Rapidity Dependence of High p_T Suppression

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We present high transverse momentum hadron spectra for $Au+Au$ and $d+Au$ collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$. The $Au+Au$ data are obtained at pseudorapidities $\eta = 0$ and $\eta = 2.2$ and the $d+Au$ data at $\eta = 0$. The $d+Au$ data do not show evidence for high p_T suppression, thus ruling out initial state effects as an explanation for the strong suppression observed in central $Au+Au$ collisions. The suppression in central $Au+Au$ collisions extends to the forward rapidities, which indicates that the medium responsible for the suppression is extended in the longitudinal direction.

1. Introduction

Measurements of particle yields from $Au+Au$ collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$ show evidence that the colliding nuclei create a region of very high energy density. The particle multiplicity and the mean transverse momentum measured at midrapidity suggest an energy density of $\epsilon > 5\,\text{GeV/fm}^3$ [1]. This value is a factor of five higher than the critical energy density needed for the formation of a quark-gluon plasma as estimated by lattice QCD calculations ($\epsilon \leq 1\,\text{GeV/fm}^3$, [2]).

A proposed effect of having an extended region of deconfined matter in the collision is a large energy loss of hard scattered partons resulting from gluon bremsstrahlung. This effect would result in a significant suppression of the high p_T particle yields and a disappearance of back-to-back azimuthal correlation of high p_T hadrons in central collisions – signatures that have both been observed [3–6]. However, other nuclear modification effects such as Cronin enhancement and parton saturation play a role in the production of high p_T particles. Measurements of different collision systems over a large span of energies is therefore necessary to disentangle and understand the different effects.

In this paper the high p_T results from the BRAHMS experiment at RHIC will be presented and discussed in view of different theoretical models that describe the nuclear effects.

The nuclear effects are quantified by the ratio of the yields from the nucleus-nucleus collisions to the binary scaled yields from elementary nucleon-nucleon collisions. This ratio is called the nuclear modification factor

$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}, \tag{1}$$

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where $T_{AA} = \langle N_{bin} \rangle / \sigma_{inel}^{NN}$ is the nuclear overlap function which can be determined from Glauber calculations. In case of no nuclear effects the yields of high p_T particles are expected to scale with the number of (incoherent) binary collisions ($R_{AA} = 1$).

Where $N + N$ reference spectra are not available, the nuclear modification can be studied by comparing central to more peripheral collisions

$$R_{CP} = \frac{T_P d^2 N^C / dp_T d\eta}{T_C d^2 N^P / dp_T d\eta}, \qquad (2)$$

where the C and P denotes central and peripheral collisions, respectively.

2. Experimental Setup

The BRAHMS experiment consists of two small solid angle magnetic spectrometers and a set of detectors used for event characterization.

The collision vertex is determined from the time signals in two sets of fast Cherenkov Beam-Beam counters placed at about 2m from the nominal interaction point. In the $d + Au$ run, additional scintillator counters were used to trigger the data acquisition and for more efficient vertex determination.

The collision centrality is determined by the multiplicity array covering a pseudorapidity range of approximately $-2 < \eta < 2$ with respect to the nominal interaction point. The array measures the energy deposited by charged particles, from which the particle multiplicity can be derived. The reaction centrality is determined from the multiplicity, taking into account the vertex dependent acceptance of the multiplicity array.

One spectrometer (MRS) covers the region around mid-rapidity, $30° < \theta < 95°$. It consists of a dipole magnet with a time projection chamber (TPC) on either side. The charged particle trajectories before and after the magnet are measured by the TPCs and the particle momentum is determined from the bending in the magnet. The other spectrometer covers more forward angles with $3° < \theta < 30°$. It consists of two TPCs, three drift chambers and four dipole magnets which are utilized the same way as in the MRS. The spectrometers are also equipped with time-of-flight and Cherenkov detectors for particle identification, although these were not used in the present analysis. The hardware is described in more detail in ref. [7].

3. The Analysis

Spectra have been constructed by counting the number of tracks in the spectrometers, correcting for detector efficiency and the limited acceptance of the detectors and normalizing to the number of events in the data sample. Measurements at several field and angle settings have been combined to achieve the largest possible p_T ranges. The acceptance correction and event normalization changes with the vertex location and is therefore done for vertex bins of 2 cm. No correction for feed-down, decay or absorption has been applied.

In order to construct the nuclear modification factor a reference spectrum from elementary collisions is needed. In the present analysis a parametrization based on unidentified hadron spectra from UA1 ($p + \bar{p}$) [8] has been used. The reference spectra are corrected for the differences in acceptances. UA1 measures particles in the pseudorapidity range

$-2.5 < \eta < 2.5$ while the BRAHMS measurements are with $-0.15 < \eta < 0.15$ for charged hadrons and $2.1 < \eta < 2.3$ for negative hadrons. The correction for differences in acceptance is made with the HIJING model. Our acceptance corrected reference spectrum at $\eta = 0$ is in good agreement with results obtained by STAR for $p + p$ collisions [3]. The correction factor to the reference ($(\mathrm{h}^+ + \mathrm{h}^-)/2$) for the $\eta = 2.2$ spectrum (h^-) is quite large (around 0.3 at $p_T = 4\,\mathrm{GeV/c}$) and relies on the HIJING model. Comparison to measured spectra at forward angles is not available (like at $\eta = 0$) and the corresponding R_{AA} is therefore very model dependent. However the R_{CP} ratio does not contain such model dependent corrections.

The number of binary collisions has been calculated using HIJING (Glauber approach) as 897±117 and 78±26 for 0-10% and 40-60% central $Au+Au$ collisions, respectively and 7.2±0.3 for minimum bias $d + Au$ collisions (corresponding to 0-91% central collisions). An inelastic $N + N$ cross section of $\sigma_{inel}^{N+N} = 42$ mb is used.

4. Results and Discussion

Figure 1 shows unidentified hadron spectra at midrapidity (left) and at $\eta = 2.2$ (right) for different centrality classes as well as for minimum bias $d + Au$ (left panel). The parameterizations of the $N+N$ reference spectra at the two pseudo-rapidities are indicated by the curves.

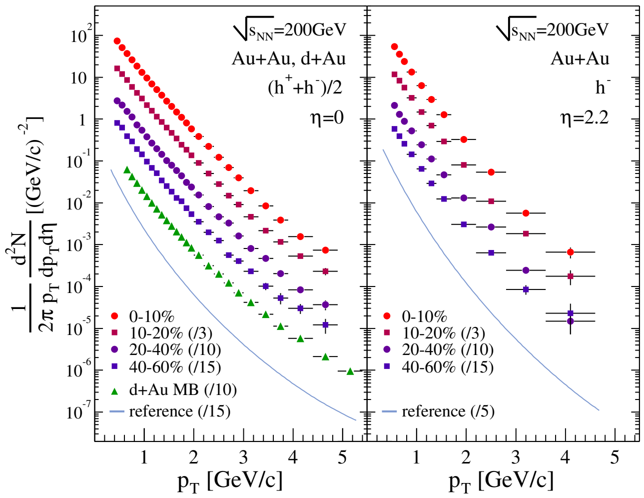

Figure 1. Unidentified hadron spectra at $\eta = 0$ (left) and $\eta = 2.2$ (right) for 4 different centralities of $Au + Au$ collisions. In the left panel the spectra from minimum bias $d + Au$ collisions are also plotted. The lines indicate the parametrization of the yields from elementary collisions.

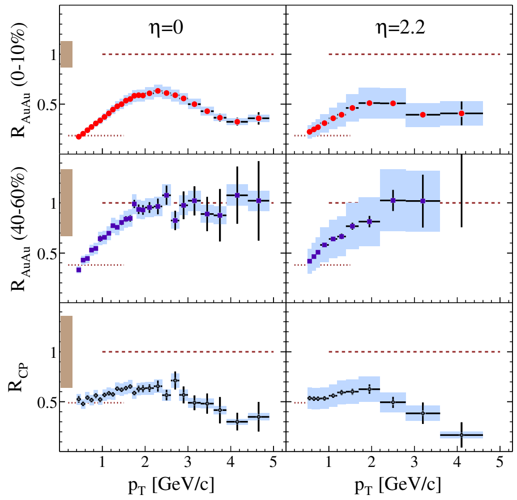

Figure 2. Nuclear modification factors for $Au + Au$ 0-10% (top) and 40-60% (middle) central collisions at $\eta = 0$ (left) and $\eta = 2.2$ (right). The bottom panels show the R_{CP} ratios.

Figure 2 shows the nuclear modification factors at the two pseudorapidities $\eta = 0$ to the left and $\eta = 2.2$ to the right. The top and the middle panels show the R_{AA} for the most central (0-10%) and more peripheral (40-60%) collisions, respectively. The central collisions show a strong suppression in the high p_T range. At $p_T = 4\,\mathrm{GeV/c}$ the yields are suppressed by a approximately a factor of three. The suppression is present and of approximately the same strength at midrapidity and in the forward direction ($\eta = 2.2$). For the semi-peripheral collisions (40-60%) the suppression seems to vanish and the yields agree with the expectation from the binary scaled yields from elementary collisions. The bottom panels in Fig. 2 shows the R_{CP} ratio where the systematic errors from the scaling to elementary collision yields are not present. These observations point to a suppression that depends on the density of the created hot and dense region such as expected for the energy loss of partons in this medium. That the suppression is also present at forward angles suggest that the dense region is extended in the longitudinal direction.

The data is consistent with a hydro-jet model [10], which describes the particle production by combining a 3-dimensional hydrodynamical model and a pQCD jet production mechanism (PYTHIA). The energy loss of the high p_T partons as they move through the extended dense medium is calculated using the GLV formalism [11]. The model assumes a high average parton density at $\eta = 2$ comparable to that at $\eta = 0$.

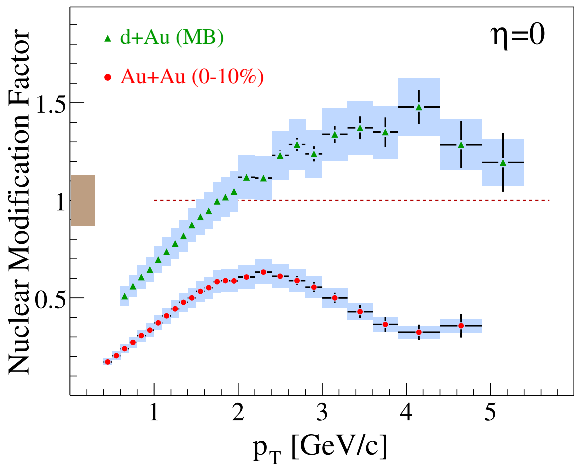

Figure 3: The nuclear modification factor for minimum bias $d + Au$ and central $Au + Au$ collisions.

Figure 3 shows the nuclear modification factor at $\eta = 0$ for minimum bias $d + Au$ and central $Au + Au$ collisions. A strong suppression is evident for the central $Au + Au$ collision yields at high p_T. A possible explanation for this suppression is that parton saturation occurs in the initial state [12]. However, this should also lead to a suppression for the $d + Au$ data that is not seen. Rather, the $d + Au$ data can be explained by the Cronin effect. In view of the $d+Au$ data, it seems unlikely that parton saturation is a significant factor in the observed $Au + Au$ suppression.

The measurements from central $Au+Au$ and minimum bias $d+Au$ is in good agreement with the Gyulassy-Vitev model described in ref. [13]. The model includes: 1) the Cronin effect, modeled via multiple initial state scatterings of the partons in the cold nuclei (broadening of the initial parton k_T distribution), 2) parton shadowing (saturation), modeled by EKS98 parametrization of the shadowing function which modifies the initial parton distribution function and 3) parton energy loss in the opaque medium, which is taken into account in the jet fragmentation function by modification to the momentum fraction carried by the leading hadron. This modification depends on the gluon density in the expanding plasma. For the $d + Au$ collisions the parton density is so low that the last effect is negligible. Also, for $d + Au$ collisions in this energy regime, the parton shadowing effect is smaller than the Cronin enhancement effect and the prediction for the $d+Au$ nuclear modification is in qualitative agreement with the data: an enhancement of 1.5 is predicted at $p_T \approx 4\,\mathrm{GeV/c}$. In the central $Au + Au$ collision parton energy loss in the opaque medium must be included to reproduce the measured suppression.

5. Conclusion and Outlook

High p_T suppression has proved to be one of the most interesting signals at RHIC [4,9]. The strong suppression in central $Au + Au$ collisions and the enhancement in $d + Au$ collisions points to a modification pattern in the central $Au + Au$ collisions similar to what is expected from parton energy loss in a deconfined medium. However many aspects of the high p_T physics at this energy are still unrevealed. Measurements at more forward rapidities where low x physics is expected to be more dominant will give information on the importance of parton saturation in heavy ion collisions. Extended identified hadron spectra will make clearer the role of high p_T parton fragmentation processes in the created medium. These studies will be done as the analysis of the $d + Au$ data is completed and as the next $Au + Au$ run provides better statistics with upgraded detector systems.

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