

# High Rapidity Physics with the BRAHMS Experiment

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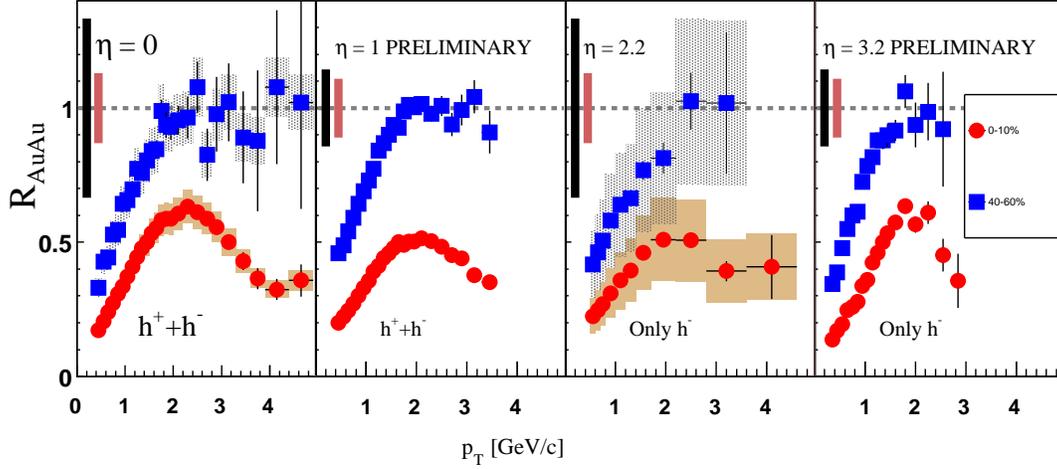
**Abstract.** We report the study of the nuclear modification factor  $R_{AuAu}$  as function of  $p_T$  and pseudo-rapidity in Au+Au collisions at top RHIC energy. We find this quantity almost independent of pseudo-rapidity. We use the  $\bar{p}/\pi^-$  ratio as a probe of the parton density and the degree of thermalization of the medium formed by the collision. The  $\bar{p}/\pi^-$  ratio has a clear rapidity dependence. The combination of these two measurements suggests that the pseudo-rapidity dependence of the  $R_{AuAu}$  results from the competing effects of energy loss in a dense and opaque medium and the modifications of the wave function of the high energy beams in the initial state.

**Keywords:** RHIC, QGP, Nuclear modification factor, high rapidity.

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## INTRODUCTION

The BRAHMS Collaboration has completed a thorough program exploring the particle production from several nuclear systems and several energies at RHIC. The wide and almost continuous rapidity coverage of the BRAHMS spectrometers stands out in the RHIC program. This coverage gives us the ability to probe deeper into the beam wave functions, that is, to be sensitive to the smallest values of the longitudinal momentum fraction carried by its partons. The particle spectra from A+A collisions have been compared to p+p yields measured at the same energy and with the same detectors, the yields from p+p collisions are scaled by the estimated number of binary collisions in the A+A systems  $\langle N_{coll} \rangle$ . The comparisons are done with the so called Nuclear modification factor:  $R_{AA} = Y^{AA} / \langle N_{coll} \rangle Y^{pp}$  where  $Y^{AA}$  denotes the invariant yield extracted from A+A collisions, and  $Y^{pp}$  the one from p+p collisions. If the A+A system is an incoherent superposition of nucleon+nucleon collisions, the ratio should be constant and equal to one. The result of the measurements has been a dramatic suppression (by as much as a factor of 5 at the highest energy) that extends to high values of transverse momentum ( $\sim 20 GeV/c$ ). All RHIC experiments have already reported these results at mid-rapidity and they are now considered as a consequence of the formation of a dense and opaque medium dubbed sQGP [1]. Such a conclusion was reached after the nuclear modification factor extracted for d+Au collisions showed a Cronin type enhancement at mid-rapidity implying that the suppression seen in Au+Au events is a final state effect. The study of d+Au collisions as function of rapidity has generated renewed interest in the contribution to particle production in hadron-hadron interactions coming from partons with the smallest longitudinal momentum fraction  $x$ . The high rapidity suppression measured in d+Au collisions [2] has been described as the modification of an already saturated gluonic system present at RHIC energies. Such modification results from the



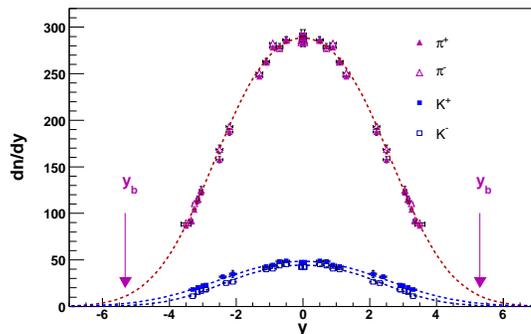
**FIGURE 1.** Nuclear modification factor  $R_{AuAu}$  at  $\sqrt{s_{NN}} = 200$  GeV extracted from two centrality samples: central 0-10% shown with filled circles (red online) and semi-central 40-60% shown with filled squares (blue online), at four values of pseudo-rapidity:  $\eta = 0$  and 1. for charged particles  $h^- + h^+$ , and  $\eta = 2.2$  and 3.2 for negative hadrons  $h^-$ . Statistical errors are shown with bars and the estimated systematic errors are shown with boxes, the normalization errors are shown on the left of each panel and centered at the value of 1.

interplay of additional gluon emission as well as gluon fusion in the initial state of the interaction [3, 4]. This modification of the nuclei wave function should also be present in A+A collisions but may be masked by the fact that any measurement at high rapidity probes the projectile as well as the target fragmentation regions of both beams (here, for convenience, we borrow the naming scheme familiar in fixed target p+A physics).

## THE $R_{AuAu}$ FACTOR AS A FUNCTION OF RAPIDITY

Figure 1 shows the nuclear modification factor extracted from Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV/c versus  $p_T$  and pseudo-rapidity  $\eta$ . Each panel shows the  $R_{AuAu}$  factor for charged hadrons extracted from two centrality samples: The factors extracted from the most central events (0-10%) are shown with filled circles (red online), and the ones extracted from semi-central events (40-60%) are shown with filled squares (blue online). At  $\eta = 2.2$  and  $\eta = 3.2$  the  $R_{AuAu}$  factor was calculated with negative hadrons. The results at  $\eta = 0$  and 2.2 have been published and more details about the analysis can be found in [5].

Remarkably, Fig. 1 shows that the  $R_{AuAu}$  reaches an almost constant maximum at all rapidities ranging from 0 on the left-most panel to 3.2 on the right. Naively, if these measurements were controlled by energy loss in the medium, one might expect less suppression at  $\eta = 3.2$  because the measured pion yield shown in Fig. 2 drops by a factor of 2 between  $y=0$  and  $y=3$  (while  $\langle p_T \rangle$  changes by at most 10%). If we make use of the parton-hadron duality hypothesis, this variation in the pion density will also be present in the gluon density of the formed medium.



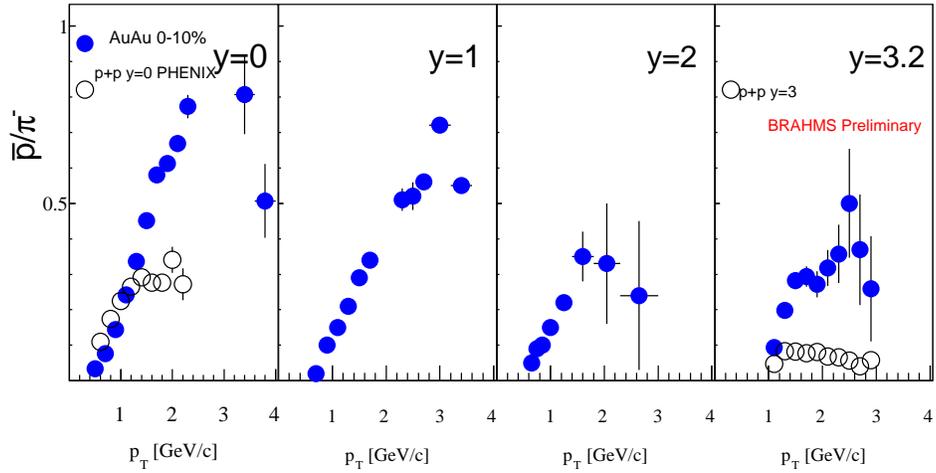
**FIGURE 2.** Rapidity density for charged pions and kaons produced in the 0-5% central Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV.

The absence of rapidity dependence in the  $R_{AuAu}$  is a puzzle that may be difficult to solve because many effects compete in the transverse momentum range of the measurement. For a strong energy loss that results in the preferential detection of particles that originate close to the surface of the medium, the softening of the spectra at high rapidity can produce a similar effect. We propose in this work the use of the  $\bar{p}/\pi^-$  ratio as a tool to characterize the evolution of that system with rapidity; The comparison of the yields of anti-protons and negative pions shows a strong rapidity dependence that can be contrasted with the one found to be practically absent in the  $R_{AuAu}$  ratio.

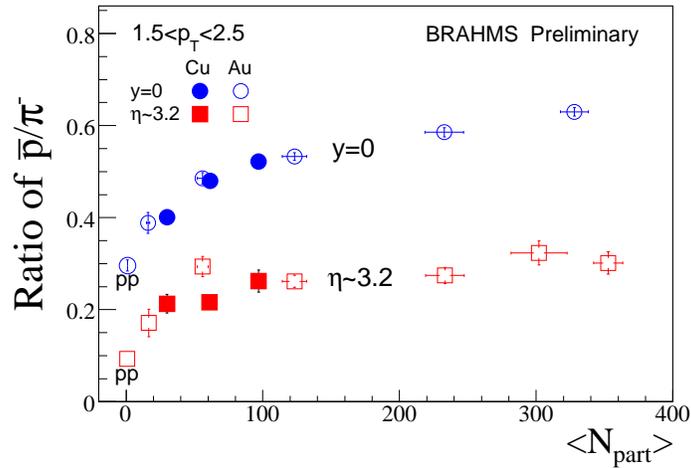
## THE RAPIDITY DEPENDENCE OF $\bar{p}/\pi^-$ RATIO

In  $e^+e^-$  annihilations around the Z pole, the  $\bar{p}/\pi^-$  ratio is small and doesn't exceed 0.2 [6]. This ratio is the result of single parton fragmentation in the vacuum. Such a mechanism favors the production of many particles sharing the original parton momentum. Because the parton is colored, an assumed string breaking mechanism will favor the production of mesons over that of baryons [7]. At RHIC, the  $\bar{p}/\pi^-$  and  $p/\pi^+$  ratios have been found to reach values close to 1 and in some cases, even bigger than 1 at intermediate values of  $p_T$  (2-3GeV/c). In a medium with high parton density, fragmentation and recombination compete in the formation of hadrons, and recombination with its additive nature may be more efficient at forming particles at higher values of  $p_T$ . The same mechanism would also generate more protons at intermediate  $p_T$ , since the momentum a protons would be the sum of momenta from three partons in contrast to the two required to form a meson. These measured high values of the  $\bar{p}/\pi^-$  and  $p/\pi^+$  ratios have been explained as resulting from the recombination of partons present in the thermalized medium [7].

The  $\bar{p}/\pi^-$  ratio extracted from Au+Au collisions at top RHIC energy is shown in Fig. 3 with filled circles. The left-most panel shows the ratio at mid-rapidity reaching values as high as 4 times the values found for the so called fragmentation in the vacuum. As rapidity changes to  $y=1$  the maximum of the ratio decreases visibly and at the highest rapidity ( $y=3.2$ ) on the right of the figure, the ratio reaches its smallest value. For comparison, the same ratio extracted from p+p collisions by the PHENIX collaboration



**FIGURE 3.** The  $\bar{p}/\pi^-$  ratio extracted from Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV as function of transverse momentum at four values of rapidity. The ratios were extracted from central events 0-10%. The same ratio extracted from p+p collisions is shown with open circles at  $y=0$  and  $y=3.2$ . The errors are statistical.



**FIGURE 4.** Compilation of the integral of the  $\bar{p}/\pi^-$  over the  $1 < p_T < 2.5$  GeV/c interval for various colliding systems at  $\sqrt{s_{NN}} = 200$  GeV. The integral for Cu+Cu collisions at  $y=0$  shown with filled circles (blue online), and  $y=3.2$  with filled squares (red online). The results obtained from Au+Au collisions are shown with open circles (blue online) at  $y=0$ , and open squares (red online) at  $y=3.2$ . The p+p results are shown with similar symbols and are located at  $\langle N_{part} \rangle = 0$ .

at  $y=0$  is shown in the left-most panels as well as the same ratio measured by BRAHMS at  $y=3.2$ , also from p+p collisions, shown in the right-most panel.

Figure 4 summarizes the variation of the  $\bar{p}/\pi^-$  ratio with the calculated mean number of participant nucleon  $\langle N_{part} \rangle$  at a determined centrality of the collision. The integral over  $p_T$  in an interval that includes the maxima seen in all panels of Fig. 3, should convey the evolution of this ratio in shape as well as magnitude as function of rapidity.

For the purpose of this report, the main feature in Fig. 4 is the fact that the  $\bar{p}/\pi^-$  ratio extracted from the most central Au+Au collisions at  $y=3$  has the same value as the one measured at  $y=0$  in to p+p collisions at the same energy.

If recombination is the effect that drives the  $\bar{p}/\pi^-$  ratio, its clear rapidity dependence seen in Fig. 3 puts in doubt any explanation of the suppression measured with the  $R_{AuAu}$  factor at high rapidity as being solely produced by energy loss in a dense medium. The behavior of the  $\bar{p}/\pi^-$  ratio seems to indicate that the sQGP does not extend to high rapidity, or if it does, its effects on partons traversing it at high rapidity cannot be strong. The small values of the  $R_{AuAu}$  factor at high rapidity may rather be due to other effects that stand out as energy loss weakens as one approaches the beam fragmentation regions. One such effect at high rapidity may be the modification of the beam wave functions as they are now probed into even smaller values of  $x$ .

## SUMMARY

We have shown the almost rapidity independent nuclear modification factor  $R_{AuAu}$  extracted from Au+Au collisions at two centralities. The suppression of the  $R_{AuAu}$  at mid-rapidity is produced by energy loss in the dense and opaque sQGP formed early in the Au+Au collisions. We postulated the use of the  $\bar{p}/\pi^-$  to probe the density and degree of thermalization of that medium at different rapidities. The strong rapidity dependence of the  $\bar{p}/\pi^-$  ratio led us to conclude that the effects of the dense and opaque sQGP do not extend to high rapidity. The continued suppression seen in the  $R_{AuAu}$  factor may then be the result of a compromise between energy loss in the sQGP that dominates around mid-rapidity and the modification of the beam wave functions that become apparent at high rapidity.

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