Collective phenomena in ultra-relativistic nuclear collisions: anisotropic flow and more

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Abstract

Many features of multiparticle production in ultra-relativistic nuclear collisions reflect the collision geometry and other collision characteristics determining the initial conditions. As the initial conditions affect to a different degree all the particles, it leads to truly multiparticle effects often referred to as anisotropic collective flow. Studying anisotropic flow in nuclear collisions provides unique and invaluable information about the system evolution and the physics of multiparticle production in general. Being not able to cover all aspects of anisotropic flow in one lecture, I decided in the first part of the lecture to discuss briefly a few important and established results, and in the second part, to focus, in a little more detail, on one recent development – a recent progress in our understanding of the role of fluctuations in the initial conditions. I also discuss some future measurements that might reveal further details of the multiparticle production processes.

1 Introduction

In ultra-relativistic nuclear collisions, the particle momentum distributions, and in particular particle azimuthal distributions strongly depend on the initial geometry of the collision. Such dependence is usually discussed in terms of anisotropic collective flow, for a recent review, see [1]. Anisotropic flow has been studied since the first experiments at Bevalac, but the first measurement of the in-plane elliptic flow ($v_2 = \langle \cos[2(\phi - \Psi_{RP})] \rangle > 0$, where $\Psi_{RP}$ is the reaction plane angle) by the E877 Collaboration in Au+Au collisions at the BNL AGS [2, 3] marked a new page in the history of anisotropic flow as a start of flow studies in truly ultra-relativistic collisions. Since then, the anisotropic flow measurements became one of the most productive direction in our pursuit to understand the physics of the high energy nuclear collisions and multiparticle production in general.

This lecture consists of two parts. For the first part, out of several major results from RHIC, I have selected three well established and very important measurements that are directly related to the anisotropic flow: elliptic flow of charged particles, the number of constituent quark (NCQ) scaling of elliptic flow, and charge dependent correlation measurements sensitive to the so-called chiral magnetic effect (CME). I also compare these RHIC results to recent LHC measurements. The selection of these three topics is based on the following. The charged particle elliptic flow measurement was crucial in building of the picture of sQGP - strongly interacting/coupled quark-gluon plasma, with a conclusion that the system created at RHIC behaves as almost ideal liquid with the lowest ever observed viscosity over entropy density ratio. The NCQ scaling of elliptic flow is considered as a strong evidence for deconfinement, one of the major characteristics of QGP. The charge dependent azimuthal correlations
relative to the reaction plane are directly sensitive to the CME - the charge separation along the strong magnetic field of colliding nuclei that is intimately related to the properties of the QCD vacuum. The level of uncertainty in the interpretation of the above mentioned three measurements (and the corresponding backgrounds) is different - increasing from the first one to the last, but taking into account the importance of the questions, the coalescence hadronization picture in the case of NCQ scaling, and, possibly, the first direct measurement related to the non-perturbative structure of QCD vacuum in the last, all three measurements cannot be undervalued.

The second part of this lecture is about the rapid development over the last couple years in our understanding of the role of anisotropic flow fluctuations, and their relation to seemingly unrelated phenomena observed via two-particle correlations, such as the “ridge” and “Mach cone”. The uncovering of this relationship has resolved a long standing issue of the relative importance of flow fluctuations and the so-called nonflow. For several years we were puzzled by a possibility to explain the difference between two- and multi- (more than two) particle measurements of elliptic flow either almost entirely by flow fluctuations, or again, almost entirely by nonflow assessed via analysis of two-particle correlations. It appears that the resolution of this puzzle is simple: two approaches are just different descriptions of the same phenomena - the system response to the fluctuating initial conditions. This understanding allows us to propose totally new and promising new insights measurements, such as the femtoscopic analysis of the particle production relative to the higher harmonic event planes.

2 Major results from RHIC era and comparison to LHC data

2.1 Integrated and differential elliptic flow of charged particles

One of the main (and probably most widely known) result from RHIC is the observation of strong elliptic flow ($v_2$), which for the first time is quantitatively close to the predictions of ideal hydrodynamics. Although for many this result appeared as totally unexpected, an analysis of the BNL AGS and CERN SPS data indicated that the elliptic flow exhibited a strong increase with collisions energy in that energy domain. A simple extrapolation to RHIC (and the LHC) energies, e.g. performed using suggested in $v_2/\varepsilon$ scaling with particle density (here $\varepsilon$ is the eccentricity of a nuclear collision overlap zone) suggested a significant increase in $v_2$ up to the RHIC energies with some kind of a saturation at larger energies. The experimental measurements [5] agree well with such a conclusion, see the excitation function of elliptic flow in mid-central collisions in Fig. 1. The recent data from LHC [6] supports the picture indicating that at even higher system temperatures at LHC, the elliptic flow remains to be large in an agreement with hydrodynamic calculations.

Ever more precise measurements of anisotropic flow was developing along with a significant progress in viscous relativistic hydrodynamics calculations. The comparison of the experimental results with theory allowed unprecedented extraction of transport properties of sQGP, first of all the ratio of shear viscosity to entropy density. That appeared to be the lowest ever observed, of the order of a few times the lower bound $1/4\pi$, see Fig. 1 right panel, which shows a comparison of $v_2$ centrality dependence to different viscous hydrodynamic calculations [7, 8].

2.2 NCQ scaling of elliptic flow

The QGP is a thermalized and deconfined QCD matter. To test if the deconfinement has been reached in nuclear collisions is not a simple task, in particular because at present we do not have any theoretical model that would self-consistently describe the hadronization process. This is the reason why the idea [10], that in heavy ion collisions there might be a region in transverse momentum where the particle production will be dominated by quark coalescence and, at the same time, can be described by
Elliptic Flow: A Brief Review

The energy dependence of the average elliptic flow in 20-30% centrality bin at different collision energies (from [6]). (Right) $v_2$ centrality dependence in Pb+Pb collisions at 2.76 TeV [6] compared to viscous hydro calculations (this figure is taken from [9]).

the standard coalescence formalism attracted a lot of attention. (Note that in general the standard coalescence formalism is applicable only to the so-called rare processes in which the “parent” distributions are weakly affected by the coalescence process – just recall that the formalism was developed for the light nuclei production.) Based on the coalescence hadronization picture one can make predictions on the dependence of the particle mean transverse momentum on particle density, baryon-to-meson ratio, and most importantly for this discussion, for anisotropic flow of baryons and mesons.

The essence of the coalescence formalism is the statement that the invariant spectrum of produced particles is proportional to the product of the invariant spectra of constituents:

$$
\frac{dN_B}{d^2p_\perp} (p_\perp) = C_B \left[ \frac{dN_q}{d^2p_\perp} (p_\perp/3) \right]^3, \quad \frac{dN_M}{d^2p_\perp} (p_\perp) = C_M \left[ \frac{dN_q}{d^2p_\perp} (p_\perp/2) \right]^2,
$$

where the coefficients $C_M$ and $C_B$ account for the probabilities for $q\bar{q} \rightarrow meson$ and $qqq \rightarrow baryon$ coalescence. The quark spectra are not uniform relative to the reaction plane, and according to Eq. [1] the anisotropy should be amplified almost a factor of two in meson spectra and about factor of three in baryon spectra. Within that picture (and only in the limited region where the formalism is applicable), elliptic flow, $v_2(p_T)$, of baryons is expected to be about 3/2 times larger than that of mesons [10] [11].

Such a relationship has been observed experimentally later within about 10-20% accuracy – typical for such kind of predictions (of “additive quark model”). This observation is considered as a strong evidence that the system created in heavy ion collision is in a deconfined state during most of its evolution. The preliminary results from LHC seems to be in agreement with the NCQ scaling, though the detailed analyses of LHC data are ongoing.

2.3 Testing the chiral magnetic effect

QCD links chiral symmetry breaking and the origin of hadron masses to the existence of topologically nontrivial classical gluonic fields, instantons and sphalerons, describing the transitions between the vacuum states with different Chern-Simons numbers. Quark interactions with such fields change the quark chirality and are $P$ and $CP$ odd. Though theorists have little doubt in the existence of such fields, they have never been observed directly, e.g. at the level of quarks in the deep inelastic scattering. The experimental search for the local strong parity violation in heavy ion collisions was greatly intensified once it was noticed [13] [14] that in noncentral nuclear collisions it could lead to the asymmetry in the
emission of positively and negatively charged particle perpendicular to the reaction plane. Such a charge separation is a consequence of the difference in the number of quarks with positive and negative helicities positioned in the strong magnetic field ($\sim 10^{15}$ T) of a noncentral nuclear collision, the chiral magnetic effect [13, 15]. The direction of the charge separation varies in accord with the sign of the domain topological charge, which makes the observation of the effect experimentally difficult. A correlator sensitive to the CME was proposed in Ref. [16]:

$$\langle \cos(\phi_a + \phi_b - 2\Psi_{RP}) \rangle = \langle \cos \Delta \phi_a \cos \Delta \phi_b \rangle - \langle \sin \Delta \phi_a \sin \Delta \phi_b \rangle$$

$$= \langle v_{1,\alpha}v_{1,\beta} + B_{in} \rangle - \langle a_{1,\alpha}a_{1,\beta} \rangle \approx -\langle a_{1,\alpha}a_{1,\beta} \rangle + [B_{in} - B_{out}],$$

(2)

where the $a_1$ coefficients describe the (first harmonic) up-down asymmetry in particle production. Subscript $\alpha$ denotes the particle type. STAR Collaboration measurements [17, 18] of this correlator are consistent with the expectation for the CME and can be considered as evidence of the local strong parity violation. Preliminary ALICE results [19], see Fig. 3, show very similar signal. The ambiguity in the interpretation of experimental results comes from a possible background of (the reaction plane dependent) correlations not related to CME. As the detailed quantitative predictions for CME do not yet exist, it is difficult to disentangle different contributions. At the same time there exist no model which would fully describe the data in terms of “conventional” physics. The most notable in this respect is the paper [20] where the authors show that the difference between the same sign and opposite sign correlations as measured by STAR can be explained within a blast wave model that includes charge conservation along with radial and elliptic flow with parameters tuned to the data.

Note that a key ingredient to CME is the strong magnetic field, while all the background effects originate in the elliptic flow. This can be used for a possible experimental resolution of the question. One possibility is to study the effect in central collisions of non-spherical $U$ nuclei [21], where the relative contributions of the background (proportional to the elliptic flow) and the CME (proportional to the magnetic field), should be very different in the tip-tip and body-body type collisions (see right panel of Fig. 3) and differ from those in central Au+Au collisions. The body-body $U + U$ collisions would correspond to a strong background (elliptic flow due to the ellipsoidal shape of the nuclear overlap zone) and small CME signal, as the magnetic field is expected to be relatively weak in such collisions.

Figure 2: (Left) Identified particle elliptic flow in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV. (Right) Test of the NCQ scaling. Both figures are taken from review [12].
As discussed below, fluctuations in the initial conditions lead to significant higher harmonic flow. This opens new possibilities for estimates of the background in the measurements of charge dependent correlations sensitive to the CME. The idea here is that the CME, the charge separation along the magnetic field, should be zero (highly suppressed) if measured with respect to higher harmonic event planes, while the background effects due to flow should be still present, although smaller in magnitude (according to higher harmonic flow). An example of such a correlator, where the CME contribution expected to be strongly suppressed, would be:

$$\langle \cos(2\phi_\alpha + 2\phi_\beta - 4\Psi_4) \rangle,$$

(3)

where $\Psi_4$ is the fourth harmonic event plane. The value of the background due to flow could be estimated by rescaling the correlator Eq. 2. These measurements will require good statistics; detail interpretation would also need calculations of the magnetic field fluctuations. Finally, I note that many other experimentally possible tests, in particular with identified particles, can be found in 22.

Figure 3: (Left) The correlator Eq. 2 measured by STAR and ALICE collaborations 19. (Right) Tip-tip (a) and body-body (b) configurations of $U + U$ central collision.

### 3 Recent developments: higher harmonic flow

For a long time, the main systematic uncertainty in the interpretation of the elliptic flow measurements was the unknown relative contribution from flow fluctuations and nonflow – the correlations not related to the initial geometry. These two effects determine the difference in $v_2\{2\}$ and $v_2\{4\}$ - elliptic flow measurements with two and 4-particle cumulants. $v_2\{2\}$ is biased toward higher values by both, flow fluctuations and nonflow, and $v_2\{4\}$, basically free from nonflow, is biased toward smaller values by fluctuations. It is thought that flow fluctuations are mostly due to fluctuations in the position of the participating nucleons, the distribution of which determines the participant plane (that is different from the reaction plane). The first realistic estimates of flow fluctuations 23 24 showed that almost the entire difference between $v_2\{2\}$ and $v_2\{4\}$ can be accounted for by flow fluctuations without much “room” left for nonflow contribution. A little earlier to these flow fluctuations estimates, it was argued 25 that in a nuclear collision the spatial correlations of particles produced in the same nucleon-nucleon collision in conjunction with the radial flow lead to a narrow in azimuth and long ranged in rapidity correlations. Such correlations were observed later experimentally and called ridge. In 26 27 it was shown explicitly in the event-by-event hydrodynamical calculations that the fluctuations in the initial density distribution that extends over large rapidity range lead to the ridge structure in two particle correlations (for a bit more detail discussion of this question see 28). An important and striking
The resolution of the puzzle appeared to be simple: although the appearance of the ridge and anisotropic flow fluctuations look as totally unrelated phenomena, they have the same roots and appear to be different descriptions of the same phenomenon – the reaction of the system to fluctuations of anisotropic flow that was recently measured by several collaborations at the LHC and RHIC, see the results from ALICE Collaboration [34] in the right panel of Fig. 3.

Different shapes in the initial geometry of the collision, as shown in Fig. 3, to a different degree will be preserved in the system freeze-out shapes. It was shown in [28] that those shape can be addressed experimentally with azimuthally sensitive femtoscopy analysis. Recall that for a Gaussian source, the correlation function appears to be a Gaussian

\[ C(\mathbf{q}, \mathbf{P}) \propto 1 + \exp \sum_{i,j} R_{ij}^2 q_i q_j, \]  

where \( \mathbf{q} = \mathbf{p}_1 - \mathbf{p}_2 \) is the pair relative momentum, \( \mathbf{P} = (\mathbf{p}_1 + \mathbf{p}_2)/2 \approx \mathbf{p} \) is the particle average momentum, and \( R_{ij}^2 = \langle (r_i - V_{it})(r_j - V_{jt}) \rangle \) are the HBT radii. The idea of the azimuthally sensitive femtoscopy analysis, to study the radii dependence on the pair emission angle with respect to the reaction plane, was first proposed in [35] with an extension to non-identical particle correlation in [36].

Figure 4: (Left panels) 10k Au+Au collision events at \( b = 8 \) fm rotated to different event planes. (Right panel) Differential flow for harmonics \( n = 1 - 5 \) by ALICE Collaboration [34].
Details of femtoscopic analyses and discussion of the experimental results can be found in a review [37].

Figure 5: Left: side-out coordinates. Middle: illustration of predominant expansion along shorter directions. $v_n(pt)$ for typical values of parameters used in this work.

The dependence of the HBT radii on the higher harmonic ($n > 2$) flow appears to be a bit more complicated compared to the “standard” analysis with respect to the reaction plane. In the discussion below I use a standard side-out-long system [37] (see figure 5 left). For a stationary (not expanding) source the radii azimuthal dependence can be expressed as

$$R_{side}^2 = \langle x_{side}^2 \rangle = \langle x^2 \rangle \sin^2 \phi + \langle y^2 \rangle \cos^2 \phi - \langle xy \rangle \sin 2\phi,$$

which has only $n = 2$ harmonic. Higher harmonics azimuthal dependence appears only as a deviation from the Gaussian shape of the correlation function, e.g. in $\langle x_{side}^6 \rangle$ and $\langle x_{side}^4 \rangle$ for triangular and quadrangular shapes respectively, which would greatly complicate the analysis (for the effect of non-Gaussiness on HBT radii, see [38]). But this is true only for a stationary source. The picture changes if one considers azimuthal variation in the expansion velocity, see Fig. 5 middle panel, where the thickness of the arrows indicate the expansion velocity. As shown in [28] using a blast wave model calculations with realistic parameters, the azimuthal dependence of the HBT radii is significant, see Fig. 5 right panel, which indicates that the higher harmonics shape effects become clearly visible and measurable. That was also confirmed in the AMPT [39] model calculations [35].

4 Summary

Heavy ion collisions is unique laboratory to study QCD, including the physics of hadronization and properties of QCD vacuum. Anisotropic flow is one of the most important and sensitive tool in this study. The recent progress in the understanding of the physics of anisotropic flow fluctuations and their relation to the structures in two particle $\Delta \eta \times \Delta \phi$ correlations, further advances the physical interpretation of the measurement. Measurements with higher harmonics flow promise new insights to the correlation measurements related to CME, and the system shape and velocity fields via femtoscopy.

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