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. This is accomplished by studying hadrons with a very wide range of momenta and angle. In doing so we can scan various phases of QCD, from a hadron gas, to quark gluon plasma and perhaps the color glass condensate.

1. Introduction

The purpose of RHIC is to map the phase structure of QCD. So far the community has concentrated on AuAu, d-Au and pp collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ in the hope of discovering the quark gluon plasma. BRAHMS' special contribution to this work has been to study the hadrons produced in these collisions over a very broad range of momentum and angle [1]. A great deal of evidence supporting the creation of partonic matter in AuAu collisions was presented at this conference. However QCD is a rich theory that probably has many phases. It has been suggested that when viewed by a fast probe a heavy nucleus may appear to be a sheet of highly correlated gluons called the Color Glass Condensate [2]. This system would rapidly break up into a dense system of partons, which one would expect to approach 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 freeze-out.

This scenario is speculative and our evidence is both incomplete and somewhat indirect. Nevertheless we will attempt to map out this evolution by starting from the final state and working our way backwards. The RHIC experiments have a beautiful complimentarity but we will report only on BRAHMS' data, with an emphasis on recent results. In particular we will discuss:

- Charged multiplicity distributions from d-Au;
- Particle spectra from AuAu [3] since these can give information regarding;
  - kinetic freeze-out via blast wave fits to p_T spectra,
  - chemical freeze-out via fits to particle ratios,
  - nitial pressure and longitudinal flow from pion dN/dy distributions,
- High p_T suppression [4] which is sensitive to the early density of color charges
- The ratio of d-Au and pp spectra at different rapidities [5] since this can give information on the Au wavefunction.

2. Global Observables

Multiplicity distributions are sensitive to all stages of the collision and can be used to limit the total production of entropy. Figure 1 shows our $dN^{\pm}/d\eta$ results for minimum-bias and central d-Au collisions (for AuAu see [7, 8]). Panel (c) shows the ratio of the 0-30% and 30-60% samples normalized by the number of participants. The ratios appropriate for Au- and d-participant only scaling are indicated by the left and right arrows. Particle production away from mid-rapidity appears to follow the participant scaling of the respective fragment. In the deuteron frame of reference we see very similar yields to lower energy data. This phenomenon is known as “limiting fragmentation” [9, 6, 8, 10]. The HIJING and AMPT models are close to the data [11, 12, 13, 14]. Note that the saturation model results have been updated since the conference with a better centrality determination and an increase of the saturation scale from $Q_s^2 = 0.25$ to $0.34 GeV^2$ [15]. The new calculations are very close to the data.

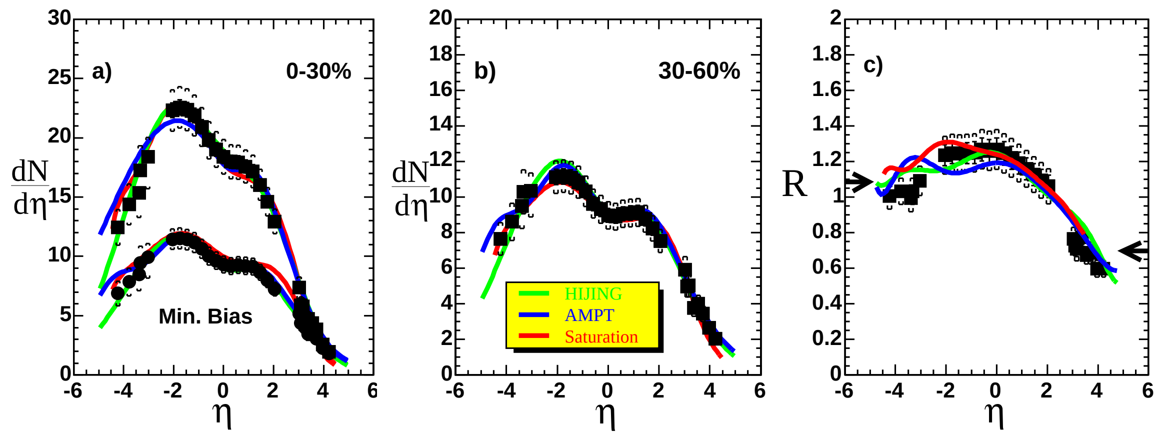

Figure 1. $dN^{\pm}/d\eta$ distributions from d-Au collisions for a) minimum-bias and 0-30% central events and b) 30-60% central events. c) Scaled multiplicity/participant ratio R. The left (right) arrows show corresponding values for Au- (d-) participant scaling.

3. Particle Spectra

The distribution of particles in rapidity and p_T may give information on the transverse and longitudinal flow while the mix of different kinds of particles may tell us about the “quark chemistry” of the system. Our AuAu 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, [3]. 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 that increass 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

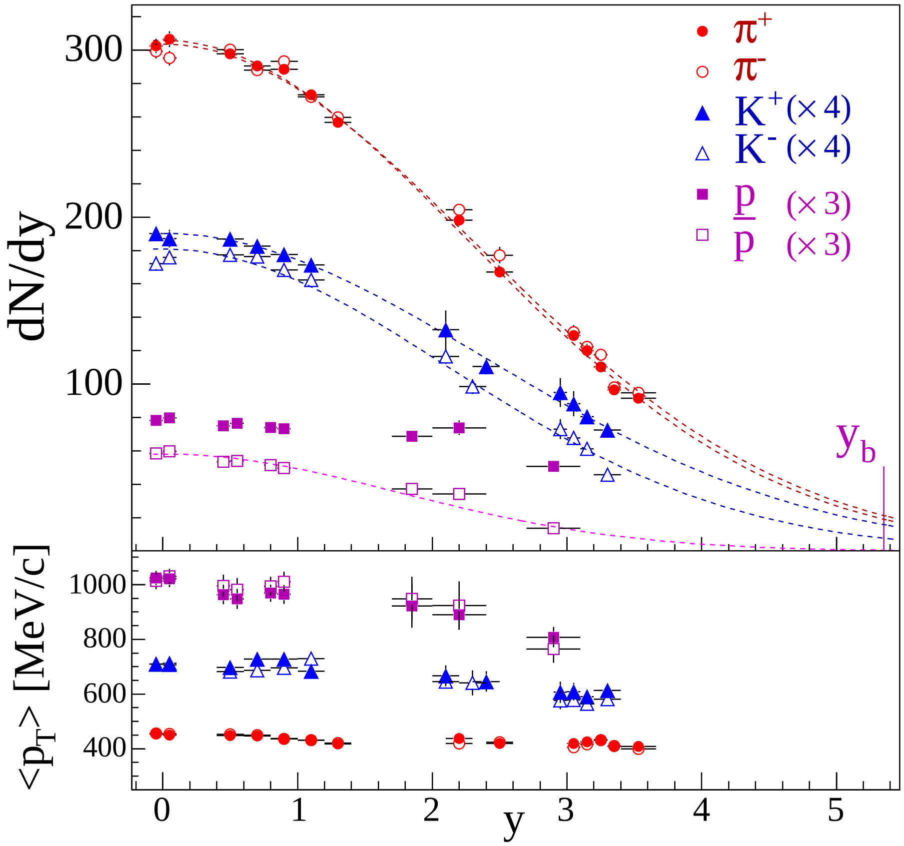

Figure 2. (a) Rapidity densities and mean transverse momentum (b) as as a function of rapidity. Errors are statistical.

rapidity dependence of $\langle p_T \rangle$ increases with mass suggesting that 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, $\delta E = \int EdN/dydy$. We find that $\delta E = 25 \pm 1$ TeV, or 75 GeV per participating baryon [3, 16]

3.1. Rapidity Dependence of Kinetic and Chemical Freeze-out

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 [17, 18]. At y=0 we see a very slow change of the freeze-out parameters with centrality so we shall consider only central data here. The left panel of Fig. 3 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. 3 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.

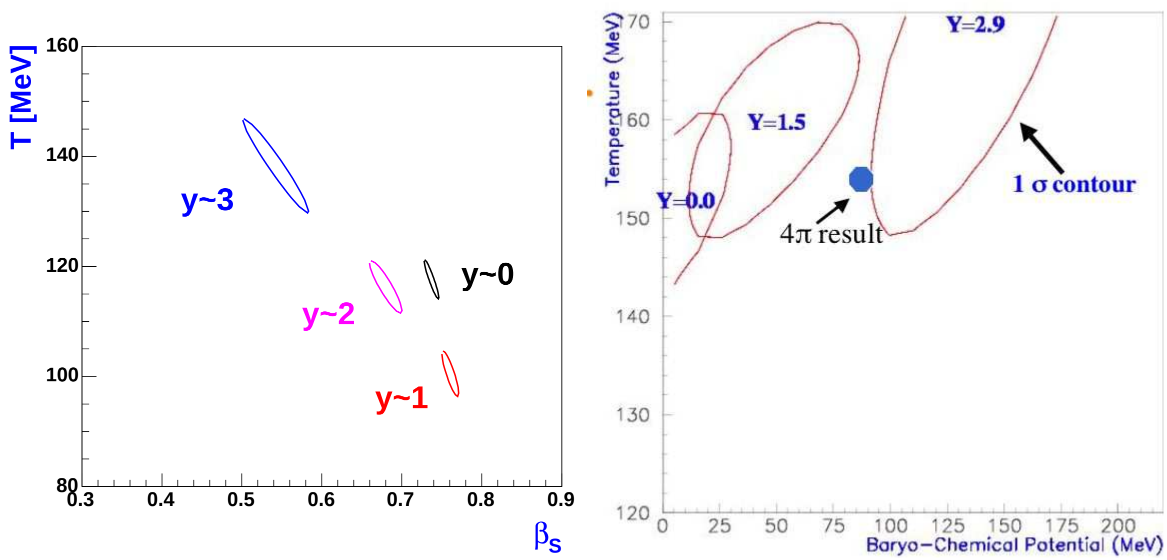

Figure 3. Preliminary blast wave (left) and thermal (right) fits to our data various rapidities. For the blast wave plots 1 and 3 sigma contours are shown for y=0,1,2 and 3 while for the thermal plot only 1 sigma contours are shown for y=0, 1.5 and 2.9.

3.2. Bjorken and/or Landau Hydrodynamics

We now turn to the longitudinal flow which may be sensitive to the initial pressure in the system and possibly the equation of state. Bjorken proposed [19] that away from the fragmentation regions, $y \approx \pm 4$ at RHIC [16], the system produced by heavy ion collisions should be boost invariant, i.e. independent of rapidity. This assumption is pervasive in the theoretical literature. Such an expansion is the fastest possible one in the longitudinal direction. If the expansion is slower than the Bjorken limit then freeze-out occurs later and it may be easier to explain the fact that the pion HBT radii are the same in the "sidewards" and "outwards" directions.

For $|y| < 1$ all of our data are consistent with boost invariance. However looking globally at Fig. 2 the Bjorken scenario clearly fails. This is most noticeable in 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 because the pions dominate both the multiplicity and transverse energy, $E_T \equiv \sqrt{p_T^2 + m^2}$, distributions 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 (constant entropy) expansion governed by an equation of state [20]. This approach was extended by Carruthers *et al* to pion rapidity distibutions by assuming that the pion mass is negligible compared to the average pion momentum and that their p_T and rapidity distributions approximately factorize [21]. 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 for 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 4(a) shows $dN/dy(\pi)$ and Landau's prediction for $\sqrt{s_{NN}} = 200$ 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 4(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 $\sqrt{s_{NN}}$ is in contrast to the linear increase of the multiplicity with $\sqrt{s_{NN}}$ [22]. It is all the more striking considering that the degree of transparency drastically changes from AGS to RHIC energies [16].

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 in AuAu collisions is not entirely an initial state effect but rather is a result of the hot and dense medium produced in AuAu collisions [23]. We quantify this effect by normalizing our spectra to pp distributions using the nuclear modification factor defined by:

$$R_{AA}(p_T, y) \equiv \frac{1}{\langle N_{coll} \rangle} \frac{dN^{AuAu}}{dN^{pp}_{inel}}. \tag{2}$$

Here $\langle N_{coll} \rangle$ is the average number of nucleon-nucleon collisions in each event. Figure 5 shows the π^- $\eta = 2.2$ at y=2.2 for AuAu and d-Au collisions. For central d-Au collisions there is already some suppression at y=2.2 although it is not as strong as in central AuAu collisons [23, 4]. Note however that this measurement relies on an extrapolation of the pp reference based on PHENIX measurements, see [4].

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 [2]. Figure 6 shows R_{dAu} as a function of p_T and η. 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 settings. From simulations

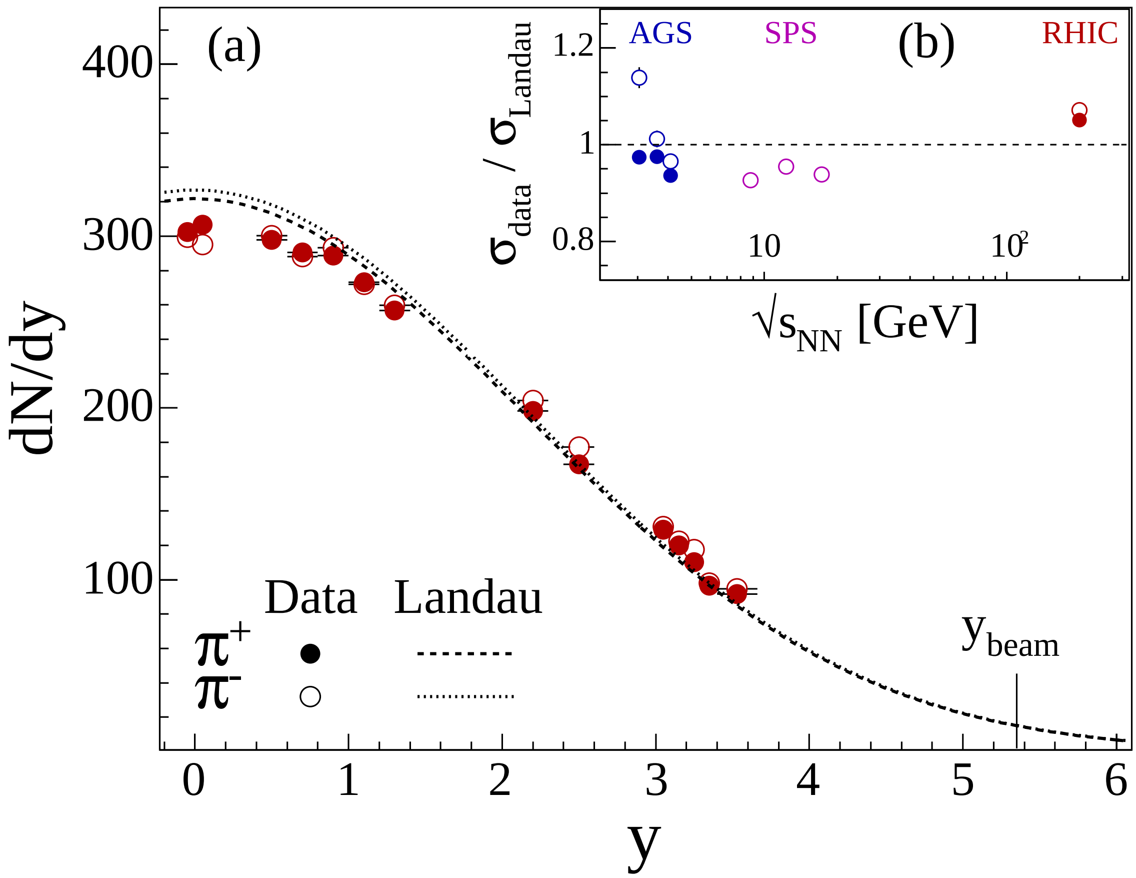

Figure 4. (a) Comparison $dN/dy(\pi)$ and Landau's prediction at $\sqrt{s_{NN}} = 200\,\text{GeV}$; (b) Ratio $\sigma_{N(\pi)}/\sigma_{Landau}$ as a function of $\sqrt{s_{NN}}$ (b). Errors are statistical.

of pp collisions at forward angles we can state that R_{dAu} is smaller for h^- than for $(h^+ + h^-)/2$.

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 [25] 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 pp collisions $\frac{1}{\langle N_{coll}\rangle}\frac{dN/d\eta(dAu)}{dN/d\eta(pp)}$ shown in Fig. 6 with dashed lines at $p_T < 1GeV/c$ [6, 26]. Saturation effects should increase with the 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. [24, 5].

6. Summary and Conclusions

For d-Au collisions we see a significant asymmetry in $dN^{\pm}/d\eta$ with a peak at $\eta = -2$ (i.e. on the Au side of the collision) and a slight shoulder at $\eta = +2$. This indicates

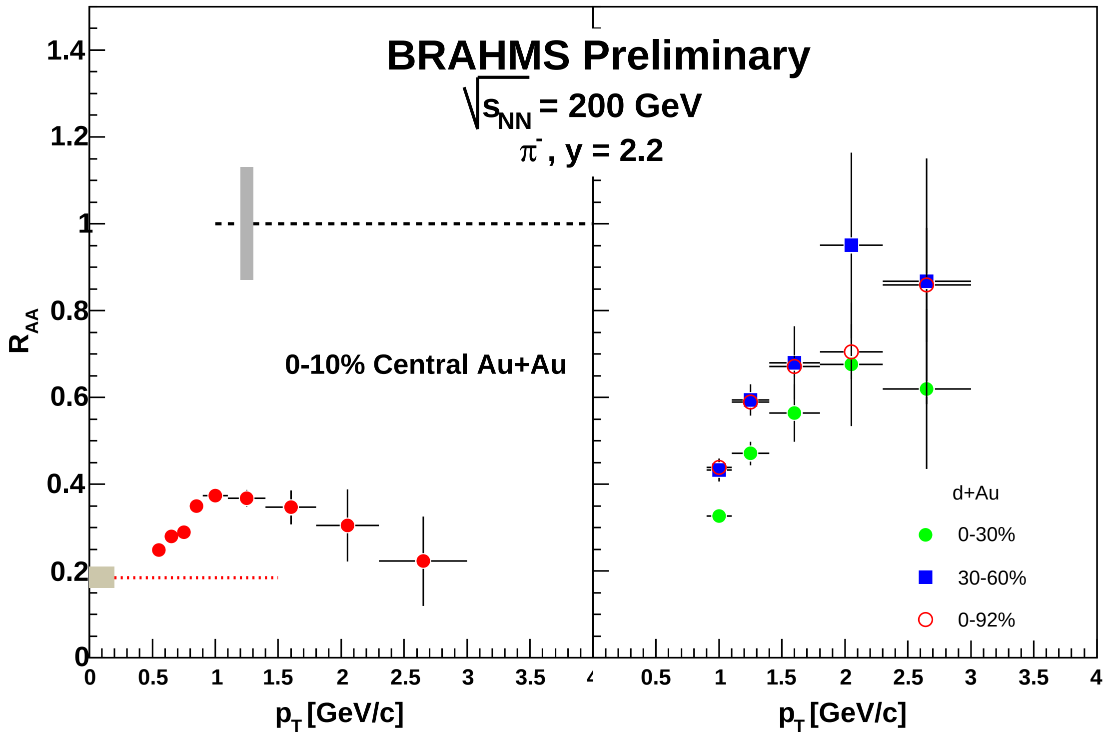

Figure 5. The π^- nuclear modification factor at y=2.2 for AuAu and d-Au collisions

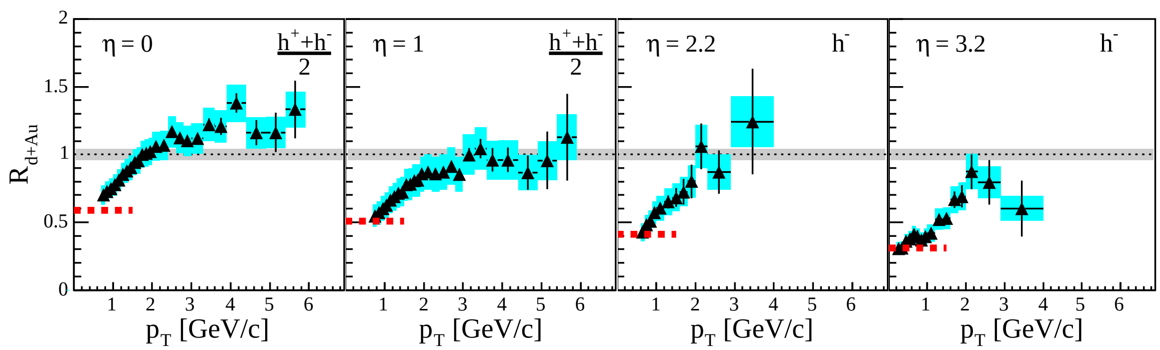

Figure 6. Nuclear modification ratio for charged hadrons versus p_T and η. Systematic errrors are shown with shaded boxes. The band around unity indicates the estimated error on $\langle N_{coll} \rangle$. Dashed lines at $p_T < 1$ GeV/c show the ratio $\frac{1}{\langle N_{coll} \rangle} \frac{dN/d\eta(d-Au)}{dN/d\eta(pp)}$.

significant rescattering within the d-Au system since these peaks 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 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 boost invariance 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 integrating the energy distribution of our net protons, [16].

We see evidence for jet quenching in AuAu collisions at both y=0 and y=2.2. This is based on the reduction of yield of high p_T particles from AuAu collisions compared to pp collisions. However at y=2.2 some suppression of π^- is already observed in d-Au collisions. This may be a result of a saturation in the yield of low momentum gluon in the gold nucleus. This effect increases with pseudo-rapidity and centrality. This hints that the Color Glass Condensate may represent the high energy limit of QCD.

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