JET QUENCHING AT RHIC

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ABSTRACT

We present high transverse momentum ($p_T$) measurements made at the Relativistic Heavy Ion Collider (RHIC) for Au+Au, d+Au, and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV, as well as for Au+Au collisions at $\sqrt{s_{NN}} = 62$ GeV. We observe a suppression in the yield of high $p_T$ hadrons measured in central Au+Au collisions, relative to the yield in p+p collisions scaled by the number of binary nucleon-nucleon collisions. This observation, together with the absence of such a suppression in d+Au collisions, leads to the conclusion that a dense medium is formed in central Au+Au collisions.
1 Heavy Ion Collisions

Numerical simulations of quantum chromodynamics (QCD) on a lattice predict a phase transition (or crossover) from hadronic matter to deconfined, chirally symmetric matter at sufficiently large energy densities [1]. The critical energy density calculated is typically $\sim 0.7 \text{ GeV/fm}^3$, approximately 5 times the density of normal nuclear matter. The primary goal of high energy heavy ion physics is to achieve such a transition and to study this new state of matter, the Quark Gluon Plasma (QGP), in order to better understand fundamental properties of QCD. With the new collider RHIC, the field has recently reached a new energy regime, which will be a milestone in the endeavor to attain this goal.

The Relativistic Heavy Ion Collider (RHIC) is located at Brookhaven National Laboratory (BNL) on Long Island, New York. RHIC has provided Au+Au collisions at $\sqrt{s_{NN}} = 130 \text{ GeV}$; Au+Au collisions at $\sqrt{s_{NN}} = 62 \text{ GeV}$; and Au+Au, d+Au, and p+p collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$. At these energies, hard scattering is expected to contribute significantly to particle production.

1.1 Hard Scattering in Heavy Ion Collisions

In order to understand the complicated dynamics of a heavy ion collision, one needs a calibrated, understood probe. This can be provided by hard-scattered partons, for which the fragmentation dominates particle production at high $p_T$. In particular, it is known that the fragmentation of partons into jets dominates the production of hadrons above $p_T \sim 2 \text{ GeV/c}$ [2] in p+p collisions. For the hard-scattered partons to serve as a probe of heavy ion collisions, a baseline for high $p_T$ particle production, at the same $\sqrt{s_{NN}}$, must first be established from p+p collisions. Figure 1 shows the neutral pion production cross section measured in p+p collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$ by the PHENIX experiment [3]. The production cross section is well described by NLO pQCD calculations [4, 5]. Therefore, the measurement in p+p collisions can provide a baseline for measurements in Au+Au collisions.

In heavy ion collisions, the boundary between where hard and where soft production dominates the measured hadron yields is affected by flow [6, 7] and possibly parton coalescence [8, 9, 10, 11]. This complicates the high $p_T$ region between 2 and 4 GeV/c. However, in Run II at RHIC ($\sqrt{s_{NN}} = 200 \text{ GeV}$), hadrons have been measured up to $p_T \sim 10 \text{ GeV/c}$ in Au+Au collisions [12, 13, 14]. At such large transverse momenta, interactions are expected to be incoherent even in heavy ion collisions, and perturbative QCD calculations can reliably be used as a baseline for hadron production [15, 16, 17, 18]. Thus, at sufficiently high
Neutral pion production cross section as a function of $p_T$ measured in $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV by the PHENIX experiment [3]. Comparisons are shown to NLO pQCD calculations with two different fragmentation functions [4, 5].

Figure 1: Neutral pion production cross section as a function of $p_T$ measured in $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV by the PHENIX experiment [3]. Comparisons are shown to NLO pQCD calculations with two different fragmentation functions [4, 5].

transverse momenta, we still have a calibrated probe for heavy ion collisions. Hard scatterings provide a particularly valuable probe, in fact, because they occur early in the collision, leaving the hard-scattered partons sensitive to the properties of the collision medium. A hard scattering occurs on a timescale of $\sim 1/p_T$, which for $p_T = 2$ GeV is approximately 0.1 fm/c. This is smaller than the time it takes for the system to equilibrate [19]. Therefore, the hard-scattered partons experience the entire space-time of the system and serve as a probe of the produced medium. It has been predicted that the hard-scattered partons will reinteract in a deconfined medium of free color charges, losing much of their energy [20]. This would result in a suppression of the high transverse momentum tail of the hadron spectrum, where the hadrons are likely to be the leading particles of jets, and is known as “jet
quenching."

1.2 Centrality

In a Au+Au collision, the properties of the produced medium depend on the centrality of the collision. At large impact parameter, the overlap region between the two nuclei (or system size) is small; and at small impact parameter, the system size is large. Heavy ion collisions are generally binned into centrality selections. Such selections can be classified according to their geometry, with a class of events having a mean number of participating nucleons $N_{part}$ and a mean number of binary nucleon-nucleon collisions $N_{binary}$ determined by a Glauber [21] model simulation. The maximum $N_{part}$ possible for a Au+Au collision is 394 (2x197), and $N_{binary}$ exceeds 1000 for the most central events. Physics observables are presented as a function of centrality, from the most peripheral selection, corresponding to the events with the least amount of overlap between the nuclei, to the most central selection, corresponding to the events with the most overlap. Centrality is expressed as a percentage of the total inelastic cross section.

2 Scaling of Hadron Production

At large transverse momenta, where the cross sections are small and particles are expected to undergo incoherent interactions, a heavy ion (A+A) collision can be viewed simply as a superposition of binary nucleon-nucleon (N+N) collisions. The scaling between systems of different sizes is the number of sources for hard parton scatterings. Therefore, to compare Au+Au collisions with p+p collisions, the scaling is the mean number of nucleon-nucleon collisions $N_{binary}$, or alternately the Glauber nuclear overlap function $T_{AA}$. We quantify the effects of the nuclear medium by the nuclear modification factor $R_{AA}$, which is the fraction of yields at high $p_T$ measured in A+A collisions to those measured in p+p collisions scaled by $N_{binary}$ (Eq. 1) or $T_{AA}$ (Eq. 2).

$$R_{AA}(p_T) = \frac{\langle \text{Yield per A + A collision} \rangle}{\langle N_{binary} \rangle \langle \text{Yield per p + p collision} \rangle} \frac{d^2 N^{A+A}/dp_Td\eta}{d^2 (\sigma^{p+p}/dp_Td\eta)/d^2 \sigma_{inelastic}/dp_Td\eta}$$

$$= \frac{\langle N_{binary} \rangle (d^2 \sigma^{p+p}/dp_Td\eta)/\sigma_{inelastic}^{p+p}}{d^2 N^{A+A}/dp_Td\eta / \langle T_{AA} \rangle (d^2 \sigma^{p+p}/dp_Td\eta)}.$$  

At low $p_T$, where soft production dominates the measured yields, $R_{AA}$ is less than one because soft production is expected to scale with the number of participants...
$N_{\text{part}}$, rather than $N_{\text{binary}}$. At transverse momenta sufficiently large to be in a hard-scattering regime and in the absence of any nuclear effects, $R_{AA}$ is expected to be equal to unity; in which case a A+A collision can be described as a superposition of binary N+N collisions. A deviation from unity at high $p_T$ is a measure of the effect of the nuclear medium. Previously measured nuclear effects include the “Cronin” effect [22], an enhancement in the yields relative to binary scaling ($R_{AA} > 1$) attributed to $k_T$ broadening due to initial state multiple scattering [23, 24]. The predicted energy loss due to the dense medium, or jet quenching, is a suppression in the nuclear modification factor ($R_{AA} < 1$).

3 Measurements of $R_{AA}$

The invariant yields of hadrons as a function of $p_T$ have been measured in Au+Au collisions at $\sqrt{s_{NN}} = 130, 200$, and most recently 62 GeV. The charged hadron $p_T$ spectra have been measured by all 4 RHIC experiments \cite{13, 14, 25, 26}, and the neutral pion $p_T$ spectra have been measured by the PHENIX experiment \cite{27, 12}. In Fig. 2 the neutral pion $p_T$ spectra are shown for all centrality selections from the most central bin (0-10%) to the most peripheral (80-92%), at $\sqrt{s_{NN}} = 200$ GeV.

Figure 3 shows the nuclear modification factor $R_{AA}$ (Eqs. 1 and 2) for the most central and for the most peripheral Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The central data show a significant suppression (which was first observed at $\sqrt{s_{NN}} = 130$ GeV at moderate $p_T$ of 2-4 GeV/c \cite{27}) of a factor of $\sim 4 - 5$ at high $p_T$; while $R_{AA}$ for peripheral events is consistent with binary-scaling within errors (p+p yields scaled by the number of $N_{\text{binary}}$ in the peripheral event sample). This indicates that the nuclear effects are large in central Au+Au collisions and small in peripheral collisions. Shown in Fig. 4, by the lower red points, is the evolution of $R_{AA}$ from the most peripheral to the most central collisions for yields integrated over $p_T > 4$ GeV/c, in terms of the mean number of participating nucleons $N_{\text{part}}$ in a centrality selection. Here, one sees that the suppression gradually increases from peripheral to central events.

It is also useful to investigate the dependence of $R_{AA}$ on the $\sqrt{s_{NN}}$. Figure 5 shows the measured $R_{AA}$ for neutral pions in Pb+Pb collisions at $\sqrt{s_{NN}} = 17$ GeV at the SPS \cite{28} (re-analysis of p+p reference \cite{29}) and in Au+Au collisions at $\sqrt{s_{NN}} = 62$ GeV and at $\sqrt{s_{NN}} = 200$ GeV \cite{12} at RHIC. At the SPS, in Pb+Pb collisions, there is no apparent suppression, and any possible energy loss effect present in these collisions is dominated by the Cronin effect. At RHIC, for the first time, a suppression was observed in central Au+Au collisions consistent with the prediction
Figure 2: Invariant neutral pion yields as a function of $p_T$ measured in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the PHENIX experiment [12]. Spectra for different centrality selections are scaled by factors of 10 for presentation.

for jet quenching. The suppression persisting up to $p_T = 10$ GeV/c, observed in Run II for $\sqrt{s_{NN}} = 200$ GeV, was successfully predicted by theoretical calculations that invoke an energy loss proportional to the energy of the parton combined with shadowing and initial-state $k_T$-broadening [30, 31]. A comparison with theoretical predictions is shown in Sec. 6. The most recent measurement at $\sqrt{s_{NN}} = 62$ GeV from Run IV is also included in the figure and shows a similar suppression for $p_T > 4−5$ GeV/c.

4 Correlation Measurements to Detect Jets

Due to the high multiplicity environment, jets cannot be directly observed in a heavy ion collision. When interpreting the modification of the particle spectra at high $p_T$ as an effect of the medium on the hard-scattered partons, one assumes that the hadrons measured at high $p_T$ emanate from jets. A method to detect the presence of jets in high multiplicity environment is via two-particle angular correlation measurements. To extract the jet signal from the correlation distributions, other sources of correlation, such as flow and resonance decays, and the combinatorial
Figure 3: The $R_{AA}$ for neutral pions as a function of $p_T$ measured in Au+Au collisions by the PHENIX experiment [12]. The red points are for central events (0-10% centrality), and the blue squares are for peripheral events (80-92% centrality). The shaded bars indicate the fractional normalization error (shown as the fraction of the first data point), which is dominated by the uncertainty in $\langle T_{AA} \rangle$.

background need to be disentangled from the correlations due to jets. The STAR experiment has made such a measurement [32] and found that the away-side jet disappears in central Au+Au collisions. This is shown in the bottom right panel of Fig. 6. The "near-side" correlations are those at $|\Delta \phi| \sim 0^\circ$, and the "away-side" are at $|\Delta \phi| \sim 180^\circ$. Since the near-side contains the trigger particle, the correlation function can be understood as a conditional probability. When triggering on a high $p_T$ particle, the near-side correlation looks very similar to the correlation due to jets measured in p+p collisions (black histogram); but there is no jet correlation seen on the away-side in central Au+Au events, contrary to what is measured in p+p collisions. A possible interpretation is that the hadrons that we measure at high $p_T$ in central Au+Au collisions come from hard scatterings near the surface of the system. This would allow one jet to escape the medium; while the corresponding jet must traverse the dense medium where it could interact, lose much its energy, and become lost in the low $p_T$ soft part of the spectrum.

Although both observations that were made in central Au+Au collisions
Figure 4: The $R_{AA}$ for neutral pions as a function of $N_{part}$ (or centrality) measured in Au+Au collisions by the PHENIX experiment [12] for integrated yields for $p_T > 4$ GeV/c. The lower red points show $R_{AA}$ as defined in Eq. (1), while the upper blue points show $R_{AA}^{part}$, for which $N_{binary}$ in Eq. (1) is replaced by $N_{part}$. The shaded bands around the points indicate the systematic errors on $N_{binary}$ or $N_{part}$.

at RHIC (the suppression in the hadron yields at high $p_T$ and the disappearance of the away-side jet) seem to indicate that the hard-scattered partons lose energy in the dense medium, the effect of the “cold” nuclear medium (p+A or d+A collisions) is essential to rule out initial-state nuclear effects.

5 Results from d+Au Collisions

In Run III at RHIC, high $p_T$ particle production was studied in d+Au collisions. To distinguish initial-state effects from final-state effects on the suppression observed in central Au+Au collisions, d+Au collisions provide a good comparison experiment with only initial-state nuclear effects. Figure 6 shows the results from all 4 RHIC experiments [33, 34, 26, 35]. From these results, the consistent conclusion is that the suppression observed in central Au+Au collisions is not observed in d+Au collisions. Similarly, the disappearance of the away-side jet (bottom right panel) is also not observed in d+Au collisions. This indicates that the novel phenomena observed in central Au+Au collisions at RHIC are due to effects of the medium produced in
Figure 5: $R_{AA}$ for neutral pions in central Au+Au collisions at RHIC at $\sqrt{s_{NN}} = 200$ GeV \[12\] and $\sqrt{s_{NN}} = 62$ GeV (PHENIX preliminary), and central Pb+Pb collisions at the SPS \[28, 29\] ($\sqrt{s_{NN}} = 17$ GeV). The boxes surrounding the data points indicate the systematic uncertainties that are correlated in $p_T$. The black line at 1 shows the percent normalization error on the data for $\sqrt{s_{NN}} = 200$ GeV, and the red line for $\sqrt{s_{NN}} = 62$ GeV.

these collisions, rather than initial-state nuclear effects.

6  Comparison to Theory

The measurements of high $p_T$ hadron production in Au+Au and d+Au collisions have been compared with theoretical calculations. Figure 7 shows the model prediction for $R_{AA}$ in central Au+Au events (lower red line), which includes the effect of energy loss of hard-scattered partons. It is in good agreement with the data. For the comparison to the measurement in d+Au collisions, the predictions from the same model include only initial-state effects, shown by the different lines (for varying initial-state effects) near and above $R_{AA} = 1$. The model results for d+Au collisions are also in reasonable agreement with the data. This supports the conclusion that a final-state nuclear medium effect, such as parton energy loss, is necessary to describe the suppression observed in central Au+Au collisions.
Figure 6: Results of measurements in d+Au collisions from all 4 RHIC experiments as a comparison to the novel effects observed in central Au+Au collisions. The two upper and the lower left panel show $R_{AA}$ vs. $p_T$, and the bottom right panel shows the angular correlation measurement due to jets. The upper left shows $R_{AA}$ for neutral pions and charged hadrons measured in d+Au collisions by PHENIX [33]. The upper right shows $R_{AA}$ for charged hadrons measured in different centrality selections in d+Au collisions by PHOBOS [34], where the most central in d+Au collisions is compared to the measurement in central Au+Au collisions (the red line). The lower left is $R_{AA}$ in d+Au collisions compared to central Au+Au collisions measured by BRAHMS [26]. The lower right is the jet correlation signal measured in p+p collisions, d+Au collisions, and central Au+Au collisions by STAR [35].
Figure 7: The measured $R_{AA}$ as a function of $p_T$ compared with theoretical predictions for central Au+Au collisions [36] and d+Au collisions [37]. The boxes around the data points indicate the systematic errors correlated in $p_T$, and the shaded grey band at 1 indicates the percent normalization error.
7 Conclusions

At RHIC, one of the most significant observations thus far is the depletion of high $p_T$ hadrons in central Au+Au collisions. Such a suppression is consistent with predictions in which hard-scattered partons lose energy in a dense medium. Complementing this observation is the discovery of the disappearance of the away-side jet in central Au+Au collisions, which can also be explained by interactions of the hard-scattered partons in a dense medium. As a reference for the effect of cold nuclear matter on hadron spectra at high $p_T$ and on correlations due to jets, the same measurements were made in d+Au collisions. The charged hadron and neutral pion spectra were found not to be suppressed relative to the binary-scaled spectra measured in p+p collisions, and the away-side jet was found not to disappear.

The measurements of $R_{AA}$ are in agreement with theoretical predictions both for central Au+Au and for d+Au collisions. The model includes the effect of energy loss in a dense medium, as well as initial-state nuclear effects, in central Au+Au collisions, and only initial-state effects in d+Au collisions.

Both the results from d+Au collisions and the comparisons to theory support the conclusion that the suppression of high $p_T$ hadrons is an effect due to the produced medium in central Au+Au collisions.

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