NUKLEONIKA 2006;51(Supplement 3):S37–S41

PROCEEDINGS

Influence of the non-flow effects and fluctuations on the v_2 measurements at RHIC

Xianglei Zhu,
Marcus Bleicher

Abstract The cumulant method is applied to study elliptic flow (v_2) in Au+Au collisions at $\sqrt{s}$ = 200 AGeV, with the UrQMD model. We find that the four and six-particle cumulants are good measures of the real elliptic flow over a wide range of centralities except for the most central and very peripheral events. There the cumulant method is affected by the v_2 fluctuations. In mid-central collisions, the four and six-particle cumulants are shown to give a good estimation of the true differential v_2, especially at large transverse momentum, where the two-particle cumulant method is heavily affected by the non-flow effects.

Key words relativistic heavy-ion collisions • collective flow • Monte-Carlo simulations

X. Zhu✉
Frankfurt Institute for Advanced Studies (FIAS),
and Institut für Theoretische Physik,
Johann Wolfgang Goethe-Universität,
1 Max-von-Laue-Str., D-60438 Frankfurt am Main,
Germany
and Physics Department, Tsinghua University,
Beijing 100084, China,
Tel.: +49-69-798-47520, Fax: +49-69-798-47611,
E-mail: zhu@th.physik.uni-frankfurt.de

M. Bleicher
Institut für Theoretische Physik,
Johann Wolfgang Goethe-Universität,
1 Max-von-Laue-Str., D-60438 Frankfurt am Main,
Germany

Received: 30 September 2005
Accepted: 11 May 2006

Introduction

Elliptic flow v_2, which is defined as $\langle \cos 2(\phi - \Phi_R) \rangle$ (Φ_R is the reaction plane angle), is the second Fourier harmonic in the transverse angular distribution of the emitted particles in relativistic heavy-ion collisions [19, 23]. It can provide many insights on the bulk properties of the matter created in those collisions [1, 2, 4, 5, 7, 15–17, 19, 21, 23] and becomes one of the most important observables in heavy-ion physics. However, the accurate experimental measurement of elliptic flow is not a trivial task, because the exact reaction plane angle Φ_R of a single event is not known.

Usually, the v_2 is measured with the reaction plane method [20] in which the reaction plane should be estimated from the flow itself, or the two-particle correlation method in which the v_2^2 is estimated directly from two-particle correlations $\langle \cos 2(\phi_i - \phi_j) \rangle$.

In general, these two-particle methods are affected by the so-called non-flow effects, which are the particle correlations not related to the reaction plane, such as resonances decay, momentum conservation and jet productions. In order to decrease the contribution of the non-flow effects to the flow measurement, the many-particle cumulant method was proposed (please see Refs. [10, 11, 13] for the details). In the many-particle cumulant method, the flow is estimated with the many-particle cumulants, which are the many-particle correlations with subtraction of all the contributions from the lower-order multiplets. It has been shown in Refs. [10, 11] that, in the cumulant method, the contribution of the non-flow effects should be much smaller.

However, as indicated in Refs. [3, 18, 22], the v_2 from many-particle cumulants might also be affected by the event-by-event v_2 fluctuations, because we cannot get directly $\langle v_2 \rangle$ from the cumulant method. For example, from the two-particle cumulant, we get $\langle v_2^2 \rangle^{1/2}$, which is not $\langle v_2 \rangle$ if there are event-by-event v_2 fluctuations. In Ref. [18], a rough estimation of the fluctuations' contribution to the measured elliptic flow is given. The estimation is based on the assumption that v_2 of an event is propotional to inital eccentricity of the nucleons or quarks. The authors found that the difference between $v_2\{2\}$ and $v_2\{4\}$ (v_2 from 2- and 4-particle cumulants) can also be explained by definite amount of v_2 fluctuations which give larger $v_2\{2\}$ and smaller $v_2\{4\}$ than the exact v_2. However, which effect, non-flow effects or v_2 fluctuations, is dominant in the difference between $v_2\{2\}$ and $v_2\{4\}$ is still not clear.

In this work, we will use the UrQMD model (v2.2) [8, 9, 14] to test the cumulant method on the elliptic flow analysis. There are some advantages in this model for the test. Firstly, the UrQMD model which describes the heavy-ion collisions dynamically contains few-particle non-flow correlations naturally. Secondly, the UrQMD is an event-by-event model, hence it contains the event-by-event fluctuations of the elliptic flow. Finally, the reaction plane is known in the model, which enables the calculation of the exact elliptic flow from its definition. Therefore, the UrQMD model, even if for the time being still undershoots the integral v_2 in $\sqrt{s}$ = 200 AGeV Au-Au collisions at RHIC by about 40%, will be an ideal tool to find out whether the v_2 fluctuations and non-flow effects have large effect on the cumulant method.

Results from the cumulant method in UrQMD

Before the application of the cumulant method, we have examined the magnitude of the spatial and v_2 fluctuations in the UrQMD model. We found the magnitude of the spatial (eccentricity) fluctuations in UrQMD is very similar to that estimated with Monte Carlo Glauber Model in Ref. [18]. We also find that the v_2 fluctuations in the UrQMD model are also in magnitude similar to the v_2 itself. Therefore, due to the large event by event fluctuations, $\langle v_2^2 \rangle^{1/2}$, $\langle v_2^4 \rangle^{1/4}$ and $\langle v_2^6 \rangle^{1/6}$ are much larger than $\langle v_2 \rangle$, especially in the most central and very peripheral centralities where the $\langle v_2 \rangle$ is very small.

The observation of large v_2 fluctuations puts some doubt on the accuracy of the experimental methods for the extraction of the elliptic flow parameters. Therefore, we will now focus on the cumulant method and compare the model results (with fluctuations and non-flow effects) obtained by different order cumulant methods with the exact v_2. For the integral v_2 analysis, we use all particles in the pseudorapidity range $|\eta| < 2.5$. The centralities in our analysis are selected according to the same geometrical fractions of the total cross section (0–5, 5–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70%) as used by the STAR experiment [1].

Figure 1 shows the calculated integral v_2 results as a function of centrality.

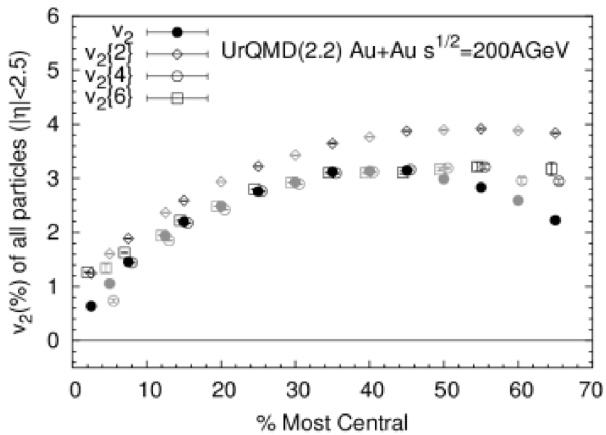

Fig. 1. The integral v_2 results ($v_2\{2\}$, $v_2\{4\}$ and $v_2\{6\}$) from the cumulant method are compared to the exact v_2 in different centrality bins. The grey points are the corresponding results from the enlarged centrality bins which merge two of the original bins.

For mid-central collisions (σ/σ_{tot}: 10–50%), the elliptic flow parameters extracted from four particle ($v_2\{4\}$) and six particle cumulants ($v_2\{6\}$) show almost no difference and both agree well with the exact v_2 as obtained from the known reaction plane. However, the two-particle cumulant $v_2\{2\}$ deviates rather strongly from the theoretically expected v_2. From Fig. 1, one clearly observes the fact that the exact v_2 agree with $v_2\{4\}$ very well and is not in the middle of the $v_2\{2\}$ and $v_2\{4\}$. This behavior is not expected, if the differences between the cumulant methods are mainly due to v_2 fluctuations [18]. Therefore, we conclude that for semi-central to semi-peripheral centralities the contribution of the v_2 fluctuations to the cumulant results is almost negligible and the difference between $v_2\{2\}$ and $v_2\{4\}$ or $v_2\{6\}$, is mainly due to non-flow effects in the UrQMD model.

However, from Fig. 1, we have also seen that both $v_2\{4\}$ and $v_2\{6\}$ do not agree with the exact v_2 in the most central and the very peripheral bins. This means at central and very peripheral collisions, the v_2 fluctuations indeed play an important role as indicated in [18]. In the peripheral bins the higher order cumulants give larger v_2 than the exact one. In the most central bin, the $v_2\{4\}$ is smaller and even becomes complex (not shown in Fig. 1) due to the fluctuation, while the $v_2\{6\}$ is slightly larger than the exact v_2. These findings are qualitatively consistent with previous results within a simplified Monte-Carlo Glauber treatment [18].

In order to estimate how sensitive the cumulant method is to impact parameter fluctuations in a centrality bin, we also performed the cumulant analysis in enlarged centrality bins. The grey points in Fig. 1 show the results for the enlarged bins (0–10, 5–20, 10–30, 20–40, 30–50, 40–60, 50–70%). One can see that the v_2 values from any order cumulants are still in line with the corresponding v_2 results from the original bins although the impact parameter fluctuations in the enlarged bins are larger than those in the original (narrower) centrality bins. Thus, the main contribution to the v_2 fluctuations in the original centrality bins should be due to v_2 fluctuations at the same impact parameter,

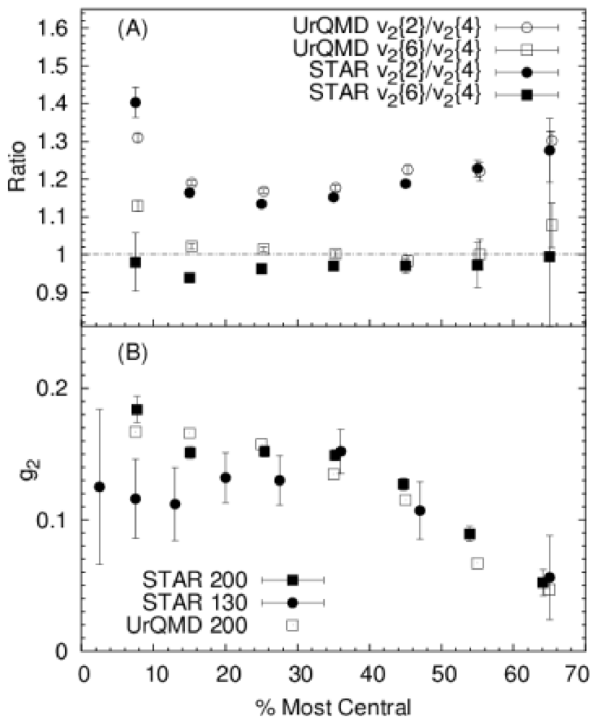

Fig. 2. (A) The ratios $v_2\{2\}/v_2\{4\}$ and $v_2\{6\}/v_2\{4\}$ from UrQMD are compared to the STAR data [5]. (B) The g_2 factors from the UrQMD model are compared to the STAR data. Note that g_2 from UrQMD has been scaled down by a factor of 0.186.

e.g. due to the spatial eccentricity fluctuations from event-to-event or the multiplicity fluctuations.

While the total elliptic flow values extracted from the calculation are lower than the experimental results, the relations between $v_2\{2\}$, $v_2\{4\}$ and $v_2\{6\}$ are similar to the results reported by the STAR collaboration at RHIC. As shown in Fig. 2(A), open symbols denote the calculation, while full symbols show the STAR data on the ratios $v_2\{2\}/v_2\{4\}$ and $v_2\{6\}/v_2\{4\}$ for comparison. The good agreement between UrQMD results and the data may indicates that the mechanism which accounts for the differences between $v_2\{2\}$ and $v_2\{4\}$ or $v_2\{6\}$ is the same. In Fig. 2(B), we show the g_2 factor from the UrQMD model. The g_2, is defined as [12] $g_2 = N(v_2\{2\}^2 - v_2\{4\}^2)$, where N is the event multiplicity (for our analysis) or the number of wounded nucleons (for the STAR data) which should be approximately proportional to the multiplicity. g_2 should be a measure of the non-flow effects and independent with the centrality as originally suggested by [12]. However, the STAR [1] and SPS [6] data show that with the increase of the impact parameter, the g_2 will decrease by about a factor of 3. This decrease of observed g_2 is consistent with the results based on the eccentricity (or v_2) fluctuations [18], which confirms the conjecture in Ref. [12]. As we can see in Fig. 2(B), the g_2 from the UrQMD model also has similar shape as the data (please note that g_2 from UrQMD have been rescaled by a factor of 0.186 to compare to the 200 A GeV STAR data, since magnitude of the v_2's are too small). The g_2 decrease in the UrQMD model is (at least partially) due to the v_2 fluctuations that naturally appear in the model, because $v_2\{2\}$ and $v_2\{4\}$ are affected by the fluctuations at the most central and the very peripheral centrality bins where the g_2 decreases (cf. discussion above).

Let us now turn to the study of the the differential v_2. In the cumulant method, the differential v_2 in one p_T or rapidity bin is estimated with the cumulants between the particles in this bin and those in one common "pool". The average v_2 of the particles in the "pool" should be known from the integral flow analysis. For our differential v_2 analysis, we always use all the particles within $|\eta| < 2.5$ as the "pool". One should also notice that the non-flow correlations which affect the differential flow analysis will be those between the particles in the chosen bin and those in the "pool".

Firstly, let us show the p_T dependence of v_2 in a semi-central (20–30%) centrality bin. At large transverse momenta (p_T), non-flow contributions are expected to be large and might influence the results obtained by the cumulant method. Figure 3 shows the calculations for the v_2 of particles within $|\eta| < 2.5$ as a function of p_T. As we can see, $v_2\{2\}$ is always larger than exact v_2. Especially towards large p_T, $v_2\{2\}$ stays roughly constant, while exact v_2 decreases when $p_T > 2.5$ GeV/c. The saturation of $v_2\{2\}$ is consistent with STAR's $v_2\{2\}$ results [2]. This strong deviations point towards substantial contributions from non-flow effects in the two-particle cumulant method. The higher order cumulants do a much better job in reproducing the exact v_2. Here, the difference between $v_2\{4\}$ and the exact v_2 is much smaller especially at large p_T. However, $v_2\{4\}$ is still larger than the exact v_2, indicating that even four-particle cumulants are not free from non-flow disturbances. When we go to the six-particle cumulant results $v_2\{6\}$, we get good agreement with the exact v_2 in the whole p_T range within the statistical error, which shows that the non-flow effects have been completely eliminated.

Finally, we will study the pseudorapidity (η) dependence of v_2 with the cumulant method using the same set of semi-central events as for transverse momentum analysis. It is usually expected that at large η, the non-flow effects to be less important than at mid-rapidity because of the larger rapidity gap between the particles in the rapidity bin and the "pool" particles. So the difference between $v_2\{2\}$ and $v_2\{4\}$ is expected

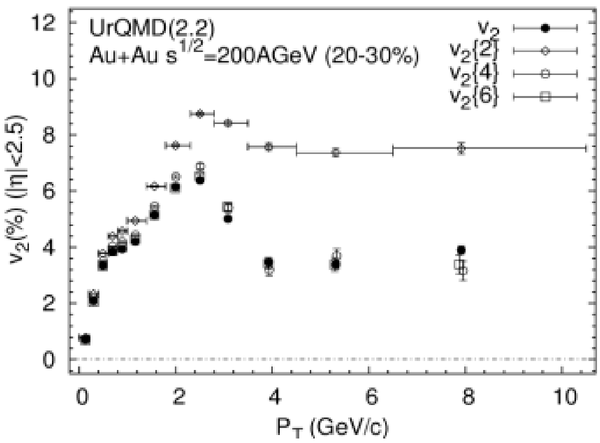

Fig. 3. $v_2(p_T)$ in the semi-central collisions: results from the cumulant method are compared to the exact v_2.

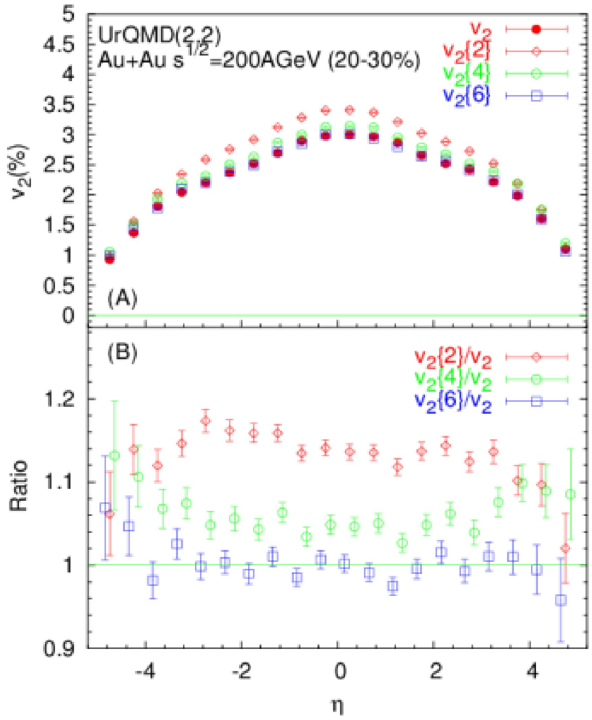

Fig. 4. (A) $v_2(\eta)$ in semi-central Au+Au collisions at $\sqrt{s}$ = 200 A GeV. Results from the cumulant method are compared to the exact v_2. (B) Ratios of $v_2\{n\}$ over the exact v_2.

to be smaller at large η compared to mid-rapidity. Figure 4(A) shows the results on $v_2(\eta)$ obtained from the different methods. Indeed one observes that at large η, $v_2\{2\}$, $v_2\{4\}$ and $v_2\{6\}$ are almost similar and they all agree well with the exact v_2. This is in line with the STAR results on the $v_2(\eta)$ also indicating agreement between $v_2\{2\}$ and $v_2\{4\}$ at large η [1]. However, the smaller difference between the v_2's from any-order cumulants at larger rapidity must not be taken as a sign that the non-flow effects are less important at larger rapidities, because the v_2 itself decreases towards large rapidity. Figure 4(B) shows the ratios of $v_2\{n\}$ over the exact v_2. One observes that the ratios are roughly independent of the rapidity. Therefore, the non-flow effects at forward rapidity might be as important as those at mid-rapidity.

Conclusion

We have applied the cumulant method to analyze the v_2 of the Au+Au reactions at $\sqrt{s}$ = 200 A GeV within the UrQMD model. On the integral v_2 analysis, we reproduce the hierarchy of $v_2\{2\}$, $v_2\{4\}$ and $v_2\{6\}$ observed by the STAR experiment even if the v_2 from UrQMD is only about 60% of the data. We found that v_2 fluctuations affect the results from the cumulant method in the most central and very peripheral collisions. However, this effect is almost negligible over a wide range of the mid-central collisions (about 10–50% of the total cross section). While the two-particle cumulant results are heavily affected by non-flow effects especially at large p_T, non-flow effects can indeed be nearly eliminated using four and six-particle cumulants.

Acknowledgments This work was supported by GSI and BMBF. We are grateful to the Center for the Scientific Computing (CSC) at Frankfurt for the computing resources. The authors thank A. Tang, N. Xu, G. Wang and R. Snellings for stimulating discussions. XZ thanks the Frankfurt International Graduate School for Science (FIGSS) at the J. W. Goethe-Universität for financial support.

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