FLAVOR DYNAMICS

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The purpose of BRAHMS is to survey the dynamics of relativistic heavy ion (as well as pp and d-A) collisions over a very wide range of rapidity and transverse momentum [1]. The sum of these data may give us a glimpse of the initial state of the system, its transverse and longitudinal evolution and how the nature of the system changes with time [2]. Here I will concentrate on the origin and dynamics of the light flavors, i.e. the creation and transport of the up, down and strange quarks. The results presented here are certainly not the end of the story. It is my hope that in a few years new detectors will reveal the rapidity dependence of the charm and bottom quarks [3].

1. Overview of particle production

Figure 1 shows our preliminary yields of $\pi^{\pm}, k^{\pm}$ and antiprotons versus rapidity for central Au+Au collisions at $\sqrt{s_{NN}} = 62.4$GeV. The yields of all produced particles are well described by Gaussian fits up to rapidities of $0.8 \times y_{beam}$. The widths of the two pion curves are very close to the prediction by Carruthers for massless particles undergoing Landau flow, i.e. $\sigma_\pi = ln\gamma$ where γ is the Lorentz factor of the incoming beams [4, 5, 6]. This model assumes that all of the entropy of the system is created at the instant the two beams collide and that the system then expands adiabatically until freezeout. One might expect that massive particles would have somewhat narrower widths than this. The data show ordering of the rapidity widths that is the same as at $\sqrt{s_{NN}} = 200$GeV, namely $\sigma_{k^+} > \sigma_{\pi^{\pm}} > \sigma_{k^-} > \sigma_{pbar}$ [7]. This is suggestive of a correlation between the production of protons and Kaons. We have investigated this link in terms of a chemical analysis of quark rapidity densities, as discussed below.

Since the initial protons are explicity *excluded* from the Landau/Carruthers model we should not expect them to be controlled by the same dynamics. Figure 2 shows our distribution of net protons, $dN^p/dy - dN^{\bar{p}}/dy$ at various energies [8]. These data suggest that the average rapidity loss $\langle \Delta y \rangle$ of the incoming nucleons rises steadily with the beam rapidity up to $\sqrt{s_{NN}} = 62$ GeV before saturating at $\langle \Delta y \rangle = 2$.

Figure 3 shows average values of $\langle m_T \rangle$ versus rapidity for $\pi^{\pm}, k^{\pm}$, protons and antiprotons versus rapidity for central Au+Au collisions at $\sqrt{s_{NN}} = 62.4$GeV. The $\langle m_T \rangle$ values are about 10% lower than at 200GeV for all particles at all rapidities but the relative drop with rapidity is very similar (14%). Radial flow gives a uniform velocity boost to all particles and so a bigger boost in $\langle m_T \rangle$ to the heavier particles. Our data are consistent with a pattern of radial flow that weakens as the rapidity increases and/or the beam energy drops.

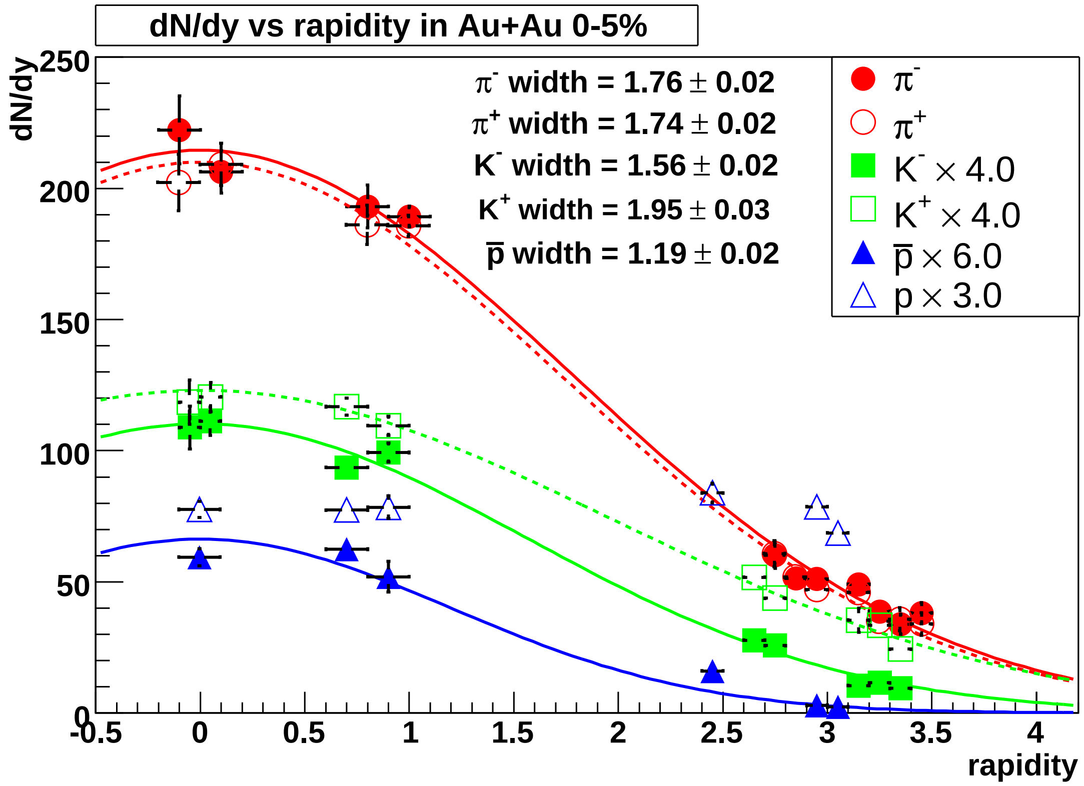

FIGURE 1. Preliminary dN/dy versus y from central Au+Au collisions at $\sqrt{s_{NN}} = 62.4$GeV

The fact that the k^+ dN/dy distribution is wider than the pion distribution may be because strangeness is related to the net baryon density. We have investigated this in the context of thermal fits to the data. Using the "Thermus package" [14] we have fit five independent particle ratios at each rapidity to a grand canonical distribution described by a temperature, and two chemical potentials, μ_s for strange quarks and μ_q for light quarks. More details can be found in [15]. Figure 4 shows μ_s for versus μ_q at several different rapidities for $\sqrt{s_{NN}} = 62.4$ and 200 GeV. Note that $\mu_s \approx 1/4\mu_q$. The chemical freeze-out temperature drops as the rapidity increases or $\sqrt{s_{NN}}$ decreases. T $= 160 \pm 5$ MeV at $\sqrt{s_{NN}} = 200$ GeV and y=0 and falls to 116 ± 9 MeV at $\sqrt{s_{NN}} = 62.4$ GeV and y=3.

For non-central heavy ion collisions the geometric eccentricity of the initial state may create pressure gradients if the system is strongly interacting. Elliptic flow, i.e. v_2 the 2^{nd} harmonic of the momentum distribution in azimuthal angle, is sensitive to these gradients. Since these gradients are self quenching v_2 tells us about the early state of the system. Figure 5 shows v_2 for protons and pions (for clarity the Kaons are not shown) as a function

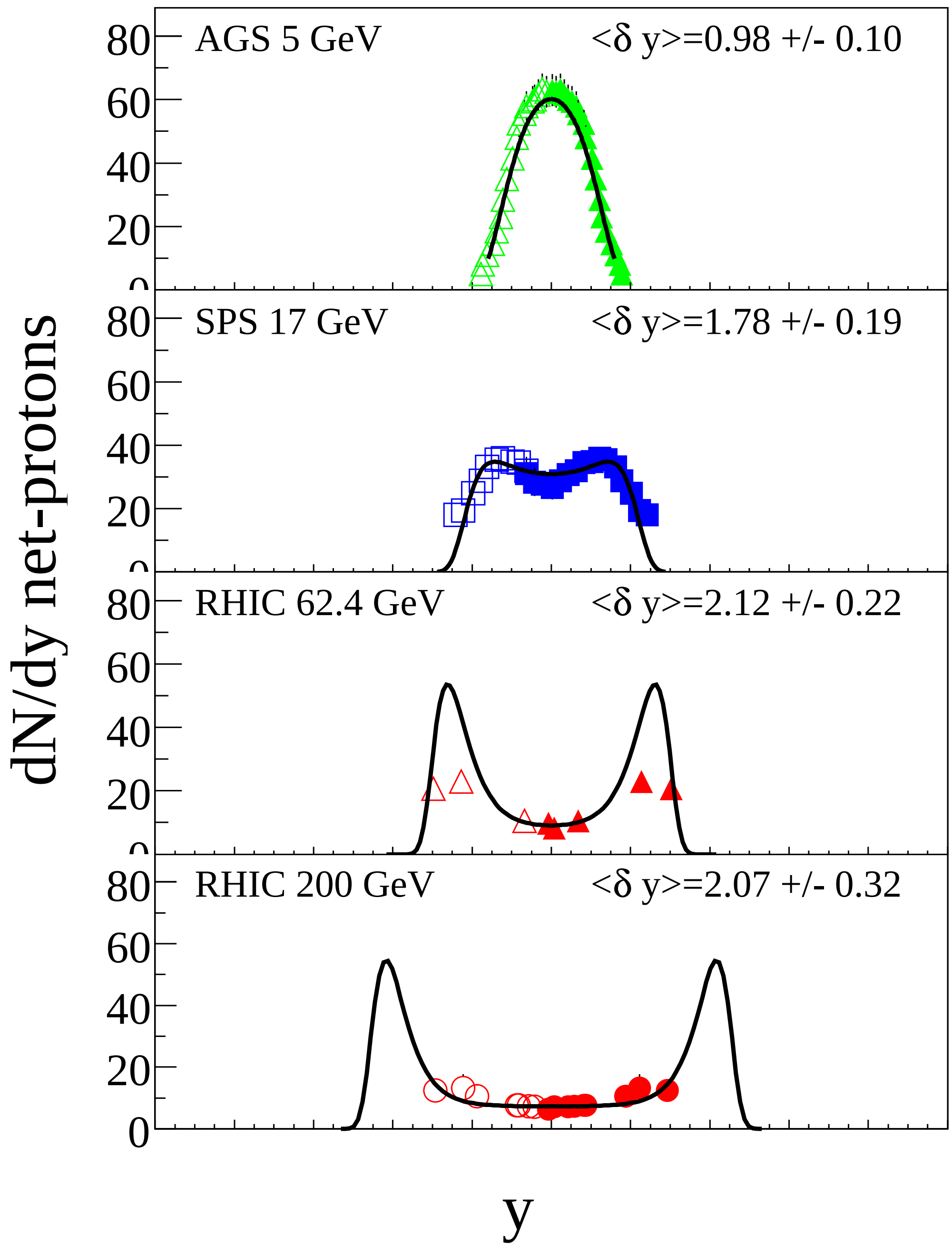

FIGURE 2. Net proton distributions versus rapidity and $\sqrt{s_{NN}}$ from E917,E802 and E877 5GeV [9, 10, 11], NA49 (PbPb) 17GeV [12] and BRAHMS 62 and 200GeV [13]. The 62GeV data are preliminary with statistical errors only.

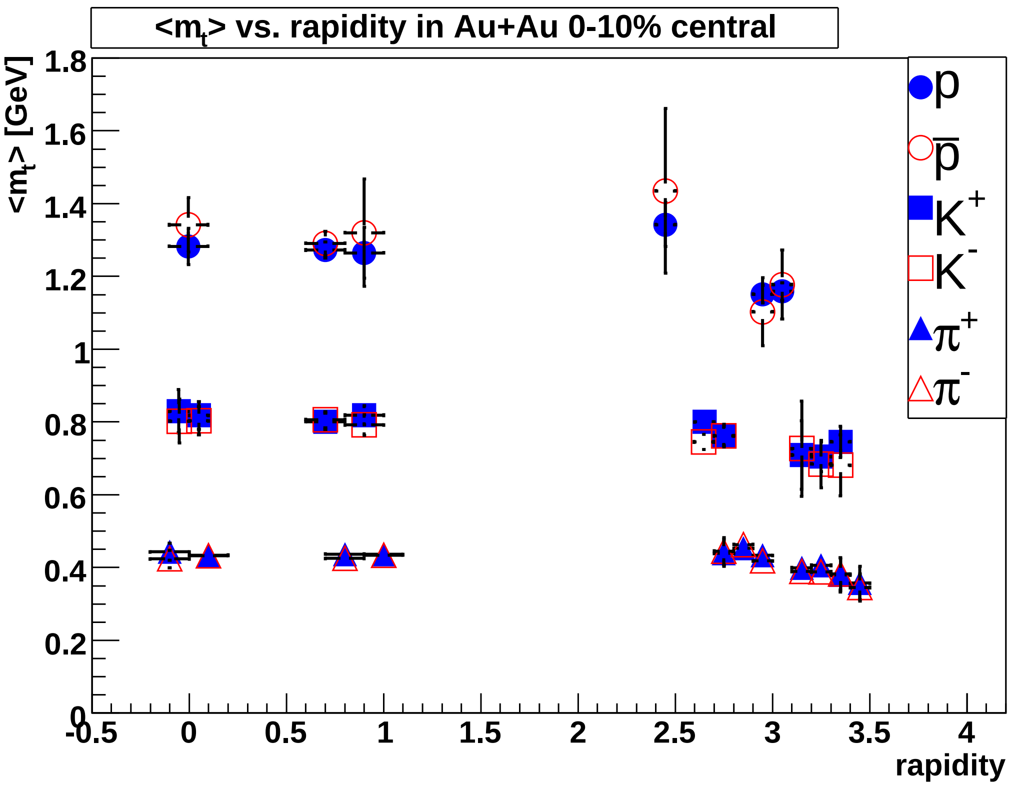

FIGURE 3. Preliminary values of $\langle m_T \rangle$ versus rapidity for $\pi^{\pm}, k^{\pm}, p$ and $\bar{p}$ versus rapidity for central Au+Au collisions at $\sqrt{s_{NN}} = 62.4$GeV. The errors are statistical only.

of p_T, and $k_T = \sqrt{p_T^2 + m^2} - m$ as well as v_2/n_{quark} versus k_T/n_{quark} at central (top) and forward rapidity (bottom). A striking feature of these data is how little $v_2(p_T)$ changes with rapidity. This is despite the fact that when one averages over p_T, $\langle v_2 \rangle$ drops by about a factor of two from y=0 to y=3 [16, 17]. The values of $v_2(p_T)$ at all rapidities are close to the maximum values allowed by ideal hydrodynamics, under the assumption that all of the initial spatial anisotropy is converted into momentum anisotropy. This effect implies very early thermalization.

Objects produced at forward rapidities will tend to come from the collisions of partons with very unequal momenta. Such collisions have a $\sqrt{s}$ that is lower than the balanced collisions which produce particles near mid-rapidity, and so are less likely to produce particles at high p_T. We find that the mean p_T of pions, Kaons and protons drops steadily with rapidity [7]. Thus even though $v_2(p_T)$ is rather constant, $\langle v_2 \rangle$ drops quickly with rapidity.

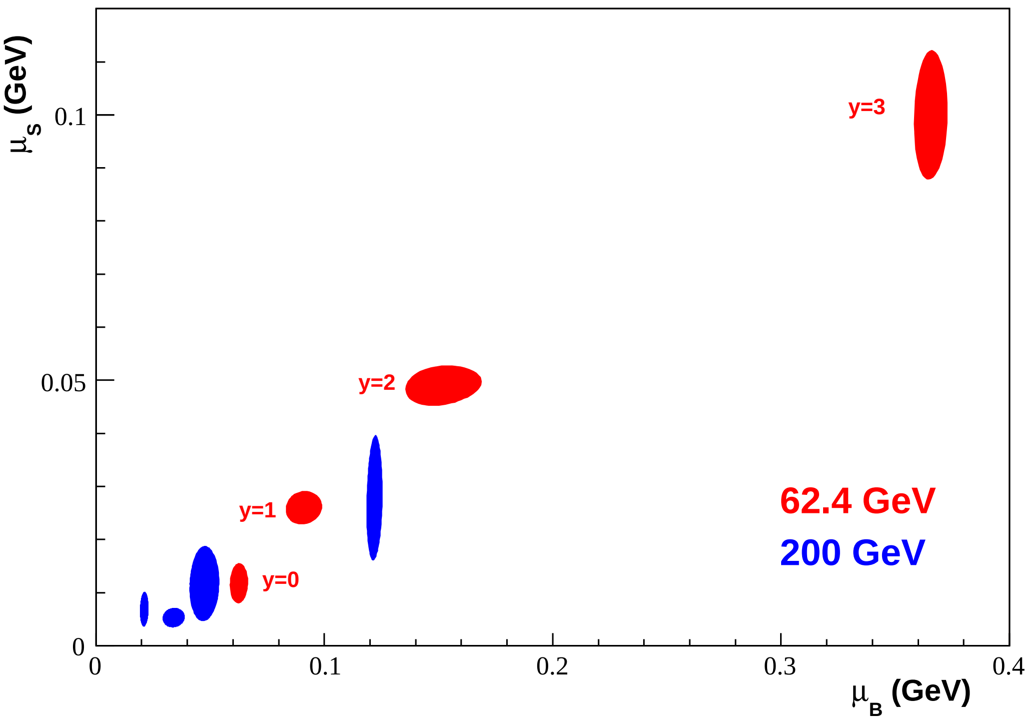

FIGURE 4. Preliminary μ_s versus μ_q at several different rapidities for $\sqrt{s_{NN}} = 62.4$ and 200 GeV. The errors are statistical only.

Of course we should not discount the effect of radial and longitudinal flow but this will have to wait for a more complete analysis.

At y=0 the proton and pion data are closest when plotted as v_2/n_{quark} versus k_T/n_{quark}. This effect has been seen by several experiments and suggests that the quarks themselves flow until they coalescence into hadrons. This scaling does not work quite so well at y=3 where v_2/n_{quark} at a given k_T/n_{quark} is slightly lower for pions than for protons. Since only $\approx 4\%$ of our reconstructed pions come from k^0_{short} decays it is unlikely that this effect is caused by a "dilution" of $\langle v_2 \rangle$ for the pions. Rather it may reflect a breakdown of coalescence, perhaps caused by recombination, in the forward direction.

The success of non viscous hydrodynamics in describing both the longitudinal and elliptic flow suggests that thermalization is archived very rapidly in heavy ion collisions. Black holes are a possible generator of very rapid thermalization [18]. Because of the uncertainty principle black holes radiate with a temperature that only depends upon their mass, charge and angular momentum. For uncharged black holes with zero angular momentum $T = 1/(8\pi GM)$. The radiation carries away energy which causes the temperature to increase,

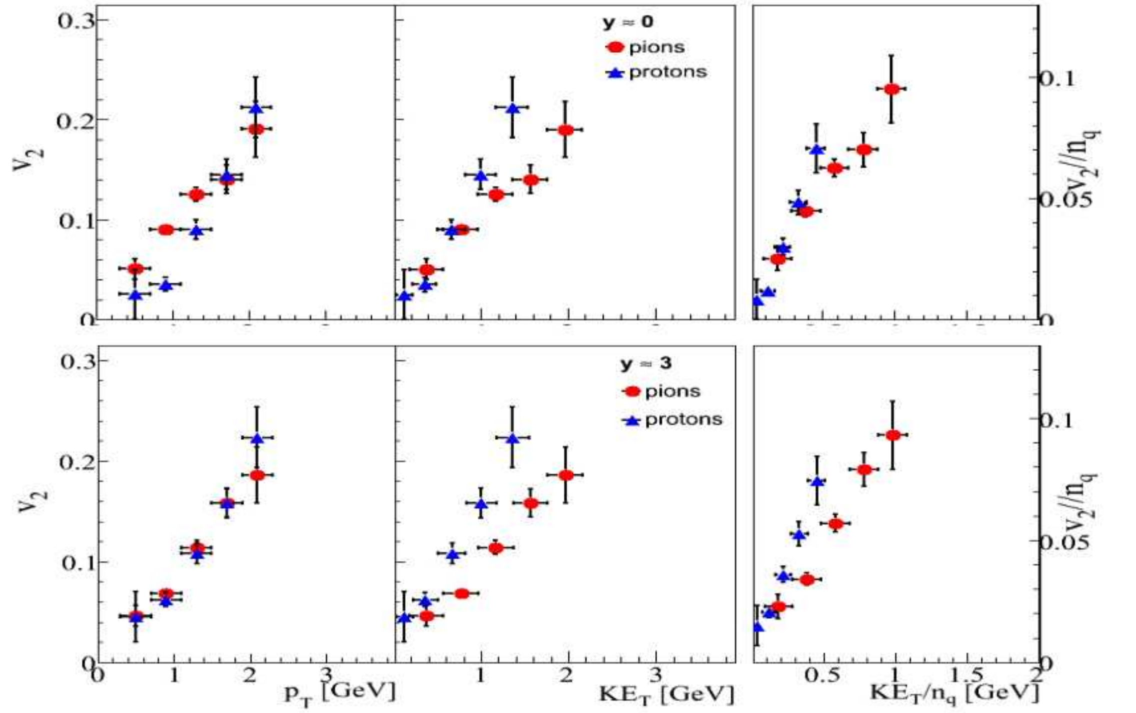

FIGURE 5. Preliminary v_2 for protons and π^+ versus p_T (left) and k_T (center) and v_2/n_{quark} versus k_T/n_{quark} (right) for y=0 (top) and y=3 (bottom)

further increasing the rate at which mass is lost. This effect means that very small black holes would evaporate very quickly, converting there energy to a thermal distribution of particles. For charged black holes the temperature drops, eventually reaching zero when $Q^2 = GM$. One can make an analogue of strongly coupled QCD which can be mapped onto general relativity using the ADS/CFT correspondence. In this transformation

$$M \to E, \text{ i.e. } \mathrm{dE_T/dy}$$
$$Q \to B, \text{baryon number}$$
$$G \to 1/2\sigma, \text{ string tension}$$

and the temperature T_Q of a black hole becomes,

$$T_Q(B) = T_Q(0) \times \frac{4\sqrt{1 - 2\sigma B^2/E^2}}{(1 + \sqrt{1 - 2\sigma B^2/E^2})^2} \tag{1}$$

which falls very slowly as the ratio B/E increases until $2\sigma B^2/E^2$ reaches 0.9 when it suddenly dives to zero. The temperature $T_Q(B)$ is then identified as the chemical temperature deduced from an analysis of particle ratios. We make the following working definitions;

$$E = \sum_{i=\pi,k,p} \langle m_T^i \rangle dN^i/dy \tag{2}$$

$$B = dN^p/dy - dN^{\bar{p}}/dy \tag{3}$$

and take $\sigma = 200 MeV^2$.

Figures 1 and 3 show that both $\langle m_t \rangle$ and dN/dy decrease with rapidity. At $\sqrt{s_{NN}}$ =200 GeV both quantities are larger [7]. Therefore dE_T/dy decreases with rapidity and increases with $\sqrt{s_{NN}}$. Figure 2 shows that $B = dN^p/dy - dN^{\bar{p}}/dy$ has the opposite dependence, rising with rapidity and falling with $\sqrt{s_{NN}}$. Thus our largest lever arm for testing Equation 1 come from comparing T at y=0 and $\sqrt{s_{NN}} = 200$GeV with T at y=3 at $\sqrt{s_{NN}} = 62.4$GeV. We find that $2\sigma B^2/E^2$ changes from $(1.0 \pm 0.3) * 10^{-4}$ to $(3.6 \pm 0.2) * 10^{-2}$ over this range while the freeze-out temperature drops from 160 ± 5 MeV to 116 ± 9. To accommodate such a temperature change within the model would require rescaling our B/E measurements by a factor of 5. Using HIJING we estimate that the net baryon number is a factor of 2.0 times the net proton yield at y=0. At y=3 this factor rises to 2.1. Modifying our definition working of B/E to use these estimates and taking $\pi^0 = (\pi^+ + \pi^-)/2$ increases B/E by a factor of 1.4 ± 0.1.

Conclusions

The rapidity distributions of particles produced from central Au+Au collisions are Gaussian at RHIC energies with widths that increase with $\sqrt{s_{NN}}$. The pion widths are well described by the Landau/Caruthers model of a relativistic fluid expanding at constant entropy in one dimension until it hadronizes into massless particles. Of course the motion of the particles is not only along the z axis. The increases $\langle m_T \rangle$ with mass suggests there is a radial component to the expansion. The strength of the radial flow decreases with energy and rapidity. The fact the the scaled elliptic flow $v_2(k_T)/n_{quark}$ is proportional to k_T/n_{quark} at y=0 suggests that it is the partons that flow before they coalesce into hadrons. There are hints that this proportionality breaks down at y=3 but we need to finish our study of the systematic errors of this analysis. The ordering of the rapidity widths, $\sigma_{k^+} > \sigma_{\pi^\pm} > \sigma_{k^-} > \sigma_{pbar}$ does not depend upon energy and has been investigated in terms of a thermal model of flavor production. The chemical freeze-out temperature drops with rapidity and energy while $\mu_s \approx 1/4\mu_q$. All of these data are suggestive of very early thermalization. This can be explained by assuming that particles are radiated from black holes. We have made the first moves towards testing this hypothesis. Currently its seems that this theory predicts too slow a change of the chemical freeze-out temperature as the ratio of net baryon number to transverse energy increases.

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