Anisotropic Flow at STAR

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Abstract

We first review previous work on anisotropic flow at the AGS and SPS. Then the physics related to flow is discussed as well as the interaction of flow with other non-flow measurements. From 40k RQMD and 100k HIJING events predictions for anisotropic flow at RHIC are presented. Using the STAR detector acceptance, estimates for the resolution obtainable with STAR are shown. We conclude that it should be possible to obtain good measurements for elliptic flow with either the STAR main TPC or forward TPCs. Anisotropic flow should be easily one of the first results from STAR.

1 Introduction

The study of collective flow in nuclear collisions at high energies has been attracting increasing attention from experimentalists [1, 2]. This is partly because recent progress has been made in the development of new techniques suitable for flow studies at high energies [3, 4, 5, 2, 6, 7]. Instead of studying $\langle p_x \rangle$, in these new methods a Fourier expansion of the azimuthal distribution of particles is used in which the first harmonic coefficient, v_1, quantifies the directed flow and the second harmonic coefficient, v_2, quantifies the elliptic flow. In some cases $A1$ and $A2$ were reported, which in modern terminology, are twice the square of the sub-event resolution. Using these new techniques anisotropic flow has now been observed for heavy symmetric systems at both the AGS and SPS.

At the AGS the E877 Collaboration pioneered the use of the Fourier expansion method to measure v_1 and v_2. They studied these quantities (as well

as v_4) from a calorimeter as a function of centrality in different pseudorapidity windows [8]. Then they studied nucleons as well as pions as a function of pseudorapidity for different centralities [9]. Using their spectrometer to identify particles while still obtaining the event plane from the calorimeter, they measured v_1 and v_2 as a function of p_t for different rapidities and centralities [10]. They also reported $\langle p_x \rangle$ as a function of rapidity [10]. In their latest papers they extended this study to light nuclei [11, 12]. The E802 Collaboration studied $\langle p_x \rangle$ for light nuclei in the target rapidity region using a forward hodoscope to determine the event plane [13].

At the SPS NA49 first observed elliptic flow in a calorimeter study which reported $A2$ as a function of centrality [14]. WA98 reported $A1$ as a function of centrality for protons and π^+ in the target rapidity region [15, 16]. They also studied $\langle p_x \rangle$ in the target rapidity region [16]. NA45 used silicon drift detectors to study v_1 and v_2 as a function of pseudorapidity [17]. NA49 has presented a differential study of v_1 and v_2 as a function of p_t and y [6] and has also started to study the centrality dependence [18].

Also, the importance of flow for other measurements has just begun to be studied. For two particle correlations relative to the event plane the mathematical scheme has been worked out [19, 20, 21, 22]. Some first results have been given by WA98 [15]. Also, for non-identical particles the correlation relative to the event plane has been discussed [24].

2 Physics Motivation

Anisotropic flow, in particular elliptic flow, in spite of the relatively small absolute value of the effect, contains very rich physics. In general words, it is very sensitive to the equation of state which governs the evolution of the system created in the nuclear collision. Being such, anisotropic flow provides important information on the state of matter under the extreme conditions of the nuclear collision. The anticipated phase transition to QGP should have a dramatic effect on elliptic flow due to the softening of the equation of state.

First it was pointed out in the pioneering work of Ollitrault[3], who suggested elliptic anisotropy as a possible signature of transverse collective flow. Within the hydro-dynamical model Ollitrault analyzed the role of different equations of state and phase transitions on the final anisotropy. Hung and Shuryak [25] suggested scanning with beam energy in order to look for the

QCD phase transition. Using their idea of the softest point in the equation of state combined with hydro-dynamical calculations, Rischke [26] predicted a dramatic drop in the elliptic flow signal at the corresponding beam energies (in the original calculations this was at AGS energies). Sorge has shown[27] that the elliptic flow is very sensitive to the pressure at maximum compression, which is the most interesting time in the system evolution. Recent studies [28] within the parton cascade model yield similar conclusions providing also the relation between the strength of the elliptic flow and parton-parton cross sections. Recently, Sorge also tried [29] to combine the early system evolution in accordance to a QGP equation of state with a later hadron cascade. He looked at the centrality dependence of the elliptic flow in order to detect QGP production. Summarizing this part, we would conclude that the effect of QGP should be seen in the anisotropic flow dependence on the energy of the colliding nuclei, or in the dependence on the centrality of the collision. If the situation would be such that a QGP is produced only in a small fraction of the collisions than fluctuations in flow would be one of the best observables for this effect.

The formation of DCC in nuclear collisions could also result in an event anisotropy. It could be due to the anisotropic shape of the DCC domains [30] or just to local fluctuations in the charged multiplicity, which should result in "orthogonal" flow in charged and neutral sectors [31].

The very magnitude of anisotropic flow is sensitive to the degree of equilibration in the system. Note that at present there is no calculation based on the hydro-dynamical picture which accounts for the experimentally observed values of the effect. This could have its origin in the obvious difficulties of hydrodynamic model calculations, but it could also indicate a non-applicability of the picture to nuclear collisions. The cascade models such as RQMD describe the data much better. From this point of view the analysis of elliptic flow in the collision-less and hydrodynamic limits performed in [22] is very interesting. The HBT interferometry performed relative to the event plane [19, 20, 21, 22, 23] becomes also extremely important at this point. Does the system really expand in the reaction plane as prescribed by hydrodynamics? Simultaneous measurements of the anisotropic flow and the two-particle, identical as well as non identical [24], correlations in principle should answer this question.

We must also mention the importance of anisotropic flow measurements to the vast variety of other measurements, which from first look have nothing to do with anisotropic flow. Let us consider high p_t particle production. It

could be that the production mechanism (hard parton scattering) is very insensitive to the in-plane expansion, but that the rescattering of high p_t partons is different in the different directions of particle emission due to the anisotropic geometry of the collision zone. This would lead to anisotropy in high p_t particle production and gives another opportunity to study how it develops [32, 33].

Another example is HBT measurements averaged over all orientations of particle emission. One would think that this does not require reaction plane measurements, but this is not really true. The mixed pair distribution usually used in the correlation function calculation can strongly depend on the relative orientation of the reaction plane of the events used to create the mixed pair. Therefore one should have this information even in the case where the dependence of the HBT parameters on the reaction plane is not studied.

3 Technical Requirements

The study of azimuthal anisotropy of unidentified charged hadrons needs the momenta of the particles but does not have any unusual requirements for calibrations, momentum resolution, acceptance, efficiency, two-track resolution, or two-track efficiency. However, for future analyses it would be good to have particle identification.

4 Directed and Elliptic Flow at RHIC

The anisotropy in the azimuthal distribution of particles is often characterized by v_1, v_2 and called directed and elliptic flow respectively. This anisotropy, especially v_2, plays an important role in high energy nuclear collisions and is expected to be even more important at RHIC energies [27]. The azimuthal distribution of particles is described by a Fourier expansion [4]

$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_t\mathrm{d}p_t\mathrm{d}y}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\phi-\Psi_r)]\right), \qquad (1)$$

where Ψ_r is the true reaction plane angle. The reaction plane is defined by the beam direction and the impact parameter vector $\mathbf{b}$. In a given rapidity

(y) and p_t interval the coefficients are determined by

$$v_n = \langle \cos[n(\phi - \Psi_r)] \rangle. \tag{2}$$

Similarly this Fourier expansion can be done in coordinate space, where for a given rapidity and p_t interval the coefficients are determined by

$$r_n = \langle \cos[n(\arctan(\frac{y}{x}) - \Psi_r)] \rangle \tag{3}$$

where x, y are the particle space coordinates at freeze-out. Of course, these equations only apply to simulations where one knows Ψ_r.

Comparing the anisotropy coefficients in momentum space (v_n) with the anisotropy coefficients in coordinate space (r_n) as a function of p_t helps us to understand the space-time evolution of nucleus-nucleus collisions [19, 34]. To study this space-time evolution at RHIC, 40 000 Au+Au collisions at $\sqrt{s} = 200$ AGeV have been analyzed using the RQMD v2.4 model.

Figs. 1a-d show the first harmonic both in momentum and coordinate space for nucleons and pions. For nucleons at mid-rapidity note the similarity in shape of v_1 versus y and r_1 versus y. Here (Fig. 1a) both the slopes of v_1 versus y and r_1 versus y show a reversal of sign. This finds an explanation in a picture with strong (positive) space-momentum correlations, taking into account the correlation between nucleon stopping and the original position of the nucleons in the transverse plane [35]. For pions, the rapidity dependence of v_1 is predominantly governed by rescattering on comoving nucleons. Figs. 1e-h show v_2 for nucleons and pions. For both nucleons and pions v_2 is positive and is larger for particles with $p_t \geq 1.5$ GeV. Particles acquire a large p_t when they are produced by a hard collision (which should not produce an event anisotropy) or when they have a large number of soft collisions (rescattering). The latter would explain the increase in v_2 and it explains why r_2 goes from negative for nucleons integrated over all p_t to positive for nucleons with large p_t.

Collective flow and the coefficients v_1 and v_2 are usually associated with soft processes. However, the coefficients describe the event anisotropy and are not limited to only soft physics. At RHIC energies hard processes become important. They happen early in the reaction and thus can be used to probe the early stage of the evolution of a dense system. During this time a quark-gluon plasma (QGP) could exist. Associated with hard processes are jets. However, when the transverse energy of the jets becomes smaller it becomes

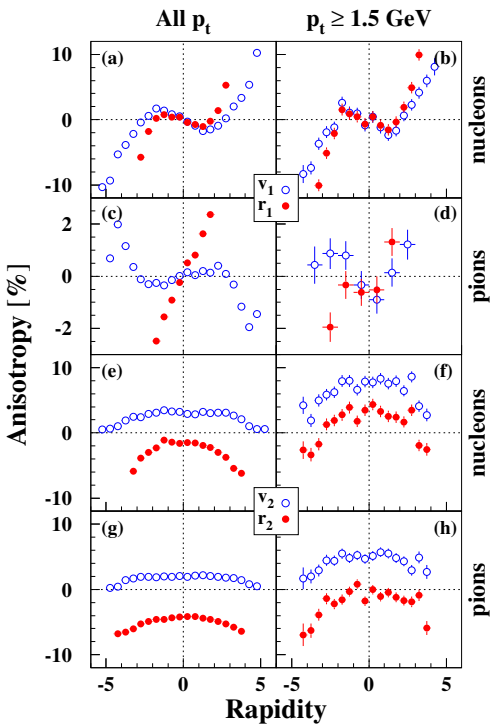

Figure 1: *Anisotropy coefficients for nucleons and charged pions in RQMD for collisions in the impact parameter range of* $5 \leq b \leq 10$ *fm.*

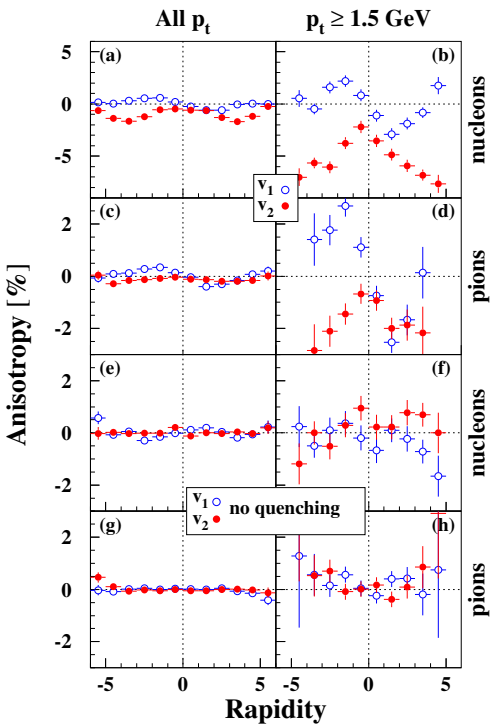

Figure 2: *Anisotropy coefficients for nucleons and charged pions in HIJING for collisions in the impact parameter range of* $5 \leq b \leq 10$ *fm.*

increasingly difficult to resolve them from the "soft" particles. These jets with $E_T < 5$ GeV are usually refered to as mini-jets. At RHIC energies it has been estimated that 50% of the transverse energy is produced by mini-jets [36].

Medium induced radiative energy loss of high p_t partons (jet quenching) could be very different in a hadronic medium and a partonic medium. Recently it was shown that this energy loss per unit distance, dE/dx, grows linearly with the total length of the medium [37]. For non central collisions the hot and dense overlap region has an almond shape. This implies different path lengths and therefore different energy loss for particles moving in the in-plane versus the out-plane direction. To study this anisotropy with respect to the reaction plane [32], 100 000 Au+Au collisions at $\sqrt{s} = 200$ AGeV have

been generated using HIJING [38] v1.35.

Figs. 2a-d show v_1 and v_2 for nucleons and charged pions. The coefficient v_1 shows a small negative slope around mid-rapidity for both nucleons and pions and this becomes more pronounced for particles with $p_t \geq 1.5$ GeV. The coefficient v_2 is slightly negative over the whole rapidity range for both charged pions and nucleons. For particles with $p_t \geq 1.5$ GeV, v_2 becomes more negative especially at forward and backward rapidity. Figs. 2e-f show that without jet quenching the anisotropy coefficients become zero. This indicates that interactions among particles, either quenching or rescattering, are important for producing the anisotropy.

5 Event Plane Resolutions

Within event generators the true reaction plane angle Ψ_r is known. This is not the case experimentally and the reaction plane has to be estimated from the data. This is done using the anisotropy in the azimuthal distribution of particles itself. The estimated reaction plane angle for the n^{th} harmonic is called Ψ_n. The magnitude of the anisotropy and the finite number of particles available to determine this event plane leads to a finite resolution. Therefore, the measured v_n^{obs} coefficients with respect to the event plane have to be corrected for this event plane resolution

$$v_n = \frac{v_n^{obs}}{\langle \cos[n(\Psi_n - \Psi_r)] \rangle} \ . \tag{4}$$

However, eq. 4 uses the true reaction plane which is not known experimentally. Following Ref. [7], if one constructs the event plane from two random subevents one can relate the resolution of the subevents to the full event plane resolution,

$$\langle \cos[n(\Psi_n - \Psi_r)] \rangle = C \times \sqrt{\langle \cos[n(\Psi_n^a - \Psi_n^b)] \rangle}, \tag{5}$$

where C is a correction [7] for the difference in subevent multiplicity compared to the full event and Ψ_n^a, Ψ_n^b are the angles of the event planes determined in the subevents.

To calculate how well the event plane can be determined in STAR, we considered the TPC (-1.5 $\leq y \leq$ 1.5) and the FTPCs (2.5 $\leq |y| \leq$ 4.). For this the RQMD v2.4 model predictions for Au+Au at $\sqrt{s} = 200$ AGeV have been

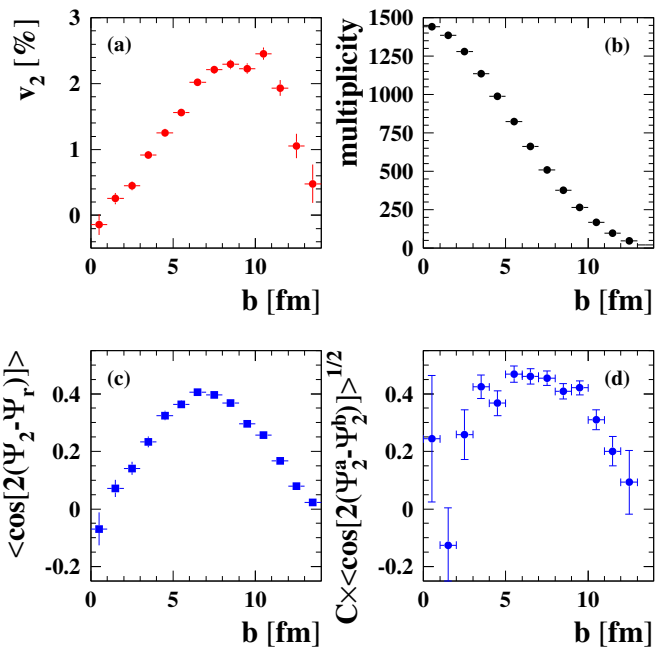

Figure 3: *RQMD v2.4 prediction for v_2 using $\pi^+ + \pi^-$ within -1.5 $\leq y \leq$ 1.5. The multiplicity and event plane resolution are also shown.*

used. In Fig. 3a, v_2 for charged pions integrated over the TPC rapidity region is shown versus the impact parameter b. Fig. 3b shows the corresponding multiplicity as a function of b. These quantities lead to a resolution for v_2, calculated using the true reaction plane, as shown in Fig. 3c. The resolution for v_2 which can be obtained in the STAR TPC using subevents is shown in Fig. 3d. For v_2 charged pions and protons both contribute positively and therefore do not need to be identified. However, the multiplicity of protons at mid-rapidity is small compared to that of pions and, therefore, including protons does not significantly change the resolution.

In Fig. 4a, v_2 integrated over the FTPC rapidity region is shown versus the impact parameter b. For the FTPCs the π^+, π^- and protons are combined. It was shown in Fig. 1e that v_2 is relatively flat as a function of rapidity and its magnitude is therefore comparable in the FTPC and TPC regions. Fig. 4b shows the corresponding multiplicity as a function of b for the combined FTPCs. These quantities lead to a resolution for v_2, calculated using the true reaction plane, as shown in Fig. 4c. The resolution for v_2 which can be

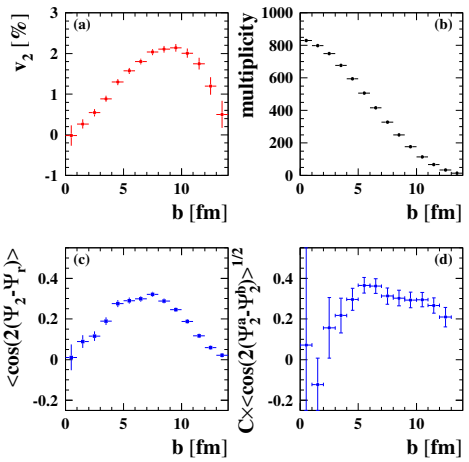

Figure 4: *RQMD v2.4 prediction for elliptic flow using π^+, π^- and protons within $2.5 \leq |y| \leq 4.0$.*

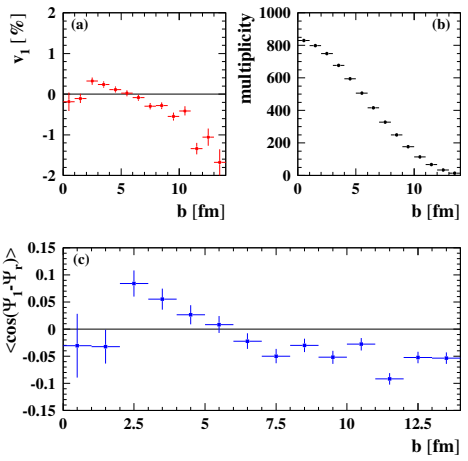

Figure 5: *RQMD v2.4 prediction for directed flow using π^+, π^- and protons within $2.5 \leq |y| \leq 4$.*

obtained in the STAR FTPCs using subevents is shown in Fig. 4d. If only one FTPC would be used this resolution would be approximately $\sqrt{2}$ smaller.

Using v_2 the event plane can be determined, however the sign of v_2 is not determined relative to **b**. This sign could be determined from v_2 relative to Ψ_1. Fig. 1c shows that around mid rapidity v_1 is maximally 0.5% which makes Ψ_1 extremely hard to measure. From Fig. 1a and 1c it is clear that the best region to measure v_1 is at forward rapidity. Fig. 5a shows v_1 integrated over the FTPC rapidity region, versus b. As for v_2, the π^+, π^- and protons are combined. This decreases the magnitude of v_1 because their signs are opposite but the FTPCs are not able to separate these particles. At large b the magnitude of v_1 becomes $\approx 1\%$ and, although this is already hard to measure, also the multiplicity decreases rapidly at large b. This leads to negligible resolution for v_1 at all values of b, which is shown in Fig. 5c.

6 Conclusion

We have investigated the feasibility of reconstructing the event plane. Both Fig. 3 and Fig. 4 show that it is possible to determine the second harmonic event plane and calculate v_2 within STAR, assuming the RQMD predictions (multiplicity distribution, magnitude of v_2) are correct. For v_2 both the TPC

or the FTPCs can be used. This would initially provide a cross check and later combining both detectors would increase the resolution. For this study we only need the momenta of the charged hadrons and thus anisotropic flow could be one of the first results from STAR. For future analyses it would be good to have particle identification. Because it is important to study the dependence of v_2 as a function of b [29] we would like to have 10 centrality bins, which would be possible with 1 000 000 minimum bias events.

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