

# On the evolution of the nuclear modification factor $R_{dAu}$ with rapidity and centrality in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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We report on a study of the transverse momentum dependence of nuclear modification factors  $R_{dAu}$  for charged hadrons produced in deuteron + gold collisions at  $\sqrt{s_{NN}} = 200$  GeV, as a function of collision centrality and of the pseudorapidity ( $\eta = 0, 1, 2.2, 3.2$ ) of the produced hadrons. We find a significant and systematic decrease of  $R_{dAu}$  with increasing rapidity. The midrapidity gain enhancement and the forward rapidity suppression are more pronounced in central collisions relative to peripheral collisions. These results are relevant to the study of the possible onset of saturation at RHIC energies.

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Studies of deep inelastic scattering of leptons on hadronic systems (protons and nuclei) have revealed a large component of gluons in the nuclear systems with small fractions of the nucleon momentum (i.e. small Feynman- $x$ ,  $x_F = p_g/p_N$ ) that appears to diverge with decreasing  $x_F$  [1]. However, it has also been suggested that the density of gluons remains finite due to the increased role of gluon-gluon correlations ('gluon fusion'), forcing an upper limit on the total number of highly delocalized small- $x$  gluons [2, 3]. Phenomenological descriptions of HERA and FNAL results [4, 5] based on gluon saturation appear to successfully describe the data. As a consequence, nuclei at high energies may be thought of as highly correlated systems of small- $x$  gluons, and authors McLerran and Venugopalan have from these concepts developed a QCD based theory for dense small- $x$  systems, termed the Color Glass Condensate (CGC) [6].

Collisions between hadronic systems at center-of-mass energies  $\sqrt{s_{NN}} = 200$  GeV at the Relativistic Heavy Ion Collider (RHIC) provide a window on the small- $x$  gluon distributions of swiftly moving nuclei. In particular, collisions between deuterons and gold nuclei

in which hadrons, mostly produced by quark-gluon interactions, are detected close to the beam direction but away from the direction of motion of the gold nuclei, allow for probing the small- $x$  components of the wave function of the gold nuclei. It has been predicted that gluon saturation effects will manifest themselves as a hardening of the transverse momentum spectra of particles produced in the nuclear collisions [6–8]. The momentum transfer scale for the onset of gluon saturation depends on the gluon density and thus on the number of participating nucleons, and is connected with the rapidity of measured particles by  $Q_s^2 \sim A^{\frac{1}{3}} e^{\lambda y}$ . Here  $\lambda \sim 0.2 - 0.3$  is from an empirical parametrization of the saturation scale. Thus saturation effects are most evident at large  $y$  or pseudorapidity  $\eta$ , i.e. at small angles relative to the beam direction.

We report measurements of transverse momentum spectra of hadrons from p+p and d+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV in four narrow pseudorapidity ranges around  $\eta = 0, 1, 2.2$ , and  $3.2$  (where the rapidities of the deuteron and the gold nucleus is  $+5.4$  and  $-5.4$ , respectively). Results around midrapidity have previously

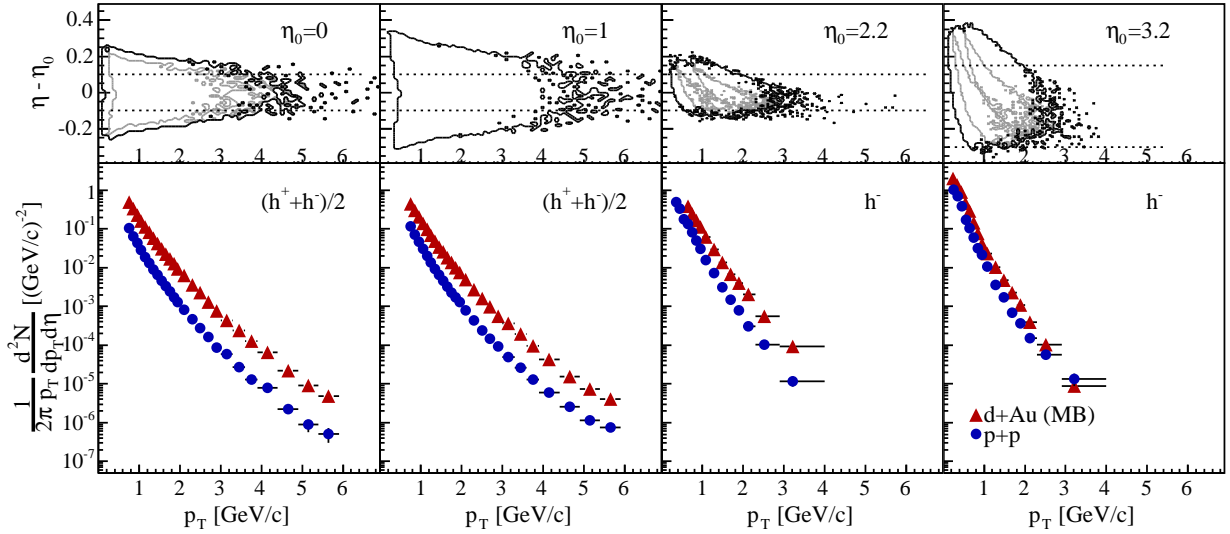


FIG. 1: Bottom row: Invariant yield distributions for charged hadrons produced in d+Au and p+p collisions at  $\sqrt{s} = 200$  GeV at pseudorapidities  $\eta = 0, 1.0, 2.2, 3.2$ . Top row: Outline of the combined acceptance in  $\eta$  vs  $p_T$  of the BRAHMS spectrometers at the various angle and magnetic field settings (shifted in  $\eta$ ). The dotted lines indicate the cuts applied in  $\eta$ .

been reported [9, 10].

The covered pseudorapidity range would correspond to probing the gluon structure of the gold nuclei (with  $p_T = 2$  GeV/c pions) in an  $x$  range from 0.01 to  $4 \times 10^{-4}$ . We compare the yields from d+Au collisions to those from p+p, scaled by the average number of binary collisions  $\langle N_{coll} \rangle$  in a d+Au event.

The data presented here for d+Au and p+p collisions were collected with the BRAHMS detector system, consisting of event characterization detectors and two magnetic spectrometers, the Forward Spectrometer (FS) and the Mid-Rapidity Spectrometer (MRS), which can be rotated in the horizontal plane around the direction defined by the colliding beams. For the present studies the MRS was positioned at 90 and 40 degrees and the FS at 45 and  $-4$  degrees with respect to the beam direction. The orientation of the beams was such that the spectrometers measured particles emitted on the deuteron fragmentation side.

A description of the BRAHMS experimental setup can be found in ref. [11]. The experimental method and analysis techniques employed here are similar to those used for the study of d+Au and Au+Au collisions [10], except that the present data at  $\eta = 2.2$  and  $\eta = 3.2$  were analyzed using the front part of the FS detector systems only.

The minimum bias trigger is estimated to select  $91\% \pm 3\%$  of the d+Au inelastic cross section and  $71\% \pm 5\%$  of the total inelastic proton-proton cross section of 41 mb. Figure 1 shows the invariant yields of charged hadrons obtained from d+Au collisions and p+p collisions in narrow pseudorapidity intervals around  $\eta = 0, 1, 2.2$  and  $3.2$ . The FS was set up to measure negatively charged particles, the spectra at  $\eta = 2.2$  and  $3.2$  are for negative

hadrons only. The top panels show the outline of the corresponding acceptances of the spectrometers for the employed settings, in terms of  $\eta$  and transverse momentum  $p_T$ . Each distribution was constructed from independent measurements at several magnetic field settings, and is corrected for the spectrometer acceptance and tracking efficiency. No corrections for the finite momentum resolution, absorption or weak decays have been applied, but the systematic error on the spectra includes an estimate of the effect of momentum resolution. The momentum resolution of the spectrometers at the maximum magnetic field setting is  $\delta p/p = 0.0077p$  for the MRS and  $\delta p/p = 0.0018p$  for the FS.

In Fig. 2 we compare the d+Au spectra to normalized p+p distributions and show the nuclear modification factor defined by:

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

Inherent in this definition is the assumption that the production of moderately high transverse momentum particles ( $p_T \gtrsim 2$  GeV/c) scales with the mean number of binary collisions  $\langle N_{coll} \rangle$ . For our d+Au minimum-bias sample we estimate  $\langle N_{coll} \rangle = 7.2 \pm 0.3$ , using the HIJING v.1.383 event generator [12] and a GEANT based Monte-Carlo simulation of the experiment. The denominator in Eq.1 refers to the differential yields from inelastic p+p collisions. The measured yields have been corrected for effect of the experimental trigger, estimated using the PYTHIA model to be  $3 \pm 5\%$ , approximately independent on  $p_T$  and  $\eta$ . The presented ratios most systematic errors cancel out. Remaining systematic errors arising from variations in collision vertex distributions, trigger efficiencies and background conditions are esti-

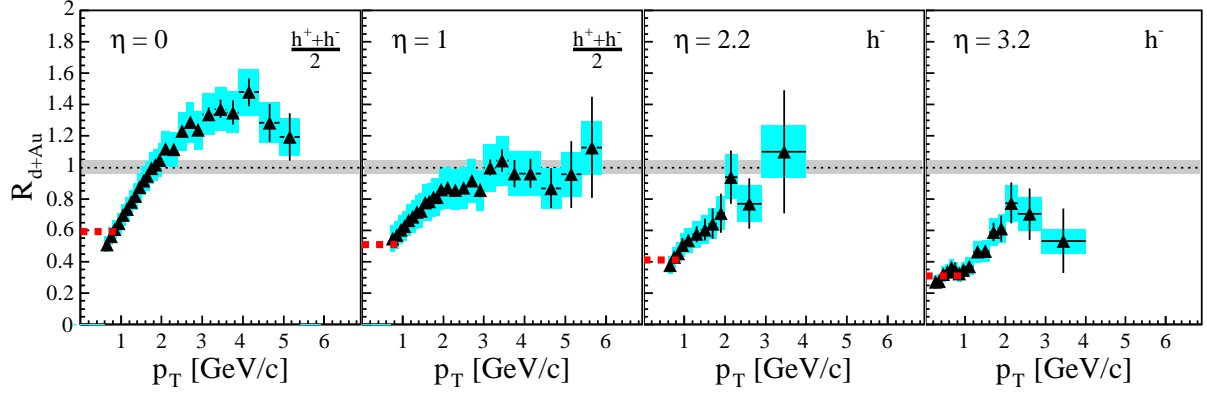


FIG. 2: Nuclear modification factor for charged hadrons at pseudorapidities  $\eta = 0, 1.0, 2.2, 3.2$ . One standard deviation statistical errors are shown with errorbars. Systematic errors are shown with shaded boxes. The vertical shaded band around unity indicates the error on the normalization to  $\langle N_{coll} \rangle$ . Dashed line  $p_T < 1$  shows  $\frac{1}{\langle N_{coll} \rangle} \frac{dN/d\eta(Au)}{dN/d\eta(pp)}$ .

mated to be less than ???% in the MRS and less than ???% in the FS.

Figure 2 reveals a striking variation of the  $R_{dAu}$  as a function of pseudorapidity. At midrapidity,  $R_{dAu}(p_T > 2 \text{ GeV/c}) > 1$  evidencing an enhancement as compared to the binary scaling limit. This so-called Cronin enhancement is attributed to multiple scattering of partons in the initial stages of the collisions resulting in an accumulation of the yield of the final state partons in the  $p_T$  range 2 – 5 GeV/c, at the expense of yield at lower  $p_T$  [13]. At  $\eta = 1$  the Cronin peak is not present and at more forward rapidities ( $\eta = 3.2$ ) the data show a suppression of the hadron yields. A rise with  $p_T$  in the range of 0.5 – 3 GeV/c is observed at all rapidities. There is a strong correlation between the values of the  $R_{dAu}$  at low  $p_T$  and the charged-particle pseudo rapidity densities in d-Au and pp collisions. This is demonstrated in Fig. 2 by the values of  $\frac{1}{\langle N_{coll} \rangle} \frac{dN/d\eta(Au)}{dN/d\eta(pp)}$  (dashed lines at  $p_T < 1$ ) exhibiting a similar suppression with pseudorapidity [19, 20].

Figure 3 shows the ratio  $R_{cp}$  of yields from collisions of a given centrality class (0-20% or 30-50%) to yields from more peripheral collisions (60-80%), scaled by the mean number of binary collisions. The centrality selection is based on charged particle multiplicity in the range  $-2.2 < \eta < 2.2$  as described in [19]. Assuming that the nuclear modification is relatively small in the peripheral collisions the deviation from unity of the  $R_{cp}$  is dominated by the nuclear effects in the more central collisions. The  $R_{cp}$  ratios thus allow for study of the nuclear modification independent of the p+p reference spectrum. The data from the different centrality classes are obtained from the same data run and the ratios shown in Fig. 3 are therefore free of systematic errors due to acceptance variations and run-by-run detector performance. The dominant systematic error comes from the determination of  $\langle N_{coll} \rangle$  in the centrality bins and is assumed to have only a small rapidity dependence. We estimate the mean number of binary collisions in the three centrality classes

to be  $\langle N_{coll}^{0-20\%} \rangle = 13.6 \pm 0.3$ ,  $\langle N_{coll}^{30-50\%} \rangle = 7.9 \pm 0.4$  and  $\langle N_{coll}^{60-80\%} \rangle = 3.3 \pm 0.4$ .

Figure 3 demonstrates that there is a qualitative change in  $R_{cp}$  between  $\eta = 0$  and the forward rapidities. At low pseudorapidity, the central-to-peripheral collisions ratio is larger than the semicentral-to-peripheral ratio, suggesting the increased role of Cronin multiple scattering effects in the more violent collisions. Conversely, at forward pseudorapidities the more central ratio is the most suppressed, indicating a mechanism suppressing the high  $p_T$  yield, that scales with the number of participating nucleons. In Fig. 4 we summarize this behavior of  $R_{cp}$  for the transverse momentum interval  $p_T = 2.5 - 4.0 \text{ GeV/c}$ . A slightly stronger decrease with  $\eta$  is observed for most central  $R_{cp}$  relative to the semicentral  $R_{cp}$  as indicated by the full drawn and dashed lines.

The observed suppression of the high  $p_T$  yield in d+Au collisions (as compared to p+p collisions) has been qualitatively predicted by several authors [14–16] within the framework of the gluon saturation model, although no detailed numerical predictions are yet available. These approaches also predict the observed centrality dependence on pseudorapidity of the high  $p_T$  suppression. Other authors [17, 18] have based their predictions of nuclear modification factors 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 the HIJING microscopic event generator [12]. HIJING uses the effect of ‘gluon shadowing’ as a method of reducing the number of effective gluon-gluon collisions and hence the multiplicity of charged particles at lower  $p_T$ , and also includes an explicit cutoff parameter for mini-jet production. The HIJING model has been shown to give a good description of the overall charged particle distribution in d+Au collisions [19, 21].

In summary, we have observed a significant reduction of the yield of charged hadrons with transverse momenta

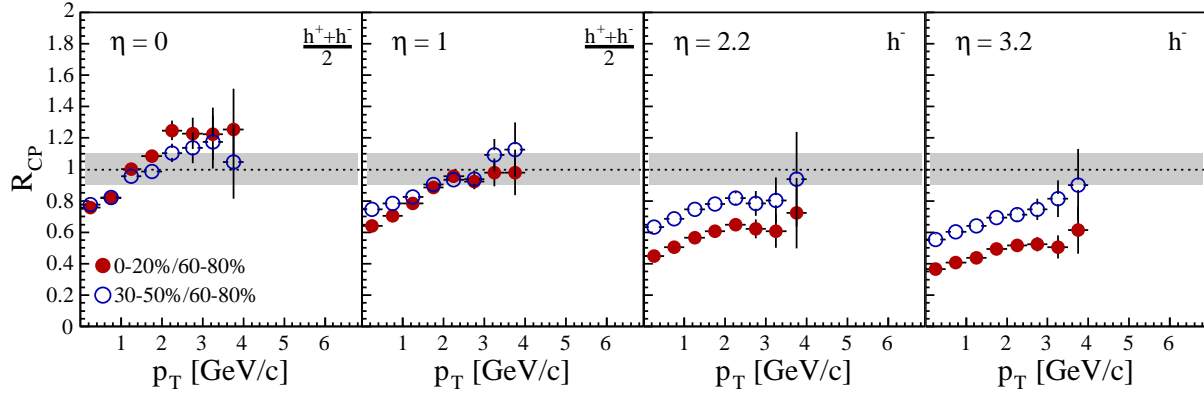


FIG. 3: Central (full points) and semi-central (open points)  $R_{cp}$  ratios (see text for details) at pseudorapidities  $\eta = 0, 1.0, 2.2, 3.2$ .

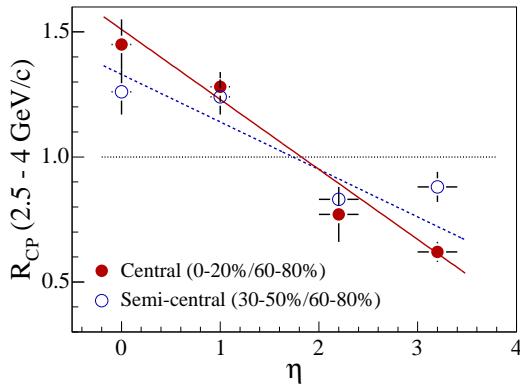


FIG. 4: Evolution of the central/peripheral (full points) and semicentral/peripheral (open points)  $R_{cp}$  ratios on pseudorapidity.

$p_T > 1.5 \text{ GeV/c}$  measured in d+Au collisions, as compared to scaled p+p collisions at forward pseudorapidities. This suppression, which is absent at midrapidity, increases smoothly with pseudorapidity, i.e. as the veloc-

ity of the particles relative to the source increases. At the change from mid- forward rapidities is strong for central collisions than for semi-peripheral collisions, indicating an additional suppression mechanism scaling with pseudorapidity in central d+Au collisions. These results indicate that initial state partonic effects play an important role in the high  $p_T$  suppression at forward rapidities, in contrast to the situation around midrapidity where such effects are found to be unimportant [10, 22]. The theoretical framework for understanding the details of the observed phenomena needs further development, we note that the effects are in qualitative agreement with the prediction of the color glass saturation model, in which the density of small- $x$  gluons is limited by gluon fusion effects.

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