Vol. 35 (2004) *ACTA PHYSICA POLONICA B* No 1

EXPERIMENTAL STATUS OF PARTON SATURATION AT RHIC*

Peter A. Steinberg

Brookhaven National Laboratory
Upton, NY 11973, USA

(Received December 1, 2003)

We review the basic phenomenological predictions of parton saturation models and evaluate their relevance in light of the data from Au + Au collisions at RHIC.

PACS numbers: 25.75.Dw

1. Introduction

The RHIC collider at Brookhaven National Laboratory is a facility dedicated to the study of QCD under extreme conditions of temperature and density. This is achieved by colliding gold nuclei at $\sqrt{s_{NN}} = 200$ GeV (where $\sqrt{s_{NN}}$ is the CMS energy per nucleon–nucleon collision).

One of the more intriguing theoretical developments of the last 10 years is the evolving understanding of the low-x sector of QCD. Various authors have concluded that the initial state soft and semi-hard gluons is best understood as a "Color Glass Condensate" (CGC) [1], also reviewed by Armesto in these proceedings.

The CGC has several important features relevant to RHIC phenomenology. It is a description of the low-x color degrees of freedom, and so pertains dominantly to "soft" physics (produced particles below $p_{\rm T} \sim 2$ GeV). It treats these degrees of freedom as freezing out from the higher-x partons in the incoming nucleons, a time-dilation effect which makes the CGC a "glass". The soft gluons are coherent over large longitudinal distances, since the coherence length scales as $\Delta z \sim 1/xM_p$ (an analogy to a Bose condensate). Finally, it is thought that the low-x sector is universal, and so the CGC phenomenology

* Presented at the XXXIII International Symposium on Multiparticle Dynamics, Kraków, Poland, September 5–11, 2003.

should be applicable to a wide range of systems, *e.g.* at HERA and RHIC. The only difference is the "saturation scale" $Q_{\rm s}^2$, which controls the low-x gluon structure and is proportional to the transverse parton density.

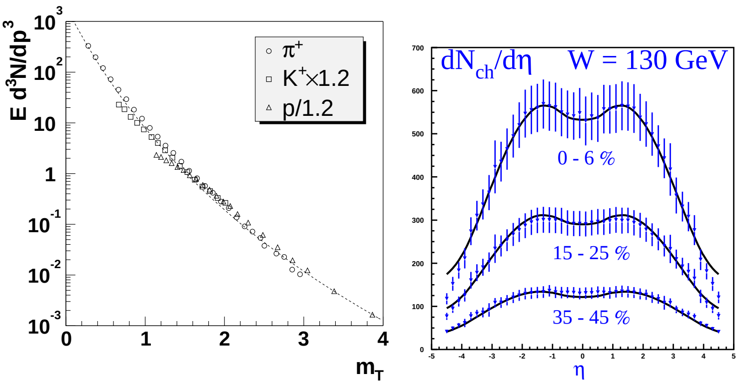
2. Geometric scaling

CGC phenomenology for RHIC collisions [2] is based on the observation of geometric scaling in HERA data on the total $\gamma^* p$ cross section, such that the cross section does not depend on Q^2 and x separately, but rather in the ratio $\tau = Q^2/Q_{\rm s}^2$, where $Q_{\rm s}^2 = Q_0^2(x_0/x)^\lambda$ [3, 4]. The existence of this scaling determines the energy dependence ($Q_{\rm s}^2 \propto s^\lambda$) and rapidity dependence ($Q_{\rm s}^2 \propto \exp(\lambda y)$) of particle production.

Given the importance of this observed scaling in the HERA data, it is an open question whether similar scaling is seen at RHIC. In Ref. [5], it was shown that the production of pions, kaons, and protons at RHIC obeyed a strong $m_{\rm T}$ scaling, such that the yield of identified particles goes as $(1 + m_{\rm T}/p_{\rm s})^{-n}$ and thus a single scale $p_{\rm s}$ controls the phenomenology. However, the data shown in [5] has been updated recently [6], with large corrections to remove the contribution of weak decays in the kaons and protons. This reveals significant deviations from $m_{\rm T}$ scaling are seen at low $m_{\rm T}$. Although these deviations have a natural explanation in terms of a flow velocity, it also complicates claims of geometric scaling in the RHIC data.

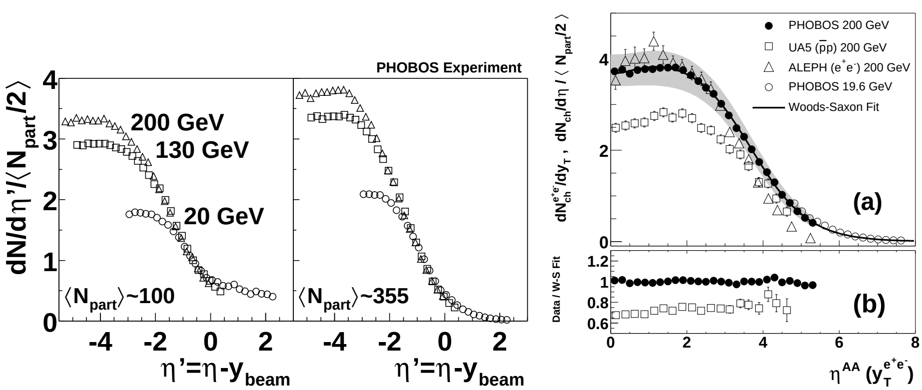
3. Multiplicity measurements

The most cited example of a successful saturation calculation is that done by Kharzeev and Levin [2], shown in Fig. 1(b). This incorporates the above-mentioned dependencies on energy, centrality, and rapidity and only requires two parameters, one taken from HERA data ($\lambda \sim 0.3$ from Ref. [4]) and one constant of proportionality fit to the central Au + Au data (which is an implicit assumption of Local Parton Hadron Duality [7]). Another observation consistent with the saturation approach is "limiting fragmentation". Experimentally, in proton–antiproton collisions at high-energies, it has been observed that the yield of charged particles depends only on the difference between the rapidity of the emitted particle and the beam rapidity $\eta' = \eta - y_b$, independent of the collision energy. This is shown for Au + Au collisions at RHIC for two different collision centralities in Fig. 2(a) [8]. The idea is that the forward degrees of freedom serve as sources for the particle production at lower x (*i.e.* lower η'). While this is a succinct explanation for the phenomenon, the observation of the same phenomena in proton–antiproton collisions at RHIC energies, where the saturation regime is not reached, questions the importance of saturation in understanding this observable. Moreover, it has been observed that the basic shape of the pseudorapidity distributions in Au + Au and $\overline{p}p$ are the same up to a linear scale factor (seen in the bottom panel of Fig. 2(b) [9]. This suggests that the shape successfully described in the saturation approach may be far more general, a point emphasized by the e^+e^- data also shown, which is also quite similar to the Au + Au data, with no additional scaling.



(a) (b)

Fig. 1. (a) m_{T} spectra of identified pions, kaons, and protons in 200 GeV Au + Au collisions, showing deviations of scaling at low m_{T}. (b) Pseudorapidity density of charged particles in 130 GeV Au + Au collisions, compared with results from KLN parton saturation results.



(a) (b)

Fig. 2. (a) $dN/d\eta$ for three different collision energies and centralities in Au + Au collisions at RHIC, showing "limiting fragmentation" in the forward region. (b) Comparison of the pseudorapidity distributions for Au + Au, $\overline{p}p$ and e^+e^- collisions at the same $\sqrt{s}$.

4. Soft scaling of hard processes

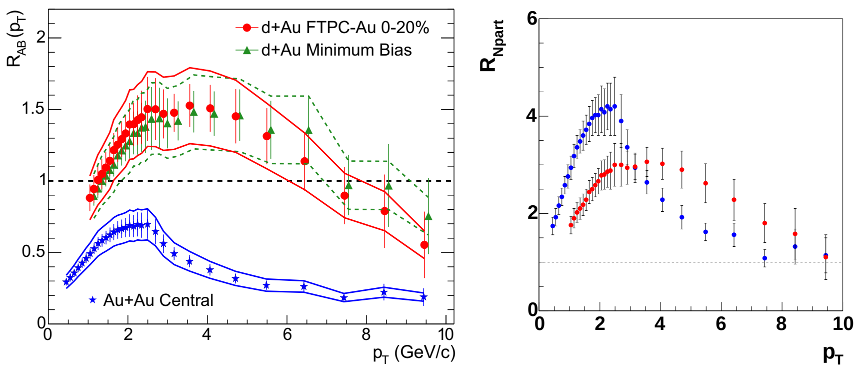
While it was not surprising for saturation calculations to describe soft physics, it turned out that they could also account for an interesting effect at large transverse momentum. The differential yield per binary collision in Au + Au collisions compared to *pp* showed a dramatic suppression attributed to energy loss of the outgoing quark and gluon jets and minijets. However, it was also noticed that the suppression corresponded simply to the yield at high-p_{T} scaling with N_{part} [10], almost as if (short-distance) hard processes scaled like (long-distance) soft ones. A particular CGC calculation [11] could explain this through the quantum evolution retaining memory of the initial configuration of color sources (which scales as the number of participants).

To test this hypothesis, RHIC devoted a large portion of Run-3 (in 2003) to collisions of deuterons, which should exhibit little saturation effect, with gold nuclei, which should have a strong suppression of low-x partons. Thus, one would expect a suppression pattern somewhere between a null effect and the strong effect seen in Au + Au. RHIC data released in June 2003 [12] appear to be in strong contradiction to the CGC predictions, since strong Cronin-type *enhancement* is observed at large p_{T}. Even studying more central events, where the saturation effects should be strongest, showed no significant suppression near mid-rapidity.

5. Conclusions and outlook

After the recent data, it has been thought that it is no longer reasonable to think of the CGC initial conditions as controlling all of the physics observed in the final state. It may be possible that CGC controls the initial-state entropy, but it does not seem to be the dominant effect at larger momentum transfer. However, it is the opinion of this author that the appearance of soft scaling both at low and high p_{T} in Au + Au physics suggests that while the conceptual framework of parton saturation may be broadly relevant to RHIC collisions, particular calculations may be problematic. It is interesting to consider how the Cronin enhancement appears in Au + Au and d + Au when one scales by $N_{\mathrm{part}}/2$ rather than the N_{coll}, shown in Fig. 3(b). Despite the large errors at high p_{T}, one can discern a similar enhancement structure, although the peaks sit at different momenta.

Thus, one may conclude that the CGC approach should be a compelling perspective on strongly interacting systems. Coherence in the initial state generates a momentum scale that controls a large fraction of the final state phenomena. A large set of data is consistent with this phenomenology, even if saturation is not yet a unique description. While the deuteron–gold data is at present (Autumn 2003) at odds with the CGC prediction, further analyses, especially in $d+$ Au collisions and at forward rapidities, should be a crucial testing ground for these ideas.



(a) (b)

Fig. 3. (a) Nuclear modification factor from 200 GeV $d+$Au and Au + Au collisions at RHIC. (b) The same curves, but normalized to the number of participant pairs.

REFERENCES

[1] E. Iancu, R. Venugopalan, `hep-ph/0303204`.

[2] D. Kharzeev, E. Levin, *Phys. Lett.* **B523**, 79 (2001).

[3] K. Golec-Biernat, M. Wusthoff, *Phys. Rev.* **D59**, 014017 (1999).

[4] A.M. Stasto, K. Golec-Biernat, J. Kwiecinski, *Phys. Rev. Lett.* **86**, 596 (2001).

[5] J. Schaffner-Bielich, D. Kharzeev, L.D. McLerran, R. Venugopalan, *Nucl. Phys.* **A705**, 494 (2002).

[6] S.S. Adler *et al.* (PHENIX Collaboration), `nucl-ex/0307022`.

[7] Y.L. Dokshitzer, V.A. Khoze, S.I. Troian, *J. Phys. G* **17**, 1585 (1991).

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

[9] B.B. Back *et al.* (PHOBOS Collaboration), `nucl-ex/0301017`.

[10] B.B. Back *et al.* (PHOBOS Collaboration), `nucl-ex/0302015`.

[11] D. Kharzeev, E. Levin, L. McLerran, *Phys. Lett.* **B561**, 93 (2003).

[12] J. Adams *et al.*, *Phys. Rev. Lett.* **91**, 072304 (2003); S.S. Adler *et al.*, *Phys. Rev. Lett.* **91**, 072303 (2003); I. Arsene *et al.*, *Phys. Rev. Lett.* **91**, 072305 (2003); B.B. Back *et al.*, *Phys. Rev. Lett.* **91**, 052303 (2003).