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2012 J. Phys.: Conf. Ser. 381 012042

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New information on the dynamics of relativistic nucleus-nucleus collisions

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Abstract. Relativistic heavy-ion collisions offer a unique opportunity to study highly excited dense nuclear matter in the laboratory. We present measurements of identified charged hadron production at different rapidities from Au+Au and p+p collisions at 200 GeV. Coulomb effects on pion spectra in relativistic nuclear collisions at RHIC energies will be investigated. The nuclear modification factors for identified particles show distinct meson/baryon dependence. At high p_T the charged pion yields are suppressed by a factor of ~ 5 , while the baryon production is enhanced in Au+Au collisions, when compared to the binary scaled p+p data from the same energy.

1. Introduction

Heavy ion collisions at relativistic energies are used to study the properties of nuclear matter in extreme conditions of temperature and density and to analyze the possible phase transition from hadronic matter to a new state of matter called the quark and gluon plasma, QGP [1-4]. Since hadrons contain basic information about collision dynamics, the production of hadrons is one of the important probes of QGP.

Transverse momentum spectra of hadrons produced in relativistic nuclear collisions provide valuable information on particle production mechanisms as well as dynamics and properties of the matter produced. The intermediate p_T region is considered to have both soft and hard hadron production mechanisms. The soft part includes hydrodynamic collective flow, parton recombination and the hard part includes jet fragmentation and its quenching.

2. BRAHMS Experiment

The data presented here were collected with BRAHMS detector system [5] from RHIC (Relativistic Heavy Ion Collider) [6]. BRAHMS (Broad Range Hadron Magnetic Spectrometers) consists of a set of global detectors for event characterization and two magnetic spectrometers, the mid-rapidity spectrometer (MRS) and the forward spectrometer (FS), which identify charged hadrons over a broad range of rapidity and transverse momentum. Collision centrality is determined from the charged particle multiplicity measured by a set of global detectors.

The Mid-Rapidity Spectrometer (MRS), which operates in the polar angle interval from 90° to 30° , is composed of a single dipole magnet placed between two Time Projection Chambers (TPC) and a Time-of-Flight (TOF) detector for particle identification. The Forward Spectrometer (FS), which operates in the polar angle range of $15^\circ < \theta < 2.3^\circ$, has two TPCs, three Drift Chambers and four dipole magnets. Particle identification in the FS is provided by TOF measurements in two separate hodoscopes (H1 and H2) and/or by using a Ring Imaging Cherenkov detector (RICH) located at the end of the spectrometer. The mid-rapidity arm is capable of separating pions from Kaons up to 2 GeV/c and charged kaons from protons or antiprotons up to 3 GeV/c, while the forward arm can identify particles up to 35-40 GeV/c by using the Cherenkov ring detector (RICH).

3. Experimental results

3.1. Enhancement factors

One of the proposed quark-gluon plasma (QGP) signals is the increased strangeness production compared to that of a hadron gas [7]. Strange particles are of particular interest since all strange hadrons must be formed in the matter produced. Other processes can also enhance strangeness production [8] and, therefore, elementary p-p collisions, where QGP formation is unlikely, are important as a reference. We investigate the kaon production in Au+Au collisions to gain better insight into strange quarks production. The pion and kaon enhancement factors are presented in Fig. 1. The enhancement factor is defined as the yield per mean number of participating nucleons, N_{part} , in Au+Au collisions divided by the respective value in p+p collisions at the same energy:

$$E = \frac{2}{N_{part}} \left(\frac{dN^{A+A}}{dy} \bigg/ \frac{dN^{p+p}}{dy} \right) \quad (1)$$

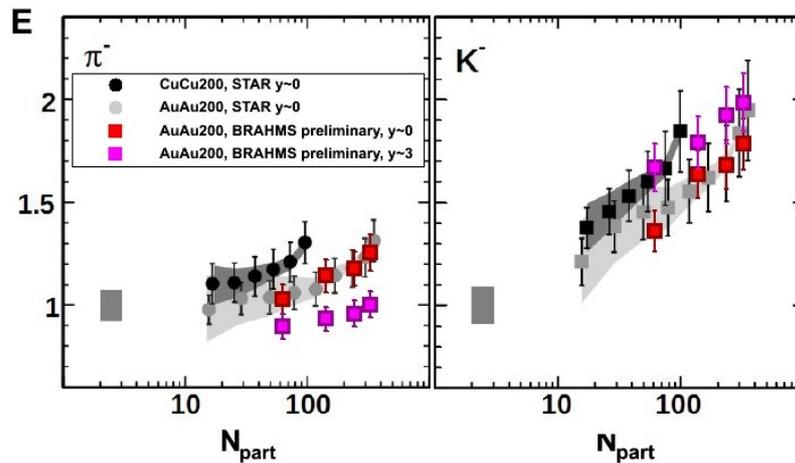


Figure 1. Enhancement factors for negatively charged pions and kaons as a function of N_{part} in 200 GeV Au+Au and p+p collisions. STAR data are from ref. [9]. Error-bars represent statistical and systematic uncertainties on the A+A measurements added in quadrature. The shaded bands depict model uncertainties on number of participants calculation. The bands on the left show uncertainties from the pp measurements that are correlated for all data points.

An enhancement of kaon production with respect to pions as a function of collision centrality is observed at midrapidity as well as at forward rapidity. At rapidity $y \sim 3$ the enhancement factors for negative charged kaons are about 2 with respect to elementary interactions. The different behavior for pion and kaon enhancement factors at forward rapidity may suggest that there are different particle

production mechanisms at work as a function of rapidity. Such a difference would still have to be checked in terms of modifications from pp collisions, as manifestation of the isospin effect.

Van Hove in ref. [10] discusses the possibility that the mean-transverse momentum vs. rapidity density correlation could provide a signal for QGP formation, considering that the dN/dy reflects the entropy and the transverse momentum spectrum is related to the temperature of the system and the transverse expansion of the hadronic matter.

From the p_T spectra obtained in most central 0-10% Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV, the particle yields are evaluated for each rapidity interval by integrating the covered p_T range and extrapolating to regions outside the experiment acceptance. The chosen rapidity intervals for this analysis were: (-0.1, 0.1), (0.8, 0.9), (2.7, 2.8), (2.8, 2.9), (2.9, 3.0), (3.0, 3.1), (3.1, 3.2), (3.2, 3.3), (3.3, 3.4), (3.4, 3.5) and (3.5, 3.6). The kaon spectra were fitted with an exponential formula and the resulting kaon yields were calculated by extrapolating the fit function to the full p_T range. The mean transverse momentum of charged kaons is calculated using $\langle p_T \rangle = \int p_T f(p_T) dp_T / \int f(p_T) dp_T$, where $f(p_T)$ is the exponential function. The $\langle p_T \rangle$ - dN/dy results are shown in the Fig. 2.

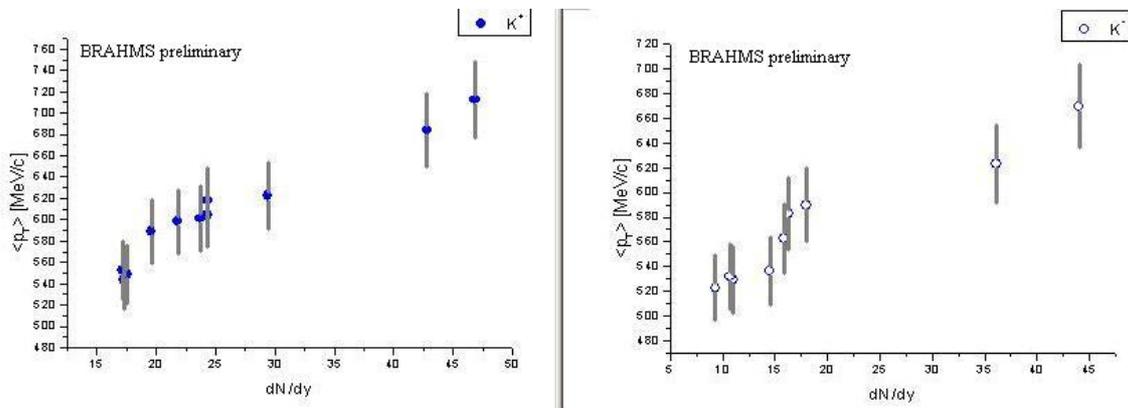


Figure 2. The mean transverse momentum as a function of dN/dy for positive (left) and negative (right) kaons produced in central 0-10% Au-Au collisions at 200 GeV.

The two points from $y \sim 0$ and 0.85 may correspond to the QGP phase at midrapidity, in the central region of the collision. As the rapidity increases, $\langle p_T \rangle$ and dN/dy values decrease and may be interpreted in terms of formation of a mixed phase of QGP and hadrons during the evolution of the heavy-ion system. The points from $y \sim 3$ reflect the hadronic phase, because at the projectile and target rapidities, the system temperature and the particle density are both lower and we don't expect QGP formation in these regions. However, the p_T distributions of the hadrons produced do not reflect the conditions from the early stages of the collision and are influenced by collective flow.

3.2. Coulomb interaction at relativistic energies

The asymmetry in the number of charged pions produced in heavy ion collisions at AGS and SPS energies was interpreted as an effect of Coulomb interaction between the pions produced and the positive charge from reaction partners. At lower energies, the colliding nuclei are fully stopped and expand relatively slowly in all directions; therefore the total charge stays together for sufficient time to significantly accelerate or decelerated the charged pions produced. The interaction between charged pions and net charge of protons changes the transverse momentum of pions with the Coulomb "kick", p_c [11]:

$$\frac{\pi^-}{\pi^+} = \left\langle \frac{\pi^-}{\pi^+} \right\rangle \exp\left(\frac{m_{\perp}^- - m_{\perp}^+}{T}\right) \frac{p_T + p_c}{p_T - p_c} \quad (2)$$

where $m_{\perp}^{\pm} = \sqrt{m^2 + (p_T \pm p_c)^2}$. At higher energies the colliding nuclei are no longer stopped; the system expands faster in longitudinal direction (a higher degree of transparency) resulting in a smaller Coulomb effect.

The ratio of negative to positive pions produced in Au+Au collisions at two different energies, $\sqrt{s_{NN}} = 5$ GeV (at E866-AGS) and $\sqrt{s_{NN}} = 200$ GeV (at BRAHMS-RHIC), as a function of transverse mass, is shown in the left panel of the Fig. 3. At low m_T - mass, the pion ratios behave differently, while at high m_T - mass both ratios approach one. A pronounced enhancement in the π^- / π^+ ratio at low transverse kinetic energy is evident for the AGS data while the BRAHMS data are found to be almost flat with respect to m_T -mass. If stopping is significant, a large amount of positive charge from the beam and target nuclei will concentrate around the mid-rapidity of the colliding system. Therefore, the AGS enhancement could be explained if low- p_T positive pions are pushed towards higher p_T by a large net positive charge at mid-rapidity; conversely, negative pions would be attracted. At RHIC energy a low net-baryon density is observed at midrapidity [14] and consequently, there are negligible Coulomb effects.

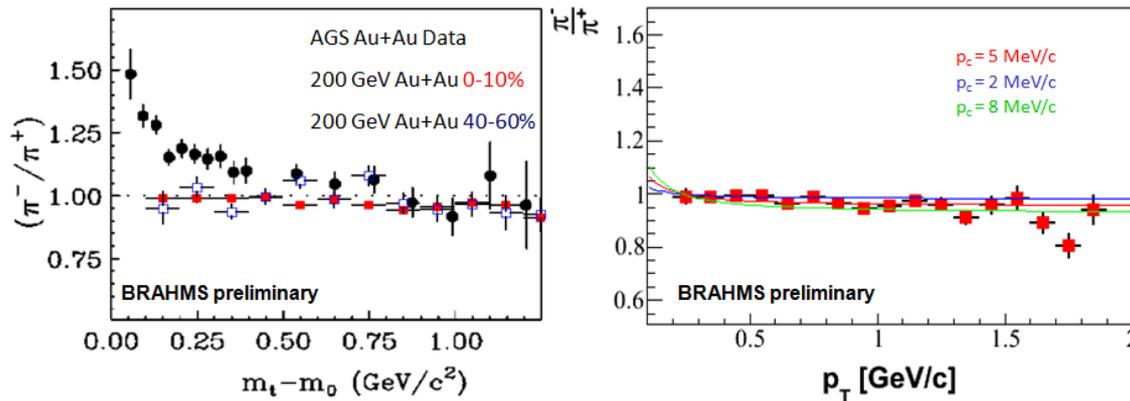


Figure 3. Left: AGS Au+Au at 11.6 AGeV/c (full symbols) [12] and BRAHMS Au+Au at 200 GeV [13] (red full symbols are for 0-10% centrality, blue open symbols for 40-60% centrality). Right: Charged pion ratio produced in 0-10% Au+Au collisions at 200 GeV [13] as a function of transverse momentum. The lines are the calculations using the relation (2) for $p_c=2$ MeV/c (blue), $p_c=5$ MeV/c (red) and $p_c=8$ MeV/c (green).

In the right panel of Fig. 3 the BRAHMS negative to positive charged pions ratio, for the most central 0-10% Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, is plotted as a function of transverse momentum is compared to the ratio predicted by Eq. (2) using three constant values of Coulomb kick: 2 MeV/c, 5 MeV/c and 8 MeV/c.

3.3. High p_T suppression

The nuclear modification factor R_{AA} for unidentified charged hadrons as function of p_T for the most central Au+Au collisions at pseudorapidities 0, 0.8, 2.6, 3.0 and 3.6 is shown in Figure 4. The error bars are statistical; the shaded bands are the systematic errors. The shaded band around unity shows the systematic uncertainty in the number of binary collisions. The R_{AA} values decrease for $p_T > 2$ GeV/c showing the suppression of the charged hadron yields relative to the p+p reference. At high p_T ($p_T > 4$ GeV/c), the charged hadron yields are suppressed by a factor of ~ 3 as compared with binary scaled p+p yields. For all the studied pseudorapidities, the R_{AA} distribution remains systematically lower than unity for central collisions and shows a slight decrease of the high p_T suppression with respect to p+p collisions, going from midrapidity to forward rapidity. This suppression has been interpreted as due to

the energy loss of the energetic partons traversing the hot and dense medium produced. The high p_T suppression observed in the most central 200 GeV Au+Au collisions persists over a wide range in pseudorapidity and it is almost constant for all the angles studied.

The nuclear modification factors, for particles identified, show distinct meson/baryon dependence. Nuclear modification factors for charged pions, protons and antiprotons produced in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV for five rapidities $y = 0.0, 0.8, 2.6, 3.1, 3.4$ are presented in the Figure 5. Error bars represent statistical errors. The shaded boxes around points show systematic errors. The dotted lines indicate the expectation of binary scaling. The shaded band around unity indicates the systematic error associated with the uncertainty in the number of binary collisions.

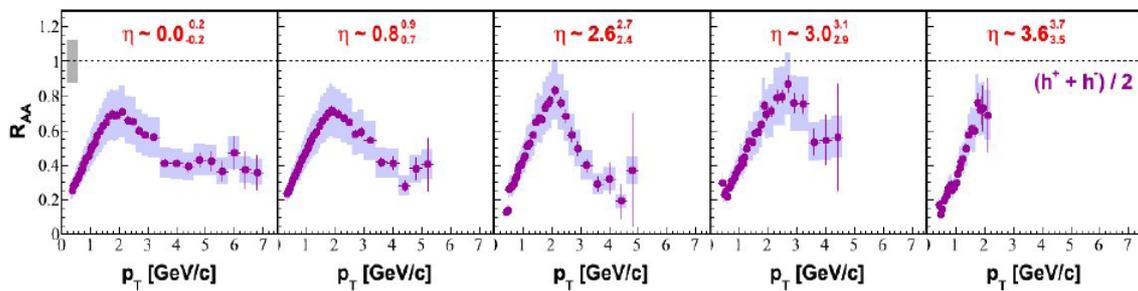


Figure 4. Nuclear modification factor R_{AA} for unidentified charged hadrons at different pseudorapidities for 200 GeV Au+Au collisions (0-10% centrality). Figure taken from ref [16].

For all the studied rapidities, the pion R_{AA} distribution remains systematically lower than unity for most central Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV. At high p_T , the charged pion yields are suppressed by a factor of ~ 5 as compared with binary scaled p+p pion yields. The suppression of pions at high p_T compared with p+p collisions indicates that the partons undergo a large energy loss due to a hot, dense medium created during the collisions. The R_{AA} shows constant high p_T suppression with respect to p+p collisions, going from midrapidity to forward rapidity. This result could be an indication that other nuclear effects than parton energy loss might contribute to the rapidity constant suppression [15].

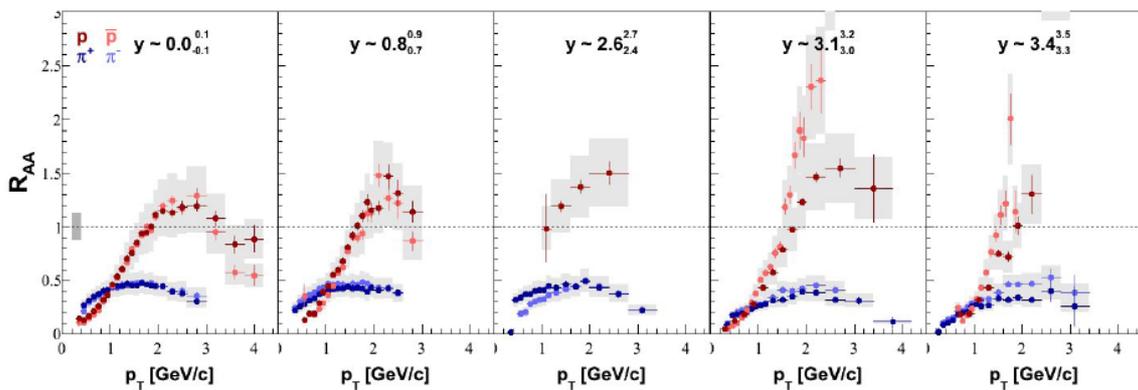


Figure 5. Nuclear modification factor R_{AA} for pions, protons and antiprotons at different rapidity for the most central collisions (0-10% centrality). Figure taken from ref [16].

In contrast, the proton and antiproton yields do not show suppression with respect to binary scaling, in the intermediate p_T range for all the rapidities. Due to the poor statistics, for rapidity $y=2.6$, which corresponds to the FS positioned at 8° relative to the beam line, we present only the R_{AA} for protons.

The R_{AA} distributions for protons and antiprotons are, within errors, approximately independent of the rapidity.

Conclusions

Pion and kaon production are enhanced as a function of collision centrality. Different behaviour for pion and kaon enhancement factors at forward rapidity was observed. At RHIC energies the Coulomb interaction is negligible. The high p_T suppression observed in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV is almost independent of rapidity but does depend on the particle type. This might indicate an interplay between (partonic) energy loss and hydrodynamics.

Acknowledgments

We thank the BRAHMS Collaboration for their excellent and dedicated work to acquire and process the unique experimental data and their support to our group. This work was partially supported by a grant of the Romanian National Authority for Scientific Research, CNS-UEFISCDI, project number 34/05.10.2011. The work of Oana Ristea and Catalin Ristea was also supported by the strategic grant POSDRU/89/1.5/S/58852, Project „Postdoctoral programme for training scientific researchers”, co-financed by the European Social Found within the Sectorial Operational Program Human Resources Development 2007-2013.

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