

## Initial fluctuation effect on elliptic flow in Au+Au collision at 1 GeV/A postprint

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### Abstract

How the initial fluctuation affects on the elliptic flow is investigated by investigating the rapidity, transverse 4-velocity, centrality dependencies of elliptic flow for Au+Au at 1 GeV/A with the help of an Isospin Quantum Molecular Dynamics (IQMD). In addition, we compare the flow calculated with respect to participant plane created by the initial geometry in coordinate space with the flow reconstructed by the experimental event-plane method, and compare the flow with the experimental data of the FOPI collaboration. It shows that there exists some discrepancy between the flows reconstructed by the above two methods.

### Full Text

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**Initial Fluctuation Effect on Elliptic Flow in Au+Au Collisions at 1 GeV/A**

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### Abstract

We investigate how initial fluctuations affect elliptic flow by examining its rapidity, transverse 4-velocity, and centrality dependencies in Au+Au collisions at 1 GeV/A using the Isospin Quantum Molecular Dynamics (IQMD) model. Additionally, we compare flow calculated with respect to the participant plane determined from initial geometry in coordinate space with flow reconstructed

using the experimental event-plane method, and we compare our results with experimental data from the FOPI collaboration. The analysis reveals some discrepancy between the flows reconstructed by these two methods.

**Key words:** Elliptic flow, Initial fluctuation, IQMD, Event plane method, Au+Au collision at 1 GeV/A

## Introduction

The characterization of collective flow has proven to be one of the more powerful probes of dynamics in heavy-ion collisions. Elliptic flow is an excellent collective flow observable that has been studied extensively at Bevalac and SIS, as well as at AGS, SPS, and RHIC [1]. At intermediate energies, microscopic transport model calculations have stressed the importance of elliptic flow for extracting the equation of state (EOS) of nuclear matter.

Recently, extensive studies of initial fluctuation effects on anisotropic flow in relativistic heavy-ion collisions have been conducted. These fluctuations can be understood as event-by-event variations in the shape of the overlap region created in initial collisions. The initial eccentricity ( $\epsilon_2$ ), which quantifies the initial spatial anisotropy, is directly affected by these fluctuations.

In high-energy collisions, model calculations have already predicted that anisotropic flow considering initial fluctuations is larger [2]. Han et al. have shown that the ratio of elliptic flow to initial eccentricity,  $v_2/\epsilon_2$ , is sensitive to fluctuations [2]. The value of  $v_2/\epsilon_2$  represents the conversion efficiency from initial geometry anisotropy to final momentum anisotropy. Many studies have demonstrated that hydrodynamic calculations of flow are in good agreement with experimental data when initial fluctuations are taken into account [3-10]. Furthermore, initial fluctuations make higher-order odd harmonic flows non-trivial. Previous studies have shown that triangle flow ( $v_3$ ) becomes significant when initial fluctuations are considered [11,12].

Elliptic flow is mathematically defined as the second coefficient of the Fourier expansion of the particle azimuthal distribution with respect to the reaction plane. The origin of elliptic flow is the initial geometry anisotropy of the collision system, which arises from the uneven density distribution in the early stages of collisions. Subsequent dynamical evolution of the system transforms this coordinate-space anisotropy into momentum-space anisotropy, leading to the collective motion observed in the final state. Based on this physical picture, it is clear that elliptic flow should be very sensitive to the initial state.

However, the initial fluctuation effect on flow has only been investigated in high-energy collisions thus far. In the intermediate energy domain, its effect has not yet been addressed. In this article, we demonstrate the initial fluctuation effect on collective flow in intermediate-energy collisions using a transport model called Isospin Quantum Molecular Dynamics (IQMD), which allows the generation of events with event-by-event fluctuating initial conditions. We also compare flow

results using two different methods and present the centrality dependence of the eccentricity  $v_2$  and the ratio  $v_2/v_2$ .

## 2 Analysis Method

In heavy-ion collisions, the particle azimuthal distribution relative to the reaction plane is not isotropic and is typically expanded in a Fourier series [13]:

$$\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_{RP})]$$

where the coefficients  $v_n = \langle \cos[n(\phi - \psi_{RP})] \rangle$  are normally referred to as the n-th order collective flow or anisotropic flow [14], and the angle brackets denote an average over all particles in all events.  $\psi_{RP}$  is the reaction plane angle. The reaction plane is spanned by the impact parameter vector and the beam direction. It cannot be measured experimentally but can be estimated in several ways.

### 2.1 Initial Fluctuation Effect on the Reaction Plane

The original reaction plane is the XZ plane in the model, where  $x_{RP}$  represents the X-axis. However, initial fluctuations affect the reaction plane as illustrated in [Figure 1: see original paper]. The effect of initial fluctuations is to make the participant plane ( $x_{PP}$ ) deviate from the reaction plane ( $x_{RP}$ ) [15]. The participant plane angle is defined as:

$$\psi_{PP} = \frac{1}{n} \arctan \left( \frac{\langle r^n \sin(n\phi) \rangle}{\langle r^n \cos(n\phi) \rangle} \right)$$

where  $r$  and  $\phi$  are the coordinate position and azimuthal angle of each particle, and  $\langle \dots \rangle$  denotes weighting by the participant density in the initial state.

The n-th order eccentricity calculated with respect to this participant plane is defined as:

$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi) \rangle^2 + \langle r^n \sin(n\phi) \rangle^2}}{\langle r^n \rangle}$$

When  $n = 2$ , the above two variables  $v_2$  and  $\varepsilon_2$  correspond to elliptic flow and eccentricity, respectively. In high-energy heavy-ion collisions, it has been found that the eccentricity taking initial fluctuations into account differs from the eccentricity without considering initial fluctuations [16].

## 2.2 Experimental Method

A commonly used method in experimental analysis is the event-plane method [17,18]. It uses the event-plane angle determined from the observed collective flow itself as an approximation of the reaction plane [14]. The event-plane angle is given by:

$$\psi_{EP} = \frac{1}{n} \arctan \left( \frac{\sum_i \omega_i \sin(n\phi_i)}{\sum_i \omega_i \cos(n\phi_i)} \right)$$

where the sum runs over all particles used to reconstruct the event plane.  $\phi_i$  and  $\omega_i$  are the azimuthal angle and weight for particle  $i$ . We choose  $\omega_i = p_T$  for  $y_0 > 0.3$  and  $\omega_i = -p_T$  if  $y_0 < -0.3$  [19]. The observed  $v_n$  with respect to the event plane is written as:

$$v_n\{EP\} = \langle \cos[n(\phi - \psi_{EP})] \rangle$$

The event plane differs in general from the original reaction plane due to finite multiplicity in events. Therefore,  $v_n$  must be corrected by the event-plane resolution  $R_n$ . The event-plane resolution for each harmonic is given by:

$$R_n = \langle \cos[n(\psi_{EP} - \psi_{RP})] \rangle$$

where the angle brackets denote an average over a large event sample. The event-plane resolution depends on the multiplicity of particles used to define the flow vector as well as the average flow of these particles via the resolution parameter  $\chi$  [18,20,21]:

$$R_n(\chi) = \frac{\sqrt{\pi}}{2\sqrt{2}} \chi e^{-\chi^2/4} \left[ I_{(n-1)/2} \left( \frac{\chi^2}{4} \right) + I_{(n+1)/2} \left( \frac{\chi^2}{4} \right) \right]$$

where  $I$  is the modified Bessel function. To calculate the resolution, we divide the full events into two independent sub-events with equal multiplicity [22,23]. Each sub-event resolution can be defined as:

$$R_n^{sub} = \langle \cos[n(\psi_{EP}^A - \psi_{EP}^B)] \rangle$$

where  $A$  and  $B$  denote the two subgroups of particles. For the given  $R_n$ , the solution for  $\chi$  in the equation above is obtained by iteration. The full event-plane resolution is obtained by:

$$R_n = \frac{\sqrt{\pi}}{2\sqrt{2}} \chi e^{-\chi^2/4} \left[ I_{(n-1)/2} \left( \frac{\chi^2}{4} \right) + I_{(n+1)/2} \left( \frac{\chi^2}{4} \right) \right]$$

The final collective flow measured with respect to the event plane can be written as:

$$v_n = \frac{v_n\{EP\}}{R_n}$$

In this method, the event plane is calculated from the final momentum space. In this case, the flows reconstructed by the event-plane method can be affected by the evolution of the dynamics. Reference [1] shows that in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV from a multiphase transport model, the elliptic flow  $v_2$  and triangle flow  $v_3$  relative to the event plane are larger than those relative to the participant plane. Therefore, it is reasonable to assume that the evolution of the dynamics influences the collective flow.

### 3 Results and Discussion

[Figure 2: see original paper] shows the  $y_0$  and  $u_{t0}$  dependencies of the elliptic flow measured with respect to the reaction plane ( $\{RP\}$ ), participant plane ( $\{PP\}$ ), and event plane ( $\{EP\}$ ), where  $y_0 = y/y_p$  is the scaled rapidity and  $u_{t0} = u_t/u_p$  is the scaled transverse 4-velocity. Please note that in the  $v_2$  calculation, we have applied the FOPI detector geometry cut so that a quantitative comparison can be made [24].

The rapidity dependence shown in Fig. 2(a) exhibits a V-shape. Protons show in-plane emission ( $v_2 > 0$ ) in projectile-like and target-like regions (larger absolute rapidity values) while displaying squeeze-out emission in the overlapping region (mid-rapidity). From mid-rapidity to projectile-like/target-like rapidities, protons transition from squeeze-out to in-plane emission. This is consistent with the shadowing effect.

The transverse velocity dependence (Fig. 2(b)) shows that as  $u_{t0}$  increases, the squeeze-out emission becomes stronger; that is, protons with higher velocity can escape more easily from the overlapping zone.

From Fig. 2, we can see that  $v_2\{RP\}$  is slightly larger than  $v_2\{PP\}$ . However, there is almost no discrepancy between  $v_2\{EP\}$  and  $v_2\{PP\}$ . This means  $v_2$  is weakened by initial fluctuations but is not sensitive to dynamical evolution. This phenomenon differs from what is known at high energies, where  $v_2$  is enlarged by both initial fluctuations and dynamical evolution. In the figure, FOPI data are also plotted to check our calculations. Even though quantitative agreement is not reached, the trend of  $v_2$  as a function of  $y_0$  and  $u_{t0}$  is consistent with the data.

[Figure 3: see original paper] displays  $v_2$  versus  $y_0$  and  $u_{t0}$  for three different centrality ranges. While the shapes look similar across all centralities, the elliptic flow of protons in mid-rapidity (upper panels) or high velocity (lower panels) regions shows a stronger squeeze-out effect at some intermediate centralities ( $0.45 < b_0 < 0.55$ ). With increasing  $b_0$ , the initial fluctuation and dynamical

evolution play an increasingly important role, as seen from the growing difference between  $v_2\{PP\}$ ,  $v_2\{RP\}$ , and  $v_2\{EP\}$ . Again, the similarity between  $v_2\{PP\}$  and  $v_2\{EP\}$  indicates that there is almost no effect from dynamical evolution.

The upper panel of [Figure 4: see original paper] shows the impact parameter ( $b$ ) dependence of eccentricity  $\varepsilon_2$ . It demonstrates that  $\varepsilon_2$  increases with  $b$  and that  $\varepsilon_2\{PP\}$  is larger than  $\varepsilon_2\{EP\}$ . The lower panel shows the ratio  $v_2/\varepsilon_2$  as a function of  $b$ . We can see that the absolute values of the ratio also increase with  $b$ , and  $|v_2\{PP\}/\varepsilon_2|$  is smaller than  $|v_2\{RP\}/\varepsilon_2|$ . The smaller absolute ratio indicates less efficient conversion from initial geometry anisotropy to final momentum anisotropy.

## 4 Conclusion

The elliptic flow in Au+Au collisions at 1 GeV/A was studied using three different methods for determining the reaction plane. We found that initial event-by-event geometry fluctuations affect the final-state elliptic flow. In our calculation, the initial fluctuation weakens the elliptic flow; in other words, it makes the conversion from initial spatial eccentricity to final momentum anisotropy less efficient. In this paper, we studied the dependence of  $\varepsilon_2$  on impact parameter with consideration of initial fluctuations and compared the ratio  $v_2/\varepsilon_2$  with and without this consideration. The results show that initial fluctuations enhance the eccentricity  $\varepsilon_2$  but decrease the ratio  $|v_2/\varepsilon_2|$ . Moreover, we found that dynamical evolution has little influence on elliptic flow in our studied cases. Our simulation gives similar trends for rapidity and velocity dependencies, but the results are quantitatively smaller than experimental data for mid-rapidity and high-velocity protons. This discrepancy may be caused by two reasons: (1) variation of physical parameters (such as ground state densities and interaction ranges) whose precise values are not known, and (2) the impossibility of building a ground state nucleus with all its detailed structure in a semi-classical molecular dynamics approach [25].

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