Recent Results on Forward Regime by the BRAHMS Experiment at RHIC

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The BRAHMS experiment has unique capabilities of measuring particle production in a wide range of rapidity. The latest results of properties of the medium evolution from midrapidity to the forward region in the ultra-relativistic collisions at RHIC are presented. The rapidity loss at RHIC energies is shown for nucleus+nucleus system. The studies of baryon enhancement to the pion yield at intermediate p_T are presented for p+p and Au+Au reactions. We also discuss measurements of the nuclear modification factor in d+Au collisions in the context of Color Glass Condensate.

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I. INTRODUCTION

The BRAHMS experiment at RHIC can measure and identify particle over a wide range of rapidity and transverse momentum. It allows to study the different aspects of strong interactions in the ultra-relativistic nucleus+nucleus collisions. BRAHMS has estimated the degree of nuclear stopping by measurement of net-baryon distributions which are related to baryon number transport during the collision [1, 2]. The rapidity dependent proton-to-pion ratio reveals which picture of hadronization in the bulk medium is supported [3, 4]. The nuleon+nucleus data are a starting point of exploration of the inital state effects [5, 6]. In this paper, the recent BRAHMS results are presented for d+Au reactions at $\sqrt{s_{NN}}$ = 200 GeV and for Au+Au and p+p collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV.

The description of BRAHMS experimental setup can be found in [7].

II. NET-BARYON DENSITY DISTRIBUTION

Wide rapidity acceptance of the BRAHMS spectrometers provides unique opportunity to study nuclear stopping in the ultra-relativistic nucleus+nucleus reactions. The average rapidity loss, $\langle \delta y \rangle = y_b$ - $\langle y \rangle$, quantifies stopping in heavy ions collisions. If initial baryon participants lose all the kinetic energy ($\langle \delta y \rangle = y_b$) we observe full stopping, for $\langle \delta y \rangle = 0$ the system is completely transparent. Before RHIC era, at Schwer Ionen Synchrotron (SIS) in Darmstadt, Alternating Gradient Synchrotron (AGS) in Brookhaven National Laboratory and Super Proton Synchrotron (SPS) in CERN, it was noticed that $\langle \delta y \rangle$ is proportional to the beam rapidity [8]. The BRAHMS results [9] show that this linear scaling is broken above top SPS energies - Figure 1. Assuming that the underlying physics is the same at highest attainable energies, the extrapolation of $\langle \delta y \rangle$ to the beam rapidity for Large Hadron Collider, $y_b \approx 8.7$, is depicted in Figure 1.

While the nuclei are colliding lose their kinetic energy. The energy loss per participant baryon is estimated to be $\langle \delta E \rangle = 21 \pm 2$ GeV for Au+Au at $\sqrt{s_{NN}} = 62.4$ GeV [9] and $\langle \delta E \rangle = 73 \pm 6$ GeV for Au+Au at $\sqrt{s_{NN}} = 200$ GeV [10] for the most (0-10%) central collisions. For two colliding nucleons the calculated energy loss constitutes about 70% of the initial energy of beam. This energy loss is transformed mainly into particle production and random (thermal) motion of produced partons and particles.

From BRAHMS measurements at the top RHIC energy one can conclude that the midra-

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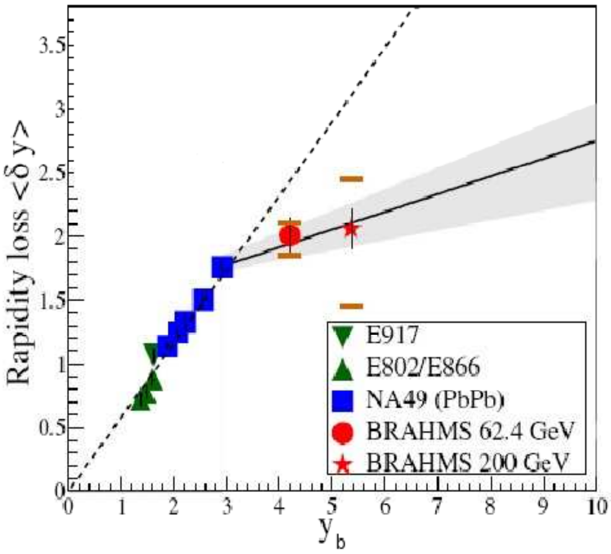

FIG. 1: The rapidity loss as a function of beam rapidity for heavy ions collisions at AGS, SPS and RHIC. The solid line represents the fit to the SPS and RHIC data. The grey band is the statistical uncertainty. The dashed line is linear fit to the AGS and SPS results [8]. Published in [9].

pidity region of the collision is almost net-baryon-free. It corresponds to picture of interacting matter proposed by Bjorken [1] with near free net-baryon content at midrapidity. At lower energy, $\sqrt{s_{NN}} = 62.4$ GeV, for Au+Au reactions at $y \approx 0$ the net-proton $\frac{dN}{dy}$ indicates that the medium is also quite transparent compared with data at SPS and AGS energy [8].

III. PROTON-TO-PION RATIO AT INTERMEDIATE P_T

The proton-to-pion ratios for Au+Au reactions at $\sqrt{s_{NN}} = 62.4$ GeV and $\sqrt{s_{NN}} = 200$ GeV can be used for characterizing the properties of bulk medium by studying baryon and meson production. As it has been shown in [11], for positively charged hadrons for heavy ion reactions the enhancement of baryon production in respect to the meson yield has been observed at intermediate p_T. At the top RHIC energy of colliding nuclei the proton and pion production seems to be comparable with each other at midrapidity at 2.5 GeV/$c < p_T <$ 4 GeV/c, but with increasing η the baryon production prevails over meson production successively. The centrality dependence of proton-to-pion ratio suggests that the p/π^+ ratios at intermediate transverse momenta scales with the size of the created medium. The ratio of $\bar{p}/\pi^-$ reaches the maximum of 0.5 at $\eta \approx 2.25$ for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and decreases for more forward pseudorapidities.

The p/π^+ ratio for Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV for $\eta \approx 2.67$, 3.2, 3.5 is depicted in Figure 2. Additionally, the p+p results at the same energy and η bins are shown. At all pseudorapidities unexpected high value of 10 at $p_T = 1.5$ GeV/c of proton-to-pion ratio is observed [12]. There is remarkably little difference in the p/π^+ ratios for a very wide range of systems. It is in contrast to the trends at midrapidity and forward rapidity regimes for Au+Au at $\sqrt{s_{NN}} = 200$ GeV where significant medium effect reflected in dependence of p/π^+ ratios on system size is observed [11]. However, the observed consistency between the results of p+p reactions and Au+Au system for all centrality bins for $\eta \approx 3.2$ is reckoned as the crossing point in pseudorapidity. These results indicate that the nuclear modification factor for protons and pions are equal in the observed p_T range, as shown in Eq. 1:

$$\frac{R_{AA}^{\text{protons}}}{R_{AA}^{\text{pions}}} = \frac{\frac{d^2N_{\text{protons}}^{A+A}/dp_T dy}{d^2N_{\text{pions}}^{A+A}/dp_T dy}}{\frac{d^2N_{\text{protons}}^{p+p}/dp_T dy}{d^2N_{\text{pions}}^{p+p}/dp_T dy}} = = \frac{p/\pi^+\,(\text{Au}+\text{Au})}{p/\pi^+\,(\text{p}+\text{p})} = 1. \quad (1)$$

The energy available from the rapidity loss of the beam dissipates and contributes through coalescence mechanism to increased proton yield at intermediate p_T. At very forward rapidities one can expect less power of nuclear stopping which might be observed as a result of enhancement of proton production to pion production that, particularly, is seen for elementary reaction. The higher value of p/π^+ for $\eta \approx 3.5$ for p+p collisions might acknowledge this argumentation. The crossing point was predicted by UrQMD [13], HIJING [14] and AMPT [15] calculations, but almost lower one unit of rapidity as experimental data indicate.

Figure 3 shows the p/π^+ ratios as a function

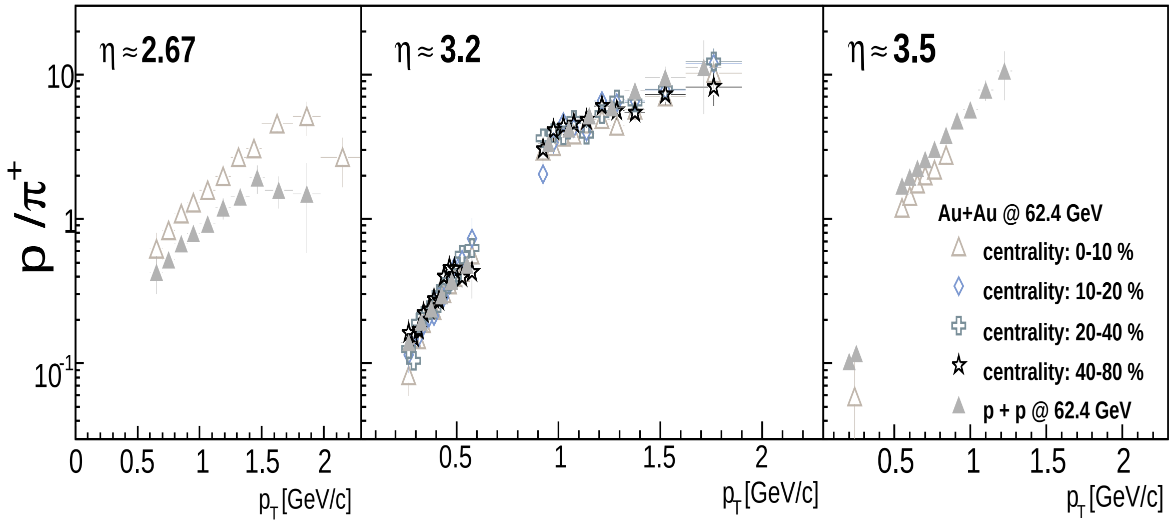

FIG. 2: The p/π^+ ratio vs. transverse momentum for Au+Au and p+p collisions at $\sqrt{s_{NN}} = 62.4$ GeV.

of p_T in the pseudorapidity range $2.6 \leq \eta \leq 3.8$ extracted from p+p reactions at $\sqrt{s} = 200$ GeV. The behaviour of $p/\pi^+(p_T)$ ratio for p+p system reveals the characteristic tendency, namely the increase of peak value with increasing pseudorapidity. A very clear difference is found as the pseudorapidity changes from $\eta = 2.6$ to $\eta = 3.8$. The value of ratio grows systematically with rising η from 0.4 at $\eta = 2.3$ reaching almost 1 at the most forward pseudorapidity interval, $\eta \approx 3.8$. That high value of p/π^+ ratio is indispensable related to the large proton yield at high p_T. At highest covered p_T for $\eta \approx 2.6$, 3.1, 3.3 the proton-to-pion ratio seems to converge a common valueof 0.4 which is consistent with the perturbative QCD predictions [16].

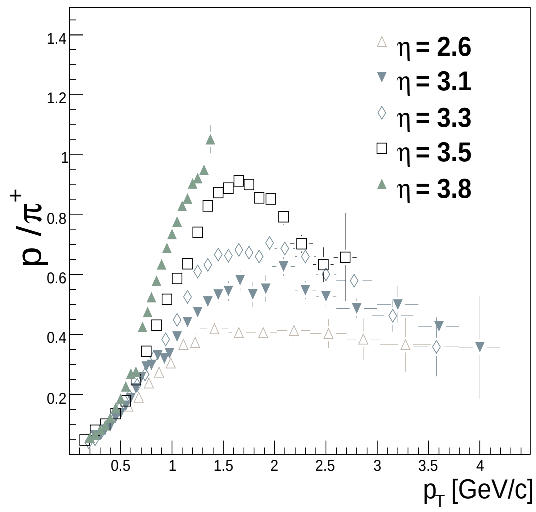

FIG. 3: The p/π^+ ratio for set of η bins in the range $2.6 \leq \eta \leq 3.8$ for p+p reactions at $\sqrt{s} = 200$ GeV.

For negativly charged hadrons, the value of proton-to-pion ratio for elementary reactions in the measured pseudorapidity interval reaches maximum value of ~ 0.15 - Figure 4. The p/π^+ ratio exceeds the $\bar{p}/\pi^-$ ratio by a factor of 5. The peak value is less than 0.3 for $\eta = 2.3$ and dropping to < 0.1 for $\eta = 3.8$. Moreover, the maximum of $\bar{p}/\pi^-$ ratio is shifted to the lower transverse momentum ($p_T \approx 1$ GeV/c) compared with the positive particles.

An interesting feature of $\bar{p}/\pi^-$ ratios is also revealed at low p_T. On the right panel of Figure 4 the comparison of $\bar{p}/\pi^-$ in Au+Au and in p+p at $\sqrt{s_{NN}} = 200$ GeV is shown. The data at the covered pseudorapidity interval, $2.6 \leq \eta \leq 3.8$, expose the same feature and the value of $\eta \approx 3.3$ has been selected for showing centrality dependence of the ratios. The $\bar{p}/\pi^-$ ratios increase with p_T for central and peripheral Au+Au collisions, while the ratio maximizes at ~ 0.9 GeV/c for p+p collisions. The ratios for Au+Au for different centrality classes and for p+p system cross each other at approximately $p_T \approx 0.9$ GeV/c. The higher value

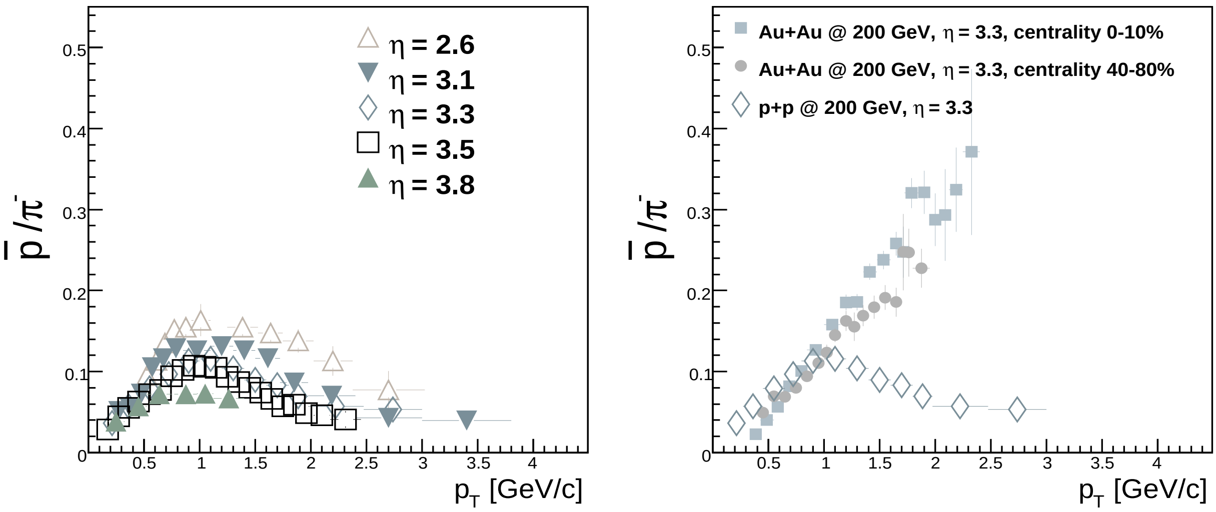

FIG. 4: The $\bar{p}/\pi^-$ ratio vs. transverse momentum for $2.6 \leq \eta \leq 3.8$ for p+p collisions at $\sqrt{s}$ = 200 GeV (left). The results of ratio for p+p reactions are compared with data for Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV for two intervals of centrality 0-10% and 40-80% at the same value of pseudorapidity, $\eta \approx 3.3$ (right).

of $\bar{p}/\pi^-$ for p+p than for Au+Au collisions at the soft p_T region might be due to medium effects in heavy ions collisions at relativistic energies.

IV. RAPIDITY DEPENDENT NUCLEAR MODIFIACTION FACTOR FOR D+AU COLLISIONS

By comparing the nuclear modification factor for pions, kaons and protons at $y = 0$ for d+Au reactions at $\sqrt{s_{NN}}$ = 200 GeV, we have observed a significant enhancement, especially for protons near $p_T \approx 2$ GeV/c [17]. This enhancement is known from SPS measurements [18] as the Cronin effect and is associated with partonic multiple scattering - an initial state broadening of the distribution of quark momenta. When we go to more forward rapidities BRAHMS has observed a significant suppression at high p_T. In Figure 5 the results of nuclear modification factor for identified hadrons for 0-30% centrality at $y \approx 3$ for d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV are presented. For central collisions at forward rapidity the suppression of R_{dAu} is evident for all kinds of hadrons and there is no noticeable difference between individual species. The existence of the Color Glass Condensate might be an explanation of this effect in forward regime [5] where the low-x components (mostly gluons) of the wave function of the gold nuclei are probed by deuteron parton rescattered into forward region. On the other hand, the Dual Parton Model with a dynamical shadowing correction has described the rapidity and p_T dependence of R_{dAu} [6].

V. SUMMARY

The net-baryon density results show the linear scalability of rapidity loss at SPS energies is broken at RHIC and slowly depends on beam rapidity. The wide rapidity range studies of the $p/\pi(p_T)$ provide information on how the hadronization process is driven with changing bulk medium properties. The ratio of p/π^- for p+p collisions at $\sqrt{s}$ = 200 GeV rise above the results for heavy ion reactions for forward η at low p_T. At lower collision energy, $\sqrt{s}$ = 62.4 GeV, a common crossing point in pseudorapidity is found for p+p and all centrality intervals for Au+Au system. The studies of R_{dAu} for identified harons at $\sqrt{s_{NN}}$ = 200 GeV are the foreword of existence of the Color Glass Condensate state, however more experimental evidences are coveted.

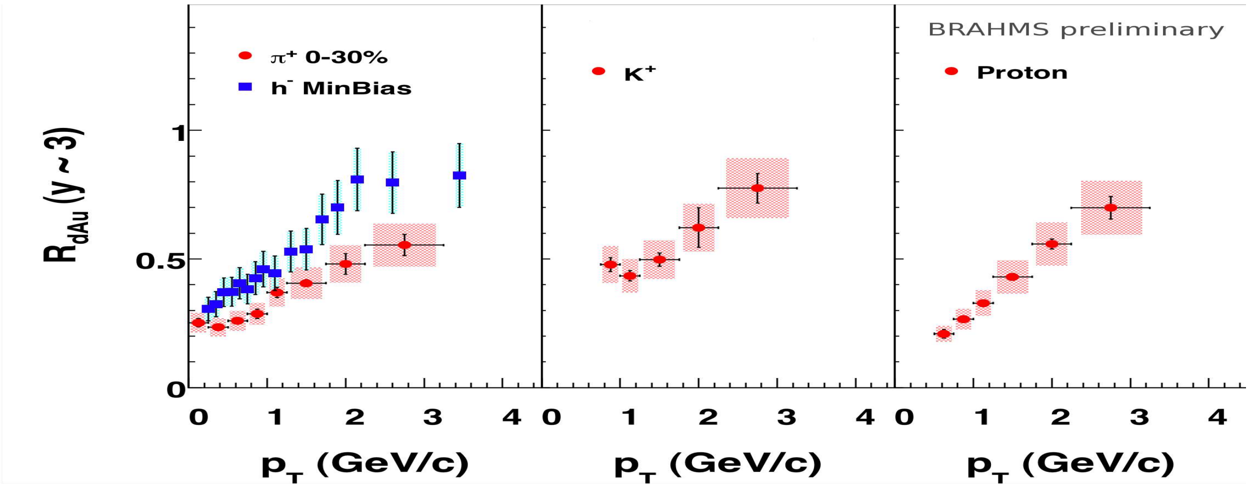

FIG. 5: The nuclear modification factor R_{dAu} of π^+, K^+ and p for d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at $\eta \approx$ 3. The R_{dAu} of negatively charged hadrons marked with blue (online) squares was published in [17].

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