Recent Results on the Forward Regime by the BRAHMS Experiment at RHIC

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The BRAHMS experiment has unique capabilities to measure particle production over a wide range of rapidity. This paper presents the latest results how the medium evolves from midrapidity to the forward region in the ultra-relativistic collisions at RHIC. The rapidity loss at RHIC energies is shown for nucleus+nucleus system. The studies of proton enhancement to the pion yield at intermediate p_T are presented for p+p and Au+Au reactions. For d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV pions, kaons and protons are all suppressed in the forward rapidity.

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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 us to study the different aspects of strong interactions in the ultra-relativistic nucleus+nucleus collisions. The description of BRAHMS experimental setup can be found in [1]. BRAHMS has estimated the degree of nuclear stopping by measuring net-baryon distributions which are related to baryon number transport during the collision [2, 3]. The rapidity dependent proton-to-pion ratio is sensitive to hadronization mechanism in the bulk medium [4, 5]. The nuleon+nucleus data are a starting point of exploration of the inital state effects [6, 7]. 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.

II. NET-BARYON DENSITY DISTRIBUTION

The wide rapidity acceptance of the BRAHMS spectrometers provides unique opportunity to study nuclear stopping in 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 the initial baryon participants lose all kinetic energy ($\langle\delta y\rangle = y_b$) we observe full stopping, for $\langle\delta y\rangle = 0$ the system is completely transparent. Before the 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]. Figure 1 [9] shows that this linear scaling is broken above top SPS energies. Assuming that the underlying physics is the same at highest attainable energies, these data constrain the value of $\langle\delta y\rangle$ for Large Hadron Collider ($y_b \approx 8.7$) as 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, longitudinal momentum and random (thermal) motion of produced partons and particles.

From BRAHMS measurements at the top

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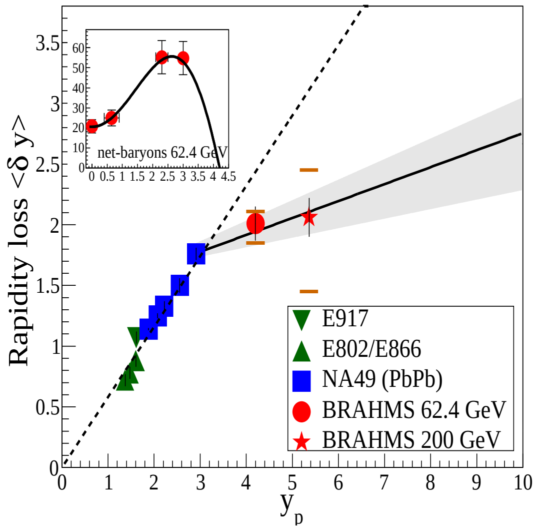

FIG. 1: The rapidity loss as a function of beam rapidity for heavy ions collisions at AGS, SPS and RHIC. The solid line represents the fit to the SPS and RHIC data. The grey band is the statistical uncertainty. The dashed line is linear fit to the AGS and SPS results [8]. Published in [9].

RHIC energy one can conclude that the midrapidity region of the collision is almost net-baryon-free. It corresponds to picture of interacting matter proposed by Bjorken [2] 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 to characterize the properties of the 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 for the most central collisions the proton and pion production seems to be roughly equal at midrapidity in the range of 2.5 GeV/$c < p_T <$ 4 GeV/c. As we go to the more forward pseudorapidity the p/π^+ ratio goes above 1. 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 $\bar{p}/\pi^-$ ratio reaches 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:

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

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

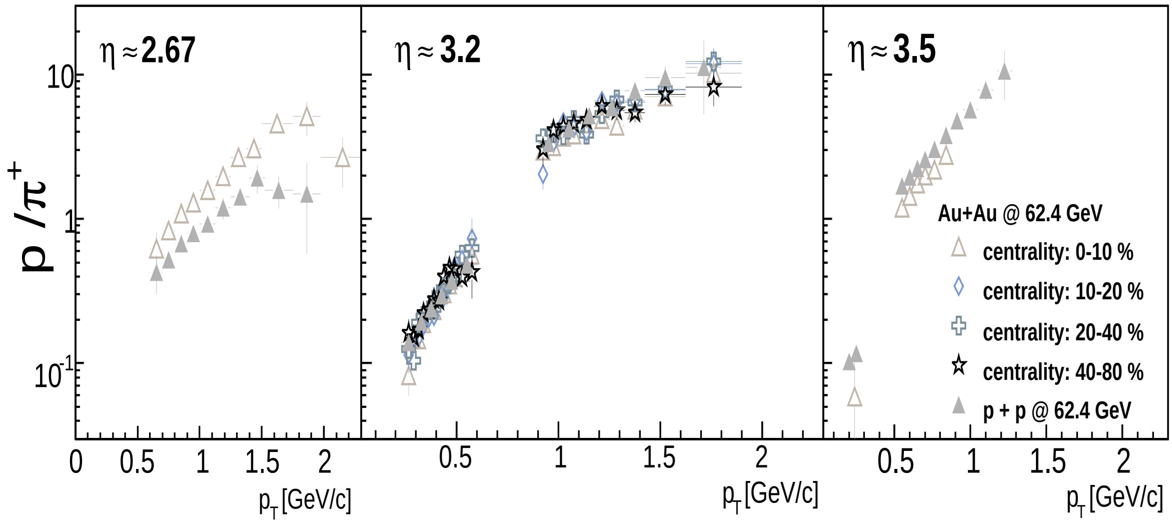

FIG. 2: The p/π^+ ratio vs. transverse momentum for Au+Au and p+p collisions at $\sqrt{s_{NN}} = 62.4$ GeV.

data indicate.

Figure 3 shows the p/π^+ ratios as a function 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, $\eta \approx 3.8$. The increase of this ratio is due 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 value of 0.4 which is consistent with a perturbative QCD calculation with partonic energy loss processes at mid-rapidity [16].

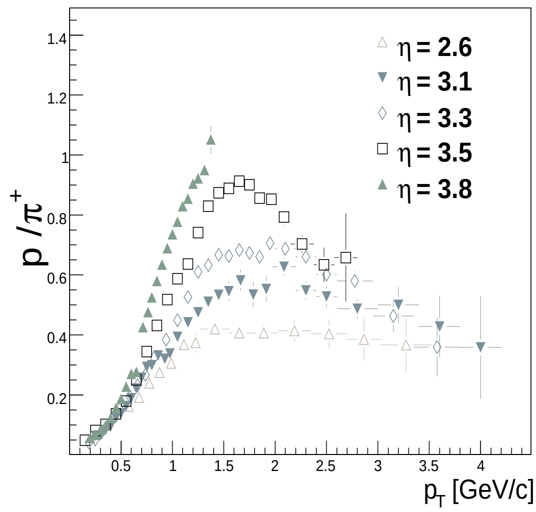

FIG. 3: The p/π^+ ratio for set of η bins in the range $2.6 \leq \eta \leq 3.8$ for p+p reactions at $\sqrt{s} = 200$ GeV.

For negativly charged hadrons, the value of proton-to-pion ratio for elementary reactions in the measured pseudorapidity interval reaches ~ 0.15 which is a factor of 5 lower than p/π^+ ratio - Figure 4. 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 central-

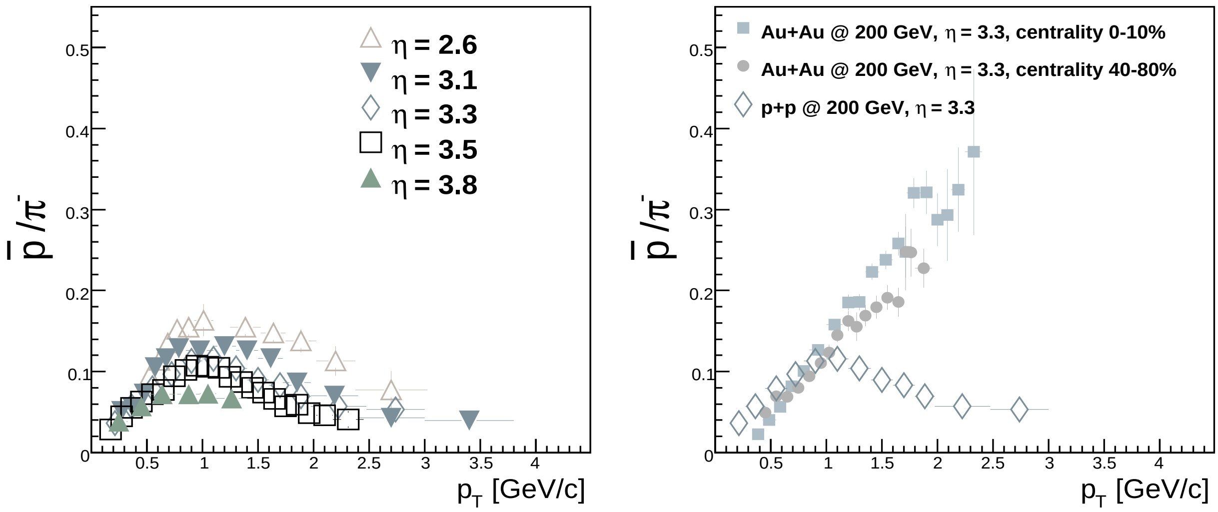

FIG. 4: The $\bar{p}/\pi^-$ ratio vs. transverse momentum for $2.6 \leq \eta \leq 3.8$ for p+p collisions at $\sqrt{s}$ = 200 GeV (left). The results of ratio for p+p reactions are compared with data for Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV for two intervals of centrality 0-10% and 40-80% at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

ity classes and for p+p system cross each other at approximately $p_T \approx 0.9$ GeV/c. The higher value 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

Deuteron+gold collisions can be used to follow the initial state of the wave function and nuclear matter effects. For d+Au reactions at $\sqrt{s_{NN}}$ = 200 GeV we have seen a significant enhancement of protons near $p_T \approx 2$ GeV/c and y = 0 [17]. This enhancement was observed at SPS [18] known as the Cronin effect that is associated with partonic multiple scattering - an initial state broadening of the distribution of quark momenta. At forward rapidities BRAHMS has oserved a significant suppression of charged hadrons. Figure 5 shows 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. For central collisions at forward rapidity the suppression of R_{dAu} is evident for pions, kaons and protons and there is no noticeable difference between the individual species. The existence of a Color Glass Condensate might be an explanation of this effect in forward regime [6] 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} [7].

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. At $\sqrt{s}$ = 200 GeV the $\bar{p}/\pi^-$ ratio at low p_T at forward pseudorapidities is higher for p+p than Au+Au collisions. At lower collision energy, $\sqrt{s}$ = 62.4 GeV, a common crossing point in pseudorapidity is found for p+p and Au+Au reactions all centralities. The studies of R_{dAu} for identified harons at $\sqrt{s_{NN}}$ = 200 GeV are consistent with the existence of the Color Glass Condensate. The data provide motivation for more detailed studies of the initial effects of heavy ion collisions.

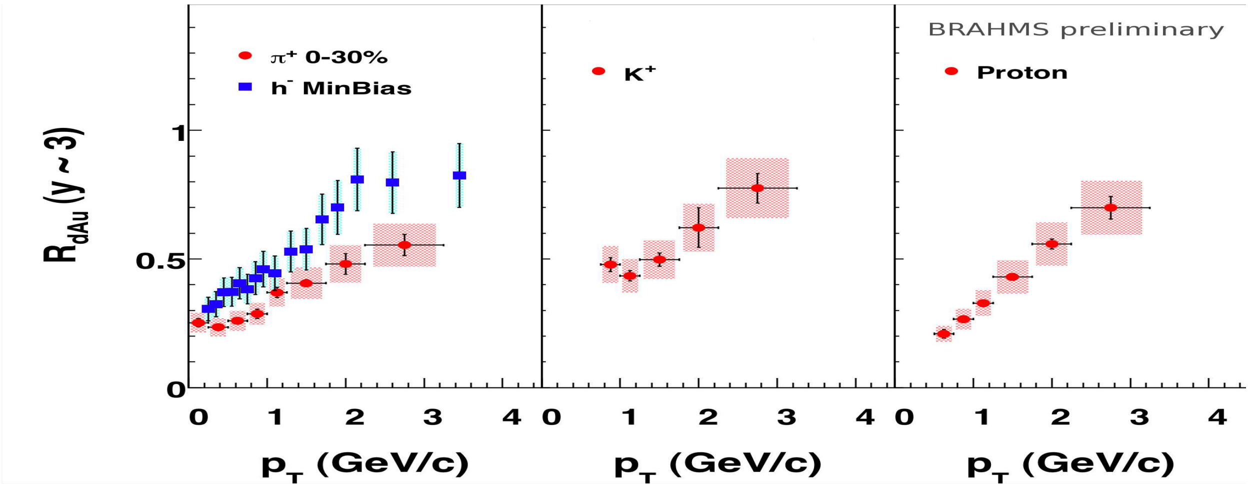

FIG. 5: The nuclear modification factor R_{dAu} of π^+, K$^+$ and p for d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at $\eta \approx 3$. The R_{dAu} of negatively charged hadrons marked with blue (online) squares was published in [17].

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