Overview and Recent Results from BRAHMS

F.Videbæk for BRAHMS collaboration

Physics Department, Brookhaven National Laboratory

Abstract

The BRAHMS experiment was designed to measure and characterize in particular the properties of rapidity dependence of particle production in heavy ion collisions. The data-taking is now over, results of several years of analysis have been published and demonstrates several important features of the rapidity dependence, not envisioned from the start of the RHIC program. The bulk properties of the system formed at high rapidity resembles that of systems for lower energies at mid-rapidity when referenced via the baryo-chemical potential. New physics in AA are essentially observed at mid-rapidity including the demonstration that high-p_T suppression is a final state effect. Another key result is that in d+A collisions at forward rapidities where the very low-x ~~reion~~ of the nucleus was probed, a strong suppression of pion production was observed consistent with the picture of gluon saturation. The latest results examines the centrality and rapidity dependence of nuclear stopping, the particle production of pions, collective expansion vs. rapidity, and the baryon enhancement at intermediate values of p_T.

1. Introduction

In these proceedings I review a number of BRAHMS results in the perspective of the early goals and expectations for the experiment, and what has been achieved over the 6 RHIC runs in which we took data. In addition I discuss a number of unforeseen results that came from later development of the RHIC physics and the open-minded approach to experimental research. This proceeding does neither give a full account of history, nor all results, for which I refer to our extensive publications in journals and conference proceedings. See e.g. Ref.[1] for early results and discussion.

The experiment was proposed in 1990, the Technical Design was approved in 1997, was ready for the first RHIC run with partial spectrometer system, and completed for the second RHIC run. BRAHMS took data for 6 RHIC runs with the last data set recorded during the 62.4 GeV p+p run in 2006.

The initial goals of BRAHMS were to measure identified particle production over a wide range of rapidity, p_T, and for a range of collisions systems A+A, p+A and p+p. This was to clarify the reaction mechanism and look for possible effect of the QGP that might be visible in inclusive spectra. Additional goals were developed during the construction process and the early RHIC running leading to the important d-Au run in 2003, and a successful BRAHMS transverse spin program (see e.g.[2]). BRAHMS took heavy ion data at $\sqrt{s_{\rm NN}}$ = 130, 200 and 62.4 GeV in Au+Au, and Cu+Cu collisions. Important reference data was recorded in d+Au and p+p at 200 GeV, and pp spin data taken at 200 and 62.4 GeV. The setup of the BRAHMS experiment is described in detail in Ref.[3].

2. Net-baryons in AA and pp

It is important to understand nuclear stopping in detail since it is a requisite for the formation of dense systems in describing the conversion of the initial kinetic energy into matter excitation at mid-rapidity. A detailed description of how this transport takes place is a necessary ingredient in our overall understanding of the reactions and in the expectations of forming and for studying the properties of QGP. The second question is whether the picture by Bjorken [4] that proposes

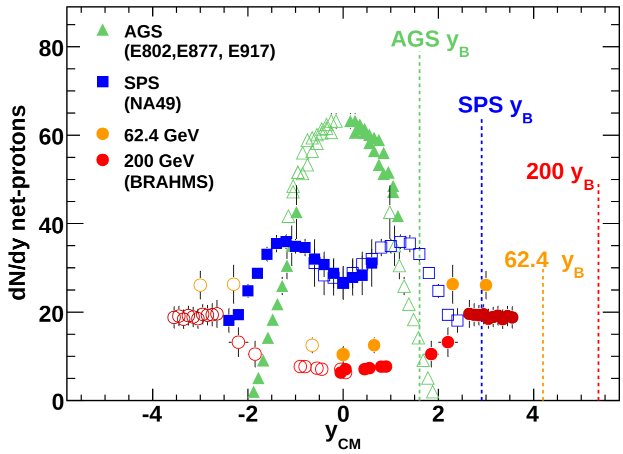

Figure 1: Net-proton distributions from AGS to top RHIC energies. The high-rapidity 200 GeV data points are preliminary. The beam rapidity y_b at each energy is indicated by the dashed lines.

a transparent scenario ~~with~~ the central region is net-baryon free, and most baryons are at high rapidity after the collision is achieved at the highest energies. At the lower AGS energies rapidity distributions are closer to a Landau description where most of the baryons end up near mid-rapidity [5]. This topic was addressed in BRAHMS via measurement of the net-proton distributions at 200 and 62.4 GeV. In Fig. 1 we show the data from Ref.[6] together with the new data at 62.4 GeV [7]. The data from AGS to RHIC show a clear development of a net-proton poor region at mid-rapidity, and most baryons in the region less than 2 units away from beam rapidity. It is also demonstrated in another proceeding for this conference [8] that the peripheral Au+Au collisions net-protons distributions are similar in shape to those of pp. At both energies we estimate that about 70% of the incident energy is available for entropy production and longitudinal momentum of produced particles.

The average rapidity loss δy is about 2 units at high energy for central collisions in contrast to p+p, where low energy data give $\delta y \approx 0.6$, and with ~~an~~ near constant distribution in dn/dx. This implies that in rapidity space one will expect that $dN/dy = Ae^{-(y-y_B)}$. In Fig. 2 we demonstrate that the data from NA49, and the BRAHMS RHIC pp data from 62 and 200 GeV fall close to such an universal curve. This common behavior leaves little room for new mechanisms in pp stopping up to RHIC energies.

3. Meson Rapidity Distributions

One of the key observations of BRAHMS is that the rapidity density distributions of produced particles, i.e., pions, kaons, and anti-protons, exhibit a nearly Gaussian distribution as was shown

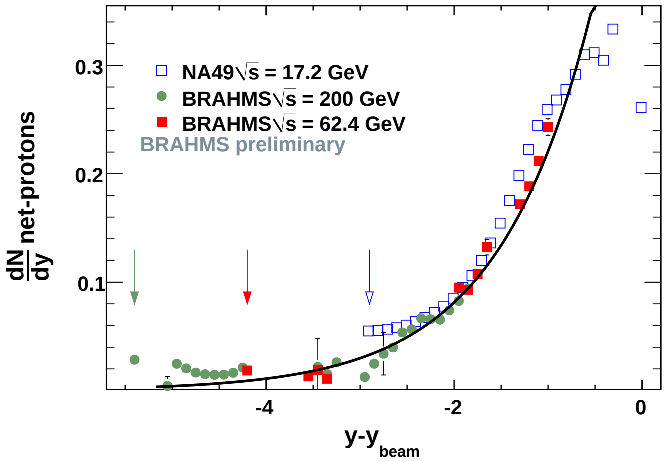

Figure 2: Net-proton rapidity distributions in pp scaled to the beam rapidity. The arrows indicate the position of mid-rapidity for 200, 62.4 and 17.2 GeV, respectively. The NA49 data are from a recent preprint[9].

in Ref.[10]. Similar overall features have already been observed in central Au+Au collisions at AGS and Pb+Pb reactions at SPS. In Fig. 3 we show the newer preliminary data from run 4 for central, i.e., 0-10% together with the published data for K^+. The data have not been corrected for weak decay feed-down, a few percent correction. This is reminiscent of the hydrodynamical

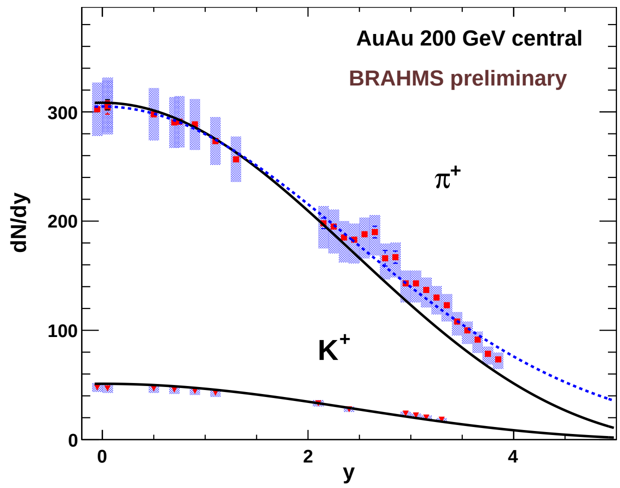

Figure 3: Rapidity distributions for pions and kaons in central Au+Au collisions at 200 GeV. The $\pi^+$are for $0 - 10\%$ centrality, while the K^+ are the published data from Ref.[10]

expansion model proposed by Landau, a feature that has attracted theoretical interest. In a recent paper, Wong [11] derived the form $dN/dy = \exp(\sqrt{y_B^2 - y^2}$, instead of Landau's original distribution, dN/dy = $\exp(\sqrt{L^2 - y^2}$, where $L \approx \ln(\sqrt{s_{\rm NN}}/2m_p)$. In Fig. 3 we show this prediction a solid line compared to the new preliminary data from the RHIC run-4. The measurements give a slightly wider distribution than the Landau description, as indicated by the dashed curve which is a Gaussian description of the data. The interpretation of this is open; the agreement with the model does not necessarily indicate that the system developed full stopping.

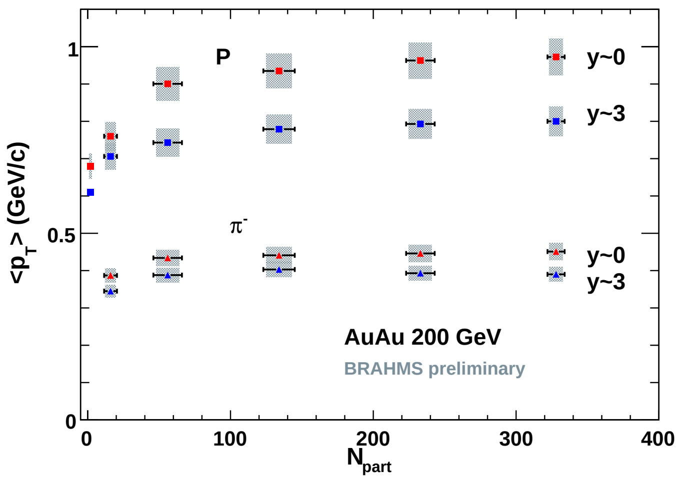

Figure 4: Mean p_T vs. centrality for protons and pions and mid and forward rapidity in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV.

4. Radial and Elliptic Flow

The centrality dependence of the spectra, in particular heavier hadrons like protons, is an indication of the importance of radial flow in the collisions. In Fig. 4 we show the dependence of the mean p_T for π^- and protons at central and forward (y = 3) rapidities. The $\langle p_T \rangle$ values are fairly constant in both rapidity and centrality for pions, whereas for protons they exhibit a rapid rise from the most peripheral collisions followed by a much slower rise. Their value at forward rapidities are clearly lower than at mid-rapidity. This change in $\langle p_T \rangle$ is consistent with a reduction of radial flow at large rapidities. Since the radial flow to a large degree develops in the later stages of the collision, it does not reflect the initial pressure. On the other hand the elliptic flow is believed to be established in the early stages of the collision. A strong azimuthal flow signature at RHIC suggests rapid system equilibration, leading to an almost perfect liquid state. The longitudinal extent of the flow behavior depends on the formation dynamics for this state and can be studied by measuring the pseudorapidity dependence of the second Fourier component (v_2) of the azimuthal angular distribution. BRAHMS has measured for identified particles [illegible] as a function of p_T (0.5 -2.0 GeV/c) for 0-25% and 25-50% centrality and pseudorapidity [illegible]) for $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV Au+Au collisions. These are discussed in more details in the contribution [12] from this conference. Figure 5 shows $v_2(p_T/n_q)$ plotted against the mean transverse energy per constituent quark , $\langle E_T \rangle / n_q$ for pseudorapidities of $\eta \approx 0$, 1 and 3 for the $0 - 25\%$ centrality selection. It is compared to the universal systematics at mid-rapidity for scaled v_2 from R. Lacey[illegible], and agrees well at $\eta = 0$ and 1, whereas $\eta = 3$ is consistent with being lower than the systematics, a trend we clearly observe in the centrality range $25 - 50\%$ (not shown here, but in[12]). This dependency with pseudo-rapidity together with the simultaneous reduction of p_T, i.e., the spectral shape of the inclusive hadrons, makes these measurements of $v_2(p_T)$ consistent the inclusive v_2 vs. pseudo-rapidity as observed by PHOBOS for charged hadrons[14].

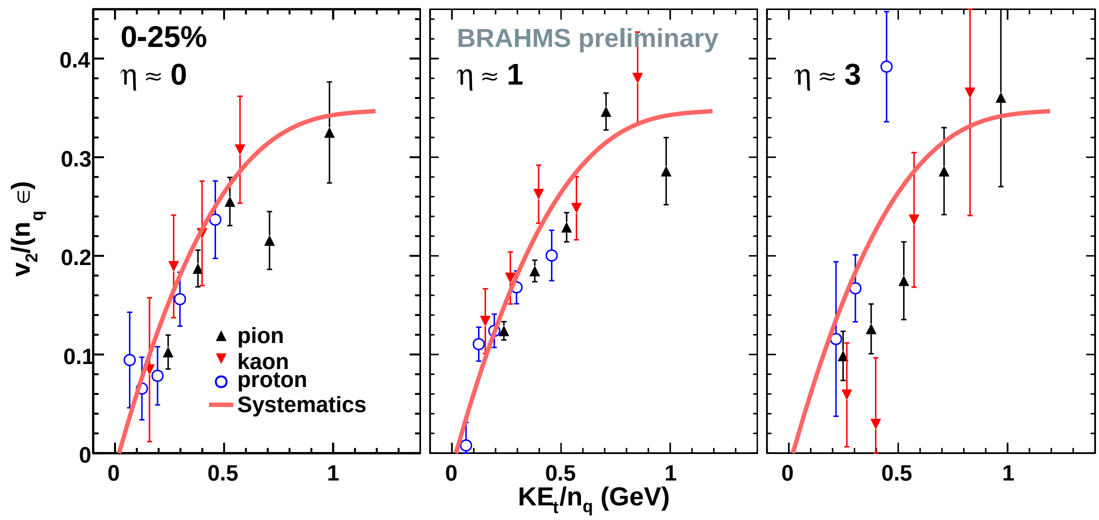

Figure 5: $v_2(p_T)$ scaled by the number of valence quarks n_q and the participant eccentricity as function of the transverse kinetic energy KE_T scaled by n_q for $\eta \approx 0$, 1 and 3.

5. Baryon to Meson Ratio vs. Chemical Potential

The discovery of a large baryon to meson ratio in 1 < 5 GeV/c at RHIC is taken as an indication that quark coalescence plays an important role for particle spectra. The spectral shape and ratios reflect the underlying hadronization scenario (recombination vs. fragmentation); importance of radial flow of bulk medium, and we would like to understand this in detail. Energy and centrality dependence of p/π^+ and $\bar{p}/\pi^-$ and their evolution on rapidity may allow us to verify the proposed scenarios. Thus at large μ_B, the picture, suggested by mid-rapidity measurements, might be contaminated by final state hadron interactions, leading to a transition from the parton recombination scheme to a hydrodynamical description that has a common velocity field for baryons and mesons [15, 16]. Figure 6 shows a comparison between the p/π measured in Au+Au collisions at $\sqrt{s_{\rm NN}}$ =62.4 GeV and η = 0.0 shown with closed black triangles and the same ratio measured in Au+Au reactions at $\sqrt{s_{\rm NN}}$ = 200 GeV and η = 2.2 shown with the open red triangles. The pseudo-rapidity intervals selected for this comparison, namely η = 0.0 for Au+Au at $\sqrt{s_{\rm NN}}$ = 62.4 GeV and η = 2.2 for Au+Au at $\sqrt{s_{\rm NN}}$ = 200 GeV correspond to similar $\bar{\rm p}$/p = 0.45, which in turn, can be connected to a common value of the baryo-chemical potential μ_B of the observed bulk media, equal to ≈ 62 MeV for these two energies [17, 18]. The lower values depicted by the grey stars show the p/π^+ ratio measured in the p+p system at $\sqrt{s}$ = 62.4 GeV. The similarity of proton-to-pion ratios for these selected heavy ions collisions suggests that the baryon and meson production at the p_T interval studied (up to 2 GeV/c) is dominated by medium effects and is determined by the bulk medium properties. These strong medium effects are also suggested by the observed enhancement of the p/π as function of p_T in the nucleus-nucleus systems compared to the ratio extracted from nucleon-nucleon interactions. In addition, Fig. 6 shows that the THERMINATOR model [19] calculations (dashed curve) describes central Au+Au data reasonably well. This model is a 1+1 D hydromodel that incorporates rapidity dependence of statistical particle production (including excited resonances) imposed on the hydro-dynamical flow. Additional details and discussion can be found in another contribution

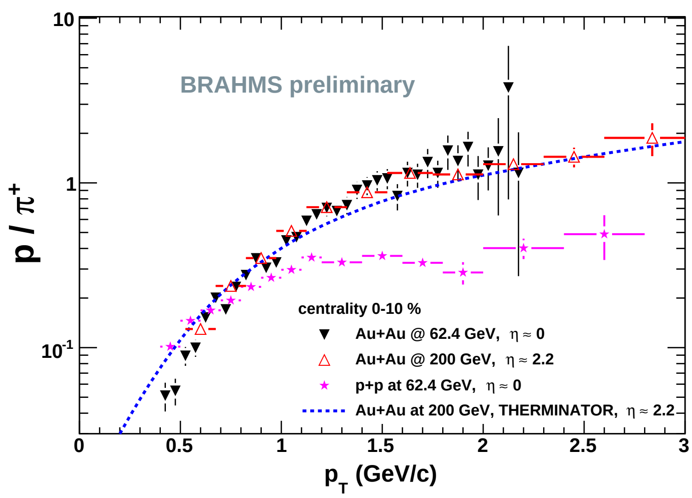

Figure 6: p/π ratios vs.p_T for central Au+Au collisions at η = 0 and η = 2.2 at approximately same $\bar{p}/p$ ratio.

to this conference [20].

6. Nuclear Suppression at High Rapidity in dAu Collisions

The RHIC run-3 with d+Au was designed primarily to determine if the large suppression seen at intermediate to high p_T in meson spectra relative to scaled yield of p+p at mid-rapidity is an initial or a final state effect. The data determined that a final-state effects are in play, and is caused

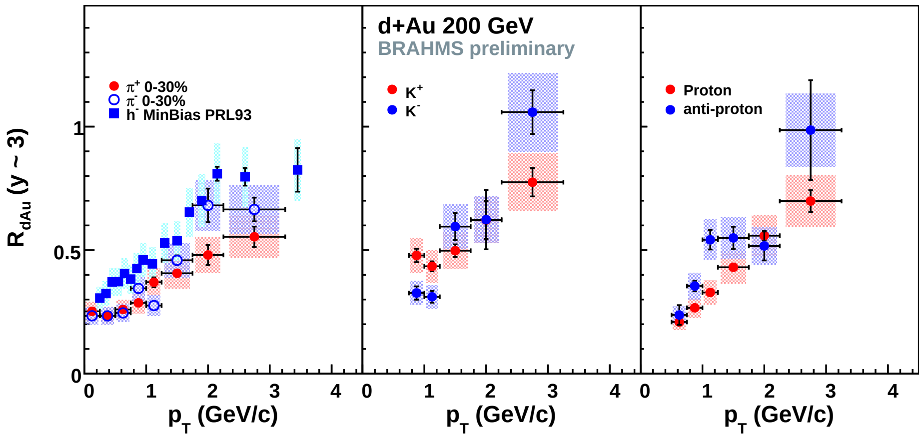

Figure 7: Nuclear modification factor identified π, K and p in dAu collisions at 200 GeV.

by partonic interactions of the hot and dense media formed in A+A collisions at RHIC energies. It was also conjectured that measurements at forward rapidities could provide evidence for a new kinematic domain, where the high gluon density in nuclei would saturate and cause a reduction in the yield of produced particles. This state of matter was named the Color Glass Condensate (CGC). The BRAHMS data provide an excellent testing ground for this idea by providing the nuclear modification factors R_{dA} vs. rapidity for charged hadrons [21]. The dependence of the data as a function of rapidity and centrality closely followed the predicted signature for the CGC, albeit other explanations cannot be ruled out. Here we present preliminary data for R_{dAu} for identified π, K, and protons at rapidity 3.2. Figure 7 shows that for the centrality bin $0-30\%$ all the identified hadron species exhibit a similar suppression pattern vs. p_T. The pions show a difference between π^+ and π^- that can be attributed to the isospin dependence of the reference p+p pion yields at forward rapidities. It also demonstrates that the h^- yield essentially equals that of π^- as expected.

The observation of this suppression at high rapidity has been a subject of many theoretical investigations since the data were published, and I will make no attempt to properly reference all of the published papers. Important modifications to the spectra can be expected from nuclear shadowing at small x, kinematic suppression at large x_F, as well as other possibilities. At this point, no definitive statement on the importance of Gluon Saturation at RHIC energies can be made and further result of correlation measurements are eagerly awaited.

7. Summary

In summary we highlight some specific lessons that have been learned from the BRAHMS data.

- The net-proton distributions in peripheral Au+Au collisions have a similar shape as pp. A clear change in net-proton rapidity shape takes place at 60% centrality from where on distributions at more central collisions exhibit more stopping, with the bulk of the Au nucleus participating in the interaction.
- The near Gaussian shape of produced mesons was a surprise, with the distrubutions bearing close resemblance to the prediction of the Landau hydrodynamical model, though it does not prove its validity.
- The baryon chemical potential μ_B is a driving physics variable for many inclusive and bulk observables such as particle ratios vs. y and p_T. In this proceeding we have shown that even the p_T-dependence of particle ratio's like p/π vs. p_T is governed in large part by this variable.
- The differential elliptic flow decreases at forward rapidity, with the decrease for central events consistent with the expectations of 3D Hydro+Cascade calculations. Mid-central collisions at forward rapidity $v_2(p_T)$ show somewhat larger decrease towards forward rapidities. A decrease is also observed in the mean p_T-values for identified hadrons, in particular protons going for forward rapidities, consistent with a reduction in radial flow.
- The d-Au high-p_T suppression observed at high rapidity is relevant for importance of the Color Glass Condensate at RHIC energies and has inspired other new instrumentation and measurements in the forward region at RHIC.

Overall the BRAHMS experiment has provided unique physics results, particular in the forward region, providing insight into several key questions. How does matter behave at very high temperature and/or density? and what is the nature of gluonic matter? and how does it behave inside of strongly interacting particles?

References

[1] I.Arsene et al. [BRAHMS Collaboration],*Nucl.Phys* **B757** (2005) 1

[2] I.Arsene et al. [BRAHMS Collaboration], *Phys.Rev.Lett.* **101** (2008) 042001.

[3] M.Adamczyk et al. [BRAHMS Collaboration], *Nucl.Instr.Meth.* **499** (2003) 437.

[4] J. D. Bjorken, *Phys.Rev.* **D27** (1983) 140

[5] F. Videbæk and O. Hansen, *Phys. Rev.* **C52** (1995) 2584.

[6] I.G.Bearden et al., *Phys. Rev. Lett.* **93** (2004) 102301.

[7] I. C. Arsene et al. [BRAHMS Collaboration], *Phys. Lett.* **B677** (2009) 267

[8] H.Dalsgaard [BRAHMS Collaboration], these proceedings.

[9] T. Anticic et al. [NA49 Collaboration], arXiv:0904.2708 [hep-ex].

[10] I.G. Bearden et al. [BRAHMS Collaboration], *Phys. Rev. Lett.* **94** (2005) 032301.

[11] C-Y.Wong, *Phys.ReV.* **C78** (2008) 054902

[12] S.J.Sanders [BRAHMS Collaboration], these proceedings.

[13] R.A.Lacey and A Taranenko, arXiv:nucl-ex/0610029v3.

[14] B.B.Back et al. *Phys.Rev.Lett.* **94** (2-5) 122303.

[15] T.Hirano and Y.Nara, *Nucl.Phys.* **A743** (2003) 437.

[16] W.Broniowski and W.Florkowski, *Phys.Rev.Lett.* **87** (2001) 272302.

[17] I.G. Bearden et al. [BRAHMS Collaboration], *Phys. Rev. Lett.* **90** (2003) 102301.

[18] I.C. Arsene et al. [BRAHMS Collaboration],*Int. Jour. of Mod. Phys.* **E 16** (2007) 2035; I.C. Arsene [BRAHMS Collaboration], IJMPE **16**, (2007) 2035.

[19] W.Broniowski and B.Biedroni, *Phys.Rev.* **C75** (2007) 054905.

[20] P.Statszel [BRAHMS Collaboration], these proceedings.

[21] I.C. Arsene et al. [BRAHMS Collaboration],*Phys. Rev. Lett.* **93** (2004) 242303.