DENSE MATTER AT RHIC: ANISOTROPIC FLOW*

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In this talk I discuss recent results on elliptic flow in Au+Au collisions at RHIC and how these results help us to understand the properties and evolution dynamics of the system created in such collisions. In particular, I discuss if and how the elliptic flow results obtained at RHIC indicate the system thermalization, deconfinement, and how much it tells us about the hadronization process.

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1. Introduction

This summer the heavy ion community, both theorists and experimentalists, made an effort to asses the main discoveries from the first three years of the RHIC operation from the point of view of if the Quark-Gluon Plasma (QGP) has been created in Au+Au collisions [1]. The thermalization and deconfinement are considered as the main attributes of the QGP form of matter. One and historically the first argument in favor of the QGP formation in RHIC collisions is the observation of strong elliptic flow [2]. Elliptic flow is a common term for the second harmonic in particle azimuthal distribution relative to the reaction plane, the plane spanned by the beam direction and the impact parameter vector [3]. Quantitatively elliptic flow is characterized by the magnitude of the second Fourier coefficient, v_2, which is studied as function of particle rapidity, transverse momentum, and centrality of the collision. Note that the term flow is used here only to emphasize the collective behavior in particle production. It does not assume necessarily the hydrodynamic flow, which in particular would require a thermalization of the system.

The origin of elliptic flow is in the initial anisotropic (almond) shape of the system in the transverse plane and in the particle rescatterings during subsequent system evolution. No rescattering means no momentum

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anisotropy in the final stage. Any delay in time when the rescatterings are switched "on" would lead to the diminishing of the system spatial anisotropy and, therefore, to a decrease in the elliptic flow signal. Based on this fact, one can conclude that anisotropic flow must be sensitive to the particle interactions very early in the system evolution, the information usually available only via weakly interacting probes. The system constituent rescatterings is by far the most common explanation of the elliptic flow. Although some speculations on the possibility of different origin of the elliptic flow exist (*e.g.* direct anisotropy in particle emission from the color glass condensate), we do not consider them here.

There exist already plenty information on anisotropic flow. In this talk I address only the following issues: the collision energy dependence of the magnitude of the integrated (average over all transverse momenta) elliptic flow, the so-called "mass splitting" — the systematic change in differential elliptic flow, $v_2(p_{\rm t})$, in the region of relatively low transverse momenta $p_{\rm t} \leq \langle p_{\rm t} \rangle$ in accordance to the particle mass, and the "constituent quark scaling" — an apparent dependence of hadron elliptic flow at intermediate transverse momenta, $p_{\rm t} \sim 2$–4 GeV/c, on the number of constituent quarks in the hadron. The last observation, the constituent quark scaling, is of a particular interest and importance. A proof that the hadronization occurs via an intermediate constituent quark stage in some sense could be even more important than the very discovery of the QGP. This is for the following reason: nobody questions the existence of such a state as the QGP, the question is only if in nuclear collisions at RHIC it has been created. The constituent quark picture of hadronization could mean more that we have already known (or agreed upon) — it means that the constituent quarks do exist as real (quasi)particles and could play an important role in dynamics of multi-particle production. That there could be yet a new state of matter — a gas of constituent quarks, which up to now has not been observed in lattice QCD (assuming thermalization — is it the reason?). Taking into account the importance of the constituent quark scaling it is discussed first.

All of the above questions are presented from different sides:

(i) Popular view, which often coincides with the most probable interpretation;

(ii) skeptic's view, a try to explain the experimentally observed phenomena by mechanisms other than the popular view and;

(iii) what should/can be done in order to resolve the ambiguity.

2. Elliptic flow at intermediate transverse momenta and the constituent quark scaling

Subject. The constituent quark model have been used often in the hadron spectroscopy, and rarely in models describing (multi)particle production. It appears that high energy nuclear collisions could provide a very interesting window of opportunity to prove that hadron production indeed happens via constituent quark phase. It has been noticed in [4] that if hadrons are formed via coalescence of the constituent quarks then there should be a region in the transverse momentum space where particle yield would be proportional to the quark density in the power equal to the number of constituent quarks, 2 for mesons and 3 for baryons. Besides other important consequences, such as enhanced relative production of baryons in this region, this picture would lead to the constituent quark scaling of elliptic flow, $v_2(p_\mathrm{t}) \approx n v_2(p_\mathrm{t}/n)$, where n is the number of constituent quarks in the hadron [4, 5]. As Fig. 1 shows this scaling holds to a good accuracy. Note that while the scaling is limited to a specific region in transverse momentum, the coalescence mechanism itself is valid at all smaller momenta.

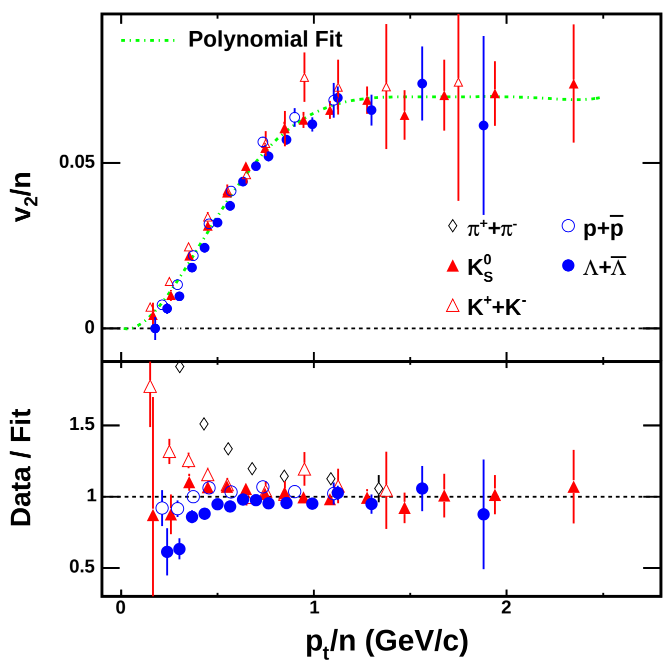

Fig. 1. (Color online) Test of the constituent quark number scaling of elliptic flow. Minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ [6].

Popular view / probable interpretation. In this approach the quantity $v_2(p_t/n)$ is interpreted as elliptic flow of constituent quarks. Two very important conclusions follow from the scaling observation. First is that the elliptic flow (collective motion) is developed at pre-hadronic stage, the phenomena often referred to as partonic collectivity. The second conclusion, the most important, is that flow at the constituent quark level means deconfinement — as the constituent quarks must be in a deconfined phase in order to be freely "reshuffled" into final hadrons. This could be the first, and very strong argument for an observation of the deconfined matter at RHIC.

More skeptical view. It was noticed in [9, 10] that the constituent quark scaling would contradict a local thermalization and freeze-out at a constant phase-space density. Note that it does not diminish the validity of the conclusion on deconfinement, but one has to have in mind that the system created can be deconfined but not thermalized matter. It also does not exclude the possibility of thermalization at lower transverse momenta.

A totally skeptical view on the constituent quark scaling would be that the experimental results have nothing to do with constituent quarks.

Means to resolve questions. The picture in which hadrons are produced via constituent quark coalescence may have many other observable effects and those have to be tested experimentally in detail. Doing this, it is important not to oversimplify the picture. For example, a typical over- (mis-) interpretation of this picture includes an assumption of global thermalization of the constituent quarks and/or an absence of any correlations at the constituent quark stage before the hadronization. It is also likely that the constituent quark stage is not separated in time, the fragmentation of partons, formation of constituent quarks, and formation of hadrons can take place at the same time. Even with all these complications the detail study of the dependence of the effect on centrality of the collision, collision energy, and the size of the colliding nuclei, in parallel with the study of correlation in particle production should be able to either confirm or disapprove this picture.

3. Elliptic flow at RHIC and the "hydrodynamic limit"

Subject. Elliptic flow has been studied long before the RHIC era. The results of the measurements were always significantly lower than hydrodynamic model predictions. That discrepancy has been usually explained by the lack of complete thermalization at low energies. At RHIC, for the first time the experimentally observed elliptic flow is close to the results of hydrodynamical calculations. This fact is considered as a strong argument in favor of thermalization in the system. Taking into account the large energy density achieved in the collisions one leans toward conclusion of the QGP formation.

Popular view / probable interpretation. Fig. 2 shows the elliptic flow measured at different energies and centralities of the collision scaled by the initial spatial anisotropy. The idea of this plot is the following: in the limit of complete thermalization the matter can be described hydrodynamically, elliptic flow would depend mostly on the initial space anisotropy (note that there exist no other parameters in the problem except the in-plane and out-of-plane sizes which have dimension of length, as the mean free path is assumed to be very small) and should not depend on the particle density. This observation is approximately confirmed by direct numerical calculation in the hydrodynamical models. In another limit, the so called low density limit, when the mean free path length is comparable or large to the size of the system the probability for a particle to re-scatter, and consequently the elliptic flow would be proportional to the particle density. Therefore, one would expect that the quantity v_2/ε should increase with particle density, and then saturate at values given by hydrodynamic. The saturation point would mean that the thermalization has been achieved in the system. As Fig. 2 shows, at RHIC energies the scaled anisotropy at relatively central collisions indeed is close to the hydrodynamic predictions. One can take it as an evidence of thermalization at RHIC. Moreover, in order to reach that high value of elliptic flow one has to conclude that the thermalization happens at very small time scale, of the order of a few tens of fm [11].

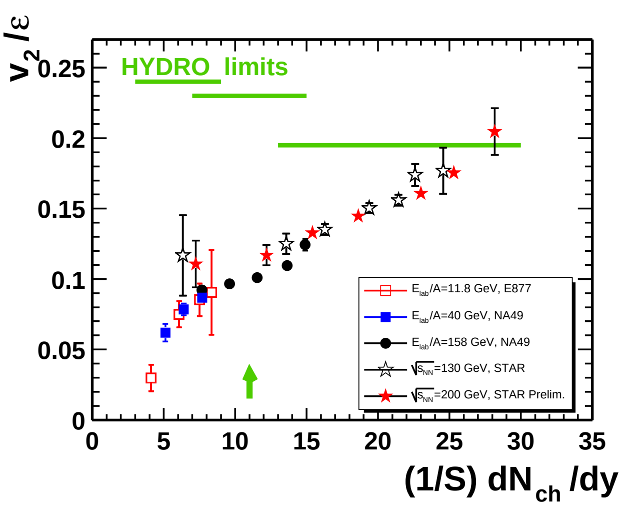

Fig. 2. (Color online) Elliptic flow scaled by initial spatial anisotropy as function of particle density in the transverse plane. The arrow indicate the position of color percolation phase transition advocated by H. Satz. Figure is taken from [7].

Skeptic's view. Do we observe any hint of saturation in v_2/ε? Could it be just a steady increase with crossing hydro predictions at RHIC energies? Also, could a particular hadronization mechanism, *e.g.* constituent quark coalescence, change the hydrodynamic limits? Is it possible that other mechanisms, beyond the "simple" rescatterings, contribute to final elliptic flow? Somewhat worrisome in this respect are the results of elliptic flow calculations obtained in some transport models [12], where for a particular parameters the resultant elliptic flow values were found to be significantly higher than given by hydrodynamic calculations. One could argue that such parameter values would correspond to unrealistic equation of state that was not considered in any hydro calculations, but the quantitative answer would definitely help here.

Means to resolve uncertainty. One can check if v_2/ε still increases at even higher particles density. For that, besides some obvious solution (like waiting for the LHC results) one can consider uranium+uranium collisions at RHIC (I think those would be extremely difficult to analyze). It is also very important to perform the precision measurements and detail study of v_2/ε dependence itself — strongly suppressing the systematic uncertainty in the results.

4. $v_2(p_t)$ of identified particles and "mass splitting"

Subject. Another argument in favor of the QGP formation at RHIC is the observation of the "mass splitting" — the difference in differential elliptic flow, $v_2(p_t)$, at low transverse momenta in accordance to particle mass, see Figs. 3 and 4.

Popular view / probable interpretation. In hydrodynamical as well as in so-called "hydro inspired" models like Blast Wave Model, this characteristic mass splitting appears as a consequence of interplay of three velocities: thermal velocity, radial (transverse) expansion velocity and the variation in the radial expansion velocity relative to the reaction plane orientation. Recall that the originally almond shaped system would have larger pressure gradient in the in-plane direction compared to the out-of-plane direction, the fact that leads to larger in-plane expansion velocity. As the result of that the particles with low transverse momentum would be mostly produced by the part of the system which moves in the out-of-plane direction (has smaller transverse velocity).

As the splitting is a very natural consequence of the hydrodynamical expansion, again, the observation of the splitting means the thermalization in the system. Moreover, the very strong dependence on mass observed experimentally, can be reconciled only with a scenario including relatively long lived QGP.

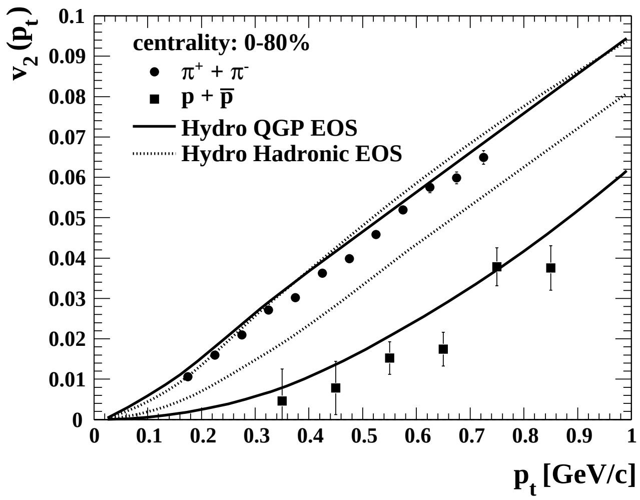

Fig. 3. $v_2(p_t)$ of identified particles in minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 130\,\mathrm{GeV}$ and hydrodynamic calculations with and without phase transition. Figure is taken from [8].

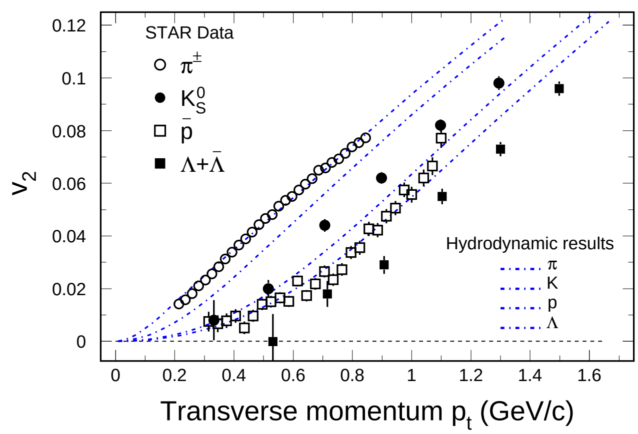

Fig. 4. $v_2(p_t)$ of identified particles at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$. Figure is taken from [6].

Skeptic's view. There could be many skeptical remarks made at this point. First, the mass dependence itself cannot be considered as something specific only to the hydro (or "hydro-inspired") models. In fact it could be very difficult to imagine a model, which would not posses such an effect. For example, in the coalescence scenario, the mass of the hadron should be related to the possible momentum difference of the coalescing quarks. Higher mass would mean a large difference in momentum, which inevitably would result in smaller anisotropic flow. The relatively good description of the experimental data by the hydrodynamical calculations with the QGP equation of state can be just an accident: first, the description is not really great and the deviations are clearly noticeable. Also one should have in mind that the comparison is done with minimum bias data obtained with two-particle correlation technique. The last one can have large non-flow contribution strongly dependent on centrality.

Means to clarify the question. Precise comparison of hydrodynamic calculations with data in narrow centrality regions. It is also important to keep the hydrodynamic model parameters tuned to single particle spectra.

5. Conclusion

Anisotropic flow studies at RHIC have produced very important and exciting results. We have to be open to different interpretations of these observations, and continue to test different hypotheses, but at the same time everybody would agree that these measurements strongly indicate that in Au+Au collisions at RHIC we have created the deconfined and mostly thermalized matter. The hadronization scenario via constituent quark coalescence is yet another important piece in our understanding of the dynamic of multi-particle production.

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