Anisotropic collective phenomena in ultra-relativistic nuclear collisions

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Abstract

For a detailed review of this subject I refer to a recent paper [1]; in this talk I only very briefly comment on a few most important questions: (a) Very recent significant progress in viscous hydrodynamics calculations (b) Initial eccentricity/flow fluctuations, the effect of which has been clarified recently (c) Initial conditions, in particular the role of the gradients in the initial velocity field, (d) Puzzling system size dependence of directed flow (e) Azimuthal correlations that are sensitive to the strong parity violation (f) Future measurements at RHIC and LHC, including pp-collisions

Key words: Anisotropic flow, directed, elliptic, parity

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Introduction

Anisotropic flow for a several years remains one of the most important measurements in the field of heavy ion collision. Those were the key measurements [2] for making a conclusion on creation of the strongly interacting Quark Gluon Plasma (sQGP) at RHIC. The observation of the constituent quark number scaling [3,4] in elliptic flow at intermediate transverse momenta is a strong evidence for deconfinement. Recently the progress in this field has been reviewed, including many technical details, in [1].

Viscous hydrodynamics.

The importance and the magnitude of the viscous effects could be judged already from the early calculations [5] where the hydro dynamical evolution at some intermediate stage was joined to the transport model to simulate late (viscous) evolution of the system. Recently there have been performed several calculations of the hydrodynamical expansion with viscous terms explicitly included into equations. A great advancement in these calculations (including in the formulations of the equations itself) has been achieved via the collaboration of several groups within TECHQM initiative [6]. Even the “minimal”
values of viscosity ($\eta/s = 1/(4\pi)$) were found to have a strong effect on elliptic flow (see, Fig. 1) leading to up to $\sim 25\text{-}30\%$ reduction in flow values in Au+Au collisions and as large as 50% in Cu+Cu. Such a strong sensitivity of the elliptic flow to viscosity values can be used for measuring viscosity. One of such attempts is presented in Fig. 2, where the calculations [8] at different viscosity values are compared to the STAR data assuming CGC initial conditions. At present, the initial conditions, and to somewhat lesser extend, the uncertainties in the hadronization stage are the main factors preventing precise measurement of viscosity. At the same time one can safely put an upper bound on $\eta/s$ of about factor of five the minimal value of $1/(4\pi)$ [7].

**Flow and eccentricity fluctuations**

The role of flow fluctuations and non-flow effects is one of a long standing problem that received a lot of attention and significant progress has been made in the recent couple years. In particular, the role of fluctuations in the initial system geometry defined by nuclear participants (interacting nucleons or quarks) has been greatly clarified [9]. At fixed impact parameter, the geometry of the participant zone fluctuates, both, in terms of the value of the eccentricity as well as the orientation of the major axes. The anisotropy develops along the plane spanned by the minor axis of the participant zone and the beam direction, the so called participant plane. As the true reaction plane (defined by the impact parameter) is not known and the event plane is estimated from the particle azimuthal distribution “defined” by the participant plane, the apparent (participant plane) flow appears to be always bigger (and always “in-plane”, $v_{2,PP} > 0$) compared to the “true”
flow as projected onto the reaction plane.

It was noticed [10] that in collisions of heavy nuclei the fluctuations in the eccentricity $(\varepsilon_x, \varepsilon_y) = \left(\langle (\sigma_y^2 - \sigma_x^2)/(\sigma_y^2 + \sigma_x^2) \rangle, \langle (2\sigma_x\sigma_y)/(\sigma_y^2 + \sigma_x^2) \rangle \right)$ can be well described by two-dimensional Gaussian, for which the higher cumulant flow $(\nu(n), n \geq 4)$ is not only insensitive to non-flow but also to fluctuations. All of higher cumulants are exactly equal to the “true” flow, namely as given by projection onto the reaction plane. This greatly simplifies the comparison of theoretical calculations to the data, as it says that in such calculation one should not worry how to take into account the fluctuations in the initial eccentricity (which is a non-trivial task) but just compare to the “right” measurement, e.g. $\nu_2 \{\nu \}$. At the same time, the apparent (participant plane) flow become unmeasurable in a sense that flow fluctuations could not be separated from non-flow contributions by means of correlation measurements.

The role of fluctuations and non-flow in the event plane method is more complicated to investigate due to non-linearity of the problem. Nevertheless, first with Monte-Carlo [11] and later analytically [12] in small fluctuation limit this problem also has been solved. It appears that this method also does not allow to separate two effects.

Now we have almost full understanding of the role of fluctuations and non-flow in different flow measurements. Unfortunately this progress in understanding the nature of fluctuations does not help in resolving the problem of measuring separately flow fluctuations and non-flow. One needs further assumptions, e.g. as done by the PHOBOS Collaboration that uses estimates of non-flow effects from correlations with large rapidity separations.

Initial flow velocity profile. Elliptic and Directed flow.

Another important and interesting direction that is just started to be explored is the role of the non-zero initial flow velocity profile, e.g. non-zero velocity gradient along the impact parameter, Fig. 3. As shown in [13] such a gradient directly contributes to the in-plane expansion rate (see Eq. 22 in [13]). The contribution to the final magnitude of the elliptic flow can be significant; to check this we need full 3d hydrodynamics study with different initial conditions.

Note that such initial flow gradients naturally would lead to directed flow (see the same Eq. 22); this question was briefly addressed in [13]. Speculating on this subject one would notice that viscous effects must also play an important role in such a scenario. It will be very interesting to compare the calculations in such a model to a very precise recent data from STAR [15].

One surprising observation made in [15] is that the directed flow is almost independent of the system size if compared at the same centrality. It is not described by any model. Understanding of such behavior can be very important in clarification of the initial conditions. Recall that predictions for non-trivial dependence of directed flow on rapidity [16] (so called “wiggle”) was based on the assumption of non-zero initial velocity profile of net nucleons similar to that shown in Fig. 3. Future measurements of directed flow with identified particles will be very important in this respect. Another possibility to address this question would be colliding beams of nuclei of the same mass but different charge, similar to what has been done at GSI at lower energies, where beams of $^{96}_{44}Ru$ and $^{96}_{40}Zr$ were used [17,18]. As discussed below such isobaric beams will be very also important for the search of strong parity violations.
Search for the strong $\mathcal{P}$-violation

It was shown in [19,20] that in the presence of topologically non-trivial gluonic fields the magnetic field of the colliding nuclei induces parallel to it electric field (the effect which violates parity). The induced electric filed leads to the charge separation (preferential emission of same charge particles) in the direction perpendicular to the reaction plane. Such anisotropy, which very much resembles “out-of-plane directed flow” can be addressed with the help of three-particle correlations [22] by measuring $\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$, where $\phi_{\alpha,\beta}$ are azimuthal angles of two (same or opposite) charged particles, and $\Psi_{RP}$ is the reaction plane angle. The estimates [21] indicate that the effect is strong enough to be observed in heavy ion collisions. The STAR Collaboration reported the preliminary results [22], see Fig. 5, that qualitatively agree with theoretical estimates [19,21]. Note, that the correlator $\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$ is $\mathcal{P}$-even and contain contributions from other effects not related to parity violation. A careful analysis of such a contribution is obviously needed before any strong conclusion can be drawn from these measurements.

Taking into account the importance of the question, one can envision a dedicated program for establishing the nature of the signal and further detail study. From the theoretical point of view, the calculation of the dependence on centrality and system size looks fully doable though requires significant computing and man power (e.g. 3d hydrodynamics is needed for the calculation of the magnetic field). Detailed predictions on the transverse momentum and particle type dependence also will be essential in differentiating this effect from possible “background” contributions. Also interesting would be a calculations of “usual” transverse momentum and rapidity two and multiparticle correlations due to topological effects responsible for the charge separation. There can be extensive experimental program. For example, the energy dependence (e.g. during the RHIC beam energy scan) of the effect can be very indicative if any threshold type behavior will be found, as the effect might be strongly suppressed in no QGP systems. Identified and multiparticle correlations studies also will be available with larger statistics. The charge separation dependence on the magnetic field [21] can be tested with collision of isobaric nuclei, such as $^{96}_{44}Ru$ and $^{96}_{40}Zr$ that were used at GSI [17,18] and
discussed above in relation to the directed flow studies (in this case one needs symmetric collisions).

**RHIC: beam energy scan. LHC: Pb+Pb and p+p.**

Coming years promise many new interesting data from low energy RHIC run and, of course, from LHC. The main interest in the low energy RHIC scan, anisotropic flow is no exception, is the search for the QCD critical point. The scan would cover the energy region from top AGS energies, over the CERN SPS, and higher. In terms of anisotropic flow two major observables to watch would be a possible “wiggle” in $v_2/\varepsilon$ dependence on particle density [24] and “collapse” of directed flow [25]. RHIC also has plans to extend its reach in terms of energy density using uranium beams. From the first estimates and ideas of using uranium beam we now have real detailed simulations [26] of such collisions with developed methods for a selection of desired geometry of the collision.

The predictions for the LHC are rather uncertain, though most agree that the elliptic flow will continue to increase [27], partially due to smaller viscous effects. Simple extrapolations [28,29], of the $v_2$ collision energy dependence to LHC energies lead to about 20-30% increase in elliptic flow values. Note that there exist calculations predicting decrease of the elliptic flow [30]. Another important observation is an increase in mass dependence (splitting) of $v_2(p_T)$ due to a strong increase of radial flow.

An exciting direction at LHC will be the study of collective effects in pp collisions. Note that event multiplicities at LHC energies will be comparable to those of central Cu+Cu collisions at RHIC. The detailed analysis of event anisotropies will be possible and very interesting; it promises new insights into physics of multiparticle production. I mention here only one possibility - the study of the so-called multi parton collisions. Fig. 6 shows the multiplicity distribution measured by E835 Collaboration at Fermilab in the so called KNO variable. It is decomposed [31] into distributions corresponding to events with one, two or three soft parton interactions. The nature and space-time picture of these interaction is not totally clear. One possibility would be that it corresponds to interactions of different number of constituent quarks. Fig. 7 shows a schematic view of such an interaction. Experimentally this question can be addressed by studying azimuthal multiplicity and transverse momentum correlations as a function of total event multiplicity.

In summary, we have had very exciting years of anisotropic phenomena study, which greatly enriched our understanding of ultra-relativistic nuclear collisions and multiparticle production in general. Future experimental programs at LHC and RHIC promise new results and new physics.

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Fig. 6. Multiplicity distribution, $\sqrt{s} = 1.8$ TeV, as a superposition of events with different number of soft parton collisions [31].

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