

# The rapidity and centrality dependence of nuclear modification factors at RHIC — what does bulk particle production tell us about the nuclear medium?

**B. H. Samset** for the BRAHMS Collaboration

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

<sup>1</sup> Brookhaven National Laboratory, Upton, New York 11973

<sup>2</sup> Institut de Recherches Subatomiques and Université Louis Pasteur, Strasbourg, France

<sup>3</sup> Institute of Nuclear Physics, Krakow, Poland

<sup>4</sup> Smoluchowski Inst. of Physics, Jagiellonian University, Krakow, Poland

<sup>5</sup> Johns Hopkins University, Baltimore 21218

<sup>6</sup> New York University, New York 10003

<sup>7</sup> Niels Bohr Institute, Blegdamsvej 17, University of Copenhagen, Copenhagen 2100, Denmark

<sup>8</sup> Texas A&M University, College Station, Texas, 17843

<sup>9</sup> University of Bergen, Department of Physics, Bergen, Norway

<sup>10</sup> University of Bucharest, Romania

<sup>11</sup> University of Kansas, Lawrence, Kansas 66049

<sup>12</sup> University of Oslo, Department of Physics, Oslo, Norway

(Dated: March 31, 2004)

The BRAHMS experiment at RHIC has measured the production of charged hadrons as a function of pseudorapidity and transverse momentum in  $Au + Au$ ,  $d + Au$  and  $p + p$  collisions at a common energy of  $\sqrt{s_{NN}} = 200$  GeV, and from these spectra we construct the nuclear modification factors for both “hot” and “cold” nuclear matter.

In this contribution I will show how these factors evolve with pseudorapidity and collision centrality. We see a Cronin-like enhancement in  $d + Au$  collisions at midrapidity, going to a strong suppression at  $\eta \gtrsim 2$ . In central  $Au + Au$  collisions we find a suppression both at mid- and forward rapidities that vanishes for peripheral collisions. We interpret this as signs of several different medium related effects modifying bulk particle production in  $Au + Au$  and  $d + Au$  collisions at RHIC energies.

The processes that govern bulk particle production in ultrarelativistic nucleus-nucleus collisions [1] are not well understood. Exploring this experimentally is one of the goals of the RHIC accelerator at Brookhaven National Lab., and of the BRAHMS experiment in particular. RHIC has now collided gold nuclei on gold ( $Au + Au$ ), protons on protons ( $p + p$ ) and deuterons on gold ( $d + Au$ ) at the same center-of-mass energy of  $\sqrt{s_{NN}} = 200$  GeV, allowing us to compare the complex dynamics of a heavy-ion collision to the comparatively simple case of a nucleon-nucleon interaction, and the particle production mechanisms in hot nuclear matter (central  $Au + Au$ ) to those in a cold nuclear medium ( $d + Au$ ).

The hope is that clear, systematic effects will emerge from these comparisons that will tell us about the gross properties of the system created in these collisions. Below we present BRAHMS data on charged hadron production from all three colliding systems, and construct the nuclear modification factors  $R_{AuAu}$  and  $R_{dAu}$  that are sensitive to such medium-related effects. We will

show that bulk properties do indeed emerge when comparing both extended systems to  $p + p$  collisions, and indicate how this can be interpreted in terms of several distinct mechanisms for modification of particle production in different parts of  $\eta - p_T$  space. Here  $p_T$  is the particle transverse momentum,  $\eta = -\ln(\tan \frac{\theta}{2})$  its pseudorapidity and  $\theta$  the angle of the particles momentum relative to the beamline.

The BRAHMS experimental setup [2, 3], one of four detectors at RHIC, is a two-arm hadronic magnetic spectrometer with three main parts – see Figure 1. The first is a set of event characterization detectors including Cherenkov scintillator arrays for multiplicity and collision point determination (BB), silicon strips and plastic scintillator tiles for particle multiplicity and centrality determination (SMA & TMA), and two zero-degree calorimeters (ZDC) used for collision point, centrality and cross section determination.

Secondly there is a midrapidity spectrometer arm (MRS) that can be positioned at angles from 90 to 30 degrees with respect to the beam axis. The MRS con-

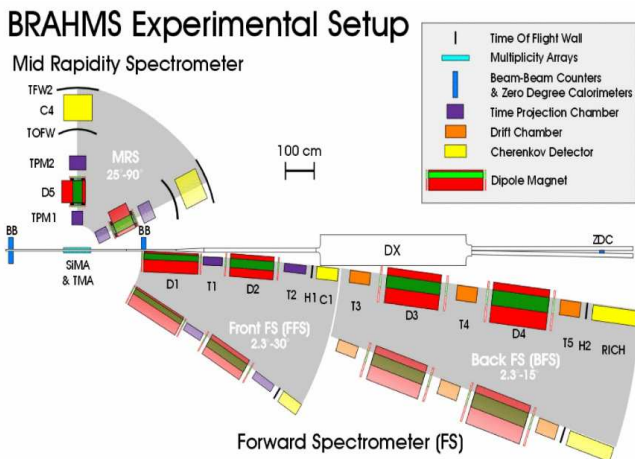


FIG. 1: The BRAHMS experiment at RHIC. For details, refer to [2].

sists of two TPCs (TPM1, TPM2) and a dipole magnet for tracking and momentum determination, and a time-of-flight wall (TOFW) for particle identification. The MRS can identify  $\pi^\pm$  and  $K^\pm$  up to  $p = 2.0$  GeV/c and  $p/\bar{p}$  up to  $p = 3.0$  GeV/c. At a single angle and magnetic field setting the solid angle coverage of the MRS is quite limited, but by rotating the spectrometer and changing the field of the bending magnet a large coverage in rapidity and transverse momentum is achieved.

Finally, the part that makes BRAHMS unique at RHIC is the forward rapidity spectrometer arm (FS), which rotates from 20 degrees (front part only) to 4 degrees relative to the beam axis. It consists of two TPCs and three Drift Chambers (T1-T5), four dipole magnets (D1-D4), one threshold and one ring-imaging Cherenkov counter (C1 and RICH). The full FS allows identification of pions, kaons and protons up to 20 GeV/c. As for the MRS, the limited geometrical acceptance is extended by rotating the FS and changing the fields. All in all BRAHMS can identify pions from midrapidity and up to  $y \approx 3.5$ , with the RHIC beam rapidity at  $y_b = 5.3$ .

For the  $p + p$  and  $d + Au$  data sets taken in 2003, the above setup was augmented by two sets of plastic scintillator rings around the beampipe (not shown in Fig. 1, see Ref. [4] for a description), four rings on each side of the nominal interaction point. These counters provided event triggering, interaction point and cross section measurements in the relatively low multiplicity events from these collision systems. For further details of the BRAHMS experimental setup, see Ref. [2]. Also note that for the  $d + Au$  data presented here, the spectrometers saw only the deuteron fragmentation side of the collision and we consequently define this to have positive rapidity.

Figures 2 and 3 [5, 6] show BRAHMS charged hadron spectra from  $Au + Au$ ,  $d + Au$  and  $p + p$  collisions at  $\sqrt{s_{NN}} = 200$  GeV for a number of pseudorapidities and centrality classes. Measuring charged particle production with BRAHMS is a multi-step process due to the lim-

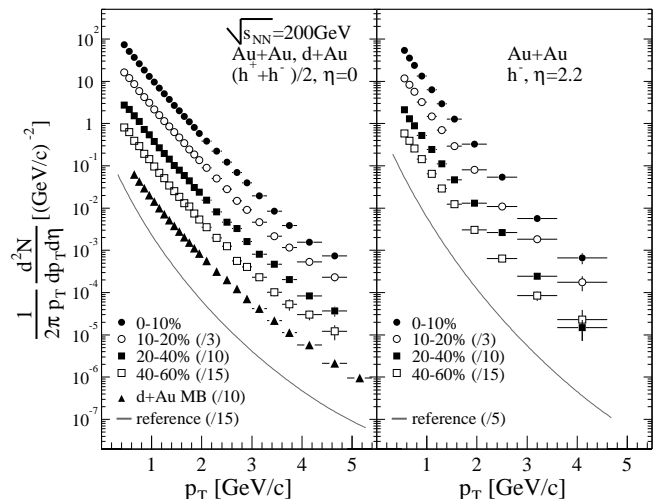


FIG. 2: Invariant spectra of charged hadrons from  $Au + Au$  collisions at  $\sqrt{s_{NN}} = 200$  GeV for pseudorapidities  $\eta = 0$  (left panel) and  $\eta = 2.2$  (right panel). Various centrality cuts are shown for  $Au + Au$ . The  $p + \bar{p}$  reference spectra (appropriately acceptance scaled) are shown for comparison. The left panel also shows the  $d + Au$  spectrum. For clarity, some spectra have been divided by the indicated factors. Published in [5].

ited acceptance — total  $p_T$  spectra of charged hadrons at one pseudorapidity [5, 7, 8] as shown are constructed by combining several such settings. Our spectra have been corrected for finite geometrical acceptance as well as trigger and detector efficiency using a GEANT-based Monte Carlo simulation of the entire detector setup. Details of the analysis can be found in Refs. [5, 6] [22].

Our aim is to extract any effects of a nuclear medium on the total particle production, by comparing to elementary nucleon-nucleon collisions where we do not expect such a medium to be produced. We construct the Nuclear Modification Factor  $R_{AB}$ :

$$R_{AB} \equiv \frac{1}{\langle N_{coll}^{AB} \rangle} \frac{N_{AB}(p_T, \eta)}{N_{pp}(p_T, \eta)}. \quad (1)$$

where A and B are the colliding systems (i.e.  $Au$  or  $d$ ) and  $\langle N_{coll}^{AB} \rangle$  is the average number of binary nucleon-nucleon collisions in such an event as estimated by the Glauber model.  $N_{AB}$  and  $N_{pp}$  are the charged hadron productions in the  $A+B$  and  $p + p$  collisions respectively, taken at the same transverse momentum  $p_T$  and pseudorapidity  $\eta$ .

If there were no medium effects, i.e. if a nucleus-nucleus collision could be viewed simply as individual nucleon-nucleon collisions, then we would expect an  $R_{AB}$  factor of unity above a certain  $p_T$  threshold and decreasing smoothly below. The latter is because at low  $p_T$  we expect a scaling of particle production with the number of participating nucleons  $\langle N_{part} \rangle$  rather than  $\langle N_{coll} \rangle$ . Both for  $Au + Au$  and  $d + Au$  collisions, we see strong deviations from this simple behavior.

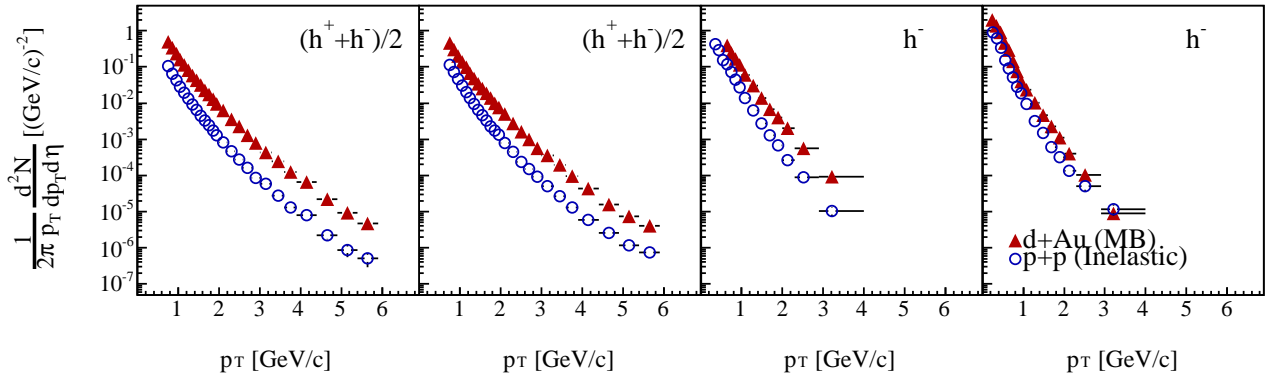


FIG. 3: Invariant yield distributions for charged hadrons produced in  $d + Au$  and  $p + p$  collisions at  $\sqrt{s} = 200$  GeV at pseudorapidities  $\eta = 0, 1.0, 2.2, 3.2$ . Published in [6].

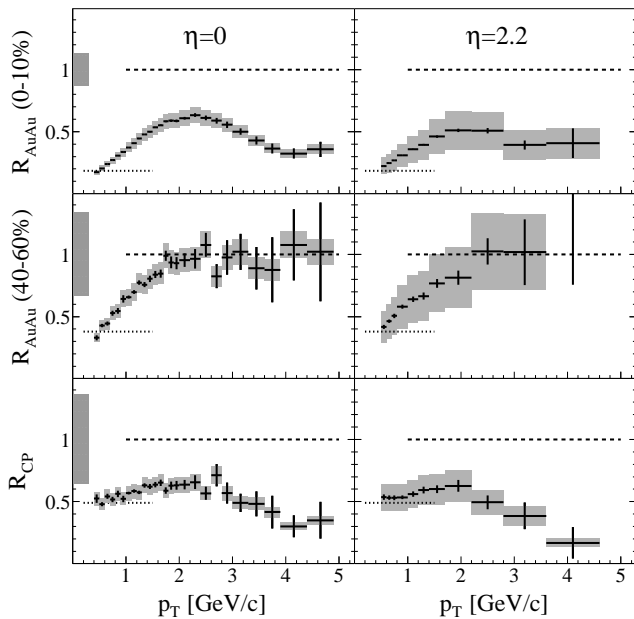


FIG. 4: Top row: Nuclear modification factors  $R_{AuAu}$  as a function of transverse momentum for  $Au + Au$  collisions at  $\eta = 0$  and  $\eta = 2.2$  for the 0 – 10% most central collisions. Middle row: as top row, but for centralities 40 – 60%. Bottom row: ratio of the  $R_{AuAu}$  factors for the most central and most peripheral collisions at the two rapidities. The dotted and dashed lines show the expected value of  $R_{AuAu}$  using a scaling by the number of participants and by the number of binary collisions, respectively. Error bars are statistical. The gray bands indicate the estimated systematic errors. The gray band at  $p_T = 0$  is the uncertainty on the scale. Published in [5].

In central  $Au + Au$  collisions, where we expect to produce “hot” nuclear matter (see e.g. [9]), we see a strong suppression of particle production relative to  $p + p$  scaling — see Fig. 4 [5], upper left panel. The expected rise at low  $p_T$  is seen up to  $p_T \approx 2$  GeV/c, but then  $R_{AuAu}$  seems to level off at a value well below unity and subse-

quently decrease again. This behavior is in sharp contrast to what was seen at SPS energies, i.e.  $Pb + Pb$  collisions at center-of-mass energies of up to  $\sqrt{s_{NN}} = 17$  GeV, where one observed a strong enhancement of  $R_{PbPb}$ , dubbed the Cronin enhancement [10], interpreted as an initial state broadening of the distribution of quark momenta ( $k_T$  broadening). We also see (middle left panel of Fig. 4) that for more peripheral  $Au + Au$  collisions the suppression vanishes and we reach the behavior expected from  $p + p$  scaling. This indicates that we may have an onset of a new mechanism for suppressing high- $p_T$  particle production between top SPS and RHIC energies, and between peripheral and central collisions at RHIC — i.e. in the collisions where we reach the highest energy densities [23]. The behavior reported here has also been seen by the other RHIC experiments [11].

To extend this picture, BRAHMS has also measured  $R_{AuAu}$  from central collisions at a more forward rapidity  $\eta \approx 2.2$ , shown in the upper right panel of Fig. 4. The suppression seen at midrapidity is still present here, showing that if it is due to some final-state mechanism prevalent in the fireball, the medium that has this suppressing property must extend out at least two units of pseudorapidity away from  $\eta = 0$ . Again, the suppression vanishes for more peripheral collisions.

Using the above definition of the nuclear modification factor we need to compare separate measurements of nucleus–nucleus and  $p + p$  collisions, introducing additional systematic errors. To avoid this problem, we can approximate  $p + p$  collisions by peripheral nucleus–nucleus collisions scaled to  $1/\langle N_{coll}^{Periph} \rangle$  and rather construct the ratio of central to peripheral collisions  $R_{CP}$ :

$$R_{CP} \equiv \frac{1/\langle N_{coll}^{Central} \rangle N_{AB}^{Central}(p_T, \eta)}{1/\langle N_{coll}^{Periph} \rangle N_{AB}^{Periph}(p_T, \eta)}. \quad (2)$$

The bottom panels of Fig. 4 show the ratio  $R_{CP}$  for  $Au + Au$  collisions, using the centrality classes 0-10% and 40-60%. Again we see a clear saturation of the modification factor at a value below unity and a subsequent further drop as  $p_T$  increases, showing that there is an attenuating mechanism present in the central collisions

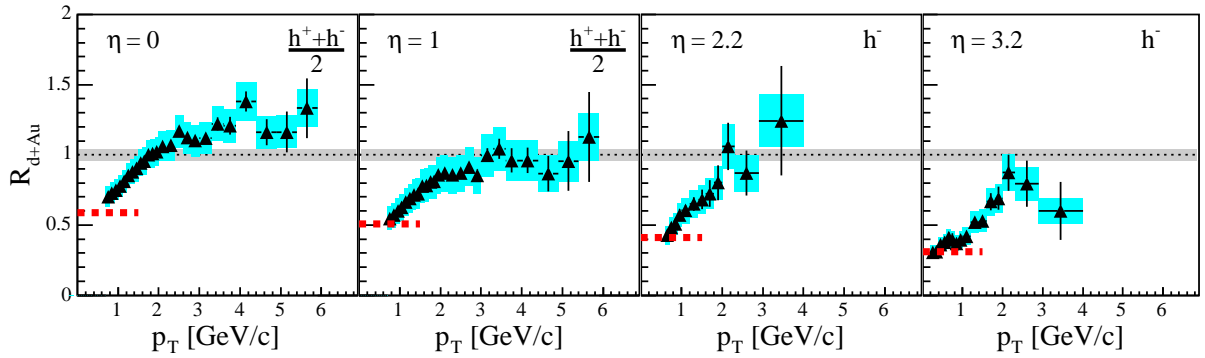


FIG. 5: Nuclear modification factor for charged hadrons at pseudorapidities  $\eta = 0, 1.0, 2.2, 3.2$ . One standard deviation statistical errors are shown with error bars. Systematic errors are shown with shaded boxes. The vertical shaded band around unity indicates the error on the normalization to  $\langle N_{coll} \rangle$ . Published in [6].

that is either not there or greatly reduced in peripheral collisions.

Figure 5 shows the corresponding ratios  $R_{dAu}$  for minimum-bias  $d + Au$  collisions at  $\sqrt{s_{NN}} = 200$  GeV, for pseudorapidities  $\eta = 0, 1.0, 2.2$  and  $3.2$  [6]. From these collisions at midrapidity, where the size of the fireball is smaller and we don't expect to produce an extended hot and dense medium, we see an enhancement of  $R_{dAu}$  very similar to the Cronin effect, rather than a suppression. However as we move to more forward rapidities, this effect vanishes and at  $\eta \gtrsim 2.2$  we once again see indications of a suppression.

In Figure 6 [6] we have defined three centrality classes (0–20%, 30–50% and 60–80%) and again constructed the ratio  $R_{CP}$  of central (or semi-central) to peripheral collisions. While the factors are approximately equal at midrapidity, there is a clear change of behavior toward higher rapidities as the  $R_{CP}$  for central collisions drops significantly below that for semi-peripheral collisions. This indicates that we have an attenuating effect on forward particle production when the deuteron hits the Lorentz contracted gold nucleus well away from the edges, i.e. where we have a constant, dense nuclear initial state.

To interpret these observations, several distinct mechanisms may be needed. Firstly, the midrapidity enhancement of  $R_{dAu}$  can be explained through a broadening of the initial momentum distributions due to multiple scattering (Cronin enhancement) as for the SPS data, indicating similar initial state medium effects at midrapidity in  $d + Au$  collisions at  $\sqrt{s_{NN}} = 200$  GeV and in  $Pb + Pb$  collisions at  $\sqrt{s_{NN}} = 17$  GeV.

Secondly and more interestingly, the suppression of high- $p_T$  particle production in central  $Au + Au$  collisions is indicative of partonic energy loss due to gluonic bremsstrahlung in a colored medium. In other words, the partons lose energy through gluonic interactions because they traverse a medium with a high density of color charges. The fact that the suppression disappears in more peripheral collisions and turns to a Cronin-like en-

hancement for central or min-bias  $d + Au$  collisions where we do not expect to produce a deconfined medium, indicates that this is indeed a final-state effect and not just a consequence of the high-energy nuclear initial state. Results from the STAR experiment on strong suppression of far-side jets in central  $Au + Au$  collisions extend and support this conclusion [12].

Thirdly, the transition from a Cronin-like enhancement at midrapidity to a clear suppression with increasing rapidity in  $d + Au$  collisions indicates yet another mechanism, related to the nuclear initial state. Recent theoretical work has predicted an effect similar to this on the basis of gluon-saturation phenomena, a scenario known as the Color Glass Condensate [13–15]. It is based on the observation from deep-inelastic scattering at HERA [16] that as the momentum transfer between the electron and the struck parton increases, the observed gluon density function seems to diverge at small values of  $x$ , i.e. there is a high density of so-called “wee gluons” carrying a very small fraction  $x$  of the total nucleon momentum. Due to the finite size of a nucleon, one can assume that at some density these small- $x$  gluons will start to fuse due to gluonic self-interaction. For a nuclear system at high energies, one can then predict a transition to a condensed state of “colored glass” — a state with a high density of color charges that evolves slowly compared to the timescale of an ultrarelativistic heavy-ion collision ( $\approx 1 fm/c$ ), and with the gluonic wavefunctions extended in the transverse directions. The transverse momentum scale  $Q_s^2$  for the onset of this saturation in a nuclear collision can be shown to depend on the gluon density and thus on the number of participating nucleons, and is connected with the rapidity of measured particles by  $Q_s^2 \sim A^{\frac{1}{3}} e^{\lambda y}$  (see e.g. [14]), where  $\lambda \sim 0.2 - 0.3$  is obtained from fits to HERA data. At RHIC and for the  $p_T$  range covered by BRAHMS, the onset of saturation is predicted [15] to occur between rapidities 0 and 3, in agreement with our experimental observations.

However, in this part of phase space nuclear shadowing [1] is also important. The shadowing effect, observed

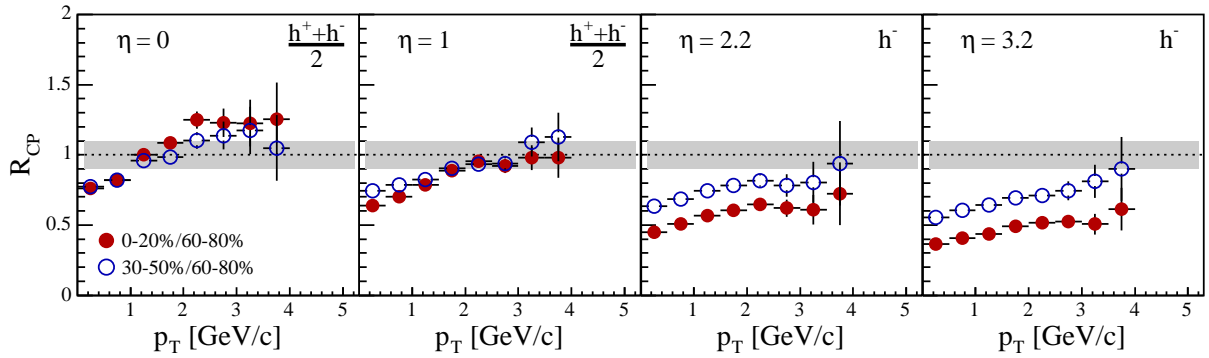


FIG. 6: Central (full points) and semi-central (open points)  $R_{CP}$  ratios from  $d + Au$  collisions (see text for details) at pseudorapidities  $\eta = 0, 1.0, 2.2, 3.2$ . Published in [6].

e.g. in muon–nucleus interactions [17], is a depletion of low- $x$  partons in nuclear systems. It has been interpreted both as destructive interference reducing the probability of interactions with partons at the back of an incoming nucleus, and as gluon recombination at high densities but without the condensation mechanism discussed above. This effect is certainly present in our data, as shown by the observation that simulations using the HIJING event generator which includes shadowing well reproduces BRAHMS data on total charged particle production at all accessible pseudorapidities [4]. A recent discussion in Ref. [18] indicates that such effects may not be enough to describe the results presented here, but this discussion relies on extrapolated fits to RHIC midrapidity data. More data at forward rapidities at higher  $p_T$  and subsequent theoretical work is needed to determine whether the observed suppression is indeed partly due to the formation of a Color Glass Condensate in the initial state at RHIC. Also, a better treatment of soft beam fragmentation effects may be needed to properly construct the  $R_{dAu}$  factor.

An effect that may affect the data and that has not been discussed in this contribution is a possible isospin dependent contribution to the nuclear modification factors. A nucleus has both protons and neutrons, and so the denominator in the  $R_{AB}$  factor should be a properly weighted average of  $p + p$ ,  $p + n$  and  $n + n$  collisions. Data on this at SPS energies have been taken by the NA49 collaboration, but are unfortunately not yet published. However, while this may have an effect on the exact shapes of the  $R_{AB}$  factors, the consequences should not be large enough to affect the overall trends presented above.

In conclusion, BRAHMS has measured the charged hadron production from  $Au + Au$ ,  $d + Au$  and  $p + p$  collisions at the same center-of-mass energy of  $\sqrt{s_{NN}} = 200$  GeV, both as a function of pseudorapidity and centrality. Our measurements cover an extensive part of phase space, uniquely including the forward rapidity re-

gion which probes the small- $x$  part of the nuclear structure functions. Through the nuclear modification factors  $R_{AuAu}$  and  $R_{dAu}$  we have uncovered a suppression of high- $p_T$  particle production in  $d + Au$  collisions at forward rapidities, in contrast to the enhancement previously seen at midrapidity. We also find a suppression of  $R_{AuAu}$  at high- $p_T$  in central collisions, extending at least two units of pseudorapidity away from  $\eta = 0$ . The results presented here can be interpreted in terms of a number of medium-related effects modifying bulk particle production:

- A Cronin-like enhancement in  $d + Au$  collisions at midrapidity, due to initial state broadening of intrinsic quark transverse momenta.
- A final-state suppression of high- $p_T$  particle production in central  $Au + Au$  collisions, interpreted as a partonic energy loss due to gluon bremsstrahlung in a deconfined medium with a high density of color charges.
- An initial state suppression of  $R_{dAu}$  at forward rapidities, at least partly due to nuclear shadowing effects depleting the number of small- $x$  partons available for interaction. There may also be an additional suppressing effect from the saturation and condensation of small- $x$  gluons, as predicted in the Color Glass Condensate scenario.

### Acknowledgments

This work was supported by the division of Nuclear Physics of the Office of Science of the U.S. DOE, the Danish Natural Science Research Council, the Research Council of Norway, the Polish State Com. for Scientific Research and the Romanian Ministry of Research.

- 
- [1] X. N. Wang and M. Gyulassy, Phys. Rev. D **44**, 3501 (1991).
- [2] M. Adamczyk *et al.*, BRAHMS Collaboration, Nuclear Instruments and Methods, **A499** 437 (2003).
- [3] C. E. Jørgensen *et al.*, BRAHMS Collaboration, elsewhere in this proceeding.
- [4] I. Arsene *et al.*, BRAHMS Collaboration, arXiv:nucl-ex/0401025. Subm. to Phys. Rev. Lett.
- [5] I. Arsene *et al.*, BRAHMS Collaboration, Phys. Rev. Lett. **91**, 072305 (2003), nucl-ex/0307003.
- [6] I. Arsene *et al.*, BRAHMS Collaboration, arXiv:nucl-ex/0403005. Subm. to Phys. Rev. Lett.
- [7] I. G. Bearden *et al.*, BRAHMS Collaboration, arXiv:nucl-ex/0312023. Subm. to Phys. Rev. Lett.
- [8] D. Ouerdane *et al.*, BRAHMS Collaboration, Nucl. Phys. A **715**, 478 (2003), nucl-ex/0212001.
- [9] L. McLerran, arXiv:hep-ph/0311028.
- [10] D. Antreasyan *et al.*, Phys. Rev. D **19**, 764 (1979).
- [11] K. Adcox *et al.*, PHENIX Collaboration, Phys. Rev. Lett. **88** 022301 (2002); S. S. Adler *et al.*, STAR Collaboration, Phys. Rev. Lett. **89** 202301 (2002); B.B. Back, *et al.*, PHOBOS Collaboration, Phys.Lett. B578, **297** (2004)
- [12] J. Adams *et al.*, STAR Collaboration, Phys. Rev. Lett. **91**, 072304 (2003), nucl-ex/0306024.
- [13] L. McLerran and R. Venugopalan, Phys. Rev. D **49**, 2233(1994), Phys. Rev. D **49**, 3352 (1994), Phys. Rev. D **50**, 2225 (1994), Phys. Rev. D **59**, 094002 (1999); Y. V. Kovchegov, Phys. Rev. D **54**, 5463 (1996), Phys. Rev. D **55**, 5445 (1997).
- [14] E. Iancu and R. Venugopalan, arXiv:hep-ph/0303204.
- [15] D. Kharzeev, Y. V. Kovchegov and K. Tuchin Phys. Rev. D **68**, 094013, (2003), hep-ph/0307037
- [16] 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.
- [17] J. Ashman *et al.*, European Muon Collaboration (EMC), Phys. Lett. B **202**, 603 (1988).
- [18] A. Accardi and M. Gyulassy, nucl-th/0402101.
- [19] C. Albajar *et al.* Nucl. Phys. B**355** 261 (1990).
- [20] J. D. Bjorken, Phys. Rev. D **27**, 140 (1983).
- [21] I. G. Bearden *et al.*, BRAHMS Collaboration, Phys. Rev. Lett. **88**, 202301 (2002), nucl-ex/0112001.
- [22] Figure 2 shows a reference  $p+p$  spectrum from UA(1) [19] scaled to our acceptance, since this was used in determining the  $R_{AuAu}$  factors shown in Fig. 4. The BRAHMS  $p+p$  spectra shown in Fig. 3, determined later, are consistent with the scaled UA(1) result.
- [23] Using Bjorkens estimate for the energy density  $\varepsilon_{Bj} = \frac{1}{\pi R_A^2 \tau} \frac{dE_t}{dy}$  [20] and RHIC measurements of total charged particle density [21], we find that we reach densities of up to  $\varepsilon_{Bj} \sim 10 - 20 \text{ GeV}/\text{fm}^3$  in central  $Au + Au$  collisions at  $\sqrt{s_{NN}} = 200 \text{ GeV}$ . Here,  $\tau$  is the time it takes to get to the densest state, usually set to 1-2 fm/c.