Anisotropic flow at RHIC: constituent quark scaling

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Abstract. Elliptic flow of identified particles recently measured in Au+Au collisions at RHIC exhibits a remarkable constituent quarks scaling in the intermediate transverse momentum region. In this talk, I discuss if and how the observed constituent quark scaling indicates the deconfinement in the created system, and how much it tells us about the hadronization process.

1. Introduction
This year, the heavy ion community, both theorists and experimentalists, made an effort to assess 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 main attributes of the QGP form of matter are considered to be the thermalization and deconfinement. One and historically the first argument in favor of the QGP formation in RHIC collisions is the observation of strong elliptic flow [3]. 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 [5]. 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.

Elliptic flow has its origin in the initial anisotropic (almond) shape of the system in the transverse plane and in the particle rescatterings during subsequent system evolution. No rescatterings during the system evolution means no momentum 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.

During the last years of intensive study of the elliptic flow a lot of information have been collected: the collision energy dependence of the magnitude of the integrated (average over all transverse momenta) elliptic flow, the information on so-called “mass splitting” - the systematic change in differential elliptic flow, $v_2(p_t)$, in the region of relatively low transverse momenta $p_t \leq \langle p_t \rangle$ in accordance to the particle mass. In this talk I concentrate on the “constituent quark scaling” - an apparent dependence of hadron elliptic flow at intermediate transverse momenta, $p_t \sim 2 - 4$ GeV/c, on the number of constituent quarks in the hadron. I think that this
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 (in these calculation the thermalization has been assumed – is it the reason?).

The constituent quark scaling I try to discuss from different sides: along with presenting the most popular interpretation, and in this case the most interesting, I also discuss more skeptical view, making an attempt to explain the experimentally observed phenomena by mechanisms not involving the coalescence of the constituent quark. I also discuss what should/can be done in order to resolve the ambiguity.

2. The constituent quark scaling of the elliptic flow at intermediate transverse momenta.

The notion of the constituent quark is 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 [6] 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 in the produced hadron, 2 for mesons and 3 for baryons. Besides other important consequences, such as enhanced relative production of baryons in this transverse momentum region, this picture would lead to the constituent quark scaling of elliptic flow, $v_2(p_t) \approx n v_2(p_t/n)$, where $n$ is the number of constituent quarks in the hadron [6, 7]. As Fig. 1 shows this scaling holds to a good accuracy. Note that while the scaling itself is limited to a specific region in transverse momentum, the coalescence mechanism itself can be valid at all smaller momenta. The reason for the scaling violation at lower momenta is the unitarity condition. The scaling is based on the equations,

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\frac{d^3 n_M}{d^3 p_M} \propto \left[ \frac{d^3 n_q}{d^3 p_q} (p_q \approx p_M/2) \right]^2, \quad \text{and} \quad \frac{d^3 n_B}{d^3 p_B} \propto \left[ \frac{d^3 n_q}{d^3 p_q} (p_q \approx p_B/3) \right]^3,
\]

which are valid only if the probability of coalescence is relatively low. At low transverse momentum, where most of the quarks hadronize via coalescence these equations break the unitarity (note that according to these equations, the hadron yield scales with power 2 or 3 of quark density).

In the constituent quark interpretation of the observed scaling the quantity $v_2(p_t/n)$ is interpreted as elliptic flow of constituent quarks. Two very important conclusions follow immediately from this scaling observation. First, one concludes 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.

Taking into account the importance of the above made conclusions one also has to consider all possible skepticism. In this line, it was noticed in [2, 4] that the constituent quark scaling would contradict a local thermalization and freeze-out at a constant phase-space density. Note that it
Figure 1. (color online) Test of the constituent quark number scaling of elliptic flow. Minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

Figure 2. (color online) Centrality dependence of elliptic flow in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV [11] compared to results of AMPT model [9].

does not diminish the validity of the conclusion on deconfinement. In fact this observation points to one very interesting possibility, namely that the system created in the heavy ion collision can be in deconfined but not completely thermalized state. It also does not exclude the possibility that the thermalization happens only at lower transverse momenta.

An extreme skeptical view on the constituent quark scaling would be that the experimental results have nothing to do with constituent quarks, in particular taking into account that the scaling is not perfect. In this case one could look for an alternative explanation for the difference in elliptic flow of baryons and mesons. Remarkably, even after about three years since the first data appeared, no single alternative explanation has been found.

How one could resolve the question? 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.

Does the quark coalescence mechanism show up at lower transverse momenta? How hydrodynamic and parton cascade models compare to the data? 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. The transport models [10, 9] in their standard configuration fail to describe the strong increase in elliptic flow with energy. They have to significantly increase the parton transport cross section or the density of the matter in the created system in order to reach the experimental values. On the other hand if one
looks carefully into what particular parameters are required in order to describe the data, an interesting picture emerges: the density and partonic cross sections are just what one would expect for the system of constituent quarks. For example, Fig. 2 shows the comparison of the experimental data to the AMPT [9] model calculations in the so-called melted string scenario. The main assumption of this scenario is that the total number of partons in the system equals to the number of constituent quarks in the produced hadrons, exactly what one would use for a model based on the picture of the system of constituent quarks. In the model the partonic cross section is a free parameter. But again, one finds that the model describes the data best with cross section of about 5 mb, the one expected for the constituent quarks.

3. 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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