

# 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

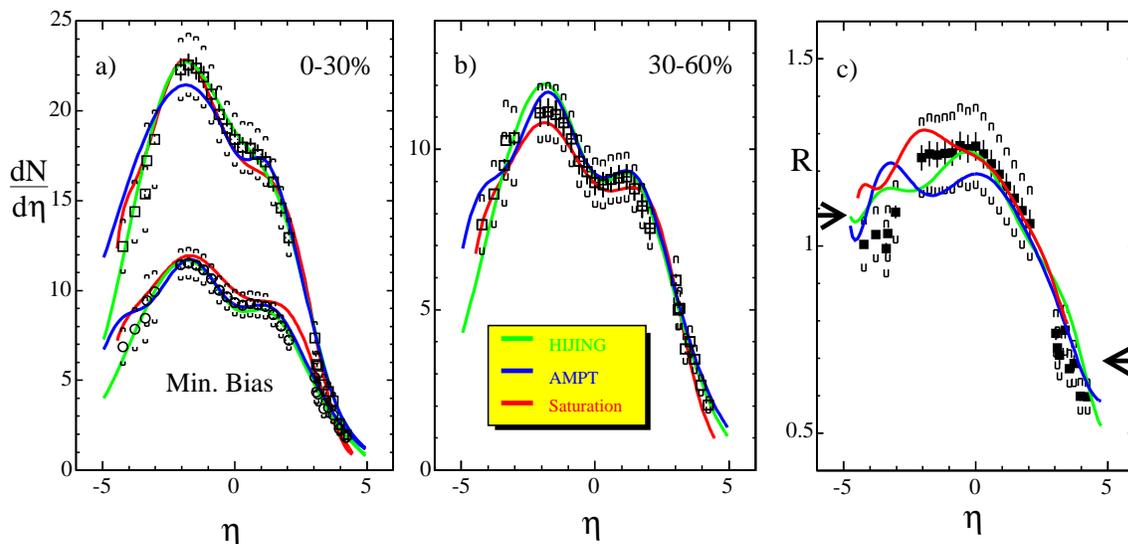
The purpose of RHIC is to map the phase structure of QCD. So far the community has concentrated on AuAu, dAu and pp collisions at  $\sqrt{s_{NN}} = 200$  GeV in the hope of discovering the quark gluon plasma. BRAHMS' special contribution to this work has been to study the hadrons produced in these collisions 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 complementarity but we will report only on BRAHMS' data, with an emphasis on recent results. In particular we will discuss:

- Multiplicity distributions from dAu collisions measure entropy production;
- 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,
  - initial 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 dAu and pp spectra at different rapidities [5] since this can give information on the Au wavefunction.

## 2. Global Observables

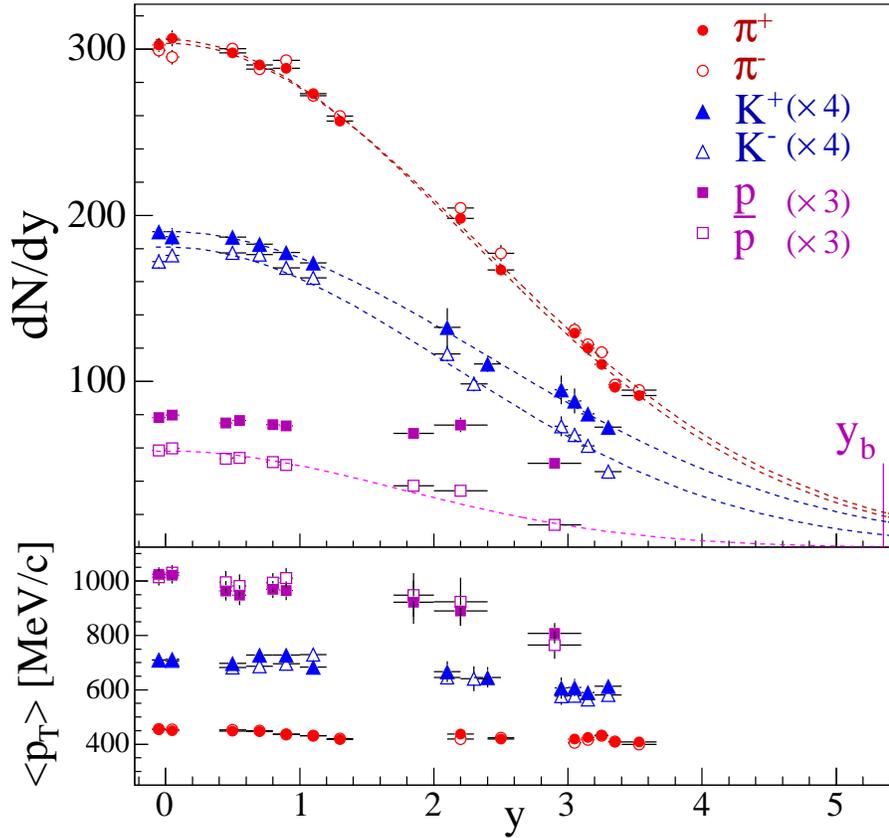
Multiplicity distributions are sensitive to all stages of the collision and can be used to measure the total production of entropy. Figure 1 shows our  $dN/d\eta$  results for minimum-bias and central dAu collisions (for AuAu see [6, 7]). Panel (c) shows the ratio of the 0-30% and 30-60% samples normalized 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” [8, 9, 7, 10]. The HIJING and AMPT models are close to the data [11, 12, 13]. 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  $0.34\text{GeV}^2$  [14]. The new calculations are very close to the data.



**Figure 1.**  $dN/d\eta$  distributions from dAu 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  $\pi$ ,  $K$ ,  $p$  and  $\bar{p}$ . as a function of rapidity. Both quantities are estimated using fits to the spectra in narrow regions of rapidity, [3]. For  $\pi$ ,  $k$  and  $\bar{p}$  the yields peak at  $y=0$  and drop significantly at higher rapidities. The  $\pi^+$  and  $\pi^-$  yields are nearly equal while



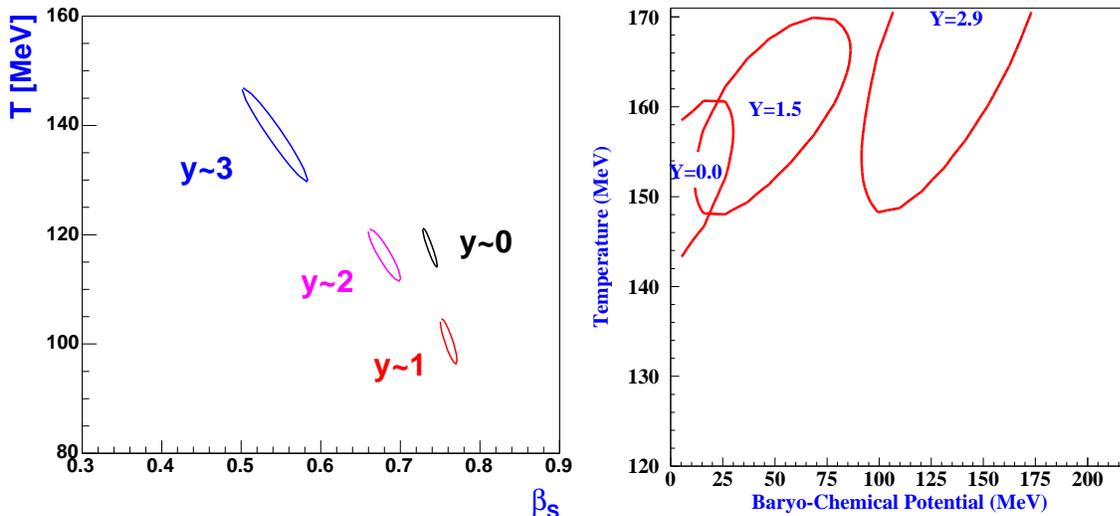
**Figure 2.** Rapidity densities (top) and mean transverse momentum (bottom) as a function of rapidity. Errors are statistical. The yields of all the produced particles are well described by Gaussian fits, shown by the dotted lines. The beam rapidity is 5.4

an excess of  $K^+$  over  $K^-$  is observed that increases with rapidity. The lower panel of Fig. 2 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 transverse flow drops with increasing rapidity. Using the net proton yield 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. We find  $\Delta E = \int E dN = 25 \pm 1$  TeV, or 75 GeV per participant [3, 15]

### 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 [16, 17]. 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  $\beta_S$  that are consistent with our data sets at  $y=0,1,2$  and 3. As the rapidity increases  $\beta_S$  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 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 at various rapidities. The curves are the one sigma contours. Note that as expected the thermal temperatures are always higher than the kinetic freeze-out temperatures.

### 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 [18] that away from the fragmentation regions,  $y \approx \pm 4$  at RHIC [15], 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 “sideways” and “outwards” directions.

For  $|y| < 1$  all of our data are consistent with boost invariance. However looking globally at Fig. 2 there is a clear breakdown of boost invariance. 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  $\pi, k$  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 complete description of the longitudinal flow. Landau developed an analytic model of relativistic hydrodynamics undergoing an isentropic

(constant entropy) expansion governed by an equation of state [19]. This idea was extended by Carruthers *et al* to pion rapidity distributions by assuming that they are massless and that their  $p_T$  and rapidity distributions approximately factorize [20]. Under these conditions  $dN/dy$  is a gaussian with a width given by

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

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%. The logarithmic growth of the rapidity width with  $\sqrt{s_{NN}}$  is in contrast to the linear increase of the multiplicity with  $\sqrt{s_{NN}}$  [21]. It is all the more striking considering that the degree of transparency drastically changes from AGS to RHIC energies [15].

#### 4. High $p_T$ suppression and energy loss

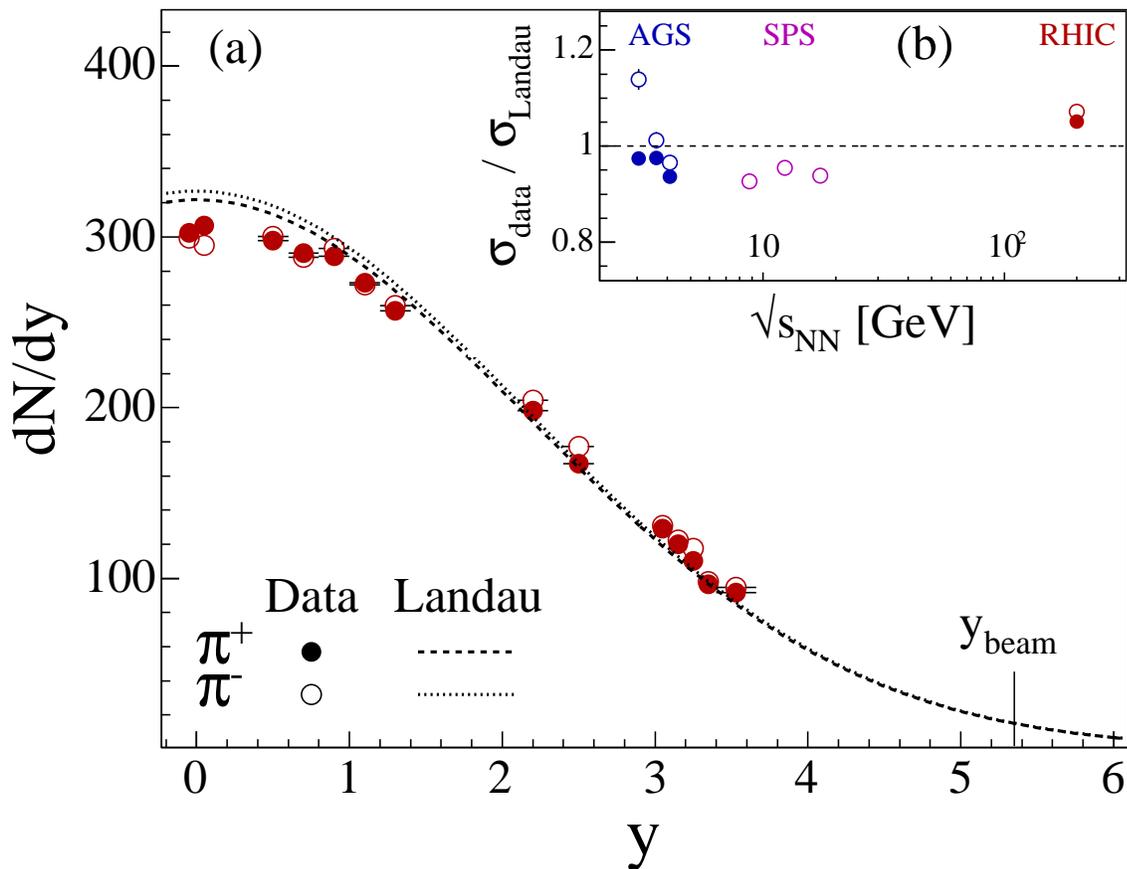
The most exciting heavy ion news of 2003 was the discovery that high  $p_T$  suppression in AuAu collisions is a result of the hot and dense medium produced in these collisions rather than a depletion of hard partons in the Au nucleus itself [22]. We quantify this effect by normalizing our spectra to pp data using the nuclear modification factor;

$$R_{AA}(p_T, y) \equiv \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N^{AuAu}/dp_T dy}{d^2 N_{inel}^{pp}/dp_T dy}. \quad (2)$$

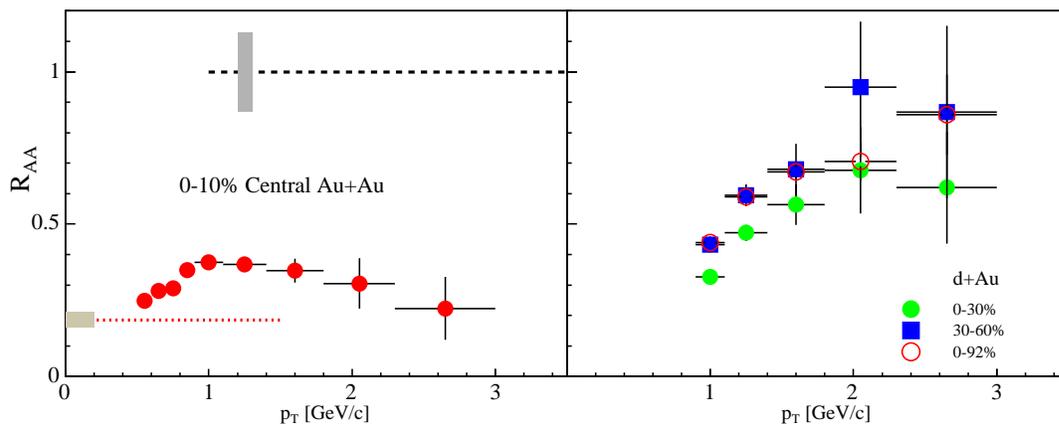
Here  $\langle N_{coll} \rangle$  is the average number of nucleon-nucleon collisions in each event. BRAHMS has the unique ability to study this effect over a wide rapidity range, [4]. Figure 5 shows  $R_{AA}$  for  $\pi^-$  at  $y=2.2$  for AuAu and dAu collisions. For central dAu collisions there is already some suppression at  $y=2.2$  although it is not as strong as in central AuAu collisions [22, 4]. Note however that this measurement relies on an extrapolation for 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]. In such a state, two soft gluons will often fuse together to produce one harder one. This effect results in a low



**Figure 4.** (a) Pion  $dN/dy$  and Landau's Gaussian prediction at  $\sqrt{s_{NN}} = 200$  GeV from Eq. 1. The errors are statistical. (b)  $\sigma_{N(\pi)}/\sigma_{Landau}$  as a function of  $\sqrt{s_{NN}}$

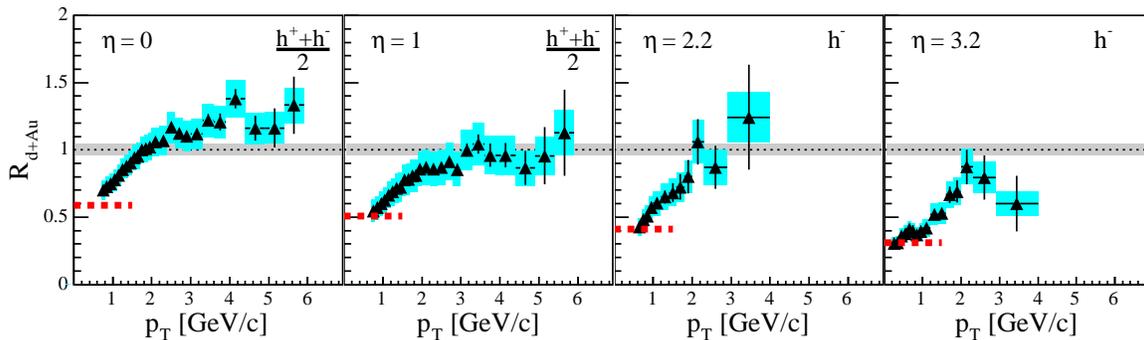


**Figure 5.** Preliminary  $\pi^-$  nuclear modification factors at  $y=2.2$  for AuAu and dAu collisions. The dashed and dotted lines represent the value expected if the yield scales by  $\langle N_{coll} \rangle$  or  $\langle N_{participant} \rangle$  respectively. The bands show our systematic errors on these quantities

$p_T$  suppression for dAu collisions compared to pp ones. BRAHMS can tune the speed

of the probe by looking at fragments that emerge over a wide range of rapidities. Since we observe fragments close to the axis of the deuteron beam we are observing the initial parton density in the gold nucleus. The partons momentum fraction, or Feynman  $x$ , probed by a given fragment is given by  $x = e^{-y}p_T/\sqrt{s_{NN}}$ . As  $y$  increases  $x$  decreases and if the Color Glass scenario is correct we should observe a stronger suppression.

Figure 6 shows  $R_{dAu}$  for minimum-bias events as a function of  $p_T$  and  $\eta$ . We use  $\eta$  instead of  $y$  because we wish to combine all particles together and so improve our statistical accuracy.  $R_{dAu}$  rises with  $p_T$  and falls with  $\eta$ . The systematic errors in  $R_{dAu}$  range from  $< 10 - 15\%$ . At midrapidity,  $R_{dAu}$  goes above 1. This so-called Cronin enhancement [23] has been attributed to multiple scattering of the incoming partons 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. At low  $p_T$   $R_{dAu}$  is close to the ratio of charged-particle pseudorapidity densities in dAu and pp collisions [9, 24]. Saturation effects should increase with the thickness of nuclear material traversed by the incoming probe and indeed we see a greater suppression for more central collisions, see Fig. 5 and refs. [25, 5].



**Figure 6.** Nuclear modification ratio for charged hadrons versus  $p_T$  and  $\eta$ . Systematic errors are shown with shaded boxes. The band around unity shows the error on  $\langle N_{coll} \rangle$ . Dashed lines from  $p_T = 0 - 1.5$  GeV/c show the ratio  $\frac{1}{\langle N_{coll} \rangle} \frac{dN/d\eta(dAu)}{dN/d\eta(pp)}$ .

## 6. Summary and Conclusions

For dAu collisions we see a significant asymmetry in  $dN/d\eta$  with a peak at  $\eta = -2$  (i.e. on the Au side of the collision) and a slight shoulder at  $\eta = +2$ . This suggests significant rescattering within the dAu 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) participants. Using our spectra of identified 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 the data are consistent with 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 analyses of our data show a decrease in the surface velocity  $\beta_S$  and an increase in the kinetic freeze-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. The thermal analysis allows us to make a rough estimate of the total energy in the produced particles. This yields  $25 \pm 5$  TeV compared to  $25 \pm 1$  TeV computed from integrating the energy in the net protons, [15].

We see evidence for jet quenching in AuAu collisions at both  $y=0$  and  $y=2.2$ . The most economical explanation for these data, is that fast partons lose energy traversing a deconfined system of quarks and gluons, [22]. In the forward region we see a low  $p_T$  suppression of the yield from dAu collisions which increases with  $\eta$  and centrality. This may be a result of a saturation in the yield of low momentum gluon in the gold nucleus and hints that the Color Glass Condensate may represent the high energy limit of QCD.

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