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SELECTED RESULTS FROM RHIC*

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The study of heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) has revealed many, sometimes unexpected, properties of strongly interacting matter under extreme conditions. Systematic surveys of these collisions over a wide range of collision energy and system size have shown convincingly that at sufficiently high energies a dense, interacting medium is formed early on in the collision process. Many qualitative connections between experimental observations and fundamental concepts of the theory of strong interactions, QCD, have been established, including the formation of the initial collision state, the interaction of fast partons with the medium and the dynamics of the expansion of the medium. Still, many important question relating to the nature of the medium and the process of its formation remain to be answered. In this paper, I will discuss selected measurements from RHIC and point out opportunities for measurements in heavy ion collisions at the LHC.

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1. QCD and heavy-ion collisions

The development of Quantum Chromodynamics (QCD) in the early 70's provided a milestone in the effort to build a complete theory of the interactions between the fundamental constituents of matter. QCD successfully describes the multitude of observed hadrons, as well as the interaction of their quark and gluon constituents at very high energies, which leads to the production of particle jets in high-energy collisions.

Still there is no analytic proof that QCD indeed describes one of the most puzzling properties of the strong interaction, the confinement of quarks and gluons inside hadrons. Numerical *ab-initio* calculations suggest that deconfinement could be achieved if strongly interacting matter were heated to a temperature of 170 MeV [1]. The resulting system of quarks and gluons was termed a Quark–Gluon Plasma (QGP) [2]. This high-temperature state is believed to have existed a few microseconds after the Big Bang.

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Heavy-ion collisions provide the best opportunity to test the predictions of QCD for matter under conditions close to the QCD phase-transition and those in the early universe. However, the system created in a heavy-ion collision is different from that simulated in lattice calculations or the early universe in several important aspects. The small size of the available nuclei sets the scale of the temporal and spatial extent of the high-density system created in the collision. The asymmetry of the incoming system, with its momentum in the direction of the incoming beams, is reflected throughout the evolution of the collision. Model calculations suggest a lifetime of the collision system of 10–20 fm/c before freeze-out occurs, *i.e.* before the collision density becomes so low that the produced particles essentially enter a free-streaming motion and are finally detected by the experiments [3].

One of the main experimental and theoretical challenge for obtaining quantitative information about the nature and properties of the strongly interacting medium is to reconstruct the dynamical evolution of the system based on the particles observed in the final state. It is to study collision systems that specifically probe the different stages of this evolution by varying the system size and collision energy. The large step in collision energy from RHIC to the LHC will be essential in this endeavor.

2. Heavy ion experiments at RHIC and LHC

RHIC started operation in summer of 2000, after a decade of planning and construction. A detailed description of the accelerator and experiments can be found in [4]. RHIC provides collisions of Au ions at center-of-mass energy of up to 200 GeV per nucleon pair and proton–proton collisions at up to 500 GeV. The construction of the machine with two (almost) independent rings of superconducting dipole magnets also allows running with different species in each of the rings. This was crucial in the 2003 run of deuteron-gold collisions. In addition, RHIC allows collisions of polarized protons, enabling a rich spin-physics program.

Originally, collisions were provided in four interaction regions which house the four heavy-ion experiments. Two experimental collaborations, PHENIX and STAR, operate large multi-purpose detectors, with STAR aiming for maximal coverage in single collisions and PHENIX using sophisticated triggering and particle identification to study rare observables. The smaller experiments, BRAHMS and PHOBOS, specialize in measuring hadron spectra at high rapidities and low transverse momenta respectively, while also providing measurements of angular distributions of charged hadrons in almost full phase-space.

In the past five years, RHIC has delivered Au+Au collisions at $\sqrt{s_{NN}} =$ 19.6, 56, 62.4, 130 and 200 GeV, Cu+Cu collisions at 22.4, 62.4 and 200 GeV, d+ Au collisions at 200 GeV and proton–proton collisions at 200 and 410 GeV.

The small experiments, BRAHMS and PHOBOS, have concluded their experimental program, while the PHENIX and STAR experiments will continue studies at higher luminosities with detector upgrades allowing improved measurements for heavy flavors and high p_{T} phenomena. As the data below will demonstrate, the information from these systematic surveys, in combination with data from the AGS and CERN fixed target program, is essential in forming a consistent dynamical picture of the evolution of a heavy-ion collision.

The start of the LHC program in 2007/2008 will greatly expand the accessible kinematic range in heavy-ion collisions. The collision energy for Pb+Pb collisions at the LHC of 5.6 TeV/nucleon represents the biggest relative increase between any two generations of heavy-ion accelerators. The LHC heavy-ion beam will be utilized by three experiments, ALICE, which is a dedicated heavy-ion experiment and the two large $p+p$ experiments, ATLAS and CMS. Overall, the three experiments complement each other well, with the particular strength of ALICE in the low to medium p_{T} range and its particle ID capabilities and the large coverage, high rate tracking and calorimetry of ATLAS and CMS being important in jet and lepton studies.

3. Key results from heavy ion collisions at RHIC

The full range of experimental results from heavy ion collisions at RHIC clearly exceeds the space available in this paper. Comprehensive surveys of the data obtained by the four experiments can be found in the four whitepapers that were compiled by the collaborations in 2004/2005 [8]. Here, I will present a brief review of key experimental results and theoretical ideas, and will try to illustrate how our present understanding can be tested at future facilities. For almost all topics, the present experimental status is unambiguous, with essentially complete agreement between the various experimental groups. The theoretical interpretation of the results, and their connection to the fundamental theory of strong interactions, has made great progress over recent years and has established an intriguing picture of the state of matter reached in heavy-ion collisions. However, I will point out some of important missing links in establishing a full dynamical understanding of the time evolution of the collision process and describe possible measurements that might shed light on parts of the picture that are so far unexplored.

3.1. Properties of the initial state

The systematics of charged particle multiplicities in high energy collisions, *i.e.* nucleon–nucleon, e^+e^- and nucleus–nucleus collisions as a function of collision energy and centrality, suggest that the multiplicity distributions are determined in the initial collision stage and that the overall multiplicity produced in heavy ion collisions is limited by coherence or destructive interference in this early stage.

A priori, a mapping of the observed multiplicity to a specific stage of the collisions seems difficult, as in principle all stages of the collision could contribute to particle production. A close examination of the available data however suggests that the multiplicity of charged particles and the distribution in pseudo-rapidity are determined very early on in the collision. Predictions for $dN_{\text{ch}}/d\eta$ at RHIC, based on lower-energy nucleus–nucleus data and $p{+}\bar{p}$ data at $\sqrt{s} = 200\,\text{GeV}$, varied by more than a factor of two [7], reflecting the uncertainty in the relative contribution of various processes in the evolution of the system. Surprisingly, the data (see Fig. 1) [5–8] show that the multiplicity for central Au+Au at RHIC energies follow a smooth, approximately logarithmic evolution from lower energy collisions, which falls at the lowest end of the range of predictions.

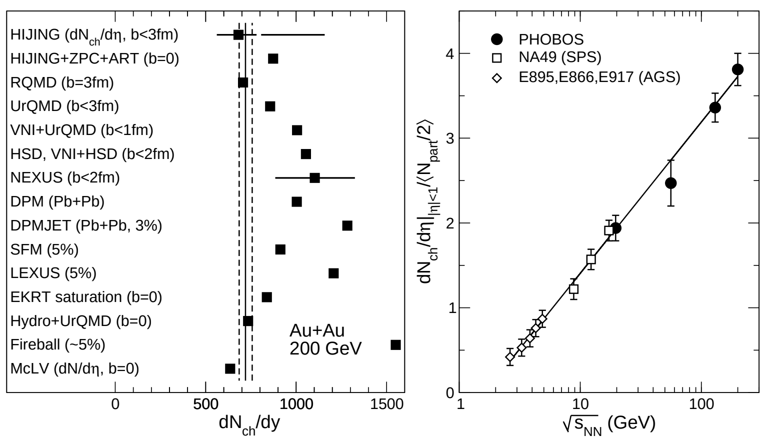

Fig. 1. Charged particle multiplicity density per participant near mid-rapidity for central nucleus–nucleus collisions. Left: Comparison to predictions in various theoretical models. Right: Energy dependence.

It has been suggested that the relatively low multiplicity seen at RHIC is a consequence of parton saturation, based on the idea that at high energies the density of low-x gluons in the transverse plane of the colliding nuclei will no longer allow them to interact independently. Rather, they will form a "Color Glass Condensate" [9], with the resultant coherent interaction of the constituents of the nuclei limiting the growth of particle multiplicity as a function of collision energy. Model calculations based on the idea of parton saturation, in combination with local parton–hadron duality, have had impressive success in describing the energy, centrality and rapidity dependence of charged hadron production in nucleus–nucleus collisions [9].

The importance of these ideas is illustrated in Fig. 2, which shows the ratios of the charged hadron mid-rapidity multiplicities at 200 and 19.6 GeV as a function of centrality [10]. This ratio is found to be flat, in sharp contrast to predictions of models like HIJING that describe charged particle production as a superposition of an empirical soft component and energy — and centrality dependent contributions from hard scattering processes. In contrast, parton saturation model calculations include this factorization approximately [9] or explicitely [11]. Clearly, the contribution to particle production from hard processes is expected to increase rapidly when going to LHC energies. A test of the factorization observed at low energies will be one of the fascinating day-1 measurements once the LHC comes online.

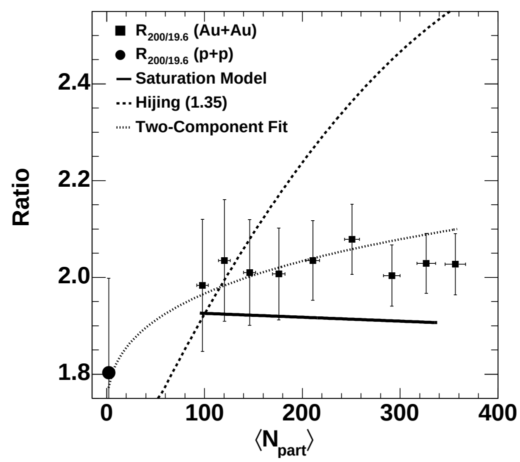

Fig. 2. Ratio of the charged hadron mid-rapidity multiplicities at 200 and 19.6 GeV as a function of collision centrality (PHOBOS).

3.2. Thermal equilibration

Studies of the angular distribution of particles in the final state show that the initial state geometry in peripheral collisions, where the interaction zone is highly asymmetric in the transverse plane, is directly reflected in the final state momentum distribution of the produced hadrons. The first study of the final state anisotropy of charged hadron production at RHIC was performed by the STAR collaboration, shown in Fig. 3 from [13]. Here, the second Fourier-coefficient, v_2, of the azimuthal distribution of charged particles relative to the reaction plane ("elliptic flow") is plotted as a function of collision centrality. As Fig. 3 shows, v_2 reaches a value bigger than 6% for the most peripheral collisions. This translation from initial state configuration space to final state momentum space implies that an interacting system of particles is formed. The figure also shows calculations of the expected maximum value for v_2, starting from the known initial state anisotropy in configuration space and assuming a hydrodynamic expansion. Surprisingly, the data reach this so-called "hydro-limit" for mid-central collisions.

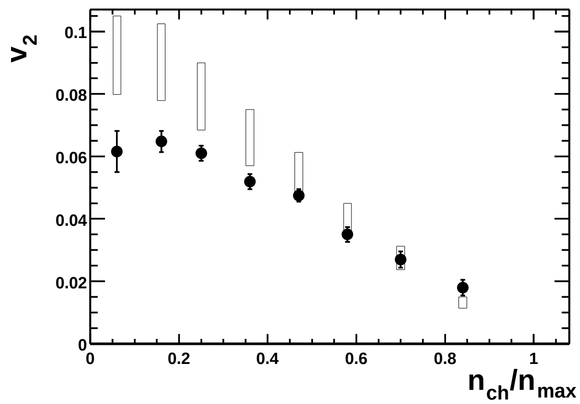

Fig. 3. Elliptic flow parameter v_2 for Au+Au collisions at 130 GeV as a function of collision centrality (STAR).

Attempts for describing the observed final state anisotropies suggest that on timescales of 1–2 fm/c or less, a strongly interacting medium is formed that undergoes an expansion following ideal hydrodynamics [3]. This is remarkable, as the comparison to hydrodynamics implies complete local thermalization and zero mean free path of the matter constituents. The data therefore suggest that the system formed in these collisions is not an ideal gas of quarks and gluons, but rather than strong interactions between the particles persist in the early collision stage. This appears to be in agreement with the (re-) interpretation of the Lattice calculations, which show a pressure above $T_{\rm C}$ significantly below the ideal gas limit. Since these first results, more detailed studies of the strength of elliptic flow as a function of particle mass, rapidity, and transverse momentum have been performed [14–16].

Although hydrodynamic models have had great success in describing the features of the final state anisotropies seen in the data, many question remain. Data from PHOBOS have shown that v_2 drops quickly for particles away from mid-rapidity. Although qualitative arguments can be made that this is related to the dropping particle density and resulting incomplete thermalization, no dynamical 3-dimensional calculations exist that successfully describe these data [17].

Recent data on elliptic flow in Cu+Cu collisions have underlined the importance of improving our understanding of the initial thermalization/isotropization process [18]. Even for the most central Cu+Cu collisions, a large value of $v_2 \approx 0.03$ is observed. This points to the importance of fluctuations in the initial geometrical shape or in the dynamics of the thermalization process, which remain to be understood.

3.3. Jet tomography

Some of the most spectacular results at RHIC have been obtained on particle production at high p_{T} up to $1\,\mathrm{GeV}/c$. Particle production in this range has only become accessible in heavy-ion collisions at RHIC, due to the steep energy dependence of high p_{T} particle yields. The very first studies of particle production at intermediate p_{T} of 2–5 GeV/c by PHENIX showed that particle production in this p_{T} range falls far short of the expectation of binary scaling relative to nucleon–nucleon collisions, as seen in Fig. 4 for both charged hadrons and neutral pions [19].

This modification of the yield and momentum distribution of particles resulting from initial hard scattering processes by so-called "jet quenching" has been predicted as the result of energy loss of high momentum partons in the dense medium created early in a heavy-ion collision [20, 21]. This phenomenon has been proposed as a diagnostic tool for characterizing the parton density in the initial stage of high-energy nuclear collisions.

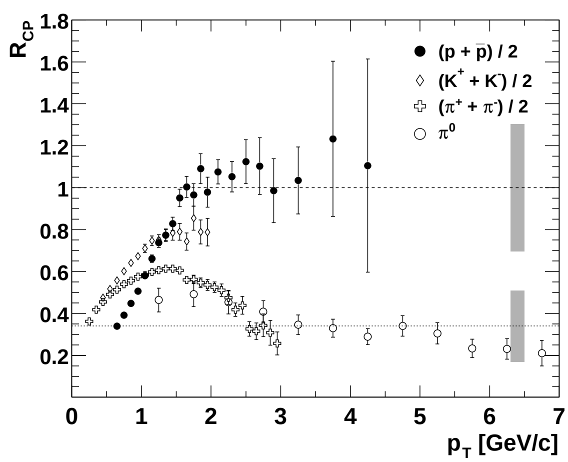

Fig. 4. Nuclear modification factor R_{AA} for charged pions, kaons and protons as a function of transverse momentum for Au+Au collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ (PHENIX).

The first striking result prompted a large array of measurements from all four RHIC experiments, studying particle production at intermediate and high p_{T} as a function of collision energy, collision centrality, particle mass and azimuthal angle (see *e.g.* [22–26] and references therein). An example of these measurements is shown in Fig. 4, where the nuclear modification factor R_{AA} is plotted as a function of p_{T} for charged pions, kaons and protons [27]. Interestingly, the yields for protons reach the binary scaling limit, in contrast to the large suppression of pions.

An impressive confirmation of the large opacity of the collision system was shown by STAR in studies of angular correlations of charged particles at high p_{T}, relative to a high p_{T} trigger particle selected for each event [28, 29]. For proton+proton and $d+$ Au collisions, these correlations shows the characteristic near-side and back-to-back correlation of high p_{T} particle jets. For Au+Au collisions, the near-side correlation is still present, whereas the back-to-back correlation is almost completely suppressed. This can be understood as the dissipation of the away-side jet due to the interaction with the medium. The absolute magnitude of the high p_{T} suppression, the lack of suppression in $d+$ Au and the disappearance of the away-side jet in Au+Au, can be understood in perturbative QCD models that include the interaction of fast partons in a partonic medium. However, the precise value of the relevant transport coefficients are still under debate [30].

The study of high p_{T} particle production will continue to play a central role in developing our understanding of heavy-ion collisions. There are several major directions that these measurements will take in the future. The most obvious is the dramatic extension of the available p_{T} range in $A+A$ collisions at the LHC. The rapid rise of jet cross-sections will allow measurements for p_{T} of several hundred GeV/c. This means that fully developed jets will be visible in the combined tracking and calorimetry of the LHC experiments, allowing detailed studies of jet shapes and fragmentations functions. Both at RHIC and LHC, tagging of jets recoiling against high p_{T} photons will allow a calibration of the jet energies for jets above $p_{\mathrm{T}} \approx 20\,\mathrm{GeV}/c$. In addition, the upgraded RHIC and LHC experiments will be able to use tagging of displaced vertices to study the interaction of heavy flavor jets with the medium.

3.4. Nature of the high density state

Many attempts have been made at estimating the initial energy density achieved in Au+Au collisions at RHIC (see *e.g.* [8]). If our understanding of the development of v_2 is correct, and thermalization is achieved on timescales of 1–2 fm/c, the energy densities are almost certainly higher than $\approx 3\,\mathrm{GeV/fm^3}$, and therefore, far exceed the energy density connected to the critical temperature in Lattice calculations.

As discussed previously, there are strong indications from data on particle multiplicity and the suppression of high p_{T} hadron production that densities for in excess of those of normal nuclear matter are reached early in the collision. Estimates of the lower limit at a time of 1 fm/c after the collision are in the range of 3–5 $\mathrm{GeV/fm^3}$. The data on elliptic flow suggest that at this time, a locally equilibrated medium has been formed, and therefore, the concept of a temperature corresponding to this density, in combination with the available degrees of freedom, is meaniningful. However, no convincing experimental data exist from which this initial temperature could be directly deduced. As discussed before, the hadronization temperature extracted from particle ratios is found to smoothly increase with collision energy, saturating at a value of 170 MeV. While this value coincides with the estimated critical temperature from lattice QCD, it also agrees with the results of statistical fits, assuming partial strangeness equilibration, for nucleon–nucleon and e^+e^- collisions. Temperatures have also been extracted from the transverse momentum distributions of charged hadrons, using a combination of an effective freeze-out temperature and a collective transverse expansion velocity field, to simultaneously describe the spectra of multiple hadron species using a common set of parameters. These temperature estimates are subject to a greater variety of theoretical approaches, giving a span of extracted values from 100 MeV to 160 MeV. However, the point here is that there is no direct experimental measurement of a temperature in excess of 170 MeV.

Clearly, a measurement that looks beyond the veil of hadronic freeze-out promises great conceptual progress in our understanding of the nature of the medium at the early stage of the collision. The leading candidate for such a measurement is the study of spectra of thermal photons and dileptons. These weakly interacting probes could in principle should carry direct information on the initially achieved conditions. However, these measurements are made extraordinarily difficult by the subsequent photon production from decays of ordinary hadrons. Measurements of direct photon production were shown by WA98 and PHENIX.

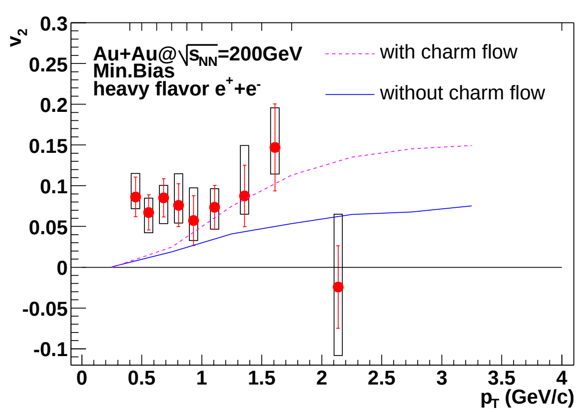

Fig. 5. Elliptic flow coefficient of "heavy flavor" electrons for minimum bias Au+Au collisions at 200 GeV as a function of transverse momentum. Data are compared to calculations with and without elliptic flow of charm quarks (PHENIX).

Another rich set of probes of the dynamics of the initial evolution is provided by measurements of particles originated from heavy quarks. As these heavy quarks will only be produced in the initial collision process and are expected to show weaker interactions with the medium than light quarks, they are ideal tools to study the dynamics of the early, dense medium. An example of such studies is shown in Fig. 5, showing the elliptic flow of non-photonic single electrons, which are mostly produced by decays of hadrons containing heavy quarks [31]. This measurement, as well as data on the nuclear modification factor for single electron $p_{\rm T}$ spectra, indicate a surprisingly strong interaction of the heavy quarks with the medium. These studies will greatly benefit from the improved detection capabilities and luminosities/rates in future data taking at RHIC and at the LHC.

4. Conclusions

The results from nearly two decades of experimental high-energy heavy-ion physics demonstrate convincingly that a unique, high-density medium is formed in these collisions. Many of the non-trivial properties of this medium and its evolution, such as the apparent initial state coherence, the strongly interacting nature of the medium and its opacity for fast partons, can be directly related to our theoretical understanding of the strong interaction. Still, many experimental and theoretical questions remain. Of highest importance are measurements related to the nature of the medium before hadronization and a theoretical understanding of how the initial equilibrated medium is formed and how the eventual decay into hadrons proceeds. To obtain these answers, a coherent experimental effort at future heavy-ion facilities and a close collaboration between experimental and theoretical groups will be required. Even though it may seem that we are close to some of the answers, nature is certain to have a few surprises for us.

REFERENCES

[1] See for example F. Karsch, *Nucl. Phys.* **A698**, 199 (2002).

[2] For a review, see *e.g* B. Muller, J. Harris, *Ann. Rev. Nucl. Part. Sci.* **46**, 71 (1996).

[3] P.F. Kolb, U. Heinz, *Quark Gluon Plasma 3*, Eds.: R.C. Hwa, X.N. Wang.

[4] H. Hahn *et al.*, *Nucl. Instrum. Methods* **A499**, 245 (2003).

[5] B.B. Back *et al., Phys. Rev. Lett.* **85**, 3100 (2000).

[6] B.B. Back *et al., Phys. Rev. Lett.* **88**, 22302 (2002).

[7] K.J. Eskola, *Nucl. Phys.* **A698**, 78 (2002), [hep-ph/0104058].

[8] The four RHIC collaborations, BRAHMS, PHENIX, PHOBOS and STAR have published papers that summarize the first years of RHIC Physics in *Nucl. Phys.* **A757**, (2005).

[9] L.D. McLerran, R. Venugopalan, *Phys. Rev.* **D49**, 2233 (1994); D. Kharzeev, B. Levin, *Phys. Lett.* **B523**, 79 (2001); A. Krasnitz, R. Venugopalan, *Phys. Rev. Lett.* **86**, 1717 (2001); D. Kharzeev, E. Levin, L. McLerran, `hep-ph/0210332`.

[10] B.B. Back *et al., Phys. Rev.* **C70**, 021902R (2004).

[11] N. Armesto, C.A. Salgado, U.A. Wiedemann, `hep-ph/0407018`.

[12] B.B. Back *et al., Phys. Rev. Lett.* **91**, 052303 (2003).

[13] C. Adler *et al., Phys. Rev. Lett.* **87**, 182301 (2001).

[14] B.B. Back *et al., Phys. Rev. Lett.* **89**, 222301 (2002).

[15] C. Adler *et al., Phys. Rev. Lett.* **87**, 182301 (2001.)

[16] S.S. Adler *et al.*, `nucl-ex/0305013`.

[17] T. Hirano, *Nucl. Phys.* **A774**, 531 (2006) [`nucl-th/0511036`].

[18] G. Roland *et al., Nucl. Phys.* **A774**, 113 (2006)

[19] K. Adcox *et al., Phys. Rev. Lett.* **88**, 022301 (2002).

[20] M. Gyulassy, M. Plümer, *Phys. Lett.* **243**, 432 (1990).

[21] M. Gyulassy *et al.*, `nucl-th/0302077`.

[22] C. Adler *et al., Phys. Rev. Lett.* **89**, 202301 (2002).

[23] K. Adcox *et al.*, `nucl-ex/0207009`.

[24] B.B. Back *et al.*, `nucl-ex/0302015`.

[25] J. Adams *et al.*, `nucl-ex/0305015`.

[26] S.S. Adler *et al.*, `nucl-ex/0308006`.

[27] S.S. Adler *et al.*, `nucl-ex/0307022`.

[28] C. Adler *et al., Phys. Rev. Lett.* **90**, 082302 (2003).

[29] J. Adams *et al., Phys. Rev. Lett.* **91**, 072304 (2003).

[30] B. Muller, `nucl-th/0609059`.

[31] S.S. Adler *et al., Phys. Rev.* **C72**, 024901 (2005).