Eur. Phys. J. A **29**, 1–5 (2006)
DOI 10.1140/epja/i2005-10287-7

THE EUROPEAN PHYSICAL JOURNAL A

Signs of thermalization from RHIC experiments

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Received: 23 November 2005 /
Published online: 8 August 2006 – © Società Italiana di Fisica / Springer-Verlag 2006

Abstract. Selected results from the first five years of RHIC data taking are reviewed with emphasis on the evidence for thermalization in central Au + Au collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$.

PACS. 24.85.+p Quarks, gluons, and QCD in nuclei and nuclear processes – 25.75.Nq Quark deconfinement, quark-gluon plasma production, and phase transitions – 25.75.-q Relativistic heavy-ion collisions

1 Introduction

The U.S. Relativistic Heavy-Ion Collider (RHIC) was built primarily to create and study the thermalized system of deconfined quarks and gluons, called the Quark Gluon Plasma (QGP), predicted by QCD at high energy densities. The first five, very successful, years of RHIC operation provided scientists with an enormous wealth of data leading, subsequently, to the conclusion that a new form of hot and dense nuclear matter was created in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV with energy density significantly exceeding QCD estimates of critical energy density for a hadron gas-QGP phase transition. The properties of this new form of nuclear matter, however, are as yet, far from being known and understood.

A number of quite unexpected observations have been reported. Perhaps the most striking is the evidence for partonic collectivity and jet quenching, both related to thermalization, discussed broadly at this conference on *Quark-Gluon-Plasma Thermalization*, held in Vienna, 10-12 August 2005.

Note that some measurements are either preliminary or statistically limited, and therefore their interpretation ought to be considered as tentative at the present time.

2 The early stage of the collision —partonic collectivity and thermalization

One of the first and most surprising RHIC results was an elliptic flow measurement in Au + Au collisions at $\sqrt{s_{NN}} = 130$ and $200\,\text{GeV}$. This is a particularly important observable which provides information on the matter created very early in the collision. During the collision the initial coordinate-space anisotropy of the system (the collision overlap region is elliptic in shape in non-central nucleus-nucleus events) is converted by secondary interactions and density gradients, built up in the collision center, into an anisotropy in the final momentum space. This is commonly parametrized by a Fourier expansion series. Elliptic flow, v_2, is defined as the second harmonic coefficient of the azimuthal asymmetry with respect to the reaction plane (the plane defined by the beam and impact parameter directions). Of course, the efficiency of this conversion depends on the medium properties. Note that elliptic flow possesses self-quenching properties —once the spatial anisotropy disappears during expansion, the development of elliptic flow stops. Therefore it is primarily sensitive to the early stage Equation Of State (EOS)[1–3].

Figure 1 shows the elliptic flow parameter v_2 for pions, kaons, protons, and lambda hyperons measured by two

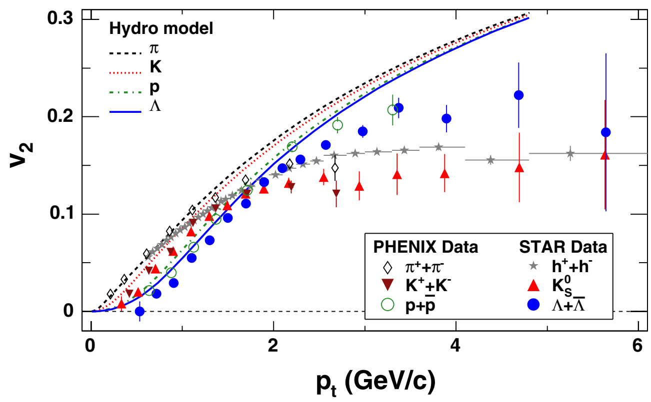

Fig. 1. v_2 for a variety of particles from a minimum-bias sample of Au + Au collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$ measured by the STAR [4] and PHENIX [5] Collaborations. The curves show the results from hydrodynamical model calculations [6].

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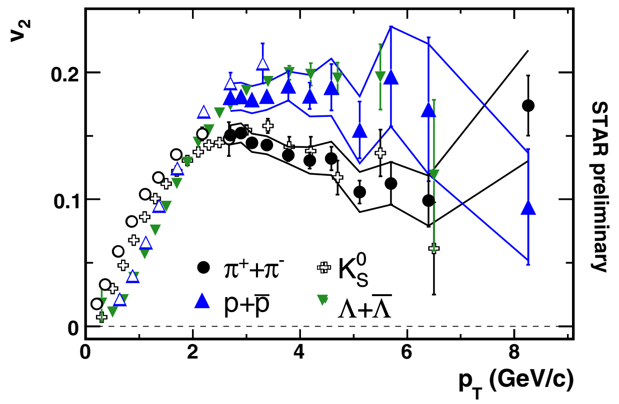

Fig. 2. Azimuthal anisotropy v_2 for $\pi^+ + \pi^-$ and $\mathrm{p} + \bar{\mathrm{p}}$ in 200 GeV minimum bias Au + Au collisions. K_0 and $\Lambda + \bar{\Lambda}$ v_2 are shown for comparison. Open symbols for $\pi^+ + \pi^-$ and $\mathrm{p} + \bar{\mathrm{p}}$ were taken from [5].

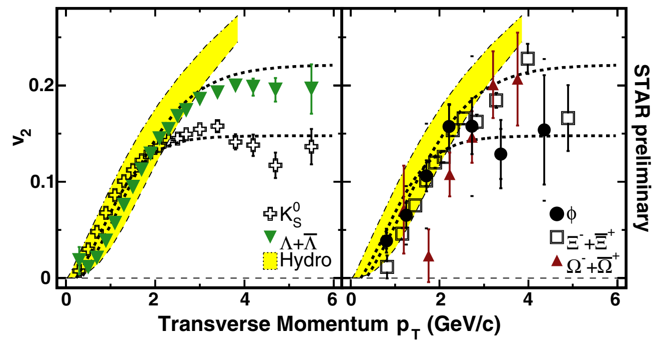

Fig. 3. Azimuthal anisotropy v_2 for strange hadrons (left) and multi-strange hadrons (right) in 200 GeV minimum bias Au + Au collisions. The dashed lines show a common fit to the K^0 and $\Lambda + \bar{\Lambda}$ data [12]. Hydrodynamic model calculations are shown as shaded areas [13].

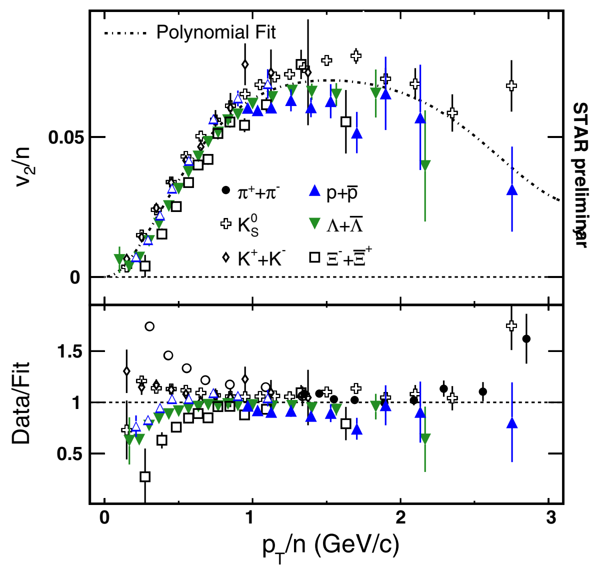

Fig. 4. Measurements of scaled $v_2(p_t/n)/n$ for identified hadrons (upper panel) and ratio (lower panel) between the measurements and polynomial fit through all data points except pions for 200 GeV minimum bias Au + Au collisions. Open symbols for $\pi^+ + \pi^-$ and $\mathrm{p} + \bar{\mathrm{p}}$ were taken from [5].

major RHIC experiments, STAR [4] and PHENIX [5]. A large v_2 is observed for all particle species indicating interactions at the early stage. For $p_t < 1.5$ GeV/c, v_2 increases gradually with p_t. This trend is well described by hydrodynamical model calculations [6]. More interestingly, the mass ordering, characteristic of a common velocity field, with heavier particles exhibiting lower values of v_2, is in good agreement with hydrodynamical models. This indicates the presence of some (perhaps significant) degree of thermalization at the early stage of the collision. At higher p_t hydrodynamical calculations break down, as expected. The model over-predicts the measured v_2 values and the particle-type dependence is reversed. Above p_t of about 2 GeV/c the shape of the v_2 distribution flattens out (saturation) while mesons and baryons form two distinct bands. The question of how v_2 was established at these p_t (above 2 GeV/c) remains open.

The run IV, data taken in 2004 [7–9], with very high statistics and greater coverage for identified particles, extends observations to even higher p_t (up to 9–10 GeV/c). And, indeed, even at the highest measured p_t, a large value of v_2 is still present —see fig. 2 [10]. The error bars in fig. 2 show the statistical uncertainty, while the systematic errors are presented as bands.

The run-IV v_2 measurements, with unprecedented accuracy for multi-strange hadrons (Ξ, Ω and ϕ), show large v_2 values and similar grouping to those observed for non-strange particles as shown in fig. 3 [10,11]. The independence of the elliptic flow on hadronic cross-sections (Ξ, Ω and ϕ have very small hadronic cross-sections compared to non-strange particles) suggests that v_2 was developed in the partonic stage very early in the collision, before the hadronization process took place. For comparison, fig. 3 shows the range of v_2 from hydrodynamical calculations. The saturation value of v_2 above p_t of 2 GeV/c for mesons is about 2/3 of that for baryons. This pattern, which holds for π, p, K, Λ, Ξ and with larger error bars also for ϕ and Ω, indicates that v_2 distributions can be scaled by the number of constituent quarks (n_q) in the hadrons under study (*i.e.* $n_q = 2$ for ϕ, $n_q = 3$ for Ω etc.). This observation points towards relevance of constituent quark degrees of freedom. Figure 4 shows v_2 as a function of p_t where v_2 and p_t are both scaled by the number of constituent quarks. All identified particles fall on one curve supporting the picture of hadronisation by coalescence or recombination of constituent quarks [14–17]. A polynomial function was fitted to the scaled values. The bottom panel shows the ratio between the measurements and the fit. At low p_t/n (< 0.75 GeV/c) the observed deviations from the fit follow a mass ordering which is expected from hydrodynamical flow. At higher p_t, all v_2/n measurements are very close in value ("constituent quark scaling") indicating the coalescence of co-moving constituent quarks. If coalescence is indeed the hadron production mechanism, then it seems natural to conclude that a deconfined phase of quarks and gluons is created prior to hadronisation.

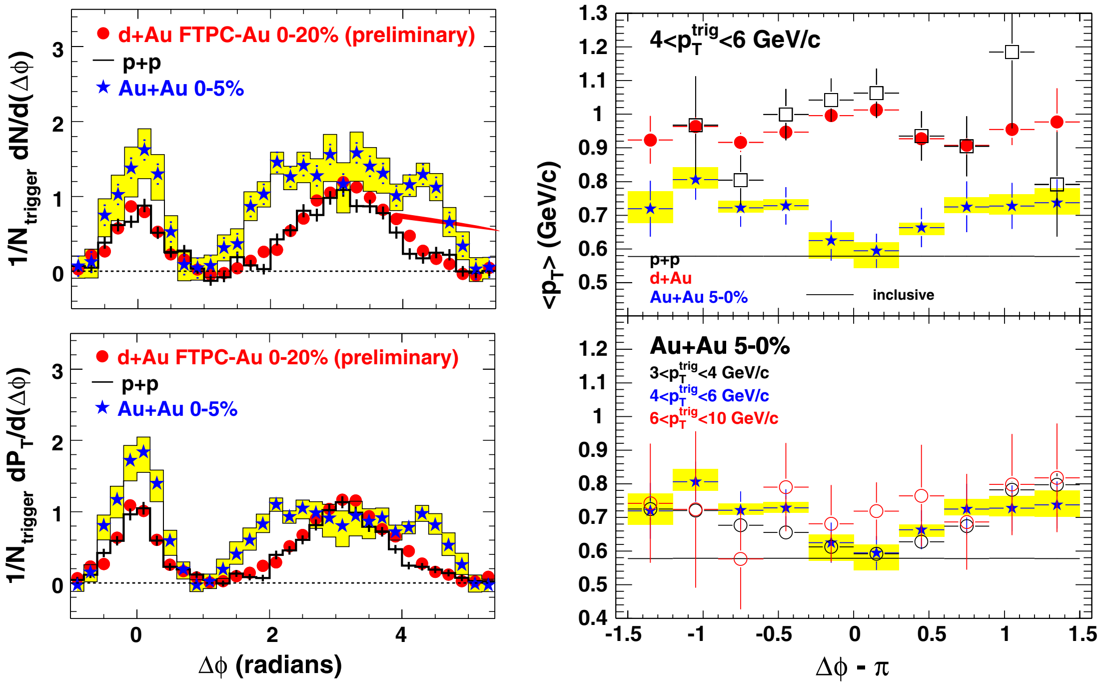

Fig. 5. Left: background-subtracted number (upper panel) and p_t-weighted (lower panel) correlation functions in p + p, central 20% d + Au and 5% Au + Au collisions [21]. Right: the $\langle p_t \rangle$ of associated hadrons on the away-side for the three systems (upper panel) and three trigger p_t selections (lower panel). The shaded areas are systematic uncertainties.

Note that gluons do not seem to be present at hadronisation. The splitting below p_t/n of 500 MeV/c appears to have mass dependence (a signature of hydrodynamical flow). In addition, the pion distribution at low p_t is expected to be affected by resonance decays.

To summarize: The quark number dependence of v_2 suggests that the relevant degrees of freedom are partonic, while the high degree of collectivity developed by the even heavier strange quarks suggests that the partonic degrees of freedom are locally equilibrated.

3 Heavy quarks as a test of early thermalization

Heavy quarks are created almost exclusively during first impact and therefore are expected to address directly the early thermalization of the system created in the collision. Unfortunately, at the present time, direct measurements of charm and bottom at RHIC are not yet feasible. Therefore v_2 of single electrons at sufficiently high transverse momenta from non-photonic semi-leptonic decays of heavy flavors is used as a substitute.

Preliminary analysis of experimental data by STAR and PHENIX shows a significant amount of flow for non-photonic electrons [18, 19], which indicates flavor collectivity with heavy quarks flowing together with light quarks.

While v_2 of non-photonic electrons clearly favors a non-zero value at p_t below 2 GeV/c, data obtained by different experiments do not agree at higher p_t ($2 < p_t(e) < 5$ GeV/c). These differences are the subject of ongoing studies. If confirmed, heavy flavor collectivity would imply light flavor thermalization.

4 The final stage of the collision —jets and thermalization

The picture emerging from the evidence for equilibration and near-ideal hydrodynamical flow is strongly supported by jet quenching phenomena observed at RHIC. For the first time in heavy-ion collisions, the cross-section at RHIC is high enough for jet production to play a measurable role. Due to their hard production scales, jets, which materialize as a result of parton-parton scattering processes very early in the collision, are embedded in and propagate through the dense environment of the collision “fireball” as it forms and evolves. Through their strong interactions with the newly formed medium, partons lose energy, before eventually fragmenting into ordinary hadrons, which preserve, to a large degree, jet-like angular correlations. This energy loss depends strongly on the properties of the evolving medium, particularly on its energy density, and therefore the study of jet quenching has become an important tool in the search for a quark-gluon plasma at the earliest stage of the system evolution.

Experimentally, jets are selected by triggering on high-p_t particles, which are predominantly generated from a fast parton escaping from the surface of the reaction volume. The other fast parton created in the hard scattering is directed into the reaction volume and traverses the medium. They are studied through the angular correlations of associated fragmentation products of the two jet

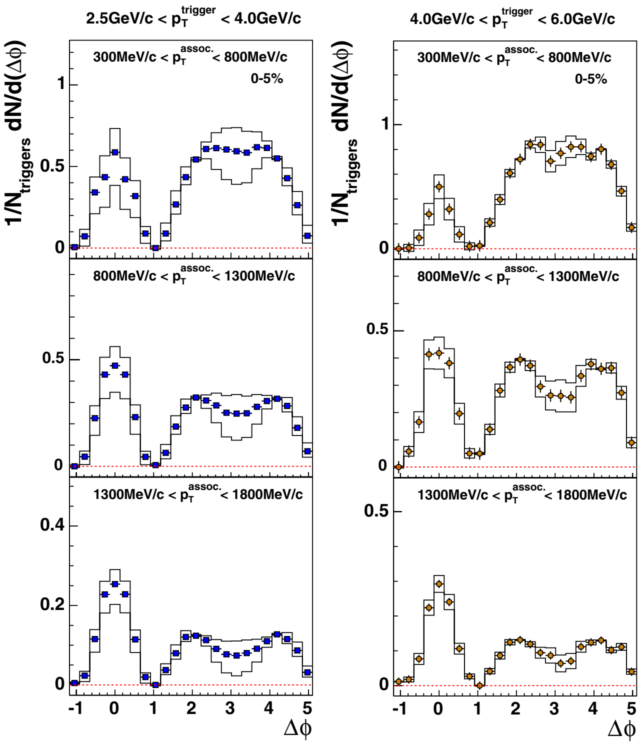

Fig. 6. Background-subtracted number correlations for two trigger bins, $2.5 < p_t < 4.0$ and $4 < p_t < 6.0\,\mathrm{GeV/c}$, for three different associated p_t windows. The evolution of the away-side structure as a function of p_t associated is similar for two trigger bins.

partners. The early RHIC results clearly demonstrated nearly complete disappearance of back-to-back correlations in central Au + Au events (large path length in medium) and only small suppression of the back-to-back correlation strength in peripheral collisions (short path length in medium) [20]. The depleted jet energy observed on the away-side (at $\Delta\phi \sim \pi$ from the direction of the trigger particle) must be redistributed into low-p_t particles. And indeed, it is the case as illustrated by the left panel of fig. 5, where lowering the p_t cut on the away-side–associated particles restores the missing away-side jet. The reconstruction of these low-p_t particles is therefore fundamental to understanding the fate of the energy lost by the primary parton and provides a unique look at the details of the thermalization process. Further study of associated particles has shown significant differences in the spectral shape between p + p, d + Au and Au + Au collisions. Figure 5 (left panel) presents the number and p_t-weighted correlation functions in p + p, d + Au and central Au + Au [21,22] after background subtraction. The p + p and d + Au distributions are similar, while the Au + Au is much broader.

Figure 5 (right panel) shows the $\langle p_t \rangle$ obtained from the ratio of the p_t-weighted and number correlation functions as a function of $\Delta\phi$ on the away-side. The $\langle p_t \rangle$ for p + p and d + Au have maxima at $\Delta\phi \sim \pi$, as expected from jet fragmentation, while the $\langle p_t \rangle$ for central Au + Au has a prominent dip at $\Delta\phi \sim \pi$ and its value is similar to the inclusive $\langle p_t \rangle$ (marked by the straight line). The lower plot shows the same $\langle p_t \rangle$ behavior for the three trigger bins. The $\langle p_t \rangle$ *versus* $\Delta\phi$ results indicate that the spectrum in the direction opposite to the trigger particle ($\Delta\phi \sim \pi$) is softer than at different angles (away from $\Delta\phi \sim \pi$). This means that fewer high-p_t particles survived the longer path through the medium. This is also demonstrated in the correlation functions with varying associated p_t —see fig. 6. With increasing associated p_t, the correlation function flattens and even develops a double-peak structure [23]. The two trigger intervals presented (intermediate (left panel) and high p_t triggers (right panel)) show very similar behavior. The new structure of the away-side is beyond the experimental uncertainty due to statistical (errors bars in fig. 6) and systematic (histograms in fig. 6) errors. It is a clear experimental evidence of the bulk response to the energetic parton.

To summarize: The lower value of $\langle p_t \rangle$ of associated particles at $\Delta\phi \sim \pi$ indicates some degree of thermalization established in Au + Au. A new shape of away-side associated correlations is evident beyond experimental errors. It is clearly of dynamical nature. A consistent picture describing the away-side structures as a function of trigger and associated p_t has yet to be developed.

5 Three-particle correlations

The two-particle correlation results are consistent with a number of quite different scenarios. It is believed that analysis of three-particle correlations will allow the selection of the correct theoretical description. Unfortunately, at the present moment, results from different experiments are in disagreement. Studies of the discrepancies are in progress.

6 Conclusions

The harvest of the first five years of data taking at RHIC is, indeed, impressive. Pions, kaons, protons, electrons, and hyperons have been measured in Au + Au collisions up to $p_t \sim 10\,\mathrm{GeV/c}$. Elliptic flow v_2 measurements made in Au + Au collisions revealed collective behavior amongst partons (particularly important ϕ and Ω v_2). The non-zero value of v_2 for non-photonic electrons indicates that interactions are copious enough for the u-, d-, and s-quarks to be in a QGP state. Suppression of high-p_t particles, resulting from jet quenching, shows that the initial density is high enough for partons to lose energy in partonic and/or hadronic medium. The study of $\langle p_t \rangle$ of the away-side–associated particles demonstrates that even hard probes start to become thermalized in the medium. Although the RHIC energy domain is not fully explored yet, the progress in assessing the degree of thermalization of Au + Au collisions (among other things) is remarkable.

This work received support in part from the U.S. Department of Energy Contract No. DE-AC02-05CH11231, Office of Nuclear Physics.

References

1. P. Huovinen, nucl-th/0305064.
2. P. Kolb, U. Heinz, nucl-th/0305084.
3. E.V. Shuryak, Prog. Part. Nucl. Phys. **53**, 273 (2004).
4. STAR Collaboration (J. Adams *et al.*), Phys. Rev. Lett. **92**, 052302 (2004).
5. PHENIX Collaboration (S.S. Adler *et al.*), Phys. Rev. Lett. **91**, 182301 (2003).
6. P. Houvinen *et al.*, Phys. Lett. B. **503**, 58 (2001).
7. STAR Collaboration (P. Sorensen *et al.*), J. Phys. G. **30**, S693 (2004).
8. PHENIX Collaboration (C. Adler *et al.*), Phys. Rev. Lett. **89**, 132301 (2002).
9. STAR Collaboration (J. Adams *et al.*), Phys. Rev. C. **72**, 014904 (2005).
10. STAR Collaboration (M. Oldenburg *et al.*), to be published in *Proceedings of the 18th International Conference on Nucleus-Nucleus Collisions, Quark Matter 2005, Budapest, Hungary, 4-9 August 2005.*
11. STAR Collaboration (P. Sorensen *et al.*), to be published in *Proceedings of the 18th International Conference on Nucleus-Nucleus Collisions, Quark Matter 2005, Budapest, Hungary, 4-9 August 2005.*
12. X.Dong *et al.*, Phys. Lett. B. **597**, 328 (2004).
13. P. Huovinen, private communication, 2004.
14. D. Molnar, S.A. Voloshin, Phys. Rev. Lett. **91**, 092301 (2003).
15. R.C. Hwa, C.B. Yang, Phys. Rev. C. **67**, 064902 (2003).
16. R.J. Fries *et al.*, Phys. Rev. C. **68**, 044902 (2003); Phys. Rev. Lett. **90**, 132301 (2003).
17. V. Greco *et al.*, Phys. Rev. C. **68**, 034904 (2003); Phys. Rev. Lett. **90**, 202302 (2003).
18. STAR Collaboration (F.Lau *et al.*), J. Phys. G. **31**, S1121 (2005).
19. PHENIX Collaboration (A. Adler *et al.*), Phys. Rev. C. **72**, 024901 (2005).
20. *Proceedings of the 16th International Conference on Ultra-relativistic Nucleus-Nucleus Collisions, Quark Matter 2002, Nantes, France, July 2002*, Nucl. Phys. A. **715**, 1-930 (2003).
21. STAR Collaboration (J. Ulery *et al.*), to be published in *Proceedings of the 18th International Conference on Nucleus-Nucleus Collisions, Quark Matter 2005, Budapest, Hungary, 4-9 August 2005.*
22. STAR Collaboration (F. Wang *et al.*), to be published in *Proceedings of the 18th International Conference on Nucleus-Nucleus Collisions, Quark Matter 2005, Budapest, Hungary, 4-9 August 2005.*
23. STAR Collaboration (M. Horner *et al.*), Poster presented at the *18th International Conference on Nucleus-Nucleus Collisions, Quark Matter 2005, Budapest, Hungary, 4-9 August 2005.*