Systematic Study of Particle Production at High $p_T$ with the PHENIX Experiment

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Abstract. A systematic study of particle production at large transverse momentum ($p_T$) with the PHENIX experiment at RHIC is shown. We demonstrate that the suppression of the yield of high $p_T$ hadrons in central Au+Au collisions compared to the scaled p+p reference persists up to highest $p_T$ for neutral pions and $\eta$ mesons. A similar suppression pattern is also observed in Cu+Cu collisions at the same energy. In addition we present the first RHIC results on high-$p_T$ particle production close to SPS energies.

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1. Introduction

One of the primary goals of the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is to study strongly interacting matter under extreme conditions. In particular it is expected that a new state of matter, the Quark Gluon Plasma (QGP), is formed when strongly interacting matter attains energy densities above $\epsilon_c \approx 1 \text{ GeV}/\text{fm}^3$. In this new phase quarks and gluons are no longer confined into the color-singlet nucleons, but instead can move freely over large distances.

One possible signature that has been proposed for the creation of such a new phase is the suppression of particles with large transverse momenta ($p_T$) in central Au+Au collisions compared to the expectation from scaled p+p reactions \[1, 2\]. The production of these particles is dominated by so-called hard processes, parton-parton interactions with large momentum transfer $Q^2$ ($\propto p_T^2$), and the subsequent fragmentation of partons into observable particles, which are observed in elementary collisions as jets of particles produced along the direction of the scattered partons. In heavy-ion collision these hard processes occur in the early stage of the reaction,
before the hot and dense medium is formed, thus providing an ideal probe for the later stage.

The first step when studying medium influences on particle production is to compare the production at high $p_T$ in heavy ion collision to the expectation for the QCD vacuum: The reference provided by the measurement in p+p collisions, scaled with the nuclear overlap function ($\langle T_{AB} \rangle$) for a given centrality in A+B reactions. This defines the nuclear modification factor:

$$R_{AB} = \frac{d^2N_{AB}/dydp_T}{\langle T_{AB} \rangle \cdot d^2\sigma_{pp}/dydp_T},$$

where $\langle T_{AB} \rangle$ is related to the number of binary nucleon-nucleon collisions $N_{coll}$ via $\langle T_{AB} \rangle \approx \langle N_{coll} \rangle / \sigma_{inel}$. They can be computed together with the number of participating nucleons $N_{part}$ in a Glauber calculation.

At low $p_T$ ($< 2 \text{ GeV}/c$) the particle production is dominated by soft processes which scales approximately with $N_{part}$ but at sufficiently large $p_T$ hard scattering dominates and the nuclear modification factor should be unity, any deviation from unity indicating an influence of the medium. Indeed one of the major discoveries at RHIC is the suppression of particle production by a factor of five in central Au+Au collisions (see Fig. 1 and [3, 4, 5, 6]), while no suppression is observed in peripheral reactions. This suppression can be explained by the energy loss of hard scattered quarks via induced gluon bremsstrahlung in a medium with high parton density (see e.g. [7]), which is supported by two key observations.

- In d+Au reactions only a slight Cronin enhancement is observed but no suppression [8, 9]: Initial state effects, such as the Color Glass Condensate, cannot be responsible for the suppression in central Au+Au collisions.
- The nuclear modification factor for direct photons is consistent with unity for all centralities in Au+Au (see Fig. 1 and [10]): The direct control in Au+Au reactions that the hard scatterings occur at the expected rate, since photons do not interact strongly with the medium.

However, to distinguish between various models for the parton-energy loss and to map out the properties of the medium, more differential studies of high-$p_T$ particle production are needed. This can involve the study of heavy quarks, jet correlations, parton energy-loss with respect to the event reaction plane, dependence on particle species, system-size and energy dependence. Here we will concentrate mainly on the system-size and energy dependence of the nuclear modification factor and will limit ourselves to the measurement of identified particles above $p_T \approx 6 \text{ GeV}/c$, a region where the difference between charged hadrons and neutral pions, which motivated the picture of quark-recombination from a thermal source as dominant particle source is no longer important [5].
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Fig. 1. Nuclear modification factor in central Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV for direct photons, \( \pi^0 \)'s and \( \eta \)s [11]. The hadrons are suppressed as expected by the energy loss calculation in a dense partonic medium [12, 13].

2. Data Analysis

The data presented here were obtained during the first five years of operation of the PHENIX experiment at RHIC. The primary detector employed in the measurement of neutral pions, \( \eta \) mesons and direct photons was the Electromagnetic Calorimeters (EMCal) [14]. In addition, the PHENIX zero-degree calorimeters and the two beam-beam counters (BBC’s) were used for triggering, vertex and centrality determination. The EMCal is located at a radial distance of \( \sim 5.1 \) m and covers \( |\eta| < 0.35 \) in pseudo-rapidity and \( \pi \) radians in azimuth. It is divided into eight sectors: six sectors lead-scintillator sandwich calorimeter (PbSc) and two sector lead-glass Cherenkov calorimeter (PbGl), which provides an excellent internal cross-check for the final results.

Neutral pions and \( \eta \)s are reconstructed with an invariant mass analysis of photon pairs in the EMCal. The combinatorial background is determined via an mixed event technique, where photons from different events with similar topology (centrality, collision vertex etc.) are combined to obtain the background from uncorrelated photon pairs. Direct photons are measured by reconstructing the inclusive photon yield and comparing to the photons expected from hadronic decays, any excess above the decay background is a signal of direct photons (see also [10, 16]).
Fig. 2. Ratio the $\eta$ and $\pi^0$ spectra measured for different colliding species and centralities at $\sqrt{s_{NN}} = 200$ GeV [11]. All measurements are consistent with each other and with a PYTHIA calculation [15].

Fig. 3. Comparison of the nuclear modification factor in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV for $N_{\text{part}} \approx 74$. 
3. High $p_T$ $\eta$ production

The fact that neutral pions and charged hadrons show the same amount of suppression above $p_T \approx 5$ GeV/c indicates that the jet-quenching mechanism seems not to depend on the identity of the (light-quark) hadron [5]. This is expected when the jet-quenching depends only on the energy loss of the parent light quark and not on the nature of the final leading hadron which is produced in the same universal fragmentation process as in hadron production in the vacuum, i.e. in p+p collisions.

However, a similar nuclear modification factor for neutral pions and charged hadrons does not provide a very strong argument for energy loss on the partonic level, since the yield of unidentified hadrons above $p_T \approx 5$ GeV/c is dominated by charged pions [5]. PHENIX has measured the production of $\eta$ mesons in Au+Au, d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV which allows to study the effects of hot and cold nuclear matter with an additional probe of identified high-$p_T$ particles and to compare with the results of neutral pion and direct photon production [11].

This is done in Fig. 4 for the most central collision in Au+Au. It is clearly seen that the nuclear modification factor for $\eta$ mesons shows the same pattern as for $\pi^0$s, a suppression of a factor of five and the same constancy at high $p_T$. These features are well described by the energy-loss calculation shown in Fig. 1 for a medium with density $dN^g/dy = 1100$ [12]. As already mentioned above, direct photons show no suppression at high $p_T$ which nicely illustrates the insensitivity of photons to the
produced medium of quarks and gluons and provides the \textit{in situ} confirmation that hard scatterings occur at the expected rate in central Au+Au reactions.

A different approach to compare the production of $\pi^0$s and $\eta$s at high $p_T$ is to study the dependence of the ratio $\eta/\pi^0$ on collision species and centrality. Since $\eta$s and $\pi^0$s are reconstructed within the same data set via their decay into two photons, many systematic uncertainties cancel. The result is shown in Fig. 2 for d+Au, p+p reactions and for three different centralities in Au+Au together with a PYTHIA calculation. The ratios for all colliding species and centralities are consistent within the errors, again demonstrating that the energy loss occurs at the partonic level and the fragmentation process is not strongly affected by the medium.

4. System Size Dependence

The study of different system sizes in general is motivated by the fact that a smaller colliding system (e.g. Cu with $A = 63$) allows for a more precise discrimination for smaller values of $N_{\text{part}}$, corresponding to peripheral collisions with Au ($A = 197$). In addition it allows for the study of the effects of collision geometry, since at the same $N_{\text{part}}$ the overlap region for the smaller Cu-system is more spherical and the surface/volume ratio is smaller. For these reasons Cu+Cu collisions were studied in the fifth year of physics running (2004/2005) at RHIC.

![Graph showing nuclear modification factor for mid-central Pb+Pb collisions ($N_{\text{part}} = 132$, $\sqrt{s_{NN}} = 17.3$ GeV) measured by WA98 at CERN-SPS and for central Cu+Cu collisions ($N_{\text{part}} = 140$, $\sqrt{s_{NN}} = 22.4$ GeV) measured by PHENIX at RHIC.]

The nuclear modification factor $R_{AA}$ is plotted against $p_T$ (GeV/c) showing the comparison between Cu+Cu and Pb+Pb collisions.

At the same number of participating nucleons and at the same $\sqrt{s_{NN}}$, corre-
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The suppressed production of hadrons at high-$p_T$, observed by the RHIC experiments at $\sqrt{s_{NN}} = 200$ GeV and 130 GeV, also triggered the discussion, if and to what extent jet-quenching plays already a role at SPS energies and how the energy dependence evolves. After a re-evaluation of the existing SPS data with an improved p+p reference [19], it appears that some amount of jet-quenching may already be present in central heavy-ion collisions at $\sqrt{s_{NN}} \approx 20$ GeV. To finally answer this question, the first step has been taken by the PHENIX experiment by measuring the production of neutral pions in Cu+Cu collisions at $\sqrt{s_{NN}} \approx 22.4$ GeV up to $p_T \approx 5$ GeV/c. Though the measurement of the p+p reference within the same experiment is still missing at the moment, there exists a wealth of data for p+p $\rightarrow \pi^0/\pi^\pm + X$ in the range $\sqrt{s_{NN}} = 21.7 - 23$ GeV which allows to construct a p+p reference with a systematic uncertainty of $\approx 20\%$.

The resulting nuclear modification shows no strong variations with centrality, instead it indicates Cronin-enhancement. The comparison of the PHENIX result for Cu+Cu and the WA98 result in Pb+Pb for similar $N_{part}$ is shown in Figure 6. Both measurements agree well where they overlap and the PHENIX measurement nicely extends to higher $p_T$. What is still missing is the measurement of the p+p reference within the same experiment, to improve the significance of the result in Cu+Cu and also a measurement of Au+Au collisions at the same colliding energy to reach higher energy densities than in Cu+Cu reactions.

6. Conclusion

We have shown a systematic study of high $p_T$ particle production by comparing the nuclear modification factor $R_{AA}$ for different particle species, colliding species and center-of-mass energies. We demonstrated that the $\pi^0$ and $\eta$ yield in central Au+Au at $\sqrt{s_{NN}} = 200$ collisions show a similar suppression pattern, indicating
that the suppression is happening at the partonic level. $R_{AA}$ for different Au+Au and Cu+Cu reactions shows a very similar dependence on $p_T$ and $N_{part}$, with some indications that geometric effects can become important when comparing the most central Cu+Cu to Au+Au collisions at similar $N_{part}$. We have also shown the first measurement of high-$p_T$ particle production near SPS energies ($\sqrt{s_{NN}} = 22.4$ GeV) at RHIC which agree with previous measurements by WA98 and extended the measurement to higher $p_T$. The reference measurement at RHIC with p+p collisions at the same energy is still needed.

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