Scanning the Phases of QCD with BRAHMS

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Abstract. BRAHMS has the ability to study relativistic heavy ion collisions from the final freeze-out of hadrons. all the way back to the initial wave-function of the gold nuclei In doing so we can scan various phases of QCD, from a hadron gas, to quark gluon plasma and perhaps the colored glass condensate.

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1. Introduction

The purpose of RHIC is to map the phase structure of QCD. During the first three runs of RHIC the community has concentrated on AuAu, d-Au and pp collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$ in the hope of discovering the quark gluon plasma. A great deal of evidence supporting the creation of such a state in AuAu collisions was presented at this conference. However QCD is a rich theory and it has been suggested that when viewed by a high momentum probe a heavy nucleus may appear to be a sheet of highly correlated gluons that have a glassy structure. Such a state has been named the Color Glass Condensate and may serve as the initial state for high energy heavy ion collisions [1]. This system would rapidly break up into a dense system partons, which one would expect to approch chemical and kinetic equilibrium while rapidly expanding in both the longitudinal and transverse directions. Eventually the partons must hadronize and after further rescattering the hadrons freez-out. In this paper we will attempt to map out this evolution by starting from the final state and working our way backwards.

2. Global Observables

BRAHMS has several detectors designed to measure the multiplicity of charged particles. Figure 1 shows our $dN^{\pm}/d\eta$ results for d-Au collisions for minimum-bias events and 0-30% and 30-60% central events. The third panel shows the ratio of the 0-30% and 30-60% samples normalized for the number of average number of participant nucleons in each sample. The participant ratios appropriate for Au- and d-participant-only scaling indicated by the left and right arrows in panel (c), respectively. Particle production away from mid-rapidity appears to follow the participant scaling of the respective fragment. When we examine our data in the deuteron frame of reference we see very similar yields to lower energy data. This phenomenon is known as “limiting fragmentation”, [2, 3, 4].

The HIJING, AMPT and (improved) saturation models are all are close to the data [5, 6, 7, 8, 9].

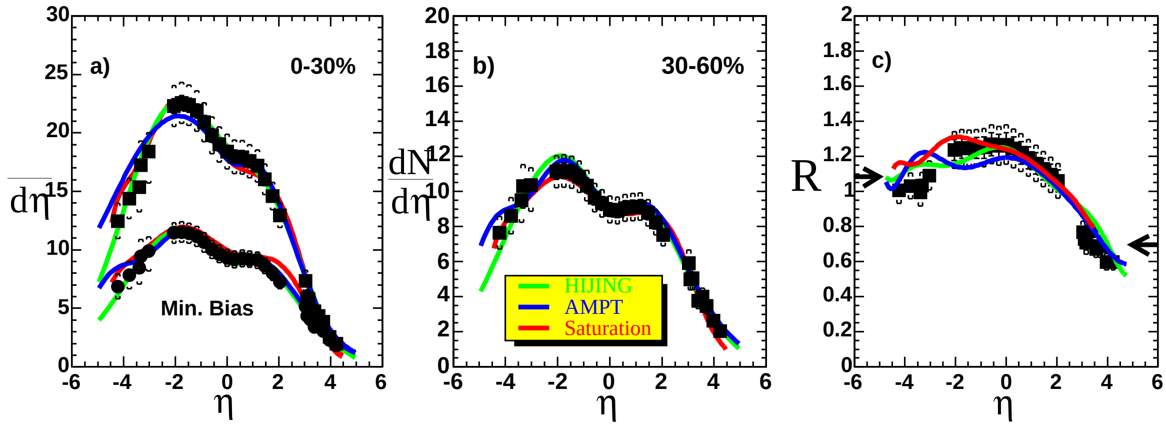

Figure 1. $dN^{\pm}/d\eta$ distributions from d-Au collisions for a) minimum-bias and 0-30% central events and b) 30-60% central events. c) Scaled multiplicity/participant ratio R. The left (right) arrows show corresponding values for Au- (d-) participant scaling. The dashed, solid and dotted curves are the results of the HIJING, AMPT and Saturation models, respectively [5, 6, 7, 8, 9].

3. Particle Spectra

BRAHMS has measured particle spectra over a very wide range of rapidity and p_T. These spectra are summarized in Fig 2, which shows the rapidity densities, dN/dy, and the mean transverse momenta, $\langle p_T \rangle$, for $\pi^{\pm}, K^{\pm}$, p and $\bar{p}$. as a function of rapidity. Both quantities are estimated using fits to the spectra in narrow regions of rapidity. The data have been corrected for the spectrometers acceptance, detector efficiency, multiple scattering and in–flight decay using a Monte-Carlo calculation.

For $\pi^{\pm}, k^{\pm}$ and $\bar{p}$ the yields peak at y=0 and drop significantly at higher rapidities. The π^+ and π^- yields are nearly equal within the rapidity range covered while an excess of K^+ over K^- is observed, increasing with rapidity. Figure 2(b) shows the rapidity dependence of $\langle p_T \rangle$. There is no significant difference between particles and their antiparticles. In general, the rapidity dependence of $\langle p_T \rangle$ increases with mass suggesting that a transverse flow drops with increasing rapidity

Using the proton and antiproton distributions combined with baryon conservation and some assumptions on the neutron and hyperon yields allows us to estimate the total energy liberated by the stopping of the baryons as $\delta E = 25 \pm 1$ TeV, or 75GeV per participating baryon [11, 10]

3.1. Bjorken and/or Landau Hydrodynamics

The idea that relativist heavy ion collisions should be characterized by a boost invariant flow was first proposed by Bjorken, [14]. Perhaps because it allows one to ignore the

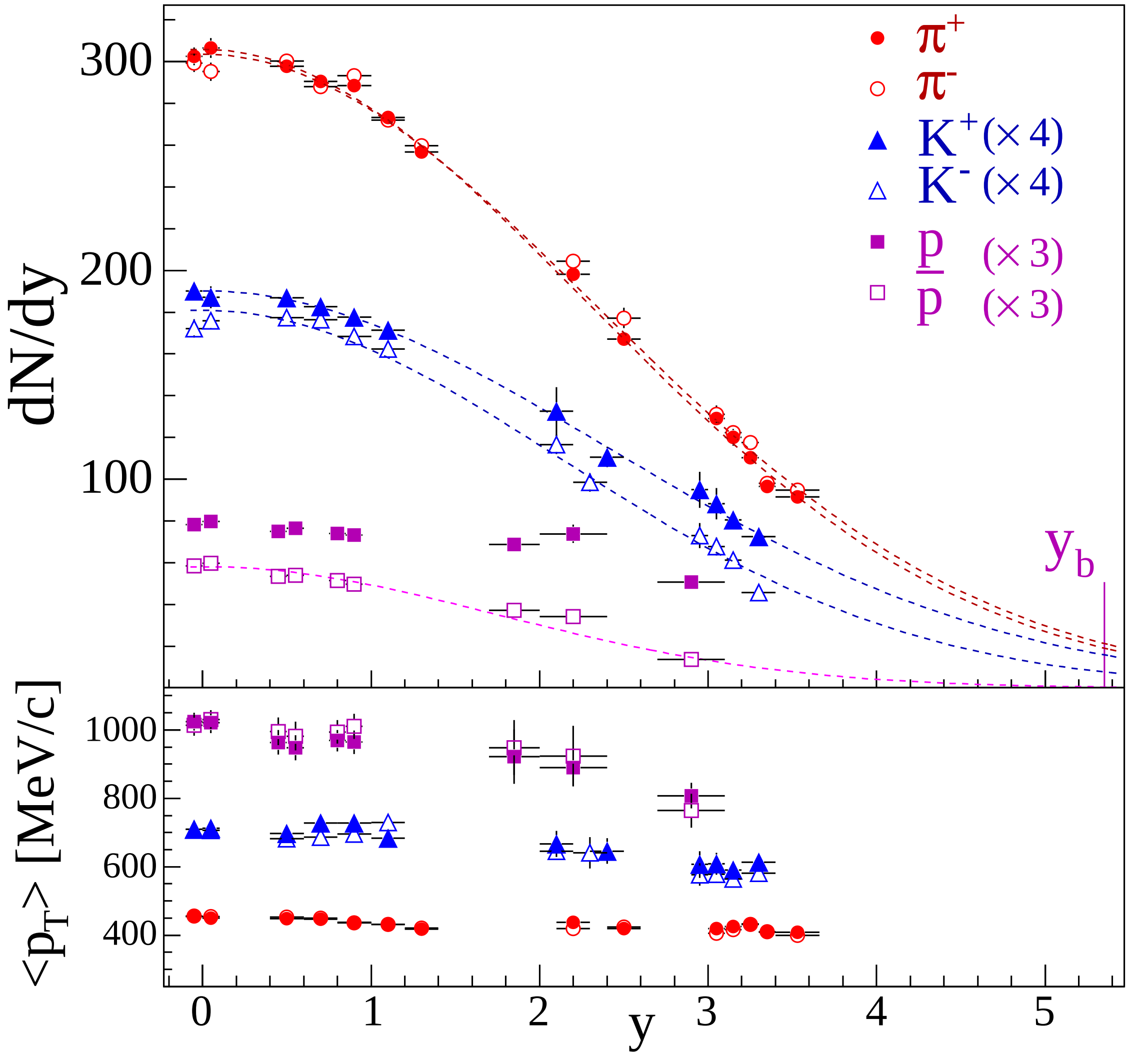

Figure 2. (a) Rapidity densities and transverse momentum $\langle p_T \rangle$ (b) as as a function of rapidity. Errors are statistical.

longitudinal dynamics this assumption is pervasive in the theoretical literature. It should be noted that such an expansion is the fastest possible one in the longitudinal direction. If the expansion is slower than the Bjorken limit then freeze-out would occur later and it would be easier to explain the fact that the pion source size as measured by HBT interferrometry is the same in the "sidewards" and "outwards" directions.

For $|y| < 1$ all our data are consistent with Bjorken scaling, see Fig. 2. However looking globally the Bjorken scenario clearly fails. This is most noticeible in the the particle yields but it is also true that the $\langle p_T \rangle$ of the kaons and antiprotons falls significantly with rapidity. Clearly a full understanding of the longitudinal dynamics would explain the $\pi^{\pm}, k^{\pm}$ and $\bar{p}$ data. However the pions dominate both the multiplicity and transverse energy, $E_T \equiv \sqrt{p_T^2 + m^2}$, rapidity distributions. Thus focussing on the pions is a good stepping stone to a full understanding of the longitudinal flow. Landau developed an analytic model of relativistic hydrodynamics undergoing an isentropic expansion governed by an equation of state, [15]. This approach was extended by Carruthers *et al* to pion rapidity distibutions by assuming their mass is negligible compared to their momentum and that their p_T and rapidity distributions approximately factorize [16]. Under these conditions dN/dy is a gaussian with a width given by

$$\sigma^2 = \ln\left(\frac{\sqrt{s_{NN}}}{2m_N}\right) \approx \ln\left(\gamma_{beam}\right) \tag{1}$$

where m_N is the nucleon mass.

This model was able to give a reasonable description of the pion distributions from pp collisions at various energies. The assumptions of the model are not entirely met our data since $m_\pi = 0.3\cdot \langle p_T \rangle$ at y=0 and $\langle p_T \rangle$ drops by 10% from y=0 to y=3. Another difference between our data and Landau is that we do not observe full stopping. Nevertheless the agreement between this very simple model and our data is rather good. Figure 3(a) shows $dN/dy(\pi)$ and Landau's prediction for $\sqrt{s_{NN}} = 200\,\text{GeV}$ using Eq. 1 with the condition that the integrals of these Gaussians must be equal to the full–space yields estimated from the data. A discrepancy of $\sim 5\%$ is observed ($\sigma_{Landau} = 2.16$). Figure 3(b) shows a compilation on pion widths from AGS to RHIC, The difference between theory and data is at most 10%. This logarithmic growth of the rapidity width with $\sqrt{S}$ is in contrast to the linear increase of the multiplicity with [17] It is all the more striking considering that the degree of transparency drastically changes from AGS to RHIC [10].

3.2. Rapidity Dependence of Blast Wave and Chemical Parameters

Is there one source or many in high energy heavy ion collisions? We have investigated this question by fitting our spectra and particle yields at several different rapidities to blast wave and chemical models [12, 13]. The left panel of Fig. 4 shows the regions of temperature T and transverse velocity of the surface β_S that are consistent with our data sets at y=0,1,2 and 3. As the rapidity increases β_S decreases while T increases. This may be because the equation of state of the matter is changing with rapidity. If the number of degrees of freedom decreases one would expect the temperature to increase. The right panel of Fig. 4 shows the the results of a chemical analysis versus rapidity. As y increases both the baryo-chemical potential and (to a lesser extent) the chemical freeze-out temperature increase. Again this may suggest that the system has fewer degrees of freedom at higher rapidities.

4. High p_T suppression and energy loss

Perhaps the most exciting heavy ion news of 2003 was the discovery that high p_T suppression is not an initial state effect but rather is a result of the hot and dense medium produced in AuAu collisions, [18]. We quantify this effect by normalizing our

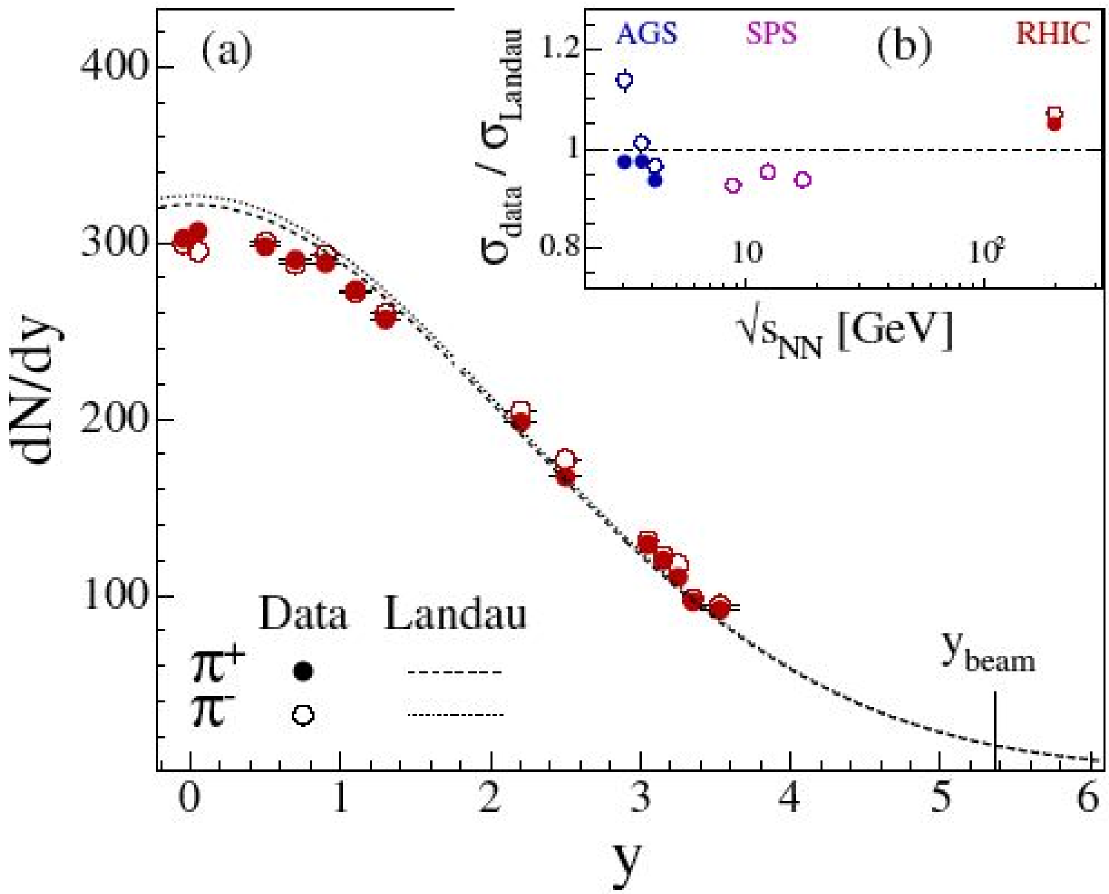

Figure 3. (a) Comparison $dN/dy(\pi)$ and Landau's prediction at $\sqrt{s_{NN}} = 200\,\text{GeV}$; (b) Ratio $\sigma_{N(\pi)}/\sigma_{Landau}$ as a function of $\sqrt{s_{NN}}$ (b). Errors are statistical.

to p+p distributions using the nuclear modification factor defined by:

$$R_{AuAu} \equiv \frac{1}{\langle N_{coll}\rangle} \frac{d^2N^{AuAu}/dp_T d\eta}{d^2N^{p+p}_{inel}/dp_T d\eta}. \qquad (2)$$

Here $\langle N_{coll}\rangle$ is the average number of nucleon-nucleon collisions in each event. Figure 5 shows the π^- nuclear modification factor at $\eta = 2.2$ for AuAu and dAu collisions. For central dAu collisions there is already some suppression at $\eta = 2.2$ although it is not as strong as in central AuAu collisons, [18, 19].

5. The Initial Gold Wavefunction

Finally it has been suggested that when viewed by a fast probe a heavy nucleus may form a new phase of QCD, the Color Glass Condensate, [1]. Figure 6 shows R_{dAu} as a function of p_T and y. The systematic errors in R_{dAu} are mainly from variations in collision vertex distributions, trigger efficiencies and background conditions. They are estimated to be $< 10\%$ at $\eta = 0$ and $< 15\%$ at all other asettings. From simulations of

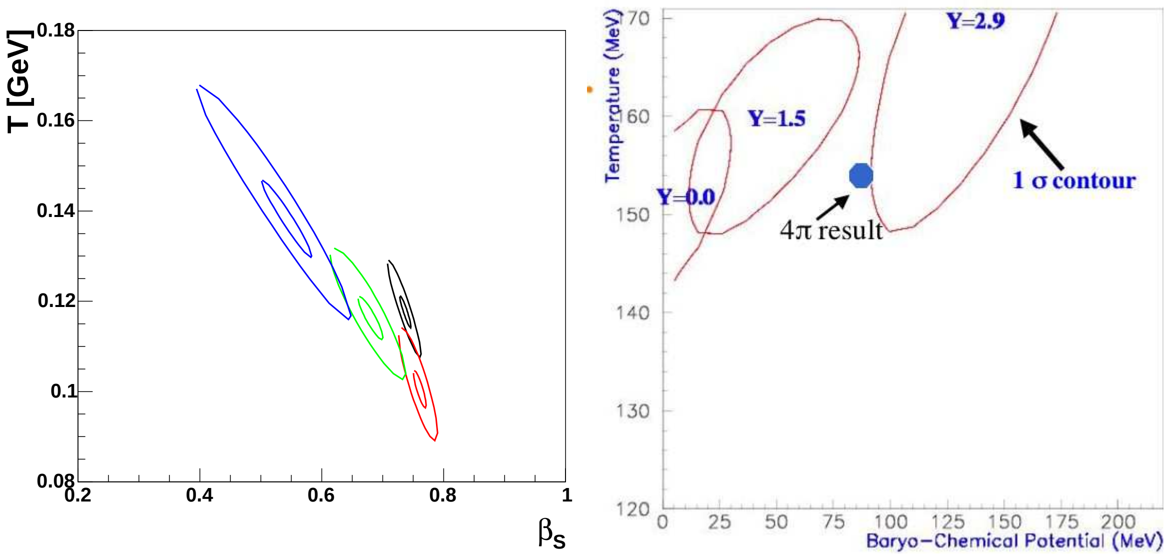

Figure 4. Preliminary blast wave (left) and thermal (right) fits to our data various rapidities. For the blast wave plots 1 and 3 sigma contours are shown for y=0,1,2 and 3 while for the thermal plot only 1 sigma contours are shown for y=0, 1.5 and 2.9.

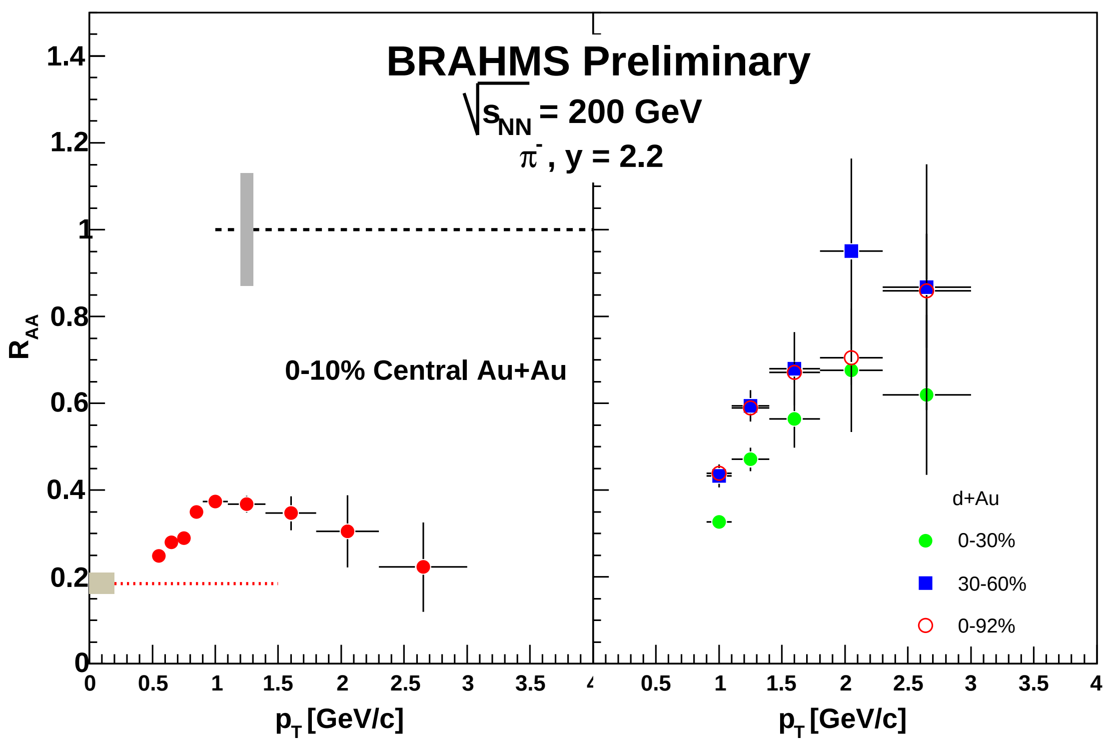

Figure 5. The π^- nuclear modification factor at $\eta = 2.2$ for AuAu panel (a) and dAu collisions (b).

p+p collisions at forward angles we can state that the ratios calculated with negative particles are greater than the ones calculated with the average $(h^+ + h^-)/2$.

R_{dAu} depends strongly on η. At midrapidity, R_{dAu} goes above 1. This so–called

Cronin enhancement is attributed to multiple scattering of the incoming partons [21]. during the collision. 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 ratio of charged-particle pseudorapidity densities in d+Au and p+p collisions $\frac{1}{\langle N_{coll}\rangle}\frac{dN/d\eta(Au)}{dN/d\eta(pp)}$ shown in Fig. 6 with dashed lines at $p_T < 1GeV/c$ [2, 22]. Saturation effects should increase with thickness of nuclear material traversed by the incoming probe . At forward angles we see a greater suppression for more central collisions, see Fig. 5 and refs. [20, 23].

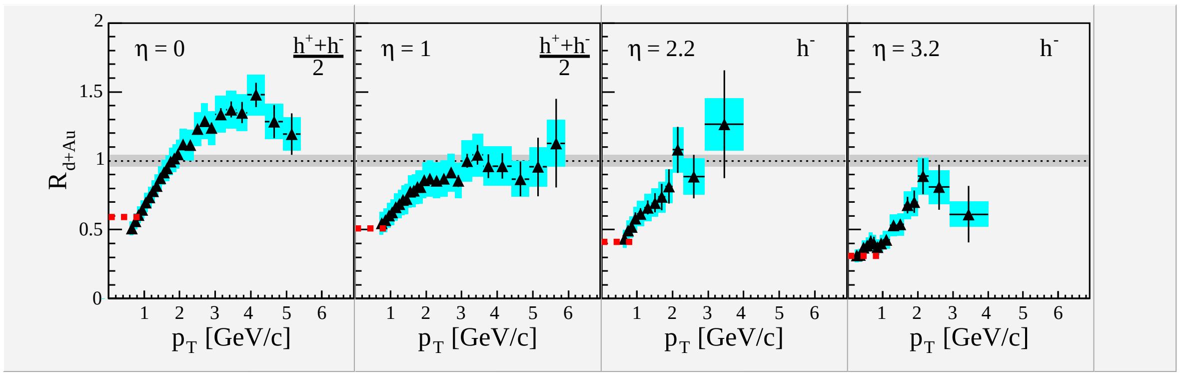

Figure 6. Nuclear modification ratio for charged hadrons at $\eta = 0, 1.0, 2.2, 3.2$ Systematic errrors are shown with shaded boxes. The first two panels represent the average of positive and negative particles while the last two show only negative particles. The shaded band around unity indicates the estimated error on the normalization to $\langle N_{coll}\rangle$. Dashed lines at $p_T < 1$ GeV/c show the normalized charged particle density ratio $\frac{1}{\langle N_{coll}\rangle}\frac{dN/d\eta(Au)}{dN/d\eta(pp)}$.

6. Summary and Conclusions

For d-Au collisions we see a significant asymmetry in $dN^{\pm}/deta$ with a peak at $\eta = -2$ (i.e. on the Au side of the collision) and a slight shoulder at $\eta = +2$. This indicates significant rescattering within the d-Au system since these peak are far away from the Au and d beam rapidities. In the fragmentation regions the multiplicity scales with the number of (the Au or deuteron) particpants. These data are consistent with the HiJing, AMPT and the recent calculations based on gluon saturation.

Using the spectrometers we have found that the rapidity distributions of all the produced charged particles in AuAu collisions are Gaussian. There is no large rapidity plateau but we cannot exclude Bjorken scaling for —y—¡1. The width of our pion distribution (and a large range of lower energy data) is consistent with Landau's picture of isentropic fluid dynamics. Blast wave analysis of our data show a decrease in the surface velocity β_S and an increase in the kinetic freeeze-out temperature with increasing rapidity. Similarly chemical analysis of our particle yields hint that both the baryo-chemical potential and the chemical freeze-out temperature increase with rapidity. One could interpret this in terms of the system becoming less partonic (with consequently fewer degrees of freedom) at higher rapidities. One side benefit of the thermal analysis is that it allows us to make a rough estimate of the total energy in the produced particles. This comes out to be 25 ± 5 TeV compared to 25 ± 1 TeV computed from our net proton distributions, [10].

We see evidence for jet quenching in AuAu collisions at both central rapidity and $\eta = 2.2$. This is based on the reduction of yield of high p_T particles from AuAu collisions compared to pp collisions. However at $\eta = 2.2$ some suppression of negative pions is already observed in dAu collisions. This may be a result of a saturation in the yield of soft, ie low Feynman x gluons in the gold nucleus. A systematic study of this effect shows that it increases with η and and centrality. Out data are consistent with the idea of gluon saturation in d-Au collisions at higher x values than the e-p results from HERA. This hints that the Color Glass Condensate may represent the high energy limit of QCD.

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