Rapidity dependence of high $p_T$ suppression at $\sqrt{s_{NN}} = 62.4$ GeV.

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We present measurements of charged hadron $p_T$ spectra from Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV for pseudorapidities $\eta = 0$, $\eta = 1$ and $\eta = 3.2$. Around midrapidity ($\eta = 0$, $\eta = 1$) we find nuclear modification factors at levels suggesting a smaller degree of high $p_T$ suppression than in the same reaction at higher energy $\sqrt{s_{NN}} = 200$ GeV. At the high pseudorapidity, $\eta = 3.2$, where nuclear modification factors cannot be constructed due to the lack of $p + p$ reference data, we find a significant reduction of $R_{CP}$ (central to peripheral ratio) as compared to midrapidity.

The observation of the suppression of the high transverse momentum part ($p_T > 2$ GeV/c) of particle spectra from central collisions between gold ions relative to similar (scaled) spectra from proton-proton collisions has been one of the central discoveries at the Relativistic Heavy Ion Collider, RHIC $^{11}$.

For particles emitted around midrapidity large suppression factors (of order 3-5) have been observed for charged and neutral hadrons in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV $^{2,3,4,5}$. Similar studies comparing spectra from $d + Au$ collisions to the same reference $p + p$ collisions, on the contrary, show a lack of suppression $^{2,3,4,5,6}$. In fact, in the $d + Au$ collisions, an enhancement of the particle yield in the $2 \text{ GeV/c} < p_T < 8 \text{ GeV/c}$ range is found. Current theory explains the observed phenomena in terms of scattering and interaction between quarks and gluons in the moments between first contact of the colliding nuclei and jet fragmentation (i.e. formation of hadrons) in subsequent stages of the collision. The high $p_T$ suppression observed in central nucleus–nucleus collisions is thought primarily to be the result of the energy loss of hard scattered partons as they propagate through a medium with a high density of unscreened color charges. The theory of the strong interaction, Quantum Chromo Dynamics (QCD), predicts a high degree of energy loss of scattered partons due to stimulated gluon emission (in a manner proportional to the square of the distance traversed) $^{2,4,12}$. Conversely, the enhancement seen in $d + Au$ collisions, in which an extended dense absorbing medium is believed not to be produced, is thought to be due to multiple scattering between partons (leading to a broadening of measured $p_T$ distributions), the so-called Cronin effect.

For particles emitted at forward rapidity ($\eta > 2$) large suppression factors have also been observed at $\sqrt{s_{NN}} = 200$ GeV in $Au + Au$ collisions $^{2,12}$ as well as in $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV $^{13}$. The underlying mechanism is at present unclear. An intriguing possibility relies on the fact that particles observed at large rapidities, i.e. small angles relative to the beam direction, may originate from scatterings involving a gluon carrying a small fraction of the nucleon momentum (low–x gluon). The theory of the Color Glass Condensate $^{14}$ predicts that the number of such low–x gluons may be limited due to fusion among highly delocalized gluons. This, in turn, has been predicted to lead to an overall reduction.
of the yield of charged particle seen at forward rapidity in $d + Au$ collisions on the Au 'shadow side', i.e. for collisions predominantly involving a low-$x$ gluon from the gold and a higher momentum parton from the deuteron.

In the present letter we extend these studies to $Au + Au$ collisions at $\sqrt{s_{NN}} = 62.4$ GeV and investigate to what extent the suppression phenomena observed at the top energy of RHIC persist at lower CM energies. The PHOBOS experiment has presented studies of high $p_T$ production for $Au + Au$ at $\sqrt{s_{NN}} = 62.4$ GeV averaged over an interval of pseudorapidity $\eta = 0.2 - 0.4$ [13]. The present measurement addresses the pseudorapidity dependence of the high $p_T$ particle production in $Au + Au$ collisions at this energy with measurements in narrow intervals ($\Delta \eta = 0.2$) around $\eta = 0, 1$ and 3.2.

Measurements of high $p_T$ particle production at lower energy (i.e. at the SPS, $\sqrt{s_{NN}} = 17.2$ GeV) are sparse and the interpretation of the data is at present unclear. Depending on the chosen nucleon–nucleon spectrum to compare to, the nuclear modification factors obtained in the SPS energy range vary from a large enhancement [13, 19, 20] in the range $p_T = 2-3$ GeV (which would exclude significant jet quenching), to consistency with unity [21]. The latter situation might correspond to a trade-off between initial state multiple scattering (Cronin effect) and final state high $p_T$ suppression.

The data presented here have been collected with the BRAHMS detector at RHIC [22]. BRAHMS consists of a detector system for triggering and for vertex and centrality determination and two magnetic spectrometers for precision measurements of charged hadrons. For the measurements presented here the midrapidity spectrometer was positioned at 90 and 45 degrees relative to the beam direction corresponding to average pseudorapidity $\eta = 0$ and $\eta = 1$ and the forward spectrometer was positioned at 3 degrees enabling measurements at $\eta = 3.2$ (see actual acceptances in the top panels of fig. 1).

The trigger permitted the recording of events corresponding to approximately 90% of all inelastic $Au + Au$ collisions at $\sqrt{s_{NN}} = 62.4$ GeV. The collision centrality has been determined from the measured charged particle multiplicity in a detector covering $|\eta| < 2$. The collision vertex is determined from the difference in arrival time of particles scattered at small angles into two arrays of Cherenkov radiator counters situated on either side of the nominal interaction point around the beam pipe. The momentum of charged hadrons is obtained by determining their trajectories through the magnetic spectrometers using time projection chambers and position sensitive drift chambers.

Figure 1 shows the measured spectra for four different centrality classes at $\eta = 0$, $\eta = 1$ and $\eta = 3.2$. The upper row shows the corresponding acceptance of the spectrometers at the three nominal angular settings (90, 45 and 3 degrees). The spectra have been obtained by counting the number of measured charged particle tracks per event in the spectrometers in each of the centrality ranges and have been corrected for the finite acceptance of the spectrometers, the efficiency of the tracking chambers and for smearing due to the momentum resolution. Corrections to spectra for feed–down from weakly decaying particles have not been applied since the yields of different species of particles are not directly measured. The systematic errors on the normalization of the spectra is estimated to be $\approx 10\%$. In general, the analysis is similar to that described in ref. [2].

In Figure 2 we display the nuclear modification factors $R_{AuAu}$ as function of $p_T$ for the different centrality classes at $\eta = 0$ and $\eta = 1$. The nuclear modification factor is defined as: $R_{AuAu} = \frac{d^2N_{AuAu}}{dp_Td\eta}/\frac{d^2N_{NN}}{dp_Td\eta}$. It involves the scaling of the $p_T$ spectra from elementary nucleon–nucleon (in practice proton–proton) collisions by the mean number of binary nucleon–nucleon collisions, $\langle N_{bin} \rangle$. For the different centrality classes $\langle N_{bin} \rangle$ has been estimated using HIJING events including the constraints imposed by the actual detector geometry and resolution. We have used $\langle N_{bin} \rangle$=752$\pm$100, 459$\pm$70, 217$\pm$42 and 70$\pm$18 for the centrality classes 0 $-$ 10%, 10 $-$ 20%, 20 $-$ 40% and 40 $-$ 60%, respectively. The uncertainties arise both from the estimated uncertainty on the efficiency of our min bias trigger ($\pm 5\%$) and from estimates of the dependence of $\langle N_{bin} \rangle$ on variations of the parameters for the Glauber model calculation.

At $\sqrt{s_{NN}} = 62.4$ GeV, $p + p$ collisions have not yet been measured at RHIC. Thus, in order to construct the $R_{AuAu}$ we must rely on results from earlier experiments. In particular, we have based the analysis on parametrizations of $p + p$ data [23] obtained at the ISR collider at $\sqrt{s_{NN}} = 53$ GeV and $\sqrt{s_{NN}} = 62.4$ GeV. The ISR distributions have been scaled to the present energy and

![FIG. 1: Spectra of charged hadrons measured with BRAHMS](image-url)
rapidly range using scaling factors obtained by simulating events using the HIJING p+p event generator. In the present work, we have parameterized the measured yield by a power law $Ed^3\sigma/d^3p = A \times (1 + p_T/p_0)^{-n}$. For $\eta = 0$ we use $A = 244.2 \text{mbGeV}^{-2}\text{c}^3$, $p_0 = 2.00 \text{GeV/c}$ and $n = 14.31$, for $\eta = 1$ we use $A = 222.6 \text{mbGeV}^{-2}\text{c}^3$, $p_0 = 2.16 \text{GeV/c}$ and $n = 15.07$. The inelastic cross section is set to $\sigma = 36 \text{mb}$. A more detailed study of the reference spectrum at $\sqrt{s_{NN}} = 62.4 \text{GeV}$ can be found in ref. [21]. Our parametrization is consistent with the results quoted therein. We assign a $\pm 20\%$ systematic uncertainty to the reference spectrum.

Figure 2 shows that the $R_{\text{AuAu}}$ for $\eta = 0$ and $\eta = 1$ are similar within each of the 4 considered centrality classes. For the more peripheral collisions a pronounced enhancement above unity of the nuclear modification is seen for $p_T > 1 \text{GeV/c}$. It is much larger than the corresponding enhancement of $R_{\text{AuAu}}$ seen for $Au + Au$ collisions at $\sqrt{s_{NN}} = 200 \text{GeV}$ for the same centrality class (40-60%). As the collisions become more central, the $R_{\text{AuAu}}$ decreases systematically. For the 0-10% centrality bin the measurements are consistent with binary scaling at $p_T = 4 \text{GeV/c}$. Even considering the large systematic errors associated with the reference spectra and the normalization to $\langle N_{\text{bin}} \rangle$ the $R_{\text{AuAu}}$ around midrapidity at $\sqrt{s_{NN}} = 62.4 \text{GeV}$ is significantly above the value obtained for $Au + Au$ collisions at $\sqrt{s_{NN}} = 200 \text{GeV}$ (where $R_{\text{AuAu}} \approx 0.4$ at $p_T = 4 \text{GeV/c}$).

In order to avoid the dependence on the $p+p$ reference we construct the $R_{CP}$ ratio of the $R_{\text{AuAu}}$ for two centralities, in the present case 0-10% and 40-60%. The distributions of $R_{CP}$ around midrapidity ($\eta = 0$ and $\eta = 1$) are shown in figure 3. They exhibit similar values (around 0.6), and are similar to the ratios that have been measured for $\sqrt{s_{NN}} = 200 \text{GeV}$ collisions. $R_{CP}$ ratios have also recently been studied at SPS by the NA57 collaboration at central rapidity [23]. In that work, the $R_{CP}$ is above unity for $p_T > 2 \text{GeV/c}$ for negative hadrons. The ratios measured in this work decrease, however, to $R_{CP} \approx 0.4$ as the pseudorapidity increases to $\eta = 3.2$. At this high pseudorapidity, the $R_{CP}$ shows little $p_T$ dependence and the level of the $R_{CP}$ is similar to that observed at the same pseudorapidity for $d + Au$ collisions [14]. We note that for the $\eta = 3.2$ setting, the average angle of observation is about 4.5 degrees. At this angle the transverse momentum corresponding to scattering of a particle with full beam momentum is $p_T \approx 62.4/2 \times \sin(4.5) \text{GeV/c} = 2.44 \text{GeV/c}$. Thus, even though the absolute $p_T$ scale is moderate, particles in this $p_T$ range at forward rapidities have high momentum. It is remarkable that there is yield practically up to this kinematic limit, suggesting that the yield at the high end of the spectrum,
at the most forward angles, may be dominated by nearly inelastically scattered particles. We have also studied the $R_{CP}$ ratios separately for positive and negative hadrons, but no significant differences were found.

In figure 4 we show the systematics of the nuclear modification factor around midrapidity for central nucleus–nucleus collisions at $p_T = 4$ GeV/c as a function of beam energy. The values for the SPS energy range (which are for pions produced in central for Pb+Pb collisions) are assigned a large error reflecting the poorly known $p + p$ reference also at that energy. The figure indicates that the $R_{AA}$ at $\sqrt{s_{NN}} = 62.4$ GeV is higher than for $Au + Au$ reactions at higher energy, but below the values from the SPS, suggesting a transition in the degree of high $p_T$ suppression from the low energy regime to the high energy regime. It is, however, not possible to conclude (primarily due to the important uncertainties in the $p + p$ reference spectra for $\sqrt{s_{NN}} = 62.4$ GeV and $\sqrt{s_{NN}} = 17.2$ GeV) whether this transition occurs gradually from SPS energies or has the character of a more sudden onset between SPS and RHIC($\sqrt{s_{NN}} = 62.4$ GeV).

The present data raise a number of important issues pertaining to the understanding of high $p_T$ suppression in heavy ion collisions. At the experimental level the discussion presented here highlights the need for accumulating reliable $p + p$ reference data at RHIC for all ion-ion energies studied. The present data show that suppression diminishes with decreasing energy at midrapidity, an observation that calls for detailed theoretical study of the energy dependence of jet suppression in the parton energy loss model. At the same time we find that high $p_T$ suppression is not confined to midrapidity but appears to be a general phenomenon over a large rapidity and energy range. It may be, that the significant high $p_T$ suppression which is seen at forward angles (high rapidity) reflects a longitudinally extended suppressing medium – although this has yet to be validated by theoretical investigations (see e.g. [24, 27]). It may also be that a second suppressing mechanism is at play at forward rapidities. The Color Glass Condensate model predicts one such mechanism related to low–x gluon saturation. In any case a consistent understanding of the high $p_T$ phenomenon across a broad range of rapidity and energy is needed.

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