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Nuclear modification factor for charged pions and protons at forward rapidity in central Au + Au collisions at 200 GeV

BRAHMS Collaboration

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Abstract

We present spectra of charged pions and protons in 0–10% central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV at mid-rapidity ($y = 0$) and forward pseudorapidity ($\eta = 2.2$) measured with the BRAHMS experiment at RHIC. The spectra are compared to spectra from $p + p$ collisions at the same energy scaled by the number of binary collisions. The resulting nuclear modification factors for central Au + Au collisions at both $y = 0$ and $\eta = 2.2$ exhibit suppression for charged pions but not for (anti-) protons at intermediate p_T. The $\bar{p}/\pi^-$ ratios have been measured up to $p_T \sim 3$ GeV/c at the two rapidities and the results indicate that a significant fraction of the charged hadrons produced at intermediate p_T range are (anti-) protons at both mid-rapidity and $\eta = 2.2$.

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1. Introduction

One of the reasons for studying heavy-ion collisions at high energies is to search for the predicted quark–gluon plasma (QGP), a deconfined state of quarks and gluons, and to investigate the properties of this state of matter at extremely high energy densities. High p_T hadrons, primarily produced from the fragmentation of the hard-scattered partons, are considered a good probe of the QGP [1–3]. Due to induced gluon radiation, hard-scattered partons will suffer a larger energy loss in a hot dense medium of color charges than in color neutral matter. This results in fewer charged hadrons produced at moderate to high p_T; the hadrons are said to be suppressed. Indeed, all four experiments at RHIC have observed that high p_T inclusive hadron yields in central Au + Au collisions are suppressed as compared to $p + p$ and $d +$ Au interactions at mid-rapidity [4–7]. However, it was also discovered that the yields of protons and anti-protons at intermediate p_T (1.5–4.5 GeV/c) are comparable to those of pions and not suppressed at mid-rapidity as compared to elementary nucleon–nucleon collisions [5,8]. These experimental results have motivated several suggestions on how hadrons are produced at intermediate p_T [9–12], such as the possibility that boosted quarks from a collectively expanding QGP recombine to form the final-state hadrons [10–12]. Among the interesting results from the BRAHMS experiment is that at forward pseudorapidity $\eta = 2.2$ inclusive negatively charged hadrons are suppressed in both central Au + Au and minimum-bias $d +$ Au collisions [4,13]. This raises the possibility that initial-state effects such as gluon saturation may also influence hadron production at intermediate p_T [14–16].

To explore the effect of the nuclear medium on intermediate p_T particle production, we present in this Letter the invariant p_T spectra of charged pions and protons measured by the BRAHMS experiment at RHIC up to 3 GeV/c in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV at both mid-rapidity and forward pseudorapidity $\eta = 2.2$. The spectra are then compared to reference data from $p+p$ collisions at the same energy scaled by the number of binary collisions $\langle N_{\mathrm{bin}}\rangle$ by using the nuclear modification factor:

$$R_{AA} = \frac{d^2N^{AA}/dp_T\,dy}{(\langle N_{\mathrm{bin}}\rangle/\sigma^{pp}_{\mathrm{inel}})\,d^2\sigma^{pp}/dp_T\,dy}, \tag{1}$$

where $d^2N^{AA}/dp_T\,dy$ is the differential yield per event in the nucleus–nucleus $(A+A)$ collision, and $\sigma^{pp}_{\mathrm{inel}}$ and $d^2\sigma^{pp}_{\mathrm{inel}}/dp_T\,dy$ are the total and differential cross section for inelastic $p + p$ collisions, respectively.

2. Experiment and data analysis

The BRAHMS experiment [17] consists of event characterization detectors and two independent magnetic spectrometers, the mid-rapidity spectrometer (MRS) and the Forward Spectrometer (FS), both of which can be rotated in the horizontal plane around the beam direction. For the present studies the MRS is positioned at 90 degrees and the FS at 12 degrees with respect to the beam direction. Collision centrality is determined from the charged particle multiplicity measured by multiplicity detectors as described in [18]. The trajectories of charged particles are reconstructed in the tracking devices (time projection chambers and drift chambers). The resulting straight-line track segments in two detectors located on either side of a magnet are then matched and the particle momentum is determined from the deflection of the track in the magnetic field. The intrinsic momentum resolution of the spectrometers at maximum magnetic field setting is $\delta p/p = 0.0077p$ for the MRS and $\delta p/p = 0.0008p$ for the FS [13], where p is written in units of GeV/c. In the MRS charged particles are identified using a time-of-flight wall (TOFW), whereas in the FS a time-of-flight wall (H2) and a ring imaging Cherenkov (RICH) detector are used for particle identification (PID). To identify charged pions and protons using time-of-flight detectors, 2σ standard deviation PID cuts in the derived m^2 and momentum space are imposed for each species. With a timing resolution of $\sigma_{\mathrm{TOFW}} \sim 80$ ps in the Au + Au runs, protons and pions can be well separated from kaons up to momenta 3.2 GeV/c and 2.0 GeV/c, respectively. For pions above 2 GeV/c, an asymmetric PID cut is applied, i.e., the region where the pion and kaon 2σ cuts overlap is excluded for PID, and the pion yield in the region is obtained by assuming a symmetric PID distribution about the mean pion mass squared value. This allows the pion p_T spectrum to be extended to 3 GeV/c, at which point the kaon contamination of pions is estimated to be less than 5% and is accounted for in the systematic errors. For the FS PID in the present analysis, H2 is used only for the low momentum data. With a timing resolution of $\sigma_{\mathrm{H2}} \sim 90$ ps and a path length of four times the one in the MRS, protons and pions can be identified up to 7.1 GeV/c and 4.2 GeV/c, respectively, with a 2σ separation. Above 7.1 GeV/c, an asymmetric PID cut is applied and the proton yields in the overlap region are estimated by assuming a symmetric PID distribution about the mean proton mass squared value. Between 7.9 GeV/c and 9 GeV/c, the Cherenkov threshold for protons, the RICH detector is used to determine the kaon contamination of the proton spectrum. At 9 GeV/c the contamination of protons by kaons is estimated to be less than 6%. Above 9 GeV/c, protons are identified by using the RICH to veto pions and kaons. To identify pions, the RICH is directly used to separated pions from kaons well from momentum of 2.5 GeV/c up to 20 GeV/c. The number of good runs with the proper polarity for positively charged particles was not sufficient in 2003; we therefore restricted the analysis to π^- and $\bar{p}$ at forward rapidity.

The invariant differential yields $\frac{1}{2\pi}\frac{d^2N}{p_T\,dy\,dp_T}$ (respectively $\frac{1}{2\pi}\frac{d^2N}{p_T\,d\eta\,dp_T}$ at forward rapidity) were constructed for each spectrometer setting. As discussed in [19] the differential yields were corrected for geometrical acceptance, tracking and PID inefficiencies, in-flight decay, the effect of absorption and multiple scattering. The pion contamination from hyperon (Λ) and neutral K^0_S decays were investigated in [20] and found to be less than 5% in the MRS and 7% in the FS, respectively. The contribution to proton spectra by the Λ decays was estimated with a GEANT [21] simulation where an exponential distribution in p_T with an inverse slope taken from the PHENIX and STAR measurements [22,23] for both (anti-) protons and (anti-) lamb-

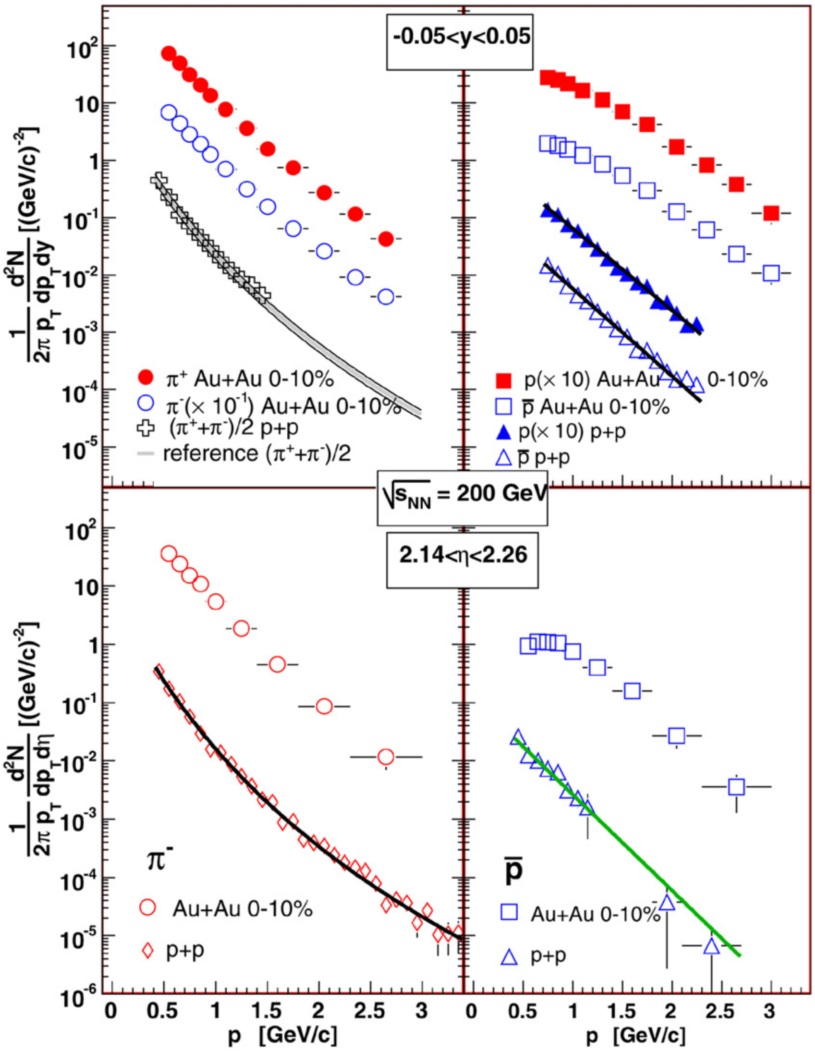

Fig. 1. Top row: p_T spectra of charged pions (left panel) and protons (right panel) at mid-rapidity in 0–10% central Au + Au and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The error bars are statistical only. The systematic errors are estimated to be less than 15% for pions and 18% for (anti-) protons. For the reference spectrum the systematic error is estimated to be less than 19% (gray band). For clarity, some spectra are scaled vertically as quoted. Bottom row: p_T spectra for π^- and $\bar{p}$ at forward rapidity $\eta = 2.2$ in 0–10% central Au + Au and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The systematic errors are estimated to be 14% for pions and 17% for anti-protons.

das was generated for several spectrometer settings. By taking the ratio of $\Lambda(\bar{\Lambda})$ to $p(\bar{p})$ yields of 0.89 (0.95) [22] in 0–10% central Au + Au and 0.45 (0.55) [23] in $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV and assuming a constant behavior in the rapidity interval $|y| \leqslant 2.2$ as indicated by HIJING model [24], it is found that the fraction of protons originating from $\Lambda(\bar{\Lambda})$ decays is at most around 35–40% in central Au + Au and 27–30% in $p+p$ collisions and decreases with p_T. In the following corrections for feed-down from the (anti-) lambda decays have been applied, whereas the contamination of pions due to weak decays has not been corrected but is accounted for in the systematic errors.

3. Particle spectra

The top row of Fig. 1 shows the p_T spectra of charged pions (left panel) and protons (right panel) at mid-rapidity in 0–10% central Au + Au and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Also shown in the left panel of the figure is the measured spectrum of $(\pi^+ + \pi^-)/2$ in $p + p$ collisions, where pions can only be identified up to 1.5 GeV/c with TOFW for 2003 $p + p$ runs. We thus constructed a reference spectrum shown as a solid line by dividing the neutral pion spectrum in $p + p$ collisions measured by PHENIX [25] by the spectrum from a PYTHIA simulation [26] at the same rapidity range and then multiplying the results by the $(\pi^+ + \pi^-)/2$ spectrum from PYTHIA (for details see [27]). The reference spectrum agrees within the errors with the measured spectrum in the overlap region. The spectra of (anti-) protons in $p + p$ collisions are measured by the BRAHMS spectrometer but to a smaller p_T coverage compared to those in Au + Au collisions due to a worse TOF resolution in the $p + p$ runs. The spectra have been corrected for the trigger inefficiency [13] and fitted with an exponential function as shown in solid lines with the rapidity density and the inverse slope parameter of 0.101 ± 0.004 (0.098 ± 0.004) and 0.304 ± 0.005 (0.285 ± 0.005 GeV) for proton (anti-proton),

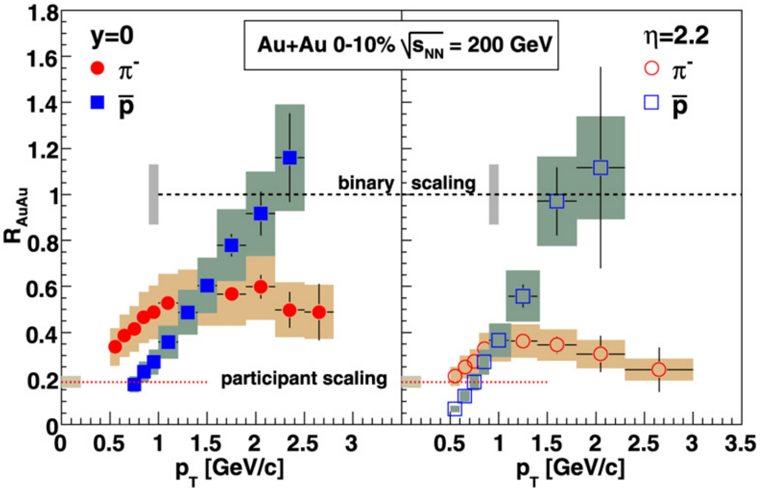

Fig. 2. Nuclear modification factors for π^- and $\bar{p}$ measured for 0–10% central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV at mid-rapidity (left panel) and $\eta = 2.2$ (right panel). Error bars represent statistical errors; the systematic errors are indicated by the shaded bands. The dotted and dashed lines indicate the expectations of participant scaling and binary scaling, respectively. The shaded bars represent the systematic errors associated with the determination of these quantities. Systematic errors other than the uncertainties in $\langle N_{\text{bin}}\rangle$ determinations are estimated to be 20% except for π^- at mid-rapidity, where they are around 24%.

respectively. The error bars are statistical only. The systematic errors in the measured spectra, which come from the uncertainties in the momentum determination, the time-of-flight measurements and ring radius reconstruction procedures, and the uncertainties in the corrections estimations, are estimated to be less than 15% for pions and 18% for (anti-) protons. The systematic error in the reconstructed reference spectrum for charged pions is estimated to be less than 19%.

The bottom row of Fig. 1 shows the p_T spectra for π^- (left panel) and $\bar{p}$ (right panel) at forward rapidity $\eta = 2.2$ in 0–10% central Au + Au and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Solid lines are curves fitted to the π^- and $\bar{p}$ spectra in $p + p$ collisions. The spectra are constructed in terms of $d^2N/dp_T d\eta$ because the rapidity coverages of the FS at 12 degrees for pions and protons are different, making a comparison of anti-proton to pion yields difficult. In addition, since the Jacobian effect is largest at mid-rapidity and gets rather small at larger rapidities at intermediate p_T range as we focused on in this Letter, we expect the conclusions drawn from the spectra expressed in terms of $d^2N/dp_T\,d\eta$ should be the same as from those of $d^2N/dp_T\,dy$.

4. Nuclear modification factor

In Fig. 2 the nuclear modification factors for π^- and $\bar{p}$ are deduced for 0–10% central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV at mid-rapidity (left panel) and $\eta = 2.2$ (right panel). Error bars represent statistical errors; the systematic errors are indicated by shaded bands. The dotted and dashed lines indicate the expectations of participant scaling and binary scaling, respectively. The shaded bars represent the systematic errors associated with the determination of these quantities. Systematic errors other than the uncertainties in $\langle N_{\text{bin}}\rangle$ determinations are estimated to be 20% except for π^- at mid-rapidity, where they are around 24%.

Similar to the unidentified charged hadrons [4] at both mid-rapidity and forward rapidity, R_{AuAu} for charged pions increases monotonically up to ~ 1.5 GeV$/c$ and levels off or even decreases above 1.5 GeV$/c$ indicating that charged pions yields are suppressed with respect to $p + p$ collisions at intermediate p_T. Furthermore, the π^- yields at forward rapidity show a similar or even stronger suppression, indicating that nuclear effects other than parton energy loss (jet quenching) might be contributing to the strong suppression. The suppression at mid-rapidity around $p_T \sim 2$ GeV$/c$ is smaller (about 30%) than the suppression that has been reported for neutral pions [28] and which is seen at forward rapidity. This difference can—to a large extent—be attributed to the construction of the reference spectrum and has been accounted for by the systematical error for π^- at mid-rapidity. Another interesting feature shown in the figure is that the anti-proton yields at both mid-rapidity and $\eta = 2.2$ are not suppressed at $p_T > 2$ GeV$/c$. At mid-rapidity PHENIX has reported a similar behavior, their R_{AuAu} for $(\bar{p} + p)$ and for more central collisions (0–5%) reaches 1 already at $p_T = 1.6$ GeV$/c$ [8].

5. Particle ratios

Fig. 3 shows $\bar{p}/\pi^-$ ratios at both mid-rapidity and $\eta = 2.2$ for 0–10% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The error bars show the statistical errors only. In the present ratios, most systematic errors cancel out. Remaining systematic errors arising from PID efficiencies, acceptance corrections, corrections for nuclear interactions with detector etc. are estimated to be less than 12% at both $y = 0$ and $\eta = 2.2$. Also shown in the figure are the corresponding ratios for $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. A comparison to PHENIX mid-rapidity data [8] (which has the same centrality selection and is feed-down corrected) shows that the ratios for central Au + Au collisions agree, while for minimum bias $p + p$ collisions our ratio is higher. This discrepancy might be to a large extent due to

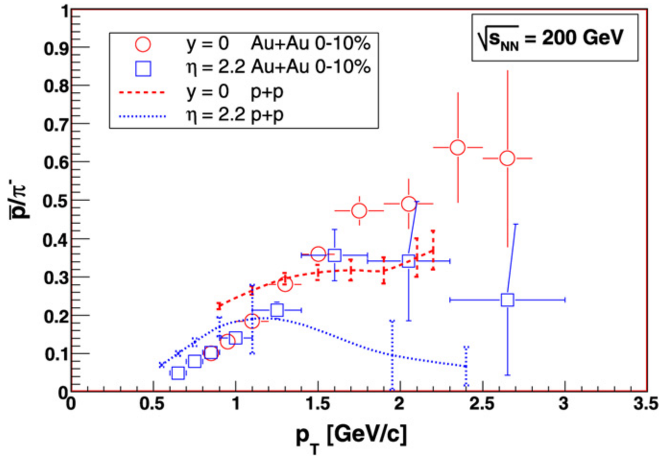

Fig. 3. $\bar{p}/\pi^-$ ratios at both mid-rapidity and $\eta = 2.2$ for 0–10% central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The error bars show the statistical errors only. The systematic errors are estimated to be less than 12% at both $y = 0$ and $\eta = 2.2$. The corresponding ratios in $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV are sketched as dashed line and dotted line, respectively.

the reference spectrum. There is an indication of an increase of the $\bar{p}/\pi^-$ ratios at intermediate p_T in central Au + Au collisions relative to the level seen in $p + p$ collisions (see also [8, 29]). Such an enhancement is most likely due to the interplay of several final-state effects and possibly a new hadronization mechanism other than parton fragmentation. Calculations based on a parton recombination scenario [12] with a collective flow at the partonic level appear to be able to qualitatively describe the data at mid-rapidity.

6. Summary

In summary, the BRAHMS measurements demonstrate a significant suppression of charged pions at intermediate p_T at both mid-rapidity and forward rapidity for 0–10% central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Such a strong suppression is believed to be caused primarily by the parton losing energy when traversing the partonic (i.e., characterized by color degrees of freedom) medium created in central Au + Au collisions. The strong π^- suppression at forward rapidity suggests that the hot dense partonic medium may also exist in the forward rapidity region. It is also possible that other nuclear effects, such as gluon saturation, contribute in this region. However, the suppression is not observed for (anti-) protons at intermediate p_T at either mid-rapidity or forward pseudorapidity $\eta = 2.2$. All these observations are consistent with a picture where a dense strongly interacting partonic matter with a strong collective flow is most likely formed in central Au + Au collisions over a large rapidity range which results in the strong suppression of charged pion yields and boosts the protons to higher transverse momentum.

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