From Quark Gluon Plasma to a Perfect Fluid of Quarks and Beyond

Csanad, M.; Csorgo, T.; Lörstad, Bengt; Nagy, M.; Ster, A.

2007

From Quark Gluon Plasma to a Perfect Fluid of Quarks and Beyond

M. Csanád[1], T. Csörgő[2], B. Lörstad[3], M. Nagy[1] and A. Ster[2]

[1]Dept. Atomic Phys., ELTE, H-1117 Budapest, Pázmány P. 1/a, Hungary

[2]MTA KFKI RMKI, H - 1525 Budapest 114, P.O.Box 49, Hungary

[3]Dept. Physics, University of Lund, S - 22362 Lund, Sweden

February 18, 2007

Abstract

With high energy heavy ion collisions one tries to create a new forms of matter that is similar to the one present at the birth of our Universe. Recent development on flow pattern, initial energy-density and freeze-out temperature shows that most likely this new form of matter is in a deconfined state, has colored degrees of freedom and is more fluid-like than gas-like. In present paper we calculate estimations on the physical properties of this new-old matter.

"We simply do not yet know enough about the physics of elementary particles to be able to calculate the properties of such a melange with any confidence. . . . Thus our ignorance of microscopic physics stands as a veil, obscuring our view of the very beginning."

S. Weinberg, about the first hundredth of a second [1]

1 Introduction

Ultra-relativistic collisions, so called "Little Bangs" of almost fully ionized Au atoms are observed in four major experiments at the RHIC accelerator at the highest currently available colliding energies of $\sqrt{s_{NN}} = 200$ GeV. The aim of these experiments is to create new forms of matter that existed in Nature a few microseconds after the Big Bang, the creation of our Universe.

Quantum Chromodynamics (QCD), the theory of quarks and gluons, the strong force interacting between them and their color degree of freedom was formulated and established soon after Weinberg's famous book [1] about the early Universe had been published. Confinement is an important (though mathematically never proven) property of QCD, its consequence is that quarks are bound into hadrons in a matter of normal temperature and pressure.

In the early Universe, energy density was many orders of magnitude higher than today, and at that high energy densities, deconfined phases of colored matter might have existed. Quark-gluon plasma (QGP) is such a phase, that might have existed during the first few microseconds after the Universe came into existence. This type of matter was searched for at the SPS, and experiments at RHIC are continuing this effort. Evidence for formation of a hot and dense medium in gold-gold collisions was found based on a phenomenon called jet quenching, and confirmed by its disappearance in deuteron-gold collisions [2].

A consistent picture emerged after the first three years of running the RHIC experiment: quarks and gluons indeed become deconfined, but also behave collectively, hence this hot matter acts like a liquid [3], not like an ideal gas theorists had anticipated when defining the term QGP. The situation is similar to as if prisoners (quarks and gluons confined in hadrons) have broken out of their cells at nearly the same time, but they find themselves on the crowded jail-yard coupled with all the other escapees. This strong coupling is exactly what happens in a liquid [4].

1.1 A sign for hydrodynamic behavior: elliptic flow

Azimuthal asymmetry of single particle spectra measured in relativistic heavy ion collisions is called elliptic flow (v_2). It is an indication of liquid-like behavior [5], and can be explained by hydrodynamics [6, 7, 8]. In the hydrodynamic picture it turns out, that elliptic flow can result from the initial spatial asymmetry but also from momentum-space asymmetry. Important is, that in contrast to a uniform distribution of particles expected in a gas-like system, this liquid behavior means that the interaction in the medium of these copiously produced particles is rather strong, as one expects from a fluid. Detailed investigation of these phenomena suggests that this liquid flows with almost no viscosity [9].

1.2 Relativistic perfect fluids

Perfect hydrodynamics is based only on local conservation of charge and energy-momentum and on the assumption of local thermal equilibrium, and this is the tool that we use to describe and calculate the properties of the matter created in relativistic heavy ion collisions at RHIC. While there are accelerating non-relativistic solutions in the literature, recent development shows also relativistic solutions that can be compared to the data [10, 11].

Local conservation of charge and four-momentum reads as

$$\begin{aligned} \partial_\nu (n u^\nu) &= 0, && (1)\\ \partial_\nu T^{\mu\nu} &= 0, && (2)\\ T^{\mu\nu} &= (\varepsilon + p) u^\mu u^\nu - p g^{\mu\nu}. && (3) \end{aligned}$$

We find the following solution (for arbitrary λ in $d = 1$, $\kappa = 1$ and for $\lambda = 2$ in arbitrary d with $\kappa = d$) [10]:

$$\begin{aligned} v &= \tanh \lambda\eta && (4)\\ n &= n_0 \left(\frac{\tau_0}{\tau}\right)^{\lambda d} \nu(s), && (5)\\ T &= T_0 \left(\frac{\tau_0}{\tau}\right)^{\lambda d/\kappa} \frac{1}{\nu(s)}, && (6) \end{aligned}$$

where $\nu(s)$ is an arbitrary function of the scale variable s, and η is the pseudorapidity. As an illustration, fluid trajectories of this solution are shown on fig. 1. See details in ref. [10].

2 Results

2.1 An advanced estimate on the initial energy density

Based on the above solution of eqs. 4-6 let us estimate the initial energy density of relativistic heavy ion or p+p reactions. As our solution is an accelerating one, and we do not neglect the initial acceleration period, we improve the renowned Bjorken estimate both quantitatively and qualitatively. Similarly to Bjorken's method [12], we can estimate the initial energy density (see

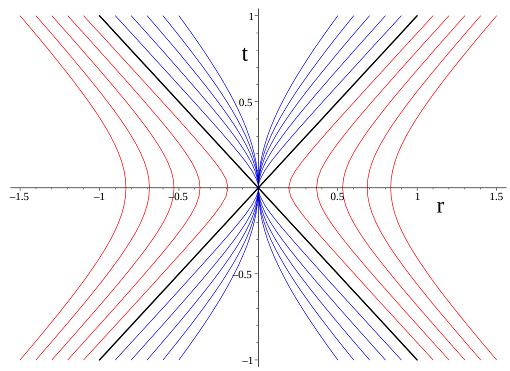

Figure 1: Fluid trajectories of the new exact solution of perfect fluid hydro, corresponding to $d = 1$ and $\lambda = 2$. The trajectories are shown both inside and outside the lightcone.

ref. [10] for details). Finally we get a correction to the widely used Bjorken formula, depending on the acceleration parameter (λ):

$$\frac{\varepsilon_0}{\varepsilon_{Bj}} = \frac{\alpha}{\alpha - 2}\left(\frac{\tau_f}{\tau_0}\right)^{1/(\alpha-2)} = (2\lambda - 1)\left(\frac{\tau_f}{\tau_0}\right)^{\lambda-1}, \tag{7}$$

The acceleration parameter can be extracted from the measured rapidity distribution [10]. For flat rapidity distributions, $\alpha \to \infty$ ($\lambda \to 1$, i.e. no acceleration) and the Bjorken estimate is recovered. For $\lambda > 1$, the correction factor is bigger than 1. Hence we conclude that the initial energy densities are under-estimated by the Bjorken formula. For realistic RHIC data from BRAHMS [13], the correction factor can be as big as $\varepsilon/\varepsilon_{Bj} \approx 2.2$ [10]. Thus smaller initial bombarding (or colliding) energies are needed to reach the critical energy density in high energy heavy ion collisions, than thought previously using Bjorken's renowned formula.

2.2 Estimating the freeze-out temperature

We estimated the freeze-out temperature of these Little Bangs, fitting data to the Buda-Lund hydro model [6, 14]. Recently, Fodor and Katz calculated the phase diagram of lattice QCD at finite net baryon density: their results indicate that the transition from confined to deconfined matter is a cross-over with a nearly constant critical temperature, $T_c = 175 \pm 2$ MeV [15]. The result

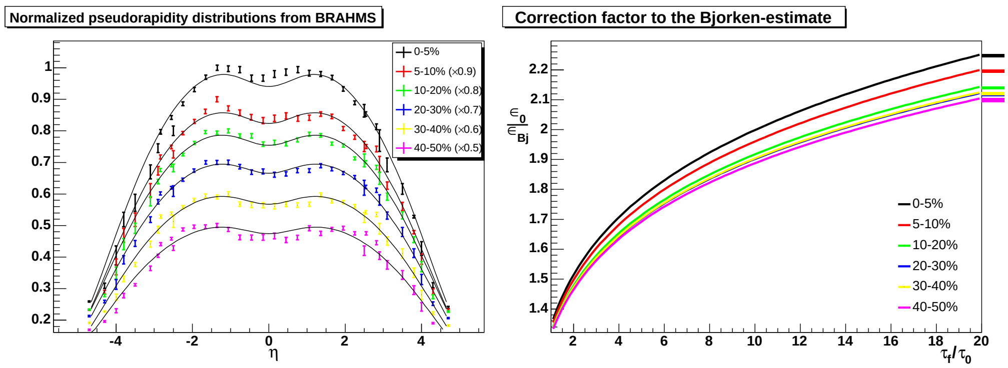

Figure 2: Left: charged particle $\frac{dn}{d\eta}$ distributions of ref. [13] fitted with the result of the relativistic hydro solution of ref. [10]. Right: the correction parameter (obtained from fits show on the left panel) as a function of freeze-out time versus thermalization time (τ_f/τ_0). At reasonable values of 10-15, the correction to the Bjorken estimate of energy density is a factor of $\sim$2.

of the Buda-Lund fits to RHIC Au+Au data of refs. [13, 16, 17, 18, 19, 20, 21, 22] (shown on fig. 3), in particular the value of the fit parameter T_0 (central freeze-out temperature, see details in ref. [23]), indicates the existence of a region several standard deviations hotter than the critical temperature. This is an indication on quark deconfinement in Au + Au collisions with $\sqrt{s_{\rm NN}}$ = 130 and 200 GeV at RHIC [23, 24, 25], confirmed by the analysis of p_t and η dependence of the elliptic flow [6]. A similar analysis of Pb+Pb collisions at CERN SPS energies yields central temperatures lower than the critical value, $T_0 < T_c$ [26, 27].

2.3 Universal scaling of the elliptic flow

The Buda-Lund calculation of the elliptic flow results (under certain conditions detailed in ref. [6]) in the following simple universal scaling law:

$$v_2 = \frac{I_1(w)}{I_0(w)}, \tag{8}$$

thus the model predicts a *universal scaling:* every v_2 measurement is predicted to fall on the same *universal* scaling curve I_1/I_0 when plotted against the scaling variable w (see details in ref. [28]).

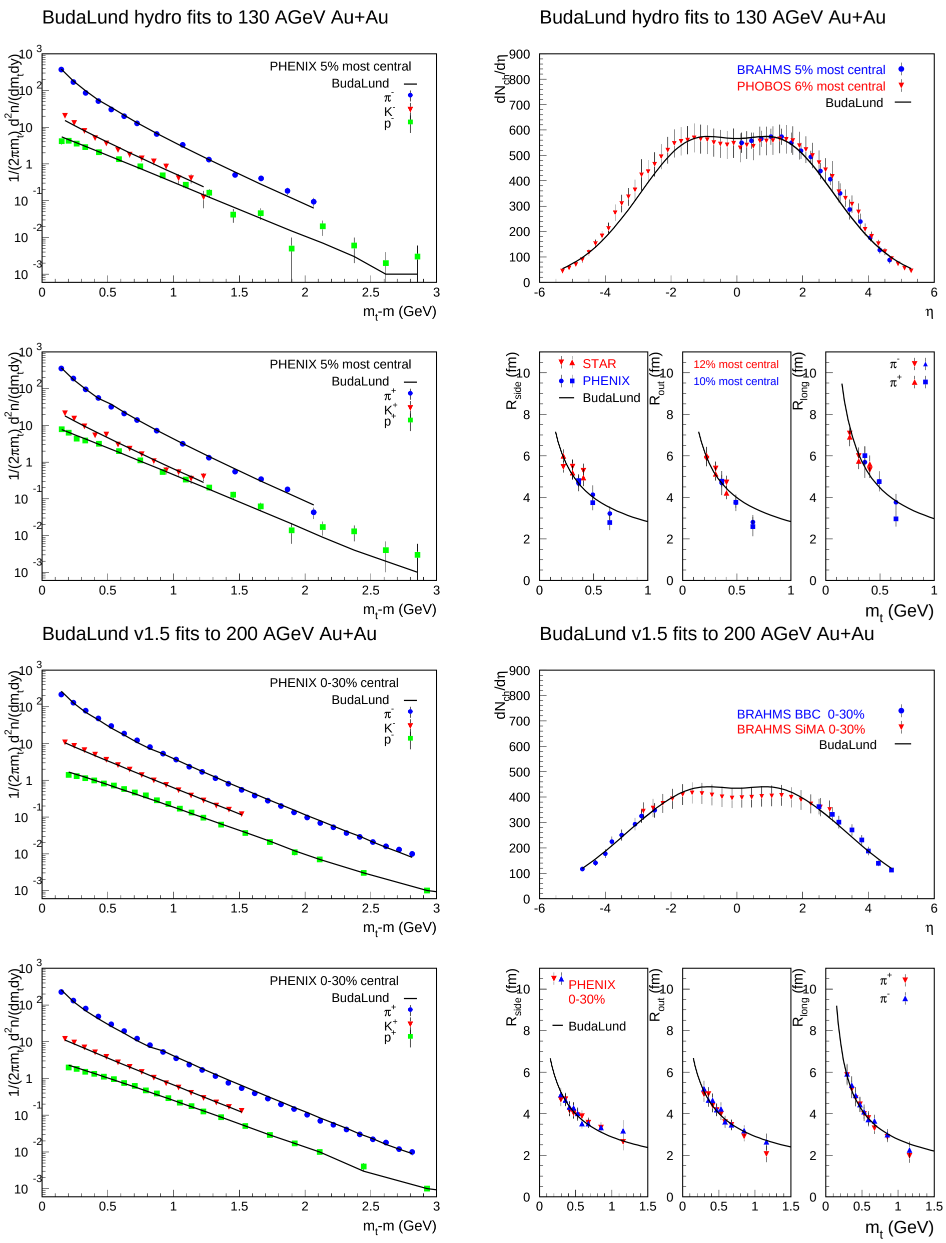

Figure 3: The upper four panels show a simultaneous Buda-Lund fit to 0-5(6) % central Au+Au data on p_t and η spectra and HBT radii at $\sqrt{s_{\rm NN}} = 130$ GeV [16, 17, 18, 19, 20]. The lower four panels show similar fits to 0-30 % central Au+Au data at $\sqrt{s_{\rm NN}} = 200$ GeV [13, 21, 22]. Fit parameters are summarized in ref. [23].

This means, that v_2 depends on any physical parameter (transverse or longitudinal momentum, center of mass energy, centrality, type of the colliding nucleus etc.) only through the (universal) scaling parameter w.

In ref. [28] we have shown that the excitation function of the transverse momentum and pseudorapidity dependence of the elliptic flow in Au+Au collisions (RHIC data from refs. [5, 29, 30]) is well described with the formulas that are predicted by the Buda-Lund type of hydrodynamical calculations. We have provided a quantitative evidence of the validity of the perfect fluid picture of soft particle production in Au+Au collisions at RHIC up to 1-1.5 GeV but also show here that this perfect fluid extends far away from mid-rapidity, up to a pseudorapidity of $\eta_{\text{beam}} - 0.5$. The universal scaling of PHOBOS $v_2(\eta)$ [29], PHENIX $v_2(p_t)$ [5] and STAR $v_2(p_t)$ [30], expressed by Eq. (8) and illustrated by Fig. 4.e provides a successful quantitative as well as qualitative test for the appearance of a perfect fluid in Au+Au collisions at various colliding energies at RHIC.

2.4 Chiral symmetry restoration

Correlation functions are important to see the collective properties of particles and the space-time structure of the emitting source, e.g. the observed size of a system can be measured by two-particle Bose-Einstein correlations [31]. The m_t dependent strength of two-pion correlations, the so-called λ_* parameter, which is related to the extrapolated value of the correlation function at zero relative momentum, can be used to extract information on the mass-reduction of the η' meson, a signal of $U_A(1)$ symmetry restoration in the source [32, 33, 34, 35].

PHENIX analyzed [36] $\lambda_*(m_t)$ with fits to two-pion correlation functions using three different shapes, Gauss, Levy and Edgeworth, described in refs. [27, 36, 37]. A comparison of the measurements with model calculations of ref. [32] using FRITIOF results for the composition of the long-lived resonances and a variation of the η' mass is presented in fig. 5. If we re-norm the $\lambda_*(m_t)$ curves with their maximal value on the investigated m_t interval, they overlap, confirming the existence and characteristics of the hole in the $\lambda_*(m_t)$ distribution.

Gauss fit results agree with former PHENIX measurements (see ref. [22]). Regarding $U_A(1)$ symmetry restoration, conclusion is that at present, results are critically dependent on the understanding of statistical and systematic errors, and additional analysis is required to make a definitive statement.

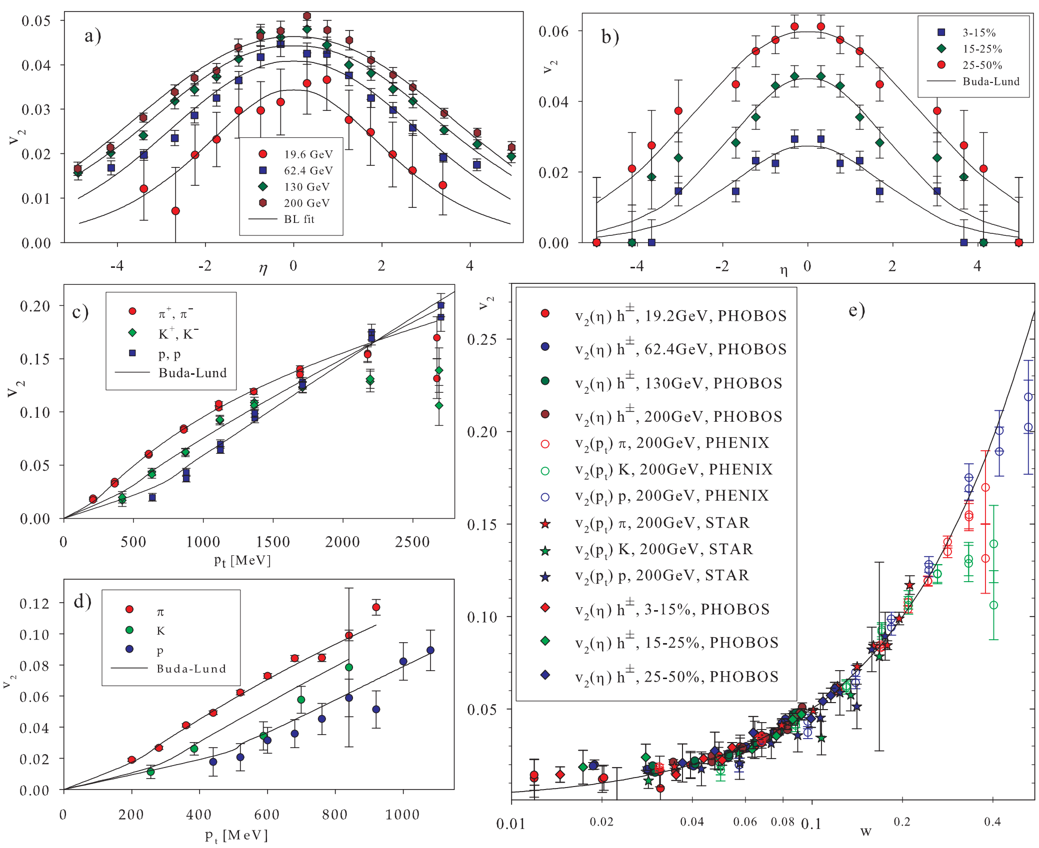

Figure 4: PHOBOS [29] (a-b), PHENIX [5] (c) and STAR [30] (d) data on elliptic flow, v_2, plotted versus p_t and η and fitted with Buda-Lund model. Elliptic flow versus variable w is plotted in panel (e): data points of plots (a-d) show the predicted [6] universal scaling. See fit parameters in ref. [28]

3 Summary and conclusions

In summary, we can make the definitive statement, based on elliptic flow measurements and the broad range success of analytic hydro models, that in relativistic Au+Au collisions observed at RHIC we see a perfect fluid. Based on our estimates on the temperature and energy density we also conclude that the observed matter is in a deconfined state. We also see a possible signal of partial symmetry restoration in the mass reduction of η' bosons. Future plan is to explore all properties of the Quark Matter, by analyzing

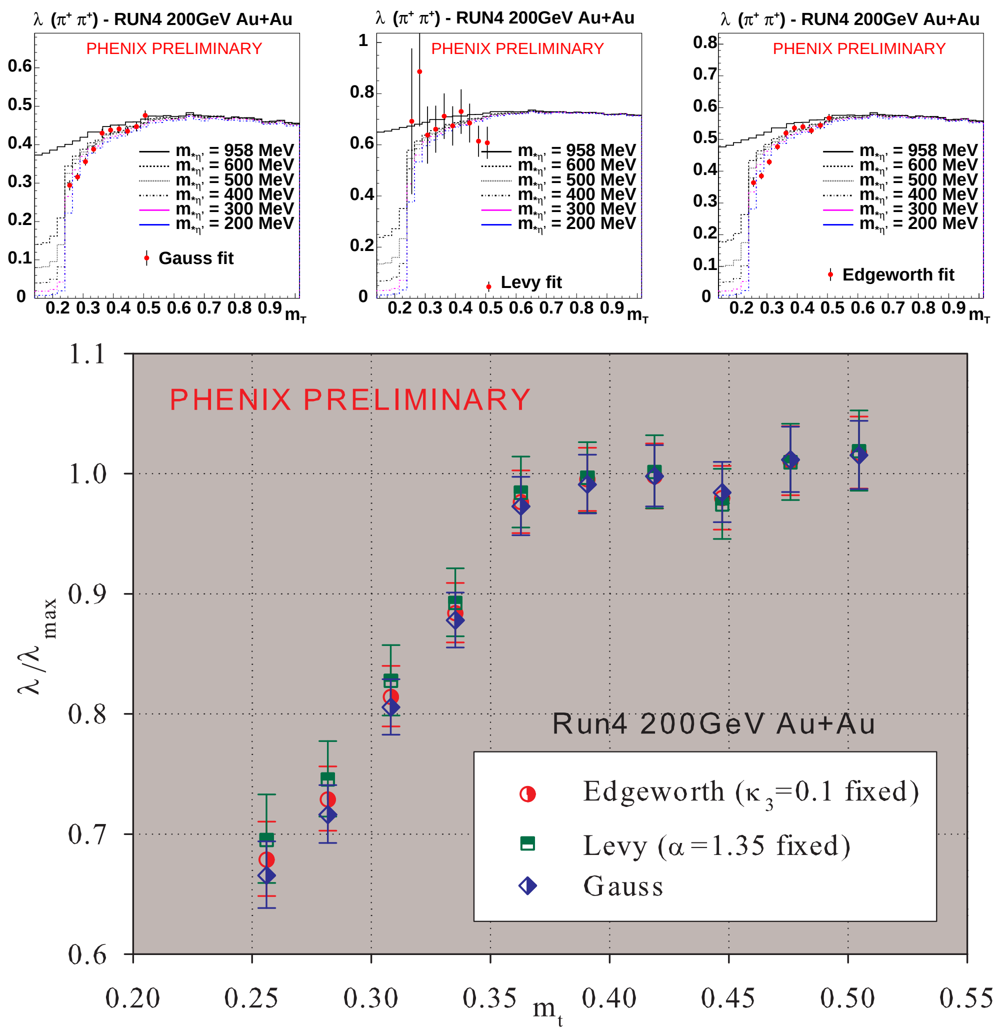

Figure 5: Top three figures: measured $\lambda_*(m_t)$ of ref. [36] compared to calculations using the model of ref. [32] with various η' mass values. Bottom figure: $\lambda_*(m_t)$ curves with equal number of fit parameters and re-normed with their maximal value on the interval of 0.20GeV< m_t <0.55GeV all show the same shape. See details of the fits in ref. [36].

more data and using higher luminosity. We are after the full map of the QCD phase diagram, and in order to explore it, we also have to go to higher energies and compare them to lower energy data. If the Quark Matter is the New World, then Columbus just realized he is not in India, but on a new continent.

"It does not make any difference how beautiful your guess is. It does not make any difference how smart you are, who made the guess, or what his name is — if it disagrees with experiment it is wrong."

R. P. Feynman, about discovering new laws [38]

References

[1] S. Weinberg, *The first three minutes* Basic Books (1977).

[2] S. S. Adler *et al.*, Phys. Rev. Lett. **91** (2003) 072303.

[3] K. Adcox *et al.*, Nucl. Phys. **A757** (2005) 184–283.

[4] M. Riordan and W. A. Zajc, Sci. Am. **294N5** (2006) 24–31.

[5] S. S. Adler *et al.*, Phys. Rev. Lett. **91** (2003) 182301.

[6] M. Csanád, T. Csörgő and B. Lörstad, Nucl. Phys. **A742** (2004) 80–94.

[7] Y. Hama *et al.*, Nucl. Phys. **A774** (2006) 169–178.

[8] W. Broniowski, W. Baran and W. Florkowski, AIP Conf. Proc. **660** (2003) 185–195.

[9] A. Adare *et al.*, nucl-ex/0608033.

[10] T. Csörgő, M. I. Nagy and M. Csanád, nucl-th/0605070.

[11] S. Pratt, nucl-th/0612010.

[12] J. D. Bjorken, Phys. Rev. **D27** (1983) 140–151.

[13] I. G. Bearden *et al.*, Phys. Rev. Lett. **88** (2002) 202301.

[14] T. Csörgő and B. Lörstad, Phys. Rev. **C54** (1996) 1390–1403.

[15] Y. Aoki, Z. Fodor, S. D. Katz and K. K. Szabó, Phys. Lett. **B643** (2006) 46–54.

[16] I. G. Bearden *et al.*, Phys. Lett. **B523** (2001) 227–233.

[17] K. Adcox *et al.*, Phys. Rev. Lett. **88** (2002) 242301.

[18] K. Adcox *et al.*, Phys. Rev. Lett. **88** (2002) 192302.

[19] B. B. Back *et al.*, Phys. Rev. Lett. **87** (2001) 102303.

[20] C. Adler *et al.*, Phys. Rev. Lett. **87** (2001) 082301.

[21] S. S. Adler *et al.*, Phys. Rev. **C69** (2004) 034909.

[22] S. S. Adler *et al.*, Phys. Rev. Lett. **93** (2004) 152302.

[23] M. Csanád, T. Csörgő, B. Lörstad and A. Ster, J. Phys. **G30** (2004) S1079–S1082.

[24] M. Csanád, T. Csörgő, B. Lörstad and A. Ster, Acta Phys. Polon. **B35** (2004) 191–196.

[25] M. Csanád, T. Csörgő, B. Lörstad and A. Ster, nucl-th/0402037.

[26] A. Ster, T. Csörgő and B. Lörstad, Nucl. Phys. **A661** (1999) 419–422.

[27] T. Csörgő, Heavy Ion Phys. **15** (2002) 1–80.

[28] M. Csanád *et al.*, nucl-th/0512078.

[29] B. B. Back *et al.*, Phys. Rev. Lett. **94** (2005) 122303.

[30] John Adams *et al.*, Phys. Rev. **C72** (2005) 014904.

[31] R. Hanbury Brown and R. Q. Twiss, Nature **178** (1956) 1046–1048.

[32] S. E. Vance, T. Csörgő and D. Kharzeev, Phys. Rev. Lett. **81** (1998) 2205–2208.

[33] J. I. Kapusta, D. Kharzeev and L. D. McLerran, Phys. Rev. **D53** (1996) 5028–5033.

[34] Zheng Huang and Xin-Nian Wang, Phys. Rev. **D53** (1996) 5034–5041.

[35] Tetsuo Hatsuda and Teiji Kunihiro, Phys. Rept. **247** (1994) 221–367.

[36] M. Csanád, Nucl. Phys. **A774** (2006) 611–614.

[37] T. Csörgő, S. Hegyi and W. A. Zajc, Eur. Phys. J. **C36** (2004) 67–78.

[38] Feynman videos, `http://heelspurs.com/zpics/feynman9.rm`.