Eur. Phys. J. C (2005)
Digital Object Identifier (DOI) 10.1140/epjc/s2005-02306-x

THE EUROPEAN
PHYSICAL JOURNAL C

The forward high p_T puzzle

The BRAHMS Collaboration

J.J. Gaardhøje[7,a], I. Arsene[10], I.G. Bearden[7], D. Beavis[1], C. Besliu[10], B. Budick[6], H. Bøggild[7], C. Chasman[1], C.H. Christensen[7], P. Christiansen[7], J. Cibor[3], R. Debbe[1], E. Enger[12], J.J. Gaardhøje[7], K. Gulbrandtsen[7], K. Hagel[8], H. Ito[1], A. Jipa[10], F. Jundt[2], J.I. Jørdre[9], C.E. Jørgensen[7], R. Karabowicz[4], E.J. Kim[1,11], T. Kozik[4], T.M. Larsen[7], J.H. Lee[1], Y.K. Lee[5], S. Lindal[12], R. Lystad[9], G. Løvhøiden[12], Z. Majka[4], A. Makeev[8], M. Mikelsen[12], M. Murray[8,11], J. Natowitz[8], B. Neumann[11], B. S. Nielsen[7], D. Ouerdane[7], R. Płaneta[4], F. Rami[2], G. Renault[7], C. Ristea[7], O. Ristea[10], D. Röhrich[9], B. H. Samset[12], D. Sandberg[7], S. J. Sanders[11], R. A. Scheetz[1], P. Staszel[4]T.S. Tveter[12], F. Videbæk[1], R. Wada[8], Z. Yin[9], and I.S. Zgura[10]

[1] Brookhaven National Laboratory, Upton, New York 11973, USA
[2] Institut de Recherches Subatomiques and Université Louis Pasteur, Strasbourg, France
[3] Institute of Nuclear Physics, Krakow, Poland
[4] Smoluchkowski Inst. of Physics, Jagiellonian University, Krakow, Poland
[5] Johns Hopkins University, Baltimore 21218, USA
[6] New York University, New York 10003, USA
[7] Niels Bohr Institute, Blegdamsvej 17, University of Copenhagen, Copenhagen 2100, Denmark
[8] Texas A&M University, College Station, Texas, 17843, USA
[9] University of Bergen, Department of Physics, Bergen, Norway
[10] University of Bucharest, Romania
[11] University of Kansas, Lawerence, Kansas 66045, USA
[12] University of Oslo, Department of Physics, Oslo, Norway

Received: 19 March 2005 / Revised version: 26 April 2005 /
Published online: 2 August 2005 –

Abstract. Recent results from BRAHMS show the persistence of high p_T suppression in Au+Au and d+Au collisions at forward rapidity. These observations have implications for Parton Energy Loss and Color Glass Condensate models. We encourage – and challenge – theorists to develop a unified description of the high p_T suppression as it is observed in energetic heavy ion collisions at RHIC across a wide rapidity range.

PACS. 25.75.q, 25.40.-h,

1 Introduction

In this paper I review some of the recent results from the BRAHMS collaboration at RHIC, mainly on the physics at high p_T for unidentified hadrons. Indeed, the discovery of a strong suppression of the production of $p_T >$ 2 GeV/c particles in central collisions between gold nuclei at 100 AGeV + 100 AGeV, as compared to the similar production (scaled by the number of elementary collisions) observed in pp collisions at the same energy, is one of the central discoveries made at RHIC. Comparison to theory suggests that the observed reduction of the high transverse momentum particle yields is due to the energy loss of scattered partons as they propagate through a medium with a high density of color charges, perhaps a kind of QGP. The findings of the exciting first years of RHIC operations have recently been summarized by the 4 experiments in whitepapers submitted to publication [1–4]. The large number of articles already produced by the four experiments at RHIC may be found on their respective homepages [5]. Likewise, extensive theoretical surveys and commentaries have been produced.

BRAHMS has among the 4 RHIC experiments the unique capability to study this phenomenon, not only close to midrapidity, but over a broad rapidity range, thereby making it possible to investigate also the longitudinal extent of the medium responsible for the suppression. The ability to measure charged hadron production at small angles of emission relative to the beam (down to 2.3 degrees) has provided the first suggestions of effects related to a possible saturation of the low x gluon content of rapidly moving nuclei, e.g. as predicted by the Color Glass Condensate theory. Recently we have extended these measurements at very forward rapidity ($y \approx 3$) from d+Au collisions also to Au+Au and find that high p_T suppression persists at forward rapidity in collisions between heavy

[a] e-mail: gardhoje@nbi.dk

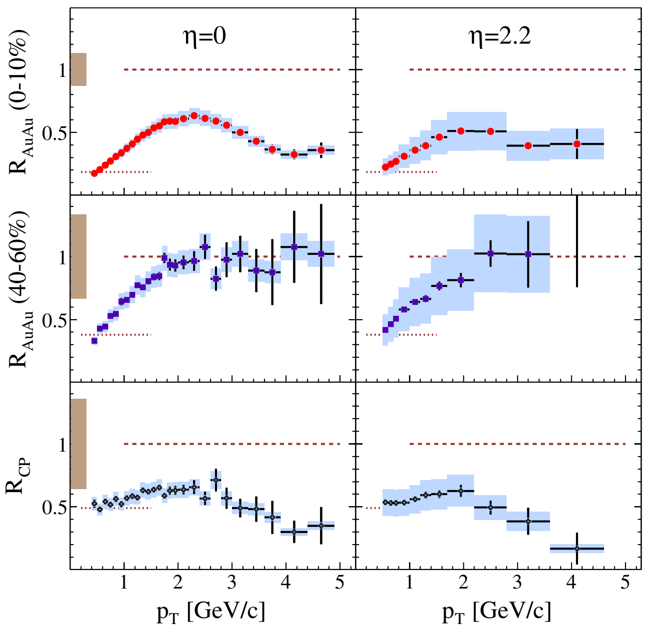

Fig. 1. Nuclear modification factors R_{AuAu}, as defined in the text, measured by BRAHMS for central (top row) and semi-peripheral (middle row) Au+Au collisions at midrapidity (left) and forward rapidity (right). Note the strong suppression of the high p_T component above $p_T > 2$ GeV/c seen at both rapidities. The lower row shows the factor R_{cp}, i.e. the ratio of the R_{AuAu} for central and peripheral collisions. This ratio has the property of being independent of the pp reference spectrum [9]

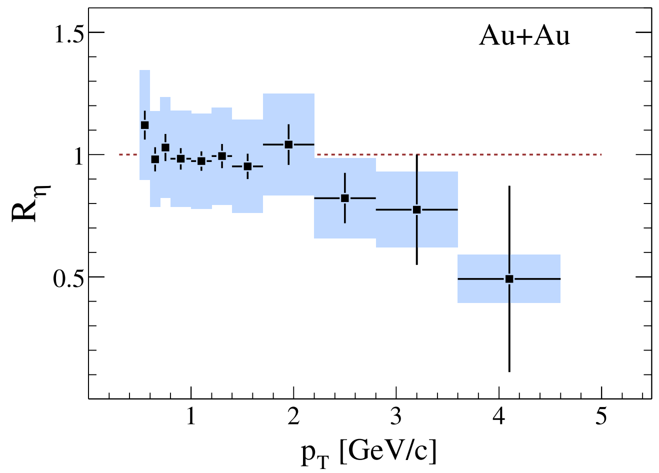

Fig. 2. Ratio R_η of the suppression factors R_{cp} at pseudorapidities $\eta = 0$ and $\eta = 2.2$ that are shown in Fig. 1. The figure indicates that high p_T suppression persists at forward rapidity (and is even more important than at $\eta = 0$) [9]

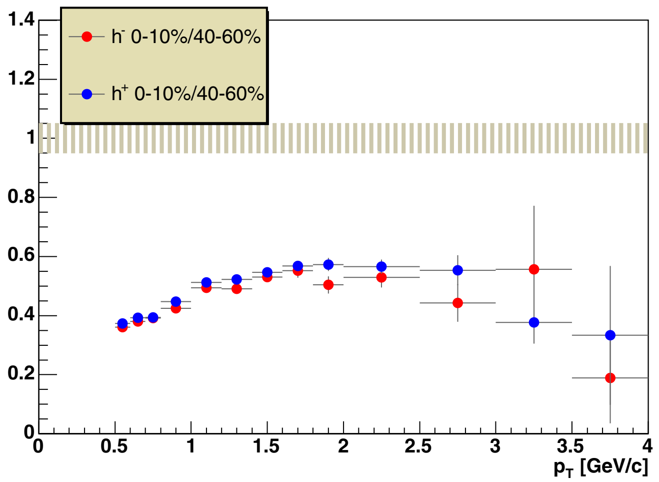

Fig. 3. Suppression factors R_{cp} at pseudorapidity $\eta = 3.2$ for Au+Au collisions at the top energy. The figure shows that high p_T suppression persists to $\eta = 3.2$. BRAHMS preliminary

nuclei, an observation that has yet to find a satisfactory quantitative description.

2 High p_T suppression from $\eta = 0$ to $\eta = 3$ in Au+Au collisions

The two upper rows of Fig. 1 show our measurements [9, 12] of the so-called nuclear modification factors for *unidentified* charged hadrons from Au+Au collisions at pseudorapidities $\eta = 0$ and 2.2. The nuclear modification factor is defined as:

$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{\langle N_{\rm bin}\rangle d^2N^{NN}/dp_T d\eta}. \quad (1)$$

It involves a scaling of measured nucleon-nucleon transverse momentum distributions by the calculated [9] number of binary nucleon-nucleon collisions, $N_{\rm bin}$. In the absence of medium effects, the nuclear collisions can, at high p_T, be seen as a superposition of elementary hard nucleon-nucleon collisions. Consequently we expect $R_{AA} = 1$ at high p_T. At low p_T, where the particle production follows a scaling with the number of participants, the above definition of R_{AA} leads to $R_{AA} < 1$ for $p_T < 2\,$GeV/c.

In fact, it is found that $R_{AA} > 1$ for $p_T > 2\,$GeV/c in nuclear reactions at lower energy. This enhancement, first observed by Cronin, is associated with multiple scattering of partons [13,14].

Figure 1 demonstrates that, surprisingly, $R_{AA} < 1$ also at high p_T for central collisions at both pseudorapidities, while $R_{AA} \approx 1$ for more peripheral collisions. It is remarkable that the suppression observed at $p_T \approx 4\,$GeV/c is very large, amounting to a factor of 3 for central Au+Au collisions as compared to pp and a factor of more than 4 as compared to the more peripheral collisions. Such large suppression factors are observed at both pseudorapidities.

The very large suppression observed in central Au+Au collisions must be quantitatively understood and requires systematic modelling of the dynamics. At $\eta = 0$ the particles are emitted at 90 degrees relative to the beam direction, while at $\eta = 2.2$ the angle is only about 12 degrees. In a naive geometrical picture of an absorbing medium with cylindrical symmetry around the beam direction, the large suppression seen at forward angles suggests that the suppressing medium is extended also in the longitudinal direction. Since the observed high p_T suppression is similar or even larger at forward rapidity as compared to midrapidity (see Figs. 2 and 3) one might be tempted to infer a longitudinal extent of the dense medium which is approximately similar to its transverse dimensions. However, the problem is more complicated, due to the significant transverse and in particular longitudinal expansion that occurs as the leading parton propagates through the medium, effectively reducing the densities of color charges seen. Also other high p_T suppressing mechanisms may come into play at forward rapidities (see discussion on the Color Glass Condensate in Sect. 5).

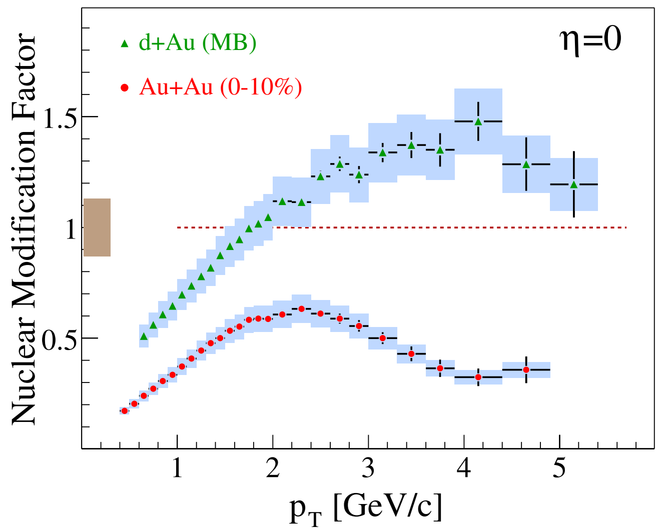

Fig. 4. Nuclear modification factors measured for central Au+Au collisions and minimum bias d+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$, showing that the important high p_T suppression observed in central Au+Au collisions [9] is absent in d+Au reactions. The shaded band around the points indicates the systematic errors. The shaded box on the ordinate around unity shows the estimated uncertainty on the value of N_{bin}

It has been conjectured that the observed high p_T suppression might be the result of an entrance channel effect, for example as might arise from a limitation of parton collisions related to saturation effects [15] in the gluon distributions inside the swiftly moving colliding nucleons (which have $\gamma = 100$). As a test of these ideas we have determined the nuclear modification factor for d+Au minimum bias collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$. The resulting R_{dAu} is shown in Fig. 4 where it is also compared to the R_{AuAu} for central collisions previously shown in Fig. 1. No high p_T jet suppression is observed for d+Au [9,17–19]. The R_{dAu} distribution at $y = 0$ shows a Cronin enhancement similar to that observed at lower energies. At $p_T \approx 4\,\mathrm{GeV}/c$ we find a ratio $R_{dAu}/R_{AuAu} \approx 4-5$. These observations are consistent with the smaller transverse dimensions of the overlap disk between the d and the Au nuclei and also appear to rule out initial state effects as the cause of the observed high p_T yield reduction observed in Au+Au collisions.

High p_T suppression at forward rapidities may also be expected to arise from the possible Color Glass Condensate phase in the colliding nuclei (see the discussion in Sect. 5). There is little doubt that a detailed understanding of the properties of the dense medium will require systematic studies of the high p_T jet energy loss as a function of the thickness of the absorbing medium, obtained by varying the angle of observation of high p_T jets relative to the event plane and the direction of the beams.

3 The flavor composition

With the excellent particle identification capabilities of BRAHMS we also study the dependence of the high p_T suppression on the type of particle. Preliminary results [12,20] indicate that mesons (pions and kaons) experience high p_T suppression while baryons (protons) do not. The reason for this difference is at present not well understood.

The observed differences may be due to baryons being more sensitive to flow than mesons, because of their larger mass. The flow contribution leads a flatter transverse momentum spectrum for baryons than for mesons, thus possibly compensating for a high p_T suppression effect similar to that of the mesons. It is also possible that the difference reflects details associated with the fragmentation mechanism that leads to different degrees of suppression of the high p_T component for 2 and 3 valence quark systems. Finally the difference may reflect the mechanism of recombination for 3 quarks relative to that for 2 quarks in a medium with a high density of quarks.

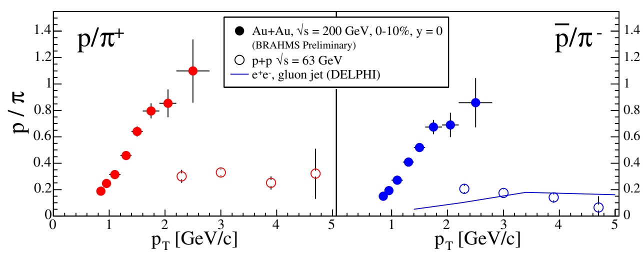

Fig. 5. Ratios of particle yields p/π^+ (left) and $\bar{p}/\pi^-$ (right) measured at mid-rapidity for 0–10% central Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$. The error bars show the statistical errors. The systematic errors are estimated to be smaller than 8%. Data at $\sqrt{s} = 63\,\mathrm{GeV}$ for pp collisions [21] are also shown (open circles). The solid line in the right panel is the $(p+\bar{p})/(\pi^+ + \pi^-)$ ratio measured for gluon jets [22] in $e^+ + e^-$ collisions

Figure 5 shows a recent investigation by BRAHMS of the baryon to meson ratios at mid-rapidity p/π^+ and $\bar{p}/\pi^-$, as a function of p_T for the 0–10% most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [20]. The ratios increase rapidly at low p_T and the yields of both protons and anti-protons are comparable to the pion yields for $p_T > 2\,\mathrm{GeV}/c$. The corresponding ratios for $p_T > 2\,\mathrm{GeV}/c$ observed in pp collisions at $\sqrt{s} = 62$ GeV [21] and in gluon jets produced in $e^+ + e^-$ collisions [22] are also shown. The

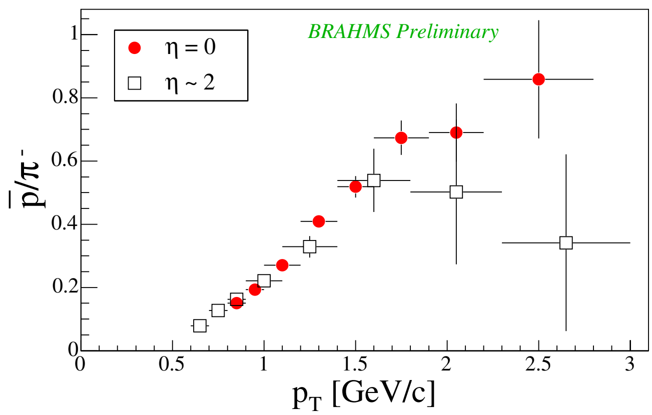

Fig. 6. Comparison of the $\bar{p}/\pi^-$ yield ratio at pseudorapidities $\eta = 0$ and $\eta = 2.2$. In spite of small statistics the data suggest that at forward rapidity the flow may be weaker resulting in a decreased yield of antiprotons relative to pions above $p_T \approx 2$ GeV/c. BRAHMS preliminary [20]

increase of the p/π^+ and $\bar{p}/\pi^-$ ratios at high p_T, seen in central Au+Au collisions, relative to the level seen in pp and $e^+ + e^-$ indicates significant differences in the overall description, either at the production or fragmentation level.

Figure 6 shows the comparison of BRAHMS data for the ratio of antiprotons to negative pions at $\eta = 0$ and 2.2. Although statistics at high transverse momentum are low there are indications that the ratio is smaller at the higher rapidity for $p_T > 2$ GeV/c. Recent calculations based on a parton recombination scenario [23–25] with flow at the partonic level appear to be able to describe the data at midrapidity, while calculations omitting flow fall short of the data already at $p_T \approx 1.5$ GeV/c.

The experimental and theoretical investigation of these questions is, however, still in its infancy. These issues can and will be addressed in depth through the analysis of the large data set collected by BRAHMS in the high luminosity Au+Au run of year 2004.

4 Does high p_T suppression persist at lower energy?

The short run for Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV has allowed us to carry out a first analysis of the high p_T suppression of charged hadrons at an energy of about 1/3 the maximum RHIC energy and about 3.5 times the maximum SPS energy. Preliminary results are shown in Fig. 7 for the nuclear modification factor calculated for the sum of all charged hadrons measured at 45 degrees with respect to the beam direction ($\eta = 0.9$). The data have been compared to reference spectra measured in $\sqrt{s_{NN}} =$ 63 GeV pp collisions at the CERN-ISR. The figure shows that the high p_T data are less suppressed at $\sqrt{s_{NN}} =$ 62.4 GeV than at $\sqrt{s_{NN}} = 200$ GeV. This is consistent with recent results from PHOBOS [27]. For comparison, at SPS energies no high p_T suppression was observed (albeit a discussion has surfaced regarding the accuracy of the

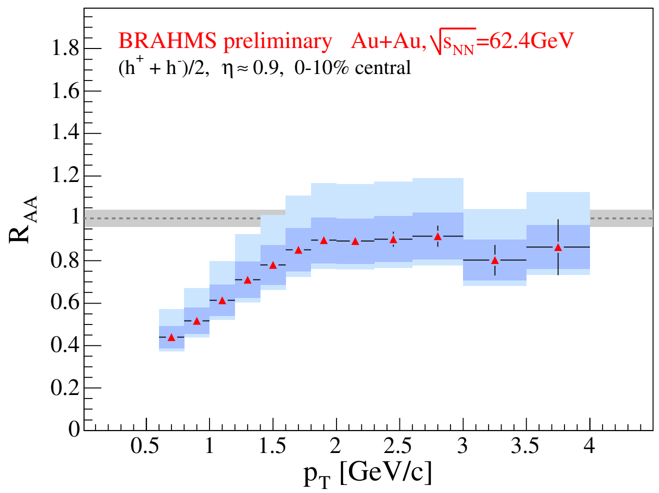

Fig. 7. Nuclear modification factor R_{AuAu} measured by BRAHMS for charged hadrons at $\eta = 0.95$ for 0–10% central Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV [26]. The dark shaded band indicates the systematic errors on the data, the lighter shaded band the combined estimated systematic error on the Au+Au data and on the pp reference

reference spectra at that energy [16]). It thus seems the suppression increases smoothly with energy.

5 The color glass condensate?

As part as the study of the high p_T suppression in nucleus-nucleus collisions BRAHMS has investigated the rapidity dependence of the nuclear modification factors as a function of pseudorapidity ($\eta = 0, 1, 2.2, 3.2$) in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. As discussed in the previous section the measured nuclear modification factors for d+Au are consistent with the absence of high p_T suppression around midrapidity. This may be taken as direct evidence for the fact that the strong high p_T suppression seen in Au+Au collisions around $y = 0$ is not due to particular conditions of the colliding nuclei (initial state effects) [17, 18, 9].

At forward rapidity in d+Au collisions BRAHMS has observed [28] a marked high p_T suppression starting already at $\eta = 1$ (see Fig. 8) and increasing smoothly in importance with increasing pseudorapidity (up to $\eta = 3.2$). It has been proposed that this effect at forward rapidity [29] is related to the initial conditions of the colliding d and Au nuclei, in particular to the possible existence of the Color Glass Condensate (CGC).

The CGC is a description of the ground state of swiftly moving nuclei prior to collisions [30]. Due to the non Abelian nature of QCD, gluons self interact so that there is a large cross section for gluon splitting which results in nuclei containing a large number of low–x gluons (x is the fraction of the longitudinal momentum carried by the parton) that appears to diverge (grow) with decreasing x. There is however, a characteristic momentum scale, termed the saturation scale, below which the gluon density saturates. This effect sets in when x becomes small

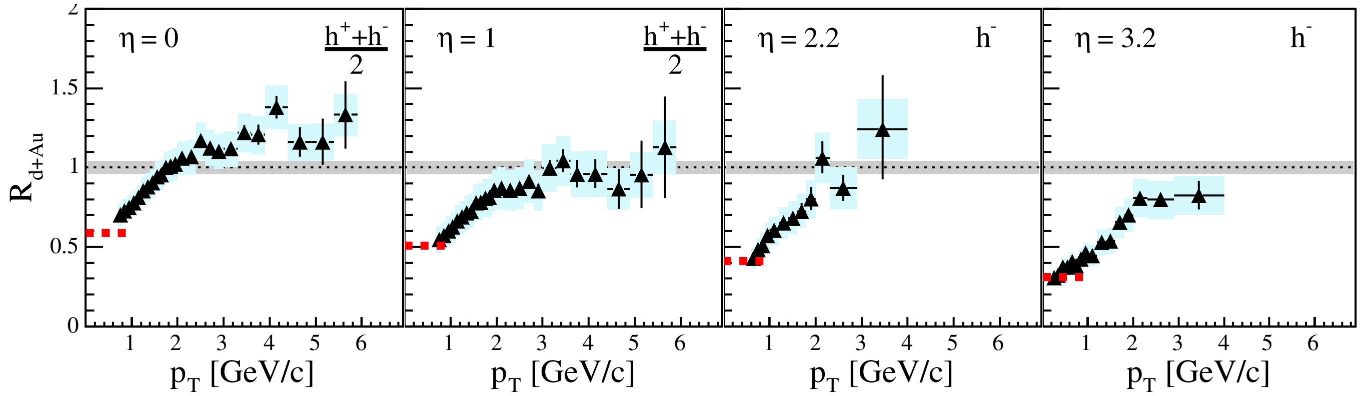

Fig. 8. Evolution of the nuclear modification factors measured by BRAHMS for the 10% most central d+Au collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$, as a function of pseudorapidity η [28]

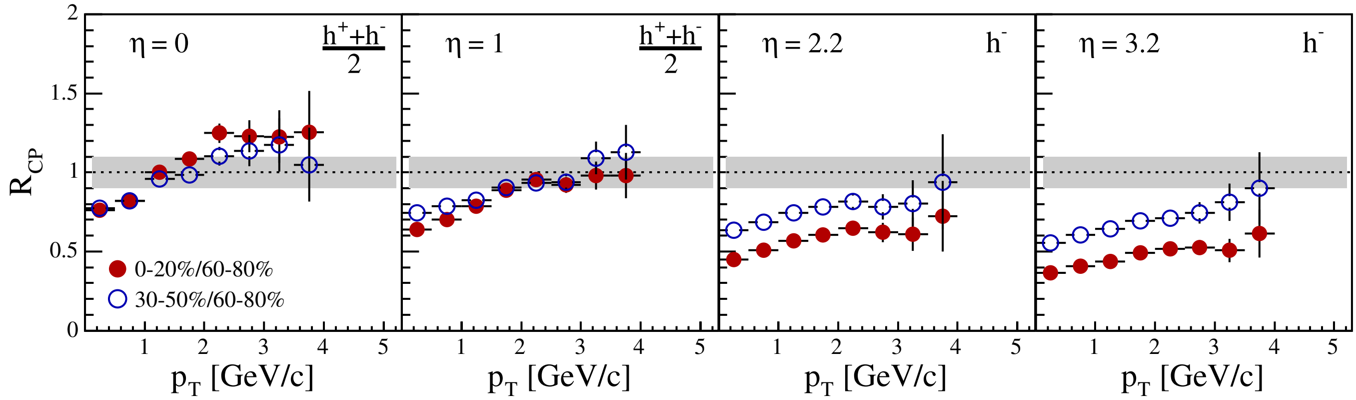

Fig. 9. Central to peripheral ratios R_{CP} as a function of pseudorapidity measured by BRAHMS for d+Au collisions at the RHIC top energy [28]. The filled circles represent the central-to-peripheral (0–20% over 60–80%) ratio. The open circles the semicentral-to-peripheral (30–50% over 60–80%) ratio. The shaded band around unity indicates the uncertainty associated with the values of the number of binary collisions at the different centralities

and the associated gluon wave length ($\frac{1}{m_p x}$) increases to nuclear dimensions. In such a regime gluons may interact and form a coherent state reminiscent of a Bose-Einstein condensate. Early indications for the formation of such non-linear QCD systems have been found in lepton-hadron or lepton-nucleus collisions at HERA [31] and have been described by the so called "Geometric Scaling" model [32].

The density of gluons $\frac{dN_g}{d(ln(1/x))} \sim \frac{1}{\alpha_s}$ in such a saturated system is high, since α_s, the strong interaction running coupling constant, decreases as the energy increases. The system can therefore be described as a (semi)classical field, and techniques borrowed from field theory can be employed to find the functional form of the parton distributions in the initial state [34].

Saturation in the wave function sets in for gluons with transverse momentum $Q^2 < Q_s^2 = A^{\frac{1}{3}}(\frac{x_0}{x})^\lambda \sim A^{\frac{1}{3}}e^{\lambda y}$. A value of $\lambda \sim 0.3$ is estimated from fits to HERA data [33]. The dependence of the saturation scale Q_s on the mass number of the target and rapidity suggests that saturation effects can be best studied at RHIC with heavy nuclei at large rapidities, although larger beam energy will also make it possible in the future to study low x phenomena in nuclear collisions closer to midrapidity.

Collisions between heavy ions with $E = 100\,\text{AGeV}$ may therefore provide a window to the study of low–x gluon distributions of swiftly moving nuclei. In particular, head-on collisions between deuterons and gold nuclei in which hadrons, produced mostly in quark-gluon collisions, are detected, close to the beam direction but away from the direction of motion of the gold nuclei, allow the low–x components (mostly gluons) of the wave function of the gold nuclei to be probed. At forward rapidity, BRAHMS can probe the region of $x < 0.01$.

The centrality dependence of the nuclear modification factors provides additional information on the mechanism underlying the observed suppression. Figure 9 shows the R_{CP} factors, defined as the ratios of the nuclear spectra for central (0–20%) and peripheral (60–80%) collisions (closed points) and for semicentral (30–50%) and peripheral collisions (open points), suitably scaled by the corresponding number of binary collisions, versus p_T and η. There is a substantial change in R_{CP} as a function of η. At $\eta = 0$ the central-to-peripheral collisions ratio is larger than the semicentral-to-peripheral ratios suggesting an increased Cronin type multiple scattering effect in the more violent collisions. In contrast, the ratio of the most central collisions relative to the peripheral, as compared to the semicentral-to-peripheral, is the most suppressed at forward rapidities, suggesting a suppression mechanism that scales with the centrality of the collisions.

The observed suppression of yields in d+Au collisions (as compared to pp collisions) has been qualitatively predicted by various authors [35–38], within the Color Glass Condensate scenario. Recently, a more quantitative calculation has been carried out [39] which compares well with the data. Other authors [40,41] have estimated the nuclear modification factors based on a two component model that includes a parametrization of perturbative QCD and string breaking as a mechanism to account for soft coherent particle production using HIJING. HIJING uses the mechanism of gluon shadowing to reduce the number of gluon-gluon collisions and hence the multiplicity of charged particles a lower p_T. HIJING has been shown to give a good description of the overall charged particle multiplicity in d+Au collisions. A similar approach was followed by Barnafoldi et al. [42]. Vogt has used realistic parton distribution functions and parametrizations of nuclear shadowing to give a reasonable description of the minimum bias data though not of the centrality dependence [43]. Guzey et al. have suggested that isospin effects may increase the suppression [44]. Hwa et al. have reproduced the measured nuclear modification factors in calculations based on quark recombination in the final state [45].

The high p_T suppression in Au+Au collisions at large rapidities discussed earlier suggests that there may be two competing mechanisms responsible for the observed high p_T suppression in energetic Au+Au collisions, each active in its particular rapidity window. It has been proposed [6] that the high p_T suppression observed around midrapidity reflects the presence of an incoherent (high temperature) state of quarks and gluons while the high p_T suppression observed at forward rapidities bears evidence of a dense coherent partonic state. Clearly, additional analysis of recent high statistics data for Au +Au collisions at high rapidities, as well as firmer theoretical predictions are needed to understand the quantitative role of gluon saturation effects in energetic nucleus-nucleus collisions.

6 Concluding remarks

High p_T suppression at RHIC has been a major discovery in the study of relativistic heavy ion collisions at RHIC. BRAHMS has demonstrated that high p_T suppression is not a phenomenon limited to the midrapidity region explored in Au+Au collisions. Instead, high p_T suppression is observed from midrapidity to forward rapidity, as far forward as $\eta = 3.4$, in collisions between heavy nuclei (Au+Au) as well as in collisions between light nuclei and heavy nuclei (d+Au). The suppression observed in d+Au collisions is on the 'Au shadow side' and in general agreement with arguments based on the Color Glass Condensate model, in the sense that this particular observation probes the low x gluon content of the gold nucleus. If that is the case, it is not clear what to expect for Au+Au collisions at forward rapidity. Will there be suppression because forward scattered particles originate from partonic collisions with a low x partner or will the signal be washed out so that the nuclear modification factor is around unity or even larger due to final state parton scattering? The recent results from BRAHMS, shown in this paper, indicate that high p_T suppression persists at forward rapidity in Au+Au collisions. Indeed, it should be noted that the R_{CP} factors measured in Au+Au collisions and for d+Au collisions have a striking similarity. So the central questions are obvious: is there a common mechanism that leads to high p_T suppression in both reactions at forward rapidity and are there two distinct physical mechanisms that underly the high p_T suppression as seen as a function of rapidity in Au+Au reactions?

Acknowledgements. This work was supported by the Div. of Nuclear Physics of the Office of Science of the U.S. Department of Energy under contracts DE-AC02-98-CH10886, DE-FG03-93-ER40773, DE-FG03- 96-ER40981, and DE-FG02-99-ER41121, the Danish Natural Science Research Council, the Research Council of Norway, the Jagiellonian University Grants, the Korea Research Foundation Grant and the Romanian Ministry of Education and Research (5003 /1999, 6077/2000). We thank the staff of the Collider-Accelerator Division at BNL for their excellent and dedicated work to deploy RHIC and their support to the experiment.

References

1. I. Arsene et al., BRAHMS Coll., nucl-ex/0410020.
2. B.B. Back et al., PHOBOS Coll., nucl-ex/0410022.
3. K. Adcox et al., PHENIX Coll., nucl-ex/0410033.
4. J. Adams et al., STAR Coll., nucl-ex/0501009.
5. BRAHMS: http://www4.rcf.bnl.gov/brahms/WWW/brahms.html; PHENIX: http://www.phenix.bnl.gov/; PHOBOS: http://www.phobos.bnl.gov/; STAR: http://www.star.bnl.gov/.
6. M. Gyulassy, L. McLerran, nucl-th/0405013.
7. E. V. Shuryak, hep-ph/0405066.
8. P. Jacobs and X. Wang, hep-ph/0405125.
9. I. Arsene et al., BRAHMS collaboration, Phys. Rev. Lett **91**, 072305 (2003).
10. J. Adams et al., Phys. Rev. Lett. **91**, 172302 (2003).
11. S. S. Adler et al., Phys. Rev. **C69**, 034910 (2004).
12. C. E. Jørgensen et al., BRAHMS collaboration, Nucl. Phys. A715 741c (2003).
13. J. W. Cronin et al., Phys. Rev. **D11** 3105 (1975).
14. A. Accardi, hep-ph/0212148.
15. D. Kharzeev, E. Levin, L. McLerran, Phys. Lett. **B561**, 93 (2003) and references therein.
16. D. d'Enterria, Phys. Lett. **B596**, 32 (2004).
17. J. Adams et al., Phys. Rev. Lett. **91**, 072304 (2003).
18. B. B. Back et al. nucl-ex/0302015 and Phys. Rev. Lett. **91**, 072302 (2003).
19. S. S. Adler et al., Phys. Rev. Lett. **91**, 072303 (2003).
20. Z. Yin, BRAHMS Collaboration, J. Phys. **G30**, S983 (2004).
21. B. Alper et al., Nucl. Phys. **B100**, 237 (1975).

22. P. Abreu et al., Eur. Phys. J. **C17**, 207 (2000).
23. R. C. Hwa and C. B. Yang, Phys. Rev. **C67**, 034902 (2003).
24. R. J. Fries et al., Phys. Rev. **C68**, 044902 (2003).
25. V. Greco, C. M. Ko and P. Levai, Phys. Rev. Lett. **90**, 202302 (2003).
26. BRAHMS Collaboration, in preparation; C.Ekman, Ph.D. Thesis, University of Copenhagen, 2004.
27. B. Back et al., submitted to Phys. Rev. Lett. (nucl-ex/0405003).
28. I. Arsene et al., BRAHMS collaboration, Phys. Rev. Letters, 93, 242303 (2004).
29. D. Kharzeev, E. Levin and L. McLerran Phys. Lett. **B561** 93-101 (2003).
30. L. V. Gribov, E. M. Levin and M. G. Ryskin, Phys. Rept. **100**, 1 (1983), A. H. Mueller and Jian-wei Qiu, Nucl. Phys. **B268**, 427 (1986), L.N. Lipatov, Sov. J. Nucl. Phys. **23** (1976), 338, E.A. Kuraev, L.N. Lipatov and V.S. Fadin, Sov. Phys. JETP 45 (1977), 199G Ya.Ya. Balitsky and L.N. Lipatov, Sov. J. Nucl. Phys. **28**, 822 (1978), L. D. McLerran and R. Venugopalan, Phys. Rev. **D49**, 2233(1994) 3352 (1994); D50, 2225 (1994), E. Iancu, A. Leonidov and L. D. McLerran, Nucl. Phys. **A692**, 583 (2001), E. Iancu and L. McLerran, Phys. Lett. **B510**, 145 (2001).
31. J. Breitweg et al. Eur. Phys. J. C7 609-630, (1999); ZEUS Collaboration, J. Breitweg et al., Phys. Lett. **B487** (2000) 53; ZEUS Collaboration, S. Chekanov et al., Eur. Phys.J. **C21** (2001) 443; H1 Collaboration, C. Adloff et al., Eur. Phys. J. **C21** (2001) 33.
32. A. M. Staśto, K. Golec-Biernat, and J. Kwieciński Phys. Rev. Lett. 86 596-599 (2001).
33. J. Breitweg et al., Phys. Lett. **B407**, 432 (1997).
34. L. McLerran and R. Venugopalan, Phys. Rev. **D49**, 2233(1994); Phys. Rev. **D59**, 094002 (1999); E. Iancu, A. Leonidov and L. D. McLerran, Nucl. Phys. **A692**, 583 (2001), and references therein.
35. A. Dumitru and J. Jalilian-Marian, Phys. Lett. B **547**, 15 (2002)
36. J. Jalilian-Marian, Y. Nara and R. Venugopalan, Phys. Lett. B **577**, 54 (2003); A. Dumitru and J. Jalilian-Marian Phys. Rev. Lett. 89 022301 (2002).
37. R. Baier et al. Phys. Rev. D68, 054009, (2003); J. Albacete, et. al., hep-ph/0307179.
38. D. Kharzeev, Y. V. Kovchegov and K. Tuchin Phys. Rev. D68, 094013, (2003); D. Kharzeev, E. Levin and L. McLerran, Phys. Lett. B **561**, 93 (2003).
39. D. Kharzeev, Y. V. Kovchegov, and K. Tuchin, hep-ph/0405045.
40. I. Vitev, Phys. Lett. **B562**, 36 (2003)
41. Xin-Nian Wang, Phys. Lett. **B565**, 116-122, (2003).
42. G.G. Barnafoldi et al., J. Phys. G**30** S1125, (2004).
43. R. Vogt hep-ph/0405060.
44. V. Guzey, M. Strickman and W. Vogelsang, Phys. Lett. B**603** 173, (2004).
45. R. Hwa, C.B. Yang and R. J. Fries, nucl-th/0410111; R. Hwa and C.B. Yang. Phys. Rev. C**70**, 024905, (2004).