - \Psi_2|$ in Eq. 5 at high mass region which will bring a smaller $v_2$, where $\phi_h(M)$ is the azimuthal angle of dilepton from hadronic phase at specific mass. The de-correlation suggests that the importance of the choices of event planes in maximizing the dilepton elliptic flows. In experiments, however, it is difficult to identify the dilepton event planes because of very low production rates dileptons.

The de-correlation effects are also present for final charged hadrons. In a recent work on two-particle correlation [45], it was pointed out that the flow angle $\Psi_n$ may depend on the transverse momentum $p_T$ and the pseudo-rapidity $\eta$. The $p_T$-dependent event plane angle for charged hadrons have also been studied in Ref. [46]. Similar de-correlation effect was found in thermal photon elliptic flows with viscous hydrodynamic simulation [23], where the event angle $\Psi_n$ from pions de-corrrelate from $\Psi_n(p_T)$ defined by thermal photons at specific $p_T$. While in our work, we realize the evolution of de-correlation effect in relativistic heavy ion collisions.

**IV. SUMMARY AND CONCLUSION**

We investigated the elliptic flows of di-electrons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by using a (2+1)-dimension event-by-event hydrodynamic model. The fluctuating initial entropy density profile is generated by the Monte Carlo Glauber model. The event-by-event hydrodynamic simulation gives a better description of transverse momentum spectra and elliptic flows of final charged hadrons in central and semi-central collisions. The event plane angle distribution indicates that the elliptic flow is largely generated by the initial geometric deformation while the triangle flow is largely generated by initial fluctuating “hot spots”.

The dilepton invariant mass spectra are harder in the HMR from event-by-event hydrodynamic simulation than the one-shot results, which is due to larger-than-average temperatures of fluctuating “hot spots”. The fluctuation effects are small when we use the event plane angle from final charged hadrons in calculating dilepton elliptic flows.

We observed bigger fluctuation effects when we used event plane angles defined by dileptons at specific $M$. The correlation between the event plane angle of dileptons at specific $M$ and that of charged hadrons becomes stronger with decreasing $M$. This provides us with a possible measure of the interplay between the effect of geometric deformation and that of fluctuating “hot spots” in relativistic heavy ion collisions.

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